Moisture Equilibrium in Straw Bale Walls

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ABSTRACT: Straw bales technology for buildings is developing in Belgium as in many other countries. The market is growing but significant uncertainties are left concerning how to model its dynamical hygrothermal performances and its long term behaviour. The present paper presents the preliminary analysis conducted on material parameters and component's response to dynamic heat and moisture solicitations. The simulations use WUFI Pro software based on material parameters form literature and both reference climate files for Belgium and theoretical climates to analyse the interactions between straw bale walls and finishing materials and their influence on component performances and durability. A specific prefabricated wall element sold on Belgian market is detailed and introduced in simulations. The influence on comfort feelings and indoor air quality are discussed with a focus on component's thermal inertia and moisture regulation capacity. The paper concludes with recommendations on wall composition to help straw bale technologies to develop in building market of Belgium and other countries.
Keywords: straw bale, earth plaster, lime coating, water repellent, moisture regulation, thermal inertia.

INTRODUCTION

Straw is traditionally considered as a waste product of agriculture, used for cattle bedding, field supplies or even burned after harvest. Since the last centuries, this situation evolved allowing the straw to be considered as a building material. Several techniques have been used around the world since the XIXth century to implement straw based materials. Most of those techniques need to be associated with a complementary loadbearing structure, except Nebraska technique.

Nebraska technique

The first agricultural baler appeared during the XIXth. This machine allowed farmers to harvest cereals from the grain to the straw itself as compressed bales. In Nebraska (USA), a state well known for its tremendous landscapes partly characterized by cereals fields and treeless prairies, there was little wood to build with but lots of straw bales from farmer's harvest. People thus started to build house out of straw-bales by stacking them as structural elements and protecting them with plaster made of cement, lime, mud, etc.

Wood-frame technique

This technique uses a timber-frame as structural element. It is mainly used in Europe. The straw-bales fill the structure as an insulating material. A plaster or a wood cladding is applied as a finishing product.

GREB technique

This technique is mainly used in Canada. It uses a double timber-frame as structural element. The straw-bales fill the structure as an insulating material. In this technique, the plaster is flowed instead of being applied by hand.

The "CST" technique

This technique is mainly used in France. It uses a timber-frame as structural element. The straw-bales fill the structure as an insulating material and the strain energy contained in the compressed bale is released by cutting the string around the bales and used as bracings.

Prefabrication

Prefabrication of straw bale walls have been used in many countries to reduce cost and to speed up the building process. A building can therefore be built within a few days. In Belgium, a young company named *Paille-Tech* is producing prefabricated walls elements with straw bales and earth plaster.

The continuous development of these techniques proves that straw bale walls are competitive in terms of price and performance. Low impact on environment and health at each step of its life cycle, together with its local availability, offer very interesting prospective for this insulating material.

Despite the knowledge acquired from past and recent experiences on how to build with straw [1], significant uncertainties are left concerning how to model its dynamical hygrothermal performances and its long term behaviour [2]. The present paper offers a methodological analysis of walls hygrothermal behaviour in dynamic

conditions focusing on the influence of finishing materials and the benefit on comfort.

OBJECTIVES AND METHODOLOGY

The results presented in this paper were obtained during the first phase of a research started in December 2011. This preliminary analysis, conducted on material parameters and component's response to dynamic heat and moisture solicitations is based on material parameters form literature and both reference climate files for Belgium and theoretical climates. This first phase of the research will be followed by a measurement campaign of material's hygrothermal parameters, as well as a dynamic characterisation of full-scale components and a monitoring in three different buildings.

The objectives of this paper is to define, for each layer, the range of value that liquid transfer coefficients can take to guarantee high performances and durability of the studied straw bale walls. Liquid transfer is still often neglected in most of scientific works on straw bale walls [2]. The present study analyses the interaction between straw bales and finishing layers (inner and outer surface) in terms of moisture storage.

The analysis is based on simulations conducted with WUFI Pro software starting from reference material parameters from literature and adapting the liquid and vapour transfer coefficients of each material to identify their influence on performances and durability of wall component. For each case, a systematic control of total water content of wall component, water content of each layer and water content of materials at strategic positions are analysed. Based on the results of preliminary studies, a rigorous methodology is applied to reduce the number of possible variations: nine series of simulations, each adapting specific parameters, were defined, focusing on most significant parameters. The nine series of simulations that will be developed in this paper are presented in Table 1.

Table 1: Definition of nine series of simulations

N°	Name
A1	Outer layer – Material type
A2	Outer layer – Protection from rain
A3	Inner layer – Material type and thickness
A4	Surface layer – Vapour permeability
A5	Straw bale – Thermal conductivity
A6	Straw bale – Thickness
A7	Straw bale – Moisture transfer coefficients
B1	Inner layer – Moisture buffer
B2	Inner layer – Thermal buffer

PRELIMINARY DATA

Wall typology

The results presented in this paper are based on the analysis of the prefabricated wall produced by the young Belgian company, *Paille-Tech*, as an example to support straw bale building development in Belgium. Products from *Paille-Tech* are still evolving and the company is open to further optimisation. Fig. 1 presents their typical wall compositions, but many variations are considered.
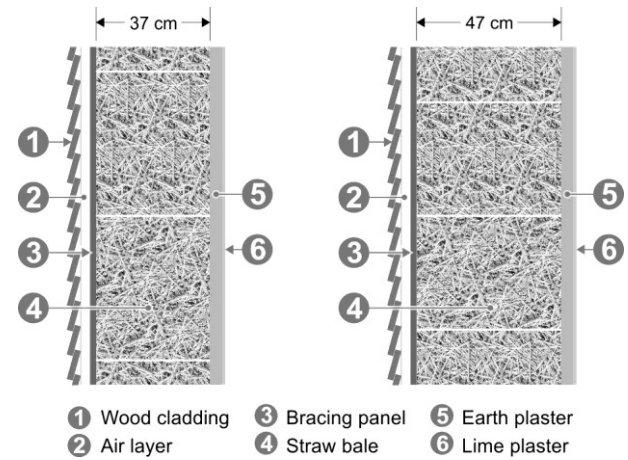

1 Wood cladding 3 Bracing panel 5 Earth plaster
2 Air layer 4 Straw bale 6 Lime plaster

Figure 1: Two typical wall compositions of prefabricated wall produced by Paille-Tech.

Properties of materials

As illustrated on Fig. 1, the typical typology of wall produced by Paille-Tech uses, on the outside surface, a bracing panel open to vapour, i.e. AGEPAN®. On inner surface, the prefabricated wall elements are covered by a relatively thick earth plaster of approximately 4cm.

All the materials properties needed to run rigorously WUFI software were not available from producers. Missing values were defined based on equivalent materials from WUFI's material database. Wood cladding and inside plaster are implemented on building site. Wood cladding is not considered in the simulations. Table 2 presents main hygrothermal parameters of initial materials used in the simulations ("$WC_{80\%}$" is the water content at 80%; "Absorption" is the A-Value).

The measurement campaign of the materials hygrothermal parameters required for modelling is not over. However, the earth plaster used by Paille-Tech had already been identified and characterized both chemically and physically. Until now, the company used clay from the Hins clay pits mixed with sand and reinforced with straw fibres. The following characterization phase was carried out on this mix and on another mix, i.e. ARGILUS®.

Table 2: Main hygrothermal parameters of initial materials used in simulations

Parameter	Units	Bracing panel	Straw bale	Earth plaster	Lime plaster	Gypsum plaster	Cement plaster
Density	[kg.m^{-3}]	570*	100 [2]	1800*	1600	850	2000
Porosity	[%]	0.5	0.9 [2]	0.3	0.3	0.65	0.3
Heat capacity	[J.kg^{-1}.K^{-1}]	2100	2000 [2]	900*	850	850	850
Therm. cond.	[W.m^{-1}.K^{-1}]	0.09*	0.085 [2]	1*	0.7	0.2	1.2
Vapour Diff.	[-]	11*	2 [2]	6	10	8.3	25
WC$_{80\%}$	[kg.m^{-3}]	8	22.5 [3]	55*	30	6.3	35
WC$_{100\%}$	[kg.m^{-3}]	100	100 [3]	150	250	400	280
Absorption	[kg.m^{-2}.s$^{-1/2}$]	0	0.05	0.068	0.047	0.287	0.076

(* data from producer, other data inspired from WUFI material database except when specified)

Hins clay

Various granulometric curves were measured, by dry process on the sand, by wet process on the coarse fraction of clay and by laser on the fine fraction of clay. With those curves, a problem in the composition of the Hins plaster was detected. Indeed, the sand has very few particles smaller than 250 µm and the clay contains a small amount of particles greater than 63 µm. A lack of particles in size classes between 63 µm and 250 µm, which creates a slight discontinuity in the total size distribution curve of the plaster (Fig.2), was observed.

Additional characterization tests were undertaken on this Hins clay. The true density was measured with a water pycnometer. The density found is equal to 2715 kg/m³. The methylene blue test identifies the highly active clays because methylene blue is preferentially adsorbed by the montmorillonite type clays (swelling clays). The blue value is equal to 40.8 g of blue per kilogram of clay fraction. The Atterberg limits are constants that are widely used in geotechnical engineering to characterize clay. They mark the limits between the liquid and plastic states of soil (liquid limit: W_L), as well as between the he plastic and solid states of soil (plastic limit W_P).

These limits are characterized by the soil water content at the considered transition limit. The difference $I_P = W_L - W_P$ (plasticity index), which defines the extent of the plastic region, is particularly important. Tests showed a liquid limit (W_L) equal to 25.6 and a plastic limit (W_P) equal to 18.8, which gives us a plasticity index equal to 6.8. This relatively low index reveals that we are in the presence of sandy clay.

The fact that we have sandy clay is confirmed by the mineralogical analysis, performed by X-ray diffraction (XRD) on the decarbonized fraction inferior to 63 µm; that showed characteristic peaks corresponding to quartz.

The semi-quantitative analysis carried out by the Rietveld method (order of accuracy of 5%) showed that the product is composed of 35% quartz, 50% mineralogical clay and 15% plagioclase. A XRD was also carried out on a fine (less than 2 microns) fraction of clay. This XRD showed the presence of kaolinite (13%), illite (42%) but also of smectite (45%) in the mineralogical clay fraction. Kaolinite and illite are known to be non-swelling clays but smectite is known to have swelling properties. The presence of this swelling clay explains the relatively large blue value.
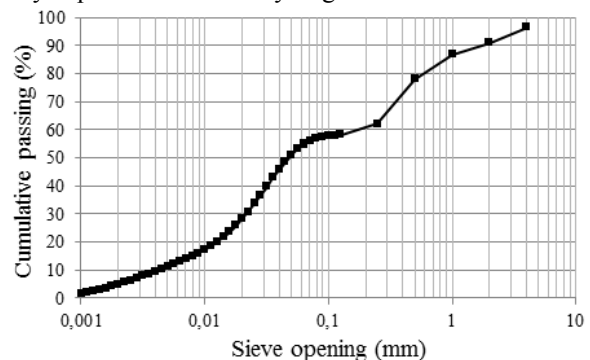

Figure 2: Cumulative size distribution of the Hins plaster.

To summarize, we have seen that the Hins clay have a sizeable part of quartz (35%) and more than 20% of swelling clay.

ARGILUS® mix

This earth plaster mix contains aggregates with a size ranging between 4 mm and 8 mm added to a mixture of sand and clay delivered in bag. The granulometric curve performed on the complete product is much more continuous than the curve previously obtained on the Hins plaster. Globally, laser analysis of the fine fraction showed that this plaster is also much thiner than the

previous plaster. The true density, also measured with a water pycnometer, is equal to 2760 kg/m³.

The methylene blue value, obtained on the sand/clay bag, is equal to 10.3 g of blue per kilogram of mixture. The Atterberg limits determination is impossible because the mixture hardens when it is in contact with water. The XRD analysis of the decarbonized fraction revealed the presence of quartz (10%), kaolinite (30%), illite (40%), chlorite or vermiculite (10%) and plagioclase (10 %). Thus, we see that only 10% of the fraction below 63 μm has potentially swelling properties (vermiculite).

The XRD analysis of the fraction smaller than 2 μm could not be performed because we have observed a rise of the background noise, typically due to an amorphous or organic compound present in the mixture. XRD on the decarbonized fraction has not been able to demonstrate an obvious presence of cement or lime.

SERIES "A"
In this first set of simulations, the typical wall of Paille-Tech (47cm) was compared to alternative walls through WUFI Pro simulations. The walls were submitted to outside climate corresponding to Test Reference Year of Brussels (Uccle). Inside climate is based on standard EN15026 (normal moisture load). If a systematic control of total water content of wall component, water content of each layer and water content of materials at strategic positions were analysed, the paper presents only the evolution of moisture content in the straw bales as a basis of comparison because it is considered to be the most relevent parameter for this study.

Type of outer layer and rain absorption
For series A1 (Fig.3), six cases were compared to analyse the influence of outside layers. *Case 1* is the typical walls of Paille-Tech (47cm). *Case 2* is the same wall, except that the wood cladding and the air layer are replaced by a complementary wood-fiber insulation of 6 cm with a very low liquid transfer render implemented in four layers. *Case 3* is the typical straw bale wall (*Case 1*) where the bracing panel is replaced by 4cm of lime render with A=0.047 kg/m².s$^{-1/2}$. *Case 4* is identical to *Case 3*, but with 4cm of earth plaster. *Case 5* is identical to *Case 3*, but with 4cm of cement plaster. *Case 6* is identical to Case 3, except that no rain load impacts the wall (Rain Water Absorption Factor set to 0).
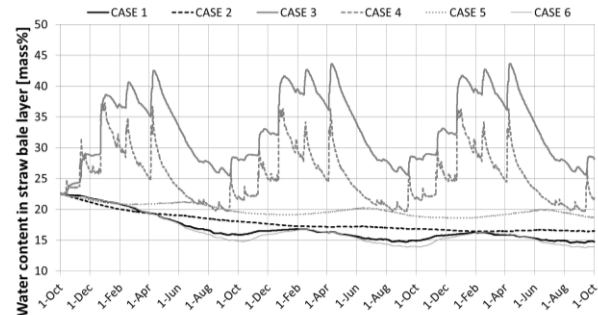

Figure 3: Series A1: Water content evolution in straw bale.

For series A2 (Fig.4), eleven cases were compared to analyse the effect of various coatings. *Case 1* corresponds to the *Case 3* of series A1 (no bracing panel, lime render). *Case 2* is identical, but 1cm of render on outside surface is replaced by a lime render with identical properties, except that the absorption coefficient is set to A=0.005 kg/m².s$^{-1/2}$ (10 times smaller than the original lime render). *Case 3* is similar to *Case 2*, but this time, A=0.001 kg/m².s$^{-1/2}$ (50 times smaller than the original lime render, i.e. with a water repellent coating). *Case 4* is identical to *Case 5* of series A1, i.e. with cement render. *Case 5* is identical to *Case 4*, but 1cm of the cement render on outside surface has lower liquid transfer coefficients: A=0.001 kg/m².s$^{-1/2}$ (7.6 time smaller than the original cement render, i.e. with a water repellent coating). *Case 6* is identical to *Case 5 with* A=0.0002 kg/m².s$^{-1/2}$ (same results as *Case 5*). *Case 7* is identical to *Case 4* of series A1 (earth plaster). *Case 8 and 9* are identical to *Case 7*, with outer layer (1cm) of render respectively with A=0.005 kg/m².s$^{-1/2}$ and A=0.001 kg/m².s$^{-1/2}$ (same results as *Case 2* and *Case 3*). *Case 10* is identical to *Case 1*, but absorption coefficient of outer layer of lime render (1cm) is set to 0 (the results are similar to *Case 3*). *Case 11* is identical to *Case 3*, but less driving rain reaches the wall, i.e Rain Water Absorption Factor set to 0,3 (only 30% of driving rain is available for absorption).
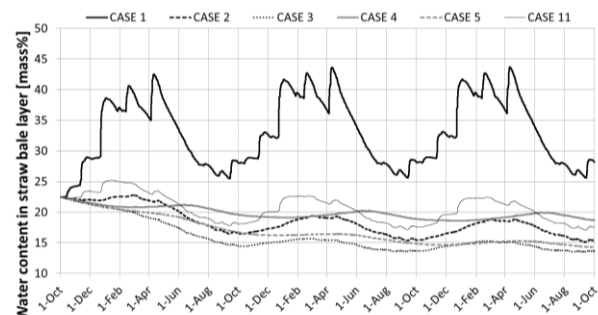

Figure 4: Series A2: Water content evolution in straw bale.

Vapour permeability of surface layer
Series A3 showed that for each case of series A1, replacing inside lime plaster with earth, cement or

gypsum plaster or changing its thickness did not have any significant effect on the results.

For series A4 (Fig.5), nine cases were defined to analyse the influence of relative vapour permeability of surface layers. *Case 1* corresponds to *Case 1* of series A1. *Case 2* is identical to *Case 1*, except a complementary vapour barrier of Sd=10m is added on inner surface. *Case 3* is identical to *Case 1*, except a complementary vapour barrier of Sd=3m is added on outer surface. No significant variations in the results were observed for this three first cases. *Case 4* corresponds to *Case 3* of series A1. *Case 5* is identical to *Case 4*, except a complementary vapour barrier of Sd=10m is added on inner surface. *Case 6* is identical to *Case 4*, except a complementary vapour barrier of Sd=3m is added on outer surface. *Case 7* corresponds to *Case 2* of series A2. *Case 8* is identical to *Case 7*, except a complementary vapour barrier of Sd=10m is added on inner surface. *Case 9* is identical to *Case 7*, except a complementary vapour barrier of Sd=3m is added on outer surface.
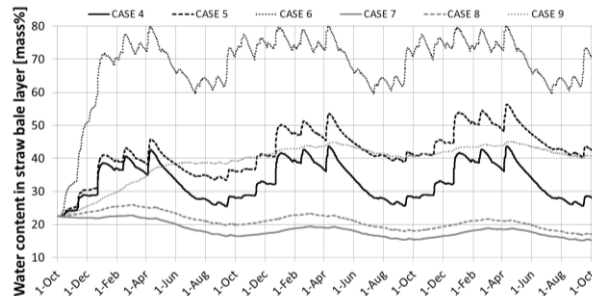

Figure 5: Series A4: Water content evolution in straw bale.

Straw bale
For series A5 and A6, *Case 1* and *Case 3* of series A1 were adapted changing either the thermal conductivity of straw bales (results for thermal conductivity of 0.6, 0.85 and 1.5 W/mK were compared) or the thickness of this layer (results for a thickness of 47cm and 37cm were compared). These variations did not have any significant effect on the results.

For series A7 (Fig.6), six cases were defined to analyse the influence of liquid transfer coefficient of straw bale. *Case 1* corresponds to *Case 3* of series A1 (where A_{straw}=0.05 kg/m².s$^{-1/2}$). *Case 2* to *Case 6* are identical to *Case 1* except that A-value of straw bale is adapted, changing at the same time both absorption and liquid transfer coefficient of redistribution. Chosen A-value were respectively A= 0.1 kg/m².s$^{-1/2}$ for *Case 2*; A= 0.5 kg/m².s$^{-1/2}$ for *Case 3*; A= 0.01 kg/m².s$^{-1/2}$ for *Case 4*; A= 0.005 kg/m².s$^{-1/2}$ for *Case 5*; A= 0.001 kg/m².s$^{-1/2}$ for *Case 6*.
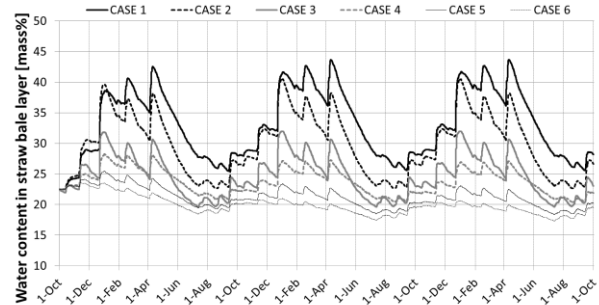

Figure 6: Series A7: Water content evolution in straw bale.

SERIES "B"
Hygroscopic materials affect indoor comfort and air quality through moisture exchanges with indoor ambiance. The Nordtest protocol and the definition of "Moisture Buffer Value" (written MBV) is one of the first attempts to characterize this moisture regulation performance [5]. The definition of MBV was used in [6] to define the "Thermal Buffer Value" (written TBV) in order to compare thermal regulation performance of building materials.

In this second set of simulations, different finishing materials used on inner surface are compared through WUFI Pro simulations. The walls were submitted to outside climate corresponding to Test Reference Year of Brussels (Uccle). Inside climate was defined with a succession of identical days. Each of them have, from 7am to 9pm, 33% of relative humidity and 20°C, and form 10pm to 6am, 75% of RH and 18°C.

For series B1 and B2, eight cases were defined to analyse the moisture and thermal regulation performance of inside plasters. *Case 1* corresponds to *Case 3* of series A1. *Case 2* is identical to *Case 1* except there is no lime plaster on inner surface. *Case 3* is identical to *Case 2* except the earth plaster layer is 8cm (vs. 4cm). *Case 4* is identical to *Case 1* except the earth plaster layer beneath the lime plaster is 8cm (vs. 4cm). *Case 5* is identical to *Case 1* except the lime plaster is replaced by a gypsum plaster. *Case 6* is identical to *Case 1* except the lime plaster is replaced by a cement plaster. *Case 7* is identical to *Case 2* except the earth plaster is only 2cm thick. *Case 8* is identical to *Case 1* except there is no inside plaster on straw bales. *Case 3* and *Case 7* gave approximately the same results as *Case 2*. *Case 4* gave approximately the same results as *Case 1*.

Heat and moisture flow on inner surface resulting from simulations were integrated to quantify heat and moisture quantity exchanged during those cycles. MBV (Fig.7) is the quantity of moisture the wall can absorb during 8 hours of higher RH divided by the variation of relative humidity (75-33=42%). TBV (Fig. 8) is the

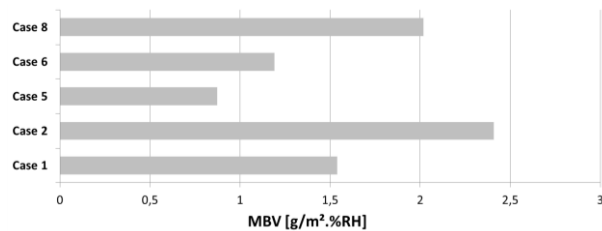amount of heat released during 8 hours of lower temperature divided by temperature variation (20-18=2K).
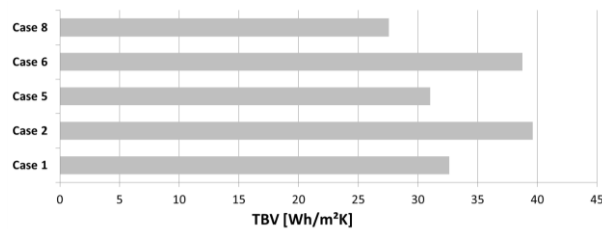

Figure 7: Series B1: Theoretical Moisture Buffer Value.

Figure 8: Series B2: Theoretical Thermal Buffer Value

DISCUSSION
Despite the unknowns that persist on composition of ARGILUS® mix (hydraulic binder, organic elements...) preliminary measurements on earth plaster showed that its granulometric curve is more continuous and it contains less swelling clay than the Hins plaster. These two parameters allow, among other things, to limit the shrinkage of this coating. These results convinced Paille-Tech to change the composition of its walls, using ARGILUS® mix instead of using Hins clay in a self-made mix.

If the thermal and environmental performances (at relatively low price) of straw bale walls are the main reasons of their development, the present paper focus on the importance of finishing layer on their hygrothermal performances and durability as literature lacks of rigorous analysis of these matters. Many laboratory measurements are still needed to model properly hygrothermal behaviour and durability of straw bale walls.

Based on literature review, maximum water content in straw bales, i.e. under which no decomposition occurs, will be considered to be 25% in mass (dry-weight basis) [2, 3]. Between 25% and 39%, the rate of straw decomposition is 0,009% a day; around free saturation water content, the rate of straw decomposition raises to 1,8% per day; approaching maximal water content, the rate of straw decomposition raises to 2,5% per day. The temperature also influences the decomposition (negligible below 5°C and optimum at around 30°C).

Series A1 and A2 showed that the typical wall produced by Paille-Tech, covered by a wood cladding, has no problem of moisture accumulation in any layer and specifically in the straw bales. It appears that driving rain absorption is the main factor to control to avoid these problems. If wood cladding on the outside surface is replaced by any kind of render, its liquid transfer coefficient must be as low as possible. In practice, the results showed that A-value of the render must remain under A=0.005 kg/m².s$^{-1/2}$. Any other way to reduce driving rain on the wall can also be considered.

Series A3 and A4 showed that vapour permeability of both inner and outer surface layer have less influence than driving rain absorption. When the wall is protected from rain (wood cladding, water repellent…) the effects of increasing Sd-value of 10m on inside surface or 3m on outside surface is negligible. However, for wall submitted to driving rain, it appears that increasing vapour permeability of outer layer have more effects than increasing vapour permeability of inner layer. Both case can lead to inadmissible water content in the straw bales (>25 mass%). The vapour permeability of surface layer must remain as low as possible to reduce equilibrium water content in the straw bales, and the use of paint or any other coating with low vapour permeability (int: Sd>10m; ext: Sd>3m) must be rejected on both sides of the walls.

Series A5 and A6 led to the conclusion the thermal resistance of straw bale layer has negligible influence on moisture equilibrium in the wall.

Series A7 shows that liquid transfer coefficients of straw bales have a great influence on the results. Many authors choose to neglect liquid transfer in straw bales [2]. It is interesting to notice that the most critical value is neither the highest, nor the lowest. In this paper, the most critical value, i.e. with A= 0.05 kg/m².s$^{-1/2}$, was chosen for all other series.

Series B1 and B2 showed the ability of the wall to regulate inside humidity and temperature through two parameter defined in literature: MBV and TBV. It appeared that earth plaster on inside surface gives the best results (high MBV and high TBV), followed by lime plaster. MBV of gypsum plaster is two times smaller than MBV of lime plaster and three times smaller than MBV of earth plaster. It is interesting to notice that the thickness of inside plaster does not have significant influence (if > 2cm).

CONCLUSION
The present paper presents the first step of a research on hygrothermal benefits of straw bale walls. The first laboratory measurements showed that the clay previously

used by Paille-Tech for inside earth plaster contains 35% of thin quartz had over 20% of swelling clay. In addition, a lack of particles in size classes between 63 μm and 250 μm was observed. Another mix, i.e. ARGILUS®, was analysed and gave better results, even if the X-ray diffraction measurement attest the presence of unknown amorphous or organic compound.

Hygrothermal parameters of straw bale and other materials used by Paille-tech, needed to run WUFI software, were found in literature. Liquid transfer coefficient of straw bales is usually not considered in literature. The nine series of simulations presented in this paper demonstrates that this hypothesis can lead to unsecure design in terms of moisture accumulation in straw bales. In addition, the results of series A1 to A7 showed that vapour permeability of inside and outside surfaces have less impact than driving rain absorption on outside layer. In terms of moisture and heat regulation of inside environment, series B1 and B2 showed that earth plasters gives the best results, followed by lime plasters.

As a conclusion, it is possible to design straw bale walls with wood cladding or appropriate render on outside surface and earth or lime plaster inside with no organic decomposition of the straw to provide comfortable living places in a sustainable way.

REFERENCES
1. King, B. (2006). Design of Straw Bale Buildings: The State of the Art. *Green Building Press, San Rafael, California, USA.*
2. Wihan, J., (2007). Humidity in straw bale walls and its effect on decomposition of straw. *PhD thesis of University of East London School of Computing and Technology, 269p.*
3. Minke, G. (2006). Building with Earth: Design and Technology of a sustainable architecture, Birkhauser, Germany.
4. Straube, J. (2003). Moisture Properties of Plaster and Stucco for Strawbale Buildings. [Internet] EBNet, Available from http://homegrownhome.co.uk/pdfs/Straube_Moisture_Tests.pdf
5. Peukhuri, R., Rode, C. (2005). Moisture buffer value: Analytical determination and use of dynamic measurements. *Working paper. IEA Annex 41 Meeting, Trondheim.*
6. Evrard, A. (2008). Transient Hygrothermal Behaviour of Lime-Hemp Materials. *PhD thesis of Univesité catholique de Louvain, 140p.*