Sustainability in Energy and Buildings: Research Advances:
Vol 3: Sustainability in Energy and Buildings (SEB-14) Short Papers pp.37-42 : seb14s-007

On the hygrothermal performance of straw bale wall elements in Belgium

Jelle Langmans[1], Alexis Versele[2], Staf Roels[1]

[1]Building Physics section, KU Leuven, Heverlee, Belgium – jelle.langmans@bwk.kuleuven.be
[2]Sustainable building research group, KU Leuven-KaHo,Ghent, Belgium

Abstract

The present article investigates the hygrothermal performance of straw bale walls in Belgian climate conditions. The first part presents measured Heat, Air and Moisture (HAM) properties of the corresponding construction materials (loam, straw and tras-lime mortar). The second part of the study verifies the hygric performance of the these construction elements based on transient numerical HAM-simulations on yearly basis. The simulation results demonstrate that the application of straw bale walls in Belgian climate conditions is vulnerable for high moisture contents and may result in mould growth during winter conditions.

1 Introduction

Environmental impact and sustainability is a growing priority for house owners. Particularly in the last decade, considerable progress has been made to minimize the ecological footprint of buildings. Countries with an overall masonry building tradition, such as Belgium are experiencing an increasing market share of timber frame construction [1]. In keeping with this growing trend toward more environmentally conscious buildings an age-old building method – straw bale construction – is gaining momentum. Such construction elements consists basically of a straw bale layer covered with a tras-lime plaster at the outside and a loam plaster at the inside (see Figure 1). The production of walls from local straw bales, plastered with local earth, has an incredibly low environmental impact. Yet the use of straw bale construction experiences strong resistance from the public opinion. The first doubts that generally come to mind is the resistance of straw bale walls to fire and rodents. While these worries can easily be dispelled by appropriate building details and application of good plaster onto straw [2], the question of the vulnerability of straw to moisture is more serious. Nevertheless these existing general doubts regarding straw bale construction, the hygrothermal performance of this building method is only scarcely documented in the international literature. Most of the existing studies concern *in-situ* measurements on occupied straw bales buildings [e.g. 4,5]. The case-studies discussed in the literature claim that the straw bale buildings moisture levels

ISSN 2054-3743 : http://nimbusvault.net/publications/koala/sebra

seldom rise above 20% in normal circumstances, and have an average of 17.5% moisture content at the outside edge of the wall, well within the accepted maximum safe level of 25% [6]. The majority of the addressed moisture problems were related to water ingress from the outside rather than vapour transport from the interior climate. Though these studies give an overall indication of the hygrothermal performance of straw bale construction elements, important information such as detailed boundary conditions and material properties are only briefly documented. In addition, the resolution of the measuring points is generally limited in these studies which implies the risk that not all phenomena are mapped.

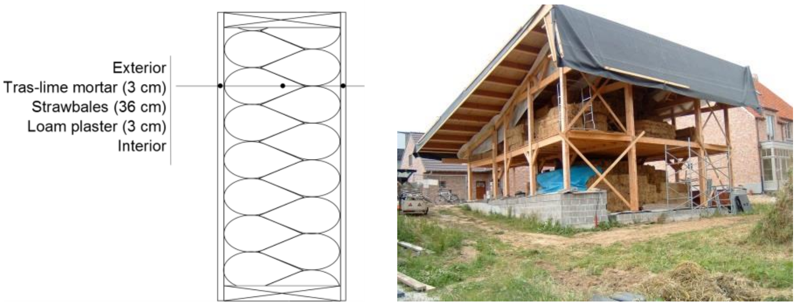

Figure 1: left) Straw bale wall and right) construction of straw bale house.

The major objective of the present paper is to collect detailed material properties of typical straw bale construction elements. The properties of loam, tras-lime mortar, and straw were measured in laboratory conditions. The second part of the article focusses on the hygrothermal behavior of a typical straw bale wall exposed to a Belgium climate. Transient numerical Heat, Air and Moisture (HAM)-simulation are performed with the state-of-art model DELPHIN 5 [9] to verify the overall hygrothermal performance of a straw bale wall and quantify the impact of natural air convection in such building elements.

2 Measurements of hygrothermal material properties

One of the key requirements for successful numerical predictions is the availability of correct material properties. Therefore most essential hygrothermal properties have been measured in the laboratory (Building Physics Section, KU Leuven). Figure 2 (left) provides the sorption isotherms of loam, tras-lime mortar and straw measured according to EN:12571. This figure illustrates the high hygroscopic buffering potential of these materials. In addition, Figure 2 (right) plots the measured vapour diffusion resistance factor µd (-) of loam and tras-lime mortar according to EN:12572. Determining reliable vapour permeability data of straw requires sufficient large test specimen. As such equipment was not available in the laboratory, its value could not be measured. Also in the international literature no reliable vapour permeability levels of straw are available to the authors knowledge. As remedy, its value will be included as a parameter in the numerical analysis in the following section (μ_s=1,2 or 3 (m)). Figure 2 shows irregularities in the properties of tras-lime mortar; the moisture content and the vapour diffusion resistance are not – as expected -continuously increasing with increasing relative humidity. This can be attributed by differences in the compositions of the specimen. It was for example noticed that the density of the specimen for the wet cup experiment were 10% higher than those of the dry cup experiment. The thermal conductivity λ (W/m²/K) of the straw bales have been measured in detail at the laboratory of BBRI on 8 full scale specimen. The results are summarized as a function of the fibre orientation in Table 1. Further, also the measured water absorption coefficient A (kg/m².s$^{1/2}$) and capillary moisture content of tras-lime are given in Table 1. For the non-capillary straw and loam these liquid transport properties are irrelevant. Finally, also the air permeability of straw is an important hygrothermal property. As straw is an highly porous medium, air convection flow might become important. Yet the air permeability levels of straw are not measured in the study, but adopted from literature [3].

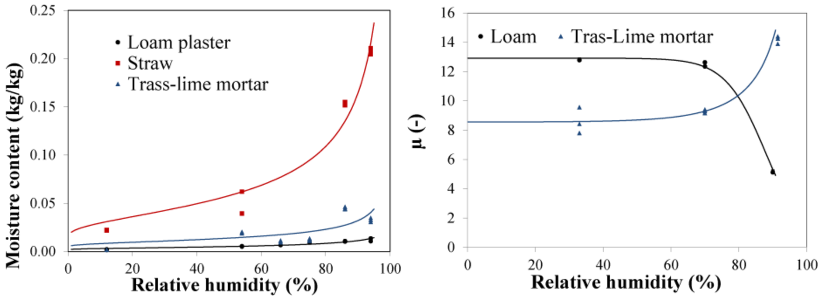

Figure 2: left) sorption isotherm and right) vapour resistance factor.

	Straw	Tras-lime mortar	Loam
ρ (kg/m³)	88	1269	1362
$\lambda\perp$ (W/m/K)	0.0589	0.73	0.30 [2]
$\lambda\parallel$ (W/m/K)	0.0667	-	-
$K\perp$ (m²)	110E-9 [3]	<8E-15	<8E-15
$K\parallel$ (m²)	63E-9 [3]	<8E-15	<8E-15
A (kg/m².s$^{1/2}$)	non-cap.	0.103	non-cap.
W_{cap} (kg/m³)	-	281	-

Table 1: Overview of the measured hygrothermal material properties.

3 Numerical simulation of hygrothermal performance

Yearly simulations under realistic climate conditions were conducted with an adjusted version of DELPHIN 5, capable to model forced and natural convection in interaction with detailed heat and moisture transport [9]. The simulation are conducted on the wall configuration of Figure 1 (left). This element concerns a 2.7 m high straw bale (36cm) wall with tras-lime mortar (3cm) at the outside and loam plaster (3cm) at the inside. In a first step 1-dimensional simulations are performed to investigate the impact of the vapour resistance factor of straw (μ_s=1,2 or 3 (m)) and the influence of the indoor relative humidity level (see section 3.1 below). In the second step 2-dimensional simulations are conducted which allows to verify the influence of natural air convection loops within the straw bale wall. The transient simulations have been conducted for yearly climate conditions (starting in October) and the mould growth index (M) [10] and the moisture content of the straw have been selected to assess the performance of these construction elements. Next section discusses the applied climate conditions.

3.1 Climate conditions

The walls are oriented to the North and exposed to Belgian climate conditions on hourly basis for the current simulations. The climatic data is retrieved from the building simulation software package TRNSYS (BE_UCCLE_64470). The inner temperature is assumed constant (20°C) throughout the year. Yet the inner humidity conditions are determined by a single zone model:

$$(\frac{V}{T_i R_V} + \frac{100\ HIR^{*} * V}{p_{v,sat}(T_i)} \frac{\partial p_{vi}}{\partial t} = (p_{ve} - p_{vi}) \frac{nV}{3600 R_v T_i} + G_{vp} \qquad (1)$$

in which V (m³) corresponds to the volume of the room and HIR* (kg/m^3%RV) to its hygric inertia, n (1/h) is the ventilation rate and G_{vp}(kg/s) is the vapour production in the room. The used parameters for the single zone model are chosen rather conservative: a small volume of 50 m^3 with a high moisture load of two active persons (120 gram/h) between 8h-22h. The nominal ventilation rate in living spaces is 3.6m^3/m^2/h according to the Belgium standard, corresponding to a ventilation rate of 1.51/h for this room. Several studies, however, indicated that the actual ventilation rate is often much lower. Therefore -to include the effect of a ventilation system in operation - the simulations are also conducted with a reduced ventilation rate (n=0.5 1/h). Finally, a value of 1.5gram/m^3%RV was chosen for the hygric inertia.

3.2 Results and discussion

Figure 3 gives the results of the 1-dimensional simulations. Two parameters are investigated in this graph: a) impact of vapour resistance factor (μ_s (-)) and b) inner humidity level (by varying the ventilation rate n in Eqn. 1). This figure shows the importance of both parameters. The black curves (lowered ventilation rate=higher interior humidity conditions) correspond to higher moisture content levels of the straw, and have thus, a higher risk for mould growth than the red curves (nominal ventilation rate=lower inside humidity conditions). Also the vapour permeability of the straw appears to have a significant impact on the predicted hygric behaviour. A higher vapour resistance factor results in lower moisture risk.

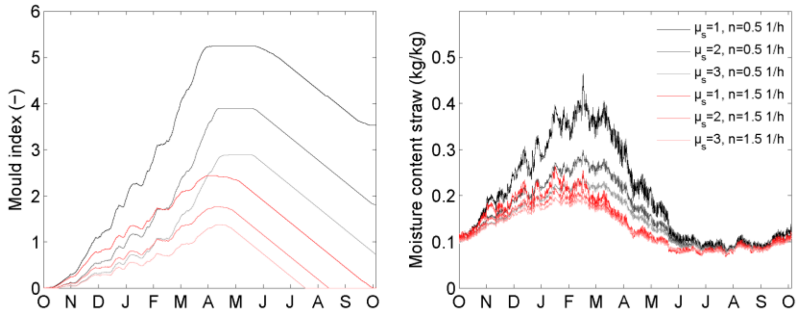

Figure 3: 1-dimensional simulations: left) mould growth index (-) and right) maximum moisture content of straw. (μ_s is the vapour resistance factor of straw (see section 2) and n is ventilation rate (see section 3.1)).

In a second step the simulations with the nominal ventilation rate (n=1.5 1/h) and a μ_s of 1 (-) are repeated with an 2-dimensional discretization grid. As a consequence these simulations account for natural air convection effects. Figure 4 compares the corresponding results (top, middle, bottom) with the 1-dimensional simulation of Figure 3 (μ_s=1, n=1.5 1/h). The graphs show that moisture redistribution becomes important when air convection is considered. As the straw bales are relative air open, a convective flow establishes in winter conditions (as illustrated in Figure 4(left)). As a result, the moisture content and mould growth risk increases at the top cold side of the wall.

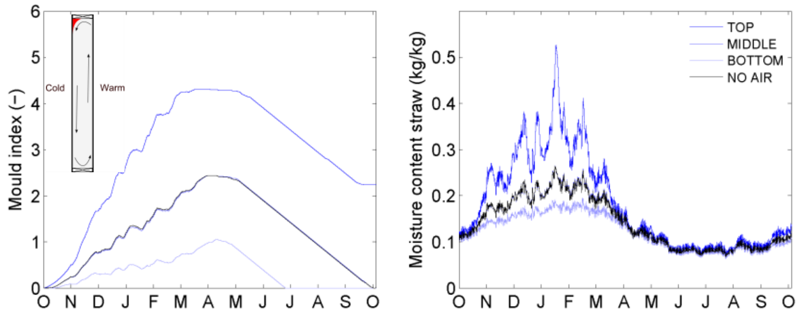

Figure 4: 2-dimensional simulations: left) mould growth index (-) and right) maximum moisture content of straw (μ_s=1, n=1.5 1/h).

The existence of natural convection in the straw bales may imply that also the thermal resistance of the wall is affected. Therefore the total heat loss of the 2-dimensional calculation is compared to the 1-dimensional simulation. The simulation result indicated that air loops in the insulation are only responsible for an 2.3% increase of the total heat losses.

5 Conclusion

The present article studied the hygrothermal performance of North faced straw bale walls in Belgium climate conditions. First, laboratory results of the most essential material properties are presented. Second, transient numerical HAM-simulations on yearly basis verified the hygric response of these wall elements. The result revealed that the straw bale walls in Belgium climate conditions are susceptible for mould growth. Even if the inner climate is sufficiently ventilated the risk for increased moisture levels remains as a consequence of moisture redistribution driven by convective air loops. The effect of these buoyancy driven convection on the overall thermal performance on a straw bale wall is limited in Belgian climate conditions. The numerical results presented in this article are partly in conflict with previous field studies in which lower moisture content levels have been found. Additional research is required to verify the origin of these discrepancies. Potential research directions might be measuring the vapour resistance factor of straw and performing hotbox/coldbox investigations on these construction elements.

References

1. Belgian Building Confederation (2011) Architect inquiry on the vision of building methods for low-energy constructions
2. Ashour, T., Wieland, H., Georg, H., Bockisch, F.-J., & Wu, W. (2010). The influence of natural reinforcement fibres on insulation values of earth plaster for straw bale buildings. Materials & Design, 31(10), 4676–4685.
3. Christian, J. E., Desjarlais, A. O., & Stovall, T. K. (1998). Straw Bale Wall Hot Box Test Results and Analysis. In ASHRAE (Ed.), Proceedings of Thermal Performance of the Exterior Envelopes of Buildings VII, Clearwater
4. Ashour, T., Georg, H., & Wu, W. (2011). Performance of straw bale wall: A case of study. Energy and Buildings, 43(8), 1960–1967.
5. Goodhew, S., Griffiths, R., & Woolley, T. (2004). An investigation of the moisture content in the walls of a straw-bale building. Building and Environment, 39(12), 1443–1451.
6. Carfrae, J. I. M. (2011). The moisture performance of straw bale construction in a temperate maritime climate. PhD thesis. University of Plymouth.
7. Wihan, J. (2009). Humidity in straw bale walls and its effect on the decomposition of straw. University of East London School of Computing and Technology.
8. BBRI (Belgium Building Research Institute) (2013).Test report: thermal conductivity of straw bales.
9. Langmans, Jelle, Andreas Nicolai, Ralf Klein, and Staf Roels. 2012. “A quasi-steady state implementation of air convection in a transient heat and moisture building component model.” Building and Environment 58 (12).
10. Hukka, A & Viitanen, H (1999), ‘A mathematical model of mould growth on wooden material’, Wood Science and Technology 33(6),475–485.