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Strength and elasto-plastic properties of non-industrial building materials manufactured with clay as a natural binder

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Abstract

The objective of this article is to study the mechanical performances of non-industrial materials made with soils containing argillaceous minerals as the sole binder (materials referred to as earthen). The renewed interest in earthen construction requires, in the current context, a scientific approach to these materials and a re-examination of certain techniques such as that of adobes. These adobes are obtained starting with very argillaceous soil saturated with water and poured into wooden moulds.

Thus with a soil containing 25% clay, two types of adobe were studied: traditional adobe and Pressed Adobe Blocks (PABs). They were made with a variation in moulding water. Once dried, they were subjected to an unconfined compression test with three loaded and unloaded cycles at 30% of the compressive strength. This test, which takes into account the specificity of adobes, made it possible to determine their compressive strength, initial tangent modulus (E_t) and equivalent modulus during cycles (E_{eq}).

From the results obtained, it appears that the mechanical performances of adobes depend on the moulding water content (W_m) and the manufacturing process used. The PABs with a lower W_m have a higher compressive strength than the adobes. Moreover, they are more homogeneous, although both types of adobe have an elastoplastic behavior. Therefore, for laboratory testing the use of PABs is recommended rather than the use of adobe.

Keywords: non-industrial building material; clay; binder; stiffness, compressive strength, adobe

1. Introduction

Given the environmental destruction and global warming caused by the excessive use of industrial materials, a certain number of individuals and researchers have been re-considering the use of non-industrial materials. The notion of non-industrial materials in building is linked to local materials and is becoming worthy of interest again (Morel et al., 2001) due to the increasing demand for housing as populations increase, and to the need to reduce the energy consumption of the building industry. The concept of non-industrial building materials means materials manufactured using a simple, quick process with low embodied energy, using raw materials from the site or nearby. To translate this concept into action, many ideas have been developed, including the use of soil as a raw material. The term soil refers to the more or less argillaceous soil found between the rock substratum and the topsoil layer. We will refer here to unfired clay soil, exclusively called "soil". This raw material thus does not have a standard composition. Consequently, each type of soil requires a specific manufacturing process to obtain a building material, and the process therefore cannot be industrialized. The soil must be taken from the construction site or nearby in order to limit transportation (Morel et al 2001), and must contain clay particles to reduce or avoid the use of industrial binders like lime and cement.

1.1. Soil variability

Soils change significantly according to the climate, relief and nature of their bedrock, thus their properties vary considerably. Therefore, looking at a map of the soil suitable for building (Houben and Guillaud, 1994), one can observe a wide diversity of soils that can be used as a raw material to manufacture non-industrial building materials. Furthermore, the properties of a soil evolve according to the organization of its particles during the sedimentary process and the depth at which it was extracted (Vasseur, et al., 1995).

Soil is a complex material composed essentially of clay minerals and sand with organic matter and associated minerals including anatase and hematite considered to be impurities. Each of these elements has different behaviors which influence soil properties. For example, the presence of organic matter increases plasticity (Malkawi, et al., 1999). Furthermore, the proportions of clay and sand change, causing variations in soil structure, plasticity, cohesion and permeability. The nature of the clay minerals also influences soil properties.

1.2. Manufacture of unfired earthen materials

The use of soil as a building material goes back thousands of years. Some examples include the oldest historical houses in the United States, the bam citadel in Kerman-Iran (Manzano-Ramírez, et al., 2007) and the Alhambra in Granada, Spain (Jaquin, et al., 2007). Many techniques have been employed, some of which are still used, yet have been modernized. These techniques can be divided into three main categories: (i) monolithic load-bearing walls; (ii) load-bearing masonry; (iii) timber frame filler mud walls. The soil is mixed until one obtains a mixture as homogeneous as possible, which is then molded or compacted into formwork and sun-dried. This moulding or compaction (dynamic or static) reduces the quantity of voids between grains and thus gives a form to the mixture thanks to cohesion. Dry samples are directly used to build houses without any other treatment, i.e. these materials are neither fired nor stabilized. Clay is the only binder ensuring strength and stabilization. However, the building must be relatively well protected from water (by architectural design), since saturation of the soil reduces its mechanical performances. Like dry-stone masonry, soil results from a non-industrial technique, and they represent the only construction materials that can be so easily re-used and do not generate waste.

1.3. Earlier studies on earthen materials

Scientific studies of earthen building materials have intensified over the last 20 years. Certain researchers focused on soil characterization and developed various techniques to identify clay minerals and classify soils (Lautrin, 1987; Lan, 1980; Ghosh and Bhattacharyya, 2002; Sei, et al., 2004; Kaufhold, et al., 2002). They showed that the soil for building materials must contain less than 20% clay minerals, and that kaolinite, is the best suited. Other studies dealt with manufacturing process optimization and the influence of compaction energy (Olivier and Mesbah, 1986, Attom, 1997; Venkatarama Reddy and Jagadish, 1995; Mesbah, et al., 1999). In general, compaction increases dry density and compressive strength, but the water content must be optimum to achieve the highest strength. The optimum water content is determined by studying the relationship between water content and dry density. The Proctor test is used in the case of road design with non-argillaceous materials, to determine optimum water content. It is not recommended for earthen construction materials. Indeed, the compaction energy of the Proctor test does not usually correspond to that used for earthen construction (Mesbah et al., 1999).

Other studies have focused on determining the hydraulic binder content (Portland cement and lime) to be added to the soil in order to improve its behaviour with water (Jagadish, et al., 2007, Kouakou, 2005).

Many new earthen architecture projects are built with compressed earth blocks (CEBs) and rammed earth. This is why several new articles have been published on these materials and structures, for example concerning the comfort of rammed earth houses (Hall and Allinson 2008), their durability (Bui et al 2008 (1)) and their mechanical behavior (Jayasinghe and Kamaladasa 2007, Bui et al 2008 (2), Maniatidis and Walker 2008). As for CEB masonry, the literature is older but there are some recent publications concerning the mechanical behavior of blocks and masonry (Morel et al 2007, Gumaste et al 2007, Reddy et al 2007) and soil mortar (Azeredo et al 2008, Reddy and Gupta 2008).

All of these studies were focused on CEBs, and sometimes on rammed earth, which is made with soil containing 5% to 15% clay. A small number of studies have been made on soil containing 20% to 35% clay, focusing mainly on the incorporation of chemical stabilizers such as cement to improve strength and water resistance and to reduce shrinkage. Presumably, earthen building materials without cement (or with less cement) are eroded by water (Temimi, et al., 1998) but old earthen construction methods using adobe without cement are still used today. Furthermore, the materials used in these studies (Temimi, et al., 1998; Ben Amor et al., 1997) are not natural. They were made by adding sand and clay to reduce the complex variations of the natural earth's behavior. Thus the behavior of these recomposed soils may be different from that of natural soils containing associated minerals such as iron or calcium minerals, aluminum oxide, and others. These studies were limited to a given material, whereas we present a more general study here.

Our building heritage is proof that the use of soil as a building material was well-known all over the world. In Europe, the technique was abandoned after World War II, whereas in developing countries earthen construction is still widely used. But it was not popular until recently, when architects began again to encourage the use of compressed earth blocks (CEBs) in India and Africa, rammed earth in Australia and Europe, and adobes (mud bricks) in the USA. This rediscovery of earthen construction materials raises questions concerning soil characterization, the manufacturing process, and material testing. Until now empiricism was sufficient in order to build with soil, but today scientific data is necessary.

2. Raw material.

2.1. The choice of raw material

In this paper we discuss blocks obtained with a simple “wet” process: the mixture of soil and water (water content > 15%) for use in masonry structures. Our tests were aimed to investigate improvements in the adobe-making process, the testing process, and how clay's binder effect enhances the mechanical performance of adobes. Adobe is one of the oldest earthen building materials in the world (Rogers and Smalley, 1995). The Pre-Colombian Taos Pueblo, a five-story adobe structure in the United States built without any cement, stabilizers or waterproofing agents, is estimated by archaeologists to be at least 900 years old (US Patent 4366657, 1980). For a reference material for our study we therefore chose a soil allowing the manufacture of adobe originating from Rochechinard, a site located in the Isère valley region (France).

2.2. Characterization of the raw material

Rochechinard soil is red and gives blocks the appearance of fired bricks. The mineralogy of Rochechinard soil was determined by X-ray diffraction (XRD) (Fig. 1). The XRD data were analyzed considering the intensity of reflections diagnosed for each mineral. Kaolinite and illite are the main clay minerals, therefore we did not observe the presence of any associated crystalline minerals. The particle size analysis in Figure 2 shows that the clay content is high (25%). Therefore, this soil is not suitable for CEBs since it is not possible to obtain a homogeneous mixture with a low water content (15%). Table 1 gives the geotechnical characteristics of the soil. The illite and kaolinite content were calculated according the method indicated by Holtzapffel (1985). It uses the height of the (001) reflection on ethylene glycol X-ray diffraction.

[Figure 1], [Figure 2] and [Table 1]

3. Block manufacturing procedures

The raw material (soil from Rochechinard) was moistened with different amounts of water and homogenized with a mechanical mixer for 15 minutes. The clay-water mixture obtained was used to make handmade blocks in two ways.

- The first method was the traditional adobe-making one using wooden moulds (wooden mould process). The dimensions of the mould were 310 x 152 x 73 mm^3. The mould was placed on the floor, and a sufficient amount of clay-water mixture was poured inside. Then the clay-water mixture was pressed with the hands and the block surface was leveled with a ruler. Finally the mould was removed, and at this stage the block was called an “adobe” and sun-dried on the floor. This process required soil with a "high" water content, i.e. material in a near-liquid state to enable the manufacturing process (see also Fig. 6). In order to decrease this moulding water content, a second method was proposed.

- The second method aimed to manufacture a new material called a Pressed Adobe Block (PAB) with a lower moulding water content, and used a GEO 50 manual press used to make CEBs (pressing process). The pressure applied during compaction was approximately 2 MPa. The non-manual adobe pressing process usually uses extruders, thus resembling an industrial process since it uses electricity or fossil energy. The CEB manual press was used with a manual compaction process similar to extrusion in our case since the material was wetter than CEBs (but less wet than adobes, see Fig. 6). When a soil is moistened with increasing quantities of water, it passes from a dry state to a plastic state, then to a liquid state with a drop in its consistency. These changes of state occur gradually without precise limits and are accompanied by the progressive reduction of the intergranular voids (Fig. 3). The purpose of compaction is to reduce the volume of these intergranular voids. To make blocks, the press mould was filled with a constant weight of soil-water mixture (8.7 kg). This amount of soil-water mixture was enough to make blocks with a good shape (Fig. 4). After pressing, the block (295 x 140 x 100 mm^3) was placed in a drying room. This block is referred to as a Pressed Adobe Block (PAB) and is different from a Compressed Earth Block (CEB) (cf. section 4).

[Figure 3] and [Figure 4]

For this study, the first water content was chosen close to the plastic limit to prevent the block from collapsing under its own weight once removed from the mould. This choice is similar to what occurs on sites where traditional adobes are made. Then the water quantity was progressively reduced until it was too difficult to obtain a homogeneous mixture.

The adobe and PABs were dried in the laboratory at room temperature (~22 °C) with a humidity of 60% until the block weight became constant (~3 weeks).

The water content of the soil-water mixture (W_m) was determined in accordance with the ASTM C138 procedure. Air-dried adobes were cut with an electric saw into four pieces (Fig. 5). Each piece and PAB was tested in compression. After the compression testing, the residual water content (W_r) of the sample was also determined. Then the volumetric drying shrinkage and the PAB oven dried density were calculated. To obtain the oven dried density, the sample was oven dried at 105°C until its weight remains constant. In the following, if not specified, dry density refers to oven dried density.

[Figure 5]

4. Effect of the block manufacturing process on its characteristics

The mechanical properties of construction materials depend on several factors, including the characteristics of the raw material and the manufacturing process. This manufacturing process is generally evaluated by measuring the dry density (Morel, et al., 2007). The dry densities of the various types of adobe samples are presented in Figure 6, which shows that the dry density of the blocks varies with the moulding water content. The dry density of the adobe samples varies, although they came from the same adobe. The adobes were thus not homogeneous. This heterogeneity was due to the manual moulding which became increasingly difficult with a drier soil-water mixture (moulding water content below a threshold value $W_m < W_l$) (Fig. 6). Therefore, when the moulding water content was decreased the dry densities were more dispersed. Beyond the water content W_l ($W_m > W_l$), the dry density of samples (a) and (b) became less dispersed, leading us to assume that the material was then more homogeneous. This homogeneity was much better for the samples (b) located in the central portion of the adobes, which illustrates the side effects. Indeed, these (b) samples had 20% of their surface in contact with the mould during their manufacture, while the (a) samples had 40% (Fig. 5). Thus the edge effects during manufacture were twice as small for (b) than for (a). These effects, i.e. the adhesion and friction of the soil-water mixture against the sides of the mould, generated defects on the surface of the adobes (Fig.5).

[Figure 6]

Figure 6 shows that the dry density of the PABs increased when the moulding water content dropped, with a good correlation. The method used to make the PABs would seem to enable the production of homogeneous blocks. However, when the moulding water content decreased below a threshold value (W_c), the PABs can no longer be manufactured due to the difficulty to mix the soil-water mixture. Indeed, since the quantity of moulding water was too small, the product obtained after mixing consists of aggregates (sand+clay) of variable size. The moulding water was not uniformly distributed. The PABs obtained cannot be anymore considered as homogeneous material. The threshold water quantity leading to this structure was at roughly 15% for the Rochechinard soil.

In addition, Figure 6 can be divided into three domains, those of the adobe, the PABs and the CEBs. The passage from the domain of the adobes to that of the PABs is accompanied by an increase in dry density due to the use of a mechanical compaction process. However, the high dry density in the case of the adobe and PABs was also due to shrinkage during drying. Indeed, when wet, the clay minerals in the soil have the capacity to adsorb water and swell (Jouenne, 1984). The larger the quantity of water brought to the soil, the larger the layer of adsorbed water will be and the more the soil will swell (Fig. 3). Thus, when the moulding water content is higher than the threshold (W_c), the compaction, supposed to bring the grains closer to each other, is not effective since the compaction energy is dissipated by the water. On the other hand, when the quantity of moulding water is lower than the threshold (W_c), the compaction energy is used completely to compact the grains, increasing the dry density (Fig. 7). This increase as the moulding water content decreases complies with the results obtained by Olivier (1994) and Venkatarama Reddy and Jagadish (1995) for Compressed Earth Blocks with a water content beyond the Optimum Water Content.

[Figure 7]

After the compaction process, the evaporation of a portion of the moulding water during drying caused shrinkage of the blocks but also ensured the development of porosity. This porosity decreased when W_m decreases (Table 2). Thus a block made with a high W_m will have more shrinkage and porosity and a lower dry density than a block manufactured with a lower W_m (Fig. 7 b and d). This is why the variation curve of the dry density of the PABs and the adobes is above the saturation curve. The saturation curve represents the theoretical case where the Rochechinard soil had all of its voids full of moulding water during the moulding process and endures no shrinkage during the air drying process (Fig. 6). Moreover, the increasing distance between these two curves when the moulding water content increases confirms the influence of the shrinkage consequences.

[Table 2]

In addition, it is proposed to continuously classify the techniques employed today to manufacture non-industrial materials into 2 categories according to moulding water content (W_m): dry processes (8% $<W_m<$15%) and wet processes (16% $<W_m<$35%). Dry processes would include rammed earth and CEBs, while the wet processes include cob and adobes. The PAB manufacturing process is classified as a wet process but constitutes the link between the two processes (half dry, half wet) since PABs represent adobes yet are compressed ("extrusio-compaction"), whereas CEBs are manufactured by pure compaction using a dry process at an Optimum Water Content below the saturation water content.

5. Compressive strength

The compressive strength is the most important parameter for earthen materials, just like any unreinforced masonry. It corresponds to the maximum load that a material can support when it is subjected to compression. It enables not only the quality control of a material, but especially represents a means to assess and compare the material performance.

Many research projects have focused on measuring the compressive strength of masonry blocks using the unconfined compression test, using samples with an aspect ratio (height/width) of 2 making it possible to have an unconfined compression strength. See Morel et al. 2007 for a review on this subject and Walker 95 and Walker and Stace 1997 for the use of an aspect ratio correction factor. In order to provide samples with this aspect ratio of 2, the adobes were sawed into 4 pieces (Fig. 5). This operation does not deteriorate the quality of the material, due to the fineness of the Rochechinard soil and the visible absence of cracks on the sawn surfaces. The pieces obtained after sawing measured 70 x 60 x 140 mm^3. Likewise, the PABs were tested on their ends in order to preserve the same aspect ratio 2 (Fig. 4) and to compare their compressive strength value with that of the adobes. The assumption that the blocks were isotropic was made here thanks to the data given by Morel et al., (2007) for the case of CEBs compacted using the dry process.

The unconfined compression test was carried out using a hydraulic press. The test was run at a constant speed of 0.01 $mm.s^{-1}$. The load sensor used has a capacity of 50 kN and a precision of ± 0.02 kN. The measurement results for the compressive strength of the adobe samples and PABs are presented in Figure 8.

[Figure 8]

This figure describes the relationship between the oven dried density and the compressive strengths of the adobes (sample (b) only) and the PABs. It indicates that in general the compressive strength increases along with the dry density. Thus, when the material becomes denser, i.e. the particles are closer to each other, the compressive strength increases. This result is classic and in conformity with those of Olivier (1986) and Morel et al., (2007) for Compressed Earth Blocks.

In addition, Figure 8 also shows that the curve has an area where the strength and dry density of the adobes and PABs coincide. This coincidence can be explained by the null effect of the compaction, since the material is saturated (Attom, 1997; Mesbah et al., 1999). The dispersion of the adobe values was already discussed in section 4 and could also be due to the fact that they were cut whereas the PABs are whole. Beyond this area of coincidence, the compressive strength of the PABs is higher than that of the adobes.

6. Deformation properties of adobe and PABs

The various mechanical loads imposed on construction materials during their lifetime generate deformation of the material prior to its failure. The study of the link between stress and strain makes it possible to determine the intrinsic properties of the material, identify these various deformation phases, and predict a material's behavior within a masonry structure. This is expressed with rheological laws including elasticity, plasticity, and viscoplasticity. The strain is examined based on the stress-strain curves resulting from a homogeneous shear test or a simple compression tensile test.

For adobes and PABs, the stress-strain curves obtained during the unconfined compression tests were used to analyze their strain properties (Fig. 9). Sensors recorded the displacement of the press piston as well as the force exerted on the sample. During the test, three unload and reload cycles were carried out at 1.2 MPa and 0.7 MPa respectively for the PABs and the adobes. These values corresponded to approximately 30% of the compressive strength. These cycles were carried out to see whether the behavior was reversible or not (elastic or not).

6.1. Stress-strain relationship of adobe and PABs

Figure 9 shows that the behavior of the adobes is similar to that of the PABs. Their behavior is not perfectly elastic due to the residual strain (ε_r) after the cycle (Fig. 9): at the end of the load and unload cycle, the strain is not equal again to zero. Their behavior is consequently also plastic. These stress-strain curves can be subdivided into two phases.

[Figure 9]

The contact adjustment phase (sample-press) corresponds to the start of loading (from the origin to point A). It is related to the fact that the surface sample is not perfectly plane, due to the asperities of the block surfaces created, since the shrinkage that occurs during the drying process is not perfectly uniform. During this phase, the rigid plates of the press crushed the asperities on the block surface. The second phase should begin at point A (Fig. 9), continued from the end of the adjustment phase until failure, and corresponded to the intrinsic behavior of the material (Fig. 9).

In order to specify this behavior for the PABs as well as the adobe sample, two moduli were given based on the stress-strain curves (Fig. 9): the initial tangent modulus (E_t) and the equivalent modulus (E_{eq}). The equivalent modulus is the modulus measured during cycles (see Di Benedetto et al 2005). The E_t and E_{eq} are very different here, also indicating that the behaviour is elastoplastic; if $E_t=E_{eq}$, the material can be considered elastic.

6.2. Influence of dry density on stiffness and compressive strength

To continue this study, accurate measurements are required, thus it is not possible to use the adobe samples, since they have a relative heterogeneity as seen previously (Fig. 6). We will study only the PABs, given that it was considered legitimate to extrapolate their behavior to the adobes, since the PABs have better homogeneity and surface quality.

Figure 10 shows the variation of E_t and E_{eq} with the dry density. It indicates that the two moduli hardly vary with the increase in dry density. This relative constancy of the modulus is against intuition since the PABs' dry density variation appears to have an influence on the sand grain skeleton and the size and distribution of the pores in the argillaceous matrix.

[Figure 10]

Moreover, a juxtaposition of Figures 8 and 10 shows that the compressive strength of the PABs increases along with the increase in dry density according to a polynomial law, whereas E_{eq} remains practically constant. The variation in x^2 of the compressive strength can be explained by the drop in porosity (Tab. 2) in general and especially by the closing of certain macropores caused by the manufacturing process. This closing of the pores corresponds to a consolidation of the material.

7. Conclusion

The contribution of clay as a natural binder to the mechanical performances of non-industrial materials such as adobes was examined. The following conclusions emerge from this study:

- The traditional adobe manufacturing process can be improved by using a manual CEB production press. These new PAB materials are more homogeneous and less deformed by shrinkage than traditional adobes, which facilitates the scientific study of their mechanical characteristics.

- The PAB technique is an intermediate one between that of CEBs and that of adobes, making it possible to classify it in two categories: wet and dry production processes for non-industrial earthen materials.

- The compressive strength of adobes and PABs increases with dry density. Pressed adobe is superior to adobe in many respects such as strength and stiffness. PABs have a compressive strength higher than that of adobes, with a gain of approximately 50%.

- Adobe and PABs have an elastoplastic behavior. Their stress-strain curve in unconfined compression gives two moduli, the initial tangent modulus (E_i) and the equivalent modulus (E_{eq}). This two moduli are different and do not vary significantly with the dry density.

It is interesting to note here that a natural soil containing approximately 25% clay (diameter < 2 µm) was used as a raw material for construction without the contribution of any industrial stabilizer. The natural properties of clay as a binder were able to contribute to obtaining a compressive strength from 3 to 4.5 MPa. However, adobe and PAB walls could soften, disintegrate and even collapse upon complete saturation. Hence, buildings made of such blocks should be completely protected from moisture ingress due to rain and natural weathering conditions.

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Figure 1:X-ray diffractograms on clay from Rochechinard; Q=quartz; K=kaolinite; I=illite; NC=no crystallized mineral

Figure 2: Grain-size distribution of clayey soil sample used in this study, soil from Rochechinard (France, Europe)

Figure 3 : Scheme of the different states of water in a soil : filling the inter-granular voids, W_{p}=plastic limit; W_{L}=liquid limit

Figure 4: A PAB made with Rochechinard soil

Figure 5: Adobe samples for compression testing (W_m=24 %); samples (a) and (b) from the same adobe block, aspect ratio of 2

Figure 6 : Relationship between oven dried density and moulding water

Figure 7 : Diagram of block structuring during a dry period:
wet material a) W_m=20.7 % clay particle ; c) W_m=16.4 % more compact clay particles: dry material, appearance of macro- and micropores b)W_m=20.7 % predominance of macropores ; d) W_m =16.4 % predominance of micropores

Figure 8: Relationship between oven dried density and compressive strength

Figure 9: Stress-strain curve; E_t: initial tangent modulus; E_{eq}: equivalent modulus; ε_i: residual strain.

Figure 10: relationship between oven dried density and moduli (load of cycles: 1.2 MPa) E_t: initial tangent modulus; E_{eq}: equivalent modulus

Table 1: Properties of Rochechinard soil

Table 2: Shrinkage and porosity of PABs

Table 1: Properties of Rochechinard soil

Table 2: Shrinkage and porosity of PABs

Table 1

		Rochechinard clay
Atterberg limit	Liquid limit	38 %
	Plastic limit	20 %
	Plasticity Index	18 %
Particle size distribution	Sand	44.5 %
	Silt	30 %
	Clay	25.5 %
Clay Minerals	Kaolinite	~90 %
	Illite	~10 %
Adsorption of methylene blue	Blue value	2.5
	Activity	10

Table 2

Moulding water content (%)	Volumetric shrinkage (%)	Standard deviation (%)	Porosity (%)	Standard deviation (%)
14.7	6.4	1.3	21	0.6
16.4	9.4	0.4	22.6	0.4
17.4	12.7	1.4	24	0.4
20.7	14.6	1.3	25.7	1

Figure 1:X-ray diffractograms on clay from Rochechinard; Q=quartz; K=kaolinite; I=illite; NC=no crystallized mineral

Figure 2: Grain-size distribution of clayey soil sample used in this study, soil from Rochechinard (France, Europe)

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Figure 8: Relationship between oven dried density and compressive strength

Figure 9: Stress-strain curve; E_t: initial tangent modulus; E_{eq}: equivalent modulus; ε_i: residual strain.

Figure 10: relationship between oven dried density and moduli (load of cycles: 1.2 MPa) E_t: initial tangent modulus; E_{eq}: equivalent modulus

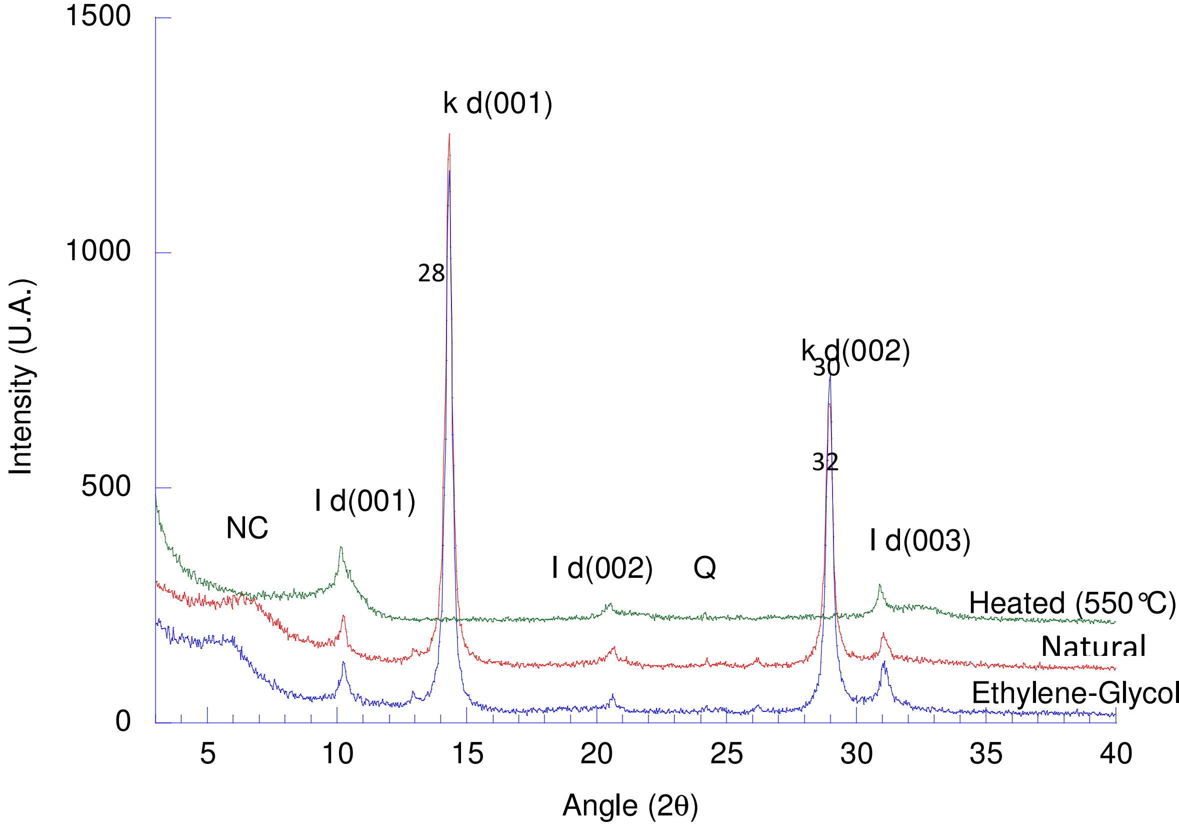
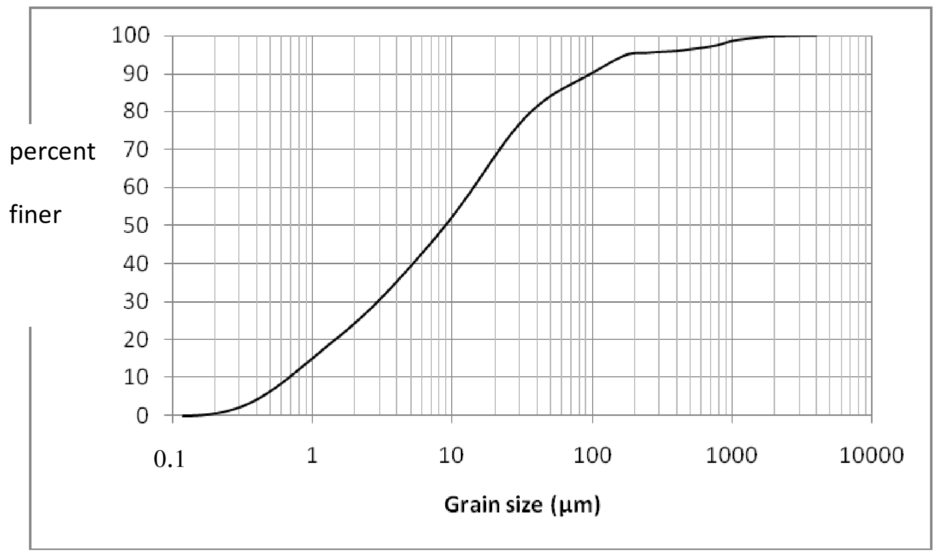

1500
1000
500
0
Intensity (U.A.)
k d(001)
k d(002)
NC
I d(001)
I d(002)
Q
I d(003)
Heated (550℃)
Natural
Ethylene-Glycol
5
10
15
20
25
30
35
40
Angle (2θ)

Figure 1



percent
finer
100
90
80
70
60
50
40
30
20
10
0
0.1
1
10
100
1000
10000
Grain size (µm)

Figure 2

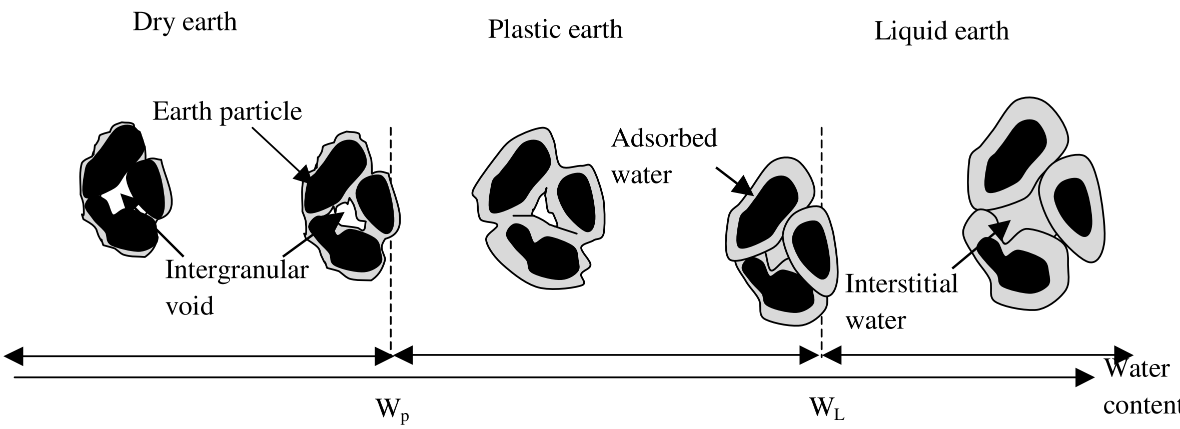

Dry earth
Plastic earth
Liquid earth
Earth particle
Adsorbed water
Intergranular void
Interstitial water
Water content
W_p
W_L

Figure 3

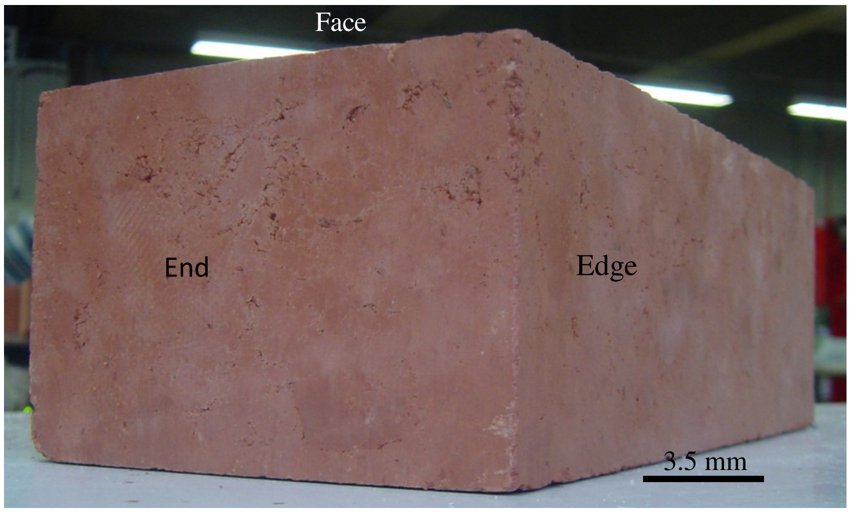


Figure 4

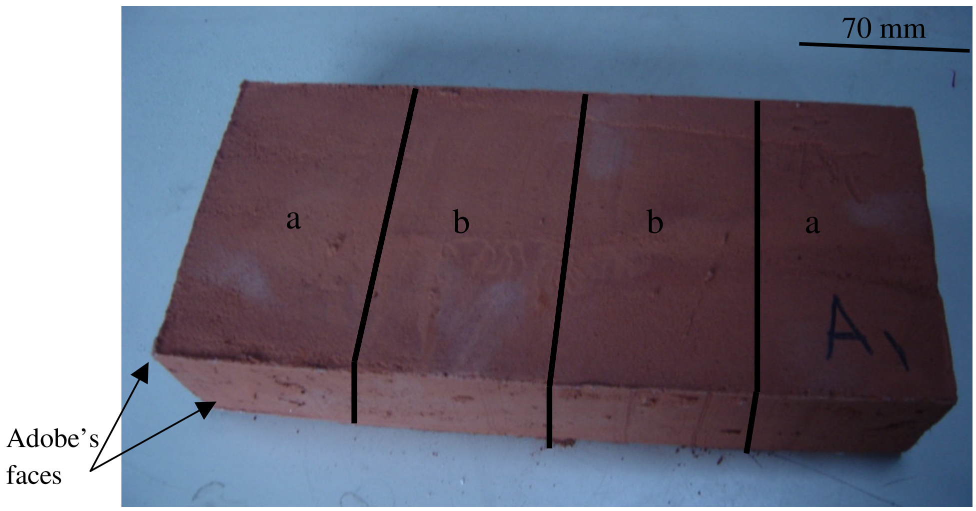


Figure 5

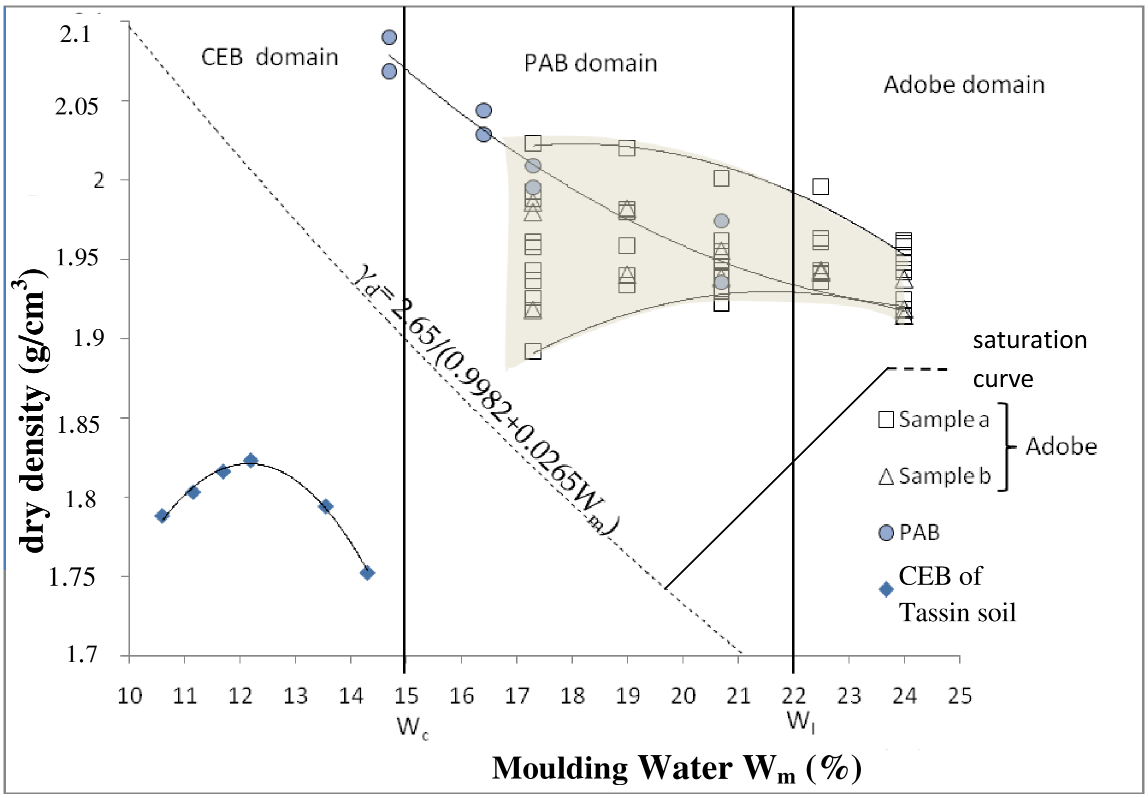

CEB domain
PAB domain
Adobe domain
dry density (g/cm³)
2.1
2.05
2
1.95
1.9
1.85
1.8
1.75
1.7
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
Wc
Wl
Moulding Water Wm (%)
γd= 2.65/(0.9982+0.0265Wm)
saturation curve
Sample a
Sample b
Adobe
PAB
CEB of Tassin soil

Figure 6

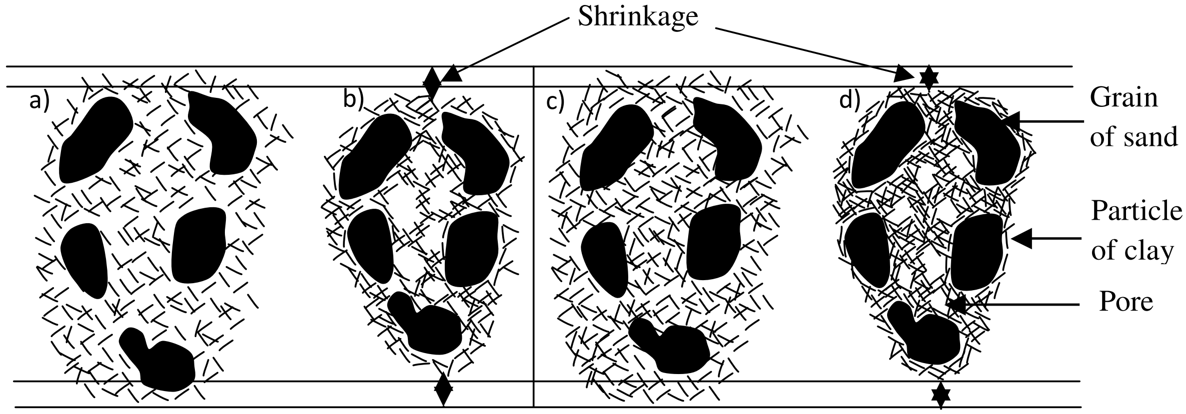


Figure 7

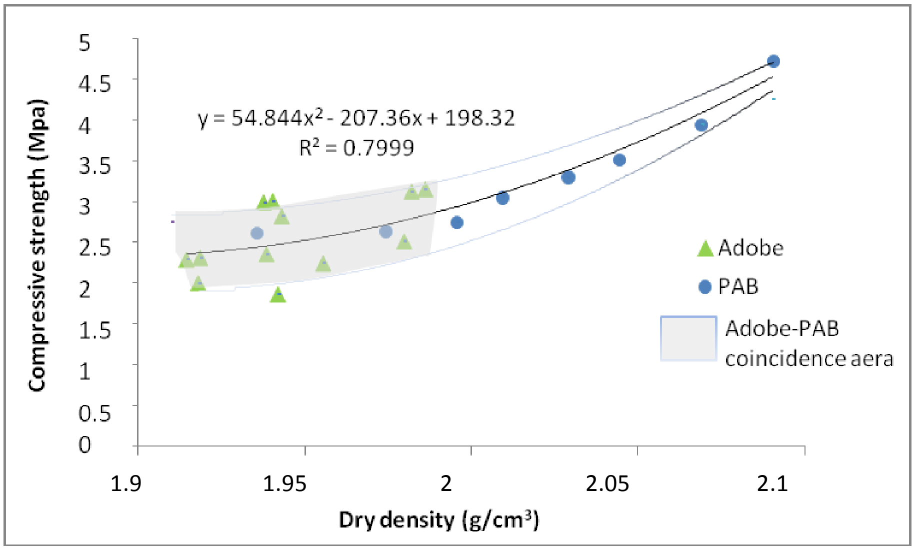

y = 54.844x² - 207.36x + 198.32
R² = 0.7999
Compressive strength (Mpa)
Dry density (g/cm³)
Adobe
PAB
Adobe-PAB coincidence aera
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
1.9
1.95
2
2.05
2.1

Figure 8

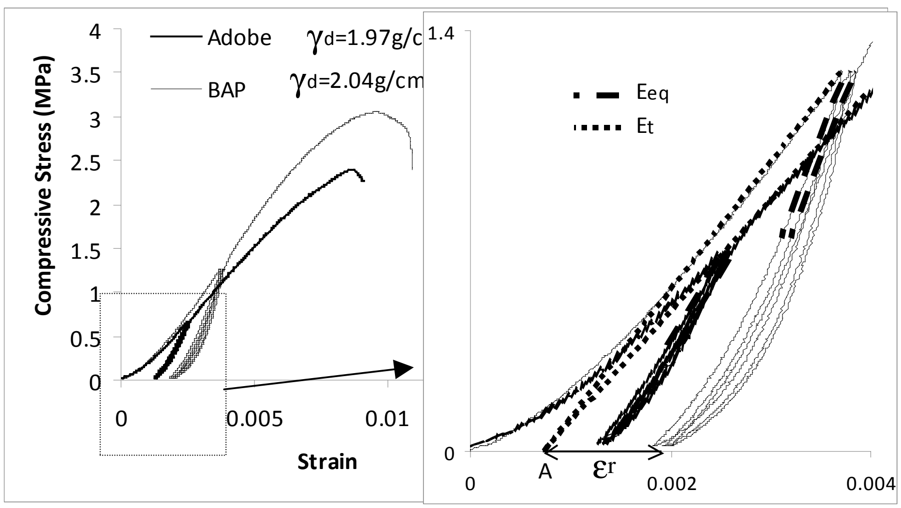

Adobe
γd=1.97g/c
BAP
γd=2.04g/cm
Compressive Stress (MPa)
4
3.5
3
2.5
2
1.5
1
0.5
0
0
0.005
0.01
Strain
1.4
Eeq
Et
0
A
εr
0
0.002
0.004

Figure 9

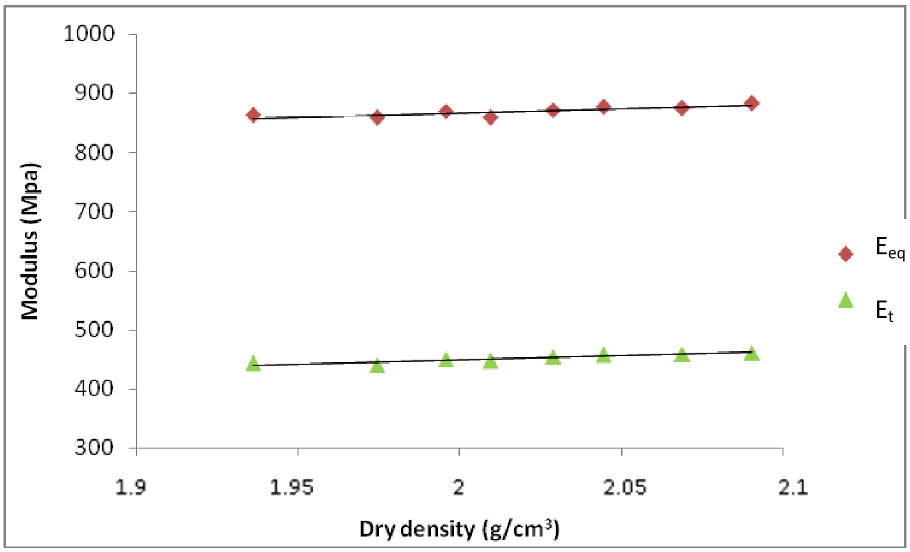

1000
900
800
700
600
500
400
300
Modulus (Mpa)
1.9
1.95
2
2.05
2.1
Dry density (g/cm³)
Eeq
Et

Figure 10