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Building structures in swelling soils: problems and foundation alternatives

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Building structures in swelling soils:
Problems and foundation alternatives

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Final Year Project

Bachelors in Fundamentals of Architecture

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''A field of clay touched by the genius of man becomes a castle.''

Og Mandino.

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Abstract

The soil is a dynamic entity prone to movements and failure that condition the choice of structure, materials, construction techniques, and so much more regarding the architectural project, this final year project will focus on clay soils and one of their characteristic behaviour: expansivity, which is the volumetric change of the soil due to a change of water content, potentially causing mild to severe structural problems and the apparition of pathologies.

The properties of clayey soil are covered going from the mineralogy to the response to environmental conditions. Techniques for the characterization of expansive soils are also analysed, proposing different types of testing to qualify study samples. Pathologies caused by the expansivity such as the observed damages on the foundations among other problems are listed as well. Furthermore, different constructive solutions both on the level of the structure and the soil are explained in detail.

To better visualize the topic, a case study that is based in Illescas, Toledo, near the capital of Madrid, will be approached. The company Amazon, Inc. has invested in a project of 180.000 m2 of surface area to place their future logistics warehouse. The project is programmed to be built based on special constructive propositions and the technique of lime enhancement has been adopted. A quantitative study with results of two laboratory sample tests before and after the enhancement treatment are compared, concluding that the management of the nature of soil and the method used to control the swelling issues has been successful.

Overall, the objective of this final work project is to get familiarized with expansive soils, specifically on clayey one, and to consider it exigent rather than troublesome. With the right knowledge, building on such nature of ground is perfectly possible and safe at the condition of conducting a rigorous technical study based on the site's observation, tests and the correct choice of preventive measures, all under the consideration of economic costs.

Key words: Clays, expansive soils, structural pathologies, soil improvement, chemical stabilization, foundations.

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1. Introduction

Context

Clay soils represent approximately 80 percent of the earth's land surface (Al Ani and Sarapää, 2008). Besides being so widely spread on the earth’s crust, its uses are incredibly diverse because of the richness of its mineralogy. Architecture professionals tend to view clay soils as very challenging for future projects, but a soil can never be qualified as good or bad. A bad knowledge of its nature and properties is what would define the building experience.

The main objective of this final year project is to study clay soils, in particular its potential expansive behaviour, and the possible method used to control the excessive swelling along with the adequate choice of foundations. These constructive solutions are applied on a real case study: The new warehouse of Amazon located at Illescas, Toledo.

These constructive solutions are applied on a project of Amazon in., based in Illescas, Toledo and near the capital of Madrid, as a case study.

On the other hand, the Spanish technical code (CTE) classifies expansive soils as type 3 unfavorable grounds (Tipo T-3 Terrenos desfavorables) for their risk of provoking cracks, breakage of sanitation and drainage pipes, etc. As can be observed in the table [Fig.1], T-1 grounds are the ones that are favorable with little variety, where the choice of a classical punctual foundation is sufficient, whereas T-2 grounds do have variability that might require different structural approaches depending on the case, considering the existence of anthropic fillings of a thickness of less than 3 meters.

It can be observed that T-3 regroups all categories that are not part of T-1 and T-2, which are generic and do not require special attention.

What can be observed is that this category (T-3) only names examples of unfavorable soils rather than giving further explanation and special considerations regarding the adopted foundations. Rightly, the Spanish code does not give nearly enough information about the topic, nor does it cover procedures to be chosen when it comes to expansive clay, simply categorizing it as unfavorable without further details, when it is one of the most structurally challenging and important types of soil.

Grupo	Descripción
T-1	Terrenos favorables: aquellos con poca variabilidad, y en los que la práctica habitual en la zona es de cimentación directa mediante elementos aislados.
T-2	Terrenos intermedios: los que presentan variabilidad, o que en la zona no siempre se recurre a la misma solución de cimentación, o en los que se puede suponer que tienen rellenos antrópicos de cierta relevancia, aunque probablemente no superen los 3,0 m.
T-3	Terrenos desfavorables: los que no pueden clasificarse en ninguno de los tipos anteriores. De forma especial se considerarán en este grupo los siguientes terrenos: a) Suelos expansivos b) Suelos colapsables c) Suelos blandos o sueltos d) Terrenos kársticos en yesos o calizas e) Terrenos variables en cuanto a composición y estado f) Rellenos antrópicos con espesores superiores a 3 m g) Terrenos en zonas susceptibles de sufrir deslizamientos h) Rocas volcánicas en coladas delgadas o con cavidades i) Terrenos con desnivel superior a 15° j) Suelos residuales k) Terrenos de marismas

Figure 1. Table 3.2 for groups of soils. Source: Technical Spanish code CTE, DB-SE-C.

On the other hand, the CTE states that buildings of small height are more vulnerable in this scenario since the tensions that are transmitted to the ground are not enough to handle the swelling. Similarly, a bad choice of foundations due to reasons that can vary from economical restraints to a lack of knowledge also facilitate the problem.

Personal motivation

I have always had, for as long as I can remember, an unwavering passion for topics related to geology and the sciences of the earth. Understanding the processes that shaped the earth is like a journey through time that allows us to commiserate about the impact such operations can have on different fields of human life.

Back in 2017, I oversaw the scientific rubric of our local school's journal, and I have discovered an immense interest in geology and related sciences. Although I was not yet aware of the impact of geotechnics on an architectural project, the significance of such topics was already clear to my eyes.

Architecture is a practice that is not only built on design, composition, and creation but is also tightly related to the environment in which it is constructed (Mentor, 2016). Geotechnics is a branch that is focused on the study of soils and their behaviors under different circumstances. This practice helps decide what foundations and structural elements are required to build a stable and safe structure.

Expansive clay forms a part of soils that are naturally unstable (Gonzalez de Vallejo, 2002), requiring foundations that consider its complex geological behavior. Building on such ground necessitates special types of structural solutions to ensure the secureness of the building and to respect the local regulations and health conditions stated, such as the CTE-DB-SE normative.

On the other side, I am very sensitive to site investigations, and as much as I am regretful for the lack of time that hindered my desire to visit the site where the case study is located, the analysis of the laboratory results was very stimulating and extremely descriptive of the situation. Furthermore, such a nature of study is purely scientific and requires the correct reading of graphs, curves, and tables, which was a huge part of my formation at the École Nationale d'Architecture de Tetouan, which was more focused on the technical aspects of architecture.

Objectives of sustainable development

The correct knowledge of the behavior of clay soils is a principal part of the preliminary study when a construction is foreseen (Roy and Kumar Bhalla, 2017). In a century where societies are more sensitized to the impact of the construction industry on the economy, environment, and society, it is necessary to consider sustainable development as a requirement.

During the 19th and first decades of the 20th century, supporting civil engineering studies has been the objective of soil science research (Lal, 2008), helping to reach the recently adopted UN Sustainable Development Goals (SDGs) in the most effective manner.

A global exploiter of resources is the construction industry, which witnessed a categorical change during the industrial revolution (1760–1840). If, at that period of history, the impacts of activities related to the construction fields were not recognized, today a much more sustainable approach is taken (Spence et al., 2000). In the sustainable development agenda shared by the United Nations in 2015, several points can be linked to the study of expansive clay and the constructive solutions to be adopted to avoid future pathologies:

OSD 9 (Industry, innovation, and infrastructure), where the correct choice of foundations and a complete geotechnical study contribute to the construction of sustainable architectural projects, all while promoting industrial and economic growth. In such a manner, infrastructure and cities can be developed to be more resilient in the face of natural hazards, coinciding with OSD 11 (sustainable cities and communities). It goes without saying that the constructive field requires important amounts of materials such as concrete and steel and sometimes involves the use of chemical substances for the management of soil, like lime. OSD 11 (climatic changes) and OSD 15 (life on earth) both refer to that, as they cover the consideration of environmental preoccupations and the minimization of disturbances to ecosystems.

Professors Robin Spence and Helen Mulligan stated in their article about the goals of sustainable development regarding construction, that the coordination of various stakeholders plays an important role, referring to OSD 17 (partnerships for achieving the goals).

2. Expansive Soils

Introduction

Clay is a fine, flat mineral particle that effectively retains moisture. Its behavior is related to the percentage of water present: there is swelling the higher it is and shrinking when it's dried up. Clay soils tend to retain water, which can make them heavy, dynamic, and challenging. They therefore require good management to avoid compaction and insufficient drainage.

Clay soils present several potential risks to buildings, ranging from swelling and shrinkage in terms of volumetric changes, damaging foundations and structures, to the problem of settlement over time, resulting in uneven subsidence of the building. These problems have the consequence of making the foundations unstable since excessive movements and uneven settlements can cause major cracks and deformations in the construction.

Construction costs can also be very significant depending on the severity of the case, and the precautions required for building on clay soil, such as the provision of special foundations and drainage systems, can result in expensive amounts. It is important to remember that the later actions are taken, the more severe the damage and, consequently, the higher the cost. The costs resulting from structural damages due to expansive soils in key countries is onerous, reaching beyond 300 million USD in Saudi Arabia, where clay is more prevalent [fig. 2].

Country	Amount (USD)
UK	>3.7 billion
China	>1 billion
France	>2.71 billion
India	>73 millions
Saudi Arabia	>300 million
Sudan	>6 millon
USA	>9 billion annually

Figure 2. Estimated cost of damage due to expansive soils in some countries. Source: Enhancing the engineering properties of subgrade materials using processed waste (Amakye, 2021)

It is clear, then, that a correct previous study and preventive measures are a much better investment in terms of construction costs on the long term.

Classification, composition, and types of clay

Classification by sizes

The Unified Soil Classification System (SUCS) classifies grounds in general into coarse grain soils and fine grain soils, where a sample is classifies as coarse if it has 50% of particles with a diameter less than 0.074mm or 0.08 mm UNE (Una Norma Española) or can be classified as fine if more than 50% of particles have a diameter less than 0.074mm or 0.08 mm UNE. If the sample is inorganic, clay classifies as a fine grain soil with a diameter inferior to 0.002m.

Further information can be concluded based on Casagrande's plasticity chart (1948) based on the index of plasticity (1) and the liquid limit (2) symbolized (IP) and (LL) respectively. The process is relatively easy. Line A [Fig. 2] is defined with the equation:

$$IP = 0.73 \times (LL - 20)$$

Using this equation and the value of LL that is generally obtained by laboratory tests, IP is found, allowing the localization of a point on the chart. This emplacement is what is going to qualify the sample as a clay of low to medium plasticity, symbolized CL) if LL<50, or a clay of high plasticity (CH) if LL ≥ 50 [fig. 3].

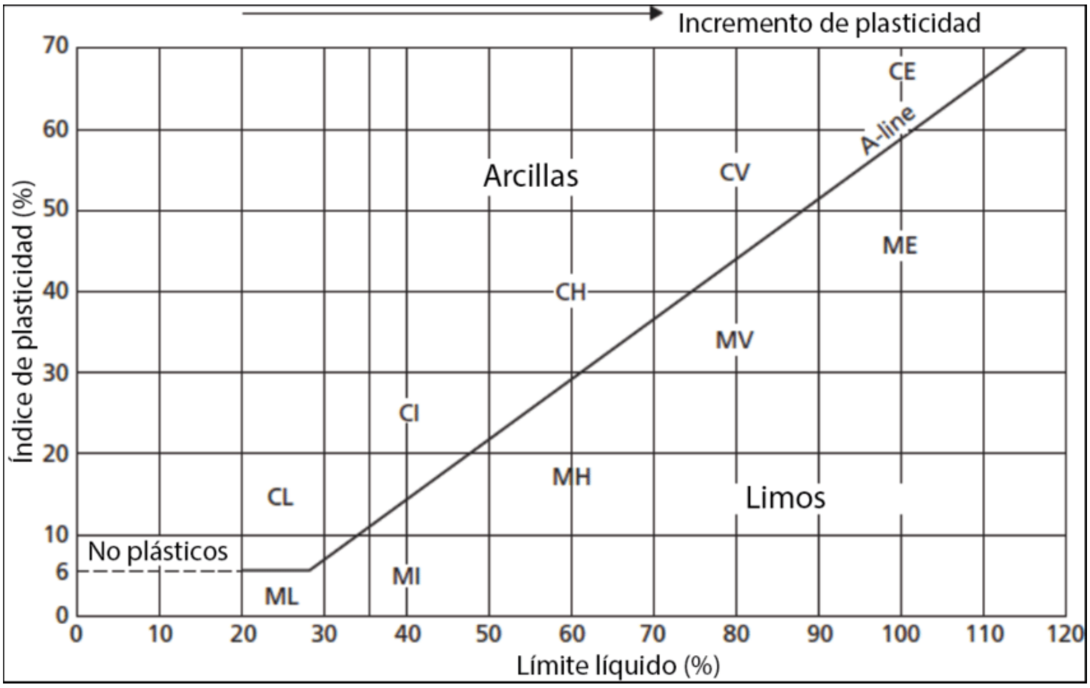

Figure 3. Casagrande's plasticity chart. Source: Craig's soil mechanics (Craig et al., 2012)

The Spanish Technical Code (CTE) offers a classification that is based on the diameters of the grains, grouping them into coarse soils and fine soils [fig. 4]. As stated before, particles with a diameter inferior to 0.002mm are automatically considered clays.

Gravels	Thick	20,0-60,0 mm
	Medium	6,0-20,0 mm
	Fine	2,0-6,0 mm
Sands	Thick	0,60-2,00 mm
	Medium	0,20-0,60 mm
	Fine	0,06-0,20 mm
Fine soils		
Silts	Thick	0,020-0,060 mm
	Medium	0,006-0,020 mm
	Fine	0,002-0,006 mm
Clays	<0,002 mm	

Figure 4. Table D.1. classification of soil. Source: Spanish technical code, DB-SE-C.

The CTE further specifies that if a percentage of less than 35% of coarse grain (gravel or sand), it can classify the soil as clay or lime, and a secondary name can be given if said percentage is comprised between 35% and 65% [fig. 5].

Denomination		% of clays or sand
Principal name	Clays or limes	<35
Secondary name	Sandy or sandy with gravel	35-65

Figure 5. Table D.21. Qualified name for fine soils with percentage of fines > 35%. Source: Spanish technical code, DB-SE-C.

By using granulometry to analyze the distribution of different particle sizes in a soil sample, it is possible to estimate the amount of clay that is present. It does not, however, allow for the precise identification of the mineralogical nature of the clay particles.

For that matter, mineralogy classification is required for a more thorough and accurate characterization since a precise identification of clay minerals is crucial for a thorough understanding of soil behavior.

<u>Classification by mineralogy</u>

Clay does not only correspond to the grain size cut, but to the minerals where the term that is often used to describe it is phyllosilicates.

(1) According to Casagrande, is a measure used in geotechnics to evaluate the behaviour of a soil according to its plasticity, its capacity to deform under stress. This index influences the cohesion and compressibility of soils and is usually symbolized by (IP)

(2) According to Casagrande, is the water content of a soil to a point where it begins to change from a plastic to a liquid state. It is determined by specific laboratory tests, and is symbolized by (LL)

Classification by mineralogy

Clay does not only correspond to the grain size cut, but to the minerals where the term that is often used to describe it is phyllosilicates.

Originally, silicate is the parent rock clays (Bailey, 1980b; Rieder and al., 1998). It develops then, depending on environmental factors, to three families: Tectosilicates, phyllosilicates, and other types. The studied clay minerals all source from phyllosilicates (4). Type one (1:1) is the source for kaolinites, whereas type 2 (2:1) develop with weathering into Smectites and micas, parent of Illite [fig. 6].

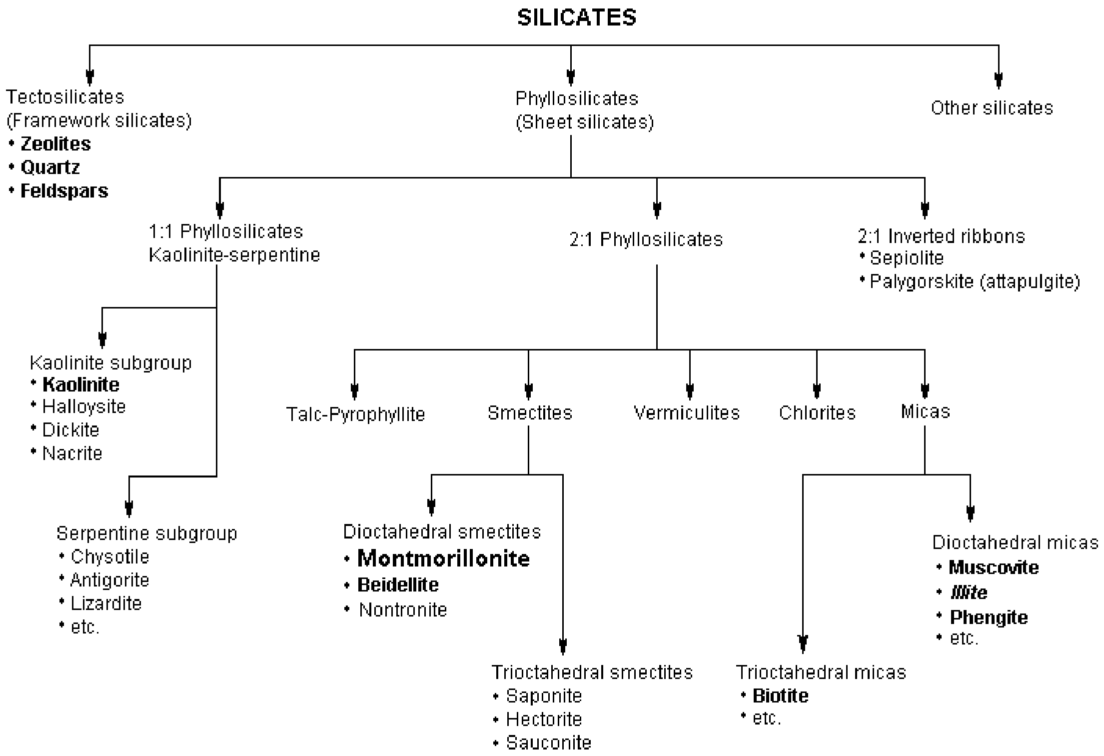

Figure 6. Classification of silicates and clay minerals (Rieder and al., 1998)

In this context, two main groups of clays can be distinguished: Group 1 composed of kaolinites, and group 2 composed by illites and smectites (Gonzalez de Vallejo,2002). These minerals differ in their chemical composition, properties, and in the way the basic units combine to form their crystal structures [fig. 7].

(4) These minerals are part of the silicate group and are composed of tetradic layers that share three of their four summits (the "basal oxygens"), with the fourth summit (the "apical oxygen") connected to an octadic layer (the "O") that is occupied by various cations (Al, Mg, Fe, Ti, Li, etc.).

Kaolinite is composed by sheets that are stacked evenly and linked by weak hydrogen bonds [Fig. 7]. Chemically, each sheet is composed of layers of silicon dioxide (SiO4) tetrahedra bonded to aluminum dioxide (AlO6) octahedra (WA, Howie RA, Zussman, 1992). When it comes to smectites, their distinctive feature is their ability to swell when absorbing water due to their porous structure, in a way where the leaflets can move away from each other when water is introduced between them. It is important to note that smectite with a high percentage of calcium has significantly less swelling capacity than smectite that hold a higher amount of sodium but is equally less prone to shrinking when desiccated (Barast and al., 2017). Illite also has a sheet structure, however, in comparison with kaolinite, illite sheets have a greater variety of possible ions and substitutions in their crystal structure (Robinson D, 1999), making them more complex.

Subsequently, a more specific chemical description can highlight such differences between groups, and what alters their characteristics, giving the formed clay varied physical properties.

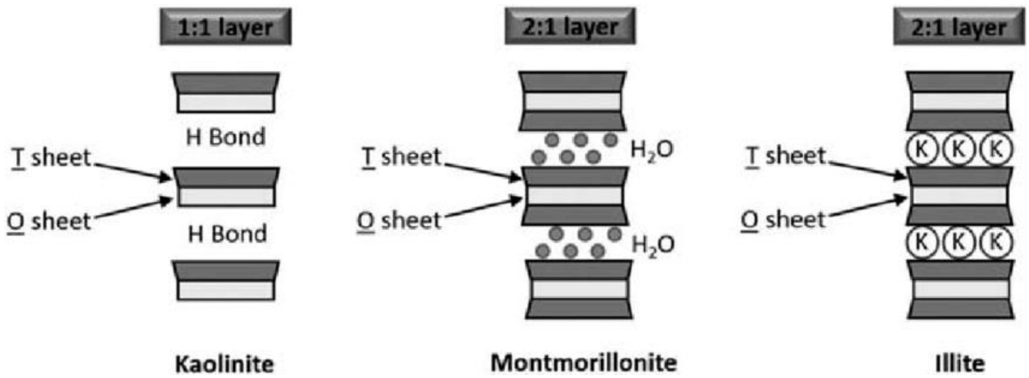

Figure 7. Structures of kaolinites, illites and smectites. Source: Managing clay minerals in froth flotation (Chen, 2016)

Kaolinites

Kaolinite is mainly composed of silicon dioxide (SiO2) and aluminum dioxide (Al2O3) (Perry DL, 2011). Its crystal structure is in sheets, where a layer of silicon dioxide is linked to a layer of aluminum dioxide. Regarding its electrical charge, it is negative on its surface. Kaolinite is formed primarily through the process of decomposition of aluminum minerals, particularly feldspars and micas, in the presence of water and specific geological conditions.

Kaolinite formation begins when aluminum minerals in rocks undergo chemical weathering (Jean-Pierre and al., 2000). Commonly involved minerals are potassium feldspars and aluminum-rich micas. A process of hydrolysis happens afterwards, which causes minerals to dissolve and aluminum ions (Al^{3+}) to be released into the solution. The ions then react with the silicon ions (Si^{4+}) thus forming kaolinite sheets. On a microscopic level, kaolinite has a characteristic crystalline shape with tight sharp geometries [fig. 8].

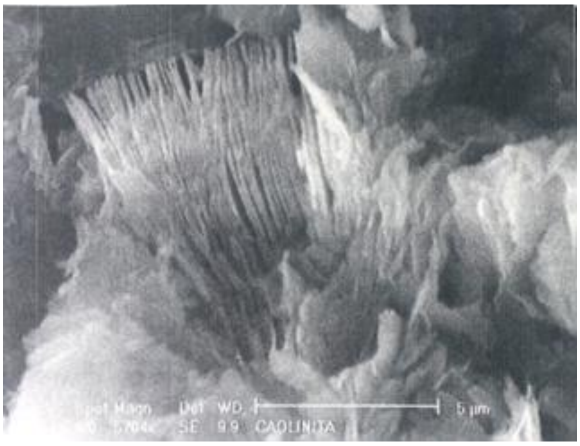

Figure 8. Kaolinite observed under the electronic microscope (curtesy of S.Leguey). Source: Ingenieria geologica (Gonzalez de Vallejo, 2002)

Smectite

Smectite is a relatively common mineral in clay soils, typically found as extremely fine-grained masses of grayish white to silvery-gray, sometimes greenish-gray, material. It has a more complex chemical composition, including silicon dioxide, aluminum dioxide, and a cation exchange capacity that is higher (Klockmann, 1978). Smectite sheets have a negative electrical charge that can be compensated by positive cations, conferring them a high adsorption capacity. They also have a porous structure which gives them a higher capacity of swelling when absorbing water, and that is due to a flaky crystal structure (CNRLT, 2012).

When it comes to its formation, smectite is a perfect example of weathering and chemical transformation which occurs over large geological periods. It is created due to the chemical alteration of minerals containing aluminum and iron, such as feldspars, micas, amphiboles, or even basalts. A process of hydrolysis is also undergone by water reaction, causing minerals to dissolve and release aluminum ions (Al^{3+}), silicon ions (Si^{4+}), as well as other cations such as iron and magnesium. These ions released are the ones that react and form the structural sheets of the smectites.

Similarly, to the previous case, characteristic folds, and curves similar to fumes under the microscope, are behind the swelling behavior of smectites, as they allow its particles to aspirate and keep water in [fig. 9].

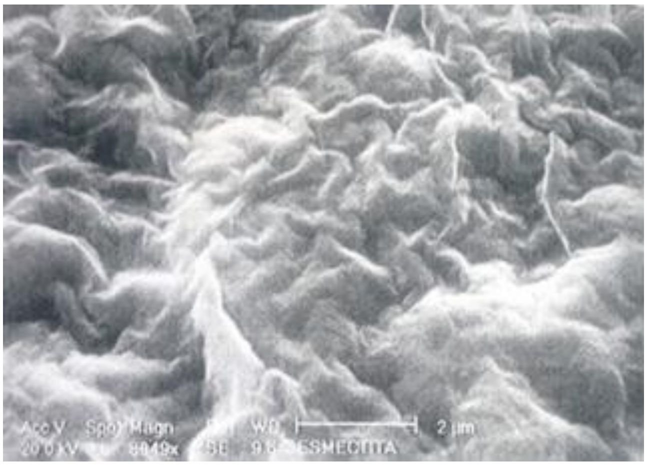

Figure 9. Smectite observed under the electronic microscope (cortesia de S.Leguey). Source: Ingenieria geologica (Gonzalez de Vallej, .2002)

The minerals that make clay expansive are primarily smectites, which, as explained previously, have a characteristic expandable structure, where its sheets can spread apart to accommodate water molecules and positive cations between the layers. These minerals are sought after for their expansive properties in certain fields, making them useful in a variety of applications where water retention, controlled expansion, and adsorption capacity are important. But their high percentage on a soil where a construction project is to be started makes the probability of expansion issues and severe swelling/shrinkage cycles that can affect the building, even higher.

In the scheme below [fig. 10], the molecular process of swelling and shrinkage are clearly explained: The structure of smectites is composed of two sheets separated by a layer of polar water molecules, at the presence of moisture, more water molecules are attracted and added to the existing layer, separating the two formative sheets (CNRLT, 2012). After the drying process, molecules of water dimmish due to evaporation, leaving a thinner layer which brings the sheets closer.

It can be concluded then that the expansion of smectites occurs when water molecules penetrate between the crystalline sheets, causing them to separate (CNRLT, 2012). This expansion is associated with cation exchanges between the positive cations present between the sheets and the hydrated ions of the water, as demonstrated before [fig. 10].

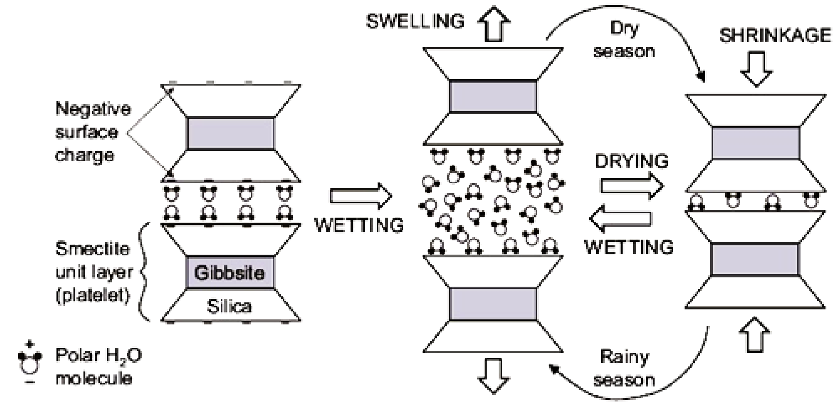

Figure 10. Microstructural swelling and shrinkage of smectites. Source: Drying and wetting soil-water retention behavior of a highly expansive clay under varying initial density (Murison, 2023)

<u>Illite</u>

It is an excellent example of ubiquitous minerals and is formed by the association of one CO (aluminous) and two CT (siliceous), but there can be substitutions (USGS, 2019). They can also contain other types of minerals such as iron, magnesium, and potassium. It has a sheet crystal formation like kaolinite but has a greater variety of ions and possible substitutions in its structure.

Illite is often associated with sedimentary rocks, clays, and shales, and its formation results from a combination of geological factors, including the mineral composition of the original rocks, chemical weathering conditions and the presence of water (Robinson D, 1999). Afterwards, a chemical alteration happens releasing aluminum ions (Al3+), silicon (Si4+), and other cations. From there a conclusion can be drawn concerning the difference between illite and smectite: Despite similar origins, and resemblant chemical alternations, smectites have negative electrical charges on the surface of the sheets, which distinguishes them from illites. Illites also usually undergo a long process of crystallization, making them more rigid, while smectite is known for its expansive swelling in the presence of water (Gharrabi M and al., 1998).

Illite have a more organic structure that is slightly similar to smectite but without the characteristic folds [fig. 11]. On the other hand, the microscopic observation between kalinite and smectite with illite is extremely clear, proving furthermore the genius of organizing clay minerals into two main groups: Kaolinite seem very sharp, crystallized and rigid as demonstrated [fig. 11], when smectite and illite have an overall organic form.

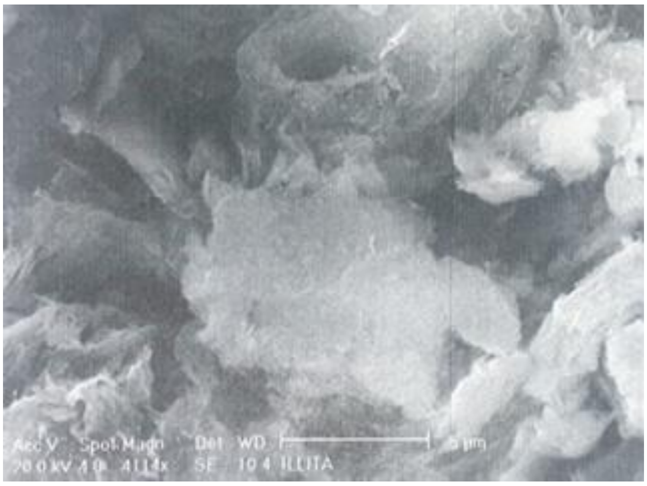

Figure 11. Illite observed under the electronic microscope (curtesy de S.Leguey). Source: Ingenieria geologica (Gonzalez de Vallejo,2002)

In terms of resistance between the three main types of clays, it can vary depending on several factors, including their crystal structure, chemical composition, degree of compaction, and mechanical properties. It is essential to remember that the strength of clays can be modified by factors such as water content, pressure, temperature, and environmental conditions, as well as compaction (5) (Bergaya and al., 2006) which a very important parameter [fig. 12].

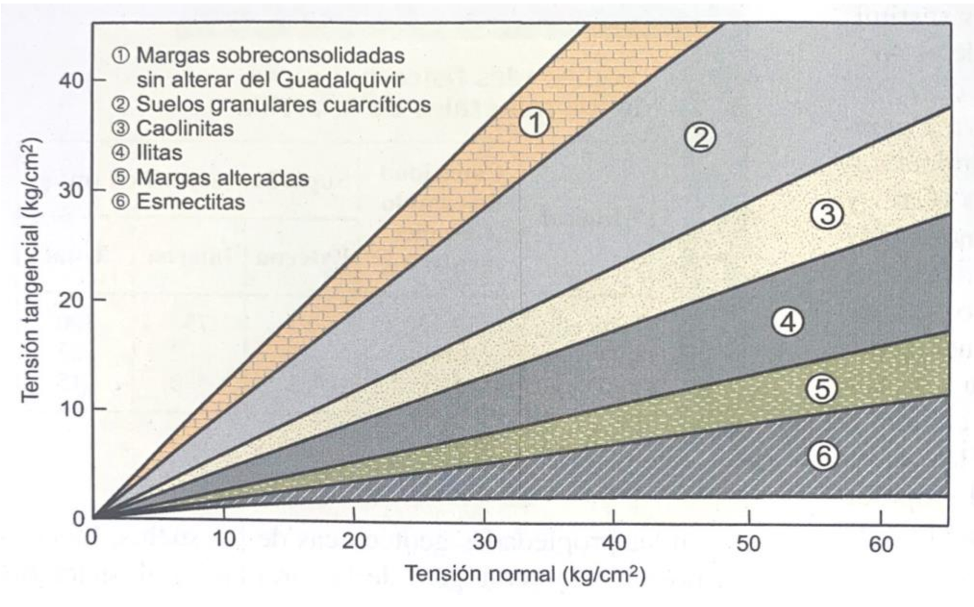

Figure 12. Influence of the mineralogy on the resistance (Tsige,1999). Source: Ingenieria geologica (Gonzalez de Vallejo,2002)

(5) Refers to the process of densifying soils by reducing their volume through the application of mechanical forces, increasing the density of the soil by eliminating voids that may be present between its particles (Xiaoyang, 2019).

The differences in compaction between kaolinites, smectites, and illites lie primarily in their responses to humidity and pressure. Kaolinites are generally the least reactive to water and the most difficult to compact, while smectites are the opposite and are the easiest to compact due to their plasticity. Illites fall in between in terms of water reactivity and compaction behavior.

Based on the graph of free swelling [5] in function of time [fig. 13], the slopes are greater in kaolinite and illite, which means that the process is quicker in their cases then with smectite. Rightly, kaolinite does not significantly change structurally over time and maintains its volume. Illites can swell to some extent, particularly when in contact with water, however, this swell tends to be less noticeable than that of smectites. Smectites, however, may continue to swell, particularly in moist environments. If the ground dries out before it becomes wet again, the swelling may decrease.

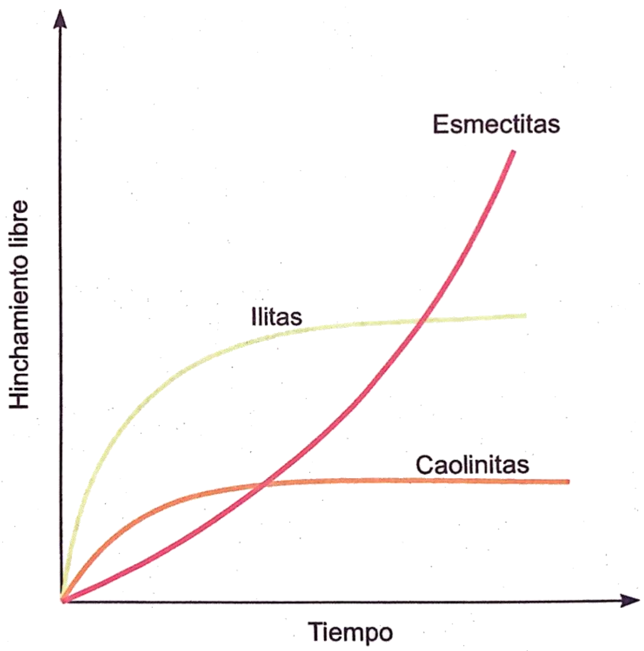

Figure 13. Influence of the mineralogy on the compaction (Left), change of volume in functon of mineralogy (right) (Tsige,1999). Source: Ingenieria geologica (Gonzalez de Vallejo,2002)

Modern advanced tests ((X-ray diffraction, infrared spectroscopy, etc.) can identify specific minerals present in clays. It isn't usually required in construction project because it gives very deep specific microscopical information about the sample, which generally does not affect the risk of expansion.

[5] It refers to the natural increase in volume because of water absorption in clay-rich soils

Cartography of expansive soils: Worldwide, Spain, and Morocco

The location of clay soils is of great importance in architecture. Undeniably, one must be aware of the nature of a ground before initiating the process of construction as a first preventive measure against the negative consequences of an ignored high clay composition. To ensure the stability, durability, and safety of buildings, an accurate understanding of soil composition allows suitable foundations to be designed and possible soil enhancements or replacements to minimize potential problems associated with them.

Firstly, on a global level, as demonstrated on the map [fig. 14], expansive soils are mostly present around the equator. Grounds with a high percentage of clay are mainly localized in northern America, south-eastern America, north, central, and southern Africa, south-western Europe, the Middle East, and south-eastern Asia.

The distribution of clay in specific areas of the world and its absence in others can be attributed to environment, climatic, and geological factors. Of course, areas with formations rich in minerals that contain high percentages of aluminium and silicon, and with the right combination of other geological factors and sufficient time for it to form or accumulate in significant quantities, are more prone to the formation of clays. Additionally, the climate of a region can influence the presence of clay. As an example, regions with adequate moisture levels (regular rainfall or proximity to water sources) are more likely to develop clays.

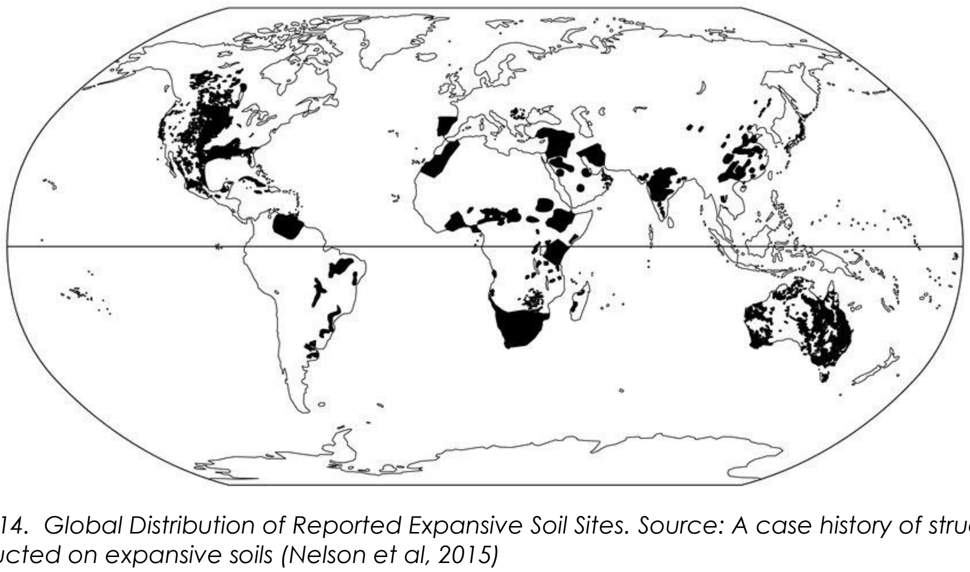

Figure 14. Global Distribution of Reported Expansive Soil Sites. Source: A case history of structures constructed on expansive soils (Nelson et al, 2015)

A formal list of countries with potential expansive soils would be the following: Ethiopia, Ghana, Kenya, Morocco, South Africa, and Zimbabwe in the Africa continent; Burma, China, India, Iran, Israel, Japan and Oman in Asia; Argentina, Canada, Cuba, Mexico, Trinidad, USA and Venezuela in the Americas; Cyprus, Germany, Greece, Norway, Romania, Spain, Sweden, Turkey and UK in Europe; and the entire land of Australia (Harrison et al, 2012).

On a local level and focusing on the country of Spain [fig. 15], the cartography explicates the different levels of expansivity risks. In contrast with the global cartography, it can be observed that even on a restricted surfacy, expansive soils can present different properties and risks of expansivity.

It can be concluded that potentially expansive soils exist in regions such as the Community of Madrid, especially in the peri-urban areas and surroundings of the city, which where the case-study is located, Extremadura, located in southwest Spain, Andalusia, the southernmost region of Spain especially in the cities of Sevilla and Cordoba, and finally the Castile-La Mancha region that is situated in the central part of the country.

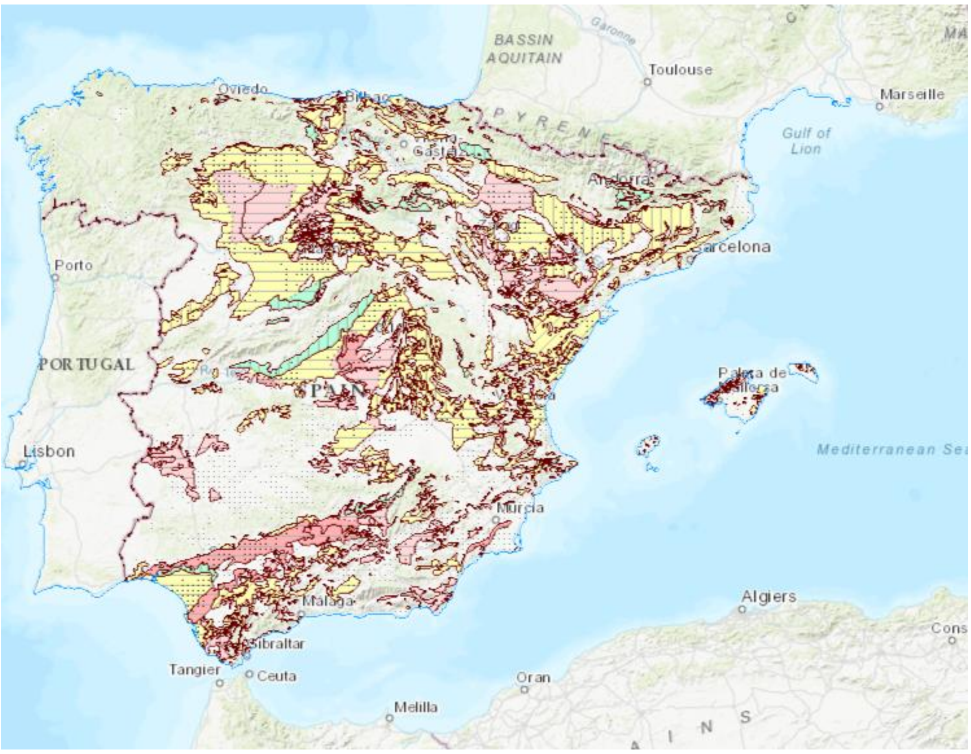

Figure15. Distribution map of expansive soils, in pink zones that have presented problems of expansivity, and pose a very high risk. Source: Mapa previsor de riesgo por Expansividad de Arcillas de España (Cartografía digital del IGME,current)

An extremely important observation can be based regarding the climatic map [fig. 16]: When superposed with the map of swelling risk zones, the areas where expansive soils exist coincide with the different climatic zones within Spain, which further proves the important influence that the weather has on clay formation.

Certainly, expansive clay soils form in climates characterized by wet and dry seasons, which is more common in regions where seasonal variations in precipitation and humidity are marked.

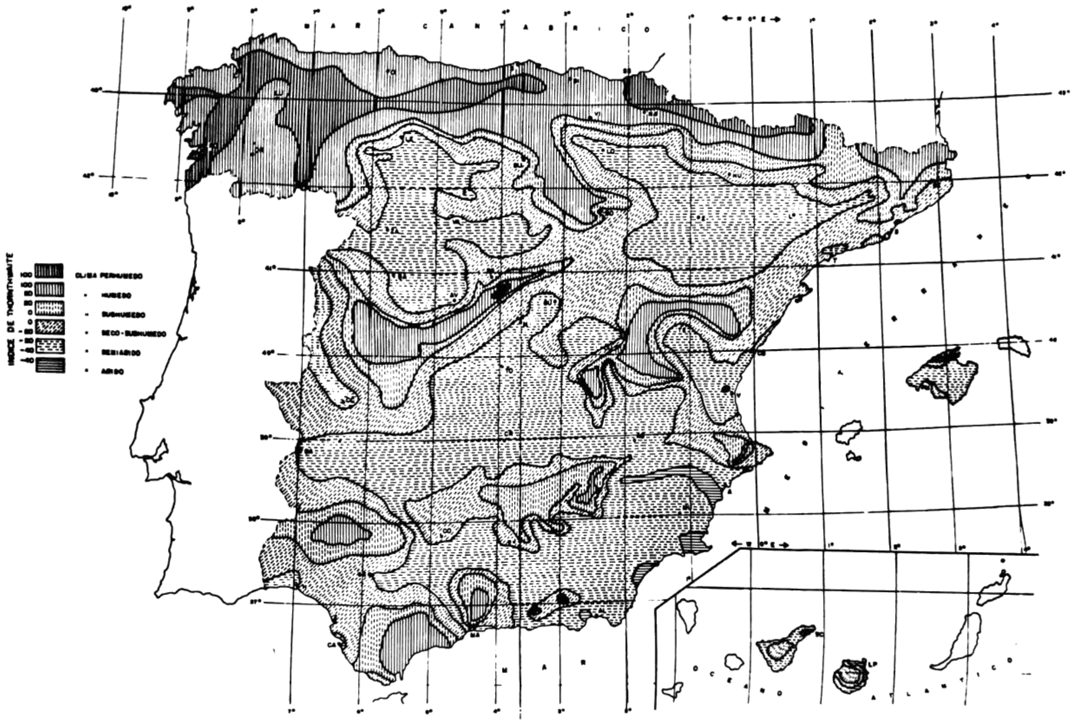

Figure 16. Climatic map of Spain following the Thorntwaite index (Rodriguo Ortiz, 1974). Source: Geotenica y cimientos (Jimenez Salas,1999)

The climate can also be an identification hint as to whether to expect the existence of expansive soils on the ground or not, as proven in figure 16. In fact, there is a specific table showing how the classification of the climate influences the situation of the soil and the risk of expansion, from favourable to extremely unfavourable [fig. 17].

Qualification	Symbol and justification	Normal variations of the precipitations	Maximum duration for dry periods of time
Favorable	F (Favorable)	Small	4
Intermediary	I (Intermediate)	Moderade	6
Unfavorable	U (Unfavorable)	Considerable	6 a 12
Extremely unfavorable	EU (Extremely Unfavorable)	Big	More than 12

Figure 17. Qualification of the climate. Source: Geotecnica y cimientos (Jimenez Salas,1999)

On the other side of the Mediterranean, Morocco is another example of a zone that is high with clay minerals and prone to expansivity.

From the map [fig. 18], it is comprehensible that expansive soils are in the Atlantic coastal regions and interior plains of the country, particularly in the areas around the cities of Casablanca, Rabat, Fez, Meknes and Marrakech, the reason being that these areas often benefit from sufficient rainfall to encourage the formation of clay. The Atlas foothills, including areas around the Atlas Mountains, may have clayey soils due to geological weathering processes and the flow of mountain runoffs as well. Besides that, the Draa valley, located in the south-east of Morocco. Although it has a desert climate, the presence of rivers and irrigation areas can contribute to the formation of clay. The Rif region of northern Morocco, mostly mountainous, can also feature clay soils in some areas.

Clay soils develop under the presence of several factors from which are: Humid climate or rainy season, frequent precipitation, weather and geological weathering, nature of parent material, topography and drainage, vegetation, and organic matter, and other factors that interact in complex ways to determine the presence and composition of clay soils in each region.

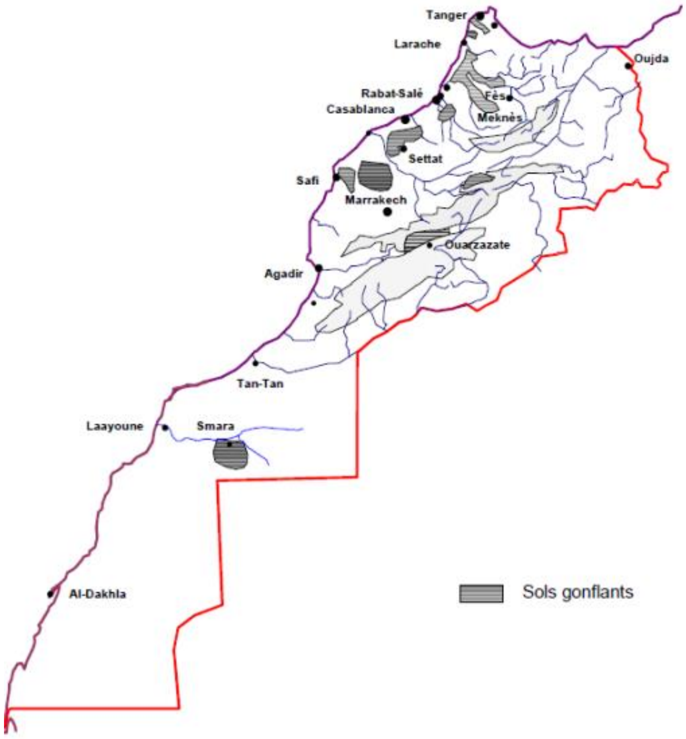

Figure 18. Localization of expansive soils within the Moroccan territory. Source: Interactions of foundations and expansive soils: pathology, calculations, and experimental studies (Chola, 1991)

Clay textures offer a lot of information about the geological and environmental history of a studied area, as well as data about their past conditions and properties, which can give a general visual about the types of minerals that compose their particles and set expectations for future considerations.

The first photograph [fig. 19] shows a section made in a clayey area in the Gharb plane [6], which is situated on the west bank of Morocco. This layer can be extremely plastic when moisture is high, and its richness of minerals come handy to the local farmers. Black clay is of volcanic origin and is a totally natural rock that is classified as one of the softest types. Usually, the thickness oof the clay layers in this area are not very important and can easily be controlled if a construction in projected.

[6] The Gharb, frequently referred to as the West or occasionally Rharb—both are transcriptions of the Arabic word for region—is a historic and geographical region in northern Morocco. It is a large plain in the north of the country, northeast of Rabat and northwest of Meknes, encircled by the Atlantic Ocean and the Rif Mountains. The area it covers is roughly 8,000 square kilometers.

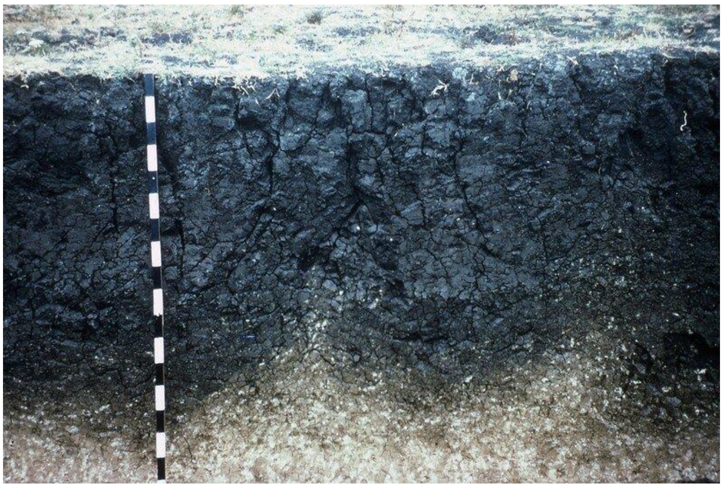

Figure 19. Black horizon, very clayey soil in Gharb Plain, Morocco. Source: Regards sur le sol (Ruellan, 1995)

3. Expansion phenomenon

Definition

It is the increase in volume when prone soils [7] absorb water, and the loss of volume when the amount of water is reduced. This expansion and contraction can cause problems in constructions, such as cracks in foundations and structures, due to dimensional changes in the soil in response to changes in humidity. This behaviour is typical of clay soils due to their crystal structure and electrical charges that attract positive cations and water molecules.

Expansive soils exhibit a variety of structural and visual indicators because of their distinctive behaviour in response to moisture changes. When wet, expansive soils swell; when dry, they shrink. These changes of volume cause the ground to heave and push up against building foundations which can cause uneven settlement, tilting, or even upheaval of the structures.

Manifestation of expansivity

Indications of an expansive soil

Cycles in expansion and contraction due to changes in humidity can cause cracks to form, especially when considering that such variations do not occur uniformly across the site; some places may remain wetter than others, which causes differential pressure in the ground. The cracks can be especially noticeable during times of drought, when shrinking soil cracks due to water loss [fig. 20].

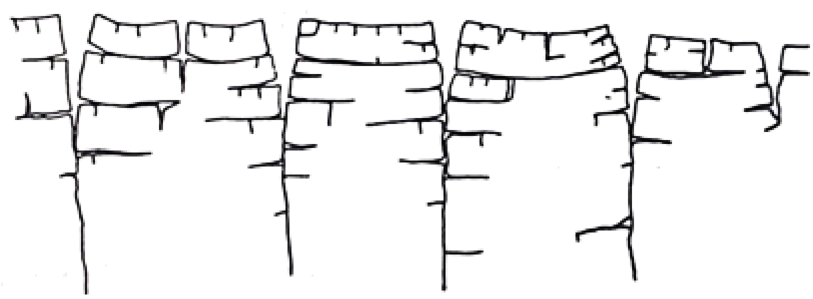

Figure 20. Apparition of cracks due to the expansion/contraction cycles. Source: Geotenica y cimientos (Jimenez Salas,1999)

(7) Commonly soils including vertisols, bentonite clays, black cotton soils, and some silty soils with a substantial amount of clay minerals. When faced with the difficulties caused by expansive soils, they may employ mitigating measures such proper foundation design, control of moisture, or soil stabilization.

Expansive soils can result in various kinds of cracking in buildings, particularly in the foundations, and the severity and extent of these fissures depend on the soil's composition, the climate where the building is situated, and the layout of the structure.

The emergence of withdrawal fissures [Fig. 21] happens when the ground shrinks and retracts, causing cracks in the foundation, the walls, and the flooring. Conversely, swelling fissures form when expansive soil absorbs moisture and expands, exerting pressure on the foundation and resulting in cracks.

Figure 21. Withdrawal crack. Source: Effects of expansive soil on building (Lowy et al.,2022)

The majority of stairwell cracks form in the corners of buildings and follow an escalator motif [fig. 22]. They are frequently connected to expansive soils that go through cycles of expansion and contraction. As a result of the pressure exerted by the expansion of the expansive soil, foundational cracks develop. They can be either vertical or horizontal and endanger the stability of the building.

Figure 22. Example of stair crack in Georgia. Source: Foundation cracks and the damage they cause (Contreras et al., 2022)

Another common kind of cracks, such the spider web-shaped ruptures frequently observed in interior walls [fig. 23], and conjuncture cracks that typically originate from diverse movements in the floor and spread outward from a focal point, which is often where the walls and ceilings intersect.

Figure 23. Example of a spider web crack. Source: Ceiling cracks and settlements (Gohl, 2022)

Additionally, fractures inside the structure are an invocable sign of severe expansive behavior and they can be observed in floor coverings made from tile or wood. Building's façade walls are equally indicative, jeopardizing the integrity of the envelope [fig. 24].

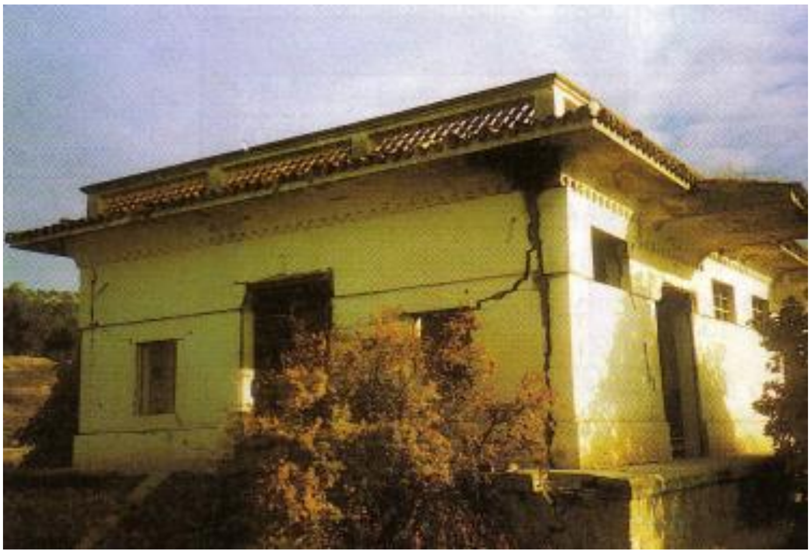

Figure 24. Example of a facade crack in Jaen. Source: Photo (Gonzalez Vallejo et al., 2002)

Doors and windows can be particularly affected, as difficulties opening or closing doors and windows appear. Since the soil exerts an upward pressure on the building structure, a shifting can happen leading the frames to warp slightly, causing excessive friction and material damage [fig. 25]. In addition to functional problems, deformations and cracks around the opening can also have an aesthetic impact on the building. Air and water infiltration therefore happen, causing insulation, humidity, and mold problems inside the building.

Figure 25. Example of a window crack. Source: Expansive soil and cracks in exterior walls (Narron, 2010)

Mechanisms of expansive soils

Expansive soils undergo significant changes in volume over time, as explained before. When they absorb water, they tend to swell and put upward pressure on the home's foundation. This can lift the house, cause uneven sagging, or create stress on the structure. It can also have for consequence differential subsidence, where different parts of the house move at different rates [fig. 26].

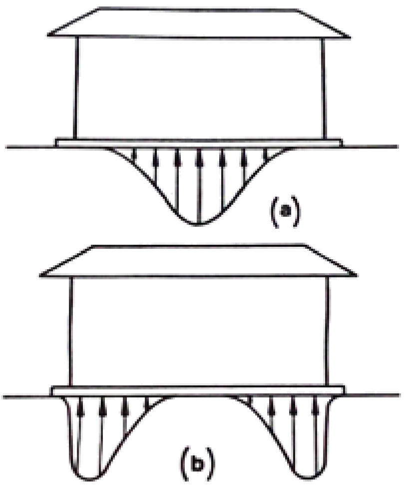

Figure 26. Irregular distribution of the pressures under the structure, due to expansive soils. Source: Geotenica y cimienots (Jimenez Salas,1999)

The swelling of clay exerts an upward pressure on the building [fig. 27]. This may result in the foundation partially heaving and could cause the walls to break vertically or the structure to warp. On the other hand, when clay shrinks loses water, it shrinks, which leads to foundation settlement [8] that can be unevenly or develop horizontal fissures because of partially sinking foundations.

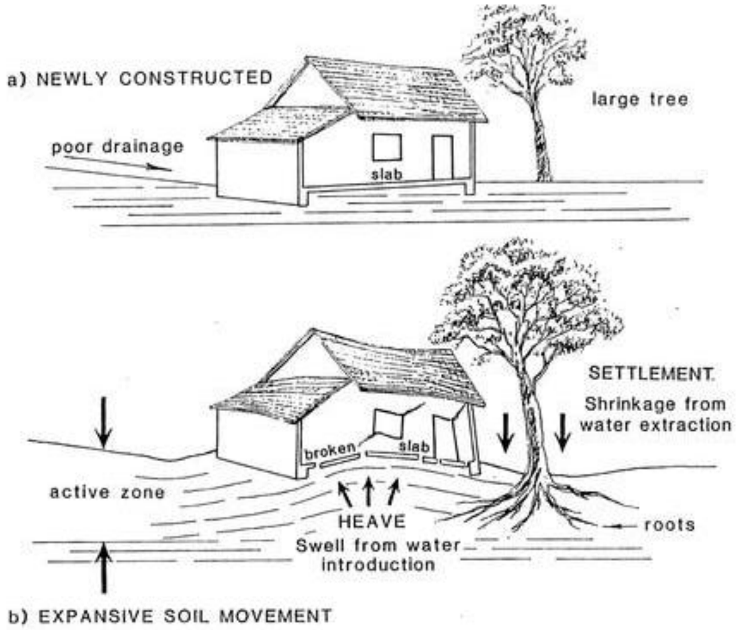

Figure 27. Swelling of soil under a house. Source: Revised expansive soils study (American Geotechnical foundation, no date)

The problem of uneven settlement is that it causes foundations movement that leads to the apparition of cracks [fig. 28]. These differential settlements happen between the side of a building and its core center, since they are the critical structural points where foundations, slabs, beams, and pillars are placed. The movement is then like a translation that can be vertical or horizontal, while the soil pushes against the foundations while everything else follows.

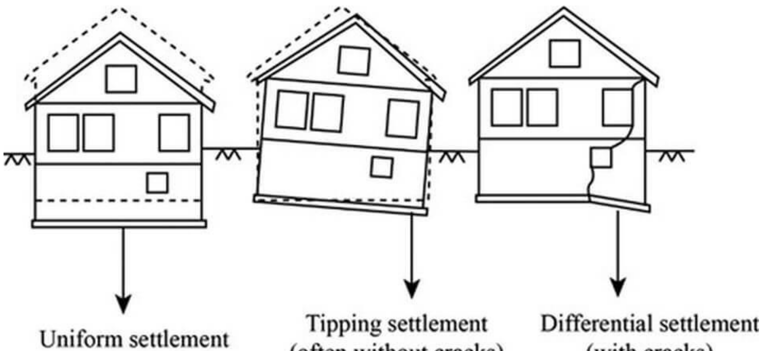

Figure 28. Slopping of floors due to differential settlement, and comparison with uniform scenario. Source: Geotechnical Settlement: Typologies and procedures (Lees, 2019)

The evolution of settlements

As the weight of the building compresses the soil beneath it during and right after its construction on expansive soils, there is initial settlement (9) which can take place quicky. The soil swells and slightly elevate the foundation during wet weather. In contrast, it contracts during dry weather, causing the foundation to settle even more.

Expansive soils can continue to go through cycles of swelling and contracting over time because of changes in moisture content. This may result in the elevation of the structure's foundation changing continuously over time.

In substance, there is a continual movement, as it was demonstrated with the experimental houses that were constructed in Odendaalrus, South Africa (Donaldson,1965). The percentage of movement is seen to be augmenting with time for each of the houses, proving a continuous motion due to the translation caused by the push of the expansive soil [fig. 29].

(8) It refers to the downward movement of the ground (soil) when a load is applied to it (Doug,2018).

(9) It refers to the settlement that happens during the process of construction, and a couple of years after (Doug,2018).

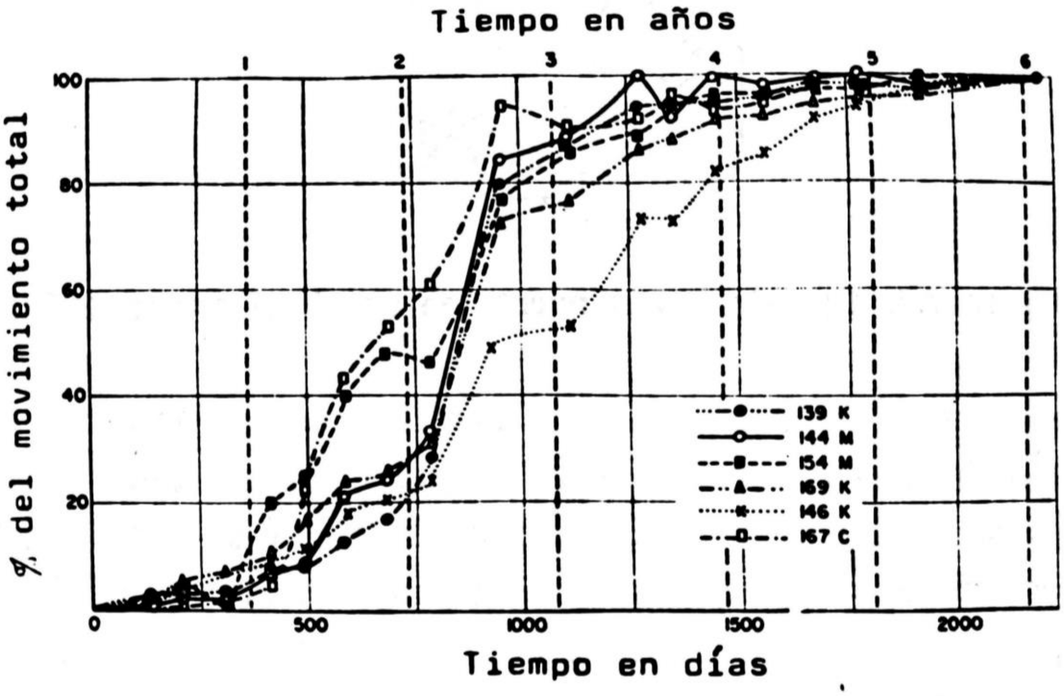

Figure 29. Diagram of movements of experimental houses constructed I Odendaalrus (South Africa), according to Donaldson,1965. Source: Geotenica y cimientos (Jimenez Salas,1999)

Methods of identification and classification of expansion potential

The first step is always observation, be it on site, or using laboratory tests (Salas, 1999). When it comes to already existing buildings, the existence of cracks, unevenness, and other manifestations, as well as testimonies from residents can be enough to establish whether a construction is built on clay grounds or not (Jimenez Salas, 1999).

There is no identification sample that can give a final certain answer to whereas the clay soil will cause expansion issues, or not (Jimenez Salas, 1999). But several indications can be given with laboratory tests. For example, the Lambe index (10) can be used to evaluate the risk of expansion of the soil, using the potential volume change index (11) [fig. 30].

Lambe index (PVC)	**0-2**	**2-4**	**4-6**	**6-12**
Danger of swelling	Not critical	Marginal	Critical	Highly critical

Figure 30. Table of the index of risk of Lambe. Source: Geotecnica y cimientos (Jimenez Salas,1999)

It can be deduced from the PVC index what is the degree of risk of expansion of the clay sample, ranging from not critical to very critical risk of swelling, which can help orient to adequate preventive measures.

Another parameter that is based on the swelling potential (12) is the plasticity index (IP) (13), which is one of the most fundamental data in the study.

Another swelling related data can be studied based on the Holtz and Gibbs table [fig. 31], which an older method, where the risk of swelling is represented based on the percentage of movement in millimeters. Another possible method is represented in the following table [fig. 32]

Plasticity index	0-15	10-35	20-55	>35
Swelling potencial	Low	Medium	High	Very high

Figure 31. Table of the index of risk of Lambe. Source: Geotecnia y cimientos (Jimenez Salas,1999)

%0,001	<15	13-23	20-30	>28
Danger of swelling	Low	Medium	High	Very high

Figure 32. Table of risk of swelling, method of Holtz and Gibbs. Source: Geotecnia y cimientos (Jimenez Salas,1999)

Fundamental variables of expansive soils

Many fundamental values are used during the identification and classification of expansion potential.

Active depth is the depth of the soil where external factors, including moisture change, significantly affect the mechanical behavior of the soil. To put it another way, it refers to the depth at which seasonal changes in soil moisture effect soil expansion and contraction, particularly in expansive soils (Yermolin et al., 2016).

(10) It refers to a parameter used in geotechnics to describe a soil's compressibility, also known as the compressibility coefficient. The variation in soil volume in response to changes in stress and water content is measured by the Lambe coefficient, which is particular to a given soil (Intrinsic property) (Bucksch, 2013).

(11) It quantifies, while maintaining a constant water content in the soil, the link between the change in the void ratio (a measurement of porosity) and the change in the effective stress or pressure applied to the soil. It evaluates how much a soil may contract or expand in reaction to pressure changes, to put it another way (Bucksch, 2013).

(12) It refers to a soil's capacity to expand or increase in size when it absorbs water, especially clay soils. It is used to determine how susceptible a soil is to experiencing major volume changes in response to its water content and is frequently referred to as "swelling index" or "free swelling index." (Bucksch, 2013).

(13) It is explained on page 16, chapter 2: Expansive soils.

This parameter varies depending on the location of the sample. In Spain, the active depth is found at 1.5-3m from the surface [fig. 33]. When constructing foundations, active depth should be considered to maintain stability throughout the course of the year and to reduce the impact of soil expansion and contraction.

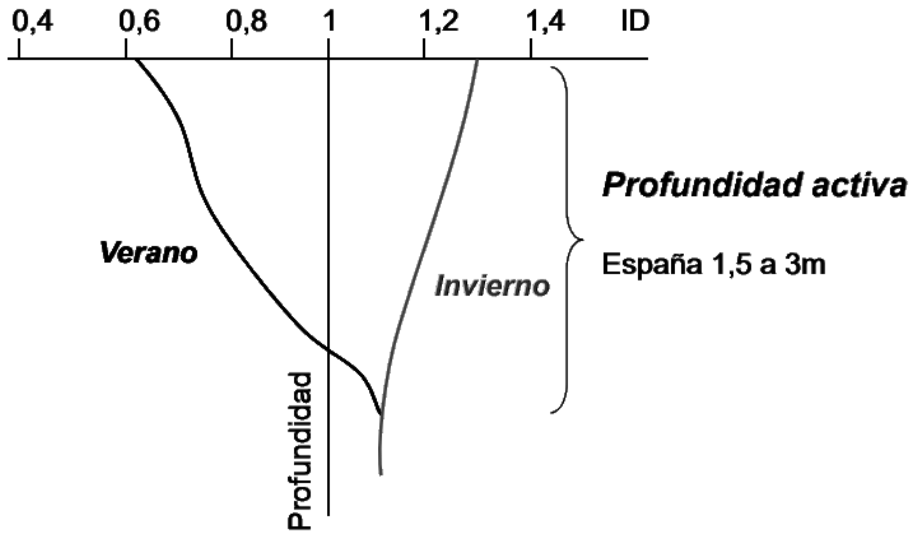

Figure 33. Active depth in Spain. Source: Expansive soils guide, class notes *(Carrión Carmona)*

The desiccation index is a value that demonstrates how much water or moisture a soil can lose when exposed to drying circumstances (Bucksch, 2013). It is the ease with which a soil can dehydrate or dry out in reaction to moisture removal is measured using this index.

This index can be found based on water content (14) (w) and the plastic limit (15) (LP), using the following equation:

$$\mathrm{ID} = \frac{\mathrm{w}}{\mathrm{LP}}$$

The desiccation rate and active depth are both linked to how a soil responds to moisture changes. Active depth might affect the rate of desiccation: The rate of desiccation in that location is low when soil at the active depth swells due to water absorption during wet spells. On the other hand, the rate of desiccation rises in that region when the soil at the active depth contracts because of water loss during dry spells.

The activity (16) of a soil is closely related to the percentage of clay particles present in the soil [fig. 34].

Low Activity (A < 0.75) implicates that the soil has less clay particles as a fraction of other soil constituents, like silt and sand. It is then less sensitive to changes in moisture content and have less flexibility and compressibility. When wet or dry, low-activity soils are less likely to experience substantial volume changes.

Medium Activity (0.75 < A < 1.25) implicates moderate flexibility and compressibility, due to the limited amount of clay particles, and are thought to be somewhat sensitive to changes in moisture content. Soils with medium activity can change their volume slightly in response to changes in water content.

And High Activity (A > 1.25) which qualifies soils that exhibit great flexibility and compressibility, are extremely sensitive to changes in moisture level, and contain a relatively high percentage of clay particles. Such grounds handle significant volume changes.

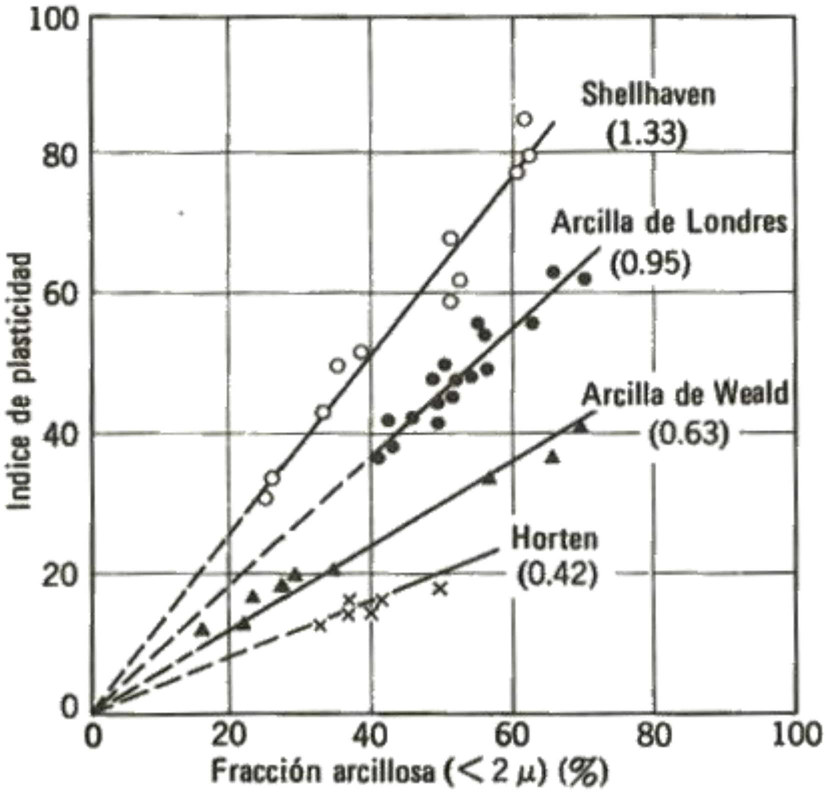

Figure 34. Activity in function of percentage of clays. Source: Reliability of the Plasticity Index for Estimating the Liquefaction Potential of Clayey Sands (Gratchev et al, 2003)

Correlation between the Atterberg limits, mineralogy of clays, and the expansive/swelling potential

Understanding the behavior of expansive soils requires an understanding of the relationship between the Atterberg limits, the mineralogy of a soil, and its expansive potential.

Due to their capacity to hold onto water, clay minerals, including smectites (such as montmorillonite), often have a high LL. High smectite-content soils typically offer more potential for expansion (Barast et al., 2017). The LP can also be affected by mineralogy because some clay minerals, such as kaolinite tend to have lower LPs than smectite minerals [fig. 35].

Low LP and swelling potential have an opposite relationship. In general, soils with lower LP are less expansive, which means they will go through less volume changes when they are wet and dry.

Expansive clays			
	Kaolinites	**Illites**	**Montmorillonites**
Particles thickness	0,5 _ 2 µ	0,003 - 0,1µ	9,5 A
Specific superficy (M^2/g)	5 - 30	65-100	600-800
Cation exchange capacity (mE/100g)	3-15	10-40	80-150
Liquid limits	29-39	60-80	150 - 350
Plasticity index	1-10	27-44	100 - 250
Maximum swelling%. (p=1 Kp/cm^2)		350	1500

Figure 35. Atterberg limits in function of the minerology. Source: Reliability of the Plasticity Index for Estimating the Liquefaction Potential of Clayey Sands (Gratchev et al, 2003)

Mineralogy also influences IP, as soils with a higher proportion of expansive clay minerals tend to have higher IP. A higher IP indicates that the soil has swelling capacity [fig. 36].

Swelling potential	**Plasticity index**
Bajo	0 -15
Medio	10-30
Alto	20-55
Muy alto	> 40

Figure 36. Classification of swelling potential depending on IP. Source: Reliability of the Plasticity Index for Estimating the Liquefaction Potential of Clayey Sands (Gratchev et al, 2003)

Seed et al (1962) have formed a table with expansitivty potential considered for a vertical tension of Presión 6,9 kPa, and 4 qualifications has been given to it, facilitating regulation checks [fig. 37].

	Quantitative information
Swelling potentical (%)	**Classification of the swelling potencial**
0-1,5	Low
1,5-5	Medium
5-25	High
> 25	Very high

Figure 37. Variation of classification of swelling risk according to Seed et al. (1962). Source: Reliability of the Plasticity Index for Estimating the Liquefaction Potential of Clayey Sands (Gratchev et al, 2003)

The swelling potential can be qualified as very high, high, medium, or low depending on several criteria, from which IP [fig. 38].

Data from index tests				
Colloid content % finer than 0.001 mm	**PL**	**SL**	**Probable expansion % total volume change***	**Potencial for expansion**
>28	>35	<11	>30	Very high
20-31	25-41	7-12	20-30	High
13-23	15-28	10-16	10-30	Medium
<15	<18	>15	<10	Low

Figure 38. Classification of swelling risk based on data gathered from index tests. Source: Reliability of the Plasticity Index for Estimating the Liquefaction Potential of Clayey Sands (Gratchev et al, 2003)

A similar table representing the degree of expansion based on LL among other factors can allow a better understanding of the relations between values [fig. 39].

Laboratory and field data					
Percentage passing 75 µm sieve	**Liquid limit (%)**	**Standard penetration resistance blows/ 300mm**	**Probable expansion percent total volume change**	**Swelling pressure, (KN/m^2)**	**Degree of expansion**
>35	>60	>30	>10	>1000	Very high
60-95	40-6O	20-30	3-10	250-1000	High
30-60	30-40	10-20	1-5	150-250	Medium
<30	<30	<10	<1	<50	Low

Figure 39. Classification of swelling risk. Source: Reliability of the Plasticity Index for Estimating the Liquefaction Potential of Clayey Sands (Gratchev et al, 2003)

<u>Lambe test</u>

Allows a rapid detection of soils that might have expansivity issues. Under predetermined humidity levels, a compacted soil test piece's expansiveness is evaluated using the swelling index.

<u>Free swelling test of a soil in an oedometer</u>

Using an oedometer, calculate a soil's free swelling. A laterally constrained soil specimen that has been flooded and subjected to a vertical pressure of 10 kPa experiences free swelling, which is measured as an increase in height expressed as a percentage of the starting value.

Knowing the swelling that will happen for a specific vertical pressure can occasionally be interesting.

4. Pathologies

Percentage wise, it is important to remember that in Spain, 32% of the existing geological formations contain expansive clays and 67% of the territory is under climates in which significant changes in humidity can occur in the soil, with dry periods ranging from two to eight months, making the country a place with high probability of structural problems and appearance of pathologies due to these circumstances.

Swelling clays, can cause several problems and pathologies on a construction. In fact, the existence of an expansive clay is sometimes discovered due to the apparition of pathologies (Lincoln Handy, 1995).

Observed pathologies

Some of the typical observed pathologies in construction built on expansive soil are the following:

<u>Cracks on vertical elements like facades</u>

These soils cause shearing and cracking problems combined with horizontal thrusts, which manifest themselves in cracks in the facade walls. Additionally, the cyclical pressure of the swelling/shrinkage can cause cracks can also affect the stability of the structure.

In the photography [fig. 40], a huge lateral crack crosses the façade of two adjacent buildings, giving a worrying sign of severe effects of an expansive soil. The fact that this pathology appears in both buildings in the same way shows that if similar faulty constructive techniques, problems will appear in both cases. Such scenarios can induce high structural damage and lead to the demolition if the problem is not corrected.

Figure 40. Severe case of cracking on the façade of a southern riad in Morocco. Source: Clay pathologies case studies (The constructer, 2009)

Cracking and breaking of structural elements

Seasonal movements of expansive soil can cause structures to warp, causing them to malfunction. Excessive differential settlements result in the movement of pillars or groups of pillars, exceeding the elastic limit of some structural elements. These damages are manifested in principle in the facades. In this case [fig. 41], the crack runs so deep and affects the load-bearing wall of the basement. A lack of sensitization to such structural damages can lead to unfortunate incidents on the long term.

Figure 41. High risk observed crack on the basement wall. Source: Reasons why buildings crack (Prathima Seethur,2018)

Foundations failure

Water pressure variations exert pressure on the foundations, causing fissures in the walls and slabs [fig. 42], which can affect the overall stability of the structure. Cracks can be of particular concern as they can compromise the overall security and make the building vulnerable to water infiltration, among other issues.

Slabs can be prone to flexural cracks and distortions that can lead to twists and breakage of it, while stilts experience breaks due to flexion, shear or flexion, and thrusts.

Figure 42. Upheaving of the basis of a house. Source: A case scenario of a failure of foundation (Parathima Seethur, 2018)

Damage to openings

Expansive soil can cause structures to distort, translating different points of the construction, affecting doors and window frames, which can lead to them malfunctioning, as shown below [fig. 43].

Figure 43. Door levelling issue due to floor rising. Source: Malfunction properly (Unknwon.2021)

On the picture [fig. 44], which was shared on a helping platform, shows the severity of the levelling issues that can happen due to the uneven settlements and upward movements. The door is constantly rubbed against the pavement and cannot be used properly. Similarly, deep cracks can be observed around the basement window, causing the frame to almost fall out of place while the walls are eroding with time.

Figure 44. Apparition of severe cracks and frame distortions. Source: Foundation Wall Repair in Northwestern PA (Total foundation inc, 2014)

Movement of ducts and pipes

Ground movement can move underground and façade pipes, including sewer and water pipes, which can lead to leaks and damage. In the above case [fig. 45], another serious pathology of expansive soil damage can be observed: The moments caused by the clay soils around the wall are too high to be handled, which causes the bolting and damages the canalisations that are placed in the wall. A similar issue happens due to the damage of slabs with ducts and pipes running inside of it. In more dangerous cases, even gas pipes can be affected, leading to the liberation of it in the sanitary space or in the construction.

Figure 45. Reinforcement bars to support a damage basement wall. Source: A case scenario of a failure of foundation (Parathima Seethur, 2018)

Damage to interior walls and pavements

Important interior wall cracks can appear [fig. 46], spreading on the pavements as well due to differential movement, leading to cracking, and bad settling.

Figure 46. Settling produced due to the inundation of expansive clays (Breakage of pipes). Source: Geotenica y cimienots (Jimenez Salas,1999)

The bad management and lack of knowledge about expansive clays can lead to the apparition of worrying cracks on the slab, which is the case of this garage [fig. 47], covered in concrete and that was highly damaged due to the consistent movements of the structure, leading to the apparition of a crack that grew with time and became more noticeable.

The damage to pavements is over more obvious when materials like tiles are used, as the perpetual dynamic of expansiveness is clearly shown in that case.

Figure 47. Damage on the pavement of a garage due to expansive soils. Source: Expansive soils (Property health inspection,1999)

Mold or mildew growth

It is one of the most famous expansive soils pathologies and is due to humidity issues, and thermal bridges apparitions due to the damage of joints. The water and air infiltrated cause the apparition of all sorts of mold and growths as well as roots, in some cases. The below photograph [fig. 48] shows the example of a case where molds has appeared on a corner of the wall, at the joint between the two walls which is a strategic place for molds, as corners are the place where growths have access to water and air due to the infiltration.

Figure 48. Mold growths on a corner of the wall due to water infiltration. Source: Reparations of humidity consequences (Valleywide, 2000)

Other sorts of pathologies that were also considered manifestations signs of expansive clay in chapter 3 usually appear as pathologies, such as stair cracks [fig. 49], swelling cracks [fig. 50] and façade cracks [fig. 51].

Figure 49. Damage on the stair bearing wall showing stair cracks. Source: Crack Patterns (United structural systems, 2023)

Figure 50. Crack due to bad settling because of clay swelling. Source: Foundation Problems vs. Settling (Flicker, 2022)

Figure 51. Facade crack. Source: Common Bay Area Foundation Problems and Their Solutions (Egloff, 2019)

5. Constructive solutions

Soil movements induced by the shrinkage and swelling of clay constitute a major risk due to the extent of the material damage they cause, because they affect the structure of the buildings. It is therefore essential to reduce the number of claims related to this phenomenon, especially since the application of simple and well-known rules of the art makes it possible to avoid any claims. In addition, making suitable foundations when the building is designed is also less expensive than underpinning once the building is built. Two types of constructive solutions can be identified: Solutions applied on the structure, and solutions applied on the ground (Jimenez Salas,1999).

Actions on the structure

Three types of interventions on the structure can be cited: Stilt house, Rigid or semi-rigid structure, and flexible structure (Jimenez Salas,1999).

<u>Piles or deep-rooted foundations</u>

It is originally a residential structure that is raised on an elevated platform and stilts or wells that are deeply rooted in the ground [fig. 52], offering more stability. It represents one of the safest but expensive constructive solutions that can be chosen. Furthermore, to avoid the possible lifting that happens due to the expansivity, an adapted method was to leave the shank in the formwork if it isn't sufficient to reinforce it (Jimenez Salas,1999).

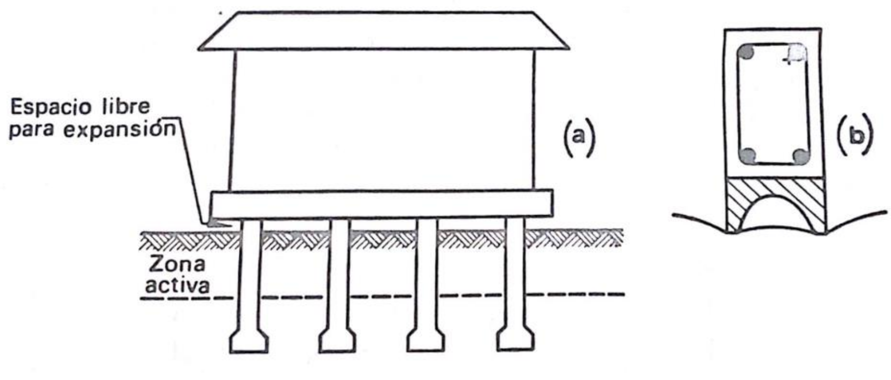

Figure 52. a) Piles foundations. b) Expansion space closure solution for better appearance and cleanliness. Source: Geotecnia y cimientos (Jimenez Salas, 1999)

Deep foundations stay very expensive, and the price gets higher the deeper the stable strata is located. Nevertheless, it is sometimes the only possible solution in highly clayey zones, to stabilize the construction safely.

There is also the possibility of using double stilts that need to reach the active depth to be efficient [fig. 53], depending on the required thrust and amounts of concrete afforded for that.

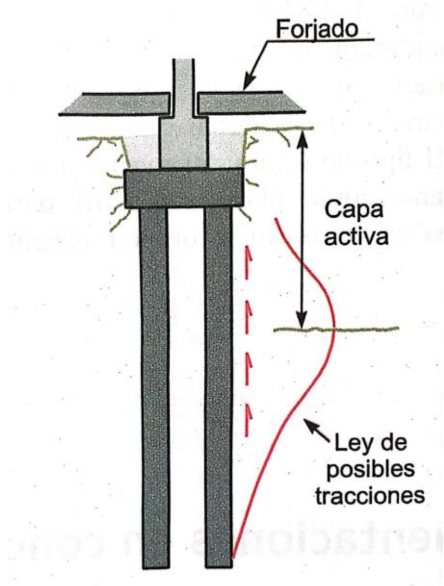

Figure 53. Section of required selected depth for piles. Source: Ingenieria geológica (Gonzalez de Vallejo, 2002)

Well foundations are another technique based on the digging deep wells, sometimes called beds, until reaching more stable layers of soil beneath the expansive layer [fig. 54]. This method allows the load of the structure to be distributed evenly over a larger area, which can be advantageous for heavy structures. And unlike stilts, they can be used to create a continuous base beneath the structure, at the condition that such base is on a stable non-expansive layer of soil.

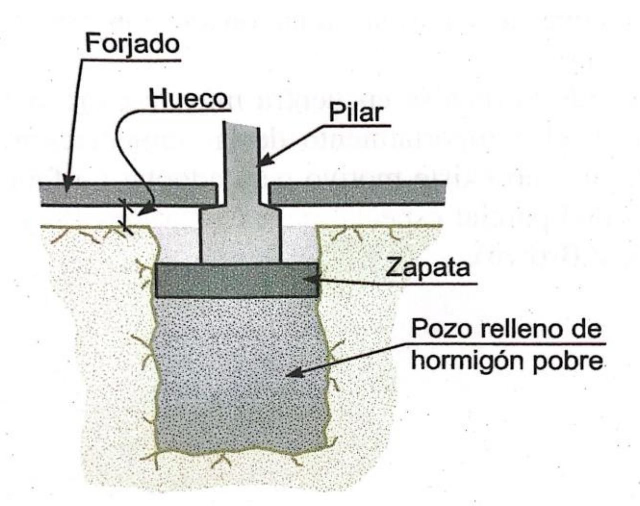

Figure 54. Section of a well foundation. Source: Ingenieria geológica (Gonzalez de Vallejo, 2002)

Rigid or semi-rigid structures

They are the types of structures that offer enough compacity and strength as to follow the movements of the soil without breaking. For example, in the case of reinforced concrete foundations, they effectively distribute the load of the structure on the ground and can resist expansive soil movement while minimizing structural deformation, which is below [fig. 55].

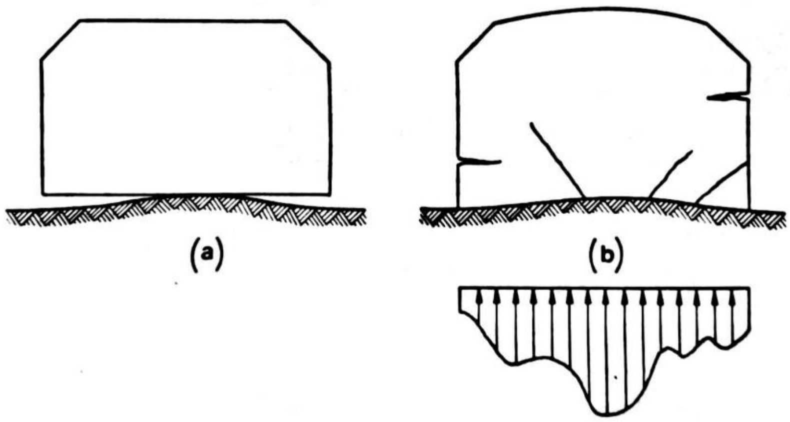

Figure 55. Schematization of how a rigid structure adapts to the deformations. Source: Geotecnia y cimientos (Jimenez Salas, 1999)

Flexible structures

they are designed to adapt to deformations of expansive soil, by being more tolerant to ground movements. They incorporate expansion joints, flexible materials, and load transfer mechanisms to allow the structure to move without suffering serious damage. Expansion joints, strategically placed to allow the structure to expand or contract in response to changes in soil moisture, without creating stress. This behaviour is demonstrated further [fig. 56].

Flexible foundation techniques are extremely varied and have a very interesting dynamic behaviour. Some examples can be piers and beam foundations (crawlspace), elevated structural slab, slab-on-grade with post-tensioning, deep concrete beams and grade beams, mat foundations with controlled joints, rubberized foundations and post-tensioned slabs.

The choice of the action taken on the structure of the construction depends on many factors, such as the result of the geotechnical investigation, the design and the costs to be considered.

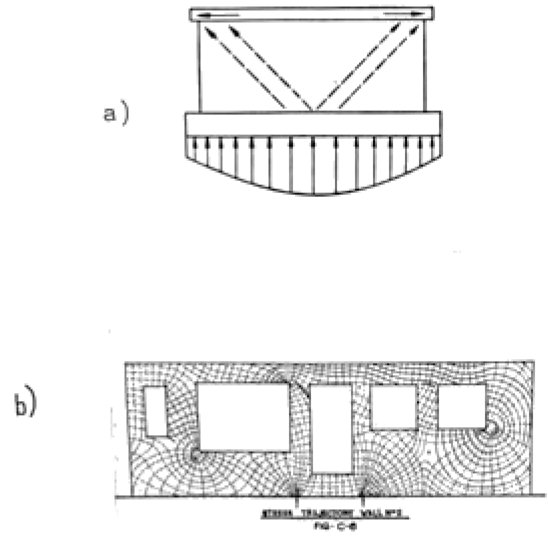

Figure 56. a) A reinforced concrete ring at the head turns the wall into a high beam capable of resisting large bending moments. The bricks transmit the shear forces. b) The necessary existence of openings produces stress concentrations in the corner, and cracks (Jennings, 1954). Source: Geotecnia y cimientos (Jimenez Salas, 1999)

For example, well foundation is a very cheap alternative to stilts, whereas if an important depth is not required, they can be a sufficient solution. Continuous slabs, and stilts on the other hand are very pricey, which is to be considered when the percentage of expansiveness if very high.

Actions on the ground

Treating expansive soil is essential to ensure the durability and stability of the construction, and to help prevent any structural damages. As stated before, it is primordial to safety and save costs in the long run. Besides, if good constructive methods are taken on the ground, it can avoid mistakes and the time of choosing the adequate structure later.

Actions on the ground can be divided into two procedures: Substitution and stabilization.

Soil replacement

It is a method that involves the removal of expansive clays, and its replacement with a more stable and less expansive type of soil. This technique is generally expensive and complex and may not be a practical solution in many situations.

Nevertheless, in cases where the expansive clay doesn't have a big thickness or doesn't cover a huge surface, and if costs can be overlooked, it stays a valid and radical solution to control the expansion.

Above is an example of a typical natural soil's replacement [fig. 57] to tackle the volume changes that occur in expansive soils. The depth of the replacement depends on where the expansive layer is and what is its thickness.

The expansive clay can be replaced by four types of fillings: Piles or deep foundations, and material elevation from a structural point of view, and replacement with non-expansive soils such as sand, gravel, or specially designed filling materials.

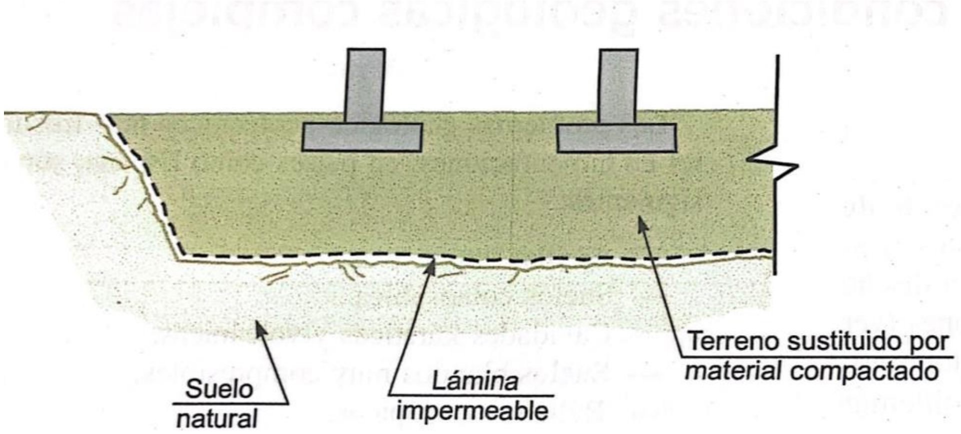

Figure 57. Substituion method using compact material. Source: Ingenieria geológica (Gonzalez de Vallejo, 2002)

Chemical stabilization

It is a method that uses additives, and more common method for making the ground suitable. It is also less expensive and quicker than the substitution.

As usual, it is essential to perform a thorough geotechnical assessment beforehand. Then, depending on the characteristics of the soil and budget, several types of additives can be chosen, from which the most popular are lime, cement, chemical stabilizers, or other specific mixtures.

Each additive has different characteristics and projected influences on the expansivity of the soil, or example:

- Additives that retain moisture are common salts and chloride of calcium.

- Moisture resistant additives can be resinous and water-repellent waterproofing agents, bituminous materials, and reduced asphalts

- Soil-cement mix, in most cases it is made with Portland cement.

- Lime and cement react with the soil chemically allowing pozzolanic reactions

- Dispersing agents: among which are the silicate of sodium and sodium polyphosphate that reduces the liquid limit, plastic index, and permeability.

Sulfonated oil stabilization

It is an effective method for mitigating the problems posed by the expansivity and uses sulfonated oils as an additive.

These oils are typically derived from petroleum or vegetable oils and are chemically modified to create sulfonate compounds, that when they interactions with the soil, it chemically alters the surface properties of the clay minerals, resulting in the significant reduction in the soil's ability to expand and contract [fig. 58].

Some of the benefits of this method are that the treated soil is easier to work with, the excessive swelling and shrinkage are controlled, and stabilization is enhanced, transforming the unstable ground into a more solid basis to construct on. On the other hand, and as every other stabilization method, this technique requires the selection of the appropriate sulfonated oil and the correct dosage rate and keep on with the quality control measures. Furthermore, Sulfonated oil is a chemical that can impact the environment, it is then important to consider environmental regulations and impacts associated with its use.

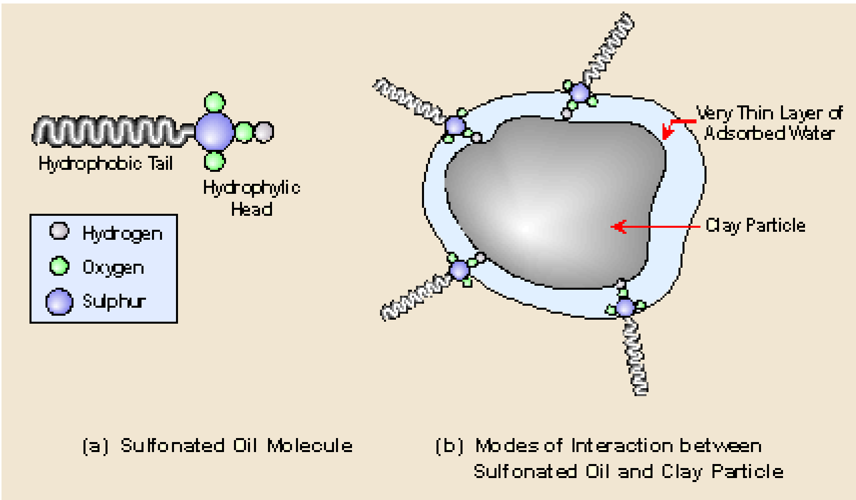

Figure 58. Reaction of clay particles with sulfonated oil. Source: Soil's stabilization and dirt control (CBR plus,2023)

Stabilization with fly ash

Fly ash, flue ash, coal ash, or pulverized fuel ash, is a coal combustion product that is composed of the particulates that are driven out of coal-fired boilers together with the flue gases. A 25% concentration of ash in the soil can be very beneficial, affecting the granulometry, flocculating the clay percentages of the soil and reducing the liquid limit and the plastic index of the soil. The pozzolanic reactions allow to increase the support capacity of the subgrade and with it better the road structures. Fly ash reacts with lime to form a cementing material used to strengthen soils for the construction of bases and subbases for pavements.

Stabilization with fly ash stabilization offers several advantages, such as the improved soil's strength, controlled expansivity and reduced plasticity, and cost-effectiveness, it is also relatively environment friendly as it can be recycled.

However, it has some disadvantages related to the setting time that is excessive, and the need for proper mix design and quality control, like sulfonated oil stabilization.

A photograph [fig. 59] shows the process of pressure injection of lime-fly slurry in a canal bank in Fort Worth, Texas. A truck carrying the additive is used to spread it over the surface of the ground, mixing it then compacting before starting the process of execution.

Figure 59. Slope stabilization of a canal bank by pressure injection of lime-ash slurry (Hayward Baker, inc). Source: Foundation engineering (M.das, 1984)

Another example of stabilization with the fly ash technique can be observed below, with the different types of heavy machinery is used [fig. 60].

Figure 60. Stabilization with fly ash procedure. Source: Fly ash stabilization steps (KCFA,2012)

Stabilization with lime

This technique, which consists of mixing lime with clay soil, then compacting this mixture to obtain a better bearing capacity of the soil. The lime allows the reduction of the liquid limit and the plastic index, in such a way that the volumetric changes are also decreased. The stabilization of clay soils with lime is a technique which aims to improve the properties of soils using an alkaline material.

Chemically speaking, the reaction between the lime and clay strengthens continuously the soil, improving its durability, as seen in the below figure.

Chemically speaking, the reaction between the lime and clay strengthens continuously the soil, improving its durability. It has the effect of reducing the plasticity that is problematic of expansive soils, becoming less likely to swell when wet and shrink when dry [fig. 61].

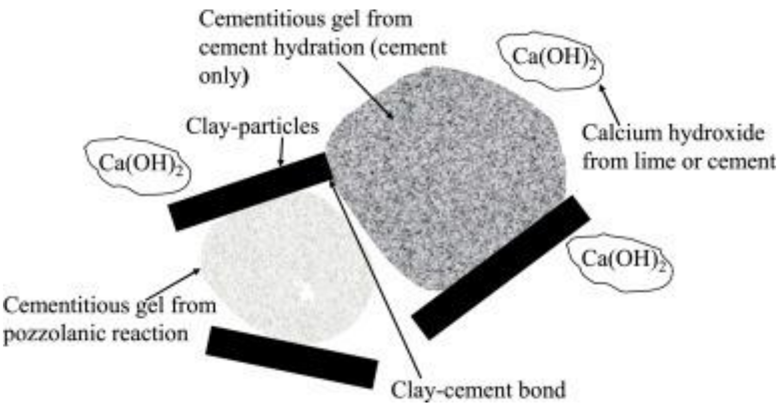

Figure 61. Chemical reaction between the lime additive and the clay particles. Source: Stabilization of expansive soils using chemical additives (Barman, 2023)

This technique is commonly used in construction to make clay soils more suitable for infrastructure projects [fig. 62], which is the situation faced in the case study of the Amazon warehouse in Illescas, in the following chapter, where the lime stabilization method will be further applied.

Figure 62. Lime stabilization. Source: Soil stabilization - road recycling - development work and road cleaning - stone crushing – sodding (SPRL Burtaux, 2022)

The lime stabilization procedure is done using several heavy machines [fig. 63]. Firstly, the lime is spread evenly over the surface, typically in dry form [fig. 64], or as a slurry [fig. 59], depending on the project's specific needs. Then a specialized equipment such as rotary mixers or graders work on the soil to make a homogenous mixture of lime and soil. Afterwards, the compaction stage that ensures that the treated soil achieves the desired properties. This step can be done using rollers or other heavy equipment.

The curing period is when the chemical bond between lime and the soil continue to improve its properties, until it reaches the required levels.

Figure 63. Lime stabilization procedure. Source: Lime and cement stabilization methods (The engineering community, 2018)

Figure 64. Pressure injection of lime slurry for a building pad (Hayward Baker). Source: Foundation engineering (M.das, 1984)

It is essential to conduct a testing after the curing period ends, to assess the effectiveness of the lime stabilization. These laboratory tests should include the verification of moisture content measurements, compressive strength tests, among other geotechnical assessments.

In comparison to the two previous types of additives, lime stabilization has certain advantages that can hardly be overpassed, such as the rapid setting, contrary to the fly ash stabilization, the enhanced workability, versatility, and durability. This goes without saying that lime is environment friendly and shows a consistent performance overtime concerning the control of the soil's swelling, and the enhancement of the strength and load-bearing capacity of the soil, making it suitable for construction.

On the other hand, the curing period can be very important until the ideal characteristics are reached, and it is a lengthy process that includes a throughout testing for safety. Another inconvenient is that lime presents a danger to the health of workers, as it can cause skin irritations and respiratory problems, which requires that the storage happens in a well-ventilated space. Besides that, lime is highly reactive component that can sometimes react with other minerals, causing undesirable effects, altering the curing period, which is why it is important to identify the mineralogy of the soil because starting the process.

To conclude, the problematic of swelling can be solved with a multitude of techniques, each with different advantages and inconvenients [fig. 65]. The choice of the adequate solution is decided by the engineers based on several factors, among which the performance of the technique on the long term, the workability, the time required, and the costs. But in a generation where the environmental cause is a primordial factor, it is highly important to consider the impact of every solution on nature. That is exactly why, in general, the most popular technique is the chemical stabilization using lime. It is important to consider that this method can produce dust and other particles, which can cause air pollution. But if done properly, it can reduce dust emissions, improving both air quality and people's health. Due to the expansion and contraction of the soil, expansive soils frequently assist in uprooting vegetation. The natural vegetation cover, which is essential for wildlife habitat and biodiversity, can be preserved with the use of chemical stabilization. It is also important to prevent the leakage of dangerous contaminants into groundwater, that is why the product are to be carefully chosen and should be environmentally friendly. Furthermore, for the protection of the environment during construction and soil stabilizing works, several regions have laws and regulations in place. The use of proper techniques guarantees adherence to these rules.

Despite lime stabilization being an excellent solution, in certain cases other treatments can be more adequate than the last, it all depends on the case and project criteria.

Soil improvement techniques							
Soil replacement		Chemical stabilization					
		Sulfonated oil stabilization		Fly ash stabilization		Lime stabilization	
Advantages	Inconvenients	Advantages	Inconvenients	Advantages	Inconvenients	Advantages	Inconvenients
Improved stability	Costly	Improved stability	Variability	Improved stability	Variability	Improved stability	Time-consuming
Predictable behavior	Negative environmental impact	Dust control	Regulatory considerations	Enhanced compactation	Long-term performance	Versatility	Regulatory compliance
Constructive ease	Logistical challenges	Environment friendly	Limited application	Sustainable	Compatibility	Environmental benifit	Environmental precautions
Risk mitigation	Soil waste	Cost effective	Quality control	Cost effective	Settlement problems	Cost-effective	Cost of lime

Figure 65. Table of comparison between different expansive soil control methods. Source: Personal

5. Case study: The Amazon warehouse in Illescas

Context

This case study was proposed by Ricardo Valiente Sanz, professor in the department of Geological and Geotechnical Engineering at the Polytechnical university of Valencia, with the objective of applying the anterior knowledge.

Amazon, the international commercial firm, had the project of implementing a warehouse or industrial building, in the surroundings of Madrid, specifically in Illescas, Toledo.

Figure 66. Localization of Toledo,Spain. Source: Crónica de la provincia de Toledo (Mariátegui, 2022)

The project covers an important surface of 14.9053 m^2 was planned, with an occupation of the industrial building of 50.000 m^2, adding the accessibility roads to it. Specifically, the study area is located southeast of the town of Illescas, close to the A-42 highway that connects Madrid with Toledo, as shown in the two photos below [fig. 67].

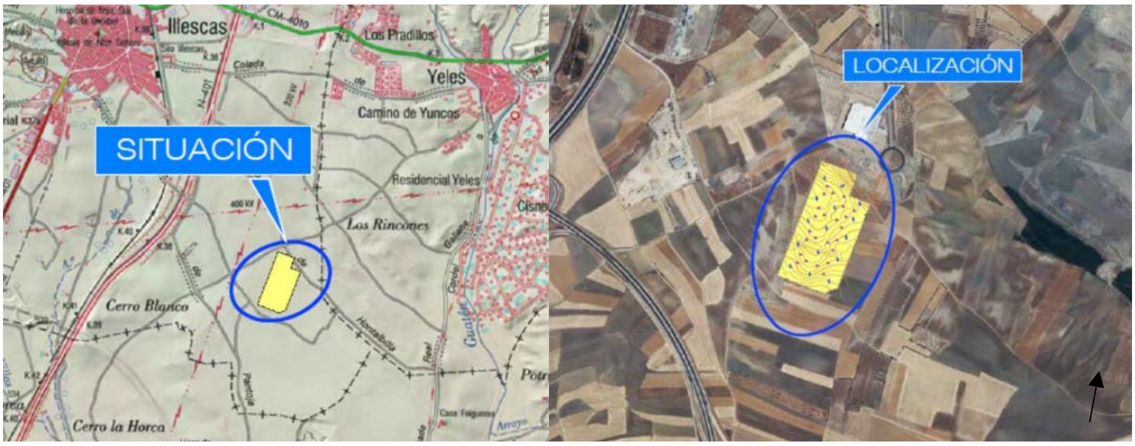

Figure 67. Situation of the warehouse. Source: Application of soil stabilization using lime to improve and reinforce the ground in industrial actions (Valiente Sanz, 2022)

Concerning the natural geology of the soil, two main types of particles have been identified: Red sandy silt, and Shales and marls.

<u>Red sandy silt</u>

It falls in between sandy soil and silty soil in terms of particle size distribution and typically contains sand, silt, and some clay-sized particles. They are thin deposits that are usually of a thickness between 0.60-1.50 m, and usually forms near valleys. In terms of texture, when moistened, it can be slightly slippery due to the existence of clay minerals in it. It is also very cohesive, which provides it with binding capacities.

<u>Shales and marls</u>

They are both types of sedimentary rocks but have different properties. Shales are fine-grained and composed primarily of clay-sized particles (less than 0.002 mm in diameter). Whereas marls are a mixture of clay and calcium carbonate with a variation proportion between both. Generally, marls are recognized for their moderate cohesion when shales are known for their ability to retain water.

A practiced section on the soil clearly shows both groups, number one being the red sandy silt that is the first superficial layer, followed by the shales and marls layer that has a more important thickness [fig. 68].

Figure 68. 1) Red sandy silt 2) Shales and marls. Source: Application of soil stabilization using lime to improve and reinforce the ground in industrial actions (Valiente Sanz, 2022)

Two geotechnical studies have been done: The study of the project before construction and during the construction phase as a complementary study using mechanical pits to get unaltered/altered samples. After getting tested in the laboratory, the following results have been obtained.

Material classification

Based on the Atterberg limits concluded [fig. 69], and the granulometry graph in [fig. 70 and 71], the material of the soil is mainly made of clay sands (SC), and clay loams (CH). From the granulometry, it can be deduced that the soil is uniform. What can be deduced for the material classification is that expansive behaviors are to be expected, with a high potential of swelling, high plasticity, low saturation capacity and a bad workability.

Unidad	USCS	PG-3	Compacidad	LL
Arenas ar-cillosas	SC	Tolerable	Media	40
Margas arcillosas	CH	Marginal	Muy Firme	61-108

Figure 69. Table of the liquid limits of the studied soil. Source: Application of soil stabilization using lime to improve and reinforce the ground in industrial actions (Valiente Sanz, 2022)

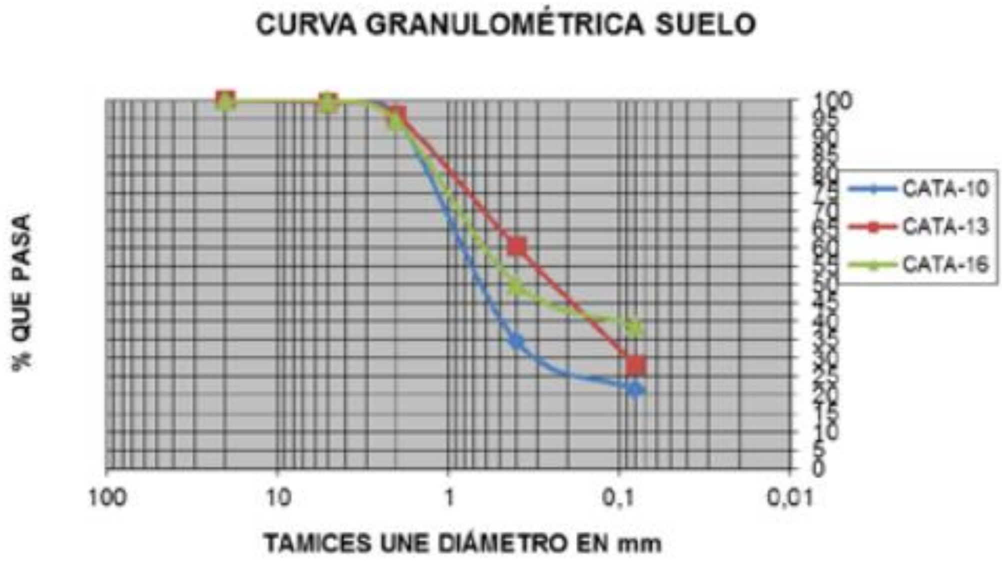

Figure 70. Granulometric curve of clay sands unit. Source: Application of soil stabilization using lime to improve and reinforce the ground in industrial actions (Valiente Sanz, 2022)

The most important values concluded from the testing are the following:

- Swelling pressure 40-100 kPa
- Free Swelling [17] between 5-11% altered samples of pits.
- CBR (100% PM) < 2.00

It can be deduced that a preventive method is required, due to the nature of the soil and its high plasticity, to avoid future structural problems.

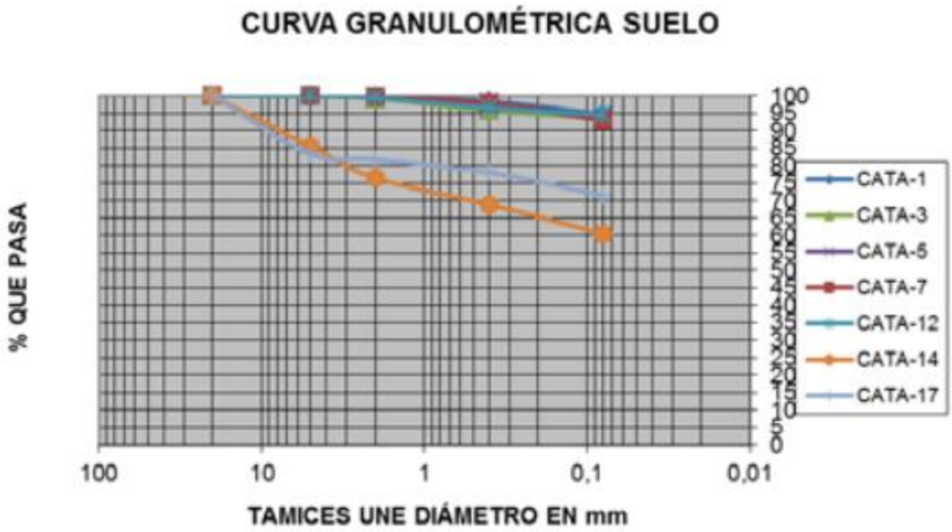

Figure 71. Granulometric curve of clay loams. Source: Application of soil stabilization using lime to improve and reinforce the ground in industrial actions (Valiente Sanz, 2022)

Only the alternative of soil stabilization has been considered, since the technique of replacement is far more expensive, less preserving of the existing soil, more disruptive and damaging to the environment, less time efficient, more time of settlement and an important number of transported materials. In fact, the soil stabilization of expansive grounds is often the preferred choice because it allows a more flexible procedure that can be adapted to the project's needs and requirements.

When it comes to the chosen additive, lime has been chosen for its great capacity in improving the soil's structure by reducing its plasticity and increasing its cohesion, in reducing the problematic swelling and shrinking, in demonstrating rapid durable results, all while being the most cost effective among the other additives seen before. Based on the complementary tests carried out, it was decided to use soils stabilized with lime with percentages of 3%. In practically 7 days, HL values of less than 1.50% were achieved with these percentages.

The objective fixed after the testing of the soil was to considerably increase its bearing capacity, going from very low CBR to values higher than 12, which would correspond at least to an adequate soil for safe construction.

(17) It refers to the natural expansion of clayey soils when they absorb water and the subsequent contraction when they dry *(Braja M.das, 1984)*.

Figure 72. Lime enhancement method on the warehouse site. Source: Application of soil stabilization using lime to improve and reinforce the ground in industrial actions (Valiente Sanz, 2022)

Results

The swelling has been significantly reduced with the current soil. Between the unaltered, altered, and lime treated samples; the last one comes in between the two with an adequate amount of volume changes.

The treated soil sample is the one with the least registered swelling for the same percentage of humidity than the altered and unaltered samples [fig. 73 and 74]. It is observed that the treated sample has a reduced swelling percentage than the altered sample, which puts it in acceptable values for the start of the construction project.

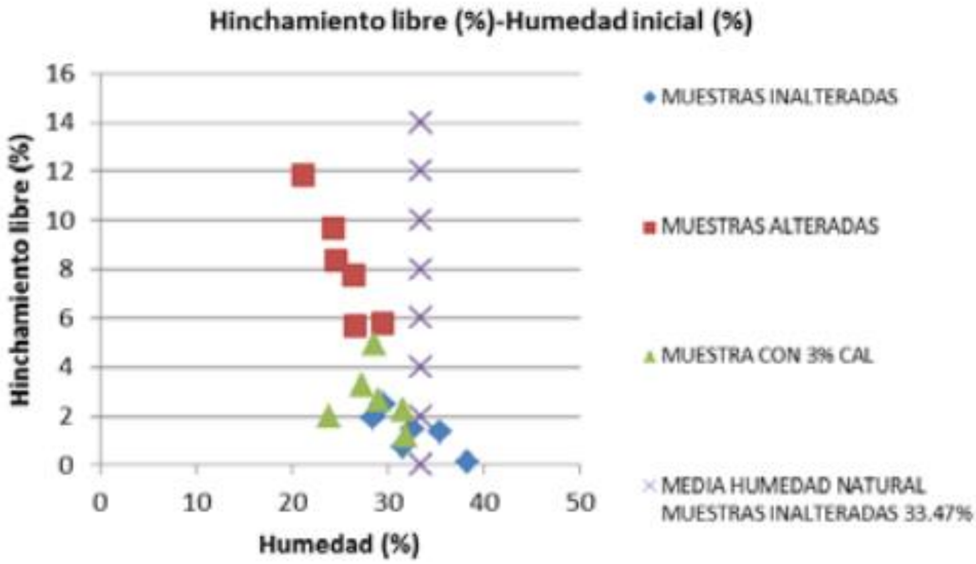

Figure 73. Free swelling percentage in function of humidity. Source: Application of soil stabilization using lime to improve and reinforce the ground in industrial actions (Valiente Sanz, 2022)

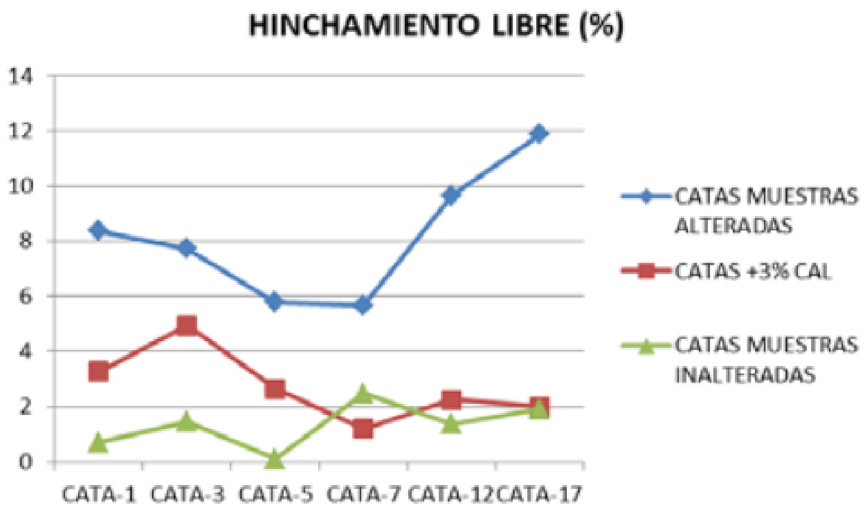

Figure 74. Free swelling percentage in function of the sample. Source: Application of soil stabilization using lime to improve and reinforce the ground in industrial actions (Valiente Sanz, 2022)

Furthermore, an increase in bearing capacity has also been observed [fig. 75]. In samples that are treated with lime, a dramatically higher bearing capacity has been observed, whereas the altered sample's capacity is almost zero.

In the curves representing the variation of swelling with time also lead to the same conclusion, where it shows that the treated sample's swelling is significantly reduced after 7 days, in comparison with the results that were registered after 24 hours, proving the efficiency of the lime enhancement method, and the important changes it brings to expansive soils. These results are shown in the graph [fig. 76], and also ensures the importance of the curing period where all the enhancements happen.

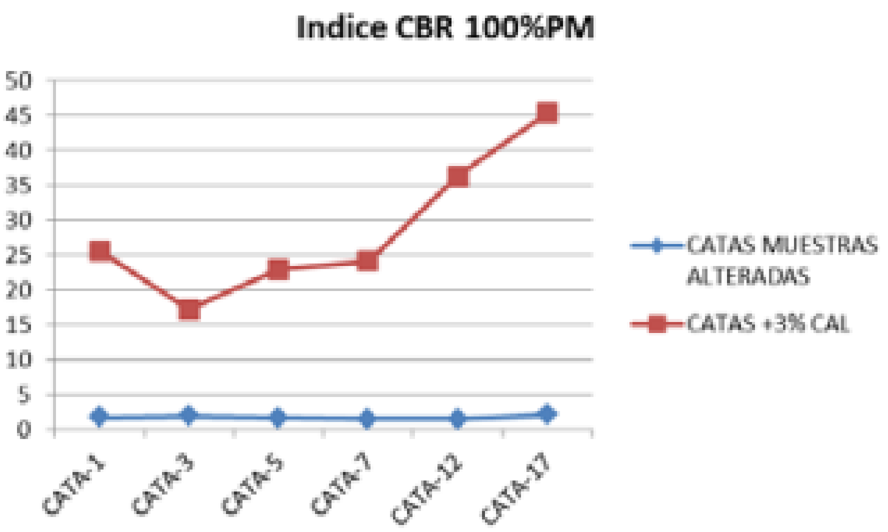

Figure 75. Baring capacities in function of the sample. Source: Application of soil stabilization using lime to improve and reinforce the ground in industrial actions (Valiente Sanz, 2022)

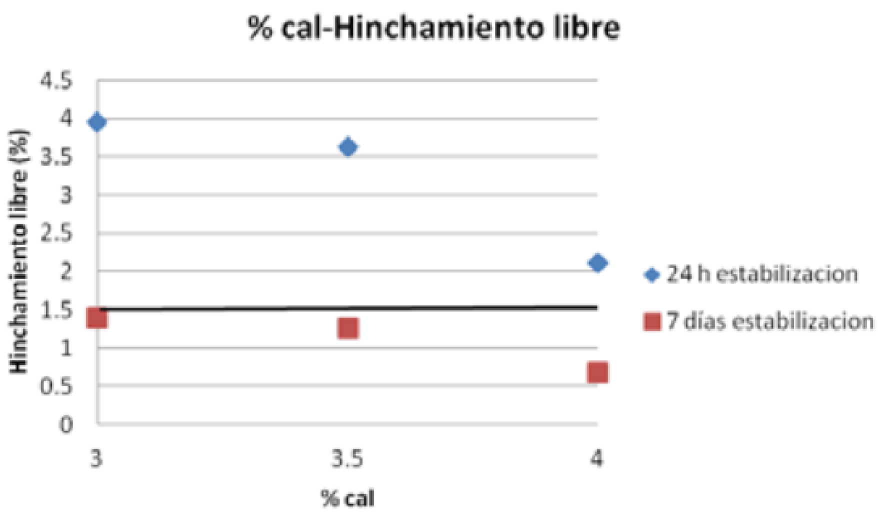

Figure 76. Percentage of free swelling after 24 hours and 7 days of curing. Source: Application of soil stabilization using lime to improve and reinforce the ground in industrial actions (Valiente Sanz, 2022)

Besides that, the texture and visual of the soil have also drastically changed. The soil has a very granulated, almost rocky texture that is very different from what is known of clays [fig. 77]. That is the effect of flocculation that happens during the chemical reaction between lime and clay particles.

Figure 77. Soil's detail once stabilized. Source: Application of soil stabilization using lime to improve and reinforce the ground in industrial actions (Valiente Sanz, 2022)

Constructive proposition

As a complementary measure aside from the soil's enhancement with lime, further constructive solutions were proposed at the level of the structure.

From the regulations of the Construction document, an esplanade E2 was required to support the slabs inside the industrial building and an esplanade E3 was going to be used on the outside.

Section of warehouse E2

The esplanade was formed with tolerable soil stabilized with 3% lime and tolerable soil. Regarding the embarkment core, a marginal soil stabilized with 3% lime, plus a box bottom stabilization in situ.

Section of access roads E3

The esplanade was formed with tolerable soil stabilized with 3% lime (30cm of thickness), then Soil stabilized "in situ" with 3% lime. Regarding the embarkment core, its soil was stabilized in situ with 3% lime (60 cm of thickness organized into 2 layers of 30 cm of thickness). The case back stabilized in situ 3% lime SEST2 (40cm of thickness). Additionally, natural terrain with a minimum CBR of 1.50 was added as well [fig. 78].

Figure 78. Execution of the roads. Source: Application of soil stabilization using lime to improve and reinforce the ground in industrial actions (Valiente Sanz, 2022)

Test embankments were later carried out with different sections to proceed to the control phase using loading plates at different stages of the curing of the stabilized material, achieving the same after 21 days, with practically zero swelling at the bottom of the esplanade.

In the graph [fig. 79], the load bearing capacity of EV1 goes through a decrease during approximately the 12th or 13th day of curation, to later increase significantly starting from the 15th day until reaching its maximum capacity of around 250 Mpa. As for EV2, it has a continued uniform, almost lineal evolution through the period of curation and does not experience a decrease, reaching a maximum of more than 350 Mpa.

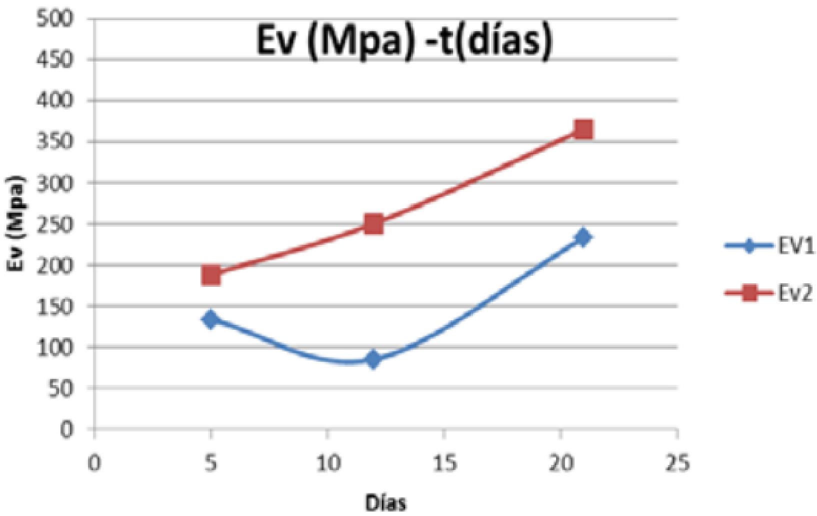

Figure 79. Load plate results. Source: Application of soil stabilization using lime to improve and reinforce the ground in industrial actions (Valiente Sanz, 2022)

The case study is a very interesting application to what was theoretically explained in terms of expansive soils, clay and its different mineralogy, the factors to influence its different properties such as plasticity, compacity, bearing capacity and water content, the manifestations of the expansivity phenomenon and its influencing criteria, different constructive and preventive methods as much as on the structural ground than the geotechnical one, and so on.

7. Conclusion

Clay soils represent approximately 80 percent of the earth's land surface. Their expansive behavior represents a major risk for constructions because they tend to contract and expand in response to variations in humidity, which can cause damage to foundations, deteriorating walls, floors, openings, and ducts.

A variety of pathologies can be signs of expansive clay. Architecture professionals tend to view expansive clays as very challenging for future projects. A specific geotechnical characterization is crucial as it will allow to carry out a rigorous and efficient design of the foundations to support the load of the construction. Different soil improvement techniques and foundation types were analyzed to control the expansive character of the clay.

The case study of the Amazon warehouse is a perfect example of the excellent management of clay soils using the lime stabilization method that effectively transforms highly expansive unstable soils into granular more coherent ones, facilitating the construction and opening the door to more foundation's options, as well as avoiding huge unnecessary costs. Through the preliminary laboratory results, certain properties were registered and later compared with the final values, after the treatment of the soil with lime. It was observed that the lime metho enhances drastically the stability of the ground, making it more compact, less prone to swellings, and with a much higher bearing capacity.

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