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Earthen-based building: *In-situ* drying kinetics and shrinkage

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Abstract

Present work focuses on the study of drying and shrinkage kinetics in cob and light earth layers constituting a hybrid walling system. *In-situ* measurements were performed on the walls of a CobBauge prototype building under construction in Saint-André-de-Bohon (France). To do so, an adapted monitoring system has been designed and implemented. Thus, volumetric water content sensors and dial indicators were immersed and placed in different positions in different walls of the building.

Drying kinetic and shrinkage rate in both layers have been measured. Correlations between water content and materials shrinkage have been found and discussed. This study will contribute to the optimization of earth construction times in general, and in particular, form-stripping times.

Keywords: Cob, light earth, water content, drying kinetics, shrinkage

Highlights

- Construction and instrumentation of an earthen-based prototype building made with a hybrid walling system
- *In-situ* study of drying kinetics in cob and light earth layers constituting a hybrid walling system
- *In-situ* study of vertical shrinkage in cob and light earth layers constituting a hybrid walling system
- Correlation between water content and shrinkage in cob and light earth layers constituting a hybrid walling system

1. Introduction

Currently most scientists agree to say that the earth's climate is changing. Since the industrial revolution, at the end of the 18th century, greenhouse gas emitted in the atmosphere have increased considerably All economic sectors have contributed to this increase but emissions from buildings and the construction sector is one of the largest contributors. In France, as example, this sector represents 45% of total energy consumption and 22% of CO_2 emissions in 2019 [1]. To tackle this situation, national regulations around the world, especially in the developed countries, are evolving. Regulations which were focusing only on energy consumption in buildings also seek to reduce any associated carbon footprint.

It is therefore likely that the introduction of thresholds associated with greenhouse gases (GHG) emissions will be imposed to the new buildings very soon. In addition to the GHG emissions generated by buildings during their occupation, those due to materials from extraction and production to their end-of-life, passing by their transportation will be considered. Regarding the high environmental impact of the mostly used materials in today's constructions, such as cement-based, steel and glass, new solutions should be investigated. To anticipate this evolution, researchers and construction actors are intensifying their efforts in the research and development of alternative low carbon building designs.

As part of this new trend to provide low carbon buildings earthen based materials (cob, light earth, rammed earth, etc.) are attracting a particular interest [2–10]. This is due to multiple advantages that these materials are presenting, especially renewability, recyclability of the main components and their low carbon footprint. Earth and vegetal fibers are natural resources worldwide available allowing the reduction of GHG emissions due to transportation. In addition, these materials present an interesting ability to regulate building hygrometry, at a low economic and environmental cost. Thus, promoting a healthy indoor environment.

Cob is a vernacular material common to parts of the United Kingdom and France. Its use dates back to several centuries. It is formed of soil, water, and a fibrous material. Unfortunately, during the last decades, cob attracted less interest. This is due to many factors: poor measured insulating properties (although many sources state that earth buildings perform well as comfortable low-energy dwellings),building timescales due to drying, labor intensity and skill shortage [11]. Indeed, constructing with cob (in its primary conception) does not currently comply with the thermal aspects of many building regulations across the world. To overcome this issue, material intrinsic properties and implementation methods should be improved in order to reduce the cob building energy consumption and construction times. Thus, many key points need to be considered carefully: cob thermal properties, shrinkage rate and drying kinetic.

To undertake this research, a EU Interreg project, called CobBauge, has been initiated. This focuses on developing, testing, and establishing an innovative low carbon technology using local soil and vegetal fibers. This technology, based on earth-fiber mixes, aims the development of a hybrid walling combining two layers: a structural one (cob) and an insulating one (light earth). In the first phase of the project, different formulations have been elaborated and studied in order to determine optimal earth-fiber mixtures allowing construction of two levels building that meets the French and UK standards. In this first stage, studies concerned soils and fibers properties and then soil-fiber mixtures mechanical and thermal properties [7,12].

Otherwise, when constructing with cob, to minimize deformation, walls are traditionally formed by successive lifts. Each lift requires a certain drying time, before the wall can be continued higher, leading to longer construction times when compared to other materials. This drying time is dependent on the lift's water content and the prevalent weather conditions [13]. In order to optimize construction times, a better understanding of cob and light earth lifts drying kinetics become of a crucial interest. In addition to drying times, water content has also a well-known impact upon the development of wall strength and corresponding rates of shrinkage. Indeed, shrinkage can be related to many factors including soil type, fiber properties, but also is likely to be impacted upon by initial water content and rate of drying.

In this sense, two prototype buildings are being constructed, within the second phase of CobBauge project, in France (Manche) and England (Devon) in order to assess the site behavior of housings made with a hybrid walling. Among others, these prototype buildings will allow *in-situ* studies of both cob and light earth drying kinetics and shrinkage rate. Drying is one of the main parameters determining the final mechanical properties of raw earth [14,15]. Indeed, this is one of the major problems facing the various earthen construction techniques being studied since many years [16–18].

Present paper seeks to investigate *in-situ* drying time and kinetic. Also, shrinkage rate in cob and light earth constituting the hybrid walls. This study will contribute to the optimization of construction times in general and to know the needed time to reach a hydric equilibrium particularly. In addition, this will investigate an eventual relationship between studied materials water content and shrinkage. This is of capital importance in the comprehension of cracks appearance and mechanical resistance in such construction techniques.

2. Materials and experimental methods

2.1. Material Characterization

2.1.1.Particle size and geotechnical characterization

Three soils were used in the construction of prototype building. Geotechnical characterizations were performed. Firstly, particle size distribution was evaluated by mechanical wet sieving and laser granulometry. For particles above 80µm, mechanical wet sieving is used according to standard XP P94-041 [19]. For particles under 80µm, it is laser granulometry which is used following standard ISO 13320 [20]. Secondly, the clay activity was evaluated by the methylene blue value test according to standard NF P94-068 [21] and Atterberg's limit according to standard NF EN ISO 17892-12 [22]. Retrieved soils properties can be found on **Table 1**~~**Table 1**~~.

Table 1: Atterberg limits, methylene blue values and soil classification.

Soil	LL [%]	PI [%]	MBV [g/100g]	USCS classification
Soil 1	27.6	3.6	1.61	Low plasticity silt (ML)
Soil 2	23.7	2.7	0.47	Silty sand with gravel (SM)
Soil 3	57.4	14.9	6.37	Sandy elastic silt (MH)

2.1.2.Mineralogical characterization

Clay proportion and nature to liaise with the drying and shrinkage curves

2.1.3. Vegetal straws

Two different straws were used in cob and light earth mixes. The specific density and water absorption capacities of the flax and reed straws are presented in **Table 2**. Water absorption capacity of the straws influences the mixes properties in the fresh state as well as in the long-term (hygrometric balance).

Table 2: Vegetal straws properties

Straws	Flax	Reed
$W_{Absorption}$ at 24 hours [%]	450 ± 11	198 ± 4
$\rho_{specific}$ [kg/m^3]	1266 ± 55	1305 ± 11

3.2. Materials preparation and implementation

At each new lift, formworks are installed and disposed in a way to ensure a good link with the previous one. The two layers of each wall are built at the same time in order to ensure a bond between them, see Figure 1~~Figure 1~~. It is probably the clay present in light-earth elastic silt which allows to create a natural bond between cob and light earth layers. Indeed, cob is prepared by mixing a silty clay, sandy silt, and flax straw. Then, it is covered by a tarp until its implementation within the wall's formwork. Theoretical mass content (Wt.%) of each element constituting the cob is as follow: 32.5% soil 1, 65% soil 2, and 2.5% flax straw. Added water is equal to 22% of the soil mass. Light earth is usually prepared in the same day than its introduction within the formwork. Implemented light earth is made of soil 3 (66.7%) and reed (33.3%). Added water is equal to 100% of the soil mass.

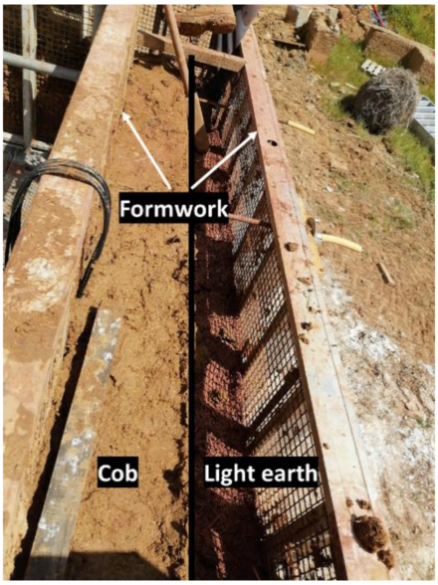

Figure 1 Implementation of cob and light earth layers within the wall's formwork.

3.3. Moisture monitoring

When monitoring moisture content, techniques based on the knowledge of dielectric permittivity are often used. This property is strongly dependent on materials water content. Many methods based on measurement of soil impedance or capacity [23–25] can allow dielectric permittivity. *In-situ*, methods based on reflectometry principle are preferred due to their robustness and ease of use. In present work, Campbell scientific CS655 sensors, based on reflectometry principle, have been used to locally measure Volumetric Water Content (VWC). This type of sensors has already shown their efficiency when measuring water content in earthen-based materials [26,27]. Their accuracy is equal to ±3% (±1% with specific soil calibration) [28].

The fundamental principle of CS655 water content reflectometer is based on the velocity of an electromagnetic wave propagation along the sensor rods. This latter is dependent on the dielectric permittivity of the material surrounding the two rods. Then, Topp equation is used to convert dielectric permittivity to volumetric water content [29].

To monitor moisture content in both layers constituting each wall, sensors have been placed in cob and light-earth at the same heights and depths. The CS 655 sensors were placed horizontally to ensure a better contact between mixtures and rods. But also, for the ease of implementation. Probes were positioned parallel to walls surfaces at two different heights, 25 and 50 cm from the lift basis. For both height, probes are at 12.5 cm depth, from the inner surface in the case of cob, and from the outer surface in the case of light-earth. In order to investigate an eventual impact of exposition on the VWC evolution, probes have been placed in the west, south and north walls. 12.5 cm represents the middle of each layer in the south and west walls. In order to be consistent and able to compare, the same depth has been kept in the north wall presenting a thickness of 70 cm (40 cm cob and 30 cm light-earth). Placing probes at two different heights will allow the observation of an eventual inflow of water when building-up an additional lift (wet mix) on the monitored one (dry mix). These will also permit to observe the penetration depth of this water coming from top of the monitored lift. Moreover, data collected by CS

655 sensors have been saved in the CR1000X data-logger every 15 min during more than one year period. Furthermore, site weather conditions are recovered by a WS-GP1 weather station. Figure 2~~Figure 2~~ presents temperature, relative humidity, wind speed and direction, radiation and rainfall which are recovered every 15 min during more than one year and half. Instrumentation used on site to study the building prototype is shown on Figure 3~~Figure 3~~.

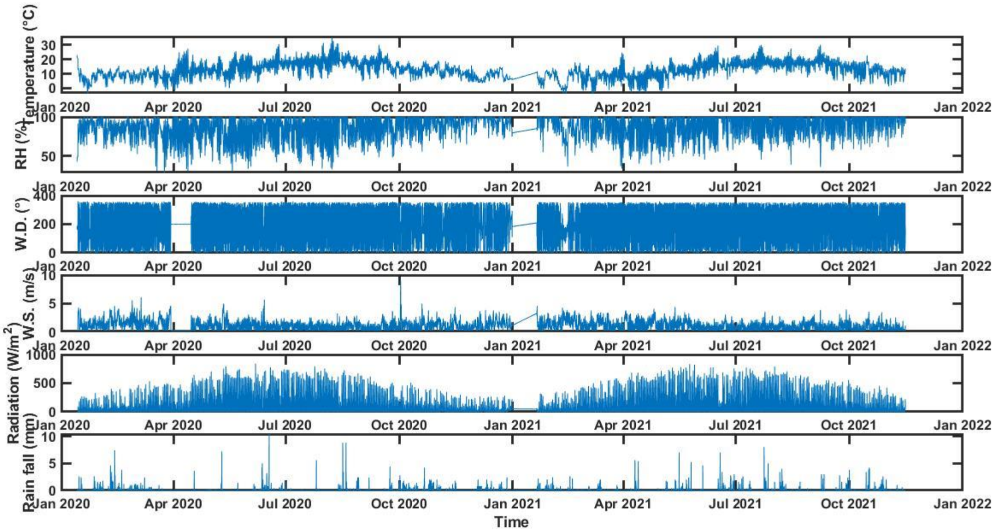

Figure 2 Site weather conditions recovered by a WS-GP1 weather station.

Figure 3 Global view of the prototype building, and instrumentation made on site.

3.4. Shrinkage monitoring

When monitoring *in-situ* shrinkage and deformations occurring in buildings and infrastructures, many techniques can be used: fiber-optic sensors, 3D Laser scanning technology, and extensometers, etc. For economic considerations and site suitability, fiber-optic sensors and 3D Laser scanning technology have been discarded. Extensometers are often used when monitoring *in-situ* deformations [30]. Considering the site constraint (especially the presence of a formwork) and fixing problems on such materials, it was stated that this technology was not adapted. Therefore, an alternative solution, inspired from the laboratory studies, was conceived. *In-situ* vertical shrinkage was measured by using digital indicators (SC25 from BORLETTI). Two dial indicators were placed at the center of each layer (cob and light earth). The tip of each indicator was placed on a metal slat driven into the ground. Here-used apparatus present a measuring range of 25 mm and a resolution of 0.01 mm. To hold these indicators, metallic supports have been designed and produced. To maintain them stationary, the metallic supports have been fixed to the concrete floor and dried cob lifts, see Figure 4~~Figure 4~~. Data discussed in present paper have been collected on the north wall, every 2-3 days at the beginning: then every 10 days after the first month. Data have been collected during more than 50 days period.

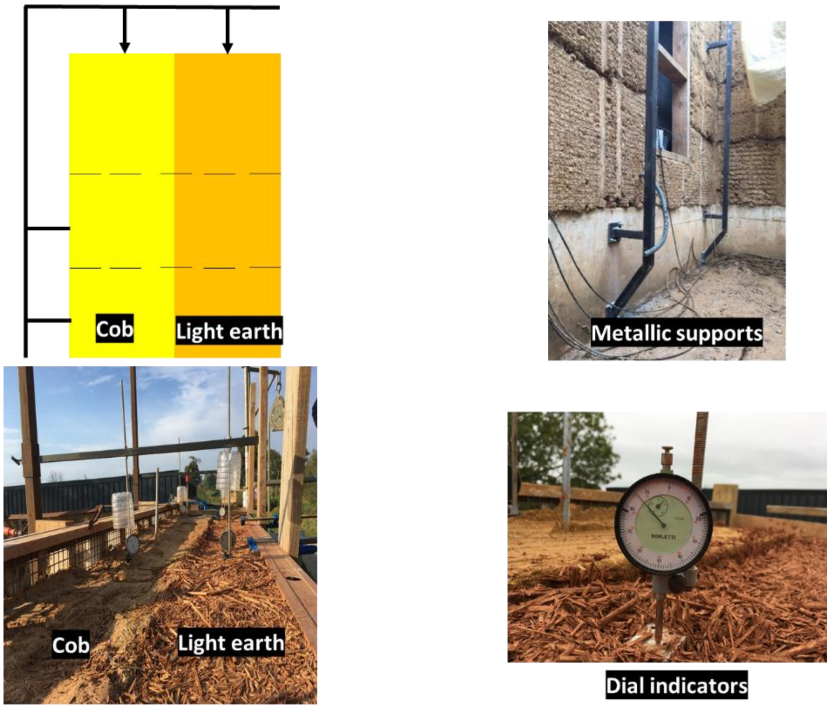

Figure 4 Shrinkage measurement with dial indicators fixed on static metallic supports.

4. Results and Discussions

3.1. Moisture

The evolution of water content in implemented cob and light earth is reported on Figure 5~~Figure 5~~. First, in cob layer, the curves of volumetric water content (VWC) drop directly and present a sharp decrease during the first days following cob implementation. Then, when raising an additional lift, the decrease in water content is stopped, see index 1 on Figure 5~~Figure 5~~. Indeed, water content is halted going down during approx. 16 days at the top of lift (at 50 cm from the lift basis) and approx. 10 days at its bottom (25 cm from the lift basis). This can be explained by the fact that water brought by the new lift is mostly fixed at top of the in-place lift. After this temporary halt, VWC continues its decrease but with a less sharp slope. In the south and west walls (more exposed to winds), the tendency becomes quasi-linear with a low slope, while in the north wall a kind of stabilization is observed. This is temporary because when radiation and temperature restarts to raise (after February), North wall VWC follows again a quasi-exponential decrease and then retrieve a slop similar to the one of the south and west walls, see index 2 on Figure 5~~Figure 5~~.

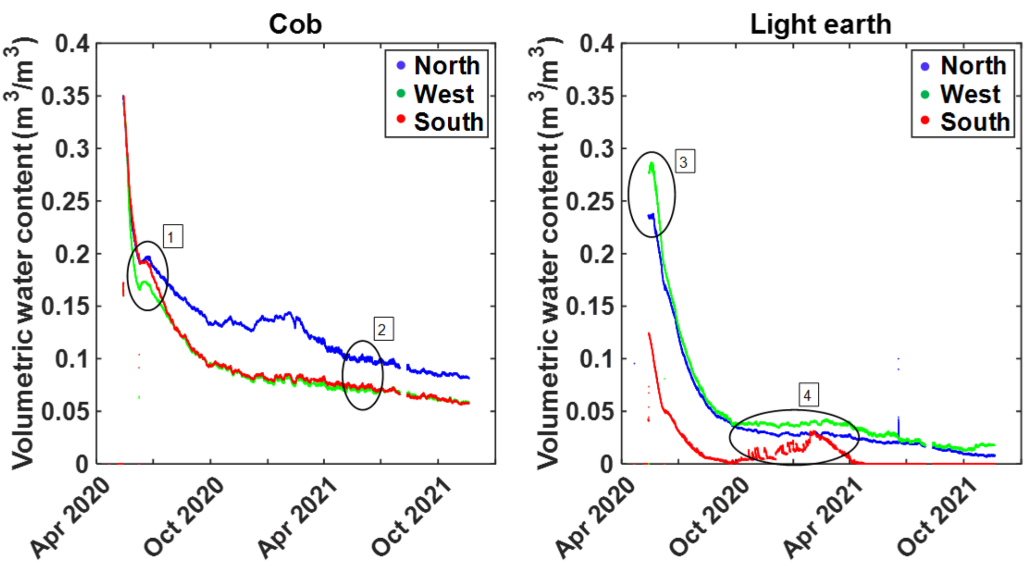

Figure 5 Water content evolution in the north, west and south walls (2nd lift).

Regarding the light earth layer, the curves on Figure 5~~Figure 5~~ revealed that there is a large variation in initial water content (even in the same lift). These variations can be due to many factors: material preparation method, moment in the journey at which the mix is implemented within the formwork (evaporation), and to water addition by the craftsmen during processing. Indeed, light earth is prepared on site in small quantities (by using a standard concrete mixer), and then it is put in big bags. Sometimes, light earth is implemented directly in the wall's formwork, but in some other times, it stays few hours in the big bags before being implemented. This fact can lead to a loss of a large quantity of water and variation of water content during implementation. This phenomenon is less obvious in the case of cob because, in contrary to light earth, this latter is prepared few days before at a time for all the lift in the different walls (therefore initial water content is homogeneous). This can also be due to the use of less water during preparation, lower fiber content, and mix density. On another note, during the first days (approx. 08 days), VWC remains approximately steady in the light earth, see index 3 on Figure 5~~Figure 5~~. This may be due to water exchange processes between clay and reed fibers constituting the mix. Indeed, the assumption is that reed fibers have absorbed a lot of water during mixing (see **Table 2**~~**Table 2**~~) and then this water liaise reed fibers with clay particle instead of going in ambient air. After this period, drying process begins.

Thus, VWC decreases by following an exponential decay. This is different from what can be observed on cob. In this latter, VWC starts to decrease directly after its implementation. Also, when compared to cob, the effect of adding a new lift on the dried one is less marked in the case of light earth. This can be due to the same phenomenon observed at the beginning of implementation: water particles are linked to either fiber or clay. Consequently, a slight quantity of water migrates down into the previous lift.

The fact that light earth is in the walls external side makes it more exposed and sensitive to variations in climatic conditions. Between October and April, different peaks can be observed on the light earth water content. South and west walls are particularly affected, see index 4 on Figure 5~~Figure 5~~. This is supposed due to the lateral rain coming from South-West (SW) direction. Actually, at the building location (Saint-André-de-Bohon, France), the SW wind is dominant. It can be noticed here that building walls were covered from their top but not from lateral sides.

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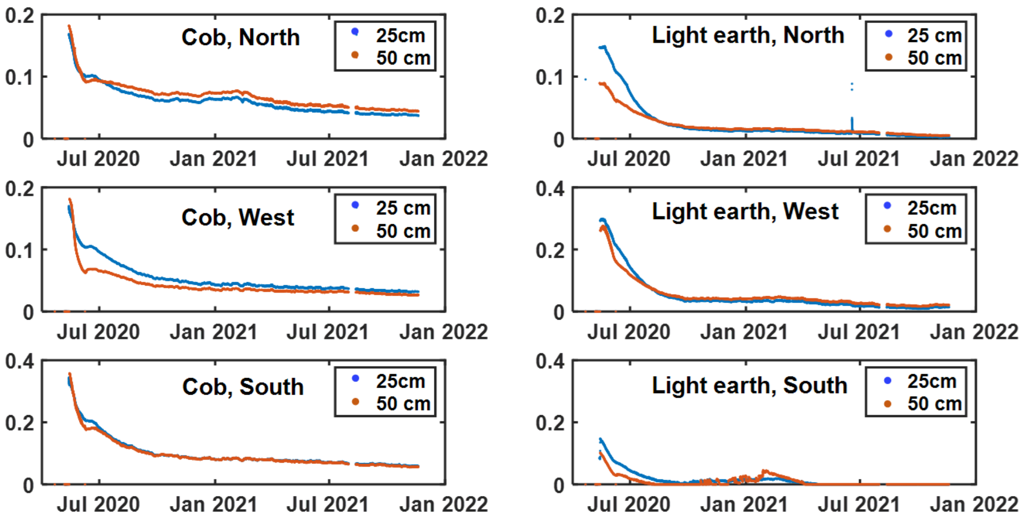

Figure 6 Impact of the height on water content evolution in cob and light earth of the north, west and south walls.

3.1.1.Differential drying rate

A differential drying rate can be observed between the upper and lower part of the same lift. In fact, before adding a new lift, the upper part (at 50 cm) of a cob layer dries faster than the lower part (at 25 cm), see Figure 6~~Figure 6~~. This could be due to the fact that upper probes are more sensitive to eviction of water from the lift top side (in plus of lateral one that the lower probe sense also). When raising an additional lift, water exchanges from the top side of the existing one (not completely dry) is stopped. More, water flows from the new lift into the existing one leads to a change in its drying kinetics. Consequently, drying at the top of lift become slower but after a certain time, top and bottom of the lift dry approximately at the same rate.

In the light earth, given the gap in the measured initial water content at different heights (in contrary to cob), the differential drying rate is less evident, see Figure 6~~Figure 6~~. Nevertheless, the fact that water liaise with clay particles and reed fibers before vaporization let think that drying rate will be similar regardless the height.

Also, an effect of wall thickness on the drying rate of cob can be observed (especially after adding a new lift). From Figure 5~~Figure 5~~, it can be clearly seen that the north wall (40 cm) dries more slowly than west and south ones (25 cm). More than one year after its implementation, cob in the north wall contains approx. 27 % more water than cob in the south or west walls, see index 2 on Figure 5~~Figure 5~~.

3.1.2.Drying modeling

Either in cob or light earth, VWC follows an exponential decay function, see Figure 7~~Figure 7~~. Experimental data can be best modeled by a two-term exponential model. Data recovered by twelve sensors placed in both layers (6 in cob and 6 in light earth) have been fitted numerically. Experimental data are best fitted by the following equation:

$$f(x) = a.e^{b.x} + c.e^{d.x} \qquad (1)$$

In the case of cob, constant a, b, c and d are found to be as follow:

a = 0.001266, b = -3.024, c = 0.1154, d = -0.05605.

In the case of light earth, the fitting constants are as follow:
a = 0.000147, b = -4.239, c = 0.02047, d = -0.3323.

It can be stated the law that governs the drying of cob and light earth considered as universal for similar materials and conditions as those studied in present work. However, fit parameters are only valid for the mixes and conditions reported in present work.

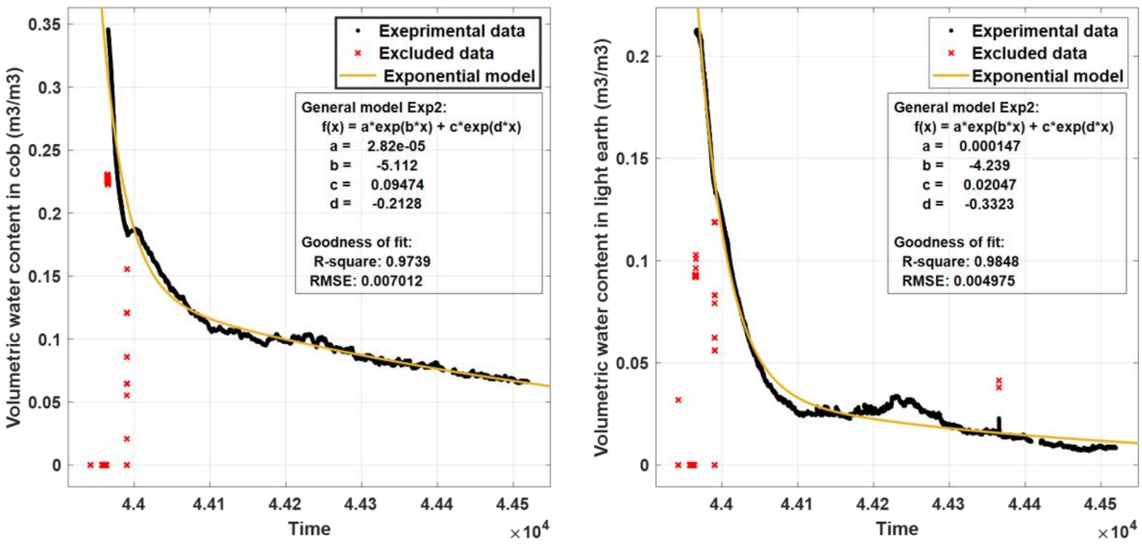

Figure 7 Numerical fit of water content evolution in cob and light earth.

3.2. Shrinkage

The shrinkage rate in implemented cob and light earth layers is reported on Figure 8~~Figure 8~~. On this figure, it can be seen that shrinkage in both cob and light earth follows an exponential decay. During the first three weeks, shrinkage is higher in cob layer. Indeed, during the first week, shrinkage slope in cob layer is sharper than the light earth one. This supposed due to the gravity effect which is more noticeable in cob (heavier). Even though it is not completely finished, after approx. four weeks, shrinkage in both layers becomes in phase and tend to a kind of stabilization at values ranging between 3 and 4%. Similarly, to volumetric water content, shrinkage can also be modeled by eq. 1. In light earth, constants a, b, c and d are found to be as follow: a = -4.818, b = -0.004899, c = 4.723 and d = -0.04117. In cob, these are equal to: a = -2.369, b = 0.007512, c = 2.33 and d = -0.2285. The R^2 in light earth and cob is equal to 0.9948 and 0.9935, respectively.

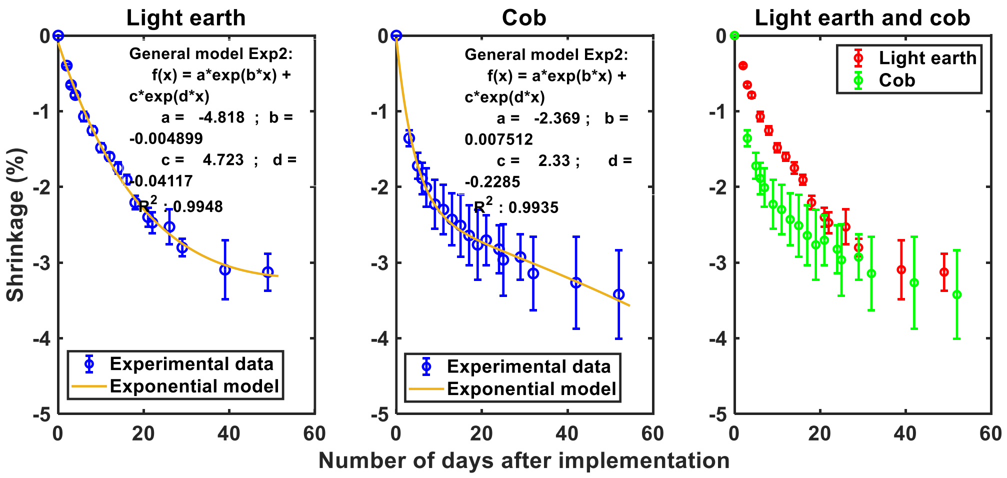

Figure 8 Shrinkage rate in light earth and cob.

3.3. Water content-shrinkage correlation

On Figure 9~~Figure 9~~, two linear correlations between shrinkage and moisture content are revealed. This is true for both light earth and cob. In the case of light earth, during the first week, shrinkage rate reached approx. 1.1% even without a significant water content variation. This can be considered as typical settlement under the effect of gravity. After one week, a linear dependence can be observed between shrinkage and drying. When regarding the cob layer, during the first three days (cob being heavier than light earth), shrinking processes are faster than drying one's. After three days, shrinking and drying processes retrieve a linear dependence as for light earth. On Figure 9~~Figure 9~~, it can also be remarked that approx. a third of the overall observed shrinkage represent soil settlement caused by gravity and approx. two-thirds are a consequence of the drying process.

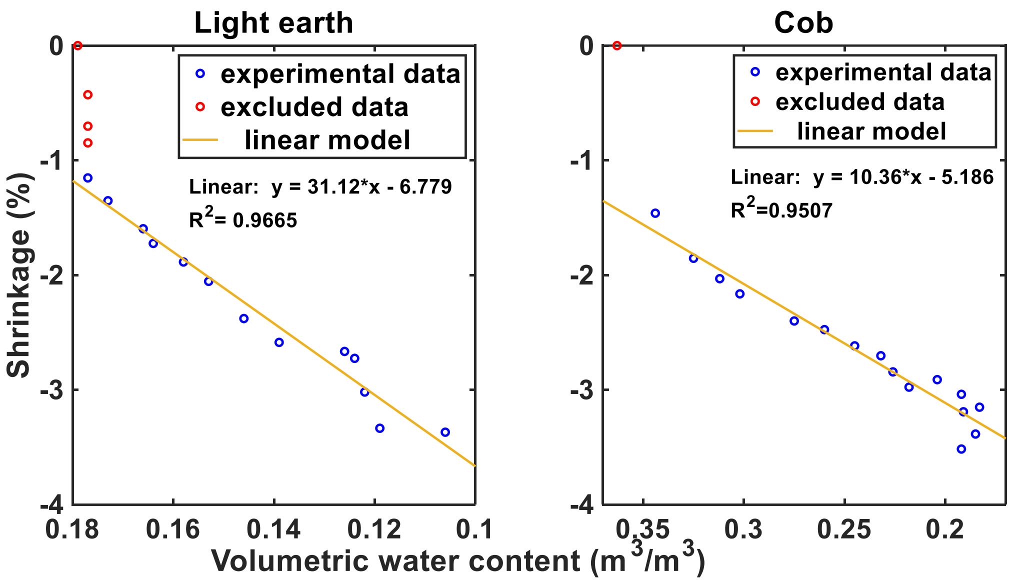

Figure 9 Shrinkage rate as function of water content in cob and light earth constituting a CobBauge double walling system

4. Conclusion

This study aimed to improve the understanding and quantificationof shrinkage and drying processes in both layers constituting a CobBauge double walling system. It was found that whether in cob and light earth, drying and shrinkage follows an exponential decay function. An exception was observed in light earth during the first week after construction. In fact, volumetric water content (VWC) remained approximately steady. This was supposedly due to water exchange processes between clay and reed fibers constituting the mix. VWC decrease in both layers is best fitted with a two-term exponential model. It was also observed that initial VWC is more homogeneous in cob than light earth. These variations are likely to be due to many factors: preparation method of the material, evaporation, and to water addition by the craftsmen during processing. Cob is prepared few days before at a time for all the lift walls (therefore initial water content is homogeneous.

From another side, a differential drying rate between the upper and lower part of the same lift have been observed especially in cob. Regarding the effect of thickness, it was found that thick walls dry more slowly than thin ones. More than one year after its implementation, cob in the north wall contains approx. 27 % more water than cob in the south or west walls.

Elsewhere, shrinkage in both layers follows an exponential decay. During the first three weeks, shrinkage is higher in cob layer. This is supposed due to the gravity effect which is more noticeable in cob than in light earth. Few weeks later, shrinkage in both layers becomes in phase and tend to a kind of stabilization at values ranging between 3 and 4%. Similarly, for volumetric water content, shrinkage in both layers is best fitted with a two-term exponential model.

Considering the exponential decay of both water content and shrinkage, a correlation between these two processes was searched. Two linear correlations were found between water content and shrinkage in both layers. The analysis of these correlations leaded us to suppose that approx. a third of the shrinkage happening in the layers is typical settlement under the effect of gravity. The approx. two other thirds of the overall shrinkage are directly linked to the drying process.

Any recommendations? Or aspects that future practitioners can use?

Acknowledgments

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