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THE IMPACT OF EXTERNAL FINISHES ON THE WEATHER RESISTANCE OF STRAW BALE WALLS

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Abstract: This paper describes an investigation into moisture levels in straw bale walls which had been rendered with a range of different hydraulic mortars. These had been erected on an exposure site which was subject to high rainfall levels. The moisture content of the straw was monitored at a number of different points within each wall over a period of 11 months. The study validated the effectiveness of low cost relative humidity sensors. The study showed that poor detailing or an inadequate thickness of render resulted in significant water damage to the underlying straw, and that the use of breathable paints made a small difference to the breathability of the render. Where detailing and thickness were adequate, the study showed that the render provided an effective barrier to wind driven rain whilst still allowing the wall to ‘breathe’. This ongoing study makes a contribution towards raising confidence levels in the use of straw bales as low carbon building material in mainstream construction.

Keywords: Moisture, Straw bale construction, Monitoring, Low carbon building, Durability

1. 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 (King, 2006). 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 stores carbon within its structure thereby reducing atmospheric CO_2

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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 susceptible 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 (Wooley, 2006). 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 (Grandsaert et al, 2001; Nichols & Raap, 2001; Faine & Zang, 2001; Walker, 2004). 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.

2. 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 (Acharya, 1935). 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 rain screen. 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:

- nutrients contained in the straw
- availability of oxygen in the straw
- temperature of the straw
- 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 flooding 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% (Summers, 2006). 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.

3. 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:

- The technique is highly invasive.
- Relatively large amounts of material (render / rain screen and straw) are removed from the structure which then requires replacement.
- 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 (Canada Mortgage & Housing Association, 2000). 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 (MC) 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 (Goodhew et al, 2004. 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 / rain screen and a void in the straw.

Previous work has produced an empirical expression (Lawrence et al, 2009) which relates RH measurements with straw 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. 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.

This expression takes the form:

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

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 constants used in this expression for wheat straw are:

$n = 44$; $K_m = 0.9773$; $K = 0.0227$; $i = 1.6$; $C_s=400$

The expression can be represented graphically, as seen in Fig.1.

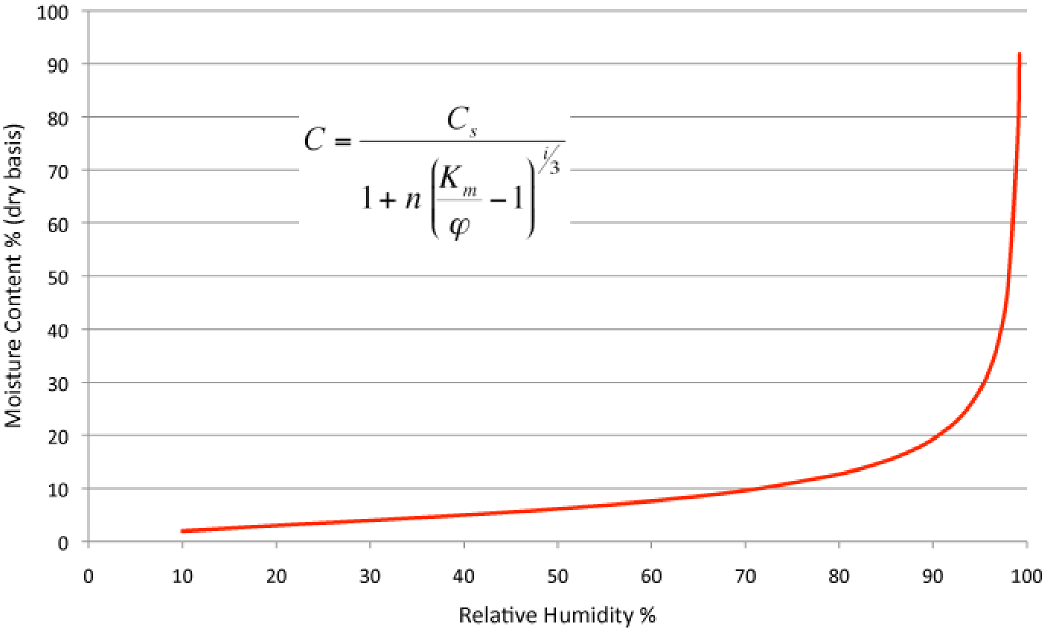

Figure 1: Relationship between wheat straw and RH

4. Experimental panels

A series of panels were constructed using 81mm thick three-ply timber from a sustainable source. Panels were 1900mm high and 1170mm wide (external dimensions), and were oriented so that the exposed surface faced South-West, the direction of the prevailing wind at an exposure site in South Cornwall, UK. The panels were filled with five straw bales, tied together with timber stakes, each with sensors located as shown in Figure 2.

The rear of each panel was sealed with building paper underneath a sheet of 21mm OSB, with a silicone seal between the building paper and the timber panel. Each panel received a different treatment as described in Table 1 and shown in Figure 3.

The sensor used was a Humirel HTM1735LF capacitive humidity sensor with an accuracy of ± 2% @ 55%RH, encased in a ventilated plastic tube (20mm ø, 60mm long). The sensor requires a 5v supply which was supplied from an adjustable regulated power supply, which was controlled to provide 5v at the sensor. Data were acquired by a bank of Grant Instruments Squirrel 1001 data loggers. These loggers were unable to acquire temperature data from the output of the HTM1735LF sensor, so a Grant Instruments

Thermistor type CT was used in conjunction with the Humirel sensor. Eight sensors were used in each panel, as described in Figure 2.

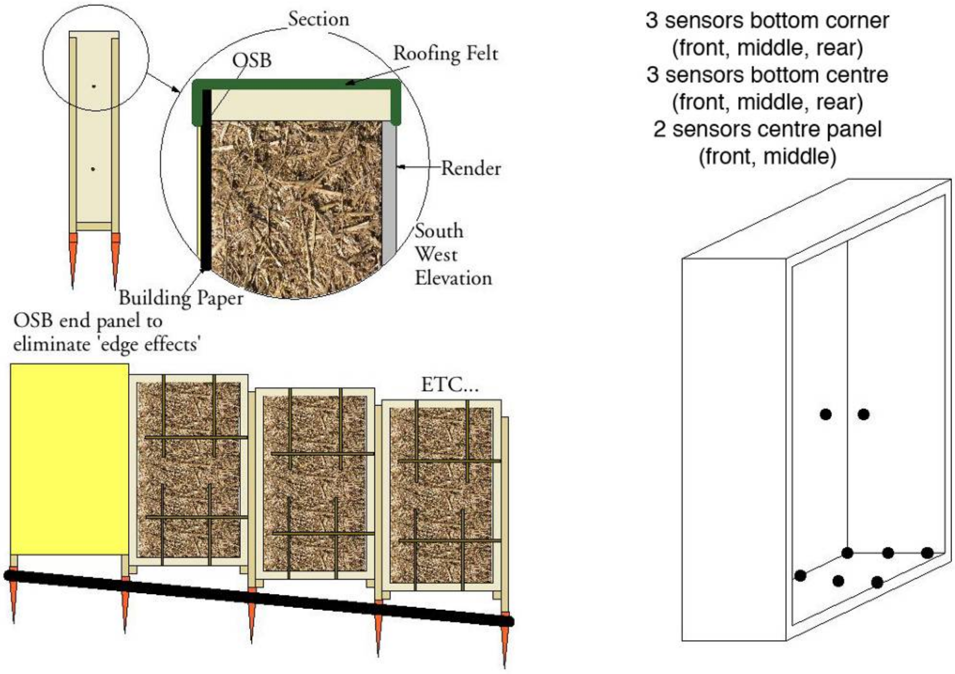

Figure 2: *Design of panels and location of sensors*

Table 1: Surface treatment of each exposure panel

Panel No	Interior	Render	Special treatment
1	Straw	10mm ‘scratch’ coat	Cedar rain screen
2	Straw	10mm ‘scratch’ coat	
3	Straw	35mm formulated lime	
4	Straw	35mm formulated lime	Cracked above sensors
5	Straw	35mm formulated lime	Painted with ‘breathable’ paint
6	Straw	10-35mm formulated lime	Areas with thin render
7	Straw	35mm formulated lime	NHL3.5 render
8	Straw	35mm formulated lime	1:1:6 render
9	Hemp-lime	35mm formulated lime	

Figure 3: Sample panels on exposure site in South Cornwall

1.1. Instrumentation

5. Experimental Data

Data acquisition was cut short after 11 months by an electrical storm, during which the wire supplying power to the sensors was struck by lightning. This resulted in data not being acquired for a month. When acquisition was regained, RH levels in all panels began to rise steadily. It was unclear whether this was the result of sound data or an artefact caused by the electrical storm damaging the sensors. It was decided to open up a panel to investigate, and it was found that the building paper at the rear of the panels had decayed due to moisture penetrating the OSB covering. This resulted in a steady wicking of moisture into the straw from the rear, producing uncharacteristically elevated moisture levels within the straw. The experiment was therefore abandoned at this stage, and a new experiment was designed using a hut with each side consisting of three straw bale panels. This will provide a weather-proof interior, and eliminate the risk of a repeat of the loss of data quality. This experiment will begin in July 2009.

In spite of this failure in the experimental design, some good quality data were acquired and the use of the sensors has been validated, not least in that they detected the elevated moisture levels, which would have allowed for remedial action to be taken in the case of an actual building.

Limitations of space do not allow a full presentation of the data, so a limited amount of data are presented to highlight key understandings gained from this experiment.

Figure 4 shows the data converted into MC for the straw at the heart of the panels, half way between the front and the back surfaces.

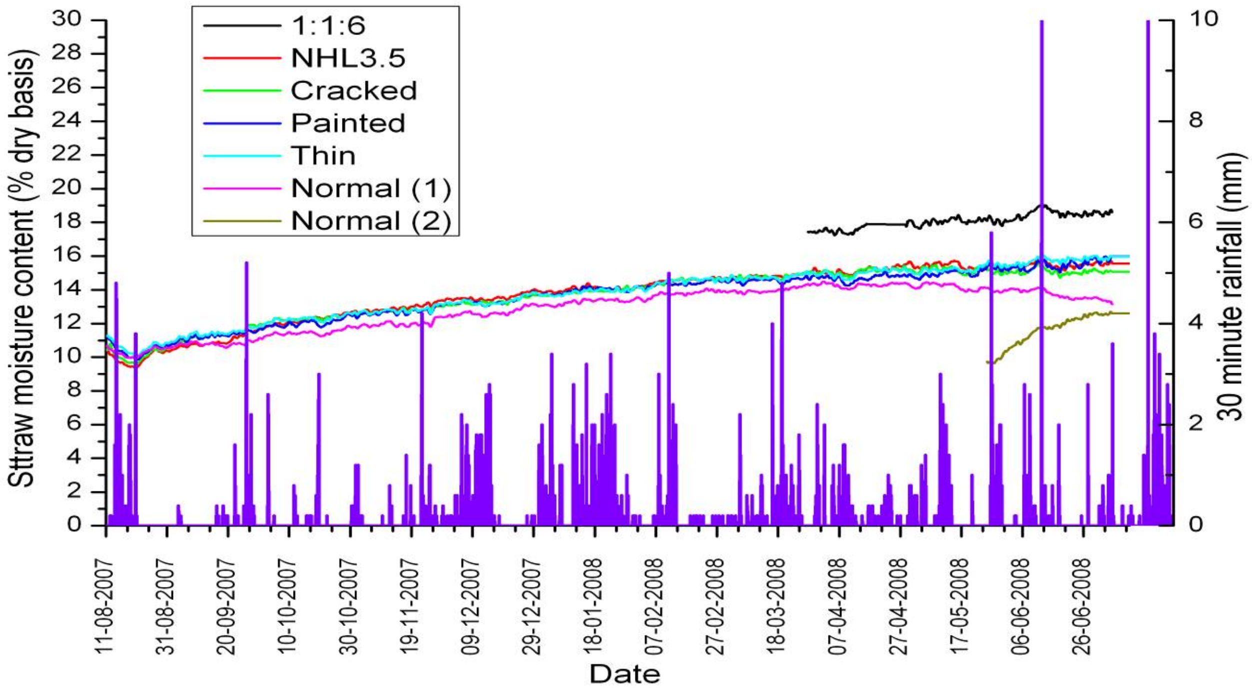

Figure 4: Moisture content at the core of the panels

6. Discussion

Over an 11 month period, the moisture content of all the straw bales gradually increased to ~15% which equates to an RH figure of ~85% according to expression (1). External RH varied over this period from a low of 40% to a high of 99%, averaging out at ~83%. This indicates that the straw bales gradually equilibrated with the average RH of the external environment. It was also seen that the straw moisture content below the render increased following rainfall with an 8 day offset from the rain event. Drying out occurred 5-6 days after cessation of rainfall. This clearly demonstrated the ability of the render to allow passage of water vapour, whilst inhibiting passage of water liquid.

The panel rendered with a 1:1:6 lime:cement:sand material, was consistently 3% higher in MC than the panels rendered with formulated lime. This is likely to be because the formulated lime render is significantly more ‘breathable’ than the cement render. The panel made from NHL3.5 and the panel that was painted with a ‘breathable’ paint, both showed MC tending to increase over the equilibration level. When these panels and the 1:1:6 panel were deconstructed, it was found that the straw immediately below the surface of the render was damp and beginning to deteriorate in all cases. This is explained by the reduced vapour permeability of these surfaces, which did not allow water that penetrated through capillary action to dry out sufficiently.

Panels that had been deliberately damaged and that had areas where the render was excessively thin (<15mm thick), showed localized deterioration of the straw immediately below the weakened areas.

The panels that were correctly detailed and undamaged equilibrated at ~ 14% (equivalent to 83% RH). No deterioration to the straw was found when they were deconstructed. Although sensor data for the core of the rain screen panel were not available, data at the exterior surface showed that the MC remained steady at ~15% and was unaffected by rainfall. The deconstructed panel revealed straw in excellent condition.

7. Conclusions

- The humidity within straw bales tends to equilibrate with ambient RH over a period of about 8 months, resulting in moisture contents that are well within acceptable levels.
- Moisture content at the render/straw interface fluctuated in sympathy with the external RH, confirming that the render was ‘breathing’.
- The use of low vapour permeable renders tends to increase humidity levels above ambient conditions, resulting in potential damage to the straw below the render
- Damage to the render, or render that is too thin (<~25mm) results in deterioration of the straw below the weak points in the render.
- Panels protected by a rain screen are the least susceptible to weather damage.

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