Chapter 30
Hygrothermal Behaviour of Cob Material

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30.1 Introduction

In recent years, there has been a renewed interest in earthen building materials for restoration/repair of historic and cultural heritage buildings and for use as a low-energy material in sustainable architecture (Aymerich et al. 2012). The renewal of the use of soil as a building material is related to the significant reduction of the environmental impact due to the use of local raw materials and simple manufacturing processes and energy-efficient (Minke 2000, 2009). In addition, earth-based materials allow better balance and thermal control and internal acoustic compared with conventional building materials. This is due to their performances in terms of moisture absorption/desorption, heat storage capacity (hydrothermal regulation) and sound transmission properties (Minke 2000, 2009; Binici et al. 2009). Currently, building owners and architects also choose earth as a building material because of the advantages in terms of aesthetics and sanitary quality of air (Röhlen et al. 2013).

Earth construction was influenced by the geographical situation and the local cultures. So many construction methods exist: adobe, compressed earth brick, cob and rammed earth. In Normandy, the most common technique is cob which is a mixture of raw earth and natural fibres (usually wheat straw). The cob building technique

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consists in the construction of a massive wall, often bearing, implemented by piling earth–fibre balls in plastic state, possibly by using formwork, compacted with the fork and the stick then cut to the wall. In order to ease mixing, largest elements are removed. Fibres allow to maintain the cohesion and to limit the shrinkage on drying (Galán-Marín et al. 2010). Usually, the mixed water content is between 10 and 20% in order to obtain a compact paste (which does not crumble). Typical soil used in cob contains about 30% gravel (2/20 mm), 35% sand (0.063/2 mm) and 35% silt (0.002/0.063 mm) and clay (<0.002 mm = 2 μm) with a variation of these parameters of more or less 10% (Akinkurolere et al. 2006).

In this study, straw fibre was used. Different cob formulations were made to evaluate the influence of different parameters (type of soil and fibre content). This study was conducted in CobBauge project which is an Interreg programme financed by European Union.

30.2 Materials

30.2.1 Soils

For this study, three different soils from the Lieusaint quarry (Normandy) were chosen: a sand (soil 1), a red clay (soil 2) and a silt (soil 3) (Fig. 30.1). Geotechnical properties of soils are presented in Table 30.1.

According to fines content, soil 1 has the largest percentage of coarse grains. Soil 1 will be used to form the material skeleton. Given their high fines fraction (<80 μm), soils 2 and 3 (between 70 and 90%) will act as binders between grains of soil 1. So two mixtures of soil 1, 2 and 3 were made: soil 1 with soil 2 (mix A) and soil 1 with soil 3 (mix B). The mass proportion retained is 2/3 of soil 1 and 1/3 of soil 2 or 3. This allows to have two mixes with a similar particle size distribution with a small difference between 0.3 mm and 80 μm (Fig. 30.2). The two curves are typical

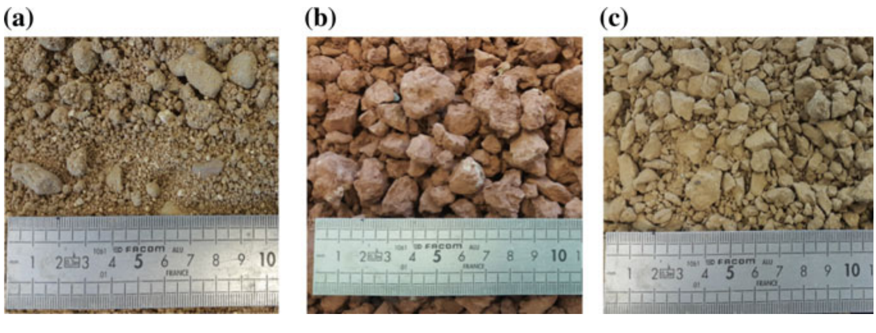

Fig. 30.1 Soils used for the study: sandy soil 1 (**a**), red clayed soil 2 (**b**) and silty soil 3 (**c**)

Table 30.1 Soil properties

	Methylene blue value (g/100 g)	Liquid limit (%)	Plastic limit (%)	Plasticity index (%)	Proctor optimum moisture content (%)	Proctor optimum dry density (kg/m^3)	Fine fraction (<80 μm) (%)
Soil 1	0.30	48.9	28.5	20.4	9.5	2034	13.0
Soil 2	0.91	53.5	24.5	29.0	15.5	1770	72.7
Soil 3	0.55	34.1	20.4	13.7	14.0	1827	89.5

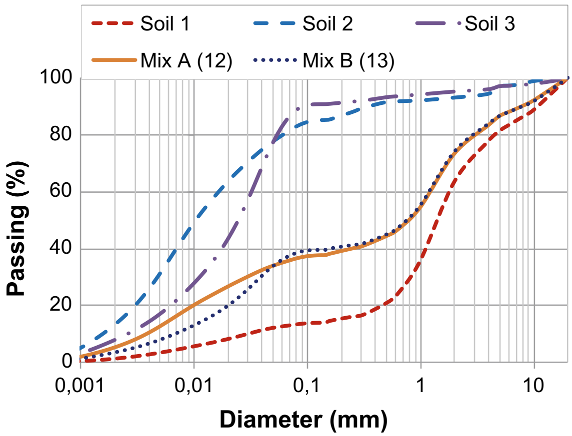

Fig. 30.2 Particle size distribution of the three soils and the two mixes

of traditional cob (Akinkurolere et al. 2006). Indeed, these two mixes have 26% of gravel, 35% of sand and 39% of silt and clay.

30.2.2 Natural Fibres

The use of natural fibres has different advantages when used as reinforcing materials. First, these fibres are widely available and cheap. Moreover, their use in construction will be new opportunities for agricultural materials. On the other hand, their valorisation allows a reduction of the environmental impact compared to mineral or polymeric fibres due to their renewable and biodegradable aspects, CO_2 emissions neutrality and low-energy products.

Furthermore, the addition of randomly distributed fibres into a material provides isotropic strength (Kumar et al. 2006). Fibres prevent cracking propagation during traction after initial deformation (Elizabeth and Adams 2005). Increasing fibre content allows to reduce cracks amount caused by shrinkage and to raise hydraulic conductivity of compacted soil (Millert and Rifai 2004; Tang et al. 2010).

As traditional cob, wheat straw was used in this study. Wheat straw comes from Laulne (Normandy). Wheat straw properties are presented in Table 30.2. Variability of wheat straw length is explained by its agricultural development but, also, its industrial processing and the harvest method.

An important characteristic of natural fibres is the water absorption. Indeed, this characteristic will influence, on one hand, the mix in the fresh state (absorption of available water) and, in the other hand, the long-term behaviour (change in fibre volume and fibre/soil interface modification). The water absorption coefficient was determined by fibres' immersion in water during several periods (1, 5, 15 min, 1, 4,

Table 30.2 Characteristics of straw fibres obtained in this study

Diameter (mm)	Density (g/cm^3)	Length (cm)	Initial water content (%)	Tensile strength (MPa)	Young modulus (MPa)
1–4	1.182 ± 0.073	15–50	8.4	28.83 ± 7.61	1734 ± 327

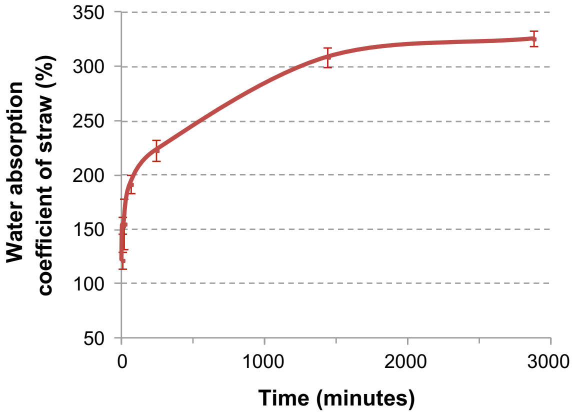

Fig. 30.3 Fibre water absorption coefficient through immersion time

24 and 48 h). After this, fibres were spun with a centrifuge at a speed of 500 rounds per minute for 15 s. Results show that straw water absorption coefficient is high (see Fig. 30.3). Indeed, absorption mean value at 24 h is 309% (each value is the average of six samples).

30.2.3 Formulations and Samples' Preparation

Two mixes A and B were used in this study. In order to study the influence of fibre, several mass fibre content were used: 1, 2 and 3%. The straw length used was 5 cm. Thus, fibres were cut to the required length, added randomly and mixed until getting a homogeneous composite. According to usual method, the water content used (18% for mix A and 16% for mix B) is 6% higher than mixtures Proctor optimum contents (between 11.7 and 12.1% for mix A and between 9.6 and 10.2% for mix B). All samples were stored at 20 ± 2 °C and 50 ± 5% relative humidity. Samples were removed from the mould after 2 days to have sufficient initial strength to stand alone. Initial mass (after manufacture) and mass after unmolding were measured in order to know the water content over time.

30.3 Methods

30.3.1 Thermal Conductivity

Concerning thermal conductivity, transitional method is often used for heterogeneous materials with high moisture content. For this method, a heat source is installed in soil and the soil temperature variations are recorded during measurement. As this method requires a short measurement time (a few minutes), change of the whole soil matrix/fibres/water (influence by the heat source–shrinkage for example) over time caused by measurement can be negligible. The hot-wire method is one of the most commonly used methods for measuring thermal conductivity of unsaturated soil (Tang 2005).

In this study, KD2 Pro device (Decagon Devices, INC) was used with TR-1 sensor. The standard used was ASTM D5334-08. Measurements were made on a cylindrical sample with a diameter of 152 mm and a high of 152 mm. For each sample, the experimental protocol consists of drilling 9 holes of the same sensor size, coating the sensor surface with a thermal paste and, then, install sensor in the hole before starting the test. Between each measurement, a minimum of 3 days is needed to dry (one day) and homogenise (two days) samples.

30.3.2 Hygrometric Properties

Dynamic vapour sorption is a gravimetric technique for measuring vapour interactions with solids. In this study, a ProUmid SPSx-1μ sorption/desorption analyser was used. According to NF EN ISO 12571, it is necessary to use at least four different atmospheres between 30 and 90% relative humidity. Here, for a greater accuracy, eighteen measurement points were made between 5 and 90% relative humidity for sorption and desorption.

For the fibres, samples of 2.5 cm length were used. For cob samples, they were approximately 40 × 40 × 30 mm in size obtained from cylindrical samples Ø150 × H60 mm. Samples were dried at 50 °C, then put in an airtight container containing silica gel in order to cool samples without letting the samples absorb moisture.

30.4 Results and Discussion

30.4.1 Thermal Conductivity

Results for thermal conductivity are presented in Figs. 30.4 and 30.5. These results show that thermal conductivity is linked to water content as found in previous studies (Tang 2005). Indeed, thermal conductivity decreases during drying. This can

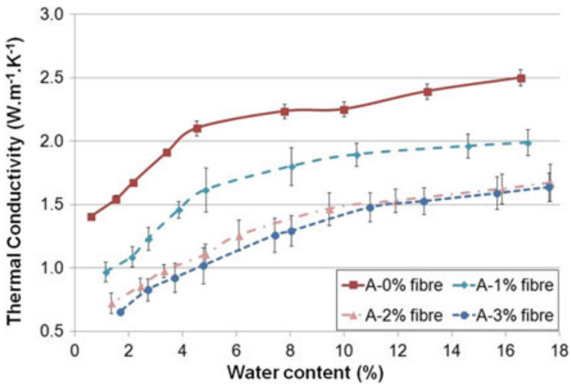

Fig. 30.4 Thermal conductivity changes of mix A with various fibre contents according to the water content during drying

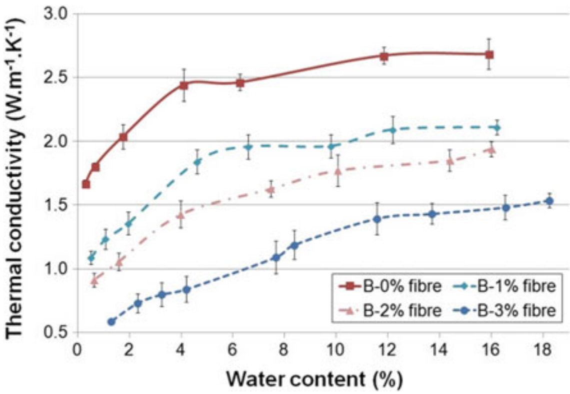

Fig. 30.5 Thermal conductivity changes of mix B with various fibre contents according to the water content during drying

be explained by the fact that water evaporates and is replaced by air which has a lower thermal conductivity than water 0.025 W m^{-1} K^{-1} instead of 0.6 W m^{-1} K^{-1}. However, it has to be noted that, above a water content of around 6%, the thermal conductivity decrease is lower (see Fig. 30.4 and 30.5). This can be due to shrinkage which increases slightly the sample dry density, therefore slightly increases the thermal conductivity. This leads to a competition between two phenomena (drying and shrinking) which have opposable effect on thermal conductivity. This explanation can be better seen in the case of mixture B. With 2% of fibre, there is less shrinkage, so the thermal conductivity decreases regularly from the beginning.

Moreover, results show that a higher fibre content leads to a lower thermal conductivity as seen by (Ledhem et al. 2000). Indeed, straw fibres have a thermal conductivity between 0.055 and 0.065 W m^{-1} K^{-1} compared to soil thermal conductivity. Figure 30.6 shows the evolution of thermal conductivity at the equilibrium (in storage

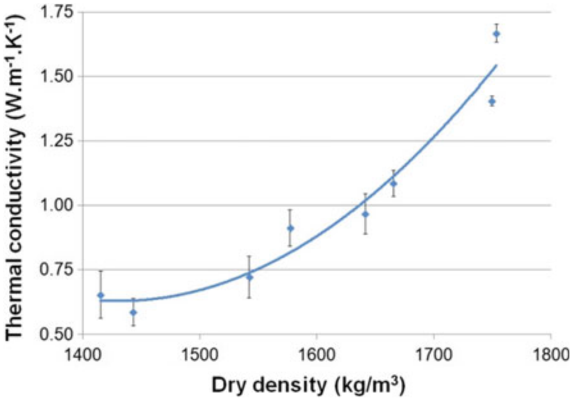

Fig. 30.6 Thermal conductivity versus dry density of mixes with various fibre contents

conditions at 20 ± 2 °C and 50 ± 5% relative humidity) according to dry density of the two mixes. An addition of fibre introduces an additional porosity and, thus, leads to a lower dry density of the soil/fibre mix. Results show that this porosity decreases thermal conductivity as seen by (Laurent 1986) Values obtained for mix A (0.72 ± 0.08 W m^{-1} K^{-1} with a density of 1560 kg/m^3) and for mix B (0.91 ± 0.07 W m^{-1} K^{-1} with a density of 1580 kg/m^3) with 2% fibre content are similar to characteristics observed in a nineteenth-century cob house (0.76 ± 0.12 W m^{-1} K^{-1} with a density of 1660 kg/m^3) (Laurent 1986).

30.4.2 Hygrometric Properties

Results for hygrometric properties are presented in Figs. 30.7 and 30.8. Firstly, these results show that values of standard deviation are lower for RH < 50% than for RH > 50%. The results for the fibre-free mixtures A and B show that the water content of the mixture A varies between 0.2 and 3.7% and that of the mixture B varies between 0.2 and 2.8%. Mixture B thus has a lower hygroscopic capacity than mixture A. This difference is probably due to the clay activity which is more important for mixture A. Indeed, since the clay activity is proportional to the specific surface area, a larger surface area means greater adsorption of water molecules.

These results also show that increasing fibre content increases the material hygroscopic capacity. Values obtained for RH = 90% show that, compared to mixes without fibre, the water content increase is equal to 3.5, 7.5 and 9.9% for an addition of 1, 2 and 3% fibre for mix A and 3.2, 7.1 and 11.1% for mix B. These results show that the water content increase seems to almost linearly depend on the fibre content. This phenomenon can be explained by the greater sorption/desorption capacity of wheat straw fibres compared to mixes A and B (Fig. 30.9). These results show

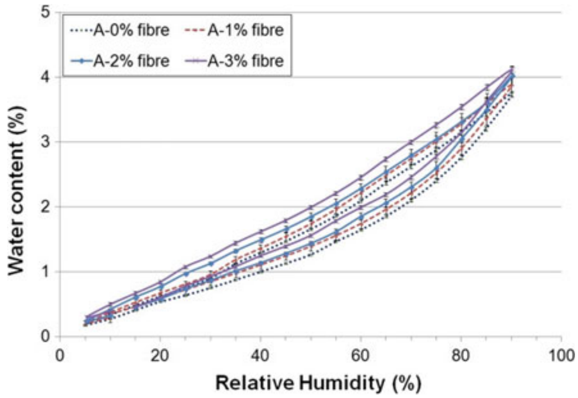

Fig. 30.7 Sorption/desorption curves of mix A with various fibre contents

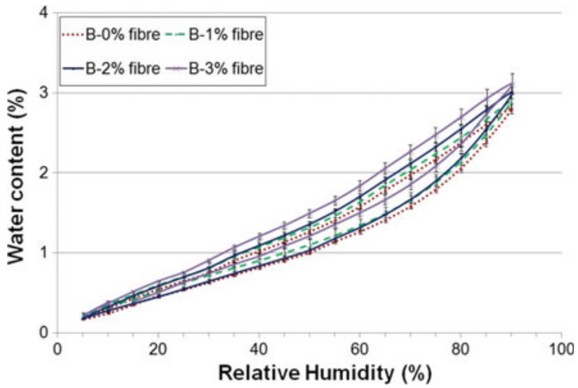

Fig. 30.8 Sorption/desorption curves of mix B with various fibre contents

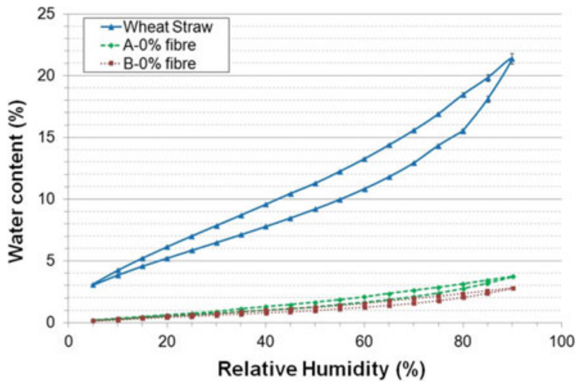

Fig. 30.9 Sorption/desorption curves of wheat straw, mix A and mix B

Table 30.3 Characteristics of straw fibres obtained in this study

Fibre-added content (%)		Mix A			Mix B		
		RH (%)		Variation	RH (%)		Variation
		90	50		90	50	
0	W (%)	3.7	1.7	2.0	2.8	1.3	1.5
	λ (W m^{-1} K^{-1})	1.969	1.568	0.401	2.220	1.933	0.287
1	W (%)	3.9	1.7	2.2	2.9	1.3	1.6
	λ (W m^{-1} K^{-1})	1.461	1.041	0.420	1.529	1.269	0.260
2	W (%)	4.0	1.9	2.1	3.0	1.4	1.6
	λ (W m^{-1} K^{-1})	1.038	0.785	0.253	1.277	1.025	0.252
3	W (%)	4.1	2.0	2.1	3.1	1.5	1.6
	λ (W m^{-1} K^{-1})	0.959	0.707	0.252	0.789	0.616	0.173

that hygrometric properties of cob can be almost determined knowing soil and fibre sorption/desorption curves.

30.4.3 Thermal Conductivity Versus Hygrometric Properties

Cob sorption/desorption curves allow to establish the influence of ambient hygrometry on material characteristics. Indeed, thermal conductivity has been followed during drying of mixes A and B. The influence of relative humidity (RH) on the thermal conductivity was thus determined and is presented in Table 30.3 for a decrease in RH from 90 to 50%. Results show that the RH decrease leads to a decrease of thermal conductivity around 20–30% for mix A and around 10–22% for mix B. Behaviour differences between mixes seem to come from clay activity. Indeed, clay activity is linked to specific surface area and, therefore, a lower clay activity leads to lower water content variations. Since thermal conductivity varies with water content, a lower water content variation results in a smaller change in thermal conductivity. It should also be noted that thermal conductivity evolution between 90 and 50% RH is greater for fibre materials than non-fibre materials. This is due to the fact that water content variation is similar for each formulation of each mixture and that thermal conductivity decreases as the amount of fibre increases.

30.5 Conclusions and Perspectives

In this study, thermal behaviour and hygrometric properties of cob formulations were presented. Results obtained show that thermal conductivity decreases when fibre content increases. This is due to material lower density and to fibre conductivity. With 3% fibre content, thermal conductivity is 0.65 ± 0.09 W m^{-1} K^{-1} for mixture A and 0.59 ± 0.05 W m^{-1} K^{-1} for mixture B. Concerning hygrometric properties, results show that knowing each component hygrometric properties will allow to predict cob properties. Knowing hygrometric properties allows to determine cob behaviour variation during the building life.

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References

Aymerich F, Fenu L, Meloni P (2012) Effect of reinforcing wool fibres on fracture and energy absorption properties of an earthen material. Constr Build Mater 27:66–72. https://doi.org/10.1016/j.conbuildmat.2011.08.008

Akinkurolere OO, Jiang C, Oyediran AT, Dele-Salawu OI, Elensinnla AK (2006) Engineering properties of Cob as a building material. J Appl Sci 6:1882–1885. https://doi.org/10.3923/jas.2006.1882.1885

Binici H, Aksogan O, Bakbak D, Kaplan H, Isik B (2009) Sound insulation of fibre reinforced mud brick walls. Constr Build Mater 23:1035–1041. https://doi.org/10.1016/j.conbuildmat.2008.05.008

Galán-Marín C, Rivera-Gómez C, Petric J (2010) Clay-based composite stabilized with natural polymer and fibre. Constr Build Mater 24:1462–1468. https://doi.org/10.1016/j.conbuildmat.2010.01.008

Elizabeth L, Adams C (2005) Alternative construction: contemporary natural building methods. Wiley, New York

Kumar A, Walia BS, Mohan J (2006) Compressive strength of fiber reinforced highly compressible clay. Constr Build Mater 20:1063–1068. https://doi.org/10.1016/j.conbuildmat.2005.02.027

Ledhem A, Dheilly R, Benmalek M, Quéneudec M (2000) Properties of wood-based composites formulated with aggregate industry waste. Constr Build Mater 14:341–350. https://doi.org/10.1016/S0950-0618(00)00037-4

Laurent, J.-P. (1986). Contribution à la caractérisation thermique des milieux poreux granulaires optimisation d'outils de mesure "in situ" des paramètres thermiques, application à l'étude des propriétés thermiques du matériau terre, Ph.D. Thesis, Grenoble INPG

Miller CJ, Rifai S (2004) Fiber reinforcement for waste containment soil liners. J Environ Eng 130:891–895. https://doi.org/10.1061/(ASCE)0733-9372(2004)130:8(891)

Minke G (2000) Earth construction handbook: the building material earth in modern architecture. WIT Press, Southampton, p 2000

Minke G (2009) Building with earth: design and technology of a sustainable architecture. Birkhäuser, Basel

Röhlen U, Ziegert C, Mochel A (2013) Construire en terre crue: construction, rénovation, finitions. Éditions Le Moniteur, Paris

Sutton A, Black D, Walker P (2011) Straw bale: an introduction to low-impact building materials. IHS BRE Press, Watford

Tang C-S, Shi B, Zhao L-Z (2010). Interfacial shear strength of fiber reinforced soil. Geotextiles and Geomembranes 28(1):54–62. https://doi.org/10.1016/j.geotexmem.2009.10.001

Tang AM. (2005). Effet de la température sur le comportement des barrières de confinement. Ph.D. Thesis, Ecole Nationale des Ponts et Chaussées, Paris