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STRAW-BALE WALLS FOR SUSTAINABLE ARCHITECTURE: IMPROVING AND PROMOTING THE USE OF STRAW-BALE USE IN EUROPEAN BUILDINGS

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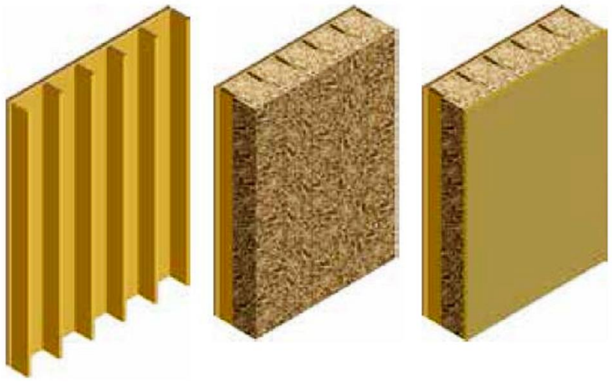

Fig 1: Straw-bale wall studied, prefabricated in Wallonia

WHICH ARE YOUR ARCHITECTURAL (R)SOLUTIONS TO THE SOCIAL, ENVIRONMENTAL AND ECONOMIC CHALLENGES OF TODAY?

Research summary

Straw-bale use in buildings may be an interesting way to decrease our energy needs and our impact on the environment. Moreover, it fosters a local economy and the creation of new jobs in the building industry. Combined with earth materials and other well-selected materials and systems, it allows creative designers to integrate highly efficient, low-tech and reusable envelopes in comfortable and healthy places. The present paper summarizes the results of a four year R&D program aiming to improve and promote the use of straw bale in buildings and also to remove uncertainties concerning this use.

Three main aspects are pinpointed and discussed: hygrothermal transfer and storage in straw-bale walls, regulation of indoor conditions and environmental impact in the long term. These three topics were submitted to European experts (France, England and Germany) in order to discuss a cross-comparison of results obtained on a larger scale.

The paper shows that straw-bale use in buildings is a relevant and innovative solution in facing one of the major challenges of today and tomorrow: "How to build/transform comfortable and affordable buildings with local resources and with a positive impact on the environment?".

Keywords: Straw-bale; hygrothermal transfer, storage and regulation; environmental impact

1. Introduction

The present paper summarizes the results of a four year R&D program aiming to improve and promote the use of straw-bale use in buildings and also to remove uncertainties concerning this use. Fig. 1 shows the straw-bale wall prefabricated in Wallonia by the industrial partner of the research. The wall is built with 46 cm or 36 cm of straw (structured with a timer framed structure), covered on the inside with a 4 cm earth plaster and on the outside with a 1.6 cm bracing panel (open to vapour). This wall's typology has been presented by Evrard et al. (2012). Many variants were also studied.

The present paper pinpoints and discusses three main aspects: hygrothermal transfer and storage in straw-bale walls, regulation of indoor conditions and environmental impact in the long term. These three topics are under discussion with European experts (France, England, Germany and Belgium) in order to cross-compare their results.

The first part of the paper proposes design guidelines to ensure an appropriate use of straw bales in buildings, taking into account moisture sorption, vapour permeability and thermal transfer. The importance of having available material data is highlighted and further research is suggested. A special focus on thermal conductivity presents the state of the art in Europe and shows that sample type can lead to significant variations in the results, especially as concerns straw orientation and density.

In the second part, results from monitoring and simulations are presented. The effects of using straw-bale walls on inner temperature and moisture regulation are discussed taking into account the presence of interior earth plasters, occupation and ventilation rate of the rooms. The Moisture Buffer Value and the Thermal Buffer Value of walls are found to be useful parameters for designers.

The last part of this paper addresses issues on the Life Cycle Assessment of the straw-bale walls studied. This analysis requires many assumptions, e.g. straw can be considered as waste from cereal production (production of straw bales is not considered), or as a by-product of food production (sharing its environmental impact).

2. Hygrothermal transfer and storage

2.1 Moisture content and organic stability

As a natural organic material, straw is sensitive to humidity. Wihan (2007) and Minke (2006) provide the rate of straw decomposition depending on its water content. Based on the sorption curve measured in this research, relative humidity in the straw should not be over the critical value set at 91.5%, corresponding to a water content of 25 mass%. The rate of straw decomposition is assumed to be: 0.009 mass% per day between 91.5% and 95%; and 1.8 mass% approaching free saturation. As humidity in the straw bale is often the highest in the region of the bracing panel (under the exterior finishing), having no decomposition at this location can be used to certify the validity of the wall. It has to be noted that temperature also influences the decomposition (negligible below 5°C and optimum at around 30°C).

Danielewicz et al. (2008) use results from measurements at the Fraunhofer-Institut for Building Physics in Holzkirchen and compare with to results from WUFI Bio simulations to draw similar conclusions.

2.2 Rain absorption

Evrard (2012) has shown that driving rain absorption is the main factor to be controlled when one wants to avoid problems of moisture accumulation in any layer and specifically in straw bales. When the wall shown in Fig. 1 is covered by ventilated wood cladding (neither rain nor sun reached the wall surface), previous research has shown that water content was always under 25 mass% under the bracing panel when submitted to Belgian climate (Test Reference Year in Uccle).

When the bracing panel is not used in this case and the outside surface of the wall is rendered, liquid transfer coefficient of the render should remain as low as possible, e.g. under A= 0.005 $kg/m^2.s^{-1/2}$, to avoid problems due to rain absorption.

Any other way to reduce driving rain on the wall can also be considered (e.g. roof overhangs□double skiné).

2.3 Vapour diffusion

When the wall shown in Fig. 1 is covered by a ventilated wood cladding, it did not appear to be sensitive to vapour permeability of inside or outside finishings.

When the wall is covered with a render with an appropriate liquid transfer coefficient, Evrard (2012) showed that vapour permeability of inside finishings can be relatively high, i.e. up to an equivalent air layer thickness of Sd= 10m, without significant effects on the water content in the straw bales. On the contrary, if the finishing on outside surfaces (render, painting□water repellenté) is not open enough to vapour, i.e. Sd-value of 3m or more, water content in the straw may rise dramatically to over 25 mass%.

2.4 Thermal transfer

Once the validity of straw-bale walls is confirmed in terms of rain absorption and vapour permeability, the most important question is the actual thermal transfer coefficient of walls. It is calculated on the basis of the thermal conductivity of each material of each layer. For all materials, this parameter is sensitive to moisture content and temperature, but usually, only one value is given. According to EN ISO 10456, the samples should be stored in an environment of 23°C and 50% of relative humidity, and measurement takes place at 10°C (e.g. hot plate at 15°C and cold plate at 5°C). The equipment must match standard measuring equipment (ISO 8302). Available equipment in Belgium was not adapted to measure full-size straw bales and a specific guarded hot plate (Dubois, 2013) was designed.

For straw bales, thermal conductivity also depends on the density of the straw bales, the type of straw and the direction of the heat flow. In this research, three directions are defined for the heat flow, as illustrated in Fig.2. Direction n°1 is the direction of the flow when the straw bales are placed on the larger side, as in the typical wall represented in Fig. 1 (thickness around 46 cm). The straw bales can also be placed vertically (thickness around 36 cm), the flow then follows direction n°2. Direction n°3 is usually not used because of the important thickness of the walls it would imply (thickness around 60 to 80 cm).

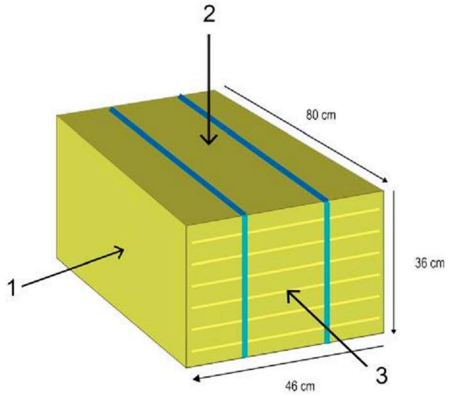

Fig 2: Direction of main heat flow

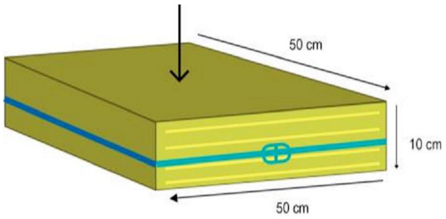

Fig 3: Example of reshaped samples

In current EPB regulations in Belgium (NBN B62-002) a value of ə= 0.065 W/mK can be used for a large range of natural insulation materials such as straw bales. Shea (2013) proposed to use ə= 0.064 W/mK as a representative design value for straw-bales at the densities used in building construction. These values may not seem favourable for promoting the use of straw bales in buildings, especially when compared with the value proposed in the German certificate (DIBt, 2014) when heat flow is perpendicular to straw fibresə= 0.052 W/mK.

The main specificity of this study is to measure full-size straw bales, as used in building construction. In most of the other studies, the samples are reshaped to fit into the measuring device, as illustrated by Fig. 3. In these samples, fibres can be organised perpendicularly or parallel to the heat flow. The two corresponding values obtained for thermal conductivity are thus usually distinguished.

In the full-size straw bales analysed in this research, it was observed that fibres generally have a random distribution in both direction 1 and 2, except for some straw bales which are produced with a special effort to organise the fibres in one direction or the other. A similar thermal conductivity is thus expected for direction n°1 and n°2. In direction n°3, fibres were found to be perpendicular to the heat flow and thermal conductivity should be lower than in the other directions.

Fig. 4 shows the thermal conductivity of tree samples tested in direction 1 (46cm)ñ1ò with a density of 58 kg/m³ñ2ò with a densitof 112 kgm³ and ñ3ò with a densit of 134 kgm³. Value ñ4ò and ñ5ò are respectivel the value proposed by Shea (2013) and (DIBt, 2014).

The measuring campaign is still running and it will lead to a complete analysis of the parameters which influence thermal conductivity: moisture content and temperature of the sample before the test, temperature during the test, direction of the heat flow, density and type of cereal or baler.

Density and orientation of the fibres are perhaps the two most significant parameters. The value proposed by Shea (2013) and DIBt (2014) should be used when appropriate.

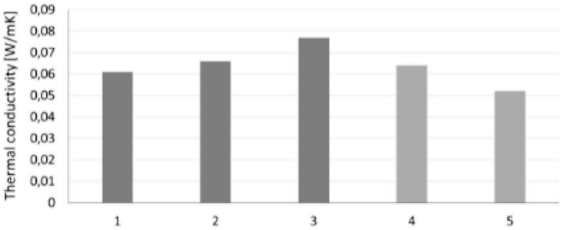

Fig 4: Thermal conductivity of few full-size samples

2.5 Moisture and Thermal Buffer Value

As detailed in Evrard (2012), hygroscopic materials affect indoor comfort and air quality. The Nordtest protocol and the definition of ñMoisture Buffer Valueò (abbreviated to MBV) is one of the first attempts to characterize this moisture regulation performance (Rode, 2005). The definition of MBV was used by Evrard (2008) to define the ñThermal Buffer Valueò (abbreviated to TBV) in order to compare thermal regulation performance of building materials and assess which material contributes the most to global thermal inertia. MBV and TBV of six finishing materials on straw bale walls is compared in Fig. 5 and 6. Inside climate is set with a succession of identical days. Each of them have, from 7am to

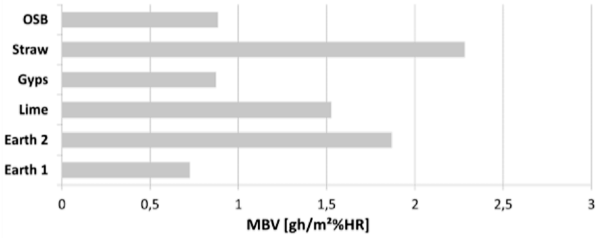

Fig 5: Moisture Buffer Value

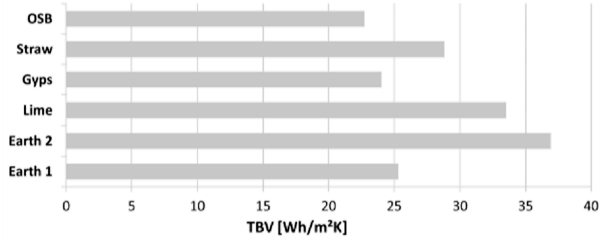

Fig 6: Thermal Buffer Value

9pm, 33% of relative humidity and 20°C, and from 9pm to 7am, 75% of RH and 18°C. Results were obtained with WUFI Pro software. ñEarth 2ò (4cm), a classical earth mixture used for plastering inside walls, has a great ability to regulate inside temperature and humidity compared to other materials (MBV and TBV are high). ñEarth 1ò (4cm) is initially produced for use with floor slabs, not for plasters (additives may have been added). The results show that a large range of behaviour can be obtained depending on the composition and the inner structure of the earth mixture. ñStrawò (the same wall, but with no finishing) is presented for comparison, but cannot be used alone. Based on MBV and TBV, the interesting ability of 2cm ñLimeò plasters to regulate inside temperature and humidity can also be observed.

3. Results from monitoring and simulations

As presented by Evrard (2014), three straw bale buildings recently built in Belgium were monitored during the research presented in this paper. For each building, results on internal evolution of temperature and humidity distribution in the walls, as well as inside and outside conditions, are analysed with WUFI Pro and WUFI Plus software.

3.1 In wall components

Fig. 7, 8 and 9 show the evolution of relative humidity at the critical point (under the bracing panel) for all monitored walls.

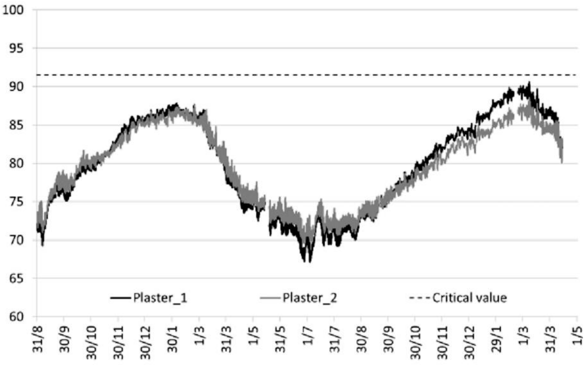

Fig 7: RH under the bracing panel in Franière

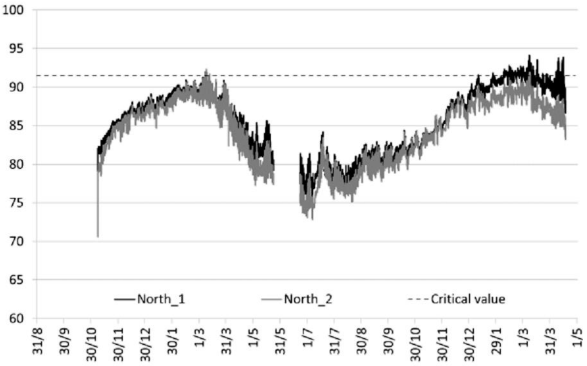

Fig 8: RH under the bracing panel in Uccle

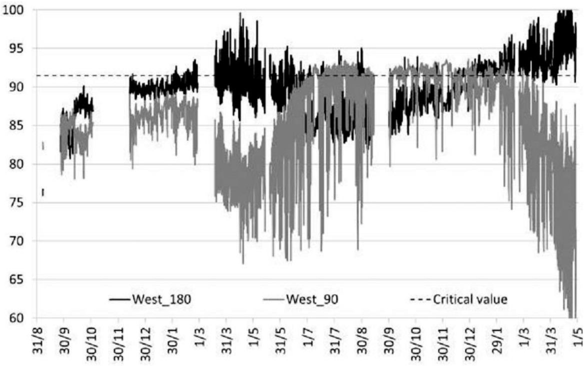

Fig 9: RH under the bracing panel in Tongrinne

Fig. 7 shows that no degradation will occur in Franière. Both walls, with two different inner plasters, are found to be valid. It has to be noted that the walls of this building are protected from the rain (and the sun).

Fig. 8 shows relative humidity under the bracing panel of North walls in Uccle. It is almost always under the critical value (91.5%). Nevertheless, a limited decomposition of straw may have occurred in this region, during only 12 hours last year, but during 684 hours since January 2015. At no time, did the relative humidity rise over 95%. As only less than 0.3 mass% of straw could have been chemically altered, and because the temperature is around 10°C at this position during the high humidity period (slower decomposition), no major problem is foreseen in these walls but attention should be paid to long-term behaviour. Relative humidity in South walls was also measured. It appeared to be always under 80%. Higher humidity of North walls is explained by a higher moisture load inside (bathroom facing North and bedroom facing south) and a good water repelling system, avoiding rain absorption of South walls (main driving rain comes from the South-West in Belgium).

Fig. 9 illustrates the results in two walls facing West in Tongrinne. The two chains of sensors were placed on the same wall of a bedroom on the first floor, one at a height of 90cm above floor level (ñWest_90ò) and the other at 180cm (ñWest_180ò). Both curves differs from what was expected based on the preliminary simulations. This observation cannot be explained except by implementation heterogeneities (e.g. air infiltration). Based on these results, an important decomposition could have occurred during the last 20 months, with a relative humidity over 91.5% during 2627 hours for ñWest_90ò (never over 98%) and over 3044 hours for ñWest_180ò (with 522 hours between 95% and 99% and 70 hours over 99%). Further investigation is needed to understand this unexpected behaviour.

These results suggest extending the period of observation until next winter if possible, at least for the buildings in Uccle and Tongrinne.

3.2 Indoor conditions

Offering comfort should be the first aim of designers. As presented in the previous section, Thermal Buffer Value (TBV) and Moisture Buffer Value (MBV) show that, submitted to identical conditions, walls do not all have the same ability to regulate inside temperature and humidity.

Evrard (2013) compared a straw-bale wall covered with interior earth plaster with two types of walls built with concrete breeze blocks insulated with XPS insulation panels respectively inside and outside. All the walls analysed have an identical dry U-value of U= 0.134 W/m^2K. The simulations are made with WUFI Plus software. This software allows taking into account the transient hygrothermal transfer and storage in walls (as does WUFI Pro), and the evolution of inside temperature and humidity (taking into account sun radiation, ventilation rate and occupation). It means that the software allows the assessment of inside comfort conditions (i.e. air temperature and humidity, surface temperature, CO_2 levelsé) as well as heat load (and latent heat effectsé) for a given comfort set point.

For cases where no ventilation was modelled, it was observed that straw-bale walls offer better comfort in terms of inside humidity. Comfort conditions in terms of inside temperature (daily variations, reduced overheating periodsé) are high as in the case with the breeze block walls insulated on the outside surface, but higher than with the breeze block walls with inside insulation.

These results confirm what appeared through the analysis of MBV and TBV.

Unfortunately, when ventilation is implemented to reduce CO_2 levels under 1000 ppmv, the moisture transferred (from inside to outside) through the inner surface of the walls, was almost 30 times lower in winter than the moisture extracted by ventilation. The correlation between the evolution of inside humidity and the wall types is no longer significant.

These rather disappointing results should not hide the high comfort conditions that straw bale can offer in terms of inside air temperature. As a matter of fact, with 4 cm of earth plaster on the inside surface, it appears that using these walls reduces the overheating period more than the two other walls, even the one with breeze blocks insulated on the outside surface.

4. Life Cycle Assessment

Life Cycle Analysis of agricultural products used as building materials requires choosing between two main hypotheses. Either the product is considered as waste from agricultural processes or it can be considered as a by-product. Unfortunately, this “by-product” hypothesis is usually not used by material producers and in official data bases such as the Environmental Product Declaration (EPD) at the European level or FDES in France. For example, LCA data of cellulose do not take into account ingoing and outgoing upstream flow for products such as newspapers, magazines, etc. It usually starts when the newspapers, considered as waste at this point, are picked up on the house front.

Obviously, this divergence in points of view leads to consistent differences in the results.

4.1 By-product of food production

The “by-product” hypothesis was used during the first part of the research. This is justified by the fact that, by definition, waste is any substance or object which the holder discards, intends to discard or is required to discard (see standard EU 2008/98/CE). But, in addition to its use in feeding livestock, straw is essential for farmers in order to preserve soil structure and initial organic content.

4.2 Waste from cereal production

The “waste” hypothesis seems to be mainly used for natural or recycled building materials. It clearly allows better results in LCAs as all upstream flows are considered neutral. In straw-bale building, the straw is generally considered as waste from cereal production. The impact of ground working processes, seeding and spraying of phytosanitary products are thus not considered in this case. The only work taken into account is the baling itself. As this approach seems to be the one chosen for a significant amount of reference data, the last part of the present research will run a new Life Cycle Analysis of Belgian straw bales in order to compare the results with previous ones and with those obtained for other materials such as cellulose insulation.

4.3 Hybrid approach

A third approach exists, balanced between these two hypotheses. It aims at taking into account the fact that the farmer has to spread fertilizer to compensate the lack of organic content in the ground created by the export of the straw from the field. The environmental impact of this additional work is allocated to the straw itself. This approach has not been tested in the scope of this research but is currently being investigated in France.

5. Conclusions

As soon as the assessment of Energy Performance of Buildings will consider a larger scope of criteria, such as thermal inertia, embodied energy, CO_2 emissions, local resources, end of life scenario, global cost, etc., the straw-bale walls will grow even more competitive compared with other types of building techniques. Today, we consider that straw bales are underused in buildings and that the market will evolve in the next few decades.
Many aspects are not covered in the present paper, such as fire resistance or structural behaviour, but these topics have been studied in other research. Airtightness may be an important topic for further investigation.
The results presented here do not show that straw-bale walls have a significant effect on humidity regulation, but their high effect on thermal inertia can be confirmed when combined with earth plasters. On the other hand, these results confirm that straw-bale use in buildings must be accompanied by a careful design with specific attention to rain absorption, vapour and thermal transfer to validate its long-term behaviour.
The paper shows that straw-bale use in buildings is a relevant and innovative solution in facing the challenge of how to build/transform comfortable and affordable buildings with local resources and with a positive impact on the environment.

6. Acknowledgments

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