Sorption behaviour of Lime-Hemp Concrete and its relation to indoor comfort and energy demand

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ABSTRACT: Recent investigations on heat and mass flows through building materials in dynamical conditions show the importance of considering moisture transport and storage when analyzing the global performance of the building envelope. Lime-Hemp Concrete (LHC) is an insulation material made out of hemp chips mixed with an appropriate rich lime binder. It can be use either in old or new buildings, to cover masonry walls or to fill walls, floors or roofs in timber frame structures. This paper analyzes drying process, final density and vapour permeability of different type of LHC-wall mixtures to point out influence of mixing, implementation and water input on material's final properties. Experiments inspired by the Nordtest project are then presented to assess moisture buffer effect in LHC material and retarded sorption effect is pointed out. Results from dry thermal conductivity measurements are also reported and influence of moisture content on this parameter is discussed. These results show why the use of LHC can help to reach high comfort feeling with low energy demand for indoor temperature and humidity regulations in sustainable buildings.

Keywords: energy savings, sustainable building materials, comfort feelings, transient transfer, HAM simulations, moisture buffering, retarded sorption, moist thermal conductivity.

1. INTRODUCTION

Many recent works contribute to apply sustainable principles in buildings. Architects and designers need a global approach to fulfil this complex task. Energy efficiency has to be obtained together with comfort and health. The choice of materials, depending on their properties and life cycle, thus became more and more significant when assessing buildings global performances.

Hemp chips were first introduced in buildings in France in the beginning of the nineties to lighten concrete mixture. If practitioners started with cement binder, better results were obtained with an appropriate lime basis binder. Lime-Hemp Concrete (LHC) is nowadays mainly used to cover masonry walls or to fill timber frame structures, in old or new buildings. It is also possible to use it for roof insulation and to realise light floor layers. For each different use, a specific mixture was defined: LHC-wall, LHC-roof, LHC-floor and LHC-plaster (depending on the quantity and the type of binder).

This innovative insulation material have already been analysed in different researches: in Belgium [1, 2, 3], France [4], Canada [5], Switzerland [6], and England [7]. Nowadays, building process, as well as binder specificities, is the two main points of interest to ensure high quality results. Previous researches [4] pointed out some thermal, hydric and acoustical qualities. Mechanical analysis showed that LHC cannot yet be used as a structural material but only to fill or cover a structure with sufficient load capacity.

Many measurements were conducted in Fraunhofer-Institut of Building Physics (IBP) and main transfer and storage parameters were presented in [2, 3]. The present paper focuses on specific aspects of sorption behaviour of LHC-wall mixtures. First, different mixtures are analysed to define the influence of significant parameters on material's final properties: type of mixing (fast/violent, slow/soft), strength of tightening during implementation (strong, neutral and soft) and water input (neutral, too high). Drying time, final density and vapour permeability of those samples are presented. Then, a dynamic sorption test inspired by the Nordtest project, allows us to assess moisture buffering of this type of material in specific relative humidity cycles. Results are compared to computer simulations executed with WUFI Pro 4.0® and retarded sorption effect is pointed out. Finally, measurements of dry thermal conductivity are presented and presumed influence of water content is analysed. This paper thus gives solid basis to establish the relationship between material properties, indoor hygrothermal comfort and energy demand for heating or to ensure indoor air quality.

2. MIXTURES

2.1 Samples

The wall mixture that was analyzed is referred as "LHC-wall". For the raison exposed in [2, 3], the products chosen for all the following experiments are Chanvribat®, for the hemp chips, and Tradical pf 70®, for the binder. This binder contains around 75% of rich lime, $Ca(OH)_2$.
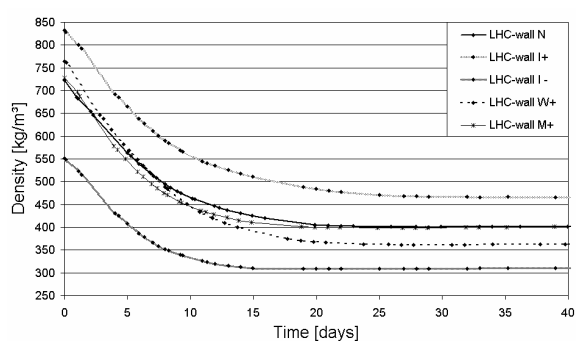
Figure 1: Drying of each group of LHC samples.

All the samples were cast in cylinder matrix (diameter: 190mm, thickness: 35mm) and were placed in saturated atmosphere (~20°C) during 3 to 5 days, with no significant weight variation during this initial period. They were then removed from the mould and placed in a room with 65% of RH (23°C) totally wrapped in aluminium foil except top surface (diameter: 190mm) for drying. Three identical prototypes of each group of sample were realised and Figure 1 presents average curves.

Each of the three reference samples, referred with "N", was made with approximately 120g of Chanvribat®, 240g of Tradical pf 70® and 360g of water (an homogenous mixture was hard to obtain with less water). The mixture was slowly hand-mix (3 to 4 min) to be sure the hemp particles are not damaged and that they were properly coated with the binder. Implementation was as close as possible to what is suggested on building sites: the mixture against edges was lightly pressed together but the rest was left loose.

All other groups of samples were realised using the same procedure but one parameter was modified. Samples referred with "I+", were strongly pressed in the mould during implementation. Samples "I-" were very lightly implemented. Samples "M+" were mixed (5 min) with a fast electric device with vertical axe and hemp chips were damaged during this process (resulting in smaller particles). The last group of samples, referred with "W+", was mixed with the same amount of hemp and binder, but with 500g of water (supplement of 40%).

2.2 Drying

For all the samples, the drying surface was 284cm². Figure 1 presents the density variation when they were placed in a climate room at 65% of RH. The volume variation can be neglected.

Table 1 express the drying time, i.e. the time needed to reach a minimal mass. Strength of tightening during implementation appears to have a great influence on this parameter: the stronger the mixture was pressed, the slower it dried. Fast and violent mixing did not imply a significant change unlike initial water input as it could be expected.

2.3 Carbonatation

Carbonatation is the chemical reaction that changes the rich lime, $Ca(OH)_2$, into lime stone, $CaCO_3$. This reaction is quite slow, but modifies the

Table 1: Drying time and mass variations due to carbonatation Δm_{28d} of each group of LHC samples.

Samples	Drying time			Δm_{28d}
	[days]	[h]	[min]	[‰]
LHC-wall "N"	28	22	5	6.67
LHC-wall "I+"	33	0	0	1.25
LHC-wall "I -"	18	22	34	11.09
LHC-wall "M+"	24	21	7	9.68
LHC-wall "W+"	30	18	15	9.64

density in the opposite way than drying because molar mass of lime stone is 35% higher than rich lime. That means that during drying process, the mass of samples first decrease until a minimum, and then increase slowly before an equilibrium. Until now no studies focused on this phenomena, but we could observed that after reaching a minimal weight, the samples got slightly heavier every days. Table 1 shows the gain of mass due to carbonatation Δm_{28d}, during the 28 days after minimal mass was reached. An interesting thing to notice is that, in theory, if all the rich lime changed in lime stone, the mass should approximately increase of 175‰ (in dry state and if water bond in hydraulic reactions is neglected). The first observation is that carbonatation was not finished at all when the measurements were stopped. In addition, strength of tightening during implementation appears to have a significant influence on carbonatation (the stronger the mixture is pressed, the slower carbonatation will occur). For the two other groups of samples, results showed that fast and violent mixing speed up the reaction, as well as higher initial water input.

2.4 Density

The evolution of density with time for each group of samples is showed on Figure 1. Table 2 presents the density obtained with the ratio minimal weight/ volume (considered as constant), as well as standard deviation between the three samples of each group. The following influence on density can be observed: strength of tightening during implementation has a significant effect; fast/violent mixing has a negligible effect; high initial water input lowers slightly the density.

Table 2: Density after drying time and standard deviation σ of each group of LHC samples.

Samples	Density after drying time [kg/m³]	σ [kg/m³]
LHC-wall "N"	400.66	± 3.84
LHC-wall "I+"	466.12	± 6.39
LHC-wall "I -"	308.40	± 2.34
LHC-wall "M+"	398.91	± 14.90
LHC-wall "W+"	361.72	±21.49

Table 3: Dry vapour resistance factor μ_s and standard deviation σ of each group of LHC samples.

Samples	μ_s [-]	σ [-]
LHC-wall "N"	5.02	0.24
LHC-wall "I+"	7.68	0.23
LHC-wall "I -"	3.59	0.04
LHC-wall "M+"	4.34	0.20

2.5 Diffusion of vapour

After four months, four of the five groups of samples were submitted to dry-cup test (EN ISO 12572). The three samples LHC-wall "W+" were not tested, because they were destroyed when aluminium foil was removed (binder powdered). Changes in mass during the four months period showed that carbonatation was still not finished for the four other group of samples.

The dry-cup test was conducted in a climate room at 50% of RH, with "cups" containing pink silica gel (3% of RH). Sides of the samples and junction between samples and glass cups were covered with paraffin to avoid vapour transfer in these places. Surface of transfer was reduced to 180mm of diameter on the top of the samples. Results of the experiments are presented in Table 3. It appears that strength of tightening during implementation has a significant effect on vapour resistance factor and that fast/violent mixing slightly lowers this parameter.

3. DYNAMIC SORPTION TEST

3.1 Moisture retention curve

Results from measurements conducted in IBP and presented in [2, 3] can be gathered to define the moisture retention curve of LHC-wall material as illustrated in Figure 2. This curve gives the equilibrium water content for different relative humidity. It was introduced in WUFI Pro 4.0® to realize simulations. The experiment described here below shows that for this type of material, some retarded sorption effect can be observed and a static curve like the moisture retention curve can lead to unrealistic results. With dynamic variation of humidity, the water content obtained in practice can be lower (in the case of a fast
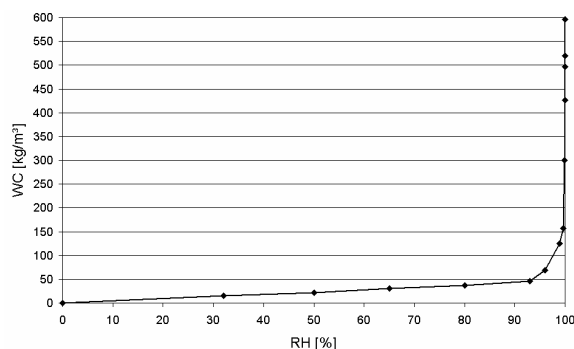
Figure 2: Moisture retention curve of LHC-wall.

Table 4: Equilibrium water content of LHC samples.

Relative humidity [%]	WC [kg/m³]	WC [mass%]
0	0	0
32	15.24	3.18
50	22.31	4.65
65	30.78	6.41
80	36.48	7.60
93	45.40	9.46
96	65.98	14.34
98.897	125.63	26.17
99.631	157.65	32.84
99.889	300.23	62.55
99.963	426.93	88.94
99.989	496.79	103.50
99.996	519.97	108.33
100	595.58	124.08

increment of humidity) or higher (in the case of a fast reduction of humidity level). For small broken samples (±20g), equilibrium water content took, for example, few days to settle in 32 or 50% of RH from dry state, but more than 15 days in 93% of RH, even when there where not starting from a dry state.

3.2 Moisture buffer effect

This test was inspired by the Nordtest project [8] which was still going on when this experiment was defined. The Nordtest method gives for each tested material a single value, called Moisture Buffer Value (MBV), which "indicates the amount of water that is transported in or out of a material per open space area, during a certain period of time, when it is subjected to variations in relative humidity of the surrounding air" [8]. The unit of MBV is [kg/m².%RH]. Different simulations with WUFI Pro 4.0® were realised to define the so-called "penetration depth" [8] and the time needed to reach a constant buffering. We chose to use humidity cycles with 16 hours in 50% of RH followed by 8hours in 80% (humidity levels do not correspond to the Nordtest protocol).

The results of the simulations gives a moisture buffer value, called $WBV_{LHC,simul}$, of 2,75 kg/m².%RH. This value was not influenced either by the thickness of the samples, if bigger than 1,75 cm, or by the humidity level (50-80%, 50-65%, and 33-75% were checked). As it appears on Figure 3, the time needed to reach a constant buffering, for samples of 1,75 cm, was 4 days (28 days for 5 cm and 90 days for 10 cm).

Automatic data acquisition gives hourly mass variations of sample submitted to the same humidity cycles. Their thickness was 1,75 cm but the buffering was not yet constant after 4 days, as presented on Figure 3. The measured "moisture buffer value", $MBV_{LHC,meas}$ was 1,39 kg/m².%RH. The buffering was barely constant after 14 days, when the experiment was stopped.
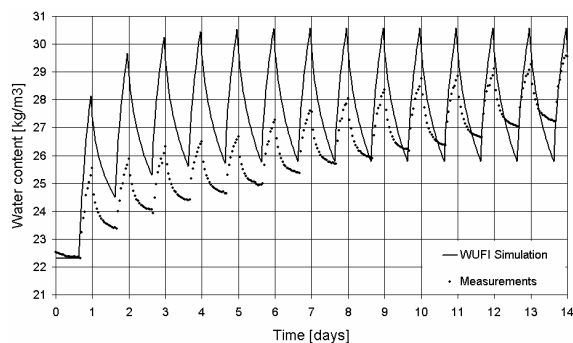
Figure 3: Moisture buffering of 1,75 cm thick LHC-wall samples with humidity cycle of 50% of RH for 16hours and 80% of RH for 8hours.

3.3 Results analysis

As it appears on Figure 3, the results from measurements are very different than those from simulation. This difference is likely due to retarded sorption effect. As sorption tests showed, equilibrium water content usually takes few days to settle down. After the first 8h in high relative humidity (80%), it can be observed that water content of the samples did not reach in practice (w_{meas}=25.5 kg/m³) what was expected from simulation (w_{simul}=28 kg/m³). After the first period of 16 hours in low relative humidity (50%), the samples released less moisture in the atmosphere (~2 kg/m³) than what was expected from simulation (~3,5 kg/m³). The time needed to reach a constant buffering was also much longer, but after this time the mean water content seems to be almost the same in the experiment and in the simulation (w_{mean}~28,5 kg/m³). Another interesting remark is that we can artificially make simulation and measurement closer together if we input in the software's data base a higher vapour resistance factor (about µ~20 in this case).

High moisture capacity and specific porous structure of LHC can explain why this retarded sorption phenomena is more significant in LHC than in other mineral material. As a matter of fact, the "macro-porosity" is composed of very wide and open pores (between the coated particles) and lead to very low vapour resistance factor (µ~5). Beside, a "micro-porosity", composed with very thin open pores (in the binder matrix and in the particles themselves), does not have the same moisture transfer properties than macroscopic material.

4. THERMAL CONDUCTIVITY

Thermal conductivity is a function of moisture content. First thermal conductivity at 10°C has to be determined in dry state. Three samples of 20x20x3cm (~0,5kg) were used. Each sample was submitted to a temperature difference of 10°C between a hot and a cold plate. As illustrated on Figure 4,, three different steps were chosen, with a mean temperature of respectively 18, 26 and 34°C. Each step take around 2hours, and water uptake of the samples after the three steps was less than 0,4% of mass. Dry thermal conductivity
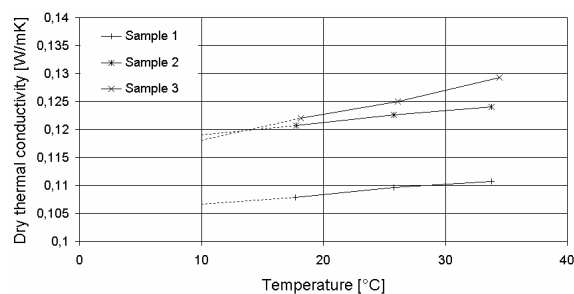

Figure 4: Dry thermal conductivity of LHC-wall.

is calculated with the measured heat flow and the temperature difference between the two plates (DIN 5216). Mean value for LHC-wall mixture at 10°C is determined by extrapolation, and its value is: 0,115W/mK (with a standard deviation of 0,56%).

Assuming a linear relationship between thermal conductivity and water content, we can define a moisture-induced supplement, expressed in [%/mass%]. Maximal water content w_{max} is reached when material's porous structure is totally filled with water. Its value for LHC-wall is 711kg/m³ [2]. If we consider that thermal conductivity of LHC-wall with this water content w_{max} corresponds to thermal conductivity of still water (0,58W/mK), we find a moisture-induced supplement of 2,73%/mass%. That means that thermal conductivity of samples at hydric equilibrium in 80% of RH ($w_{80\%}$=7,6mass%) should be around 0,139W/mK, since the increment is 20,75% with these hypothesis. This results is very close from measurements related in [4] for the same material.

5. DISCUSSION

Results presented in this paper give some practical information on the influence of different parameters on final properties of LHC-wall mixture. The aim was to help solving some questions coming up very often on the building sites: "Which kind of mixing is the most appropriate?", "How strong should I tighten the mixture during implementation?"; "Too much water is better than too less, right?"…

The paper showed that a violent mixing does not have an important impact on drying, final density or final vapour permeability. Properties of the mixture were less regular (higher standard deviations) and fast mixing seems to influence speed of carbonisation. This particular observation could be analysed in future experiment. Impact on thermal conductivity should also be studied. If a slow mixing avoids breaking hemp particles apart, a homogenous mixture has to be obtained after the mixing. In addition, if the binder contains hydraulic binder added to rich lime, the time between mixing and implementation should not be too long if binder also contains.

Strength of tightening during implementation appears to have a big influence on final properties. Drying time of mixtures with strong tightening was longer and mixture's properties were less regular. Mixtures with light tightening seem to have better carbonatation.

If water input cannot be lowered under a certain limit to ensure a thorough reaction of binder, mixtures with too high water input were destroyed when aluminium foil was removed. In fact binder powdered for the three samples and high water input should thus be avoided.

The dynamic sorption tests showed that buffering LHC-wall mixture was high. Results obtained for MBV_{meas}, as well as for MBV_{simul}, turn out to be "good" to "excellent" if we refer to the classification presented in [8] (but RH levels do not correspond to Nordtest protocol). Most of usual material have a $MBV_{practical}$ under 1 kg/m².%RH: cellular concrete, gypsum and cement concrete receive for example the respective value of 1; 0,6 and 0,4. Nevertheless, we have to notice that LHC-wall should be covered with a rich lime plaster and MBV of LHC-plaster would be more useful in practice.

Future experiments should also focus on a precise analysis of pore size distribution in LHC to go further in explaining why retarded sorption phenomena is more significant in this particular material than in other mineral materials.

Concerning the thermal conductivity and its relation to water content, it is interesting to notice that, if we refer to [9], moisture-induced variation on measured values could come from a latent heat effects due to moisture evaporating at the hot plate and condensing at the cold plate. To find good agreement between measurements and simulations, Kehrer et al. suggests neglecting either moisture-induced supplement or latent heat effects during experiment [9]. In addition, results from [4] indicate the relationship between thermal conductivity and water content may not be linear. Future research should take these two remarks into account to define a more accurate relationship between thermal conductivity and water content.

6. CONCLUSION

Lime and hemp concrete (LHC) is an innovative building material used to insulate wall, roof, or floor. Its fast development for the last 5 years, especially in France, shows that its specificities match nowadays concerns. Life cycles of each component seems to meet sustainable requirements to build comfortable and low energy buildings.

Numerous qualities were pointed out in different researches: LHC are light, hygroscopic; they contains renewable resources and stores carbon dioxide (during their life); they are biodegradable and have low energy of production; no expensive equipment is needed on the building sites…

Previous papers recently present main heat and mass transfer and storage parameters. Results confirm initial interest. A specific combination of parameters was found: it explains a high thermal load capacity and high surface temperatures, especially when material is submitted to dynamical climate variations. In addition, some latent heat effects leading to energy savings were pointed out.

The present paper first focused on the influence on final properties of important parameters met in building practice (mixing, implementation and water input). Then, a dynamic sorption test showed how material properties can help in indoor air quality regulation on the basis of the recent Nordtest project. Finally, thermal conductivity experiment demonstrated good performances, in both dry and wet state. For all this reasons, we are convinced that LHC material can help to define a sustainable architectural environment for following generations.

ACKNOWLEDGEMENT

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