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EFFECT OF TEMPERATURE ON THERMAL AND HYGRIC PROPERTIES OF HEMP-LIME PLASTERS

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Abstract

This study investigates the effect of temperature on thermal properties (conductivity and thermal diffusivity) and on Moisture Buffer Value (MBV) of two types of hemp-lime plasters. These plasters differ from their kind of hemp shiv: one is made of Chanvribat defibered hemp shiv (CHLP) and the other one is made of Terrachanvre defibered hemp shiv (THLP). The investigations are based on experimental measurements and are performed at 14°C, 17°C, 20°C and 23°C for thermal properties and at 11°C, 14°C, 17°C, 20°C and 23°C for MBV. The measurements of thermal properties are made at 50% Relative Humidity (RH). To limit the problems of water migration, the measurements are performed with transient state methods. Hot disk is used at all temperatures; it provides both thermal conductivity and diffusivity. Hot wire is used at 23°C, it provides thermal conductivity only. Over the considered temperature range (14-23°C), the impact of temperature on thermal properties is very low while it is more sensitive on moisture buffer value. It is shown that the moisture buffer value decreases by about 54 % for Terrachanvre Hemp Lime Plaster (THLP) and by about 59 % for Chanvribat Hemp Lime Plaster (CHLP) when the temperature decreases from 23°C to 11°C.

Keywords

Hemp-lime plasters; thermal conductivity; thermal diffusivity; moisture buffer value; temperature.

1 INTRODUCTION

The plasters used for building envelope must meet requirement concerning their physico-chemical, mechanical, hygro-thermal and aesthetical quality. It was shown that inadequate plaster, on physico-chemical and on mechanical point of view, can induce damage to the wall [Maravelaki-Kalaitzaki 2003]. Their hygro-thermal characteristics should keep the wall breathable while allowing a thermal correction. They may also be used as hygric regulator.

On the other hand, in a context of sustainable development, bio-based building materials are developed to replace conventional products in order to reduce the impact on the environment. Among them, hemp based materials have been studied a lot these last years because hemp shiv have many advantages (renewal, recycling, carbon sequestration…) [Amziane 2013] [Boutin 2005] [Cerezo 2004] [Collet 2012] [Collet 2014] [Evrard 2006] [Pretot 2014] [Tran Le 2010].

This study investigates hemp lime plasters. Such materials can show a high hygroscopic behavior due to the coupling of hemp shiv and binder. They keep the wall breathable as their water vapor permeability is about 3E-11 kg/(m.s.Pa) [Chamoin 2013]. More, the use of hemp shiv allows reducing density and thus thermal conductivity.

Building envelope are exposed to variation of indoor and outdoor temperature (climate, vacancy period…). This may impact the thermal properties and the moisture buffer value of materials. It is thus crucial to quantify the variation of these properties with temperature.

This study deals with two hemp-lime plasters used for building. These materials differ in their type of hemp shiv: one of them is made of Chanvribat defibered hemp shiv (CHLP) and the other one is made of Terrachanvre F defibered hemp shiv (THLP). The characterization is based on the measurement of thermal conductivity, thermal diffusivity and moisture buffer value. The effect of temperature on these properties is also investigated.

2 EXPERIMENTAL METHODS AND MATERIALS

2.1 Generality

This study investigates the effect of temperature on thermal and hygric properties of hemp lime plasters.

The investigated temperatures are 23°C, 20°C, 17°C and 14°C. A supplementary temperature (11°C) is considered for hygric characterization. Previously to the tests, specimens are stabilized to the considered temperature at 50% RH, in a climatic chamber. The tests are also performed in climatic chambers to control ambient conditions. The tests are performed from highest to lowest temperature.

2.2 Thermal properties

The measurements of thermal properties are made at 50%RH. To limit the problems of water migration, the measurements are performed with transient state methods. Hot disk provides both thermal conductivity and diffusivity; it is used at all temperatures (23, 20, 17, 14°C). Hot wire provides thermal conductivity only, it is used at 23°C.

For both methods, the sensor is sandwiched between two specimens. The contact surface of specimens is as flat as possible in order to ensure the thinner air layer between specimens. For the two materials, two pairs are realized from the three specimens. The thermal properties of the material are thus the average values of the two pairs.

Fig. 1 : Measurement of thermal characteristics in climatic chamber

The Hot Disk is based on transient plane source (TPS) theory to measure thermal conductivity and thermal diffusivity. The commercial TPS 1500 device allows measuring thermal conductivity in the range from 0.01 to 400 W/(m.K) and thermal diffusivity in the range from 0.1 to 100 mm^2/s. The Hot disk manufacturer quotes accuracies better than 5% for the instrument. The TPS sensor used in the present study is Ref.4922. The outer radius of the double-spiral heater is 14.61 mm. The heat flow and heating time are chosen to reach high enough temperature rise (0.4 to 2.6°C), probing depth lower than the available probing depth (2.5 cm) and total characteristic time between 0.33 and 1. The Mean deviation around the fitted line must be inferior to 1 e-3 K. The heating power is 50 mW for CHLP and 55 mW for THLP. The heating time is 640 s for both plasters. The thermal properties of a pair of specimens are the average of three values with a variation coefficient lower than 5%.

The measurement of thermal conductivity with hot wire is based on the analysis of the temperature rise versus heating time. The heat flow and heating time are chosen to reach high enough temperature rise (>10°C) and high correlation coefficient (R^2) between experimental data and fitting curve. In this study, the power used is 0.23 W for the two plasters and the heating time is 130 s for the CHLP and 120 s for THLP. The thermal conductivity of a pair of specimens is the average of five values with a variation coefficient lower than 5%.

2.3 Moisture buffer value

The moisture buffer value MBV quantifies the moisture buffering ability of a material. It is measured according to the method given in the NORDTEST project [Rode 2005]. This project defines the practical moisture buffer value of materials. This value relates the amount of moisture uptake (and release), per open surface area, under daily cyclic variation of relative humidity Equation 1:

$$MBV = \frac{\Delta m}{A\left(RH_{high} - RH_{low}\right)} \qquad (1)$$

With MBV: moisture buffer value [kg/(m². %RH)], Δm: moisture uptake/release during the period [kg], A: open surface area [m^2], $RH_{high/low}$: high/low relative humidity level [%].

The test method requires 3 prismatic specimens which are sealed on five out of six sides.

After stabilization at (23°C, 50%RH), specimens are exposed to daily cyclic variation: 8 h at high relative humidity (75%) followed by 16 h at low relative humidity (33%). The test goes on until the change in mass Δm is the same between the last three cycles with less than 5% of discrepancies. For each specimen, the MBV is thus the average value calculated from the last 3 cycles. The MBV of the materials is thus the average value of the three specimens.

The device used consists in a climatic chamber (VÖtsch VC4060) that can be controlled in the range +10 to +95 °C and 10% to 98% RH (Figure 2). The switch in the chamber relative humidity (75% RH; 33%RH) is done manually according to the 8/16 h scheme. Temperature and relative humidity are measured continuously with sensor SHT75 and with sensor of the climatic chamber; the air velocity is measured in the surroundings of the specimens: the vertical velocity is in the range 0.07 to 0.14 m/s and the horizontal one is 0.1 to 0.4 m/s.

The specimens are weighed out of the climatic chamber five times during absorption period and two times during desorption one. The readability of the balance is 0.01 g, and its linearity is 0.01 g. The accuracy of the moisture buffer value is thus about

5%. The same protocol was also performed at 20, 17, 14 and 11 °C, from highest to lowest temperature.

Fig. 2: Measurement of Moisture Buffer Value: experimental device and specimens

2.4 Materials and specimens

This study investigates two kinds of hemp-lime plasters, which differ from their type of hemp shiv.

The lime-based binder used is a commercial product (Tradichanvre BCB – BCB France) commonly used to produce hemp lime plasters. This binder is made of 35% of mineral additions and 65% of lime based binder composed of air-slake lime (85%) and hydraulic lime (15%).

The shiv used are commercial products Chanvribat (from LCDA France) and Terrachanvre F (from Terrachanvre France). Their bulk density is about 100 to 110 kg/m^3. Their particle size distribution, measured by sieving, are given Figure 3. The mean width of shiv (D50) is 4 mm for Chanvribat and 2 mm for Terrachanvre F. The width/length ratio is about 4 for the two kinds of shiv. The terrachanvre shiv is thus smaller than the chanvribat shiv.

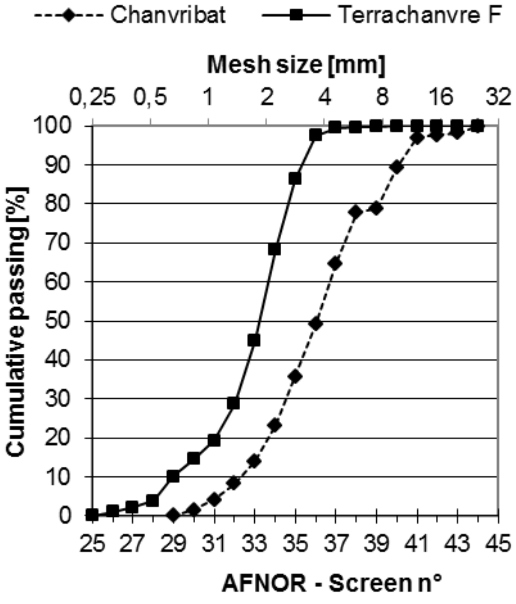


Fig. 3: Particle Size Distribution of Chanvribat and Terrachanvre F shiv

Tab.1 : composition of the hemp-lime plasters

Material	Notation	Binder	Hemp shiv	Hemp/binder mass ratio
Chanvribat Hemp-lime plaster	CHLP	Lime based binder (Tradichanvre)	Defibered Hemp shiv (Chanvribat)	0.15
Terrachanvre Hemp-lime plaster	THLP	Lime based binder (Tradichanvre)	Hemp shiv with fibers (Terrachanvre F)	0.15

Hemp-lime plaster blocks are produced by moulding. First, hemp shiv and lime-based binder Tradichanvre are mixed with a hemp to binder mass ratio of 0.15. Water content is adjusted to obtain a consistent workability of fresh hemp-lime plaster with a satisfactory rheology. Moulds are filled with the mixture and the hemp-lime plaster is slightly compacted.

Tab. 2 : Physical properties of Hemp Lime Plasters

	Density [kg.m^{-3}]	Total porosity [%]	Open porosity [%]
CHLP	723 ± 8.8	72	65.5
THLP	881 ± 16.5	65.9	64.2

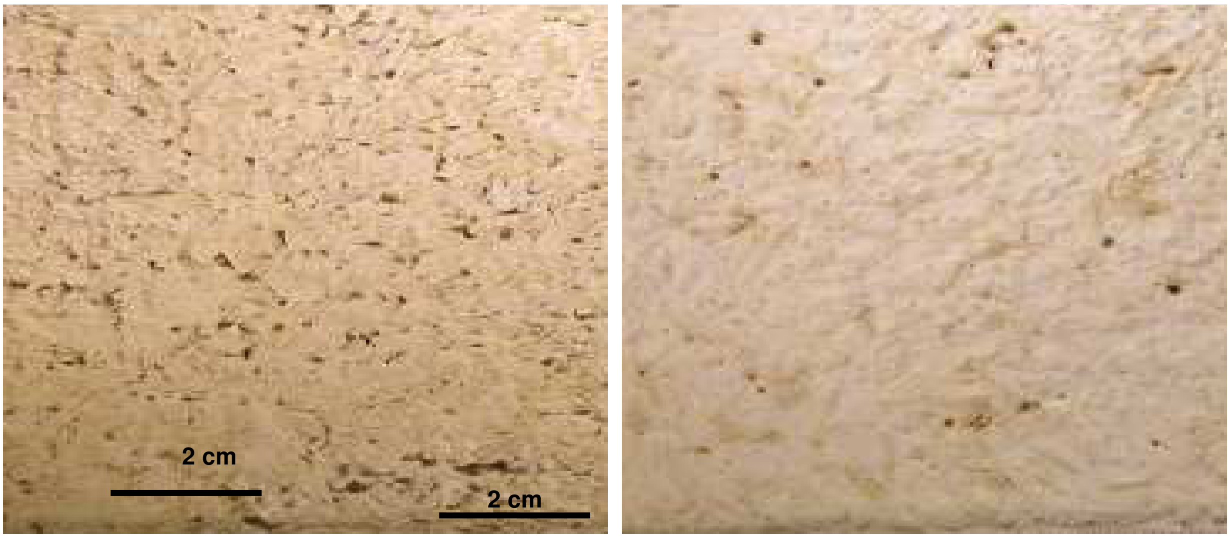
The density of hemp lime plasters is about 715-730 kg/m^3 for CHLP and 865-895 kg/m^3 for THLP. Their porosity is high (72 and 66 % respectively) and mainly open, nearly exclusively for THLP (Figure 4). More the CHLP show larger macropores than THLP, visible to the naked eye).

For thermal and hygric studies, specimens are cut from blocks with a band saw and are selected to be representative of the material (density and homogeneity). The sizes are chosen to meet the requirement of the NORDTEST project. The thicknesses must be higher than the penetration depth during the test and the total exposed surface area must be higher than 300 cm^2 for each material (adding all specimens). For sprayed hemp concrete with density about 400 to 450 kg/m^3, the penetration depth is lower than 6 cm [Collet 2012]. Hemp concrete is more porous than the hemp lime plaster so a thickness of 8 cm for hemp lime plaster is assumed to be sufficient. The chosen sizes are thus 15×15×8 cm^3 .The densities of the specimens are given in Table 3.

For each material, the numbers of specimens used are: (i) three for the moisture buffer value, (ii) three for the thermal properties.

Tab. 3: Density at (23°C, 50%RH) of specimens

Specimen	Study	Density ($kg.m^{-3}$)
CHLP	MBV	734±12
CHLP	Thermal properties	732±8
THLP	MBV	882±20
THLP	Thermal properties	886±15



(a) **(b)**

Fig. 4: Picture of specimens: (a) CHLP (b) THLP

3 RESULTS

3.1 Thermal properties

Thermal properties at 23°C

For all the measurements performed with the hot wire, the correlation coefficient between experimental data and fitting curve is very close to 1 (higher than 0.996).

Table 4 shows the mean values, standard deviations and coefficients of variation of thermal conductivity and thermal diffusivity measured with Hot Disk and hot wire. Each value is the average of 6 measures with Hot Disk (3 per pair) and 10 measures with Hot Wire (5 per pair).

For the two hemp lime plasters, the coefficient of variation between experimental data is lower than 4% as well for thermal conductivity as for thermal diffusivity. The results obtained with Hot Disk are lower than those obtained with Hot Wire (less 10%). This discrepancy is acceptable as the precision of each experimental device is 5 %.

The thermal conductivity of the THLP is higher than that of CHLP (0.214 W/(m.K) and 0.180 W/(m.K) respectively). This was expected as THLP has higher density and lower porosity than CHLP (Table 2). More, the size of porosity induced by hemp shiv may also play a role.

These results are similar to the values given by Pretot [Pretot 2009], where the thermal conductivity of hemp lime plaster is 0.193 W/(m.K) at 692 kg/m^3 and 0.227 W/(m.K) at 808 kg/m^3.

Thanks to hemp shiv, the two hemp-lime plasters have lower thermal conductivity than usual plasters. Actually, at dry state, the thermal conductivity of lime-metakaolin plasters ranges from 0.650 to 0.726 W/(m.K) with density about 1750 kg/m^3 [Vejmelková 2012a]. Hydrophobisation allows increasing porosity, and thus, reducing thermal conductivity of lime-metakaolin plasters to 0.413 to 0.499 W/(m.K) (with density of 1450 and 1580 kg/m^3) [Vejmelková 2012b]. Lastly, the thermal conductivity of commercial renovation plasters studied by Vejmelkova [Vejmelková 2012b] ranges from 0.293 to 0.366 W/(m.K) with respective density of 1296 and 1384 kg/m^3.

Compared with other bio-based building material, studied hemp lime plasters show higher thermal conductivity than the values obtained from the relationship established by Cerezo for hemp concrete [(Cerezo, 2005)]. Actually, equation (2) gives a thermal conductivity of 0.166 W/(m.K) when the density is 733 kg/m3. This is due to lower hemp to binder ratio in the case of hemp lime plaster.

$$\lambda=0.0005\times\rho+0.0194 \qquad (2)$$

Finally, studied hemp lime plasters have lower thermal conductivity than wood-polystyren composite studied by Agoua (λ=0.274 W/(m.K); ρ=664 kg/m^3) [Agoua 2013], than clay cement wood composite studied by AL-Rim (λ=0.22 W/(m.K); ρ=1010 kg/m^3)

[AL-Rim 1999] and than wood concrete in [Taoukil 2013] (λ=0.25 W/(m.K); ρ=1495 kg/m^3).

The thermal diffusivities measured on the two hemp lime plasters are similar: 0.25 mm^2/s for CHLP and 0.23 mm^2/s for THLP. They are in the range of thermal diffusivity given by Taoukil for wood concrete [Taoukil 2013]. The specific heat capacity calculated from thermal conductivity and thermal diffusivity are thus 995 J/(Kg.K) for CHLP and 1009 J/(Kg.K) for THLP. These values are also close to the values found by Vejmelkova on lime-metakaolin plasters (911 to 988 J/(Kg.K) with density about 1750 kg/m^3)[Vejmelkova 2012b]. Actually, the specific heat capacity of building material usually ranges from 800 to 1500 J/(kg.K).

Effect of temperature on thermal properties of hemp lime plasters

In this part, the influence of temperature on thermal conductivity and thermal diffusivity is investigated.

Figure 5 shows the variation of the thermal conductivity of the two studied hemp-lime plasters as a function of temperature. Like previously, the coefficient of variation are very low (lower than 3% for CHLP and than 4% for THLP).)

For the two studied materials, the value of the thermal conductivity decreases linearly with temperature. This is quite surprising as usually the thermal conductivity increases with temperature. For example, Vololonirina [Vololonirina 2014] showed that the thermal conductivity of wood-based products scaled linearly with temperature between 10°C and 40°C.

More, during the experimental study, it was observed that the specimen mass increased when the temperature decreased. So, it seems that their water content increased and thus impacted their thermal conductivity. Actually, whatever the nature of the material, the thermal conductivity increases from dry state to humid state. This was observed in several studies on various materials such as brick, autoclaved aerated concrete, lime plaster, hemp concrete, thermal insulation or even high performance concrete [Collet 2014] [Jerman 2012] [Pavlík 2013] [Taoukil 2013]. Thermal characteristics are thus studied versus water content.

Figure 7 gives the variation of thermal conductivity with water content for the two types of hemp-lime plasters. For the two studied materials, the thermal conductivity increased linearly with water content. For the THLP, the thermal conductivity increases by 8.4% from 0.208 W/(m k) at 1.76 % to 0.227 W/(m k) at 1.8 % in water content. The CHLP shows a similar increase of thermal conductivity with water content. From 1.77% to 1.80% in water content, the thermal conductivity rises by 4.5%.

Figure 8 gives the variation of thermal diffusivity with water content when water content ranges from 1.76 to 1.80%. The results are homogeneous for each point, with coefficient of variation about 5%. THLP shows more scattered results when the water content is 1.80%. For this point the coefficient of variation is 10%. The two hemp lime plasters shows similar value of thermal diffusivity when water is lower than 1.79 %. The CHLP shows an increase of thermal diffusivity with water content. Its diffusivity ranges from 0.25 to 0.30 mm^2/s. The thermal diffusivity of THLP ranges from 0.23 to 0.27 mm^2/s, with a maximal value when the moisture content is 1.78%. This variation is similar to the one given by Taoukil for wood concrete [Taoukil 2013]. For CHLP, the maximal value of diffusivity would probably appear for higher value of water content. As Taoukil state, the variation of thermal diffusivity with water content depends on the relative variations of thermal conductivity and of volumetric heat capacity ρC. When the thermal conductivity increases faster than the volumetric heat capacity, the thermal diffusivity increases. When the thermal conductivity increases slower than the volumetric heat capacity ρC, the thermal diffusivity decreases.

Tab. 4 : Thermal properties of materials at 23 °C, 50% RH

			Hot Disk			**Hot Wire**	
Formule	**Value**	**ρ $[kg.m^{-3}]$**	**a $[mm^2.S^{-1}]$**	**λ $[W.m^{-1}.k^{-1}]$**	**Cp $[J.m^{-1}.K^{-1}]$**	**λ $[W.m^{-1}.k^{-1}]$**	**R^2**
CHLP	Average	733	0.2466	0.1795	996	0.1963	0.9979
	standard deviation	7	0.0099	0.0046	55	0.0044	0.0047
	Var. Coef. [%]	1.0	4	2.6	5.5	2.2	-
THLP	Average	887	0.2277	0.2142	1009	0.2364	0.9966
	standard deviation	14	0.0066	0.0057	63	0.0082	0.0034
	Var. Coef. [%]	1.6	2.9	2.7	6.2	3.5	-

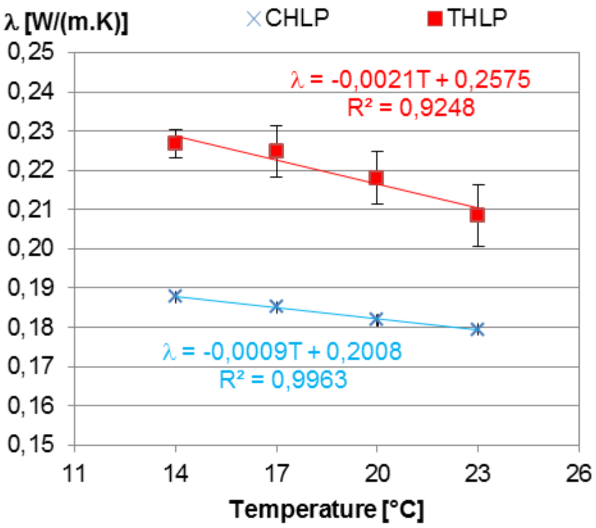


Fig. 5: Variation of the thermal conductivity as a function of temperature at 50% RH

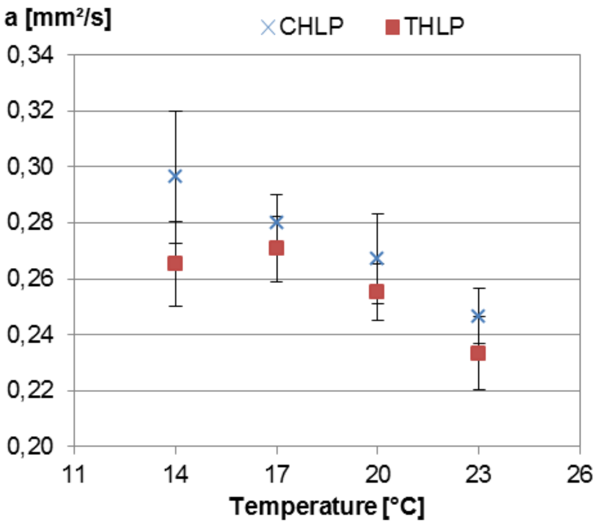


Fig. 6 : Variation of the thermal diffusivity as a function of temperature at 50% RH

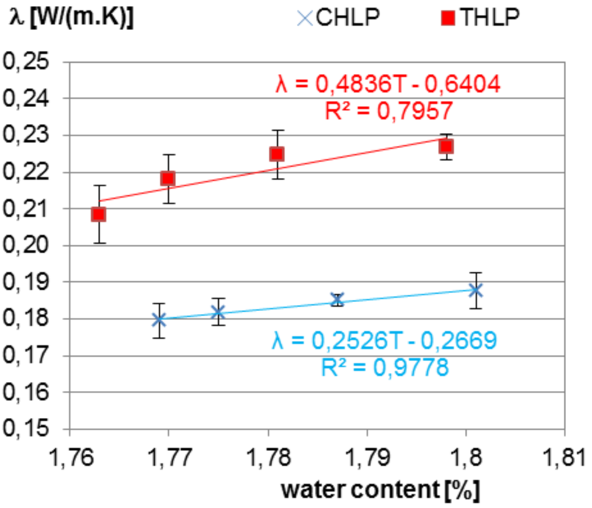


Fig. 7: Variation of the thermal conductivity as a function of water content at 50% RH

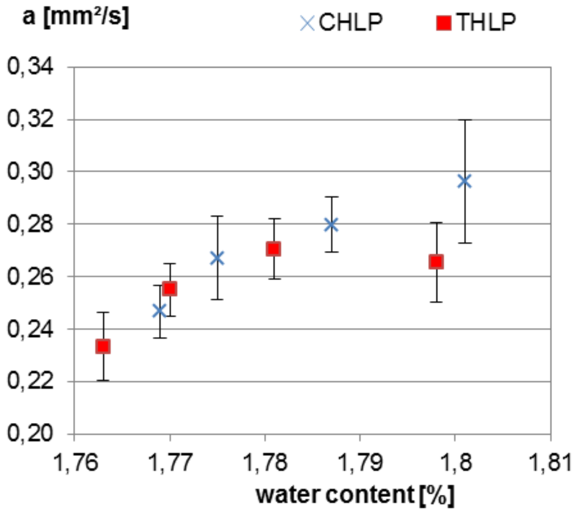


Fig. 8: Variation of the thermal diffusivity as a function of water content at 50% RH

3.2 Moisture buffer value

Moisture buffer value at 23°C

Table 5 gives the average value of the moisture buffer value calculated from cycles 3 to 5 in adsorption, desorption and average for the two materials. The value is very slightly higher in desorption than in adsorption. Actually, after stabilization at 23°C; 50%RH, the test begins under adsorption at 75% RH. These conditions are higher than the average of the quasi steady state conditions that arise after some cycles. There is thus a declining tendency in the variation of mass which induces higher value in desorption than in adsorption. These two values are approaching each other after repeated cycles.

The MBV of the THLP is higher than that of CHLP (respectively: 1.64 and 1.28 g/(m^2.%RH)). The moisture buffering capacity of THLP is thus better for ambient relative humidity regulation. According to the classification of the NORDTEST Project, these materials appear as good hygric regulators (1 < MBV < 2 g/(m^2 %RH)).

The moisture buffer value obtained for the two hemp plasters is lower than value met in literature for hemp concrete : about 1.99 g/(m^2 %RH) [Tran Le 2010] to 2.15 g/(m^2 %RH) [Collet 2012]. This is due to the lower hemp to binder ratio in hemp lime plaster which induces higher density and lower permeability in the material.

The MBV of hemp lime plasters make them better hygric regulators than other materials used for plastering like gypsum (MBV about 0.6 g/(m^2.%RH)) [Rode 2005]. However, to ensure this hygric capacity a high enough thickness must be used, higher than the penetration depth.

Effect of temperature on moisture buffer value of hemp lime plasters

Fig. 9 gives the moisture buffer value of the two studied hemp-lime plasters versus temperature.

For the two studied materials, the value of the moisture buffer value increases linearly with temperature. For the CHLP, the moisture buffer value increases by 59% from 0.67 g/(m^2.%RH) at 11°C to 1.23 g/(m^2.%RH) at 23°. The THLP shows a similar increase of MBV with temperature: the moisture buffer value increases by 54% from 0.94 g/(m^2.%RH) at 11°C to 1.64 g/(m^2.%RH) at 23°C.

The increase of MBV with temperature is partially explained by the increase of the vapor pressure. Actually the MBV is calculated from the relative humidity value which depends on temperature. The moisture buffer value is thus calculated versus vapor pressure MBV' (g/(m^2.Pa)). The variation of MBV' is given figure 10. This corrected moisture buffer value decreases with temperature. This shows that other parameter, depending on temperature, also plays a role as the MBV' is not constant as expected.

Tab. 5 : Moisture buffer value in adsorption, desorption and average for the two kinds of hemp-lime plasters

Material	HLPC	HLPT
MBV-adsorption [g/m^2 %RH)]	1.18	1.59
MBV-desorption [g/m^2 %RH)]	1.27	1.68
MBV-average [g/m^2 %RH)]	1.23	1.64

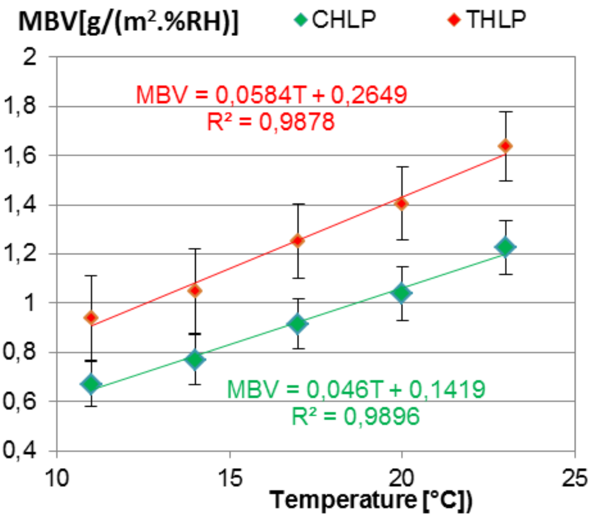


Fig. 9: Variation of the moisture buffer value as a function of the temperature

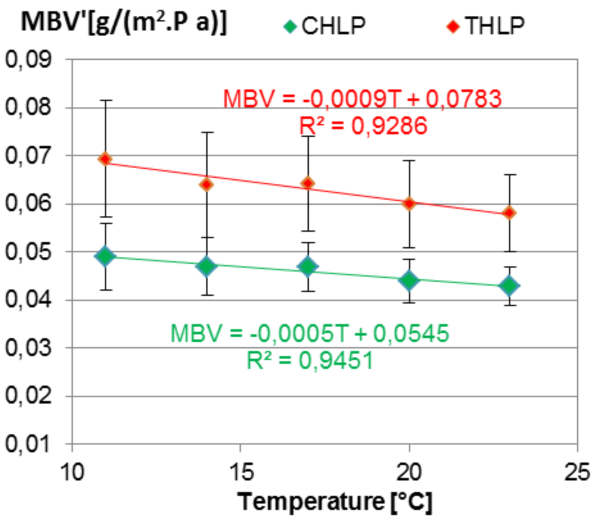


Fig. 10: Variation of the moisture buffer value as a function of the temperature

4 CONCLUSION

This paper investigates the use of bio-based raw material (hemp shiv) to produce plasters.

The two hemp lime plasters studied have quite low density (723 and 881 kg/m3) due to the use of hemp shiv which induces high porosity. They show low thermal conductivity value for plasters (0.18 and 0.21 W/(m.K) at 23°C; 50%RH) and good moisture buffering capacity (1.23 and 1.64 g/(m^2.%RH).

The results presented herein show that the temperature variation over the investigated range does not significantly impact the thermal properties. It is shown that the variations observed are due to the water content variation when the temperature changes. The thermal conductivity increases with water content by 5 to 8 %. The thermal diffusivity shows a parabolic curve versus water content, with a maximal value 20 % higher than the lower one.

On the opposite, there is a noticeable increase in moisture buffer value with temperature for the two hemp-lime plasters. It is shown that this results from the effect of variation of vapor pressure with temperature and the effect of other parameter depending on temperature.

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