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Monitoring of the moisture content of straw bale walls

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Abstract

This paper describes an investigation into moisture levels in straw bale walls used to clad a newly constructed building. The moisture content was monitored up to 10 months after the building was handed over. The sensors used for this purpose were readily available, low cost and easily installed. The moisture levels fluctuate during the first 4 months following installation of the instrumentation, followed by a period of greater stability where it is believed that the straw acts as a moisture buffer, managing the humidity levels within the building and contributing to a healthier internal environment. This ongoing study makes a contribution towards raising confidence levels in the use of straw bales as low carbon building material in mainstream construction.

Introduction

Straw has been used as a building material for thousands of years either as an additive to clay in the form of adobe or cob, or as a water resistant layer in the form of thatch. With the invention of mechanical baling in the 19th century, it became possible to use compressed straw bales as oversized building blocks. This technique was used to good effect in Nebraska in the USA where other building materials were in short supply [1]. By the end of the 19th century the technique lost popularity as railway transportation allowed ready availability of more flexible materials such as stone, brick, timber and steel. During the second half of the 20th century interest in the technique was revived, particularly in the state of California. By the end of the century interest in straw bale construction had developed in Europe because of the perceived need for low environmental impact building materials. Straw was seen as a useful contributor to low environmental impact construction for a number of reasons:

- Straw has excellent thermal insulation properties
- Straw has excellent sound insulation properties
- The production of straw is a low energy process compared with other building materials
- Straw sequesters carbon dioxide (CO_2) thereby reducing atmospheric CO_2

Straw is an organic material that carries particular risks with it in the context of living accommodation. These risks include:

- Fire – straw is inherently flammable
- Rodent and insect infestation – straw can contain protein and carbohydrates which can sustain life
- Decay – under the right environmental conditions straw is subject to both aerobic and anaerobic decay
- Structural instability – straw bales have low compressive and flexural strength and stiffness

Detailing has been developed to address many of these problems. Such detailing includes rendering with fire resistant material, which also inhibits access by rodents; protection of the junction between render and timber from wind driven rain; use of a drip detail at the base of the panel which protects from ingress by water flowing down the face of the panel; steel reinforcement to improve stiffness of the panels. The use of lime based or cementitious renders results in walls which meet statutory fire resistance criteria in the USA, in the UK and in Europe. Rendered walls have been shown to be resistant to rodent and insect attack [2]. Render also provides an outer layer which is resistant to moisture ingress from rainfall. Many structural tests have been conducted on straw bale walls both with and without render, and with and without additional reinforcement within the render [3,4,5,6]. These studies have shown that straw bale walls can be designed to be sufficiently robust to act as single storey structural walls, and in some cases two storey structural walls.

The issue of long term durability is the area of straw bale construction which attracts the most concern from all interested parties, including architects, builders, specifiers, regulators, financiers, insurers and end users. The most likely risk to long term durability is the potential of decay within the straw, initiated by excess moisture content. This paper addresses this issue, and discusses the use of sensors embedded within the walls of buildings to monitor the condition of the straw. The use of appropriate sensors provides long term data which adds to our understanding of the performance of straw bale construction. It also provides early warning of any incipient decay within the structure and improves the level of certainty about the condition of the walls.

Causes for the decay of straw

Straw can decay in one of two modes: anaerobic and aerobic. Anaerobic decay occurs in the absence of oxygen and requires elevated moisture levels [7]. In the context of straw as a building material, such conditions almost never occur. This is because the straw is generally above ground protected from moisture ingress by damp proof courses, and moisture resistant membranes or barriers such as renders or a rainscreen. The risk of decay in straw bale buildings is, therefore, confined to aerobic decay. The four main conditions that affect the rate of microbial decay in straw are:

1. nutrients contained in the straw
2. availability of oxygen in the straw
3. temperature of the straw
4. free moisture on the straw

The nutrients in straw are relatively low compared with materials such as hay, and are not possible in any event to be controlled. Temperature is similarly difficult to control in a built environment where internal wall temperatures are determined by the requirement to maintain a suitable environment for accommodation and external temperatures are subject to the vagaries of the weather.

The moisture content of the straw in a built wall can be limited by good detailing, but accidental inundation can still occur from time to time. Excessive water content will limit access of oxygen since saturated straw will only have access to the little oxygen dissolved in the water. Straw that has been rendered will also have reduced access to atmospheric oxygen.

Fungal and bacterial growth is not very active below 10ºC and few species will survive above 70ºC. Decay is very limited below 25% moisture content on a dry basis with the rate of decay decreasing above 120%[8]. There is therefore a limited range of moisture content in straw that will support decay, from a minimum of 25% to a maximum of around 120%, when free water starts to limit the availability of atmospheric oxygen, with saturation occurring at 400%.

The moisture content is the controlling factor in the decay of straw, as without a suitable moisture content any nutrients and oxygen in the straw cannot be consumed by fungi and bacteria. Since this is the case, knowledge of the moisture content within a constructed straw bale wall will provide reassurance as to their integrity.

Measurement of moisture content of straw

Measurement of the moisture content of straw can be conducted either directly or indirectly.

Direct measurement involves the gravimetric method. This requires the weighing of the specimen followed by drying and re-weighing. The moisture content on a dry basis is calculated by expressing the weight loss as a percentage of the dry weight of the straw. This technique does present a number of difficulties:

1. The technique is highly invasive.
2. Relatively large amounts of material (render/rainscreen and straw) are removed from the structure which then require replacement.
3. Obtaining moisture profiles through the thickness of the wall is problematic, and requires an even more invasive approach.

It is possible to place a known weight of straw in a ventilated container inside a hollow ventilated tube within the wall which can then be periodically removed and weighed [9]. This technique is cumbersome and would only be usable in limited numbers within a building without becoming visually invasive and compromising the integrity of the wall.

Moisture content can be measured indirectly by measuring the relative humidity (RH) of the air in the immediate vicinity of the straw sample and converting this measurement into an equivalent moisture content using isotherm data. The moisture content of timber samples embedded within the straw wall can be measured using timber moisture meters and this measurement equated to straw moisture content using suitable isotherm data [10]. Straw bale moisture probes designed for use by farmers use similar science to timber moisture meters by measuring electrical resistivity. These probes have a diameter of around 10mm and are inserted into the straw bale to a measured distance. The electrical resistivity is converted into a moisture content using calibration data for different straw types. This technique is also invasive and destructive in that it leaves a hole in the superficial render / rainscreen and a void in the straw.

The authors have developed an empirical expression [11] which relates RH measurements into MC data over the range 5% to 100% MC. This can be used in conjunction with RH sensors embedded in the straw walls to produce continuous readings of moisture content through the depth of the wall. This allows moisture profiles to be measured as well as measuring the response of the wall to wetting and drying from rainfall and sunshine. The data gathered from these sensors can be used to demonstrate the way in which straw bale walls can be considered to ‘breathe’, thereby buffering the effect of variations in moisture. In addition to these useful data, most importantly the technique can monitor the condition of the walls providing reassurance as to the absence of decay.

The expression used by this technique is a development of prior work by Malmquist [12,13] and Hedlin [14]. This expression takes the form:

$$C = \frac{C_s}{1 + n\left(\frac{K_m}{\varphi} - 1\right)^{i/3}} \qquad 1$$

C_s is defined as the fibre saturation moisture content, C is the equilibrium moisture content at relative humidity ϕ. n, K_m and i are constants where n= $C_s/C_{50\% RH}$

The moisture content of saturated wheat straw (C_s) has been taken as 400%. This value corresponds to fibre saturation assumed by Hedlin using the suction technique for high relative humidities as used by Penner [15] at a suction of 1 cm. It should be noted that the value of C_s can be varied substantially without changing the form of the calculated isotherm below 95% relative humidity if corresponding adjustments are made to the values of n and K. [14]. The constants used in these expressions, empirically determined by Hedlin, are:

$n = 44; K_m = 0.9773; K = 0.0227; i = 1.6$

The data gathered by Hedlin and those gathered by the authors are shown in Figure 1 together with the line described by the above expression and that described by the more complex expression developed by Hedlin.

It is clear that both expressions give very similar results, and that both have a slight tendency to overstate the moisture content as measured by experimentation for a given RH%. Further refinement is required to the expression, but is its considered that the current expression offers a factor of safety at higher RH levels where moisture content is most critical.

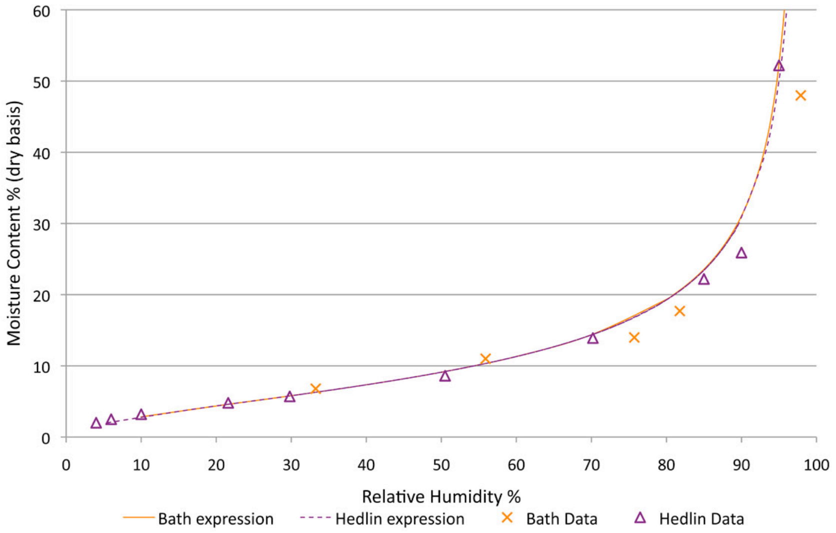

Figure 1: Wheat straw isotherms and associated expressions

Instrumentation

Figure 2: Media Centre in Bristol constructed from straw bales

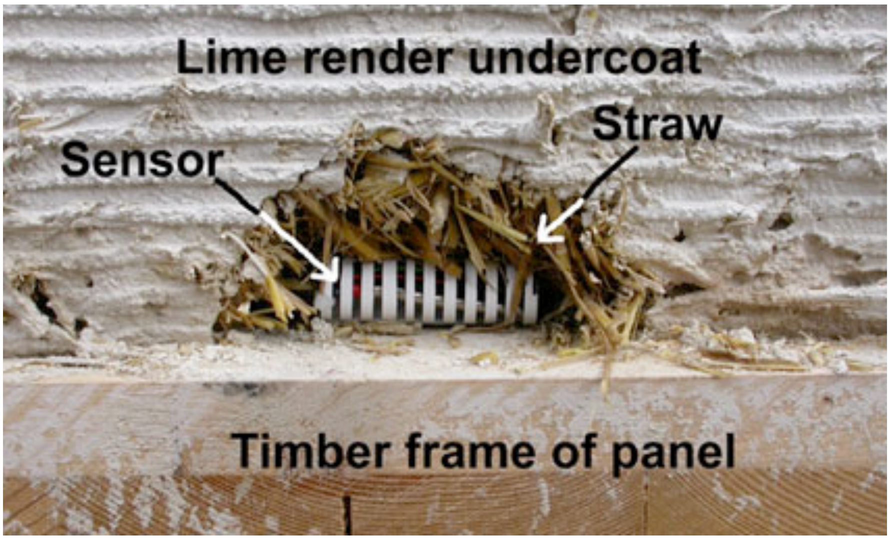

Figure 3: Sensor inserted just below the external render (prior to final rendering)

Rendered straw bale walls have been monitored in a newly constructed media centre in Bristol, UK (Figure 2) since August 2008. The sensor used was a Humirel HTM1735LF capacitive humidity sensor with an accuracy of ± 2% @ 55%RH. The sensor requires a 5v supply which was supplied from a Grant Instruments Squirrel 2020 data logger.

The sensors were inserted into ventilated 20mm ø polypropylene tubes and installed into the straw bale panel during construction (Figure 3). Sensors were positioned at the centre of the base of the panel just behind the render at both the exterior and the interior of the panel. Instrumentation was inserted into one panel on each elevation of the building (Figure 4), although subsequently it was found that the wiring to the sensors in the ‘West’ elevation was damaged during construction, and data from these were not accessible.

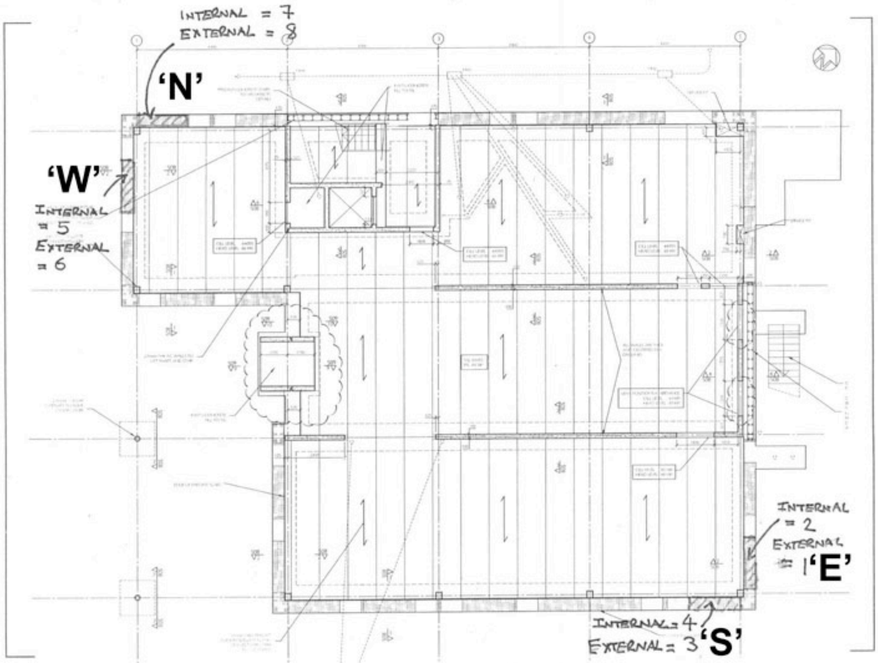

Figure 4: Location plan of sensors on the building

Wiring from the sensors was taken to a central point in the building and connected to the data logger, where data were logged at 60 minute intervals. Daily temperature and rainfall information were recorded from a publicly available weather station 500m from the building.

Data acquisition

The raw RH% data are presented in Figure 5

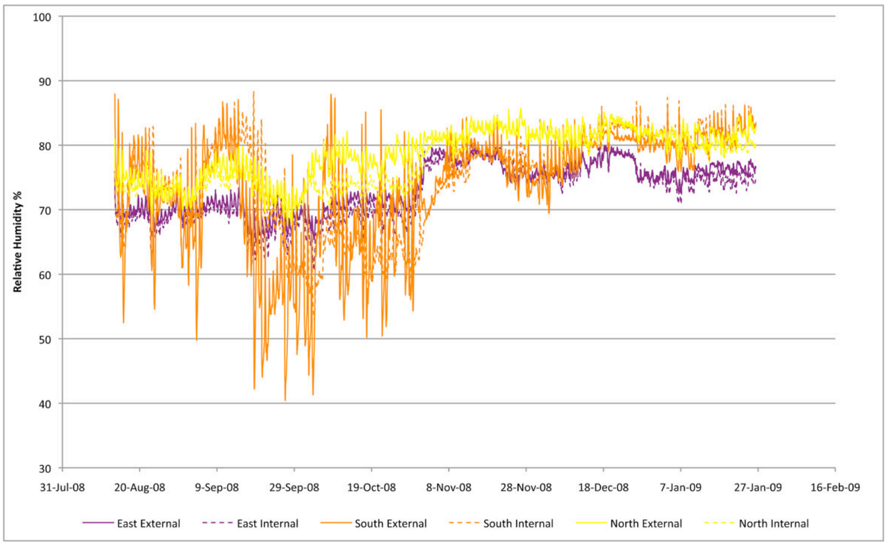

Figure 5: Raw RH% data from sensors

The expression described above was then applied to these raw data to produce moisture content (MC) data. In order to smooth out the hourly variations and obtain a curve which is more readily able to be interpreted, the resultant MC data were averaged using a rolling 24 hour average. For a given point the previous 24 hourly measurements were averaged. This produces a curve which takes out significant individual variations to produce a smoother curve which is more readily interpreted. It was decided to use a rolling average based on a 24 hour cycle because this was felt to best represent the diurnal pattern of external humidity. The rolling average of the previous 24 hours resulted in a figure which was 12 hours out of phase (earlier) than the time point on the x axis. Resultant data were therefore moved backwards by 12 hours in order to be in phase, and therefore directly comparable, with any weather events. These data are presented in Figure 5 together with daily rainfall from a nearby weather station.

It can be seen that the curve does not show the large individual variations seen in the RH data from Figure 4.

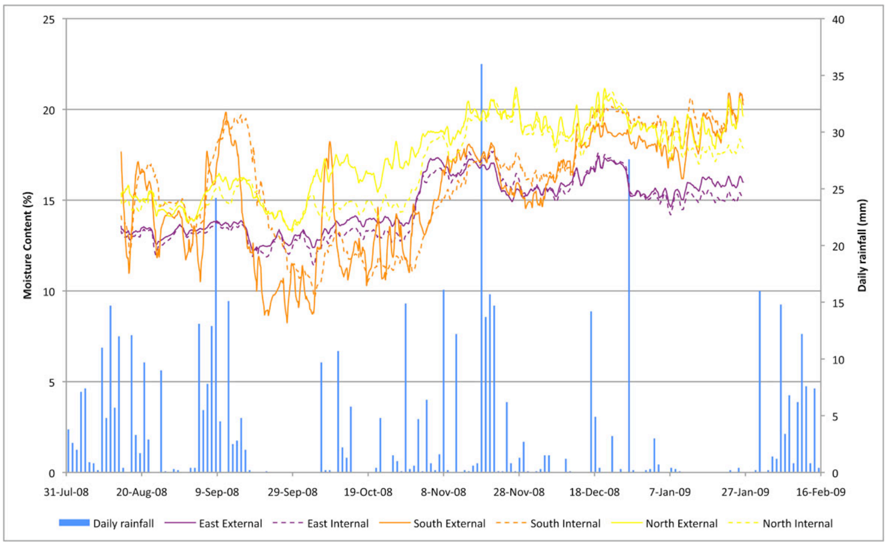

Figure 6: Smoothed moisture content data and daily rainfall data

Data analysis and interpretation

There appear to be two distinct phases to the moisture content data. The first phase runs to about 8th November. In this phase the moisture content of the straw oscillates over a wide range of values from 8% to 20%. The moisture content increases relatively rapidly about 8 days after a rainfall incident and then reduces about 6 days after the rainfall ceases. The prevailing wind is from the South West and the most exposed face of the building is the Southern elevation. It can be seen that the data from the South elevation varies by the greatest amount with the internal MC slightly out of phase and behind the external MC. This is likely to be due to the wind driven rain increasing moisture content more rapidly than on the other two elevations. When the rainfall ceases, drying will occur more rapidly on the exposed southern elevation. The East elevation is the most protected of the three elevations, and it can be seen that there is much less variation in moisture content, both internally and externally.

Between 1st November and 15th November there was a general rise in moisture content, but subsequently the MC varies over a lower range than in the first phase, varying between about 14% and 21%, a range of 7% compared with 12% in the first phase. The moisture content during the second phase appears to be less associated with external rainfall, and appears to be buffering the moisture in the building. Individual elevations vary by between 3% and 5%, compared with over 12% in the first phase.

It is noteworthy that the differential in moisture content between the interior and the exterior is quite small, of the order of 1% or 2% only, where straw bale moisture probing has shown a differential of up to 5%. An increased scope for air flow around the frame edge is expected to have contributed to this effect. From these limited data it would appear that the straw bale moisture level takes around 8 months to establish an accommodation between the internal and the external humidity conditions, after which time they act as a buffer, maintaining relatively steady moisture content. Further readings are required, in this building and in a number of future projects, to establish wider trends. However, other studies using periodic measurements of timber discs [10] have shown differences in MC between interior and exterior of 1%-2% with variations of between 2% and 5% between dry and wet periods depending on the orientation of the wall to the prevailing weather. This compares well with the data gathered in this study.

The data gathered to date accord with the reported environmental benefits of inhabiting straw bale buildings, where not only does the straw act as an effective thermal insulation, but also maintains a much more comfortable environment within the building.

Conclusions

The study is still at an early stage, and environmental data for the interior of the building are now becoming available, which will in future be correlated with the moisture content of the straw bale walls in order to establish the contribution that straw bale walls make to the internal environment of the building. Over the first 8 months of occupation of the building there had been 582mm of rainfall, with a total of 828mm to the date at which this analysis terminates (26th January 2009). During this period there has been very little opportunity for the building to dry out. During the drier months of the year it is expected that the walls will lose some of their moisture content through radiant drying.

This study suggests that straw bale walls might respond to the external environment during the early stages of the building's life, and that after about 6 months they may begin to act as a moisture buffer, maintaining a relatively constant moisture level, which should make a considerable contribution to the internal environment of the building. These tentative conclusions need to be underpinned by further planned studies. The sensors used are relatively low cost, and future buildings will be able to be instrumented to a greater extent in the knowledge that such instrumentation will provide valuable data on the performance of straw bale walls in modern construction.

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