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Determining moisture levels in straw bale construction

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Abstract

With the growing interest in sustainable building materials that are able to provide reductions in energy consumption, the viability of straw bale construction has recently been investigated, in particular, its resistance to moisture. The level of moisture that a construction is exposed to may have an adverse effect on its durability. Concerns are raised about the susceptibility of straw to decay when used as a walling system. It is an organic material, therefore is at risk of biodegradation under certain conditions. The research uses a range of measurement techniques to assess the effects of atmospheric conditions and wet render application on straw bale's moisture content, and it requires an understanding of the complexities of the transition of water vapor through the material and the interaction of moisture with the bale. Deviations in the moisture content within the straw bale caused by the second application of wet render were shown to be insignificant. Straw bale can withstand 25% moisture content for prolonged periods of time without degradation at temperatures not exceeding 10^{o}C.

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Keywords: Straw bale construction; Sustainable material; Moisture content; Relative humidity; Temperature; Monitoring devices

1. Introduction

The EPBD (Energy Performance of Buildings Directive) advises that all new buildings be "nearly zero-energy" by December 2020 [1]. Straw bale construction can be designed and built to achieve energy efficiencies [2] that surpass those required for the environmental assessment of buildings such as the BREEAM [3] and CSH [4] rating systems. In the UK, the NHPAU (National Housing and Planning Advice Unit) estimates that construction of between 223,000 and 255,000 new homes per year is required until 2026 to provide enough housing for the growing

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population. It has been estimated that in the UK alone [5], the surplus of yearly produced straw is around 4 million tons, enough for the walls of 450,000 new houses. Globally, a billion people live in slums [6] and are in need of the economical, insulated constructions that could be provided by straw bale [7].

Straw bale can be used for non-load-bearing and limited load-bearing wall [8] or in panel applications. These types of walls have good structural capacity and thermal efficiency, are durable [9, 10] and have been awarded a two hour fire safety rating [11, 12].

The overall research aim is to quantify and evaluate straw bale constructions' resistance to moisture using different monitoring techniques. This paper contributes by determining the effect of wet render application, assessing limitations of resistance meters and comparing atmospheric conditions to moisture content results taken in a test rig.

An extensive literature review [13] was conducted to critically examine, quantify and evaluate the risk posed to straw bale constructions by moisture. There has been a lack of conclusive agreement concerning the resilience of straw exposed to raise levels of moisture [14]. However, Straube [14, 15], Lawrence et al. [16] and Carfrae et al. [17], have rationalized the apparent ability of straw to tolerate moisture content but have recommend that it should not exceed 25% when in service [17].

Wihan [18] and Straube [15] highlighted the complexity of moisture interaction within a straw bale and associated deterioration or decay of the material. Furthermore, there has been a lack of critical analysis concerning moisture storage regimes [15] and factual descriptions of how moisture interacts with the straw [13]. In assessing moisture content, Lawrence et al. [16] developed, through Sorption Isotherms, a simple conversion scale that defines the interaction of moisture with straw by identifying desorption and adsorption trends.

2. Experimental program

2.1. Test rig description

A test rig (Figs.1 and 2) was constructed to provide facilities to assess different measurement systems whilst being subjected to a dynamic environment (seasonal variations in Lincolnshire, UK).

Fig. 1. Erection of test rig blocks Fig. 2. Completed rig construction

The rig consists of twelve modular straw blocks (Figs. 3 and 4), comprised of three ½ wheat straw bales (1100x330x225mm) laid vertically and compressed into place. The modular-blocks are labelled 1 to 7 (Fig. 4); 'B' represents the lower blocks and 'T' the upper blocks. Prior to construction, the bales had been kept together in dry storage for nearly a year. A lime mortar mix was applied to the bales to a thickness of around 20mm externally and 10mm internally.

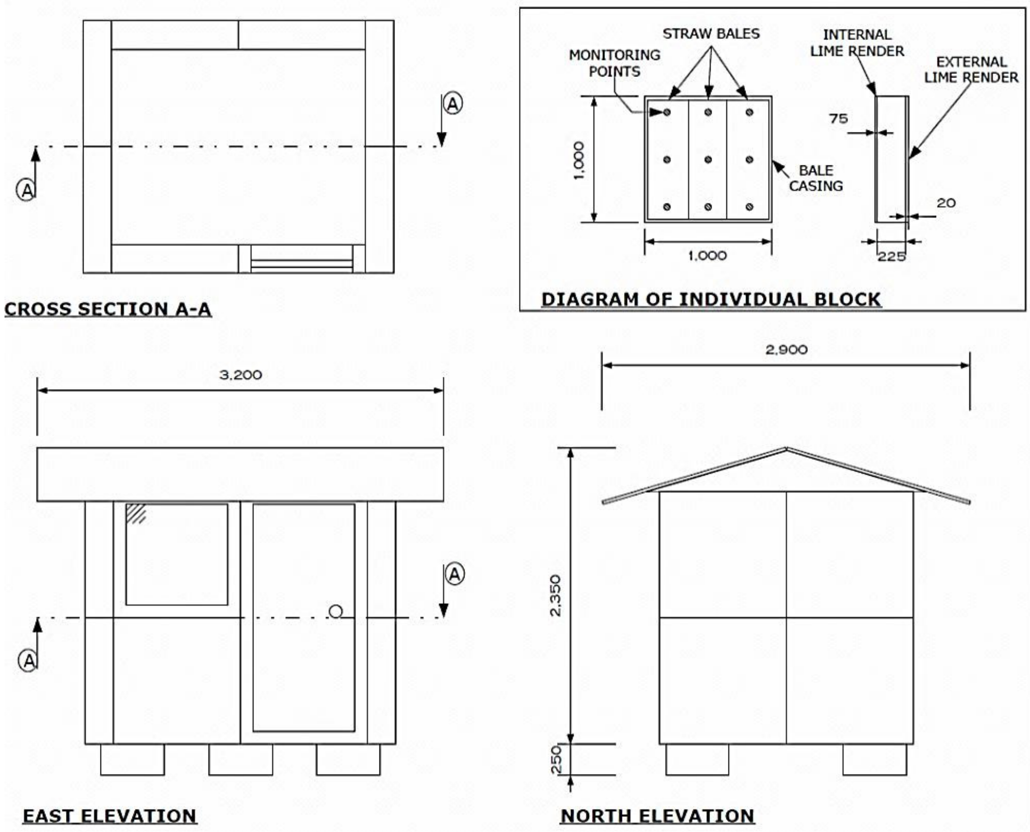

Fig. 3. Test rig plan

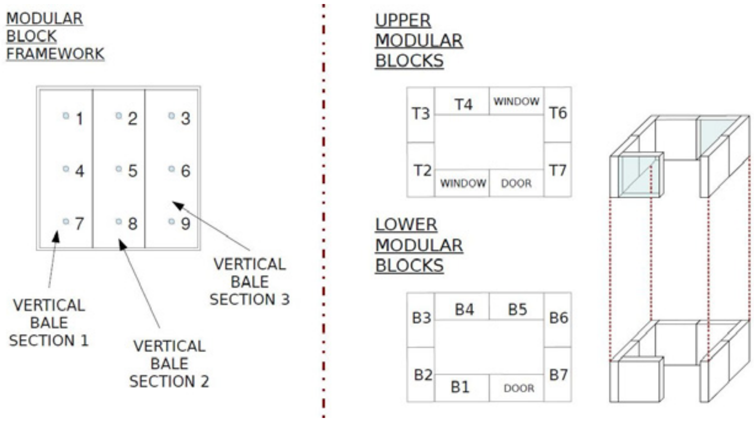

Fig. 4. Test rig block diagram

The test rig is exposed to the north (Fig. 5), shadowed by a large farm building four meters in height to the east and a three meter high hedge two meters to the south. The east façade butts up to a concrete path and the other walls are surrounded by vegetation. The north is unsheltered and a weather station was set up there to provide a comparison of internal and external conditions. Each block (Fig. 4) has nine monitoring points for the insertion of the Balemaster probe (Fig. 6), to a depth of 112 mm (approximately half the wall thickness). Moisture content measurements were taken weekly, based on the assumption that, barring dramatic failure, moisture would not be transferred through the bale at a significant enough rate to justify additional monitoring [19].

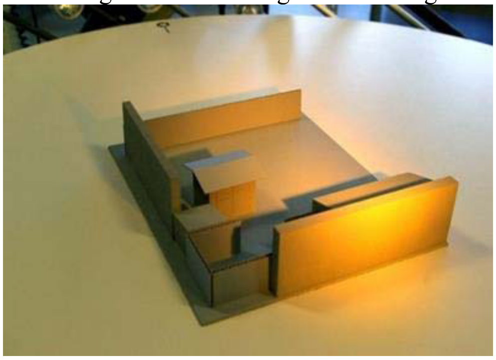

Fig. 5. Model of test rig location

Fig. 6. Balemaster probe with Timbermaster and Balemaster resistance meters, and thermocouples

2.2. Materials characterization

The physical properties of the wheat straw used in the test rig are shown in Table 1. Table 2 presents the microstructural constituents of the straw.

Table 1. Straw bale physical properties.

Straw properties	Measured values
Bale dry bulk density	100–130 kg/m^3
Porosity	46-84%
Initial moisture content	11–16%
Water absorption	65-75%

Table 2. Straw bale microstructure constituents.

Straw microstructure	Proportion
Cellulose	41%
Hemicellulose	29%
Lignin	11%

2.3. Test rig method

The straw bale test rig walls were rendered in lime, a first layer of render was applied to the external walls on the first day of the 45 day experiment. Subsequently, on day 12, a second layer of render was applied to the external walls, and on day 21, a layer of render was applied to the internal walls. As the render cures, it absorbs CO_2 and expels water, which will theoretically raise the moisture content of the wall material.

The purpose of the test rig investigation was therefore to establish the impact of wet render applied to the straw bales and to identify the limitations of using the Protimeter Balemaster as a reliable monitoring method. When using the GE Protimeter Balemaster, it is required to compensate the moisture result for temperature [20] using the following equation (1):

$$C = 0.1r(20 - t) \quad (1)$$

C: Moisture content (%)
t: Temperature (°C)
r: Balemaster reading

The US version of the Balemaster, used in this study, returns the results in a wet basis while the Timbermaster returns results in a dry basis. Fig. 7 shows how the moisture content is obtained using the Balemaster resistance meter, Balemaster probe and a digital thermometer.

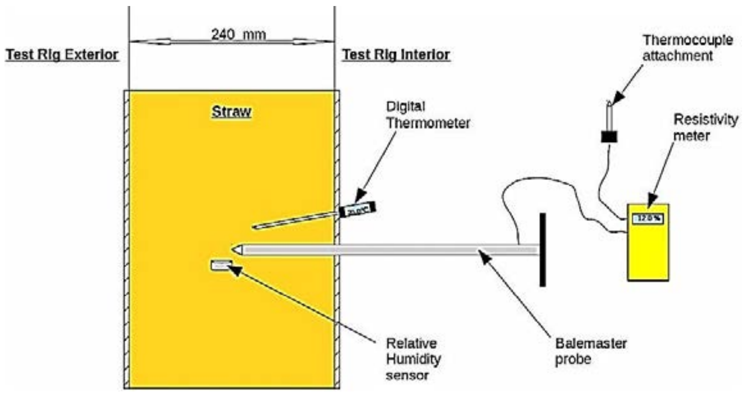

Fig. 7. Test rig measurement method

The study also compares the moisture content levels measured by the Balemaster meter to the weather conditions and to the value estimated from equation (2), developed by Lawrence et al [16] and based on relative humidity.

$$C = \frac{C_S}{1+n\left(\frac{K_m}{\phi}-1\right)^{\frac{i}{3}}} \quad (2)$$

C: Moisture content (%)
Ø: Relative humidity (%)
K_m = 0.9773 ; C_s = 400 ; i = 1.6 or 1 ; n = 44

In addition, a cyclic study was adopted in order to assess the effect of temperature on the moisture content of straw over a 24 hour period. A cyclic study records an output over a set time, and gauges whether the analyzed system returns to the initial starting position.

3. Results and discussion

Firstly, an analysis of the effect of render application on the moisture content of straw bales is performed, then, a study of individual bale moisture content. The results are shown below, followed by a 20 hour study looking into the cyclical data obtained by both a Timerbermaster and Balemaster resistance meter from several monitoring positions within the test rig. Finally, the results assess the impact of atmospheric conditions on the straw moisture levels.

3.1. Application of render

Fig. 8 illustrates the standard deviation of moisture content for each monitoring point, recorded over the 45 day period. The standard deviation has been used as it can highlight the differences in deviations between mean moisture contents under different atmospheric conditions. The results reveal two stages of moisture increase; the first between days 0 and 12 corresponding to the first application of the external render, the second between days 21 and 37 corresponding to the application of the internal render. The application of the second layer of render to the external walling on day 12 shows no effect. Moreover, Fig. 8 shows the distribution of the moisture content on day 0, spreads over a moisture content range of 5%. This range is unexpected as the bales had been equilibrated in the same atmospheric conditions for over a year prior to construction. Another surprising finding is that the moisture content of the straw varied for not only each individual bale, but for each monitoring point within the same bale. This variation demonstrates that other factors could be affecting the results, such as temperature, density, relative humidity or the resistance meter itself.

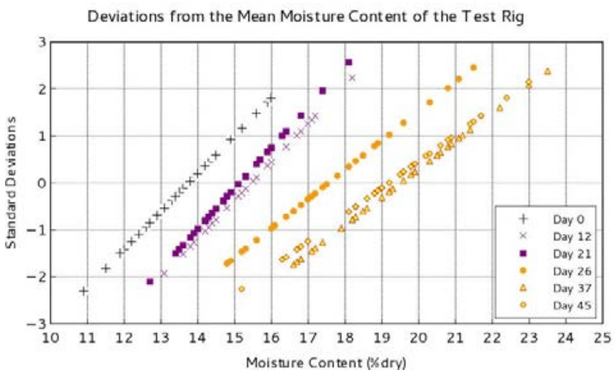

Fig. 8. Statistical analysis of the test rig

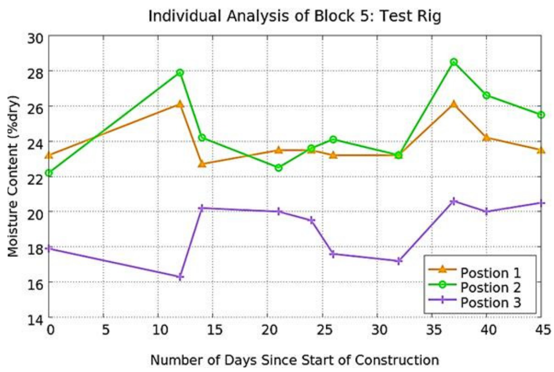

Fig. 9. Individual bale analysis

3.2. Individual bale study

Fig. 9 shows the difference in moisture readings between three points within the same bale. Although positions 1 and 2 return similar moisture contents, position 3 returns results 3-7% lower. The starting moisture content of the bales, and the relative humidity and temperature of each measurement position within the bale may be assumed the same due to the pre-construction storage conditions. The density of the straw at the point of measurement should be the influencing parameter, as it is likely to vary, in part due to the way a baling machine operates. This is supported by Carfrae et al's [17] conclusions. Therefore, further investigation into the effect of straw density on moisture readings is essential. Other influencing parameters that are potentially responsible for the increase in moisture and the irregularity of the initial readings include rainfall, relative humidity and internal and external temperature. However, it is important to mention that the only rainfall within the 45 day period was from the north and west combined with light winds of a speed less than $5ms^{-1}$. The rain during this period is believed unlikely to have had a significant effect on the overall increase of moisture content of the bales.

Fig. 9 also illustrates that the moisture content of position 2 exceeded 25% on days 12 and 37. On day 45 a sample of straw was extracted and examined. However, on inspection there was no sign of degradation. This observation confirms Carfrae et al's study [21] that moisture contents that do not exceed 37% (at the highest reading) may be tolerated by the straw. The data however must be interpreted with caution as the temperature at the time of the measurement did not rise above 15ºC, averaging at around 10ºC, since at that temperature, biological decay is slowed [16].

3.3. Cyclic study

Figs 10 to 13 show a comparative study of data collected using the Balemaster and Timbermaster resistance meters over a 20 hours period, together with the temperature data from points of measurement within the bale. The study looked at part of a cycle relating temperature within the bale to moisture content in order to assess both moisture transition and the effectiveness of using resistance meters. It can be noted that the moisture contents in each figure increase during the measurement phase. One hypothesis drawn from this result would suggest that warmer air containing more moisture is driven into the bale from the external straw-render interface; this maybe a product of wetting of the render from rain or overnight dew followed by heating of the render surface at dawn as external air temperatures rise or as the wall is subjected to solar gain. The warm moist air condenses on the cooler straw within the bale and also at the point of measurement, thus raising the moisture content. The effect of vapor transition could then reversed as the external atmosphere cools. The accuracy of the GE Protimeter's equation (1) has to be validated by further investigation so as to remove alternate hypotheses for the effects of moisture transfer rates through a bale. The data reveals differences between the Balemaster and the Timbermaster meters.

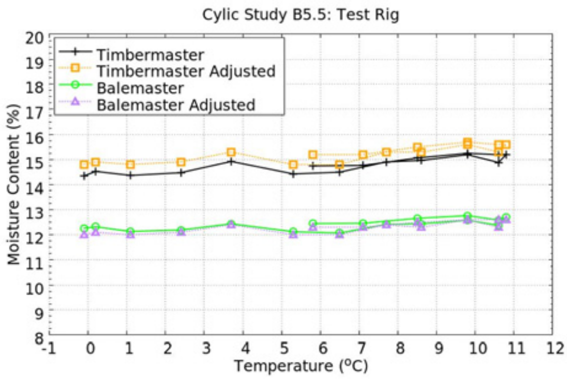

Fig. 10. Moisture content at B5.5 position

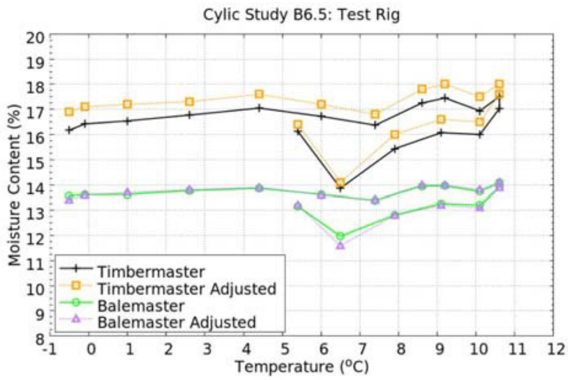

Fig. 11. Moisture content at B6.5 position

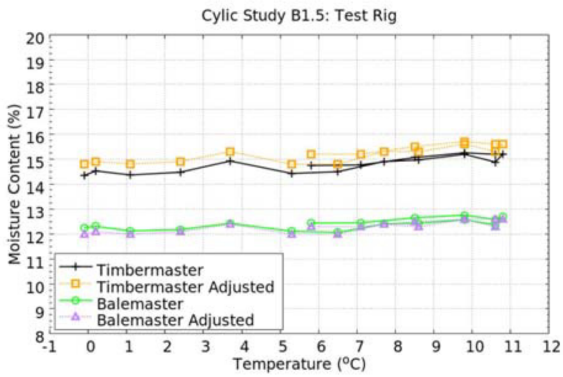

Fig. 12. Moisture content at B1.5 position

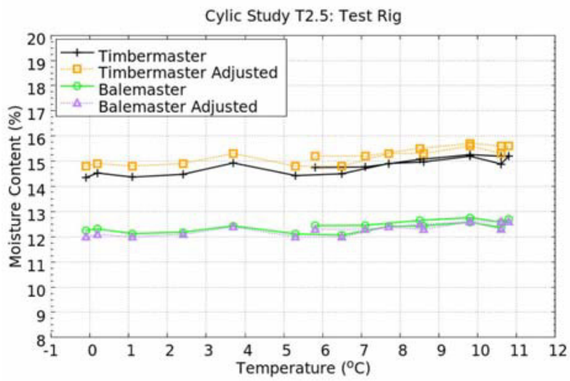

Fig. 13. Moisture content at T2.5 position

3.4. Atmospheric conditions

Regarding the moisture transfer, the effect of atmospheric conditions on the straw was studied. Analyzing the data obtained over the initial 45 day study, the study compares the effect of external relative humidity and temperature on the measured straw moisture content. Fig. 14 illustrates the measured and estimated moisture content using the GE Protimeter equation (1). The experimental values are adjusted by approximately 1% when using the Timbermaster, with temperature compensation. The Bezier formula has been used to shape the moisture content curve. The rise from 16% moisture content to 20% took around 16 days and the average relative humidity recorded during the test rig experiment is between 80 and 85%.

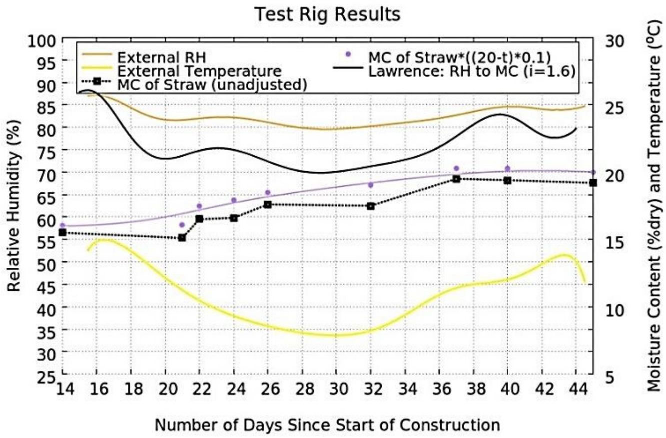

Fig. 14. Relative humidity and temperature influences

On the other hand, utilizing Lawrence et al's [16] equation (2), the equivalent moisture content as affected by the atmospheric conditions would average between 20 and 24.5%. This would suggest that the surrounding environment has affected the straw moisture content to bring it towards an equilibrium. However, this raises the issue of moisture transfer rate and the rate at which humidity can affect the moisture content of straw. It is possible to hypothesize from the results obtained in the first section of this paper that the application of the wet render has increased the moisture content of the straw up to the point at which it is in equilibrium with the exterior. This hypothesis assumes that the exterior could not have influenced the straw moisture content at the rate directly associated with the resultant moisture content. Therefore, the rate at which the moisture content increases is a product of the curing of the first layer application of lime render; as the render cures it releases water into the bale's interior, thus influencing the rate at which the straw would react to the external environment. It is therefore necessary based on the hypotheses presented that further work is undertaken to understand moisture transfer through straw bales.

4. Conclusion

The results present a level of moisture to be expected in straw bale walls. They are part of a larger study conducted to evaluate and quantify the risk posed to straw bale constructions by moisture. Highlighted are various gaps in knowledge including the effect of straw density, vapor transition and moisture transfer rates through a bale, and the accuracy of the Protimeter resistance meter and equation.

The results however do provide evidence to suggest that the application of wet render directly onto straw affects the moisture content throughout the bale, although additional applications of render on top of existing layers appear to have no further effect. The differences in starting moisture contents of the monitoring points within the bales indicate that the density of the straw is an important variable, as is the temperature at the point of measurement. The effect of density is reasoned as the differences in starting moisture content from an assumption that other influencing variables would have been equal within each bale.

Other observations included the apparent ability of straw to withstand moisture contents in excess of 25%, however other influencing factors must be taken into account regarding time and temperature. The obtained moisture content values conform to those estimated by the Lawrence equation. However, the rate at which equilibration occurs raises an important question concerning the moisture transfer rate though a bale when affected solely by relative humidity. It is proposed that the application of wet render accelerated the rate at which atmospheric moisture could have influenced the straw within the bale. The results also raise concerns about using the GE Protimeter equation, as the obtained values do not fulfil accuracy requirements.

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