

BIOCLIMATIC ENVELOPES MADE OF LIME AND HEMP CONCRETE

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ABSTRACT

Building envelopes are designed to regulate dynamic flows between interior and exterior environment. The paper presents a new type of sustainable building material made of rich lime and hemp chips and focuses on a particular mixture used to fill timber framed structures. Most of material's hygrothermal parameters were measured in the Fraunhofer-Institut for Building Physics in Holzkirchen and its specific behaviour under transient conditions is studied through simulations with WUFI[®] 4.0 software. Three case studies were defined to point out its thermal and hygric inertia. According to bioclimatic principles, these effects can help architects and designers to combine comfort feelings and low energy demand. Results are compared to other materials and future works are discussed.

RESUME

L'enveloppe des bâtiments est conçue pour réguler les flux dynamiques qui s'établissent entre les ambiances intérieure et extérieure. L'article suivant présente un nouveau type de matériau de construction "durable" composé de chaux aérienne et de particules de chanvre, et plus particulièrement sur le mélange utilisé pour habiller les constructions à ossature de bois. Les principaux paramètres hygrothermiques du matériau furent mesurés au Fraunhofer-Institut für Bauphysik de Holzkirchen et son comportement spécifique en régime transitoire est étudié à travers des simulations réalisées avec le logiciel WUFI[®] 4.0. Trois études de cas ont été définies pour mettre en évidence son inertie thermique et hydrique. D'après les principes de l'architecture bioclimatique, ces effets peuvent aider les architectes et concepteurs à combiner le sentiment de confort à une demande en énergie réduite. Les résultats sont comparés à ceux obtenus pour d'autres matériaux et les recherches futures sont discutées.

INTRODUCTION

Many sustainable aspects of using lime and hemp concrete to fill timber framed structures could be discussed since assessments on the life cycle of this "inorganic matrix composite" seems to very positive. Hemp chips were first introduced into buildings in France in the beginning of the nineties to lighten concrete mixtures. Practitioners started in using cement binder, but very few decisive results were obtained. Numerous building experiments showed that rich lime is more appropriate for this kind of use. The main reason is that slow carbonation process of rich lime is more compatible with the fast water uptake of the chips compared to reactions of hydraulic binder as cement. High pH of lime also protects hemp chips for a long time from mould or bacteria attack, and its mechanical flexibility allows slight distortion without cracking and good toughness against shocks. In addition, its density and thermal conductivity is lower than cements. A high quality rich lime for building purpose is however sometimes hard to find and its chemical transformation is quite slow compared to what is expected nowadays in building process. This rich lime basis gives thus better results if a small part of hydraulic and puzzolanic binders are added. Specific additives can also help to

enhance desired properties: water repellency, air availability during chemical reactions, surface covering of hemp chips, etc. The pre-formulated lime Tradical pf 70[®] corresponds to this special binder mixture even if it was first developed to be used in old buildings masonry. This binder was chosen to realize the samples first because its properties are uniform and then to allow comparison with other laboratory measurements [1] made on the same material using this binder. The hemp chips Chanvribat[®] were used for the same reasons.

In 2002, an important synthesis of laboratory experiments made on lime and hemp concrete has been done [2]. The document gathers what was considered as the “state of the art” and described four mixtures used by practitioners and studied in [1]. The name of the mixture is linked with the use they will fulfil: build a “wall”, cover a “floor”, insulate a “roof” or to realize a “plaster”. These uses can be found either in new or in renovated buildings. Samples submitted to measurements correspond to “wall” mixture: one cubic meter is obtained with 130 kg of hemp chips, 220 kg of binder and approximately 350 litres of water. The samples were made three years before the measurements and binder’s carbonatation and drying were considered as completed. Mechanical properties [1] of “wall” mixture are not high enough to consider this particular concrete as a structural material. It should then fill or cover a structure with sufficient load capacity like a timber frame structure. Thermal properties are detailed here after, but lime and hemp concrete should be at least a 25 to 30cm layer for an exterior wall, and must be protected inside and outside. Figure 1 illustrates the two main types of exterior wall when using “wall” mixture: both are with rich lime plaster inside, one is with hydraulic lime plaster outside and the other is with wood cladding.

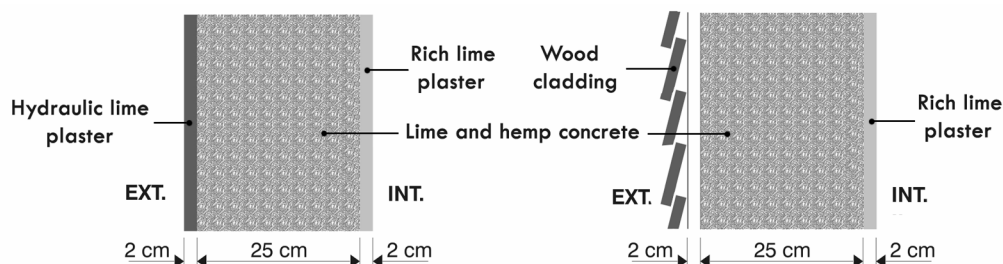


Figure 1: “Wall” mixture in two types of wall made of hemp and lime concrete

This paper presents first steps of a research realised with Lhoist R&D s.a. (B) partnership and with financial support of Waloon Region (B) and European Social Found.

HYGROTHERMAL PARAMETERS

Dry density and porosity

Dry state was obtained with an oven at 40°C, with recycled dry air, when loss of mass of samples was smaller than 0,1% during 24 hours. Mean dry density is 480 kg/m³ (Table 1). A very high total porosity of 71,1% was measured on those dry samples with helium pycnometer. With this single value, it is not possible to differentiate “microscopic porosity”, in the matrix (~1µm) or in the hemp chips (~10µm), from “macroscopic porosity” (~1mm) which is obvious when looking at the samples (Figure 2). Future measurements will define pore size distribution with Mercury and Nitrogen Intrusion Porosimetry.



Figure 2: Macroscopic porosity of lime and hemp concrete – “wall” mixture

Sorption

Three different sorption regions can be defined. Water content of “wall” mixture in the first one, the “hygroscopic region” (Figure 3), was studied in placing dry samples (~20 grams), into different climate rooms at 23°C, with relative humidity going from 32 to 93%. As expected, there mass starts to climb up due to increasing water content. Equilibrium water content was measured when gain of mass during 24 hours was smaller than 0,1% of dry mass. The time needed for this stabilisation was quite long, usually more than two weeks for thin or broken samples. Future researches will study these retarded sorption effects in details. Mean value of the results are relatively high, as presented in Table 1.

The second region starts when “capillary condensation” becomes prevalent compared to hygroscopic phenomenon (Figure 4). It is considered to begin where the slope of isotherms starts to rise much faster, generally around 80%, and goes until saturation (RH=100%). Results from Pressure Plate experiments will soon give more details on the real edges of the “capillary region” that seems to start in this case after 93% of relative humidity. Until then, it is assumed that water content rise linearly from the value obtained at 93% to free saturation. The high value of 596 kg/m³ can be used for free saturation of the “wall” mixture (575 kg/m³ for wood and 250 kg/m³ for lime plaster). It has been measured on samples placed under water until their mass was stable. The last region, called “sursaturated region” (Figure 5), is usually not taken into account in buildings physics. However, we can assume that the maximal water content of the material is reached when all the pores are filled of water. Maximal water content of “wall” mixture is then presumably 711 kg/m³.

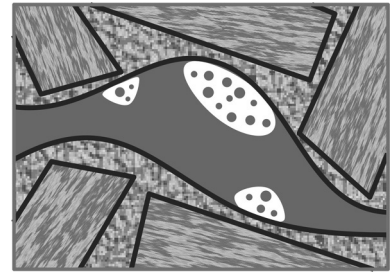
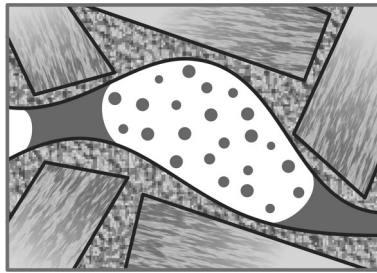
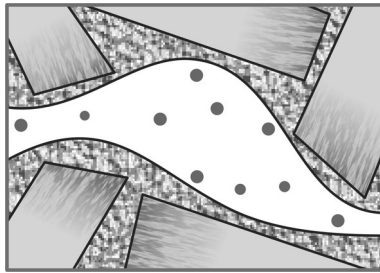


Figure 3: Hygroscopic region

Figure 4: Capillary region

Figure 5: Sursaturated region

Storage parameters

Thermal capacity was measured into an adiabatic surrounding. Samples were dried and heated to 100°C and were put into water at 22°C (room temperature). From the thermal capacity of water, the mass of water and the mass of the sample, the measure of the resulting temperature allows to determine thermal capacity of “wall” mixture. As presented in Table 1, the mean measured dry value was $c = 1550$ [J/kgK]. The method was validated with measurement on aluminum sample (920 [J/kgK]).

The slope of sorption's isotherm is called hygric capacity ξ_ϕ . In the hygroscopic region, sorption isotherm at 23°C is almost linear, hygric capacity takes then a single value: 10,2 [%].

Moisture transfer parameters

Water vapour permeability of “wall” mixture was measured following EN ISO 12572 with dry cup (RH=3% in the cup, 50% in the room) and wet cup (RH=93% in the cup, 50% in the room) methods. Results were respectively a coefficient of vapour diffusion resistance of $\mu_s = 4,84$ [-] and an apparent coefficient of vapour diffusion $\mu^* = 4,51$ [-]. But μ^* will not be use since the difference is due to liquid transport, expressed with liquid transport coefficient.

Water absorption coefficient was measured following DIN 52 617. Its value is $A = 7,5 \cdot 10^{-2}$ [kg/m²·√s]. The liquid transport coefficient for absorption D_{ws} and for redistribution D_{ww} were approximated from this value using Künzel method. Measurement with Nuclear Magnetic Resonance will soon give results closer from reality. Liquid transport in lime and hemp concrete is expected to have a certain time dependency (non fickian behavior) similarly to what is observed in wood, cellular concrete or clay bricks.

Heat transfer parameters

Dry thermal conductivity λ is estimated on the basis of other research (especially [1]). Until new measurement, it is assumed in the following simulations that its dry value is 0,11 W/mK rising linearly with relative humidity until maximal water content with a increase of 1,515 % per additional % of masse content. Table 1 presents its dependency to water content as well as two other useful thermal parameters. First is the thermal diffusivity α [m²/s], calculated by the ratio: $\lambda/\rho c$. Then is the thermal “Effusivity” ξ_{ff} [J/m²K√s] witch is calculated by $(\lambda \rho c)^{1/2}$.

RH [%]	w [kg/m ³]	ρ [kg/m ³]	c [J/kgK]	λ [W/mK]	α [10 ⁻⁷ m ² /s]	ξ_{ff} [J/m ² K√s]
0	0	480	1550	0,11	1,48	286
32	15,24	495,24	1631	0,115	1,43	305
50	22,31	502,31	1667	0,118	1,41	314
65	30,78	510,78	1708	0,121	1,38	325
80	36,48	516,48	1735	0,123	1,37	332
93	45,40	525,40	1777	0,126	1,35	343
100	596	1076	3005	0,317	0,98	1012

Table 1: Water content dependency of different parameters for lime and hemp concrete

CASE STUDY

Case 1: Thermal shock

This theoretical situation was defined to show that permanent transfer is not immediately obtained when one side of an element is submitted to thermal variations. Initial temperature is 20°C (RH50%) on both sides and through the 25cm elements of plain material. From the first time step, temperature on left side is lowered to 0°. The induced effect on relative humidity is not discussed here but will be analyzed in detail in future works. Figure 6 shows that linear temperature distribution through the element is barely obtained after 48h in lime and hemp concrete. Wood has almost the same behaviour. For cellular concrete, it took approximately 24h, for cement concrete less than 10 hours and for mineral wool around 5 hours. Referring to Table 2, it can be noticed that linear temperature distribution is thus obtained faster with high thermal diffusivity material.

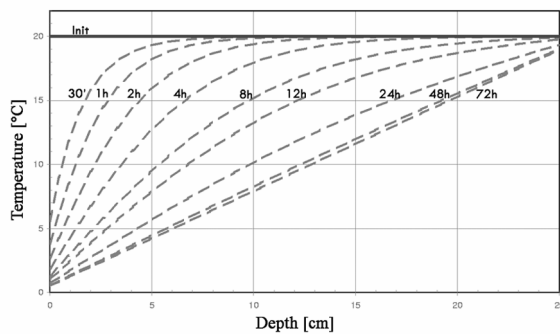


Figure 6: Thermal shock propagation in 25cm of lime and hemp concrete

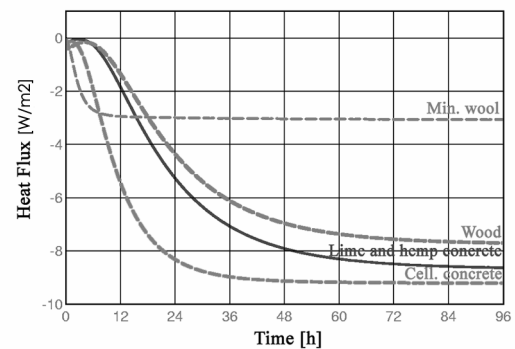


Figure 7: Evolution of heat flux through right surface (25cm)

Figure 7 shows the evolution of heat flux through opposite surface (right) for these materials. Negative value means the flux is going from right to left. It appears that approximate permanent transfer takes longer to set up in materials with high thermal Effusivity: more than 48h in lime and hemp concrete or wood; around 36 hours for cellular concrete; and less than 12 hours in mineral wool (and it was not installed after 96h in the cement concrete element). Table 2 also presents surface temperatures T_{surf} [°C] on right side after 96h. In addition, the amount of energy given to the elements from right side environment after 24h, Q_{24h} [kJ/m²], appears lower for lime and hemp concrete or wood, than for other material.

Case 2: Thermal cycles

Once again, this situation is theoretical. It was defined to illustrate that materials have a very different response when they are submitted to cyclic thermal variations. Initial temperature is 10°C (RH50%) on both side and through elements of 1m of thickness. From the first time step, temperature on left side starts to vary following a sinus curve with maximum at 20°C, minimum at 0°C (amplitude $\theta_{\text{init}}=10^\circ\text{C}$). Those cycles have a 24 hours period. The induced effect on relative humidity is not discussed in this case either but future works will detail them. Figure 8 shows that in lime and hemp concrete the wave is almost totally dampened at 25cm of depth. Dampening factor v_x [-] of thermal wave amplitude at a depth of x [cm] can be defined by $v_x = 1 - (\theta_x / \theta_{\text{init}})$. In addition, Figure 8 also shows that at this depth, maximal temperature is reached after the minimal temperature has been reached on left surface affected by the harmonic variation. Time discrepancy η_x [h] can be defined by the time difference between the maximum (or minimum) of corresponding cycle, on the surface submitted to thermal variation and at a depth of x [cm]. Table 2 present results obtained at 25cm for lime and hemp concrete and for other materials. Low v_x and low η_x is obtained when α is high.

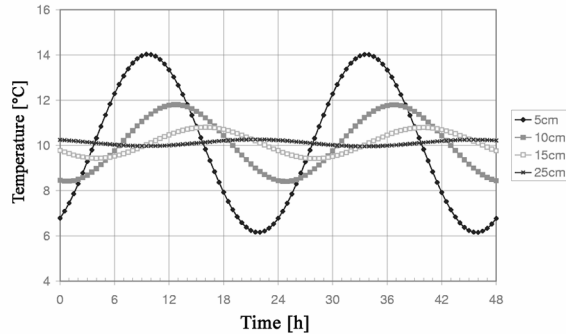


Figure 8: Propagation of thermal wave in a lime and hemp concrete element

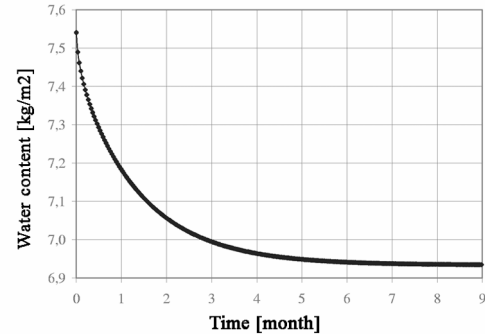


Figure 9: Water content of a 25cm element when humidity on right side is lowered

Case 3: Hygric shock

This case was defined to show that hygric equilibrium is much slower to install than thermal's one and that envelope materials can contribute to regulate relative humidity of inside air. Initial conditions were set to a relative humidity of 80% outside and 50% inside with a linear distribution through the 25cm elements of plain material. From the first time step, relative humidity on right side is lowered to 40%. The boundary temperatures are constant and fixed to 20°C. Thermal effect induced by moisture transfers will be discussed in future works.

As figure 9 shows, constant water content, and thus permanent transfer conditions, in the lime and hemp concrete element are reached only about 9 months after the hygric shock. In table 2, this time lapse is represented by τ . When permanent flow is reached, there is $g_{v,\tau} = 0,5 \text{ g/m}^2$ per hour of vapour going through the lime and hemp concrete element from left to right (NB: there is no plasters in this case !).

To precisely assess the quantity of moisture given by the element to right side environment W_t [kg/m²] on a certain time period t , moisture flux going out of right surface lowered by the flux entering from left one should be integrated on the time period. In this case, W_t was approximated by the loss of mass of the element during the time period. Nine months after hygric shock, lime and hemp concrete element gave 600 g/m² to the right side environment. After 3 months, it already gave 550 g/m², corresponding to 91,7% of final value.

Table 2 gives corresponding values for other materials. It shows that, in the hygroscopic region, materials with a low moisture transfer parameter (coefficient of vapour diffusion resistance μ_s) and low moisture storage parameter (water content at RH80% gives a good idea if hygric capacity ξ_ϕ is high or low) are getting faster to their hygric equilibrium. Besides, the amount of moisture exchanged with the environment W_τ during the time lapse τ needed to get constant water content is higher for materials with higher moisture storage parameter. Lime and hemp concrete has a very specific behaviour due to its very low resistance to vapour diffusion combined with quite pronounced hygroscopic uptake. Future works will define combined parameters corresponding to thermal diffusivity and Effusivity for hygric transfers.

	Case n°	Lime and hemp concrete	Wood	Cellular concrete	Mineral wool	CEM concrete
α [10 ⁻⁷ m ² /s]	-	~1,4	~1,35	~3	13,3	~6
ξ_{ff} [J/m ² K/s]	-	~320	~350	~330	35	~1700
T_{surf} [°C]	1	18,92	19,04	18,85	19,62	11,98
Q_{24h} [kJ/m ²]	1	187	146	410	229	3163
v_{25cm} [%]	2	98,5	98,8	95	77,5	89,5
η_{25cm} [h]	2	15	16	10,5	6	7
$w_{80\%}$ [kg/m ³]	-	36,48	60	9,8	(0)	85
μ_s [-]	-	4,84	200	8	1,3	180
τ	3	9 months	8 years	4 months	(7 days)	45 years
$g_{v\tau}$ [g/m ² h]	3	0,5	0,06	0,34	1,95	0,02
W_{3m} [g/m ²]	3	550	160	190	(35)	130
W_{3m}/W_τ [%]	3	91,7	32	97,4	(100)	15,3

Table 2: Results from case 1, 2 and 3 for lime and hemp concrete and other materials

CONCLUSION

As introduced, sustainable nature of hemp and lime concrete could still be studied in many ways. After presenting main hygrothermal parameters of this new insulation material, the paper defined three theoretical case studies to enable comparison with other material, and to point out its specific behaviour. Bioclimatic architecture takes in account the dynamic reality of climate, and it appears that transient performances of such a wall element are definitely higher than what permanent transfer calculations would assess. This conclusion is often observed in wood or earth constructions. Combined parameters can be defined on the basis of material's transfer and storage parameters to help architects and designers to choose materials when they wish to optimized comfort feelings and low energy demand of their buildings.

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