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A long-term monitoring study on the thermal comfort and durability of a straw bale Passivhaus cottage.

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Abstract. The built environment sector accounts for 40% of the UK's total carbon footprint; bio-based construction materials can play an important role in reducing the whole-life carbon of a new build. Straw bale construction is one of the most promising bio-based methods of construction, due to its availability and material properties. Among the declared benefits of straw bale construction are the internal regulation of heat and moisture and the ability of the fabric to dry out. This paper presents a long-term monitoring study aimed at understanding the indoor temperature and moisture balance of a straw bale cottage built in the UK to a near Passivhaus level. The study lasted 6 years, monitoring the temperature and relative humidity of the indoor and outdoor environments, and in ten locations within the straw bale walls. The analysis has shown that the indoor environment achieved thermal comfort throughout the monitoring period, even when the building was used intermittently. Also, an analysis of surface temperatures and a mould growth risk analysis identified very limited mould growth risk within the building fabric. This paper shows the potential of straw bale low-energy construction in providing thermal comfort and a durable building fabric while minimising the whole-life carbon of buildings.

1 Background

Straw has been used as construction material in vernacular buildings; straw thatched roofs are common in the UK and early 20th century straw bale walls can still be found in France and in the USA. However, straw bale construction has found renewed popularity since the 1990s [1], as an answer to the environmental challenges the construction industry is facing.

Anne Thorne Architects' first experience of building in strawbale was for a building in Lordship Recreation Ground in North London, where local people were able to join in the construction to create their community centre. It was found that the internal environment created was particularly stable, both in terms of temperature and humidity. This second project is in a rural location in Norfolk, approximately 2 miles from the east coast, and thus vulnerable to weather from the east. We found very little information about strawbale performance and saw this as a good opportunity to gather data.

2 Methodology

The challenge to designers was to successfully integrate readily available and minimally processed low embodied energy materials; straw, timber, clay and lime, with sophisticated Passivhaus standard windows and whole house mechanical heat recovery (MVHR).

Sensors were installed within the strawbale walls during construction, in 2014. We used the Omnisense monitoring system, as the Association for Environment Conscious Building (AECB) had suggested members use this system so that data collected across the low energy buildings data base would be easily comparable.

The monitoring was carried out between 2014 and 2020; this paper presents and discusses the results of the long-term monitoring of the strawbale walls of this case study building. The building was occupied for half of the time (e.g. weekends and holidays) until 2019, and it has been fully occupied since.

Fig. 1. Case study building, east elevation [2]

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2.1 Sensors location

Ten temperature and relative humidity sensors were installed within the walls, on the east, north and south elevations. Moreover, one sensor was installed in the living room, capturing the conditions of the indoor environment (i.e. temperature and relative humidity). Within the wall, three positions were considered:

- the inner bale position, 10 cm from the internal side of the straw bale ("inner sensor");
- the outer bale position, located 10 cm from the external side of the straw bale ("outer sensor");
- the central position, with the sensor located on the timber element at the centre of the strawbale wall ("central sensor").

An example of the sensors installation is shown in Figure 2.

Fig. 2. Outer sensor (left) and central sensor (centre) installed in the strawbale wall.

While the sensors on the east and south walls were located in areas of the wall that were fully exposed to the weather, the sensors on the north wall were sheltered by the roof and its overhangs. Also, an outdoor temperature and relative humidity sensor was located under a pergola, sheltered from direct solar radiation.

2.2 Methods of analysis

First, the indoor temperature and relative humidity over the monitoring period were analysed. The analysis then focused on the interstitial conditions, with a discussion on the temperature profiles and moisture levels across the wall, including at the internal surfaces. This analysis considered simple mould growth risk criteria, derived from the Approved Document F of the UK Building Regulations [3]:

- A maximum monthly average of relative humidity of 65% for indoor environments;
- A maximum monthly average of relative humidity of 75% for surface and interstitial conditions (representing a surface water activity of 0.75).

Finally, a mould risk analysis was performed on all the sensors located within the wall exceeding the simplified criteria.

2.2.1 Mould growth prediction

A mould growth risk analysis was performed for those locations where the relative humidity sensors exceeded 75%. The mould growth prediction is based on the VTT model [4], which considers the influence of temperature and relative humidity on a wooden substrate. The original version of the mould growth model was based on large laboratory studies with pine sapwood, considered a very sensitive substrate. Straw is found to "be able to withstand relatively high transient moisture contents without suffering serious decay" [5], especially when straw is part of a wall construction. Therefore, this analysis considered a sensitive substrate (the least sensitive for bio-based materials, similar to spruce and wooden boards) to avoid an overly conservative analysis. The default scenario (almost no decline) for mould index decline during unfavourable conditions for mould growth was considered due to lack of evidence on drying behaviour, although it is possible to consider less conservative values. The mould growth index, MI [-], is described in Table 1.

Table 1. Mould index [4]

MI [-]	Description
0	No growth
1	Small amounts of mould on surface (microscope), initial stages of local growth
2	Several local mould growth colonies on surface (microscope)
3	Visual findings of mould on surface, < 10% coverage, or < 50% coverage of mould (microscope)
4	Visual findings of mould on surface, 10%–50% coverage, or > 50% coverage of mould (microscope)
5	Plenty of growth on surface, > 50% coverage (visual)
6	Heavy and tight growth, coverage about 100%

The sensors exceeding a relative humidity of 75% were those located within the structure, in the outer location; the occurrence of mould in this location is not likely to affect the indoor environment and occupants' health. However, mould growth can be used as a conservative proxy for material decay, as it was done in this analysis. For interfaces and surfaces which are not in direct contact with the interior air, Viitanen [6] suggests a MI as threshold above which the mould growth risk is not acceptable. Values of MI higher than 2 represent a possible risk and require further assessment; values of MI higher than 3 represent high risk and should be avoided. It is worth noting that these thresholds have been developed to support design and represent a conservative estimate of mould growth risk.

3 Results and discussions

3.1 Indoor conditions

The indoor monitoring shows an average temperature of 20.7 ºC between 2015 and 2020, and an inter-quartile range of temperatures between 19.6 ºC and 22.5 ºC even when the cottage is often under-occupied, particularly until 2019 (see Figure 3). Analysing the heating and cooling seasons separately, the average temperature for the heating seasons (October to March) is 19.3 ºC (interquartile range between 17.6 ºC and 21.3 ºC). Since 2019, when the building has been occupied full time, the interquartile temperature range in the heating season has been steadily between 20.1 ºC and 21.7 ºC, with limited use of active heating systems.

The average temperature for the cooling seasons is 22.3 ºC, with a maximum temperature of 29.2 ºC during the 2018 heatwave; on that day, the outdoor sensor indicated a maximum temperature of 35.7 ºC and there is no active cooling in the building.

The indoor relative humidity is found to be within the recommended mould growth threshold for indoor environments throughout the monitoring period, apart from a very small number of instances. Also, the relative humidity is rarely below 40%, the lower threshold for thermal comfort.

This demonstrates that the strawbale construction analysed is able to maintain very steady indoor environmental conditions, within the criteria for thermal comfort and mould safety, even in case of under-occupancy and limited use of heating systems.

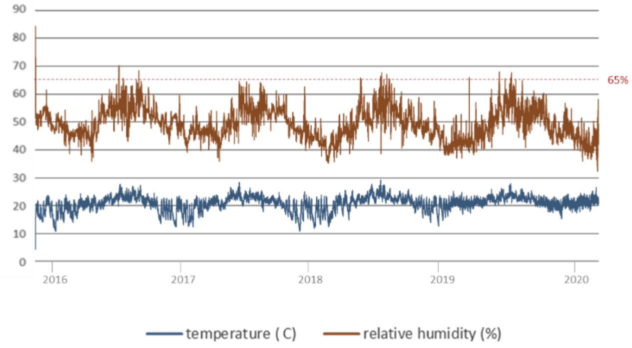

Fig. 3. Indoor conditions, measured in living room

3.2 Interstitial temperatures

3.2.1 Inner sensors and surface conditions

The inner sensors, located 10 cm from the inner side of the strawbale layer, measured the interstitial temperature and relative humidity conditions since construction, for the east (2 sensors), north and south walls.

The temperatures of the inner sensors follow closely the trend of the indoor temperature, measuring 3 ºC less than the indoor temperature on average. The relative humidity at the four sensors locations is always lower than the mould growth criterion at surfaces and interfaces considered in this analysis (75%), apart from a very short period immediately after construction for some of the sensors, as exemplified in Figure 4 (south wall). This period coincides with the drying period for the construction materials, in particular of the clay plaster and lime render that have been applied on the sides of the strawbale layer. The short duration of this initial wet period suggests little/no mould growth risk.

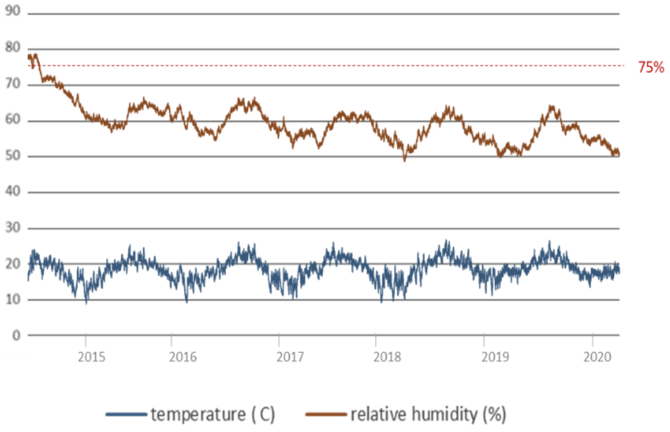

Fig. 4. South wall, inner sensor

As all the inner in-wall sensors are at lower temperatures than the indoor environment, the temperature of the wall internal surface is assumed to be between the indoor and the inner in-wall temperatures. Considering that none of the inner in-wall sensors reach relative humidity levels close to the risk threshold of 75%, the surface is expected to be in safe conditions, and mould is not likely to grow on the indoor surfaces.

3.2.2 Outer sensors

Using the same method to the inner sensors, the outer sensors were located 10 cm from the outer side of the strawbale layer and measured the interstitial temperature and relative humidity conditions since construction, for the east (2 sensors), north and south walls.

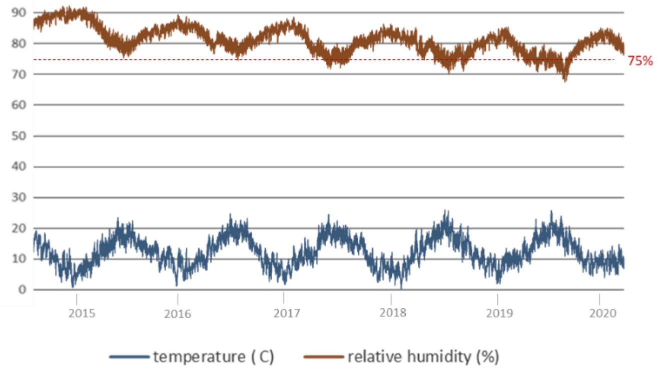

Fig. 5. North wall, outer sensor

As shown in Figure 5, the relative humidity at the outer sensors locations can be higher than the mould growth threshold of 75%; this was found to be the case for all orientations, and the north wall is shown as example. As those sensors are located towards the outside of the wall, the main concern is material decay, as opposed to indoor environmental quality, important towards the indoor environment. We decided to assess the risk of mould growth as a proxy for material degradation.

3.3 Mould growth risk analysis

Figures 6 to 8 show the mould index results for the east, north and south wall respectively, for around 5 years. No locations show a mould index higher than 3, suggesting low-to-mid risk of mould growth. Only the east wall shows a mould index between 2 and 3, requiring further assessment. However, in this instance, Figure 6 shows that the peak of mould index was followed by a reduction in the index in the subsequent years. Thomson and Walker [5] found an arrested level of mould growth on straw after initial growth; in their experiment, after an initial growth associated with exposure to high levels of humidity, mould growth was not detected a second time. Therefore, the reduction of mould index in Figure 6 suggests limited mould growth risk in this wall. Figures 7 and 8 show a mould index below the set MI thresholds.

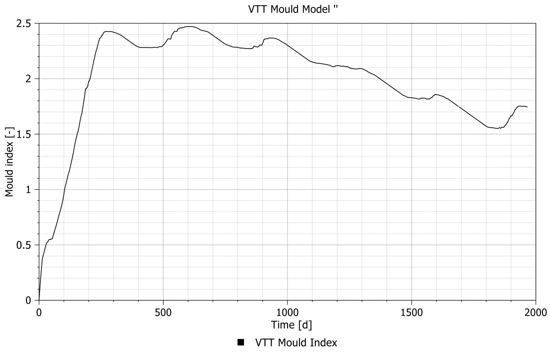

Fig. 6. Mould index for east wall, outer sensor, first floor

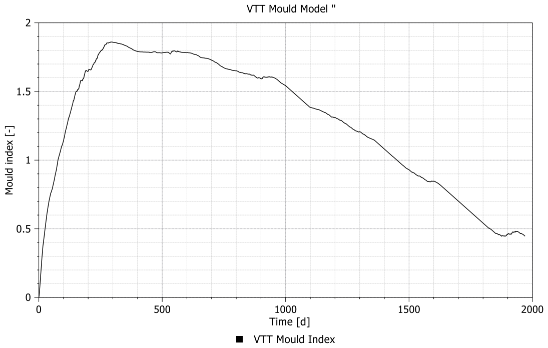

Fig. 7. Mould index for north wall, outer sensor

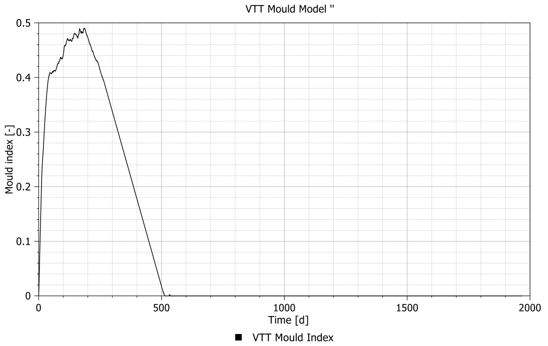

Fig. 8. Mould index for south wall, outer sensor

4 Conclusions

This paper focused on the long-term analysis of temperature and relative humidity for a strawbale Passivhaus cottage located in Norfolk, UK. It considered both the indoor environmental conditions and those within the wall.

This paper has shown the long-term settling of temperature and moisture performance in this construction, and when used in this way, low risk of mould growth in this climate. More broadly it has demonstrated that what is sometimes seen as a simple technology, can perform in quite sophisticated ways to create a healthy and stable internal environment. These results suggest low embodied energy and bio-based materials deserve to be taken seriously in our work to reduce environmental impacts and to improve comfort and wellbeing for building inhabitants.

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