Earth buildings with local materials: Assessing the variability of properties measured using non-destructive methods

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EARTH BUILDINGS WITH LOCAL MATERIALS: ASSESSING THE VARIABILITY OF PROPERTIES MEASURED USING NON-DESTRUCTIVE METHODS

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Highlights

- Non Destructive Tests on hand made earth specimens with and without natural fibres
- Thermal, electrical and mechanical properties are correlated with each other
- Coefficients of variation are generally higher for specimens including natural fibres
- Results prove the importance of using characteristic instead of average values

Abstract

The study focuses on analysing the variability of the properties for earthen materials constructed with traditional methods. Non-destructive tests are conducted on two material formulations: raw earth and raw earth mixed with hemp shives and reed. Raw earth samples exhibit coefficients of variation of 3.7%, 17.8%, 9.6%, 27.0% and 12.8% for density, electrical resistivity, thermal conductivity, volumetric heat capacity and dynamic modulus, respectively. Higher variabilities of properties are observed for the formulation that includes natural fibres: 3.7%, 25.8%, 12.1%, 23.7% and 23.3%, respectively. Correlations between properties are established and the sensitivity to fibres presence inducing heterogeneity between specimens is analysed.

Keywords: earth, natural fibres, thermal conductivity, heat capacity, dynamic modulus, electrical resistivity, repeatability, coefficient of variation

Declarations of interest: None

1. Introduction

The environmental impact of constructions is very important, both from the point of view of the consumption of natural resources and of energy consumption to ensure the comfort in residential or tertiary buildings. In order to reduce the impact of new buildings, raw earth, a vernacular and ancestral material, seems to be a credible alternative [1], [2].

Raw earth is a natural material resulting from the slow decomposition of bedrock on a geological scale, it is therefore present in large quantities on the surface of the Earth. In addition, raw earth has excellent hygrothermal regulation properties for maintaining convenient atmosphere in homes. Today we are rediscovering earthen construction techniques in order to limit the carbon impact of buildings.

Most of the publications concerning earth in buildings focus on rammed earth and compressed earth blocks (with raw material being often stabilised with lime or cement), as these solutions are more controllable in terms of consistency of results. The problem of using standardised material formulations is that the local material might not always be suitable. Earth composition can vary in significant extents between sites, and transport of materials to the building site, the use of big mechanised tools for construction or even the use of stabilisers lowers the eco-friendliness of the solution [3]. For these reasons, the present study focuses on assessing the possibility of using locally supplied materials and traditional manual building techniques and on quantifying the variabilities of several properties measured by means of non-destructive testing methods. As discussed in [4], old earth buildings were generally built using locally supplied materials. And even if in some cases the characterisation of these materials is off from modern normative prescriptions [4] the buildings constructed using local traditional methods can be in good condition after decades and even centuries of use.

The properties of earth used in buildings, be it mechanical or hygrothermal properties, can be highly variable. For this reason, while assessing different properties, the focus should not be only on the average measured values, but also on the coefficients of variation (CV) for the analysed data. As reported by different authors, the values of the computed CV's vary between different types of properties, between different types of material composition as well as between different construction techniques, with some computed values being very high.

Some authors computed high CV values for different building techniques, different materials and different number of tested samples. For the mechanical properties, Miccoli et al. [5] found CV values of up to 68% for Young modulus calculated with the slope of stress/strain curves (based on 4 cob samples tested). The results of Quagliarini and Lenci [6] (based on 8 soil-sand-straw manually compacted brick samples) correspond to a CV of 26% for the compression strength. The results of Nakamatsu et al. [7] showed CV values of 19% for 3-point bending tests (based on 4 raw earth prisms), while Silveira et al. [8] mention CV values as high as 73% for splitting tests (based on 12 adobe cylinders tested). For the thermal properties, Narayanaswamy et al. [9] mention CV's (based on tests on 3 stabilised compressed earth blocks) of up to 11% for thermal conductivity and 7% for specific heat capacity.

Despite of this situation, many studies on earthen materials, even very recent ones, tend to ignore the variability of measurements values and only present results in terms of average values, even if these studies are based on a low number of specimens. For instance, Taallah and Guettala [10] and Sujatha and Devi [11] only present the average values of the results obtained. Ashour et al. [12] present the variability of measurements for the density of the specimens, but only the mean for the measured thermal conductivity values. Silveira et al. [13] and Liuzzi et al. [14] show the standard deviation only in the figures and only for some of the tests performed, but no values are given, and no comparison is done between the tests.

Treatment of data and analysis of the impact of variabilities on the results is also not uniform among researchers. Because of this, even when an analysis of the standard deviation is made, it can be misleading. For instance, Mazhoud et al. [15], when analysing the thermal conductivity values for the specimens, only consider the measures within ±5% of the average, then mention that the coefficient of variation is 4%, even if they also state that the precision of the experimental device is 5%. Sujatha and Devi [11] present values for the properties of earth blocks reinforced with fibres but do not even mention the number of specimens tested for each formulation.

This approach, that only focuses on the average values, could be very misleading regarding the actual properties of the materials that would be used in a real building. Even more as, for modern standardised materials, the design is based on characteristic, and not average values of properties. As an example, Parisi et al. [16], when analysing mechanical properties, found that the characteristic values (values which are not exceeded by 5% of the specimens) were as low as 40% of the average measured values.

The objective of the present research is to demonstrate the variability of results obtained when measuring different properties of earthen materials. The analysed materials were not chosen, in terms of formulation and sample dimensions, with the purpose to check the reliability of using them for a specific role in a building or using a specific construction technique. On the contrary, our purpose was to obtain results that might be valid for any construction technique, by identifying the properties with high standard deviation of the results, for which a large number of samples should be tested prior to taking the decision of using the material in a real building.

The present study highlights the values of the coefficients of variation not only for different formulations of earthen materials, but also for different measured properties, while using Non-Destructive Testing (NDT) methods. In this study, NDT methods have the advantage of testing the same specimen to determine 3 kinds of properties: thermal, electrical and mechanical, in a very short time. This allows performing repeatability tests for evaluating the measurement error and also testing many samples of the same formulation to get the distribution, the standard deviation and the coefficient of variation for each measured property.

Another advantage for developing relevant NDT for earth-based materials is to improve the conservation of earth housings. Non-destructive survey techniques must be favoured as they can be used to detect and characterize defects or damage without the need for coring. Using mostly non-destructive testing and only limited destructive tests should be the favoured approach towards evaluating the health and performances of existing earth buildings. This type of approach is often used for masonry [17] or concrete structures [18].

In this research, three currently available non-destructive methods were used on earth specimens in the laboratory.

Thermal properties were measured with the Hot Disk apparatus which was already used on earth specimens by different authors [19], [20]. Nevertheless, these studies did not focus on determining the coefficient of variation and the distribution of the measured properties and were based on a low number of specimens.

The dynamic modulus was determined with the Grindosonic apparatus. Using the device, the resonant frequency of the specimens was established and then the modulus was computed based on the frequencies and the size of the sample. Even if for soils, there is a different behaviour at small or large strain levels [21], various correlations between dynamic and static modulus were proposed for concrete specimens and for rocks [22, 23]. For soils, relations between Young modulus and compression strength were proposed by Caporale et al. [24]. We did not find recent researches focusing on the analysis of the correlation between dynamic and Young modulus for earth

specimens used in buildings. Yet, older researches, such as [25], highlighted that certain correlations can be established between density, porosity, dynamic modulus and mechanical strength.
The electrical resistivity was measured using the Wenner resistivimeter. This method is often used on concrete specimens in order to assess characteristics such as porosity, water saturation and damage levels [18], [26], [27]. Even if no recent studies were found that focus on cob or adobe buildings, this method was often used in other types of soil investigations and analysis [28], [29], [30]. As moisture content affects the mechanical strength of earthen materials [5], [7], [31] and their durability [32], the detection of water content in walls should be a priority investigation for earth houses. The Wenner apparatus is a promising tool for this goal, as it represents a low-cost and easy to use solution.

The focus of this paper is the study of the results obtained by performing NDT on hand-made earth specimens both with and without fibres in laboratory conditions. Thermal (thermal conductivity and volumetric heat capacity), electrical (apparent resistivity) and mechanical (dynamic modulus) properties were measured for a large number of specimens. An assessment of the measurement repeatability was done for each type of test followed by a statistical analysis conducted on measurements of 18 different specimens made with the same formulation. A particular attention was given to thermal properties, for which the density probability functions were determined and modelled.

2. Materials and Methods

2.1. Soil and fibres

The soil used is from the Guérande area in Loire-Atlantique region in north-western France. In this region, traditional earth houses also included cob, some of the buildings still being in use today [33].

The composition of the soil in terms of particle size was determined in accordance with NF EN ISO 17892-4 [34] by means of wet sieving for the soil fraction with sizes greater than 2µm and by means of sedimentation for the fine fraction. The results are shown in Figure 1. The soil is a sandy loam composed of 8% clay, 47% silt and 45% sand. As earthen materials for buildings are often assessed based on triangle texture diagram [35], we also represented in Figure 1 the classification of the soil based on the French soil science organisation "GEPPA" [36]. It is to be noted that in the GEPPA diagram the upper dimension of the silt is 50µm, different from the one considered in NF EN ISO 17892-4 [34], such that based on this system the silt content would be 44%, while the sand content 48%. In figure 1, in the triangle texture diagram, the greyish areas are mentioned in [35] as generally considered suitable for the earth to be used for construction. The green dots in the same figure are values obtained in [35] for samples extracted from existing rammed houses. In the same figure, the greenish areas are mentioned in [37] as suitable for cob construction. It can be observed, from Figure 1, that the composition of the soil corresponds to the lower limit of the observed used soils in construction by the abovementioned authors.

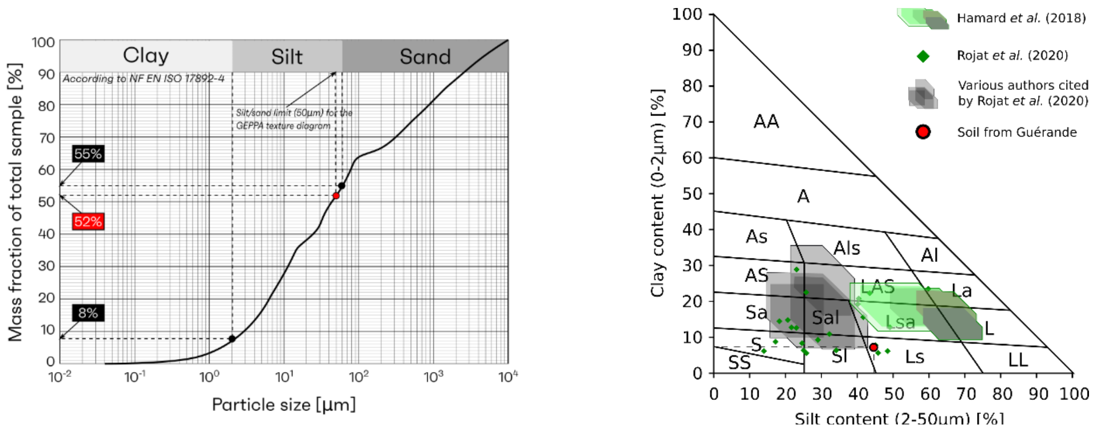

Figure 1. Particle-size distribution curve (left) and texture diagram (right) for the soil of Guérande (red dot)

The Atterberg limits were determined based on NF EN ISO 17892-12 [38]. The plastic limit is WP=17%, while the liquid limit is W_L=34%. The value of the plasticity index is I_P=17. The Methylene blue value is 1.9, determined based on NF EN 933-9 [39].

The type, size and percentage of fibres influence not only the final characteristics of soil-fibres mixes, but also the behaviour during the curing of the specimens. Various types of fibres with different lengths have been used for earth buildings. The length of fibres is often around 2 cm for shavings [9], [14], [40], [41] and 5 cm for chopped straw [16], [41], [42], [43]. Much longer fibres are sometimes used for cob buildings [5], [33]. As discussed in [42], the problem with fibres longer than 5 cm is that they can clump or fold and therefore can prove more difficult to work with and do not necessarily improve the properties of the soil.

Because traditional houses often involved the use of local fibres mixed with the soil [44], we decided to use locally available natural fibres in order to assess their influence on the mechanical, thermal and electrical properties of the material as well as on the variability of the results. The chosen fibres were hemp shives (commercial product Chanvribat) and reeds locally produced. Both types of fibres considered in this study are mentioned in the literature as being traditionally used in earth buildings [41]. The length and width of hemp shives particles were determined by 2D image analysis in another study [45]: hemp particles have an average length of 8.9 mm and an average width of 2.0 mm. The reeds, 3.5 mm average diameter, were cut at approximately 20 cm length before being added into the mixing machine. This length is used by hand-made makers of cob construction.

Including fibres in the earth mix has been used since ancient times [6], as this can reduce shrinkage and improve the mechanical properties of the material (from brittle to ductile behaviour).

Fibre content in terms of mass, for adobes and cobs, typically ranges from 0.2 to 4% [5], [10], [11], [16], [24], [40], [42], [46], [47], but higher values, of 6% [47] or even 10% [24] have been observed. Higher fibre content (10% to 20%) is often used for plasters [14], [15], [41]. Low fibre percentages (below 1%) might not influence the mechanical behaviour or the thermal behaviour [41]. Important differences in the thermal properties of the material are reported for fibre percentages of 4-12% [12], [14]. In the same time, percentages higher than 10% can cause shrinkage problems [41].

In this study, an 8% fibre content by mass was chosen for formulations including natural fibres. This percentage is used in the Loire-Atlantique area for building earth construction using the cob technique and was chosen based on discussions with craftsmen involved in earth buildings with practical construction experiences. The high fibre percentage allows to distinguish clear differences in all the measured properties between the raw earth and the fibre mixes.

2.2. Construction and curing of specimens

Our goal was not only to use locally available materials, but also to replicate simple building methods with manual application of the material. These techniques, which Minke [44] defines as “thrown loam” or “wet loam” currently represent the prevalent solution in existing buildings in some regions [48]. They involve throwing with strong impact (or sometimes manually pressing) successive clods of loam mixed with cut straw (sometimes also with other fibres) so that each new layer adheres to the previous ones and a certain degree of compaction is obtained for the material.

The quantity of materials in the mix was established based on the know-how of local craftsmen. This would have been the case in ancient [6] or even more recent [44] buildings. A 2:2:1 volume ratios of raw earth, hemp shives and reed was used. It should be noticed that even in current buildings standards such as NZS 4298: 1998 [49], mixes are sometimes described in terms of volume, and not mass ratios. The raw materials were placed in a large steel bowl and were mechanically mixed with a kneading hook at low speed while gradually adding water to the mix until the desired consistency was obtained. During the mechanical mix, reed was broken into smaller length. Based on preliminary tests, 3 minutes of mixing time were needed in order to have the reed cut into smaller pieces of maximum 5 cm length. As discussed in ASTM E2392 [50], the mix time affects both strength and durability of the cured product, and an optimal mix time must be established for a given project, depending on the earth mixture components and building method. In terms of mass, the fibres represent 8% of the mix (7% hemp and 1% reed). The initial water content was checked after drying the specimens in the oven until mass stabilization. The calculated value of the water content was 23% for the raw earth formulation and 24 % for the raw earth and fibres mix. As shown in [41], adding fibres to the mix requires having a higher water content due to water absorbed by fibres. Also, as observed by [51], unless a press is used, the manufacturing process of earth slabs requires that the material is in a near-liquid state.

The samples were cast in wooden moulds with interior dimensions of 31 × 19 × 5.3 cm placed on a base wooden tray (figure 2). Before casting the earth into the moulds, the plate was sprinkled with form release oil in order to prevent adherence. The earth was thrown with force, a handful at a time, into the mould. After the mould was filled, the excess was removed with a steel wire and the visible surface of the sample was lightly watered and flattened with a trowel.

For each mix, with and without fibres, 3 slabs were made. After the removal of the moulds, the slabs of freshly cast earth were cut into 6 pieces, with average dimensions of the specimens of 5.17 × 19 × 5.3 cm (Fig. 2). Cutting was done with a steel wire. The measurements were made on each of the 6 specimens from slabs 1, 2 and 3, which corresponds to 18 specimens without fibres (called Soil and noted S in figures) and 18 with fibres (called Soil with Fibres and noted SF in figures).

a) b)

Figure 2. Construction of specimens: a) casting earth into mould, b) specimens after wire cutting, the third slab is cut after drying

After casting, the specimens were naturally dried until constant mass in a climate chamber with constant temperature (20°C) and relative humidity (50%). Despite the initial high water content, no cracks were observed to form during the slow drying.

2.3. Tests conducted on specimens

Using non-destructive methods, the electrical resistivity, the thermal properties and the dynamic modulus of the 18 specimens for each formulation were measured. All the tests were performed after 27 days from casting on specimens of constant mass.

As water content highly impacts the properties of earthen materials [31], [32], all the tests were performed at 20°C and 50% relative humidity. The water content when tests were performed (determined after drying samples in oven at 105°C) was 3.1% for soil samples and 3.3% for soil-fibres samples.

2.3.1. Thermal conductivity and volumetric heat capacity

The thermo-physical properties of the different formulations were measured by means of the HotDisk method, based on Gustafson's theoretical developments [52]. The measurements were carried out by placing the circular probe (diameter 12.8 mm - figure 3-b) between two specimens (two sides measurement), the surfaces of which have been smoothed prior to testing in order to limit the effect of the resistance of contact between the specimens. The thermal excitation was made by the resistive temperature probe itself. The power supplied to the specimens was 20mW and the duration of the test was 20s, yielding a temperature increase between 2 and 4°C depending on the thermo-physical properties of the material. The temperature increase is used to determine the thermo-physical properties: thermal conductivity and volumetric heat capacity. These properties are calculated with the probe placed between two specimens, so the values do not correspond to one specimen, but to each of the combinations between the specimens. Measurements were done on 15 combinations for each slab.

2.3.2. Electrical resistivity

The resistivity meter is a measurement device using the Wenner protocol to determine the apparent resistivity of the materials [26]. The 4 electrodes are linearly arranged and spaced at a constant distance a (figure 3-a). For the device used in this work, $a = 5\ cm$. First, an electric current, I, is injected between the two external electrodes. Then, the electrical potential is measured between the two internal electrodes. The apparent resistivity is calculated by the control acquisition unit, based on the equation (1), where ρ is the resistivity ($\Omega \times$ m), a is the distance interval between the electrodes (m), V is the voltage (volts) and I is the current intensity injected into the sample (A).

$$\rho = 2 \times \pi \times a \times \frac{V}{I} \quad (1)$$

a) b)

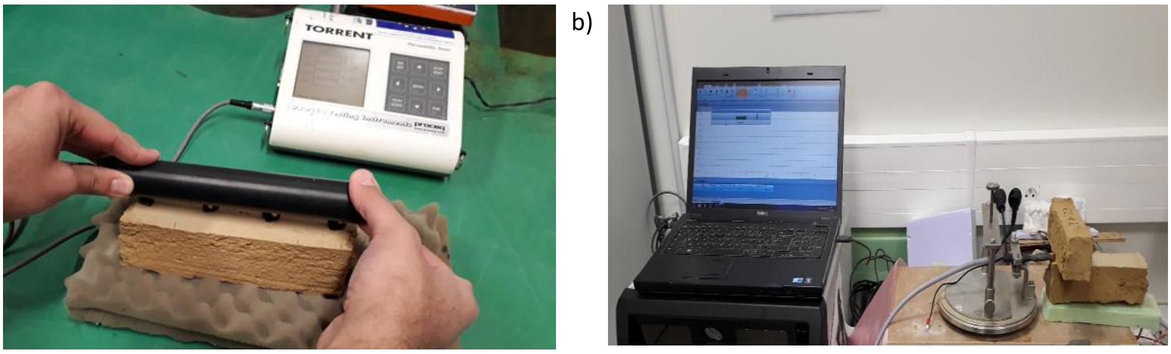

Figure 3. Non-destructive measurements: a) Wenner resistivity meter, b) Hot Disk.

In this paper the measured resistivity values are apparent values, as they were not corrected to account for sample dimension. Electrical resistivity with Wenner resistivimeter is usually used with good accuracy to evaluate concrete properties by nondestructive testing, as for instance porosity, water content and carbonation front [18]. For cementitious materials, electrical resistivity varies with the strain level and could be used to establish the damage levels in the material [27].

2.3.3. Dynamic modulus

The dynamic modulus was determined using the Impulse Excitation Technique (Grindo Sonic equipment). This non-destructive measurement is highly accurate while very simple to perform [25].

The Grindo Sonic instrument records the vibration, makes an analysis in the time domain and measures the natural frequency of the dominant vibration mode against a precision reference oscillator. The value of the dynamic modulus was computed based on the measured dimensions, mass and frequency for each sample using equation (2), according to ASTM E1876-01 [53].

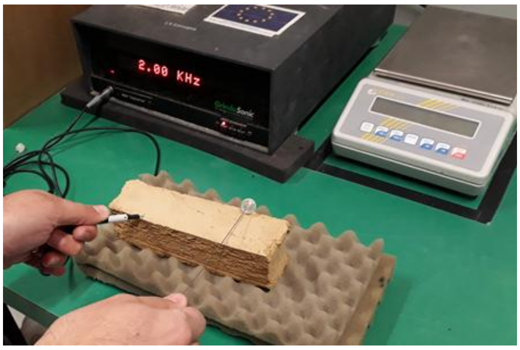

Figure 4. Non-destructive measurements: dynamic modulus using Grindo Sonic equipment

In equation (2), *E* is the Young's modulus (Pa), *m* is the mass of the bar (g), *b* the width of the bar (mm), *L* the length of the bar (mm), *t* thickness of the bar (mm), f_f fundamental resonant frequency of the bar in flexure (Hz) and T_1 correction factor that accounts for the finite thickness of bar, Poisson's ratio, and so forth.

$$\mathrm{E} = 0.9465 \times \left(\frac{m \times f_f^2}{\mathrm{b}}\right) \times \left(\frac{L^3}{t^3}\right) \times T_1 \qquad (2)$$

3. Results and analysis

3.1. Repeatability of the non-destructive measurements

Before conducting an analysis on the variability of the measured materials properties, we analysed the variability of the measurements themselves. For all the non-destructive tests, we performed series of 20 measures, on the same specimens, same positions marked on the specimens, and under the same conditions, in order to establish the reliability of the results for each type of measurement. It is important to mention that measures on a given sample were not performed in sequence.

The mean and CV values are calculated for each specimen with 20 measurements and table 1 shows the minimal and maximal values of CV and the CV average calculated with the 18 CV values. These results highlight that there is a certain variability due to the measurements themselves. This could be assimilated to the measurement error due to apparatus and operator involved in the measurement. The lowest values were obtained for the resistivity measurements and the highest for the dynamic modulus. Also, for all the tests, higher values of CV were computed when measuring the properties of the samples with natural fibres. These measurements are more sensitive with fibres samples, even if the measurements were done by placing the sensors at the same positions. As the fibred specimens are more heterogeneous than specimens with no fibres, this induces a modification in the chosen paths for electrical and thermal flow as well as in the vibrational properties. Another explanation for some of the high values observed is an imperfect contact between the sensors and the specimens or a fault in the specimens near the probed area, that might lead to variations in measurements.

It is interesting to note that results vary in large extents for different tested samples. As an example, the lowest CV value for conductivity measures on raw earth samples was 0.3%, while the highest value, for the same measurement on another sample was 9.1%. For the earth and fibres mix, the highest and lowest CV values were observed for the dynamic modulus measurements, with values of 0.8% and 12.2% respectively.

This observation is particularly important when only a limited number of tests are performed, as the precision of the measurement method might significantly impact on the measured value of the analysed property. It is therefore important, when performing studies on earth and earth-fibres materials, to establish the precision of each type of test.

Mix type		**Soil without fibres (S)**			**Soil with natural Fibres (SF)**		
Water content by mass		**3.12%**			**3.27%**		
Measure		**Thermal Conductivity**	**Resistivity**	**Dynamic modulus**	**Thermal Conductivity**	**Resistivity**	**Dynamic modulus**
CV (%) 20 measures for the same sample	**Min**	0.29	0.75	1.59	1.94	1.67	0.77
	Max	9.12	1.11	3.24	9.49	4.31	12.25
	Average	3.68	0.92	2.34	5.38	3.16	6.91

Table 1 – Coefficients of variation for 20 measurements on the same sample (done on 18 specimens for each formulation)

3.2. Analysis of variability

In order to assess the variability of the material, the coefficient of variation (CV) was consistently computed for all the performed tests. CV, equally known as relative standard deviation, is computed as the standard deviation of the considered measurements divided by the mean value of the measurements. The choice of CV as a tool for assessing the variability of measured values was done in order to be able to compare the results between different samples and between different types of measures.
As CV is relevant if the data correspond to a normal distribution, a second parameter was computed in order to verify if this assumption is correct. We chose to use the relative normalised interquartile range (NIQR). The interquartile range (IQ) represents the difference between the values corresponding to the 3rd and 1st quartile of the data. The value of the normalized interquartile range (NIQ) was computed as $NIQ = 0.7413 \times IQ$. It was then transformed into a relative value (NIQR) by dividing NIQ by the mean value of the considered data, in order to be consistent with CV.

Computing for a given set of data both CV and NIQR values allows to establish if the data correspond to a normal distribution (situation where CV=NIQR), if high values of CV can be attributed to a single out of scale value for one specimen (that could correspond to one specimen having a flaw or to a measurement error) or if many measurements are distant from the average.

The analysis of the variability was done for the samples from each slab, as well as for all the samples from one formulation. The data are computed in table 2 for each property. In the results from table 2, we refer only to CV values, as NIQR was only used as a check for the relevance of CV. Yet, in the figures, we chose to use a box-type presentation of the results, in order to show the median, the 1st and 3rd quartile values and the interquartile range (computed including the median). The whiskers extend up from the top of the box to the largest data element that is less than or equal to 1.5 times the IQ and down from the bottom of the box to the smallest data element that is larger than 1.5 times the IQ. Values outside this range (for a series of data) are considered outliers and are represented by dots on the charts.

By comparing table 1 and 2, coefficient of variation values obtained on repeatability tests (20 measurements on the same specimen) are lower than those obtained on variability tests (18 measurements on different specimens of the same batching) for all non-destructive evaluation. We can state that the repeatability CV values integrate the error due to the measuring instrument and the operator and that the variability CV values are characteristic of the sensitivity of the measurement to the hand-made specimen heterogeneity.

Mixture type	Specimen	Density		Thermal conductivity		Volumetric heat capacity		Electrical resistivity		Dynamic modulus	
		Mean value	CV	Mean value	CV	Mean value	CV	Mean value	CV	Mean value	CV
		kg/m^3	%	W / (m×K)	%	MJ / (m^3×K)	%	Ω × m	%	MPa	%
Soil without fibres (S) Water Content: 3.12 %	Slab 1	1891	1.4	0.979	11.1	1.693	24.3	1372	18.2	6404	8.8
	Slab 2	1938	1.8	0.989	11.2	1.908	25.1	1152	6.5	6352	5.2
	Slab 3	1806	3.4	1.003	6.7	1.274	12.6	1571	10.5	7994	5.1
	Slab 1+2+3	1878	3.7	0.989	9.6	1.668	27.0	1365	17.8	6917	12.8
Soil with Fibres (SF) Water Content: 3.27 %	Slab 1	1439	1.8	0.494	11.0	0.619	31.1	2412	12.2	1661	20.0
	Slab 2	1471	3.5	0.562	8.0	0.851	14.3	2552	22.8	2226	25.5
	Slab 3	1377	1.7	0.561	12.6	0.830	22.1	3809	7.6	2375	7.5
	Slab 1+2+3	1429	3.7	0.548	12.1	0.794	23.7	2924	25.8	2087	23.3

Table 2 – Mean values and coefficients of variation for density, electrical resistivity, thermal properties and dynamic modulus

3.3. Physical Properties

The mass and dimensions of the samples were measured daily after casting. The decrease in the mass due to drying averaged 21% for raw earth samples and 22% for fibres samples (table 3). The coefficients of variation for the mass loss are very low (2.2% and 2% respectively), which leads to the conclusion that the initial water contents were similar for all the samples of one formulation.

The value of the measured shrinkage was rather different (table 3 and figure 5b). For the raw earth samples, the average value of the linear shrinkage was 7.4%, while the average value of the volumetric shrinkage was 20.7%. For earth and fibres mix, the values were 3.6% and 10.5% respectively. For the linear shrinkage, a higher value was observed over the height than in-plane, which can be explained by a partially restrained shrinkage at the base of the specimen as well as a deformation under self-weight. The differences between linear and volumetric shrinkage were previously discussed by Gomes et al. [54], who mentioned that, while normative documents (e.g. NZS 4298: 1998 [49]) refer only to linear shrinkage, these might not always be representative, as volumetric values can be much higher. In terms of absolute values, the measurements are similar to those obtained by Kouakou and Morel [51] who used a similar method for constructing the specimens.

Shrinkage is, in average terms, much lower for the fibre formulation, due to enhanced tensile strength added by the reed and hemp shives. Bouhicha et al. [55] also found that an increase in the fibre content leads to a decrease in both linear and volume shrinkage.

In terms of variability of the results, a much higher CV was computed for the shrinkage of the fibred samples. This reflects the heterogeneity of the earth fibre blocks that do not have a perfectly regular geometry due to the presence of long and short fibres.

Earth mixture type	Characteristic					
	Mass loss		Shrinkage			
			Linear		Volumetric	
	Mean value (%)	CV (%)	Mean value (%)	CV (%)	Mean value (%)	CV (%)
Soil without fibres, S	20.7	2.20	7.43	11.23	20.68	10.49
Soil with Fibres, SF	22.2	2.00	3.62	30.73	10.53	29.85

Table 3 – Differences in mass and dimensions of the samples between casting and day 27

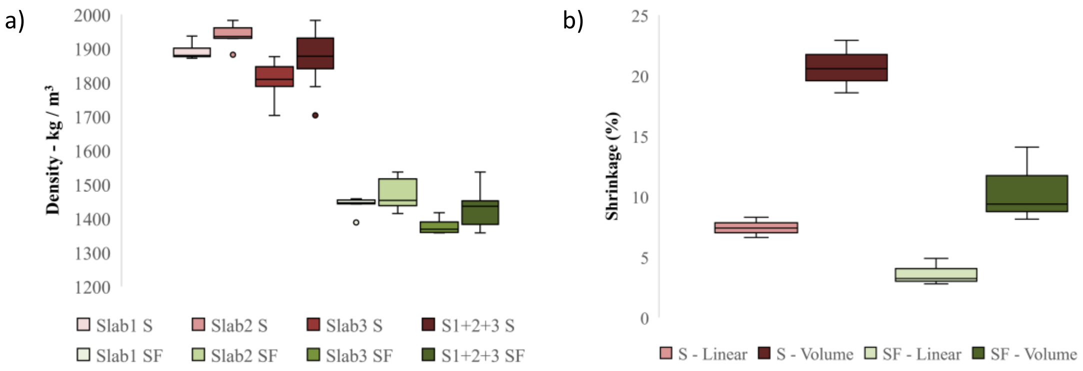

Figure 5. Final values of the density and shrinkage of specimens between casting and the 27th day of curing

The mean value of the density is 1878 kg/m^3 for the non-fibre formulation and 1429 kg/m^3 for the fibre formulation. The difference is related to the incorporation of light natural fibres. In terms of variability of the measurements, the computed CVs are low both for the raw earth and fibre mix. The values (figure 5 and table 2) range between 1.4% and 3.7%. The values computed for individual slabs are lower than the values computed for the mix. This can be explained by the inherent difference in composition due to the manual casting of the slabs. Nevertheless, based on the low values of CVs, we can state that the specimens from each mix are very similar in terms of density.

Due to the combined effects of mass loss and shrinkage, there was practically no change observed in the apparent density for the raw earth samples (initial average value 1890 kg/m^3 and final average value 1878 kg/m^3). A 13.03% decrease of the apparent density was recorded for the fibred mix (from 1673 kg/m^3 to 1429 kg/m^3).

3.4. Thermal conductivity and volumetric heat capacity

The values of the thermal conductivity and volumetric heat capacity are measured by means of the HotDisk apparatus for the different specimens with and without fibres. They are shown in table 2 and figure 6.

The mean value of the thermal conductivity is 0.99 W/(m×K) for the formulation without fibres and 0.55 W/(m×K) for the formulation with fibres. For the volumetric heat capacity, the mean values are 1.67 and 0.79 MJ/(m^3.K) respectively. The incorporation of natural fibres into the formulation decreases the thermal conductivity and thus improves the insulation properties of the material. It is due to the high porosity of hemp shives hence incorporating air with insulation properties. Similar values are mentioned in [14], [56]. Moreover, the presence of fibres, the conductivity of which is lower than the thermal conductivity of the binder (crude earth), creates longer and more complex heat transfer paths (mainly through the binder) and lowers the thermal conductivity of the composite. Indeed, the thermal conductivity not only depends on the thermal conductivity of the different constituents, but also on the internal structure of the material. Thus, the variability observed on the materials depends not only on the natural variabilities of the thermal conductivity of the constituents, but also on the specimen production process that can yield different paths for the heat flux. In particular, the operator’s handling can result in fibres being oriented in a given direction or not, creating either an anisotropic material or an isotropic one. In the case of an anisotropic material, the thermal conductivity can be different if measured in the direction parallel to the fibres or perpendicular to the fibres.

The values of the thermal capacity are lower for the fibre formulation, due to the lightness of hemp shives and reed. The thermal capacity depends on the relative proportion of the different constituents and, even if the mass of fibres is low compared to the mass of raw earth, their volume is high and leads to a lower density as well as a lower thermal capacity. The anisotropy or isotropy of the material should not influence the value of this property. Thus, the variability observed on the thermal capacity should depend mainly on the natural variabilities of the heat capacity of the constituents and less on the operator’s handling, the influence of which should only be explained by the incorporation of air inside the material.

The variability of the measured values of the thermal conductivity is low, as the values spread in a narrow range around the mean value, both for the formulation without fibres and for the one with fibres. The values of the CV’s range from 6.7% up to 11.2% for raw earth samples and from 8.0% up to 14.0% for the fibre mix. Despite the inherent higher material heterogeneity of the fibred specimens, it seems that the thermal conductivity is rather constant across the tested samples.

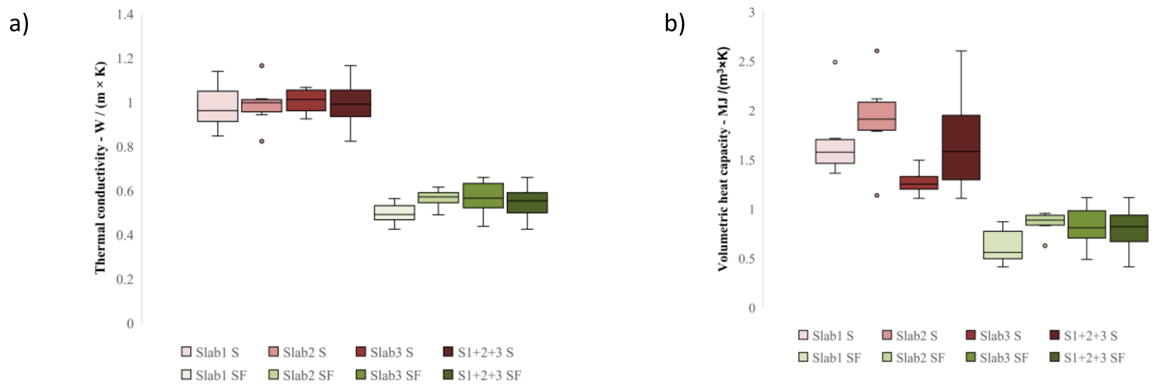

Figure 6. Thermal conductivity and volumetric heat capacity

Much higher CV values are computed for the volumetric heat capacity, ranging from 12.6% up to 31.1%. When considering results for samples cut from the same slab, we observe that CV values are often more than two times larger in the case of volumetric heat capacity than in the case of thermal conductivity.

As explained above, the value of the thermal capacity depends mainly on the amount and heat capacity of each constituent, and should depend less on the operator. Thus, we could expect a lower dispersion of the values of the heat capacity compared to the dispersion of the thermal conductivity. Nevertheless, we observe the inverse tendency. This can be explained by the Gustavson’s method used in the HotDisk treatment software, that is more sensitive to the thermal conductivity than to the heat capacity [52]. The HotDisk method thus yields a better estimate of the thermal conductivity than of the thermal capacity. We consider that the high CV values for the thermal capacity are mainly due to the measurement method used.

In order to better know the repartition of the values inside their range of variation, we determined the Density Probability Functions (DPF) for the thermal conductivity and for the volumetric heat capacity for the formulations with and without fibres. This is an interesting information in the context of numerical simulation and sensitivity analysis carried out on heat and mass transfer models at the wall, building or district scales. Indeed, as shown in [57], [58], [59], it is important to identify the most influent input parameters on the outputs of a model. In that kind of study, the knowledge of the density probability functions for the different input parameters is a key information because a first step consists in creating a set of values for these parameters randomly chosen according to the DPF.

To calculate the density probability functions, we first determined the range into which the experimental data were laying and divided it into 6 intervals of equal width between the lower and greater values. The number of intervals was determined in an arbitrary manner but depends on the total number of experimental values. As we measured 18 experimental values for each parameter, it seemed to us that a number of 6 intervals was reasonable. Then, we calculated the number of experimental values inside each interval. The values of the DPF (ordinate) have then been normalized so that the greater value is 1 in order to be able to adapt normal and log normal laws by means of minimization based on the least square method. The normal and log-normal distributions are described by the mathematical laws hereafter:

$$f(x;\mu,\sigma) = \frac{1}{\sigma\sqrt{2\pi}} exp\left(-\frac{[x-\mu]^2}{2\sigma^2}\right) \tag{3}$$

$$f(x;\mu,\sigma) = \frac{1}{x\sigma\sqrt{2\pi}} exp\left(\frac{-[ln(x)-\mu]^2}{2\sigma^2}\right) \tag{4}$$

For the sake of clarity:

- in the normal law: the mean $m = \mu$ and the variance $s^2 = \sigma^2$
- in the log-normal law: the mean is defined as $m = e^{\mu+\sigma^2/2}$ and the variance is $s^2 = \left(e^{\sigma^2} - 1\right)e^{2\mu+\sigma^2}$

Hence, for the log-normal law we indicate the values of the calculated parameters as well as the derived values of m and s, that can be compared with the parameters of the normal law. The values of the normal and log normal laws parameters are given in table 4 and can be compared to those calculated from the raw experimental data presented above (table 2).

The DPF for both parameters are presented on figure 7. We can see that the shape of the DPFs is close to that of a normal law. The DPF for each parameter has a peak around the average value and the curves decrease from this value for lower or greater values. The adaption of normal or log-normal laws on the DPFs deduced from the experimental values, shows that both laws can be used to model the data with quite a good accuracy, especially for the thermal conductivity. No evidence on the curves can incentive us to prefer log-normal law in front of the normal law, and we consider that the normal law should be preferred as it is a simpler law, the parameters of which are physically easier to interpret (mean value and standard deviation). Besides, we can directly compare the values of the mean and standard deviation obtained from the raw data and from the adaption of the normal law.

For the thermal conductivity, the mean values determined from the raw experimental data are 0.99W/m×K (CV=10%) and 0.55W/m×K (CV=12%) for the formulations without fibres and with fibres, respectively. These values are 0.93W/m×K (CV=9%) and 0.53W/m×K (CV=13%) if determined by adaption of a normal law on the DPFs. The data are thus comparable, and the difference is 5.6% for the formulation without fibres and 3.7% for the formulation with fibres.

For the volumetric heat capacity, the mean values determined from the raw experimental data are 1.67x10^{6}J/m^3×K (CV=27%) and 0.79x10^{6}J/m^3×K (CV=24%) for the formulations without fibres and with fibres respectively. These values are 1.55x10^{6}J/m^3×K (CV=13%) and 0.73x10^{6}J/m^3×K (CV=27%) if determined by adaption of a normal law on the FDPs. The data are thus comparable and the difference for the mean value are 6.9% for the formulation without fibres and 8.5% for the formulation with fibres. Thus, it seems that using the mean value determined from the raw experimental data is enough to obtain a good estimate of this parameter for the thermal conductivity as well as for the volumetric heat capacity.

Moreover, the adaption of the normal and log-normal laws on the DPFs determined from the experimental values is better for the thermal conductivity than for the volumetric heat capacity. The determination of the DPFs was based on 18 measurements of the same parameters, a higher number of measurements than in most studies regarding earth materials we refer to. Nevertheless, we consider that this number is quite low for determining the expected normal function [60]. The number of measurements should be increased in order to obtain a reliable curve and, as a consequence, a better estimate of the mean and standard deviation.

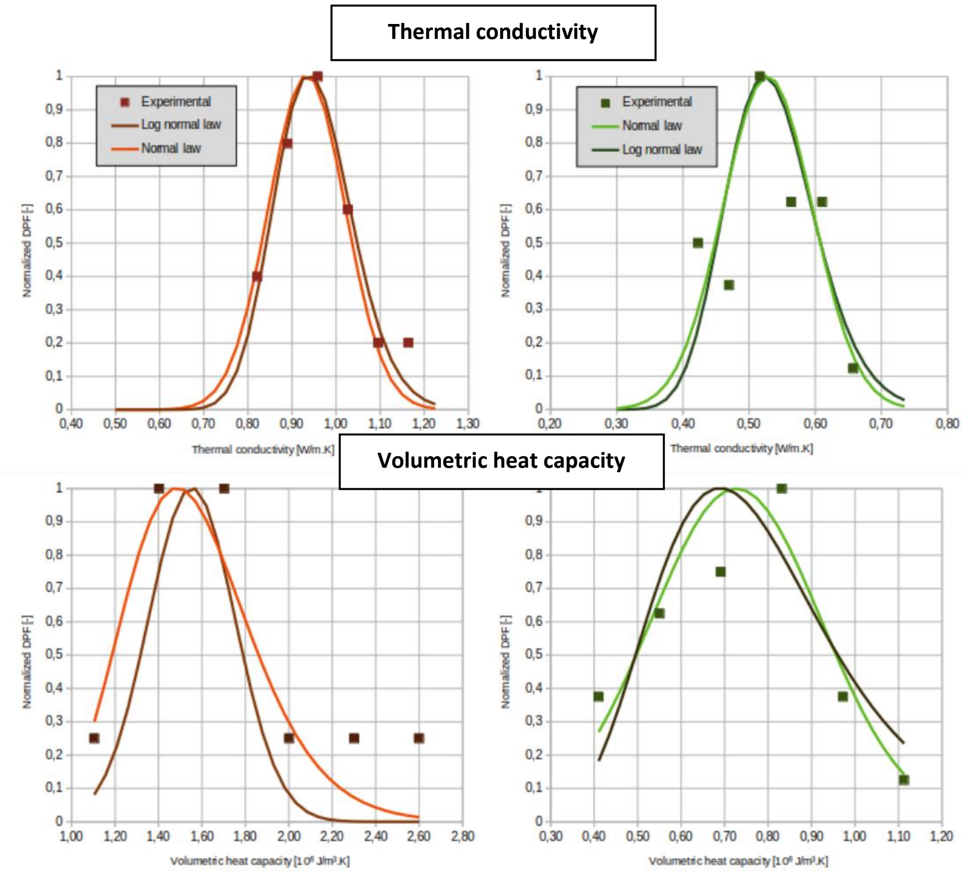

Figure 7. Normalized (ordinate) density probability functions for the thermal conductivity (top) and the volumetric heat capacity (bottom) determined from the 18 measurements of these parameters – DPFs are presented for the formulations without fibres (brown) and with fibres (green)

	Without fibres						With fibres					
	Log normal law				Normal law		Log normal law				Normal law	
	μ	*σ*	*m*	*s*	*μ=m*	*σ=s*	*μ*	*σ*	*m*	*s*	*μ=m*	*σ=s*
Thermal conductivity	-0,05	0,09	0,96	0,09	0,93	0,09	-0,63	0,13	0,54	0,07	0,53	0,07
Volumetric heat capacity	0,43	0,19	1,57	0,30	1,55	0,20	-0,29	0,28	0,78	0,22	0,73	0,20

Table 4 – Values of the normal and log normal laws parameters (μ and σ) and calculated mean (m) and standard deviation (s).

3.5. Electrical resistivity

The values of the measured resistivity values are shown in figure 8 and table 2. The mean value of the resistivity is ρ_S = 1365 Ω×m for the soil formulation and ρ_{SF} = 2924 Ω×m for the soil with fibres formulation, with a ratio of about 2.1 between these values ($\rho_{SF} = 2.1 \times \rho_S$). The comparison is relevant as both formulations have similar water content (3.1% for soil samples and 3.3% for soil-fibres samples).

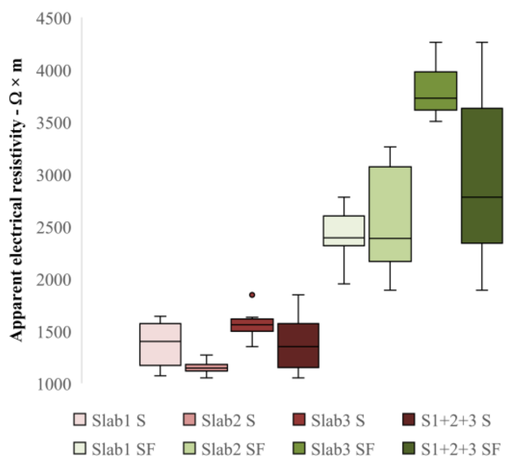

Figure 8. Apparent electrical resistivity for soil (S) and soil-fibres (SF) samples at 3.1% and respectively 3.3% mass water content

As the samples have almost identical geometry and as the measures were done similarly on all the specimens, the analysis of the results in terms of variability is relevant when apparent values are considered. The values of the CV's for the formulation without fibres range from 6.5% to 18.2%. Bonnet and Balayssac [18] measured the electrical resistivity on concrete specimens and found CV values lower than 10% for low saturation level and approximately 18% on saturated specimens when comparing different batching. This comparison with cementitious material proves that the hand-made earth specimens are as homogeneous as concrete specimen casted on site.

Higher values are obtained for the fibre formulation, ranging from 7.6% up to 25.8%. As the microstructure of the formulation with fibres is less homogeneous than the formulation without fibres, the measured values are more dispersed around the mean. The relatively low CV values (similar to those obtained on concrete specimens) indicate a good reliability of this type of measurements and suggest that for earth specimens, even those including natural fibres, the electrical resistivity can be determined using the Wenner resistivimeter. This Wenner Resistivimeter is a promising tool to detect the water content gradient on earth walls in houses.

The values of the apparent resistivity depend not only on the individual properties of the constituents and on the volumetric amount of each of them, but also on the microstructure of the material and mainly on the density, the porosity, the pore tortuosity and connectivity, as for the thermal conductivity [61]. The figure 9 represents the 3 properties: density, electrical resistivity and thermal conductivity. This comparison is possible since the water content is about the same for all specimens, as properties are dependent on that. A linear relationship between thermal conductivity and density is found with a good determination coefficient: the law is non-dependent on the mixture; it is the same with or without fibres. A similar law was shown by Laborel-Preneron et al. [41].

Concerning the electrical resistivity, negative (as expected) linear correlations are observed between the resistivity and density but with two different slopes: one very low for the non-fibre mixture and one rather high for the fibred specimens. The determination coefficient calculated by integrating differences between experimental data and the two relationships is 0.84, which is a good value.

By regarding results obtained on thermal properties, the S mean thermal conductivity is higher than the SF mean thermal conductivities, with a ratio $\lambda_S = 1{,}8 \times \lambda_{SF}$. The ratio is similar to that obtained for the electrical conductivity, which is the reverse of the electrical resistivity. By considering figure 9, as expected, the specimens with the highest resistivities present the lowest thermal conductivities, but no correlation are established between these properties, even if they are dependent on about the same material characteristics.

Some authors established strong correlation between these two properties in studies where these properties were determined on different soil specimens [61], [62]. But the mentioned studies were not performed on soils used for construction and that included natural fibres. In this study, the electrical resistivity measurement is more sensitive to the specimen heterogeneity than the thermal conductivity, mainly for fibred specimens, possible due to the high (8%) percentage of fibres used. The electrical flux may be driven only by soil and residual water content inside the specimen and the fibres. Even the smallest difference in the quantity and orientation of fibres in the material seems to strongly influence the path of the electrical flow, much more than the heat flow. This is perhaps due to the discontinuous pattern of water inside the material which is strongly dependant on fibres repartition.

Unfortunately, no data was found about the electrical resistivity and the effect of low relative humidity of the bio-fibres or bio-fibred materials. But by regarding results obtained on others fibred materials [63], when the conductivity of the fibres differs from that of the matrix, the larger presence of fibres influences greatly the electrical conductivity values, which is explained by a percolation threshold.

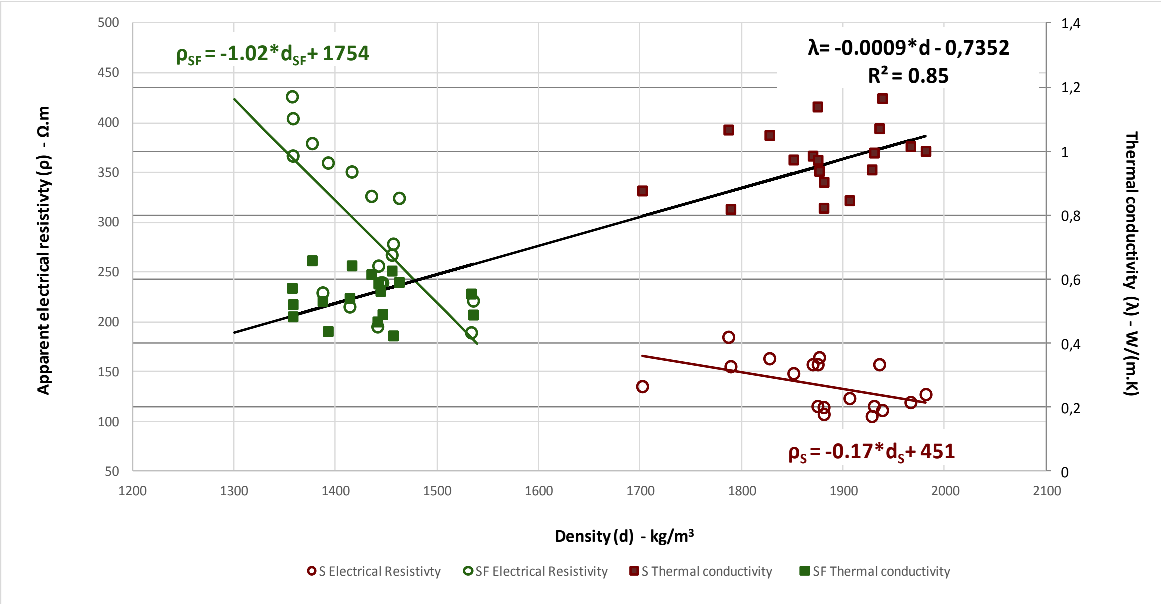

Figure 9. Apparent electrical resistivity and thermal conductivity versus density for soil (S) and soil-fibres (SF) samples at 3.1% and 3.3% mass water content respectively

3.6. Dynamic modulus

The values of the dynamic modulus determined by using the Impulse Excitation Technique are shown in table 2 and figure 10. The mean value of the dynamic modulus is E_{ds} = 6917 MPa for the formulation without fibres, and E_{dSF} = 2087 MPa for the formulation with fibres, with a ratio E_{ds}=3.3xE_{dSF}. Similar values were observed by [54], [64].

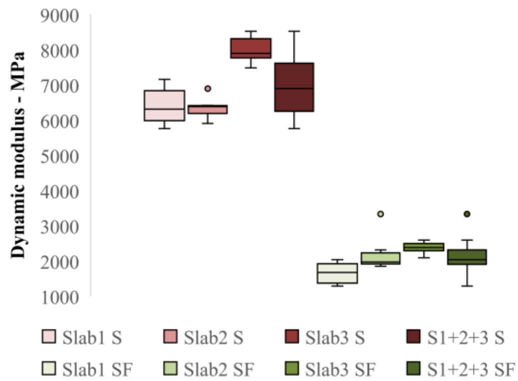

Figure 10. Dynamic Young modulus for soil (S) and soil-fibres (SF) samples at 3.1% and respectively 3.3% mass water content

Young modulus determined from stress-strain curves (destructive tests) for soil with and without fibres in different studies [47], [64], [65] generally have lower values, even if the ratios of the respective modules are similar to the ones obtained here. When large Young modulus values are mentioned [66], these high values are mainly due to the way the modulus is computed based on the stress-strain curves. The dynamic modulus corresponds to the behaviour at very small strain levels, while the Young modulus corresponds to large strain levels. For earthen materials, significant differences in behaviour can generally be observed for different strain levels.

Correlations between the dynamic modulus obtained through NDT and modulus obtained through destructive tests, if applicable, could be very useful, as NDT are very fast and easy to perform. Such linear correlations exist for cementitious materials [22], but only few studies analysed such possibility for earthen materials used in buildings. An example is Gomes et al. [54], where a linear correlation between the dynamic modulus and the compression strength is proposed.

In terms of variability of the results, rather low values were obtained for the CV's in the case of raw earth specimens, ranging from 5.07% up to 12.83%. The values for the fibre mix are higher, of up to 25.46%. This difference could be explained by a non-homogenous arrangement of the fibres between different specimens, which could influence stronger the dynamic vibrational properties.

In the case of raw earth samples, it can be noted that CV's determined for each slab are lower than the CV determined by considering all the specimens. This is due to a rather significant (25%) difference of the mean value between slabs 1 and 2 and, respectively, slab 3. This difference could be related to the non-uniformity of the manual construction of specimens. The CV values are lower than those obtained by Miccoli et al. [5] and Giroudon et al. [47] which are 25% and 34% respectively. It is important notice that those values are not as reliable, as they are calculated on few specimens (5 for Miccoli et al. [5] and 3 for Giroudon et al. [47]).

A linear relationship was found between dynamic modulus and thermal conductivity and this relationship is non dependant on the fibres' presence. This law is in accordance with the fact that both properties are density dependant. By focusing on the soil without fibres, two low thermal conductivity values were observed that correspond to high values of dynamic modulus, which is not in accordance with the linear law. The same inconsistency is found for the highest values of thermal conductivity, which correspond to low dynamic modulus values. The law obtained is much more suitable for samples with fibres. It would seem that the two properties measured are sensitive in the same way to the distribution of fibres in the samples.

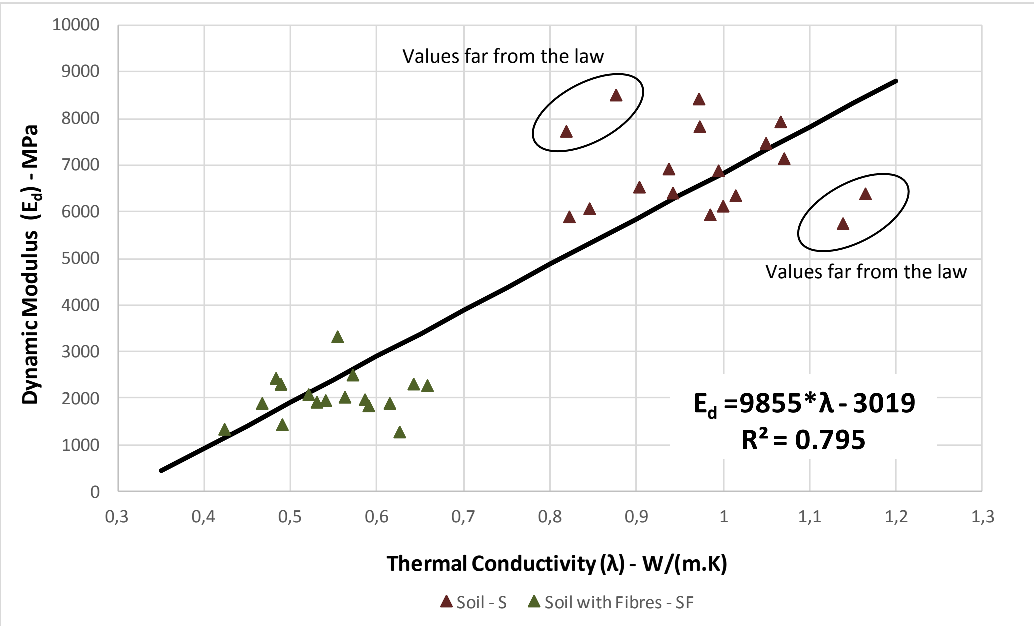

Figure 11. Dynamic Modulus versus thermal conductivity for soil (S) and soil-fibres (SF) samples at 3.1% and 3.3% mass water content respectively

4. Conclusions

In this paper, we presented the experimental results obtained on earthen materials manually manufactured using raw earth from the region of Guérande. Two formulations were tested: one including natural fibres (hemp shives and reed) and one without fibres. The investigated parameters (electrical resistivity, thermal conductivity and dynamic modulus) were non-destructively evaluated using easy to use measurement instruments that provide fast results. The values of these different parameters were obtained from 18 different specimens for each formulation. The uncertainty of the measurement methods was analysed by performing repeatability tests consisting in measuring 20 times the properties on the same specimen. The goal of the study was to determine the variability due to the intrinsic heterogeneity of the material for each of the parameters and also to check if correlations between some of the analysed properties can be established.

Coefficient of variation (CV) are required in order to compare results obtained for different formulations of earth or for different tests. CV values obtained on repeatability tests are lower than those obtained on variability tests for all the investigated parameters. But the material heterogeneity induces a significant source of variability. For earth without fibres the CV values are 2.01%, 8.59%, 9.49% and 10.66%, while for the earth with fibres, CV values are 2.93%, 25.41%, 16.23% and 11.52% for the density, the dynamic modulus, the resistivity and the thermal conductivity respectively. The CV values for earth with fibres are generally higher than the values obtained for earth without fibres, which can be explained by a non-homogenous spreading and orientation of fibres in the moulds. Yet, the values are rather low, even for fibred samples, and close to values mentioned in studies conducted on concrete specimens, which indicates that this handmade material is almost as homogenous as standardised materials.

Some relations between the different measured properties are determined, which are consistent with the physical phenomena. But the sensitivity of the investigated properties to heterogeneity induced by fibres is not the same. Electrical resistivity seems much more sensitive than the others, probably because the non-homogenous spreading and orientation of fibres influences the electrical flow, by closing the paths or by absorbing water.

As locally available earthen-based materials might prove a viable solution for reducing the environmental impact of the building sector, there are numerous recent studies that analyse these materials. Yet, many of these studies focus on average values obtained from a low number of tested specimens, while CV values are often not even mentioned. This is partly due to the fact that at the present time there is a lack of clear testing procedures for assessing the properties of earthen composites, as would be the case for concrete or cement-based materials. As the goal of research should ultimately be the development of materials to be used in actual buildings, the focus should be not only on the average values, but also on quantifying the variabilities related to the material, the mixing and fabrication procedure. Properties of earthen materials should be established by analysing data obtained from a large enough number of specimens, in order to obtain the average, the standard deviation and also the percentile of the distribution functions. This could allow to determine characteristic values for the measured properties, that might be more useful than average values for the design of actual building elements.

We intend to expand our results database through testing more specimens with different water content, as the humidity must be representative of the real cases of study. Other hygrothermal properties will also be measured, and their density probability functions will be determined, in order to be used in hygrothermal modelling.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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