INTRODUCTION

In many warm-dry and mild climate areas, earth has been a predominantly used material in construction. Currently, one third of humankind live in earth dwellings, and in developing countries, more than one half of the population do.

In our society, we are using high embodied energy materials to build our households which are in addition hard to recycle, and some of them even contain toxic elements. There is neither a concern about producing residues nor consuming materials and energy.

All these materials and resources are limited, and the reduction of their demand can be achieved by reusing, recycling, and/ or regenerating the materials used.

These are enough reasons to vindicate simplicity, the properties of earth as a construction material, and the interest in a kind of construction respectful to its surroundings as well as the environment.

The above mentioned reasons along with the present economic situation prompted architects Ángel Estévez and Sandra Martin to start a new company, *Casa S-Low* , willing to develop a bioconstruction timber-frame and earth envelope modular system, which is low cost and easy to execute, low energy consuming, and CO_2 emissions free.

Their effort to provide the necessary quality guarantees, and fulfill as much as possible the existing lack in regulations as well as the insufficient technical data on earth walls, especially regarding its thermal behavior in our climate as well as building techniques, are the reasons to design an experimental trial in a real scale timber frame, earth wall and green roof module in collaboration with the Dept. of Architectural Constructions II (Construcciones Arquitectónicas II) at EPSEB School.

At the same time, Montserrat Bosch, DAC Professor (Diploma de Ampliación de Competencias) in *impacto ambiental de la edificación y rehabilitación energética* (environmental impact in building and energetic rehabilitation) receives a petition from two students intereste in doing a Final Degree Project related to Low Tech construction. We are those two students, and Montserrat Bosch, along with Antonia Navarro, Professor at the same school, offered us the possibility of taking part in the construction and follow-up study of the S-Low Prototype.

Right after accepting the offer, the S-Low team was created, and it was composed of the above mentioned members as well as other important collaborations:

- Mariana Mas: Architect and expert in mud wall construction techniques who has studied at *Centro Internacional de Construcción con Tierra* (CRATerre), belonging to the CETAR Company.
- Fabio Gatti: architect holding a Masters Degree in *Tecnología de la Arquitectura Construcción e Innovación Tecnológica*, and who did a Masters Final Project on a comparative study of the different contemporary techniques in mud walls construction, and who was also very interested in taking part in the research and construction of the S-Low Prototype.
- Assis Ouzadouh: mud wall construction specialist, worker at the CETAR Company.

Given the relevance of the S-Low prototype and its potential, the management of the Materials Lab at the EPSEB suggested involving more students interested in the project, who might also develop some related research:

- Belén González: *PFG Ensayos de laboratorio y monitorización del prototipo* (Final Degree Project Lab tests and monitoring process on the prototype).
- Andrea Bonilla: PFG Cubierta S-Low (Final Degree Project S-Low roof).
- Diego García: PFG Revestimientos en la tapia (Final Degree Project Earth wall coating).
- Laura Milla: PFM Estudio de revestimientos de tapia (Final Degree Project Earth wall coating study).

This Final Degree Project (TFG), along with the TFG of the rest of students will be the first part of the study and will contain the following:

- Previous analytical study in the laboratory of the earth to be used. The features of two samples of earth will be determined in order to determine the most suitable one for the prototype.
- Planning, organization, and previous studies to the beginning of the construction.
- Helping in the prototype construction, from the setting-out on site until roof completion.
- Providing feedback in order to improve the constructive solutions based on the acquired experience.

1. S-LOW HOUSE PROJECT

Earth is the most important and abundant natural construction material in most parts of the world. It is frequently obtained directly on site from digging for foundation construction. In industrialized countries, the excessive exploitation of natural resources and the centralized production systems, high in costs and energy consumption, cause not only residues, but they also pollute the environment and increase unemployment rates. In such countries, earth has become a building material.

Increasingly, people who build their households demand more economic and energetically efficient constructions, and they are more aware of the importance of health and comfort temperature inside the dwelling. This is where the idea of Casa S-Low comes in.

We believe that mud, as a construction material, has better qualities than industrial materials such as concrete, baked bricks, and silico-calcareous bricks.

These are the reasons why Casa S-Low proposes using earth as a construction material:

- It is respectful towards the environment: extraction, manufacture, and transformation of many building materials often imply severe interventions in the natural environment, and the subsequent CO_2 emissions and the important energy intake.

Image 1-1 Lifecycle of earth as a material

Natural traditional materials such as timber, mud, and stone, only need to be extracted from the natural life cycle, and can be manufactured directly.

- User, comfort, health: buildings must provide a pleasant, comfortable, and healthy life.

Earth controls indoors humidity providing inside environments which are healthy for their residents. In addition, earth walls have high thermal inertia, which create mild indoors environment and are perfectly suited for temperate-Mediterranean, humid, and dry weathers. The absorption capability of earth materials is not only effective for air humidity, but it also contributes, to a lesser but measurable extent, to absorb odors. Also, lab tests have proved that earth building materials which are thick enough (≥ 24 cm) are capable of absorbing high frequency sound waves (for instance, the ones used in mobile phones networks) much better than other building materials.

- Aesthetics: currently, there are earth wall buildings that coexist with contemporary buildings, thus proving they can acquire the same quality and eye-catching features as any other conventional construction.

Due to the impossibility of using earth structurally, according to regulations, Casa S-Low uses another material, considered in the Código Técnico de la Edificación (CTE). Timber frame is used for different reasons:

- Sustainability: Timber is a fully sustainable material, it is recyclable or biodegradable, non-pollutant, its energetic charge is near to 0, and its production is almost CO_2 emissions free.
- Healthy: timber frame, conversely to iron and concrete structures, neither provokes electro-magnetic alterations nor releases emissions. It is a neutral material which also transpires. It is a natural material which offers a unique and healthy comfort.
- Easiness: the timber construction proposed is simple and widely used in countries such as de the U.S.A. or Northern Europe. It neither requires important machinery nor high energy. Timber frame is prefabricated in the factory and is assembled following dry-construction techniques (it only requires screws for joints), thus assembly is quick and accurate; it barely produces any residues, leftovers, or execution errors.

Image 1-2 Timber frame assembly

Both timber and mud together fulfill another important requirement in the prototype: an inexpensive construction system.
The S-Low prototype construction is fairly economic because the system used is very simple and requires few materials, simple machinery, and it diminishes execution terms and wages, as well as the energy necessary. It is a constructive system which reduces materials and transportation expenses since it uses the earth extracted from the same site, it barely needs additional thermal insulation, and because it uses just one kind of structural framing. According to some estimations, construction expenses are reduced by 40% with respect to a conventional construction.

1.1. Casa S-Low company

Once stated the reasons why we are using earth and timber as main materials, Casa S-Low Company introduces its bioconstruction modular system low cost and quick to execute, low energy consumption and CO_2 emissions free.

S-Low House is made of natural materials: timber and earth, which allows for the healthiest respiration and temperature transfer possible in current construction systems. It is absolutely sustainable, produces no residues, it can be dismantled, it is non-pollutant, and uses recyclable or biodegradable materials which closes the materials loop. It requires a simple technology to be built consisting in self-supporting wood-panels and earth wall envelopes.

The designs of the Casa S-Low always take into consideration a geobiological study previously carried out in order to prevent possible electromagnetic fluctuations on the plot with the aim of guarantying the healthy conditions of the dwelling.

Buildings built with the S-Low system are designed following bioclimatic parameters based on thermal inertia and the natural insulation from mud, solar gain, and cross ventilation. For the coldest days of the year, heating is backed up with a small boiler and some thermal solar panels. Thanks to this design, no cooling system is required.

Image 1-3 Casa S-Low single-house dwelling

- The Casa S-Low uses the Platform Frame system, consisting in load bearing walls made of vertical studs and horizontal plates, braced by wooden panels. The façade is an earth wall and foundations are made of concrete or stone gabions.

- The wooden panels structure is very simple: it consists on keep adding new braced platforms of walls and floors on top of the previous ones. Walls are reinforced horizontally by modules in situ before being raised. When modules are squared and plumbed they are joined together by connecting corners and junctions with other walls. Finally, a second plate is hammered on top of the studs, uniting all modules so that joints do not coincide.

- Mud wall sheathing is done once the timber frame, which will be in the interior of the dwelling, is finished. It is executed by doing alternative trenches with the same dimensions as the wooden module. A formwork is used on the outer side. Sand is introduced and then sand is compacted. It is necessary to do a basis on top of which walls will be placed in order to prevent humidity from the soil due to capillarity. It is the upper part of the foundation, made of stone gabions.

The soil extracted to do the foundations is enriched with additives or clay, depending on the composition in order to reach the cohesion needed.

Image 1-4 Low construction typologies

The purpose of Casa S-Low is to offer the service to build healthy and radically sustainable buildings by implementing the bioconstruction system and/ or other systems that renew the construction tradition by only using sustainable, natural, and healthy materials, with the purpose of creating pleasant, healthy, contemporary looking, high quality, and affordable spaces to regular users, companies, and environment and health friendly institutions.

1.2. Casa S-Low prototype

We realized there was a lack of research and information regarding thermal properties as well as the behavior of earth wall constructions in the Mediterranean climate zones, as well as a lack of information on mechanical properties and execution of mixed timber and mud walls, in which mud walls are not the main load bearing elements. At the same time, the intention is solving problems aroused during the execution, and looking for constructive solutions.

For that purpose, a cubic prototype consisting in two modules with lower and upper slabs and ten sheathing modules occupying a 3,54 m x 3,54 m surface area, and 2.9 m high will be built.

Constructive memory prototype:

Foto 1-5 Materials for the prototype execution

Foundations

Superficial foundations consisting in strip footing made of concrete blocks will be used. They will be filled with rubble and mortar. Foundations will be leveled with a mortar layer.

Structure

On top of the foundation there will be a floor structure with an air chamber underneath. It will create a module made of 2 prefabricated OSBIII panels (4,68 m²/panel) with wood as thermal insulation.

A wooden framework will be used as the vertical structure. Joints will be solved with screws.

The garden roof consists in two prefabricated OSBIII panels (4,68 m²/panel) resting on the vertical structure and screwed to it.

Envelope (earth wall)

The exterior perimeter of the prototype is made of 50 cm thick mud walls executed in situ with manual means, extracting sands from a plot in Tarragona and dosed on site. For stabilizing some sides of the sheathing, different aggregates such as cement and expanded clay have been added.

The prototype has two accesses made of a 15 mm thick OSBIII panel, jointed to the structure by 4 screwed hinges.

Envelope (panel sandwich)

One of the walls is made of panel sandwich, consisting in woolen insulation covered by two outer shading pine plywood panels jointed together with a tongue-and-groove system.

Roof

The garden roof of the prototype is divided in two equal parts, to better use the space in order to do a more comprehensive study.

- The part of the roof oriented towards south is made of the following layers, from bottom to top:
  EPDM, extruded polystyrene insulation, retainer 500 g. strap, nodular sheet, high density polyethylene, geotextil sheet, granite, a mixture of granite, sand, organic compost and lawn.
- The part of the roof oriented north is made of the following layers, from bottom to top: EPDM, extruded polystyrene insulation, 500 g retainer. strap, high density polyethylene nodular sheet, polyurethane foam, and lawn.

Image 1-6 S-Low Prototype

Prototype construction purposes:

The ultimate goal of the S-Low prototype construction is obtaining as much information as possible regarding the constructive system, its thermal behavior, and thermal comfort, as well as coming up with new suggestions to improve the issues and inconveniences aroused during construction, granted that construction will produce the least environmental impact possible, and it will take into account sustainability and ecoefficiency aspects, thus minimizing residues and favoring recycling.

Other goals of the study aim to empirically establish the following:

- Thermal properties of insulation, inertia and humidity control of mud walls in a temperate Mediterranean climate.
- Mechanical properties: cohesion and walls overturning resistance (not load bearing elements, but rather helping walls in the wood frame).
- The constructive qualities: earth wall shrinkage working together with the timber frame as one element.

The S-Low Company and CETAR have put the construction materials as well as the specialized workers by cooperation agreements with industrialists interested in developing the S-Low system, Fupicsa S.A. in the case of timber, and Urbanarbolismo S.L. in the case of the garden roof, Tepestar for lawn, Bioklimanatura S.L. for thermal insulation, and Assis Ouzadouh, from CETAR, for mud walls.

2. TESTS

Earth is the main material used in earth walls. In order to do the right dosage and to determine the optimum humidity it is necessary to use the best quality earth possible as well as doing previous analysis.

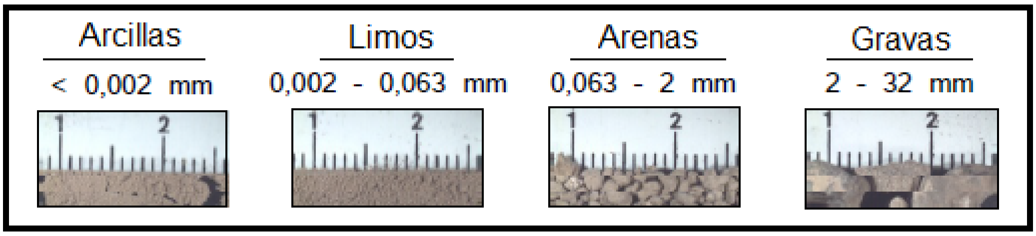
Two samples from different sites have been picked in order to analyze them and decide which one is more suitable:

SAMPLE 1: from "Parc de l'Alba" site, Cerdanyola del Vallés (Barcelona)

SAMPLE 2: from Aquiberia Industrial Polygon site, Castellbisbal (Barcelona)

In order to determine the most suitable sample, some normalized tests will be run in the lab. Later on, during execution, some in situ tests will be performed in order to prove whether the dosages at each time are the right ones. (Reference: "Ensayos: PFG. Construcció en terra d'un habitatge unifamiliar a Martorelles.")

With the aim of determining the earth characteristics, we will classify particles uppon their dimension, according to CTE-SE-C. The following will be the tests to be performed:



- **Laboratory tests:**
- Granulometry test (UNE 103-101): particle dimensions of the earth samples under study are determined by using normalized sieves, as well as the percentage and weight of each reference size in the overall sample.

- Liquid Limit Determination Test "Casagrande" (UNE 103-103-94): to determine the humidity level in which a sample loses its plastic state and turns to liquid.

- Plastic Limit Determination Test (UNE 104-93): to determine the lowest amount of water necessary for the sample to be shapeable.

- Sedimentation granulometry test for fine soils (UNE 103-102): to determine the percentage of Ø < 0,08 mm clay content in a 300 gram sample.

- "Proctor" compaction Test (UNE 103-501-94): to determine the amount of water necessary to add to the earth in order to achieve the optimum density.

- **In situ tests:**

  Following the methodology used by CRAterre (international earth construction center).

- Organoleptic tests: to identify the samples by the senses: sight, touch, and smell.

- Cohesion determination test: two different tests will be performed in order to determine the same result, by dropping a ball and the strip test, thus obtaining two references in order to find out more accurately the earth's cohesion.

- Actual density test: once completed, a test on the earth wall will be performed with the aim the actual density, as a function of the added water and compaction.

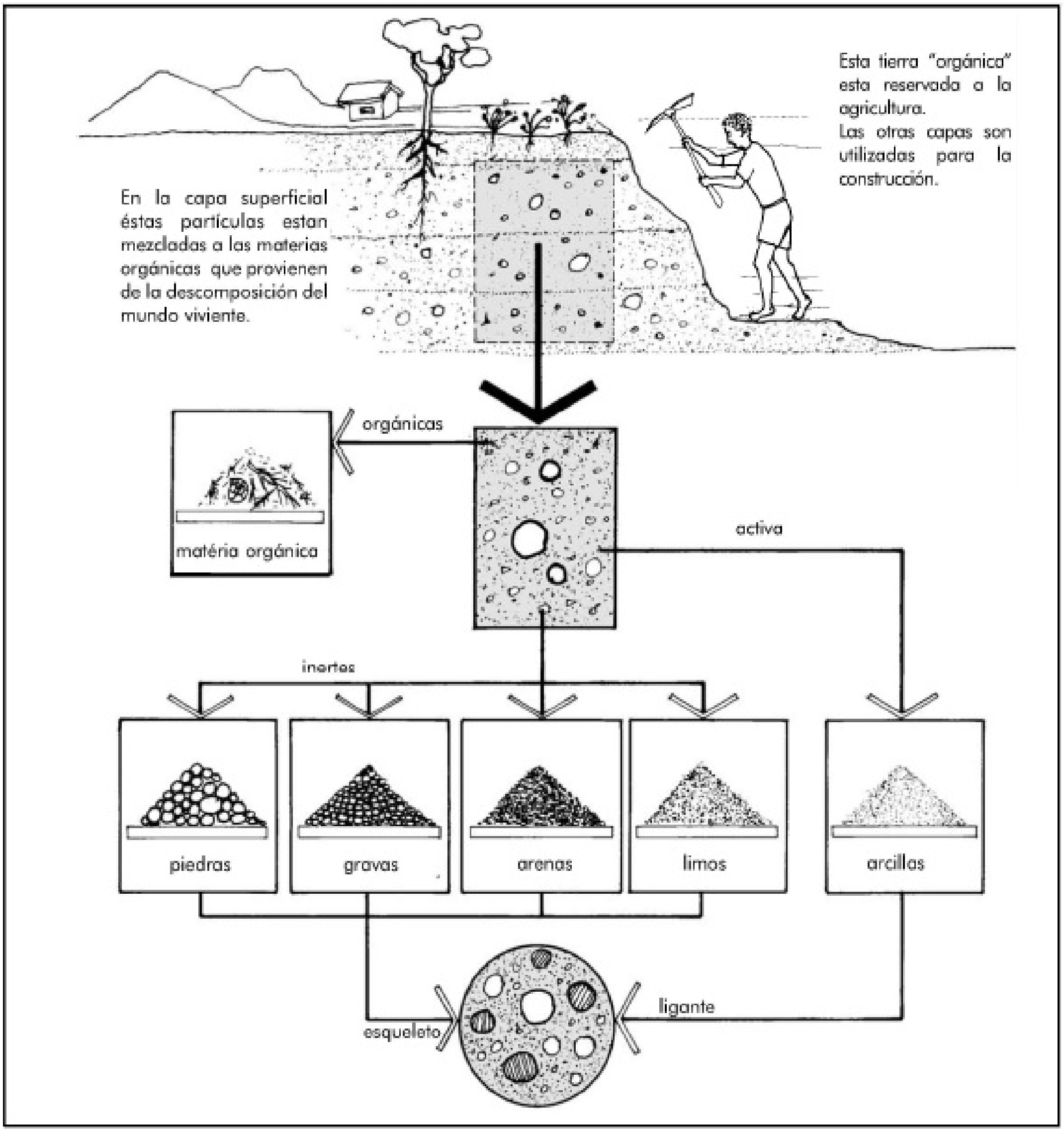


Image 2-1 Earth as a construction material

2.1. Lab tests

2.1.1. Granulometry tests for soils by sieves.

- *Purpose*

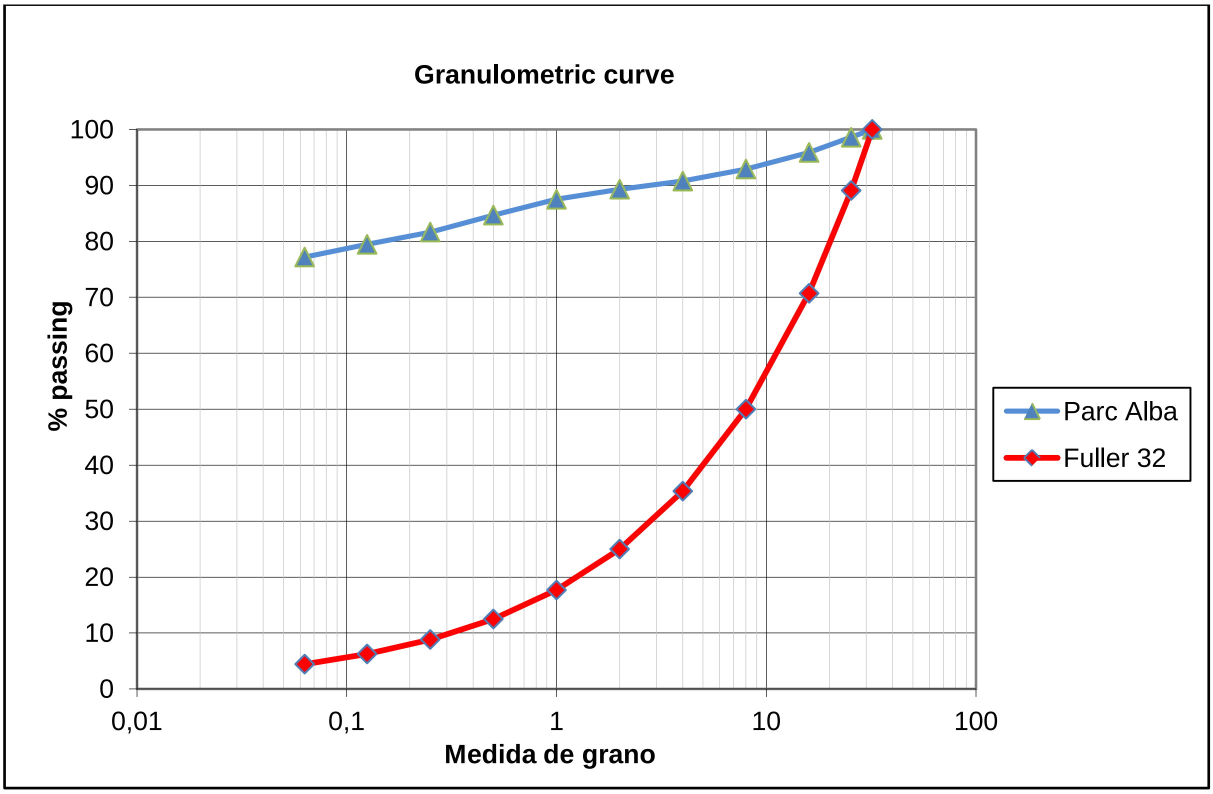
The purpose of this test is to determine the different sizes of particles in the samples since earth is the main raw material used in the prototype, as well as to determine whether the terrain is composed of fine or large aggregates.

- *Results*

During the test, the mass retained in every sieve has been weighed. With the obtained results some charts have been done, showing the following data: the retained weight, the cumulative weights, and mass and percentage of the material retained in every sieve (charts 2.1.1-1 and 2.1.1-2). Percentages retained in every sieve will allow to draw the grading curve and the Fuller 32 curve (maximum compaction curve) which will identify the soil typology (graphs 2.1.1-1 and 2.1.1-2).

	SAMPLE 1 GRANULOMETRY			
Designation and openings (mm)	**Partially retained mass in sieves (g)**	**Total cumulative retained mass in sieves (g)**	**Partially retained mass in sieves (%)**	**Mass that goes completely through the sieve %**
32	0,00	0,00	0,00	100,00
25,4	51,15	51,15	1,40	98,60
16	99,18	150,33	2,71	95,89
8	107,99	258,32	2,95	92,93
4	79,19	337,51	2,17	90,77
2	52,95	390,46	1,45	89,32
1	65,84	456,30	1,80	87,52
0,5	103,26	559,56	2,83	84,69
0,25	110,64	670,20	3,03	81,66
0,125	80,52	750,72	2,20	79,46
0,063	82,51	833,23	2,26	77,20
< 0,063	2821,82	3655	77,20	0,00

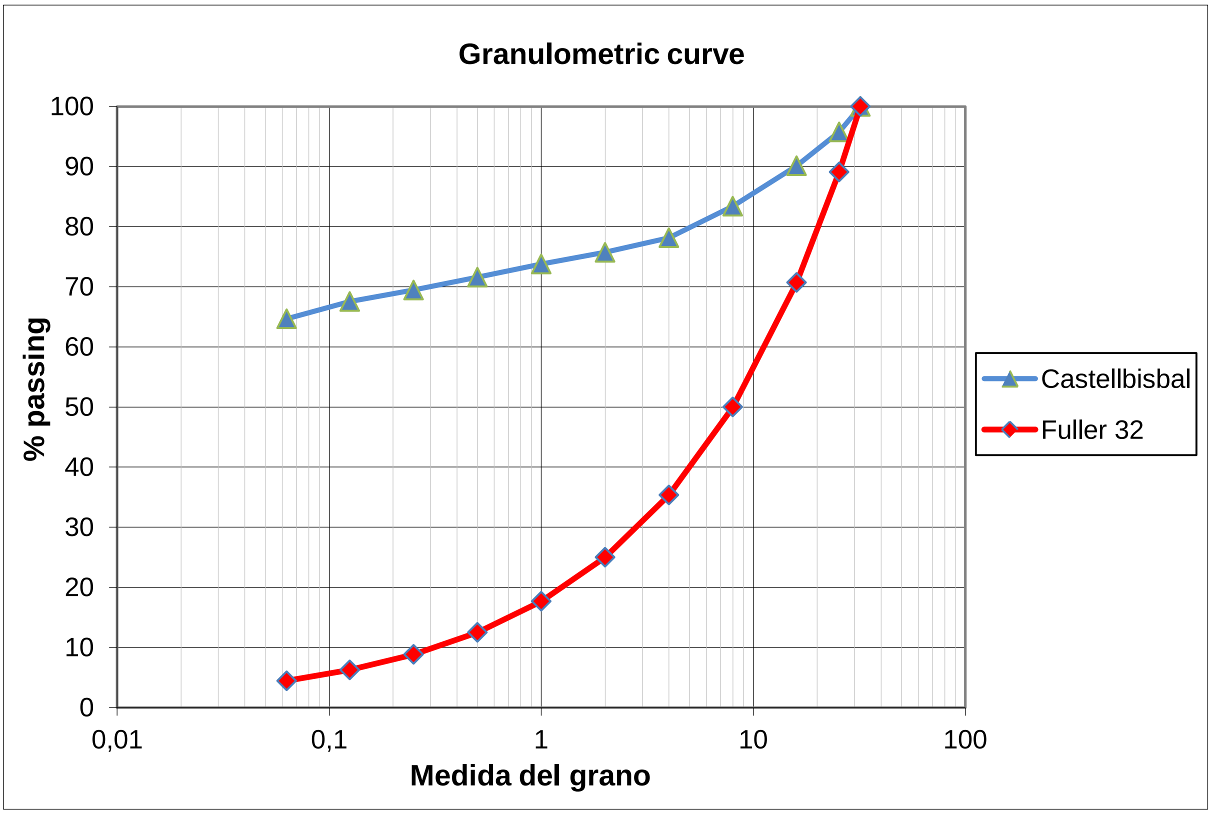
Chart 2.1.1-1. Sample 1 granulometric test results.



Graph 2.1.1-1. Sample 1 granulometric curve.

	SAMPLE 2 GRANULOMETRY			
Designation and openings (mm)	**Partially retained mass in sieves (g)**	**Total cumulative retained mass in sieves (g)**	**Partially retained mass in sieves (%)**	**Mass that goes completely through the sieve %**
32	0,00	0,00	0,00	100,00
25,4	154,80	154,80	4,24	95,76
16	205,60	360,60	5,63	90,14
8	246,10	606,70	6,73	83,41
4	191,50	798,20	5,24	78,17
2	89,30	887,50	2,44	75,72
1	70,80	958,30	1,94	73,79
0,5	79,90	1038,20	2,19	71,60
0,25	78,30	1116,50	2,14	69,46
0,125	69,80	1186,30	1,91	67,55
0,063	105,00	1291,30	2,87	64,68
< 0,063	2363,90	3655	64,68	0,00

Chart 2.1.1-2. Sample 2 granulometric test results.



Graph 2.1.1-2. Sample 2 granulometric curve.

Sample 1, extracted from Parc de Alba, according to the granulometry test results shown in Chart 2.1.1-1, is made up of 22.80% of sand and gravel (833,18 grams), 77.20% of silt and clay contents. Therefore, and according to Casagrande's unified classification, it is a fine cohesive soil.

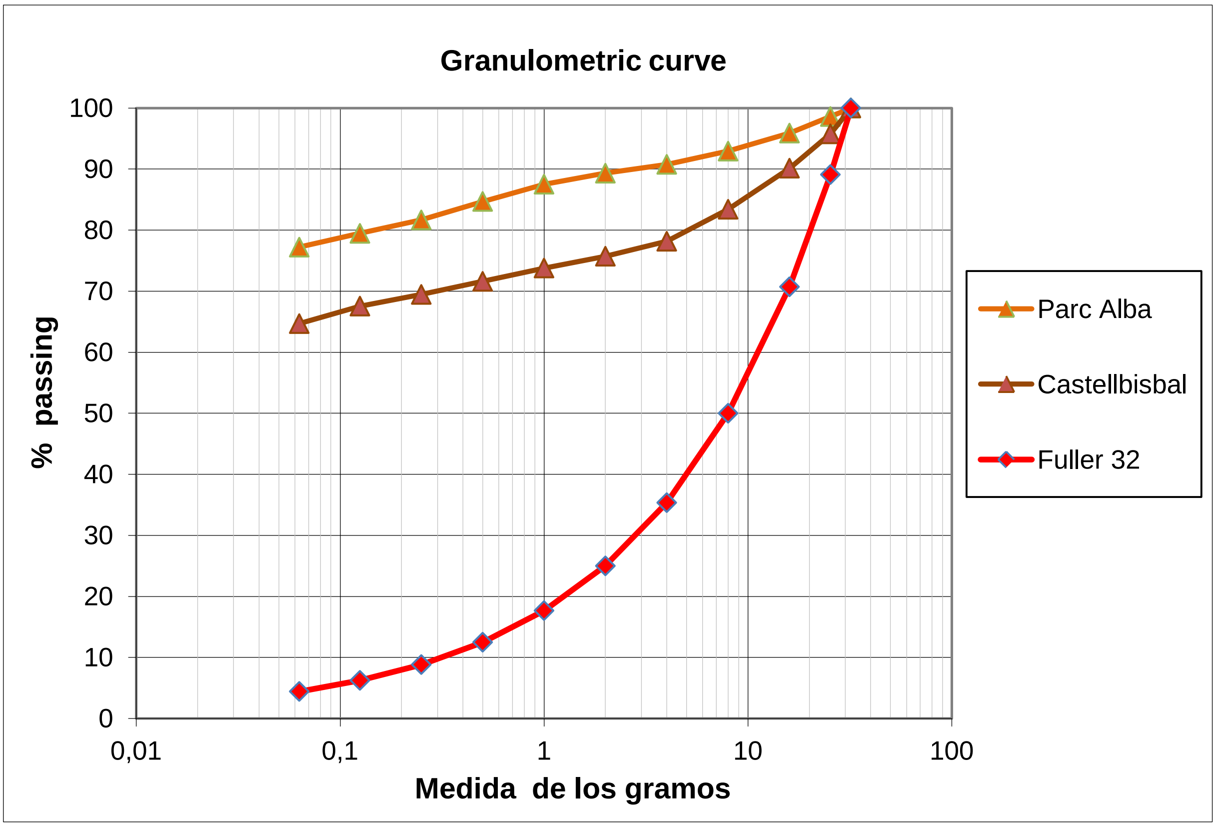
Results for the granulometry test for sample 2, from Castellbisbal, displayed in chart 2.1.1-2 is made up of 35.33% (1291,10 gr) sand and gravel and 64,68 % (2363,90 gr) of silt and clay contents. Thus, it is also a fine cohesive soil.

- *Conclusions*

Both the soil from Parc de Alba and Castellbisbal are a kind of clay soil with a clay content of 77.20% and 64.68% respectively. The results obtained and displayed in the comparative graph with Fuller 32 clearly show an important difference between the ideal maximum compact curve and the curve obtained from our tests. Nevertheless, in graph 2.1.1-3, where the two samples are compared, it is observed that sample 2 displays a more suitable curve for the earth wall since the content of stints and clay (64.68%) is lower than the content in sample 1 (77.20%) (graph 2.1.1.-4). The content of gravels is higher in sample 2 (24.28%) than in sample 1 (10.68%), thus being the granulometry curve more similar to the Fuller 32 curve.

These significant data proves sample 2 to be more suitable for the earth wall since, as the Fuller 32 curve shows, the more balanced a granulometry curve is, the more compact will be the earth during the useful life of walls, thus resulting in more resistant and long-lasting walls.

As an overall conclusion, both samples are fine soils, with more than 50% of the granulometry curve below the diameter 0.063 mm (sample 1=77.20%, sample 2=64.68%).



Graph 2.1.1-3.Granulometry curves for the samples.

Image 2.1.1-1. Sample 1 granulometry.

Image 2.1.1-2. Sample 2 granulometry.

2.1.2. *Determing the liquid limit of a soil by Casagrande's spoon method*

- *Aim*

The aim of this test is to determine the liquid limit of a soil to be used in the construction of the walls of the module. The liquid limit is the percentage of added water that makes it lose the necessary mechanical strength to be shapeable.

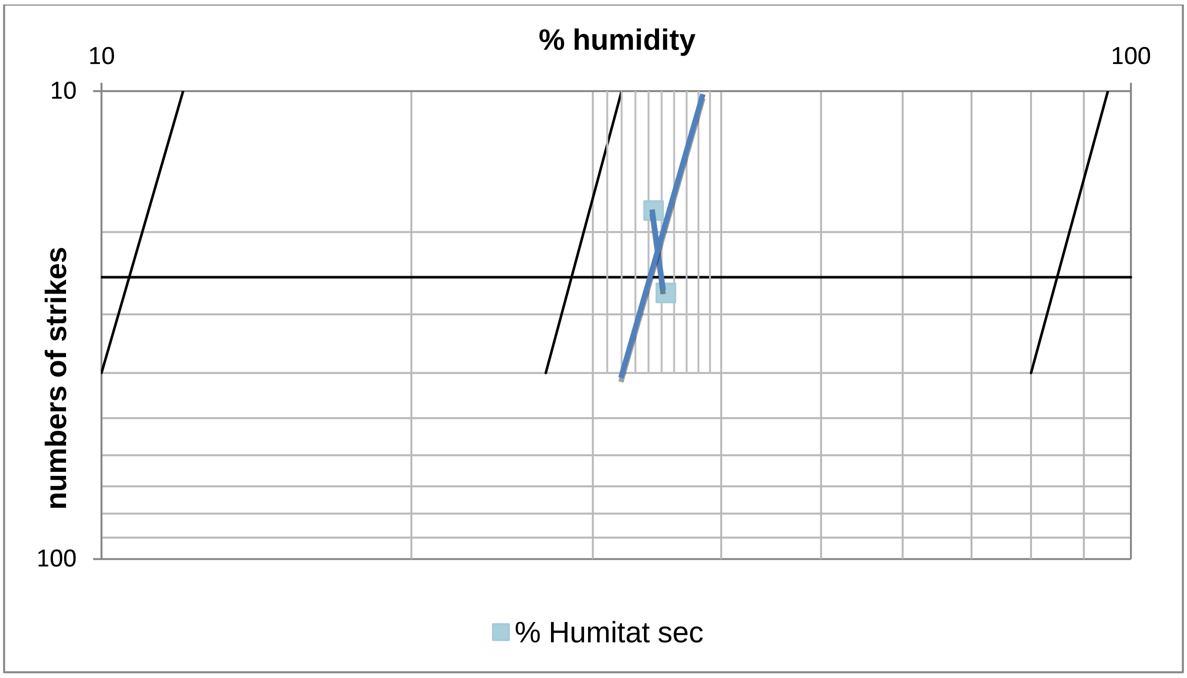
- *Results*

The liquid limit indicates the humidity content necessary for the soil to behave as a liquid. So, next, the data obtained for sample 1 will be analyzed in order to set a liquid limit for this soil. In the following chart, sample1 results are displayed, in other words, the humidity content of earth for each one of the determinations.

SAMPLE 1	DETERMINATIONS	
	Between 25 – 15 strikes	Between 35 – 25 strikes
Number of strikes	18	27
Wet weight (g)	5,59	22,75
Dry weight (g)	4,16	16,81
Water weight (g)	1,43	5,94
Humidity (%)	34,38	35,34

Chart 2.1.2-1. Test results for the determination of the liquid in sample 1.

The results for sample 1 are displayed in graph 2.1.2-1, where the x-axis represents the number of strikes, and the y-axis represents the humidity content in a logarithmic scale. The parallel line to the dotted line is drawn, at the same distance from the points determined between the 25-15 strikes and the 35-25 strikes. The humidity content at the intersection point of this line and the y-value belonging to 25 strikes, expressed as a decimal figure, is the liquid limit. As it can be observed, the liquid limit for sample 1 is 34.5% humidity



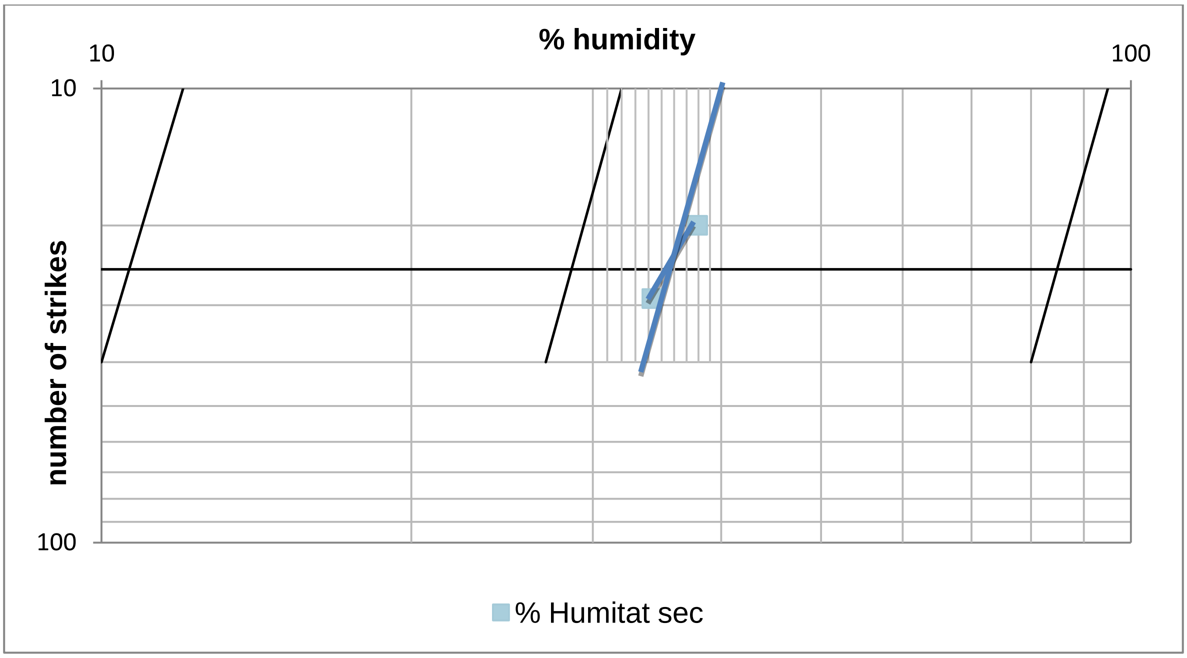
Gráfica 2.1.2-1. Liquid limit determination for sample 1.

The following chart displays the results for sample 2. In other words, the humidity in earth for each determination.

SAMPLE 2	DETERMINATIONS	
	Between 25 – 15 strikes	Between 35 – 25 strikes
Number of strikes	20	29
Wet weight (g)	23,38	15,17
Dry weight (g)	16,95	11,30
Water weight (g)	6,43	3,87
Humidity (%)	37,94	34,25

Chart 2.1.2-2. Test results for the determination of the liquid limit in simple 2.

The results for sample 2 are displayed in graph 2.1.2-2, where the x-axis represents the number of strikes, and the y-axis represents the humidity content in a logarithmic scale. The parallel line to the dotted line is drawn, at the same distance from the points determined between the 25-15 strikes and the 35-25 strikes. The humidity content at the intersection point of this line and the y-value belonging to 25 strikes, expressed as a decimal figure, is the liquid limit. As it can be observed, the liquid limit for sample 2 is 36 % humidity.



Graph 2.1.2-2. Liquid limit determination for simple 2.

- *Conclusions*

The reference norms consulted establish some slightly different limits. For instance, UNE 41410 estates a liquid limit in the 25-50% range. According to the Technological Institute in Santo Domingo, the liquid limit must be less than 45%. For the Australian norm HB 195-2002, it must be less than 35-45% or according to Houben & Guillaud (1994) it must be in the range 25-50%.

Therefore, the only value obtained during the test, belonging to the liquid limit 34.5% for sample 1 and 36% for sample 2, is a valid value accepted by many norms consulted. *(PFG. Criteris d'execució i control de qualitat en la construcció en terra d'un habitatge unifamiliar a Martorelles. Morera Roca, Gisela i Pallarès Madrid, Àngels).*

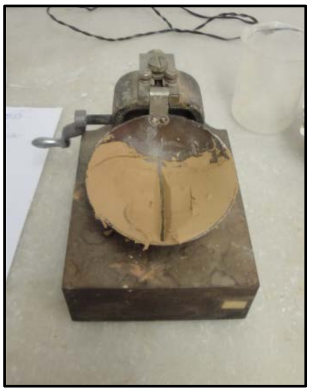


Image 2.1.2-1 Sample 1

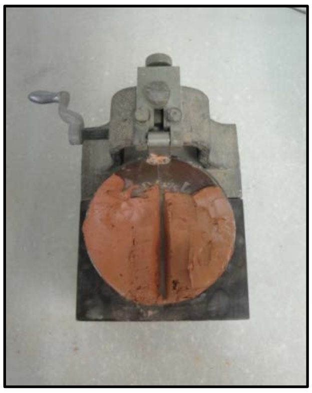


Image 2.1.2-2 Sample 2

2.1.3. Plastic limit determination for a terrain

- Aim

The aim of this test is to determine the plastic limit, that is, to specify the lowest percentage of water so that the soil in both samples is shapeable.

- Results

In order to find out the plastic limit, the arithmetic mean of the humidity values obtained in both determinations will be calculated, with the prerogative that they do not differ more than 2%.

First of all, the sample 1 data will be analyzed. The test has been performed for a SM1 and a SM2, according to the norm. Chart 2.1.3-1 shows the data obtained for sample 1, in which SM1 plastic limit is 24.35% and 18.86% for SM2. That means that the test should be repeated, since the results vary more than 2%. When it was repeated, the difference was again higher than 2%. The conclusion is that the mix is little heterogeneous. Therefore, we agree that the plastic limit for sample 1 is 21.60% humidity.

SAMPLE 1	Wet weight (g)	Dry weight (g)	Humidity (g)	Humidity (%)
Subsample 1	12,05	9,69	2,36	24,35
Subsample 2	9,20	7,74	1,46	18,86

Chart 2.1.3-1. Sample 1 determination test results.

Following the same steps for sample 1, the plastic limit in sample 2 is determined by doing the arithmetical mean of the results obtained in SM1 and SM2. As it can be seen in chart 2.1.3-2, the values obtained during the test were 24.00% in SM1 and 24.11% in SM2. In other words, the plastic limit in sample 2 belongs to 24.05% of humidity.

SAMPLE 2	Wet weight (g)	Dry weight (g)	Humidity (g)	Humidity (%)
Subsample 1	8,06	6,50	1,56	24,00
Subsample 2	11,48	9,25	2,23	24,11

Chart 2.1.3-2. Sample 2 determination test results.

Once the plasticity limits and liquid limits of the mixtures are known, these latter ones determined with the above mentioned test, it will be possible to know the plasticity limit. The plasticity index is the difference between the liquid limit and the plastic limit. Chart 2.1.3-3 shows the limits and the plasticity index for each mixture. It can be observed that sample 1 has a plasticity index of 12.90%. However, sample 2 plasticity index is 11.95%.

SAMPLES	Liquid Limit	Plastic limit	Índexes plasticity
Sample 1	34,50	21,60	12,90
Sample 2	36,00	24,05	11,95

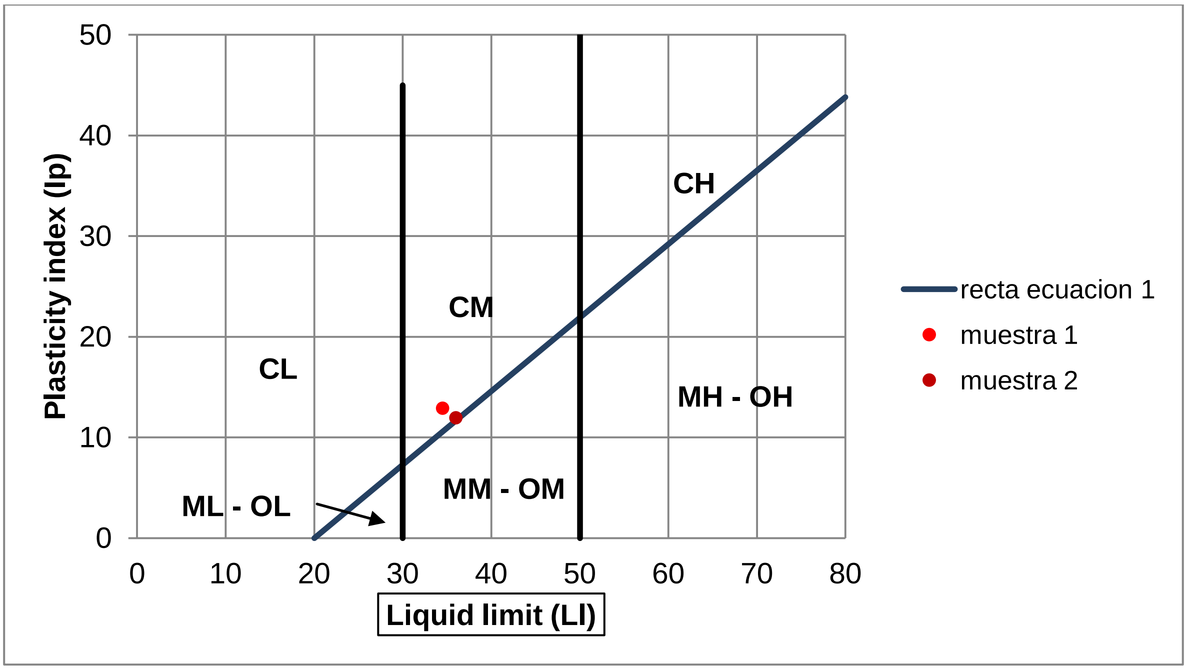
Chart 2.1.3-3. Sample's plasticity indexes.

- *Conclusions*

The insufficient existent norms on earth walls construction in the country has been the reason why norms from other countries have been consulted. In most of them, a specific plastic limit is stated, but they refer instead to the plasticity index. This index is the difference between the liquid limit and the plastic limit. For instance, according to the Santo Domingo Technological Institute, the plasticity index must be below 18%. The Australian norm HB 195-2002 states it has to be under 15-30%, or according to Houben & Guillaud (1994) it must be between 2 and 30%. The norm NBR 13553 has also been consulted, and it establishes a limit equal or below 18%. The norm UNE 41410 shows in the graph 2.1.3-3 a recommended plasticity area for soils. In this area is where the type of earth used has been placed, belonging to a inorganic clay soil with intermediate plasticity.

On the other hand, CRATERRE establishes a set of values for the liquid limit according to the kind of soil. In other words, for a clay soil, as is the case for both of our samples, it states a liquid limit between 0 and 40%. Along with the obtained data in the plastic limit tests, we find out the plasticity index for the earth, used in the "S-low module" mud walls is within the range of values stated by most norms, except for UNE 41410. This means that particles <0,063 mm, which compose this soil, are suitable to be used as a material construction.

(PFG. Criteris d'execució i control de qualitat en la construcció en terra d'un habitatge unifamiliar a Martorelles. Morera Roca, Gisela i Pallarès Madrid, Àngels).



Graph 2.1.3-3. Type of soil determination in samples 1 and 2.

CH: High plasticity inorganic clays

MH and OH: Highly compressive inorganic silts and organic clays.

CM: Medium plasticity inorganic clay.

MM and OM: Medium compressive inorganic silts and organic clays.

CL: Low plasticity inorganic clays.

ML and OL: Low compressive inorganic silts and organic clays.

2.1.4. Sedimentation Test

- *Aim*

This test allows to determine the percentages between fine sands (Ø <0,08 mm), silts, and clay contents in a soil.

- *Results*

When the test is completed and after a 20 minutes rest time, we can check the percentage of silts and clays in each one of the subsamples from both samples 1 and 2. In all cases, there is a continuous granulometry, that is, there is no clear separation between silts and clays.

- *Conclusions*

Since there is no apparent separation between silts and clays, we come to the conclusion that both sample 1 and sample 2 lack from any silt content, and therefore, the complete sample goes through the 0,063 sieve, corresponding to clays.

Image 2.1.4-1 Sample 1

Image 2.1.4-2 Sample 2

2.1.5. Compaction Test. Modified Proctor Test

- *Aim*

The aim is to determine the relationship between dry density and humidity, for 2.632 J/cm^3 compaction energy, in order to define the maximum dry density and its corresponding humidity, known as optimum humidity, according to the standardized modified proctor test (UNE 103-501-94).

This method is based upon the determination of various samples dry densities compacted under the same conditions but with different humidity contents. For each humidity content, a specific density is reached, so that these couple of values, represented on Cartesian axes, will give the relationship we are seeking for.

It is important to know this relation since it is necessary to reach a maximum density in walls. As a consequence, these walls will present less porosity, thus guaranteeing durability and mechanical strength. This test will also allow to determine the humidity used on site during the execution of the earth walls.

In order to carry out this test, only soil from sample 2 has been used, picked as the most suitable one in order to do the wall, compared to sample 1 and definitely discarded.

- *Results*

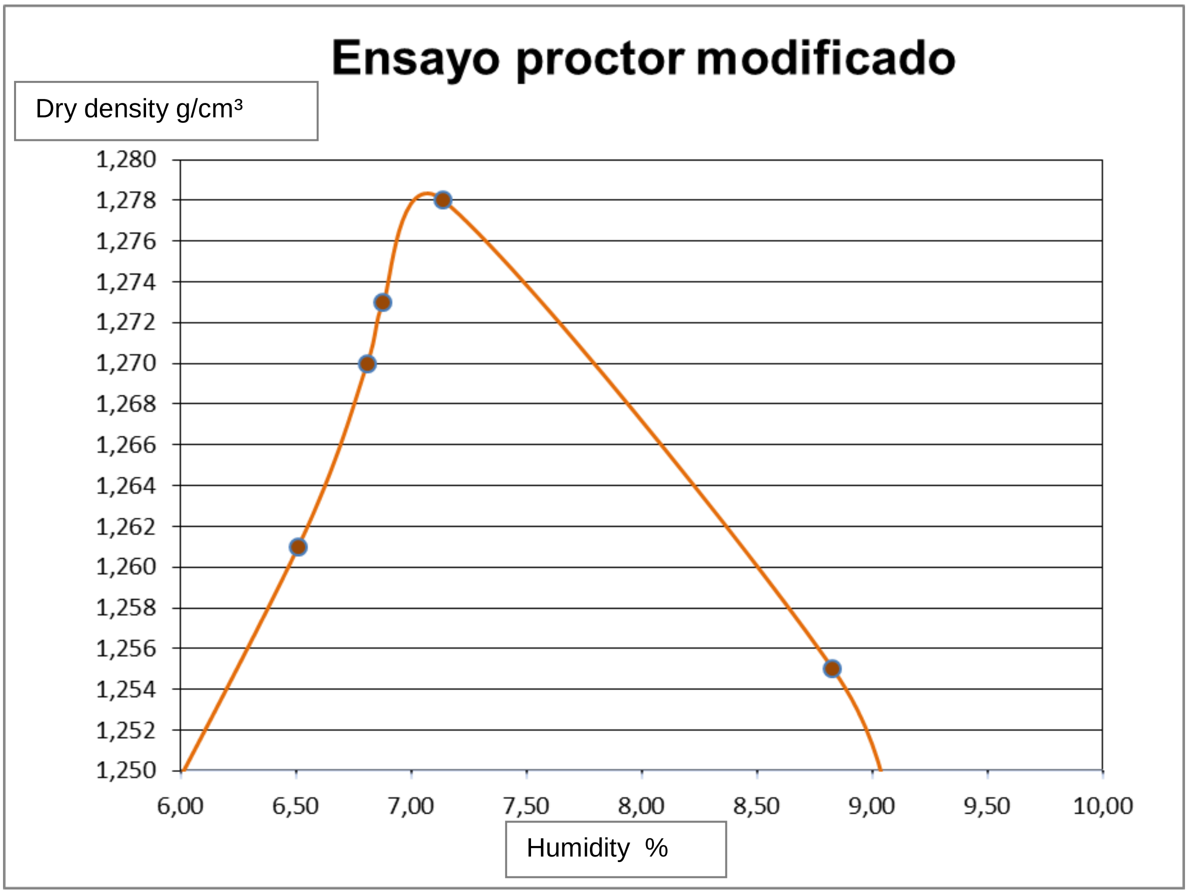
The materials and proceedings used to obtain the data are shown in the point 2.1.5 in the Annex. The results are obtained after following the operation sequence established in Annex A in the norm UNE 103-501-94. Next, the summarized charts with the resulting densities for each humidity percentage will be shown. In chart 2.1.5-1 and 2.1.5-2 are the results from the seven determinations carried out. As it can be seen, the highest density obtained is 1.278 g/cm^3, corresponding to a 7,14 % humidity content.

DRY DENSITY CALCULATION				HUMIDITY CALCULATION		
Wate (%)	Soil + water (g)	Soil (g)	Dry density (g/cm^3)	Humid soil (g)	Dry soil (g)	Humidity (%)
w	S + a	$s = \frac{(s+a) \times 100}{100 + w}$	$\rho = s/v^*$	sh	Sc	$s = \frac{(sh - sc)}{sc} 100$
2%	4415	4145,87	1,261	100	93,88	6,51
4%	4460	4175,64	1,270	100	93,63	6,81
5%	4475	4186,13	1,273	100	93,56	6,88
6%	4500	4200,11	1,278	100	93,34	7,14
7%	4490	4125,70	1,255	100	91,88	8,83
8%	4500	4086,70	1,243	100	91,56	9,28
9%	4490	4060,78	1,235	100	90,44	10,57
12%	4490	3963,63	1,206	100	88,28	13,28
* the volume of the mold: 3287,77 cm^3						

Chart 2.1.5-1. Compaction test results.

Núm. Proctor	Dry density (g/cm^3)	Humidity (%)
1	1,261	6,51
2	1,270	6,81
3	1,273	6,88
4	1,278	7,14
5	1,255	8,83
6	1,243	9,28
7	1,235	10,57
8	1,206	13,28

Chart 2.1.5-2. Compaction test results, Modified Proctor test.



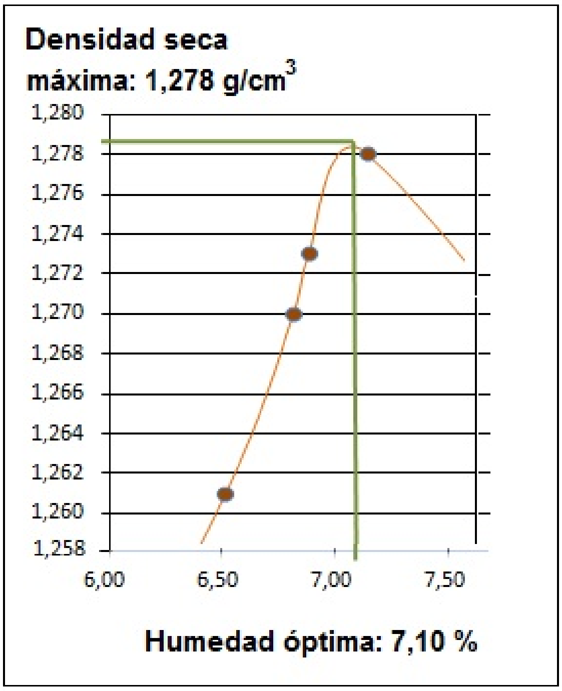
Graph 2.1.5-1. Compaction test results.

Image 2.1.5-1. Modified Proctor execution process.

- *Conclusions*

The necessary compaction degree, determined by the modified Proctor test, varies upon the kind of soil, specifically, upon its humidity content. We carried out this for soils in our samples because currently there is no test that defines the optimum humidity and the maximum dry density.

The increase in humidity, up to a value considered optimum, is due to a softening of the soil which makes it easier to compact it. Above that limit, when a pressure is applied, water occupying pores tends to separate solid particles and, thus, density decreases. Therefore, this test should be carried out in each project.



Graph 2.1.5-2. Maximum dry density point and optimum humidity.

It can be observed that, as the humidity content increases, higher dry specific weights are attained since water inside the sample's pores lubricate particles, causing their better rearrangement up to a maximum value, which in the sample the density is 1.278 g/cm^3 and the optimum humidity is 7.10%. Above this value, the increase in humidity prevents particles to unite, since water occupies the space. Water in pores absorbs the compaction energy applied and therefore, the dry specific weight diminishes. The dry specific weight increase branch is known as the dry branch. The decrease one is known as the humid branch.

The norms consulted, for instance UNE 41410 or NBR 12023, do not establish any humidity content in order to compact the earth, since for each kind of soil and compact effort there is a maximum humidity content. With this humidity level, conditions for attaining a higher compaction are obtained, that is, the maximum density. When the soil reaches the maximum density it shows less porosity, thus characterizing a more long-lasting and more mechanically resistant material.

Knowing the optimum humidity content is very important since it is very useful when looking for a solution in order to improve shear resistance, density, as well as other soil properties. In the case of the material used in our test, it reached 7.10% optimum humidity.

Point nº	1	2	3	4	5	6	7	8
Wáter added %	2%	4%	5%	6%	7%	8%	9%	12%
Mold+Soil+water (g)	9975	10020	10035	10060	10050	10060	10050	10050
Mold (g)	5560	5560	5560	5560	5560	5560	5560	5560
Soil+water (g)	4415	4460	4475	4500	4490	4500	4490	4490
Soil (g)	4145,87	4175,64	4186,13	4200,11	4125,70	4086,70	4060,78	3963,63
Soil volume (cm³)	3287,77	3287,77	3287,77	3287,77	3287,77	3287,77	3287,77	3287,77
Dry density (g/cm³)	1,261	1,270	1,273	1,278	1,255	1,243	1,235	1,206
Tare reference (g)	82,21	76,82	121,78	82,21	82,21	82,09	84,98	121,80
Tare+soil+water (g)	182,21	176,82	221,78	182,21	182,21	182,09	184,98	221,80
Tare+soil (g)	176,09	170,44	215,34	175,55	174,09	173,59	175,42	210,08
Tare (g)	82,21	76,82	121,78	82,21	82,21	82,03	84,98	121,80
Soil (g)	93,88	93,63	93,56	93,34	91,88	91,56	90,44	88,28
Water (g)	6,12	6,38	6,44	6,66	8,12	8,50	9,56	11,72
Humidity (%)	6,51	6,81	6,88	7,14	8,83	9,28	10,57	13,28

Chart 2.1.5-3. Proctor test and compact earth extraction.

Image 2.1.5-2. Realization of the proctor compacted soil extraction.