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Is stabilization of earth bricks using low cement or lime contents relevant?

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Highlights
Low cement or lime content increases the compressive strength of earth bricks slightly
Low cement or lime content does not modify the thermal conductivity of earth bricks
Low cement or lime content improves the resistance of earth bricks to water
Low cement or lime content decreases the MBV of earth bricks slightly

Abstract
The starting premise of this article is that it is not environmentally consistent to stabilize earth by using more than 4% of mineral binder (cement or lime). Thus, this paper presents a study of the effects of low mineral binder contents (2 and 4%) on the properties of earth bricks. The results obtained on two different soils show that the effects are not observable for dry compressive strengths or for dry thermal conductivities but the addition of small amounts of mineral binders significantly modifies the resistance to water and the Moisture Buffer Value.

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1. Introduction
Global warming and its obvious consequences have come to pose a challenge for the world growth model, which has, so far, been motivated by cost effectiveness only. In that context, the construction sector, like all other industries, is currently taking measures to mitigate its share of global greenhouse gas emissions. As far as construction materials are concerned, the production of cement which is the principal constituent of concrete, the backbone of the modern construction industry, is behind approximately 9-10% of global CO_2 emissions [1]. In the building sector, the interest of practitioners is increasingly being drawn toward alternative materials like unfired earth. The availability of the resource, its almost infinite recyclability, the cost effectiveness of the construction techniques, the social continuity, the hygroscopic and thermal properties, and the occupants' health are some (non-exhaustive) advantages of earthen constructions [2, 3].
The main drawback of earth material is its vulnerability to liquid water damage. In fact, high moisture, potentially caused by flooding, heavy rains or accidental water leaks, may result in a drastic reduction of an earthen structure's mechanical strength [3] or in erosion of earthen materials. That could lead loadbearing walls to collapse or cause irreversible disorders [4]. The problem of water erosion due to the rain depends strongly on the geographical situation of the earth buildings and is a major problem in tropical countries. In countries such as Burkina Faso, where the rains are rare but more and more intense, or in countries subject to the monsoon, for example, solutions must be found to avoid having to rebuild earth buildings every year. But, in numerous other countries e.g. in Europe, the earthen built cultural heritage has shown that earth buildings are able to resist the passage of time even when the earth used was not stabilized [5, 6]. In these countries, the builders of yesteryear were able to solve this problem thanks to their constructive intelligence. They developed a variety of strategies to protect earth constructions against water: orientation of the building and of its

earth walls with respect to the dominant rain direction, advanced roof, impermeable foundations or, in some cases, protective lime coating [5].

In extreme cases, for which there is no suitable design of earth buildings enabling them to resist the damage of heavy rains, stabilization by inorganic binders could be a solution [6]. The chemical stabilization of earth materials by mineral binders (sometimes lime but especially cement) is becoming more widespread, which raises the question of the relevance of the use of earth. The reasons for this stabilization are multiple. The main ones are increased water resistance and gains in mechanical performance. Another reason is related to the manufacturing conditions: in the case of rammed earth, the use of binders makes it possible to reduce stripping times and, in the case of Compressed Earth Bricks (CEB), it facilitates the handling of the bricks in the short term. A more recent trend is to make earthen concrete to facilitate the use of earth materials, to use the same tools as for concrete, and to reduce the labour required for more traditional earth-based construction techniques.

However, stabilizations using inorganic binders are not without consequences on the unfired earth material's sustainability - essentially because the CO_2 emissions of cement and lime increase the global worming potential of stabilized earth materials as pointed out by Van Damme and Houben [7]. These authors used simple tools to assess the environmental impact of Ordinary Portland Cement (OPC) addition for the stabilization of earth materials, in particular by using the binder intensity index or the carbon intensity index introduced by Damineli et al. [8]. Van Damme and Houben concluded that, in most situations, stabilization with OPC is not worth the effort, either in mechanical or in environmental terms; experimental results from the literature showed that it brings only moderate mechanical improvement at a rather large environmental cost. Furthermore, stabilizations with mineral binders limit the possibilities of earthen materials' recyclability [9, 10].

These studies have shown that it is necessary for the addition of inorganic binders in earth materials to remain consistent (from the performance and environmental points of view) with existing conventional products. For example, in the case of stabilized earth bricks, these plain bricks are in competition with aggregate concrete masonry units. In 2017, France's concrete industry federation reported the sale of 8.6 million tons of concrete blocks, representing 48.7% by mass of the national concrete production [11]. The European standard NF EN 771-3:2011 gives the specifications for the concrete blocks [12]. Although various shapes of aggregate concrete masonry units exist for specific applications, Hollow Concrete Blocks (HCB) are the most widely used for any type of masonry walls. The compressive strengths required of these blocks lie between 4 and 8 MPa [13]. In HCB, the cement content is about 150 kg/m^3 [13] and the void percentage is 50%, which gives a cement mass of 1.5 kg per block for a conventional HCB (20 cm x 20 cm x 50 cm). In a brick having the same dimensions but composed of earth with a density of 2 t/m^3, the cement content equivalent to that of an HCB is 3.75%. This means that, if there is more than 4% stabilizer in an earth brick, the cement content becomes greater than that of a concrete block that is perfectly water resistant and has a compressive strength ranging between 4 and 8 MPa.

There have been many studies on the stabilization of earth bricks using cement but, unfortunately, few of them are exploitable because important data is sometimes missing (size of the samples, conditions of curing, etc.). Table 1 shows the data of 9 papers on the stabilization of earth bricks manufactured using different techniques (CEB or adobes (earth poured in a mould)). The curing time and the aspect ratio (ratio between the thickness of a specimen and the smallest characteristic length of its surface, which is very important for the measure of compressive strength ([14,15]), are given in this table. Moreover, for each reference, it is specified whether the resistance of the stabilized earth bricks to water was evaluated or not ("+" means that the resistance to water was improved by the stabilisation).

Table 1: Literature study on cement stabilized earth bricks

Reference	Type	Aspect ratio	Curing (days)	Evaluation of water resistance	Cement (%)	fc* (MPa)
[16] - Bahar et al., 2004	CEB	1	28	+	0	1.6
					4	2.3
					6	3.2
					8	4.0
					10	4.1
					12	5.2
					15	6.1
					20	6.4
[17] - Medjo Eko et al., 2012	CEB	0.2	28	n.m.**	0	1.0
					4	3.0
					7	10.4
					10	11.6
[18] - Lima et al. 2012	CEB	1	28	n.m.	0	n.m.
					6	0.7
					12	3.1
[19] - Eires et al., 2014	CEB	1.2	56	+	0	1.0
					4	1.5
[20] - Alam et al., 2015	CEB	1	no curing	+	0	1.0
					5	1.0
					7	1.3
					10	2.0
[21] - Seco et al., 2017	CEB	1.2	28	+	0	n.m.
					10	11-14
[22] - Tran et al., 2018	CEB	2	28	n.m.	0	0.6
					4	1.5
					8	5.6
					12	6.0
[23] - Dao et al., 2018	Adobe	1	no curing	+	0	2.2
					2	2.6
					4	2.8
					8	3.0
					12	3.2

*fc: compressive strength, ** n.m.: not measured

Table 1 shows that, in the cited references, cement contents range from 4% to 20%, which is much higher than the result of the previous calculation. This does not appear in the Table but, in all cases, the water resistance of the stabilized earth bricks is improved even though the tests used in the various studies to estimate this characteristic are different. It is possible to separate these tests into three categories. The most commonly used test is the measurement of the wet compressive strength as in the French standard NF XP 13-901 on CEB [24]. According to the studies, the method used to saturate the sample changes but the principle remains the same [16,19]. The second category of water resistance tests are water spray tests. Again, according to the studies, the test procedures are variable [22, 25, 27]. Finally, some authors evaluate the water resistance of their bricks qualitatively after prolonged exposure to external climatic conditions [21].

The results of Table 1 show that the increase of compressive strength, as indicated by Van Damme and Houben [7], is very weak except in the study by Medjo Eko et al. [17] where the addition of 10% cement leads to an increase from 1.0 to 11.6 MPa. However, in this study, the bricks were tested directly and the aspect ratio was very low, which artificially increased the compressive strength [16, 17]. Seco et al. [21] also obtained resistances between 11 and 14 MPa but, this time, with an aspect ratio of 1.2. For the other studies, this increase is much lower. For example, in the studies of Alam et al. [20] and Dao et al. [23], the compressive strength increased from 1.0 MPa to 2.0 MPa with 10% cement and from 2.2 MPa to 3.2 MPa

with 12% cement but, in these two studies, there was no wet curing, which can explain the weakness of compressive strengths. Another example is Bahar et al. [16] for which resistance increases from 1.6 MPa to 6.4 MPa with 20% cement. Some of these very low resistance values raise questions because it is conventional with earth bricks produced with sufficiently clayey soil to have a compressive strength higher than 2 MPa. Aubert et al. [15] for example, worked on unstabilized extruded bricks and, for one of the specimens they studied, compressive strength reached 5.5 MPa and 7.5 MPa for aspect ratios of 2 and 1 respectively.

There are few studies on earth bricks stabilized with lime. Table 2 presents the results of five references. The data presented are the same as for Table 1 but a column has been added on the nature of the lime used because behaviours are very different between a hydraulic lime (mixture of lime and hydraulic minerals) and a "pure" lime (hydrated lime ($Ca(OH)_2$ or quick lime (CaO)).

Table 2: Literature study on lime stabilized earth bricks

Reference	Type	Aspect ratio	Curing (d)	Evaluation of water resistance	Type of lime	Lime (%)	fc* (MPa)
[26] - Millogo et al., 2008	Adobe	1	no curing	n.m.	Mix between quick lime and hydrated lime	0	2.3
						4	3.2
						6	3.3
						8	3.4
						10	3.5
						12	3.2
[19] - Eires et al., 2014	CEB	1.2	56	+		0	1.0
					Hydrated lime	4	0.8
					Quick lime	4	1.9
[20] - Alam et al., 2015	CEB	1	no curing	+	Not specified	0	1.0
						5	0.6
						7	0.8
						10	1.3
[21] - Seco et al., 2017	CEB	1.2	28	+	Natural Hydraulic Lime (NHL-5)	0	n.m.*
						10	4.5-5.5

*fc : compressive strength ; nm. : not mentioned.

In the case of lime stabilization, the improvement in water resistance exists but it is much less marked. Eires et al. [19] measured wet compressive strengths after the capillary test (24 h in water) that were very weak for stabilization with 4% hydrated or quick lime (respectively 0.1 MPa and 0.3 MPa). The conclusions are similar with the qualitative tests carried out in the studies of Alam et al. [20] and Seco et al. [21]. Moreover, the dry compressive strengths measured in these references are very low whatever the lime content (up to 12%) and whatever the nature of the lime used (even for a hydraulic lime).

The results on the stabilization of earth bricks using mineral binders (cement and lime) presented in Tables 1 and 2 confirm the conclusions of Van Damme and Houben [7]: although the effects on water resistance are noticeable (more in the case of stabilization using cement than lime), the gain in terms of mechanical performance does not seem relevant with regard to the quantities of binders added. The objective of the work presented in this paper is to study the relevance, for mechanical performance and resistance to water, of stabilizing earth bricks with low mineral binder (lime and cement) contents (≤4%). Moreover, one of the most interesting properties of earth for use as a construction material is its excellent hygrothermal behaviour with, in particular, high thermal inertia and a high potential for humidity regulation. It would be interesting to verify that chemical stabilization by adding mineral binder does not modify the hygrothermal behaviour of earth bricks [27]. Thus, a second part of the article will be devoted to the study of the effects of these stabilizations on the hygrothermal properties of the bricks (thermal conductivity and Moisture Buffer Value

(MBV)). Finally, the mineralogical modifications induced by the addition of mineral binders to earth are believed to depend strongly on the mineralogical composition of the soils and the nature of the clay minerals in particular. In order to study these modifications, two different types of soils were used in this study and the mineralogical changes in the stabilized bricks will be studied in the last part of the paper.

2. Materials and procedures
2.1 Raw materials
The two soils used for this study came from two brickworks in the neighbourhood of Toulouse in southern France. These soils were chosen because of their difference in mineralogical compositions since one of the objectives of this paper is to study the effects of low inorganic binder content on the performance of earth bricks and these effects may be strongly conditioned by the chemical reactions between binders and soils. Such reactions are influenced by the characteristics of soils and, in particular, their mineralogical composition. Previous studies in the laboratory have shown that these two soils have very different mineralogical compositions and can be considered as representative of most clay soils. The soil referred to as "soil N" is a typical, beige coloured, clayey soil of the Garonne river valley and the second one, referred to as "soil B" looks like a laterite, with a typical red colour linked to the presence of iron oxides.

Two types of inorganic binders were used for this study: a Portland cement CEM I 52.5 R and hydrated lime CL90. Various mixtures were prepared with the soils and those binders using mass contents of 0%, 2% and 4%.

2.2 Procedures
2.2.1 Physical, chemical and mineralogical characterization of soils and bricks
The size distribution of the soils was analysed using two techniques. The coarser fraction (>80 mm) was analysed by wet sieving and the finer fraction by means of a hydrometer method according to the standard ISO 17892-4 (method based on measurement of the sedimentation time of solid particles in suspension in a solution of water mixed with sodium hexametaphosphate, which acted as a deflocculating agent) [28]. The geotechnical characteristics of the soils were determined by measuring the Atterberg limits and the methylene blue value [32, 33].
The chemical compositions of the raw soils were determined with an Inductively Coupled Plasma Atomic Emission Spectrometer (ICP-AES). The crystalline phases were identified using a Bruker D8 Advance X-ray diffractometer equipped with a monochromator having a Ka (λ = 1.789 Å) cobalt anticathode, on powdered samples of raw soils and stabilized earth bricks (< 80 µm). Moreover, this analysis was completed by a specific characterization of the clay minerals contained in the raw soils that was performed on oriented aggregates using three preparations: air dried or natural, after glycolation and after heat treatment at 500 °C [31]. Thermo Gravimetric Analysis (TGA) was so carried out on crushed samples of raw soils heated to 1000 °C at a constant rate of 10 °C/min using a Netzsch SATA 449 F3 Jupiter apparatus. Finally, IR spectra of stabilized earth bricks were obtained using a Perkin Elmer UATR1 Frontier FT-IR spectrometer in the range 4000–550 cm^{-1}.

2.2.2 Manufacture of samples and curing conditions
The normal Proctor test (NF EN 13286-2) was conducted to determine the optimum water content (w$_{NPO}$) of each mixture and the corresponding dry bulk density (ρ_d) [32]. Two types of samples were then made: one group prepared with mixtures according to Proctor test outcomes and the second group made at the dry bulk densities of the unstabilized soils but using the mixtures' respective optimum water contents.
For the purposes of mechanical testing, cylindrical specimens were prepared with a diameter of 50 mm and height of 50 mm. The soil was first mixed with water at 10% of water content and stored for 24 hours in a sealed plastic bag in order to make sure that it absorbed enough water before the binder addition. Then, the required quantity of binder was manually

homogenized with the pre-humidified soil. The remaining water was finally added and mechanically mixed. The appropriate amount of this material was placed in a cylindrical mould and pressed to obtain the cylindrical specimen. Parallelepipedic specimens150 mm wide and 50 mm thick were also prepared for the hygrothermal tests using a hydraulic press. The unstabilized specimens were dried immediately in a climate-controlled room with a relative humidity of 50% and a temperature of 20 °C. The stabilized specimens were first stored in a sealed plastic bag for a curing period and then dried in the same conditions as mentioned above. The drying was considered as complete when the sample's weight varied by less than 0.1% over 24 h.

Table 3 presents the results of Proctor tests and the compositions of the specimens used for the dry and wet compressive strength and hygrothermal tests.

Table 3: Proctor test results and compositions of the various mixtures

Code	Soil	Cement (wt.%)	Lime (wt.%)	OMC* (%)	Dry bulk density (g/cm³)	Curing time (days)	Compressive strength	Hygrothermal properties
Nref.	N			14.1	1.88	0	X	X
N2C		2		14.8	1.84	21	X	
		2		14.8	1.88	21	X	X
N4C		4		14.4	1.79	0	X	
		4		14.4	1.79	7	X	
		4		14.4	1.79	21	X	
		4		14.4	1.88	21	X	X
N2L			2	17.4	1.77	21	X	
			2	17.4	1.88	21	X	X
N4L			4	16.8	1.76	0	X	
			4	16.8	1.76	7	X	
			4	16.8	1.76	21	X	
			4	16.8	1.88	21	X	X
Bref.	B			15.6	1.86	0	X	X
B2C		2		13.4	1.87	21	X	
		2		13.4	1.86	21	X	X
B4C		4		12.5	1.86	21	X	X
B2L			2	15.1	1.81	21	X	
			2	15.1	1.86	21	X	X
B4L			4	16.5	1.76	21	X	
			4	16.5	1.86	21	X	X

*OMC: Optimum Moisture Content

The results of the Proctor tests show that the addition of lime or cement had two effects on the soils: it increased the Proctor optimum moisture content and decreased the dry bulk density. These effects were observable on both soils even though they were much more marked on soil N than on soil B. The decrease in density linked to the addition of binder (lime or cement) may have led to a decrease in mechanical performance, which would be in opposition with the original objectives of adding these binders. So, it was also decided to manufacture a series of specimens at constant density equal to that of the unstabilized earth. This required a slight increase in the compaction pressure: for Proctor optimum densities, the compaction pressure was less than 5 bar and, even if it increased slightly, this pressure remained below 20 bar for constant density mixtures, which is a relatively low pressure.

The effects of the duration of a wet cure (conservation in sealed bags) were tested on bricks N only, with three curing times: 0 (no curing), 7 and 21 days. The duration of 21 days was preferred to the traditional 28 days for cementitious materials because, after this wet curing, it was necessary to "dry" the specimens (equilibrium at 20 °C and 50% RH). The drying lasted between 7 and 14 days and the hydration reactions, even if they were slowed,

continued during this period. Thus, with 21 days of wet curing, the specimens were tested at an age of between 28 and 35 days, which is consistent with what is done for traditional cementitious materials.

Finally, Table 3 shows that the dry and wet compressive strength tests were performed on the specimens compacted at Proctor optimal density and those compacted at constant density but the hygrothermal tests (thermal conductivity and MBV) were only carried out on the specimens compacted at constant densities (equal to that of the unstabilized earth).

2.2.3 Compressive strength and evaluation of the resistance to water
The compressive test was performed on the cylindrical specimens (diameter 50 mm and height 50 mm). The test was run at a constant rate of 0.2 kN/s. In order to evaluate the resistance to water, the wet mechanical strength was measured according to the French standard NF XP 13-901 on CEB [24]. The specimens were immersed for two hours in water, then withdrawn and cleaned with a damp sponge and placed in a sealed plastic bag for forty eight hours before the compressive test.

2.2.4 Thermal conductivity
The thermal conductivity was measured on dry samples. To control the humidity of the samples, the parallelepipedic specimens were dried at a temperature of 50 °C and then cooled down in a super dryer chamber to avoid any humidity uptake. Two types of apparatus were used for the measurement of thermal conductivity: a guarded hot plate and a hot-wire apparatus. The measurement was conducted on two specimens per mixture. In addition, for the hot-wire apparatus, the two plane surfaces of each specimen were tested in order to limit the dispersion of the values.
For the test with the guarded hot plate method, the samples were packed with a fine cellophane film before being placed in the apparatus in order not have humidity uptake during the test. The specimens were weighed just before and after each measurement to make sure that the weight variation was less than 0.1%. The tests were performed with an EP500 guarded hot plate at 25 °C with a difference in temperature (ΔT) of 10 °C between the two plates. When the change in conductivity was less than 1%, the test was assumed to be in steady state conditions.
The hot wire tests were carried out with a NEOTIM apparatus at a room temperature of 23 °C with a heat input of 0.5 W and a 10.9 Ω probe. The probe was placed between the plane and parallel cross sections of two samples of the same mixture. The steady state was set before beginning the measurement. It was assumed to have been reached when the temperature changed less than 0.2 °C within 60 s. The test was then set on and lasted for 100 s. The accuracy of this test method depends strongly on the parallelism and the contact effectiveness of the surface with the probe.

2.2.5 Moister Buffer Value test (MBV)
The MBVs were measured according to the Nordtest protocol [33]. Measurements were conducted on 15 x 15 x 5 cm^3 specimens (Figure 1). For each mixture, two specimens were tested. Before testing, the specimens were sealed on all but one side with aluminium tape (Figure 1). Then they were stored and initially in equilibrium with air at 23 ± 5 °C and 50 ± 5% RH. The criterion for equilibrium was a period long enough for the weight of the sample to stabilize so that two successive daily determinations (24 hours apart) of the weight agreed to within 0.1% of the mass of the test specimen. The test specimens were placed in a climatic chamber, set to expose samples to a daily relative humidity cycle (8 hours at 75%RH - 16 hours at 33% RH), and their weight gains and losses were measured with an accuracy of 0.001 g.
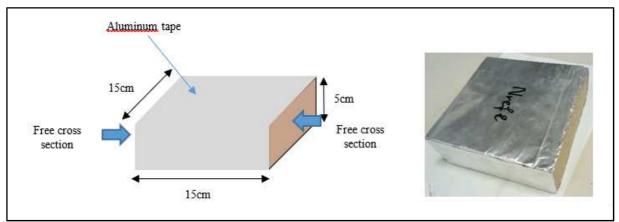
Figure 1: Specimen sealing for the MBV test

The NORDTEST protocol determined the MBV value at steady state, i.e. when, for three consecutive cycles, the material satisfied the following conditions: change in mass, Δm [g], less than 5 % between the last three cycles, and a difference between weight gain and weight loss within each cycle of less than 5% of Δm. In each cycle, Δm was determined as the average between the weight gain during the moisture uptake branch of the cycle and the weight loss during drying. The MBV of the specimen at each cycle was then computed with the equation.

$$MBV[g/(\%HR.m^2)] = \frac{\Delta m}{A \times (75\% - 33\%)}$$

where A is the total humidity exchanging area (m²) of the specimen.
The final MBVs of the specimens were calculated as the mean value of the three last cycles where the stability criteria were met.

3. Results and discussion
3.1. Geotechnical, chemical and mineralogical characterization of the soils
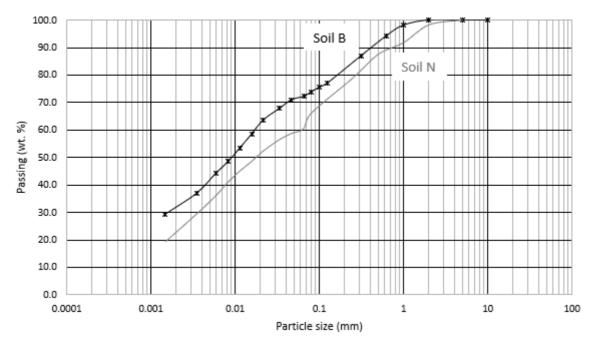Figure 2 presents the particle size distribution of the two soils.

Figure 2: Particle size distribution of the two soils

These particle size analyses were supplemented by geotechnical tests, the results of which are presented in Table 4.

Table 4: Geotechnical properties of the two soils

	Clay <2μm (%)	Silt 2-63μm (%)	Sand 63-2000μm (%)	Gravel >2mm (%)	w_l (%)	I_p (%)	Methylene Blue Value (g/100g)	w_{NPO} (%)	ρ_{NPO} (kg/m^3)
Soil N	22.5	38.5	37.0	2.0	46	15	4.10	14.1	1880
Soil B	32.0	40.0	28.0	0.0	38	21	2.65	15.6	1860

The results presented in Figure 2 and Table 4 show that soil B was thinner than soil N. For these two soils, particle quantities smaller than 2 µm ("clay") made up 22.5% of soil N and 32.0% of soil B. Moreover, the maximum grain size was 5 mm for soil N and 2 mm for soil B. Overall, these two soils were very fine and their granularity was traditional compared to what exists in the literature on earth bricks even though the quantities of clay were near the upper limit of the granular specifications proposed by the French standard NF XP 13-901on CEB [24].

Concerning the Atterberg limits, the plasticity indexes show that soil B was slightly more plastic than soil A but the values were close and remained in the class of soils considered as moderately plastic (15 <Ip <40). Compared with the recommendations of the French standard NF XP 13-901 on CEB [24], soil B respected the recommendations while the liquid limit of soil N was slightly too high. Moreover, significant differences were observed in the methylene blue values: soil N, which nevertheless contained fewer fine particles, had a blue value that was much higher than that of the finer soil B. This was certainly related to the nature of the clay minerals, which will be studied by XRD below.

Finally, the values obtained for optimal moisture content and dry density at Optimum Proctor were very similar for both soils. It can be concluded from these various characteristics that, from the physical and geotechnical points of view, the soils N and B were relatively similar and had characteristics that satisfied the recommendations of the French standard NF XP 13-901 on CEB [24].

Table 5 presents the elemental chemical composition of the two soils expressed in oxides.

Table 5: Chemical composition of the soils used in this study (LOI: Loss On Ignition)

	SiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	LOI	Total
Soil N	55.18	13.98	4.69	0.06	2.28	7.27	0.66	2.94	0.54	0.16	11.72	99.47
Soil B	61.71	17.24	5.59	0.07	1.34	1.87	0.16	3.84	0.73	0.12	7.52	100.16

The results presented in Table 5 show that the two soils were essentially composed of silica and alumina, which is quite normal for clayey soils. Soil B contained more SiO_2 and Al_2O_3 than soil N. The other important elements were iron (about 5%) and potassium (about 3%): for these two elements, the proportions contained in the two soils were similar. Finally, magnesium and especially calcium were present in significant quantities and the contents were much higher in soil N than in soil B. The same difference existed for loss on ignition measured at 1000 °C, which would seem to show that soil N contained more calcium carbonate (with possible magnesium substitutions) than soil B. This will be verified by mineralogical analysis by XRD and thermogravimetric analysis.

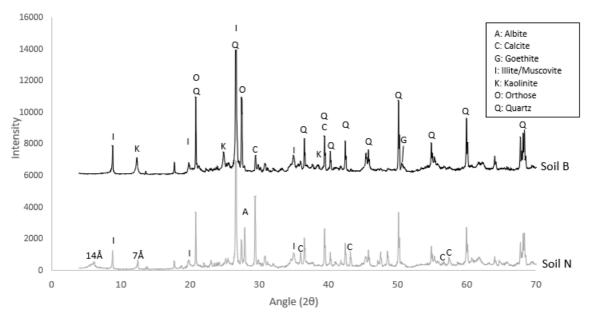XRD patterns of the two soils measured on crushed powder are presented on Figure 3.

Figure 3: X-Ray Diffraction patterns of the two soils

Figure 3 shows that the main constituent of the two soils was quartz (SiO_2), which is consistent with the results of the chemical composition. The XRD analysis of soils shows that they were both composed of quartz, feldspars, calcite ($CaCO_3$) and goethite ($FeOOH$) but there were differences between them. Firstly, the peak of calcite in soil N was much higher than that of soil B, showing a higher quantity of calcite in this soil and confirming the results of chemical analyses. In addition, the nature of the feldspars contained in the two soils was different: soil N contained albite ($NaSi_3AlO_8$) and orthoclase (KSi_3AlO_8) while soil B contained only orthoclase. Finally, there were noteworthy differences in the nature of clay minerals and this was the reason for the choice of these two different soils for this study. Soil B contained illite / muscovite (it is not possible to distinguish these two phases using XRD) and kaolinite. For soil N, it was not possible to determine the nature of clays with the diagram of Figure 3 because the peaks at 14Å can correspond to various types of clay. That justified the use of the oriented aggregates technique, the XRD patterns for which are presented on Figure 4.
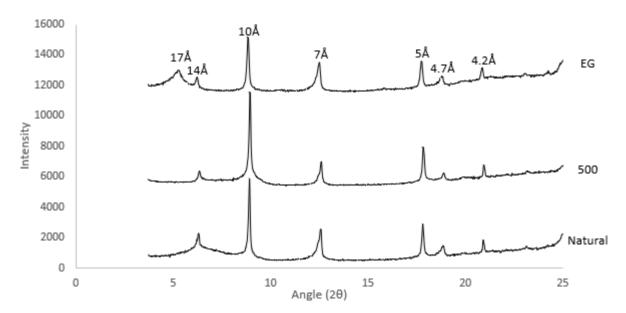

Figure 4: X-ray diffractograms of oriented aggregates (EG: ethylene glycol, 500: heated at 500 °C and natural)

An analysis of the clay minerals was carried out by considering the evolution of the first four peaks of the pattern during the various preparations. On the natural specimen, peaks at 14Å and 7Å could correspond to the reflections (001) and (002) of montmorillonite, chlorite or vermiculite. Peaks at 10Å and 5Å show the presence of illite. The intensity of peaks at 14Å and 7Å decreased after the heating at 500 °C with a broadening of peak at 10Å but these peaks did not disappear completely, which proves the presence of chlorite. Moreover, the treatment with ethylene glycol shifted peak at 14Å (from 14Å to 17Å), showing the presence of montmorillonite. In conclusion, XRD on oriented aggregates showed that soil N contained three types of clay minerals: illite, chlorite and montmorillonite while soil B only contained illite and kaolinite.

The Differential Thermo Gravimetric Analysis (DTGA) curves of the two soils are given in Figure 5.
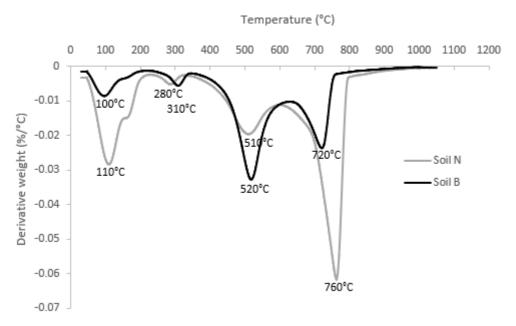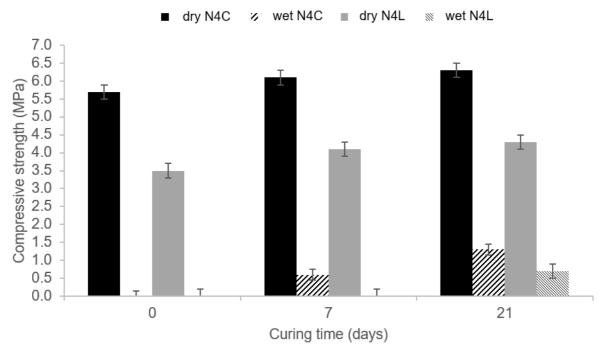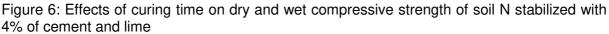

Figure 5: DTGA of the two soils

The DTGA of the two soils presented in Figure 5 shows the presence of four main peaks, around 100-200 °C, 300 °C, 500-550 °C and 700-800 °C and corresponding to the loss of hygroscopic water (water strongly linked to the material), the dehydroxylation of goethite (FeOOH), the dehydroxylation of clay minerals and the decarbonation of calcite ($CaCO_3$) respectively. These various peaks are the same for the two soils but significant differences of intensity exist. The first peak, corresponding to hygroscopic water, is much higher for soil N, consistently with the nature of the clay minerals it contains (chlorite and essentially montmorillonite are able to "stock" a lot of water). In contrast, the peak at 500 °C, which corresponds to the dehydoxylation of clay minerals is much lower, showing that soil N contains fewer clay minerals than soil B. Finally, the peak corresponding to the decarbonation of calcite is much higher in soil N, which is consistent with the previous observations (chemical composition and XRD patterns). It is thus possible to quantify the amounts of calcite for the two soils: they are equal to 11.6% for soil N and 5.3% for soil B. It is possible to do the same for goethite: the content of this mineral is equal to 1.3% and 2.2% for soils N and B respectively.

3.2 Mechanical strength and resistance to water
3.2.1 Effects of curing time

The use of hydraulic binders requires a wet cure to keep the water inside the material during the hydration time. Tables 1 and 2 showed that, in some studies, no curing was carried out, the wet specimens being dried in the air after their manufacture. The consequence of this absence of curing is a very limited gain in compressive strength for large amounts of binders. In the case of conventional cementitious materials, the standards impose a wet cure of 28 days (immersion in water or storage in a room at 20 °C and HR> 95%). In the case of earth materials in a prospect of industrialization, this duration may seem long because, after this wet curing, it is necessary to dry the stabilized earth bricks to gain strength. The study of the curing time of earth bricks stabilized using cement or lime was carried out only on soil N with binder contents of 4%. Three curing times were tested: 0, 7 and 21 days. Figure 6 shows the results of the dry and wet compressive strengths of the cured bricks.

Figure 6: Effects of curing time on dry and wet compressive strength of soil N stabilized with 4% of cement and lime

The results of Figure 6 show that, as expected, the increase in curing time led to an increase in dry compressive strengths. For a curing time of 21 days, these strengths increased from 5.7 MPa to 6.3 MPa for 4% of cement and from 3.5 MPa to 4.3 MPa for 4% of lime. Regarding the wet compressive strengths, a lack of curing made it impossible to obtain water-resistant specimens with the addition of either cement or lime. Moreover, from 7 days of curing, the samples stabilized using cement resisted and, after 21 days of curing, it was possible to measure wet compressive strength for both binders.

These results show that a minimum duration of 21 days of wet curing (conservation in sealed bags) of the bricks was necessary. The drying time of the specimens (equilibrium at 20 °C and 50% RH) after 21 days of curing was around 10 days, so the specimens thus tested were approximately 31 days old, which is consistent with the conventional tests on cementitious materials. In the rest of the paper, the same conservation procedure will be used for all the specimens: wet curing of 21 days followed by drying (equilibrium at 20 °C and 50% RH) to constant weight.

3.2.2 Dry compressive strength

Table 6 shows all the results obtained on the dry compressive strength. These results concern the two types of soil (N and B), the two types of binders (cement and lime), the 3 contents (0, 2 and 4%) and the two types of density: Normal Proctor Optimum (NPO) and constant density equal to that of the soil alone at NPO.

Table 6: Dry compressive strength of the stabilized soils

Code	Soil	Wt.% of cement	Wt.% of lime	At dry bulk density of the ref.		At NPO dry bulk densities	
				Dry bulk density (g/cm^3)	Compressive strength (MPa)	Dry bulk density (g/cm^3)	Compressive strength (MPa)
Nref	Soil N			1.88	5.5 ± 0.2	1.88	5.5 ± 0.2
N2C		2%		1.88	6.4 ± 0.3	1.84	5.6 ± 0.1
N4C		4%		1.88	9.2 ± 0.2	1.79	6.3 ± 0.2
N2L			2%	1.88	5.5 ± 0.2	1.77	3.6 ± 0.1
N4L			4%	1.88	5.3 ± 0.2	1.76	4.3 ± 0.1
Bref	Soil B			1.86	3.1 ± 0.3	1.86	3.1 ± 0.3
B2C		2%		1.86	4.8 ± 0.1	1.87	4.8 ± 0.1
B4C		4%		1.86	5.8 ± 0.2	1.86	5.8 ± 0.2
B2L			2%	1.86	3.4 ± 0.1	1.81	2.9 ± 0.1
B4L			4%	1.86	3.3 ± 0.1	1.76	2.9 ± 0.1

In order to better appreciate the effects of the addition of the binders on the dry compressive strengths, the results of Table 6 are presented in Figure 7 where they are not expressed in absolute value but in variation by comparison with the compressive strength of the unstabilized soil.
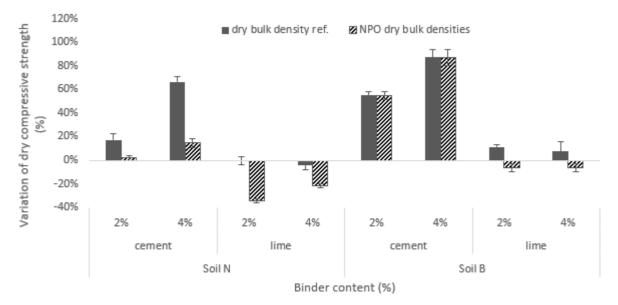

Figure 7: Variation of dry compressive strength with the addition of binder

The results of Figure 7 show that the compaction density had a very significant influence on the dry compressive strength. In fact, by working on the same compaction energy, which is an arbitrary energy used in a standardized Proctor test for road applications, additions of cement and lime induced significant decreases in dry density. This resulted in a limited increase in dry compressive strengths in the case of cement additions but there was even a decrease (negative variation) for this compaction energy with the addition of 2 and 4% of lime. This was observable for both types of soil but the decrease with the addition of lime was even more marked for soil N. The choice to work at constant compaction energy (equal

to that of the NPO) has been criticized because this energy does not correspond at all to the energies that can be used to produce CEB or to the densities that could be obtained, by extrusion for example. In addition, the study of the compressive strengths of specimens manufactured at the NPO density led to problems of interpretation because the addition of the binders led to two antagonistic effects: a reduction of the strengths related to a decrease of the dry density and an increase of the strengths expected because of the chemical actions of the binders (formation of hydrates in the case of cement, carbonation and possible pozzolanic reactions in the case of lime).

It therefore seems more consistent to compare the compressive strengths obtained on specimens having a constant density equal to that of the unstabilized sample. In this case, the addition of cement significantly increased the dry compressive strength and this increase was proportional to the cement content. These increases were observable on both types of soil but they were much less marked on soil N than on soil B. This can be explained by the mineralogical differences between the two soils. Soil B was composed of kaolinite, which will not interact with the cement during hydration, while soil N contained chlorite and montmorillonite. The chemical interactions that occur between montmorillonite and cement are complex and depend on the type of montmorillonite (including the nature of interlayer cations) but problems of setting and hardening of cement in the presence of montmorillonite are frequently observed [34–36]. Even with such densities, the addition of 2 and 4% lime had a very limited effect on dry compressive strengths. For soil N, the same strengths were obtained with or without the addition of lime with even, on average, a slight decrease in strengths for the mixture at 4%. For soil B, as in the case of cement, the results were slightly better but the increase in strength was very low (about 10%) and there was no difference between 2 and 4%.

All of these results show significant differences between the two types of soil and the two types of binder. The results of the mineralogical characterization tests (XRD, TGA and IR) of the stabilized mixtures will be presented in section 3.4 to see if it is possible to explain these differences by mineralogical changes of the mixtures.

Finally, it is possible to compare the results obtained in this study with those of the literature. Overall, whatever the compaction density of the specimens was, the strengths obtained in this study were much higher than those found in the literature (Table 1 for cement stabilization and Table 2 for lime stabilization).

For 4% of cement and aspect ratios close to 1, Bahar et al. [16] and Eires et al. [19] obtained respectively 2.3 MPa and 1.5 MPa, whereas the results of this study ranged between 5.8 and 9.2 MPa. For lime, it is difficult to draw comparisons with the literature because, in some references, there is no curing ([22, 28]) or the type of lime used is not the same as in the present study [21]. The only results that can be used are those of Eires et al. [19], who measured a strength of 0.8 MPa with the addition of 4% lime (versus 2.9 to 5.3 MPa for the present study).

3.2.3 Resistance to water (wet compressive strength)
In the absence of standardized tests on water resistance, it was decided in this study, as in many others on the subject, to evaluate the water resistance of stabilized bricks by measuring their wet compressive strength. The results obtained for the various mixtures compacted at different densities are shown in Table 7. The absence of results (symbolized by "-" in the table) means that the mixtures (3 samples per composition) did not resist the two hours of immersion in the water.

Table 7: Wet compressive strength of the stabilized soils

Code	Soil	Wt.% of cement	Wt.% of lime	At dry bulk density of the ref.		At NOP dry bulk densities	
				Dry bulk density (g/cm^3)	Compressive strength (MPa)	Dry bulk density (g/cm^3)	Compressive strength (MPa)
Nref	Soil N			1.88	-	1.88	-
N2C		2%		1.88	0.6 ± 0.1	1.84	0.4 ± 0.1
N4C		4%		1.88	2.3 ± 0.1	1.79	1.3 ± 0.2
N2L			2%	1.88	0.6 ± 0.0	1.77	-
N4L			4%	1.88	1.0 ± 0.1	1.76	0.7 ± 0.0
Bref	Soil B			1.86	-	1.86	-
B2C		2%		1.86	-	1.87	-
B4C		4%		1.86	0.6 ± 0.2	1.86	0.6 ± 0.2
B2L			2%	1.86	-	1.81	-
B4L			4%	1.86	0.2 ± 0.0	1.76	-

Unlike what has been observed for dry compressive strengths, lime and cement stabilizations were generally more effective on soil N than on soil B for water resistance. For soil B, only the stabilizations using 4% cement and 4% lime (and in this case only for the densest mixtures) resisted after 2 hours of immersion and the strengths reached were not very high (0.6 MPa and 0.2 MPa respectively). All the samples of soil N compacted at a constant density were water resistant and an increase in binder content resulted in higher wet compressive strengths. The stabilization of soil N with lime raises some questions: in fact, this stabilization had almost no effect on the dry compressive strengths, which would suggest that there was no reaction between the binder and the soil but, at the same time, this stabilization was very effective in terms of resistance to water, which shows that reactions occurred. Attempts to explain these differences will be proposed during the study of the mineralogical changes in section 3.4.

3.3 Hygrothermal properties
3.3.1 Thermal conductivity
The thermal conductivities of the stabilized soils measured using two methods (guarded hot plate and hot wire) are presented in Table 8.

Table 8: Thermal conductivity of the stabilized soils

Code	Soil	Wt.% of cement	Wt.% of lime	Hot guarded plate method (mW.K^{-1}.m^{-1})	Hot wire method (mW.K^{-1}.m^{-1})
Nref	Soil N			565 ± 24	714 ± 29
N2C		2%		529 ± 01	761 ± 28
N4C		4%		556 ± 20	731 ± 23
N2L			2%	557 ± 18	690 ± 24
N4L			4%	562 ± 43	733 ± 07
Bref	Soil B			574 ± 30	752 ± 18
B2C		2%		487 ± 05	638 ± 12
B4C		4%		520 ± 15	659 ± 35
B2L			2%	513 ± 22	637 ± 13
B4L			4%	498 ± 41	650 ± 14

Thermal conductivities obtained by the hot wire method were about 0.15 W/(K.m) higher than the values measured with the guarded hot plate. This result is well known and the value of the conductivity depends strongly on the method used for its measurement. The hot wire method is much simpler to use than the guarded hot plate method but it is much less precise as the hot wire method is a surface measurement and is therefore more sensitive to the quality of the sample surface contact. The measurement is local and less representative of

the overall behaviour of the specimen. The guarded hot plate measurements are much more accurate and they will be used for the following discussions.

The results in Table 8 show that there was no significant difference between the two soils nor between the various mixtures. The values are really close to each other and they range between 0.49 and 0.57 W/(K.m) for stabilized bricks having dry densities between 1.86 and 1.88. These values are quite comparable with those found in the literature. In their respective studies, Cagnon et al. [37] and Maillard and Aubert [38] studied the hygrothermal behaviour of extruded earth bricks with dry densities ranging between 1.94 and 2.07. Cagnon et al. [37] also used the guarded hot plate method and they measured conductivities from 0.47 to 0.59 W / (Km), which is very similar to the results of Table 8. Maillard and Aubert [38] used another method based on a heat flow meter and measured the thermal conductivities in two directions in order to highlight the anisotropy of the extruded bricks. The measured values were generally higher than those of Table 8: from 0.57 to 0.69 W/(K.m) in the direction perpendicular to the extrusion direction and from 0.72 to 1.24 W/(K.m) in the parallel direction. Since the measurement method was not the same, it is difficult to conclude on whether the differences were due to the intrinsic characteristics of the materials or to the method, as was observed with the hot wire method. Laborel-Préneron et al. [39] worked on the effects of the addition of bioaggregates on the hygrothermal properties of earth bricks. The samples tested and the method used were identical to those of this study but with a different soil and the authors measured a dry thermal conductivity of 0.57 W/(Km) on the reference bricks without addition of bioaggregate, for a dry density equal to 1.89, which is consistent with the results of Table 8. Finally, the research that is closest to that of this study is that of Saidi et al. [40] in 2018, who worked on the effects of stabilization of earth bricks on thermal conductivity and water vapour sorption. They worked on CEB stabilized using 5, 8, 10 and 12% cement or lime (hydrated lime) and they measured the thermal conductivities using the box method. They found values ranging between 0.79 and 1.10 W/(K.m) for the addition of cement or lime. These values are difficult to compare with those of Table 8 because the measurement methods were different. However, Saidi et al. showed that the thermal conductivity increased almost linearly with the increase of cement or lime contents [40]. This is not at all in contradiction with the results of Table 8 because, for the bricks stabilized using 5% cement or lime, the authors found the same thermal conductivities as for the unstabilized bricks, as confirmed by the results of the present study.

3.3.2 Moisture buffer value
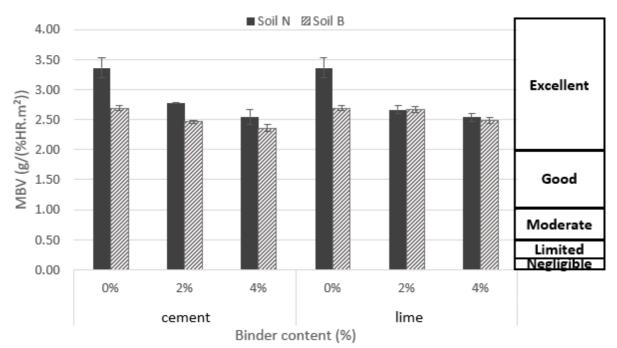The results of MBV measurements are shown in Figure 8.

Figure 8: Moisture buffer value of non-stabilized and lime stabilized soil N and soil B

Cement and lime addition reduced the moisture buffer value for both soils. Nevertheless, up to 4% of addition, the hygroscopic properties of cement and lime stabilized specimens were still excellent according to the Nordtest criterion. It was also observed that soil N was more hygroscopic than soil B. This is easily explained by the different nature of the clay minerals contained in the two soils. In addition to illite, soil N contained chlorite and montmorillonite, which have a greater surface area and greater water absorption capacity than the kaolinite contained in soil B. This confirms the results of TGA presented in Figure 5 and similar observations had already been made by Cagnon et al. [37] on the same type of soil during water vapour sorption-desorption measurements. McGregor et al. also highlighted this difference in water vapour absorption capacity between montmorillonites and kaolinites [41]. The decrease in water sorption of earth bricks with the addition of mineral stabilizers (cement or lime) is a result already observed in other sorption-desorption tests, e.g. in the study of Saidi et al. [40] and McGregor et al. [42]. These authors conclude that the main results of their study indicate that unstabilized earth material has the best thermal and hygroscopic characteristics among the materials tested. In their opinion, the addition of chemical stabilizers enhances the heat transfer through the earthen materials and reduces their water vapour permeability. A previous study of McGregor et al. adressed the effect of 4-8% addition of cement or lime on earthen material's hygroscopic properties. They have shown that this stabilization could lead to the reduction of earth materials' adsorption capacity by up to 20% [42]. Liuzzi et al. however showed a very slight increase in MBV on 5% hydrated lime stabilized earth materials, while thermal conductivity decreases because of dry bulk density reduction [43]. In the present study, the amounts of binder were limited to 4%, so the negative effects on the hygrothermal properties were also limited and did not seem to invalidate the use of mineral stabilizers.

3.4 Mineralogical changes induced by the addition of mineral binders
Although the cement and lime contents added to the soils were low in this study, the results obtained on the mechanical and hygrothermal properties have shown that the effects of these additions were not zero. Depending on the characteristic studied, the effects were more or less marked. They were not observable for dry compressive strengths and for dry thermal conductivities but the addition of small amounts of mineral binders significantly modified the resistance to water and the MBV. This shows that reactions occurred between

soils and mineral binders and the objective of this part is to see if it is possible to observe mineralogical changes of soils by traditional characterization techniques.

Figure 9 shows the X-ray patterns of soil N when unstabilized or stabilized using 4% of lime or cement after the compressive strength test (21 days of curing followed by about 10 days of drying).
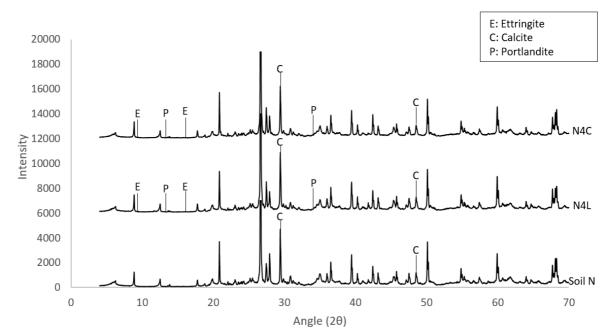

Figure 9: X-Ray Diffraction patterns of the unstabilized soil N and soil N stabilized with 4% of cement and lime

The hydration of cement typically produces three hydrates: CSH, ettringite and portlandite. CSH are amorphous minerals that cannot be observed by XRD, unlike ettringite and portlandite. The two main peaks of these minerals were identified on the patterns of Figure 9 together with those of calcite. The accuracy of the XRD does not allow for such low amounts to observe mineralogical changes. There are no neoformed phases (ettringite or portlandite or other) and there is also no marked decrease in some peaks that would show a consumption of one of the phases present in the soil. It should be noted that it is also not possible to see the anhydrous phase of cement. The only slight observable change concerns calcite, the peak intensity of which logically increases with the addition of 4% hydrated lime. Note that, for the sake of clarity of presentation, the main quartz peak of the three patterns was cut randomly, so no direct comparison of the intensities of the peaks can be made for pseudo-quantitative analysis.

It is important to point out that the same X-ray patterns with soil B are not presented because the observations were identical: with this soil, too, XRD did not reveal chemical reactions other than the formation of calcite (carbonation of neoformed portlandite in the case of cement addition or slaked lime in the case of lime addition). The same conclusions were drawn by Dao et al. [23], although the contents of cement used in their study were much higher (up to 12%).

Furthermore, Dao et al. completed their unsuccessful XRD study with IR analysis [23]. The IR spectra of soil N, unstabilized or stabilized using 4% of lime or cement after the compressive strength test (21 days of curing followed by about 10 days of drying), are shown in Figure 10.
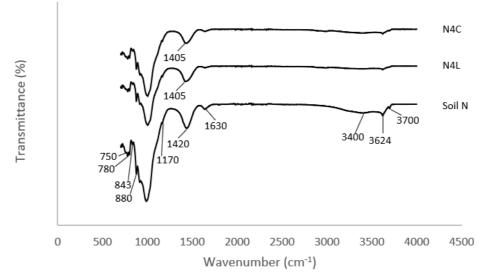
Figure 10: FT infra-red spectra of the unstabilized soil N and soil N stabilized with 4% of cement or lime

There is no difference between the IR spectra of the unstabilized soil and those stabilized using 4% lime or cement. The presence of quartz is marked by peaks around 1100, 800 and 780 cm^{-1}. The classical calcite bands are observable at 875, 1450 and 3650 cm^{-1}. However, the observations in Figure 10 contradict the conclusions of Dao et al. [23] on the formation of CSH as the authors observed an increase in intensity of the broad stretching vibration at around 3400 cm^{-1}, which corresponds to the vibrations of the hydroxide of CSH and of the physisorbed water. Dao et al. concluded that CSH had been formed in their study but the cement contents used were very high (up to 12%). In the present study, this broad band at 3400 cm^{-1} is observable in Figure 10 - but only for un-stabilized soil - and therefore corresponds to the physisorbed water already observed during TGA. This broad band disappears completely with the addition of lime or cement, which argues against a possible formation of CSH.

As for the DRX, the same IR spectra with soil B are not presented because the observations are perfectly identical: with this soil too, the IR did not make it possible to highlight chemical reactions between soil and mineral binders.

Finally, soil B stabilized using 4% of lime showed significant increases in both compressive strength and water resistance. This soil contained only illite and kaolinite able to react chemically with lime to form CSH-type compounds by pozzolanic reaction. The IR spectra (not shown here) did not reveal the formation of CSH and, to verify this, a TGA of soil B, unstabilized and stabilized using 4% of lime after the compressive strength test (21 days of curing followed by about 10 days of drying), were carried out. The results are shown in Figure 11.
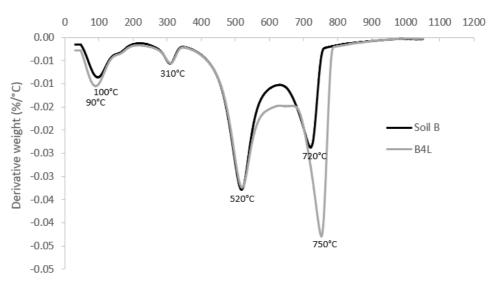
Figure 11: DTGA of the unstabilized soil B and soil B stabilized with 4% of lime

The dehydration temperature of CSH ranges between 100 and 200 °C [44] and, in this temperature range, the analyses of stabilized and un-stabilized soil were perfectly identical, which confirms the absence of CSH or at least that this formation would be too low to be observed with traditional mineralogical characterization tools. The only observable differences concerned the peaks before 100 °C, which may have been the result of a difference of drying between the two samples, and especially the peaks around 600 °C (presence of residual $Ca(OH)_2$ in B4L) and 750°C (increase in calcite content in the B4L already observed by XRD).

The three mineralogical characterization tools (XRD, IR and TGA) did not reveal any of neoformed phases other than calcite or the consumption of potential reagents contained in the soils. Nevertheless, the behaviour of soils stabilized with low binder contents was significantly modified, so "reactions" must have occurred. Two hypotheses can explain this contradiction. On the one hand, the concentrations were too low and the tools not precise enough to allow the observation of these phenomena. On the other hand, it is also possible that there was no formation of new compounds and that the effectiveness of the stabilizations can be explained differently.

For cement stabilization, hydration of the cement can lead to "sticking" of the soil particles as in a conventional concrete, which would explain the increase of dry and wet compressive strength at the same time. In the case of cement, there is no need for it to react chemically with the soil for this to work. Nevertheless, deleterious reactions between the clays (montmorillonite) and the cement were observed for soil N, which reduced the effectiveness of the stabilization with cement. These reactions are known in particular in the stabilization of clays for road works and are explained by a significant "consumption" of the calcium ions released by the cement during its hydration by montmorillonite. To reduce these negative effects, civil engineers often use a lime pretreatment before applying the treatment with cement or hydraulic binders. This double treatment could present interesting prospects to improve the efficiency of the stabilization of earth bricks using cement.

For lime stabilization, the results depend very much on the nature of the soil studied. For soil N, which contains chlorite and montmorillonite, the reactions between soil and lime are complex and should be studied with other tools than those used in this paper (such as the monitoring of chemical concentrations in reactors for example). As previously discussed, smectites have the ability to absorb various types of cations (calcium in the case of lime) within their interlayer sheets. This absorption and its effects on the bonds of interlayer sheets

are complex and will depend on many parameters including the type of montmorillonite. As the results of this study show, the consequences on the macroscopic properties are multiple and not necessarily in the same sense: we found almost no effect on the dry compressive strengths whereas there was a significant effect on the resistance to water and on the MBV. Further studies are still needed to better understand the phenomena that occur in this case. In the case of soil B, the phenomena were different because the mineralogical nature of clays (illite and kaolinite) was less complex. The mineralogical characterization tests showed that there was apparently no pozzolanic reaction between lime and these clay minerals and that the effectiveness of the lime stabilization on this soil could only be explained by the formation of calcite (as in the case of conventional lime mortars).

4. Conclusion

The title of this paper poses the question of the relevance of stabilizing earth bricks using low cement or lime contents. The results of this study on two types of soil having different mineralogical compositions provide a number of elements to find an answer to this question.

First of all, one of the major results is that it is not possible to generalize the conclusions without taking the chemical and mineralogical composition of soils into account because the effects of stabilization by mineral binders are strongly dependent on the type of soil. Too often in the literature, these aspects are not addressed and the soil is considered as a black box, the authors only being interested in the characteristics of the stabilized materials, which often leads to problems of interpretation of the results, especially during comparisons among studies.

The second strong conclusion of this study is that, from the economic and environmental points of view, it does not seem consistent to use more than 4% of mineral binders in earth bricks. Under these conditions, the results of the study showed that the effects of stabilization with low binder contents were not negligible. Depending on the nature of the soil, the binder and the compaction energy, the increase in dry compressive strength was more or less significant but, in all cases, much greater than what is necessary to build the one or two storey dwellings that represent the majority of uses of earth bricks. For larger structures requiring higher compressive strengths, specific studies are necessary but these case studies remain exceptional. As mentioned in the introduction, the main weak point of earth remains its low resistance to water. Although specific construction rules from our vernacular constructive heritage can solve these problems in temperate climates, real problems still arise in geographical areas subject to severe weather conditions. If binder contents are too low, the water resistance of earth bricks is not always improved and results have shown that it is often necessary to add 4% of lime or cement into the bricks to resist two hours of immersion. For water resistance, the soil/binder pair is also very important and, overall, cement is more effective than lime to improve this characteristic but results depend strongly on the nature of the soil. Finally, the addition of mineral binders will slightly degrade the hygrothermal performance of earth bricks but this reduction is not crippling for the stabilization of earth bricks as the insulation performance, which is poor for earth materials in any case, remains almost unchanged. The thermal interest of these materials lies in their thermal inertia, which remains unchanged whether the bricks are stabilized or not. The results on the MBV showed that, even if the addition of mineral binders slightly decreased this characteristic, the comfort of the stabilized earth bricks remained excellent.

For an equivalent amount of cement, it is important to compare the advantages and disadvantages of stabilized earth bricks and the standard Hollow Concrete Blocks (HCB). The performances of HCB do not need to be demonstrated; there is no problem of water resistance and the mechanical performances of these blocks are high. In addition, the manufacture of plain stabilized earth bricks also poses weight problems for the use of these bricks in comparison with hollow concrete blocks. Finally, the main advantage of stabilized earth compared to HCB is its high potential for moisture regulation. However, one can wonder if this benefit is sufficient to justify the use of stabilized earth bricks in replacement of HCB. The ecological interests of the unstabilized earth construction materials are undeniable but the stabilization of these materials, even with low contents of binder, remain debatable.

There are, nevertheless, interesting opportunities to explore, such as the use of low environmental impact binders to stabilize earth bricks. These may be mineral binders based on the use of slag, for example, or biopolymers, some of which, such as egg white, some plant decoctions or casein, have already been used in the past to improve the performance of earth materials. The use of these binders would improve the performance of earth materials (including their water resistance) while maintaining their low environmental impact in comparison with widely used construction materials such as concrete blocks or terracotta bricks.

Acknowledgements

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