Durability characteristics of straw bales in building envelopes

Andrew Thomson [a] and Pete Walker [b]

BRE Centre for Innovative Construction Materials, Department of Architecture & Civil Engineering, University of Bath, Bath, BA2 7AY

[a] A.J.Thomson@bath.ac.uk

[b] P.Walker@bath.ac.uk

Abstract

Cereal straw, including wheat, barley and rice, offers a renewable and sustainable resource stream for a variety of construction products, including compressed board panels, thatched roofing and bales. The successful use of straw bales as thermal insulation within the external envelope of buildings has been demonstrated by the increasing number of successful contemporary projects around the world. However, the warranty, insurance and financing of such projects is often still not as straightforward as competing solutions, which can be attributed to concerns relating to the long-term durability of the straw. This paper presents findings from an on-going experimental study into the condition monitoring of modern straw bale construction, and also reports on a study investigating the degradation behaviour of wheat straw cyclically exposed to elevated humidity levels. The findings of the study provide encouraging insight into the robustness of straw bale construction.

1 Introduction

In recent years the requirement for lower carbon buildings has acted as a catalyst for the use of, as well as research and development into, new types of wall construction. The use of cellulose based materials, such as timber, straw, bamboo and hemp, offers a simple means to reduce the total carbon impact of new buildings; photosynthesis captures atmospheric carbon dioxide which remains locked into the plant material throughout its life. Consequently there has been an increased use of novel cellulose based materials, such as straw bales, in contemporary architecture. Straw bale buildings can now be found in many locations around the world, including in particular the USA, Europe, Canada, Australasia, Japan and China [1] [2]. Straw bales are used primarily to provide high levels of thermal insulation (U values for 450 mm thick walls 0.13-0.19 $W/m^2.K$); though they can be also used in load-bearing walls in lightly loaded low rise buildings. Increasingly straw bales are being used in prefabricated panelised construction, which combines the benefits for off-site manufacture with the low carbon benefits of cellulose construction materials (Figure 1). However, whilst there are significant advantages to using straw bales in buildings the mainstream adoption of this material remains restricted by concerns relating for long-term durability [3] [4] and lack of certified supply chain for materials and products

Commented [PW1]: Needs reference

Figure 1. LILAC co-housing development in Leeds, UK

The aim of the study presented in this paper is to support the development of straw bale construction through a deeper understanding of the degradation characteristics of wheat straw bales. The paper presents results from the long-term condition monitoring of straw bale insulated buildings combined with a novel laboratory study into wheat straw degradation. This study will hopefully enable building professionals to better understand and assess the risks associated with straw bale construction.

2 Background

Lawrence et al. [5] provide a concise literature review of the methods for measuring the moisture conditions and recommended moisture content limits for straw bale construction. Unobtrusive methods for moisture conditioning include electrical resistivity measurements of either, indirectly, embedded wood blocks or directly of the straw. The relationship between moisture content of embedded wood blocks and the surrounding straw is not well developed. Alternatively, moisture contents have been derived indirectly using relative humidity measurements, but again the reliability of this approach to derive straw moisture levels is unproven.

Recommendations suggest that the initial moisture of straw bales at construction should not exceed 14-15% (by mass), though in-service acceptable moisture content limits rise to around 25% before there are concerns for the degradation of the straw. These guidelines provide a clear limit for best construction practise, but the consequences for duration of exposure and subsequent severity of degradation are not yet sufficiently understood.

Experimental testing by the Fraunhofer Institute of Building Physics has been undertaken to characterise the mould resistance of building materials [6] [7] [8]. As part of this study wheat straw specimens were subjected to a range of climatic conditions through varying temperature and relative air humidity levels. Where mould growth was observed within 100 days environmental conditions were ……..The findings of these tests were subsequently presented using a graphical isopleth system. The isopleth provides a simple 'traffic-light' guide to climatic conditions that can support mould growth on wheat straw and is shown below in Figure 2. The Fraunhofer tests were initially undertaken to investigate risk of surface mould development on different building substrates, but has been developed further to assess the degradation risk of straw bale insulation.

Figure 2 – Isopleth 'traffic-light' for wheat straw [8]

Existing approaches provide two distinct methods for degradation risk assessment of wheat straw insulation:

- Assessment of straw moisture content against an upper limit of 25% dry basis;
- Use of an isopleth to assess hygrothermal (temperature and relative humidity) data.

The moisture content limit of 25% dry basis provides a safe threshold for ensuring wheat straw will not degrade but there are difficulties associated with its use. Firstly, how to assess the risk if the limit is exceeded; literature does not provide sufficient evidence for a reliable technical assessment to be made above 25% moisture content. The second difficulty is associated with how to monitor straw moisture content inside straw bale walls. Direct measurement is invasive and time consuming whilst wood block monitoring requires species specific calibration with the straw [9] [10]. In addition, interpretation of straw moisture content with an isotherm relationship has been found to be highly sensitive to variations in RH >90%.

The use of an isopleth system could, however, help to address some of the limitations associated with using a moisture content approach for assessment. The isopleth offers the following potential advantages:

- Compatibility with moisture transfer modelling such as WUFI simulations;
- Temperature and relative humidity sensors can be remotely and wirelessly logged;
- The influence of temperature is incorporated into the isopleth .

Nonetheless, determining limits for assessing degradation risk of straw bales with elevated moisture contents is not straightforward. Straw degradation is influenced by many environmental factors, perhaps most importantly the exposure duration.

In this paper two broad cases to consider when assessing the durability of straw bales in construction are proposed. Firstly, it is necessary to understand the risk associated with the germination and growth of mould arising from elevated relative humidity levels. Secondly, the risk of serious decay resulting from the ingress of water or sustained levels of high humidity associated with the use of the building or the climate that it is built in has to be evaluated. Decay would be recognised as causing detrimental damage to the building structure through significant breakdown of the straw. An comparable example of this approach is to be found in the field of timber construction. Blue stain fungi, or surface mould, can grow causing staining and discoloration of the timber when high relative humidity or moisture content allows. However, whilst the discoloration caused by the blue stain fungi affects the value of the timber it does not cause loss of mechanical strength [11] [12]. In comparison the presence of wet or dry rot is of greater concern in timber. These fungi occur when timber is maintained at moisture contents above 20% for a sustained period. They cause decay of the cellulose and lignin that forms the structure of the timber and are thus detrimental to its integrity.

3 Condition monitoring

Monitoring the hygrothermal conditions within straw bale walls is important as it provides benchmark data for the assessment of long term durability. This paper presents results from an exposure test facility that was located near Liskeard in Cornwall, UK. The monitoring data are corroborated by intrusive inspection surveys of the straw removed from the test wall panels. Findings from the surveys and recorded monitoring data are presented in this section of the paper.

The exposure test facility was constructed in 2009 on a site exposed to prevailing wind driven rainfall (Figure 3). The test facility incorporated six different panel finishes to assess their comparative performance as protective coatings for the straw. The different panel types included a selection of render carrier boards, directly applied renders and a timber rain screen solution. This paper will consider the findings from a panel that was finished with a formulated-lime based render applied directly to the straw bales. For the purposes of this paper the panel will be referred to as ‘panel A’ and is the middle panel shown on Figure 3. The render was applied to a total thickness of 35mm in two coats and the panel faced the prevailing south west weather. The panel is representative of the most common finishing methods for straw bale buildings.

Figure 3: The ModHut exposure test facility, Cornwall

Temperature and relative humidity monitoring data were recorded for each of the panels from September 2009 through to July 2012. Relative humidity levels within the straw bale panels were measured using Humirel HTM1735 sensors, whilst temperatures were measured using Grant Instruments thermistor probes. The data were recorded using a series of Grant Instruments Squirrel 1000 data-loggers. In November 2012 the intrusive inspection survey was completed on the panels to assess condition of the straw following the 3-year exposure trial.

The temperature and relative humidity plots for the base location in the directly rendered panel A are presented in Figure 4. The plots show the annual trends in relative humidity and temperature levels with sensors on the interior, exterior and mid-depth of the straw panel. The following observations are apparent from the plots:

- Rendering of the panel caused an initial rise in relative humidity levels within the straw;
- Relative humidity levels are higher during the first year of monitoring, which may be related to local weather conditions;
- During the Spring of 2010 the hygrothermal conditions exceeded levels where degradation of the straw is understood to occur.

Figure 4: Monitoring data for Panel A (directly rendered)

Figure 5 presents mean monthly average data for relative humidity and temperature recorded from the base sensors within panel A. These data corresponds with the location of the inspection survey reported below. These data are presented against the Fraunhofer Institute isopleth boundaries for mould growth. It is evident that the straw at the base of panel A spent several prolonged periods in conditions that Sedlbauer et al [8] suggests would support significant mould growth. Whilst these monitoring results suggest that the straw may have been subject to degradation, it is important to understand the severity of this exposure and whether it posed a long term risk to the integrity of the straw. To do this the panel was opened-up to allow direct visual inspection of straw conditions. A 150 mm core of lime render was removed from the base of the exterior face of the panels using a core drill (Figure 6). The straw behind the render was inspected and photographed before a specimen of straw was taken for gravimetric assessment of straw moisture content in accordance with BS EN 12570 [13]. Figures 7 and 8 show the core removed from panel A and the straw behind the render.

Figure 5: Monthly average relative humidity data plotted against temperature for Panel A

Figure 6: Opening up at base of panels

Evidence of significant decomposition was not apparent in any of the five panels opened up. However, a level of discolouration of the straw had occurred to a varying extent in all five panels. Whilst no fresh mould growth was evident the straw at the extreme outer face felt marginally damp to touch and had a perceptible musty odour.

Commented [PW2]: To date all been about panel A, now you mention 5 panels. This needs clarifying.

Figure 7: Render core removed from base of panel A.

Figure 8: Straw behind render in Panel A

A primary objective of the intrusive inspections was to confirm the straw moisture content through gravimetric means. Therefore, after removing the render core, a specimen from the outermost exposed straw was collected to determine its moisture content by oven dry method. The prevent further moisture loss the straw was placed in an airtight container prior to oven drying at 105°C until constant mass achieved, usually within 24 hours. . For panel A the gravimetric moisture content of the straw immediately behind the render was measured at 28.4%.

Commented [PW3]: Need to give more details. How much straw?

The findings from the condition monitoring and opening up study presented in this paper provide an important reference for durability assessment of straw bale buildings. Both hygrothermal and straw moisture content monitoring data suggested a level of degradation should be expected when considered against published guidance. However, the visual inspection survey of the straw suggests this guidance may be overly conservative for assessment of serious decay risk.

4 Laboratory study of straw degradation

4.1 Experimental setup

Commented [PW4]: repetition

Despite the monitoring data showing the straw bales exceeding published guidelines for moisture levels, and environmental conditions commensurate with mould growth [8], inspection of the panel subsequently demonstrated that integrity of the straw had been maintained. The development of micro-organisms on stored straw is largely controlled by the moisture content of the straw and the availability of nutrients within the straw [14]. Wheat straw stems that make up a straw bale are formed from a relatively homogenous combination of hemicelluloses, cellulose and lignin and the degradation of cellulose is known to be limited by lignification [15]. Aerobic degradation of straw may be limited by the availability of easily metabolised carbon, nitrogen and by prior colonisation by micro-organisms that utilise readily available nutrients [14][16][17][18].

Previous research on the decay of straw has typically focussed on the degradation of straw in soil, which provides a nutrient and moisture source for supporting growth of micro-flora. In this study it is proposed that within the walls of a building micro-organism growth on straw at elevated moisture levels will either become carbon or nitrogen limited, or the straw moisture content will drop to a level that does not support growth. Where limited growth does occur it is possible for the future establishment of micro-organisms to be restricted by the previous colonisation. This is because the nutrient source has been altered through mineralisation and biosynthesis [19]. With this in mind it is postulated that straw used in construction will therefore become a poor substrate for fungal colonisation during periods of elevated moisture content associated with seasonal weather patterns. However, long-term persistent damp may still allow slower growing micro-organisms to colonise the straw.

To test this hypothesis two experiments were completed to test whether repeated mould growth within straw bale insulation can become limited following an initial fungal colonisation. In both experiments wheat straw was exposed to elevated levels of humidity known to support mould growth on fresh straw. In the first experiment a comparison was made between fresh straw and straw removed from the external face of a three year old wall panel. In the second experiment six fresh straw specimens were exposed to two cycles of elevated humidity to evaluate the rate at which successive fungal colonisation might become limited.

In both experiments the straw was used in its natural form taken directly from a fresh dry bale. This best represented the conditions present within a typical wall panel in which the indigenous fungal spores will already be present on the straw. Sterilisation of the straw and inoculation with controlled fungal spores was considered but dismissed, as sterilisation of the straw may cause unknown changes to the substrate whilst the diversity of potential inoculums adds complexity to this form of testing. In their study of C and N availability during the decomposition of wheat straw, Reinertsen et al. [17] report that there is no significant difference between CO_2 evolution or O_2 uptake when comparing inoculated specimens and specimens containing naturally occurring spores. Therefore, unless a specific strain of fungi is of interest it is most appropriate to make use of naturally occurring spores for the broader study of straw durability.

In order to identify the initiation and severity of microbial growth under specific climatic conditions a test setup was developed that allowed CO_2 evolution to be measured during the period of exposure. Carbon dioxide is a product of aerobic respiration and thus provides a useful means to measure microbial activity. Several previous studies have used this technique to study microbial growth rates [17,18,20,21,and 22]. Zadrazil [20] specifically investigated the influence of CO_2 concentrations on the growth rate of mycelium on a straw substrate, and found that only at a volume of 36% CO_2 did mycelium growth become inhibited. In this study the experiment was setup such that CO_2 concentrations could not exceed 2% volume and therefore mycelium growth was not expected to be adversely affected.

Commented [PW5]: meaning not clear. Is this co2 concentration?

In this study straw specimens were placed in sealed HDPE containers to allow CO_2 concentrations to be monitored. Saturated salt solutions within the sealed containers were used to control relative humidity within the containers and micro fans were run throughout testing to ensure the air within the container did not become stratified (Figure 9). Use of saturated salt solutions was in accordance with BS EN ISO 12571:2000. Temperature was controlled throughout the experiment by placing the containers within an environmental chamber. Relative humidity, temperature and CO_2 were monitored within the container using a single GE sensor unit mounted to the underside of the lid.

Figure 9: Test setup for durability testing

4.2 Results and discussion

The first experimental test compared the behaviour of fresh straw with straw taken from the external face of a rendered straw bale wall. This straw had been within the wall for three years and appeared discoloured though not significantly degraded. The two specimens were placed in sealed environments at 87% relative humidity and held at a constant temperature of 21.5°C. Carbon dioxide levels within the sealed containers were then monitored as a means of detecting microbial growth. Prior to testing, the specimens were both stored at 20°C and 70% RH for seven days in order to ensure they both had an equal moisture content at the start of the test. The same mass of straw was then tested for both samples. The results of the testing are shown below in Figure 10.

Figure 10: Comparative microbial activity as indicated by CO2 evolution

It is evident that the three year old straw did not support any significant new microbial growth. However, a rapid increase in CO_2 concentrations was observed for the fresh straw, indicating rapid microbial growth. This is further supported by visual inspection of the specimens after testing, as shown in Figure 11 and Figure 12. Here mould growth can be clearly seen on the surface of the fresh straw whilst no visible mould growth occurred on the straw removed from the three year old wall.

Figure 11: Three year old straw following exposure to 87% RH at 21.5°C

Figure 12: Fresh straw following exposure to 87% RH at 21.5°C

A second set of tests were carried out to further test the mould growth behaviour. Six different wheat straw specimens were exposed to a range of different hygrothermal conditions. This second phase of testing investigated the impact of cyclically exposing fresh wheat straw to elevated levels of relative humidity. The conditions used in the test are given in the legend of Figures 13 and 14. All of the straw was conditioned at 20°C and 70% RH prior to testing and 5g specimens were used throughout. The six straw specimens were tested in the same manner as described above but this time the straw was initially exposed to a 28 day period of elevated relative humidity prior to a 7 day period of drying at 20C and 70% RH. The straw was then exposed for a second time to the same initial conditions for a further 14 days.

Figure 13: CO_2 evolution with time for straw taken straight from the bale and exposed to elevated humidity levels: Cycle 01 (Legend: Ref_RH_Temp).

Figure 14: CO_2 evolution with time for straw exposed a second cycle of elevated humidity levels following a period of drying: Cycle 02 (Legend: Ref_RH_Temp).

The results of this second phase of testing clearly demonstrates an arrested level of mould growth on straw following an initial growth associated with exposure to high levels of humidity. Focussing on the specimen exposed to 91% RH at 20°C (shown on Figure 13) a rapid initial growth is detected as a steep increase in CO_2 concentration. However, this growth appears to cease after 10 days exposure. Furthermore, following drying and re-exposure, mould growth is not detected a second time. This has significant implications for the medium to long term durability assessment of wheat straw used in buildings. This is because if transient increases in humidity are measured within walls such as those at the exposure test facility, it is not likely that successive mould growth will occur. Instead it is expected that, beyond an initial mould growth, further colonisation of the straw would not occur to any substantive level. Nonetheless, currently the results only suggest that this is true for transient increases in humidity. Long term exposure to high levels of moisture may still present an increased risk of degradation

The decline in CO_2 concentrations evident from day 10 in Figure 13 are attributed to a range of factors. A similar CO_2 evolution plot for wheat straw inoculated with Plerotus florida (oyster mushroom) spores is presented by Zadrazil [20]. In this instance Zadrazil suggests that the decrease in CO_2 concentration is attributed to fixation by the fungi. It is also possible that the salt solutions used in these experiments may have acted as a store for some of the CO_2. Thirdly, it is acknowledged that a level of the loss is attributable to leakage from the HDPE container. A level of leakage was confirmed through filling each testing container with a high concentration of CO_2 and monitoring the concentration decay. A non-linear decay was observed with an increased rate of loss higher levels of CO_2 concentration. Whilst this will have influenced the measured concentrations of CO_2 to a certain extent it does not significantly affect the interpretation and basis for comparison of fungal growth activity on the tested straw specimens.

The findings presented in this paper raise the question of how the risk of straw degradation can be reliably assessed without being overly conservative. There is clearly a need for a means to assess hygrothermal monitoring data for both transient mould risk and serious degradation or decay. Based upon current assessment criteria the monitoring data recorded from the exposure test facility suggested that a significant level of degradation should have occurred at the location opened up and inspected. However, whilst a level of discoloration of the straw was evident, long-term decay was not apparent upon removal of the render. The high moisture content recorded at the time of render removal also suggests that mould growth should have been present at the time of inspection though this was not observed. This observation supports the findings of the experimental study presented in this paper and suggests that in the long-term mould growth may be arrested within a wall due to the restriction of a viable nutrient supply following previous colonisation by fungi.

5 Conclusions

The experimental evidence that straw may be able to withstand relatively high transient moisture contents without suffering serious decay is encouraging for the wider acceptance of this form of construction. However, it also highlights areas that require further consideration and research. Firstly if the conditions for mould growth are met within a new wall made with fresh straw it is possible that a certain level of mould growth could occur within the walls of a building. Therefore whilst it may be possible for practitioners to reassure building owners and users that transient exposure to elevated humidity levels does not present a serious durability concern, the presence of an initial mould growth is likely to raise health concerns; perceived or otherwise. Secondly, if elevated transient moisture levels are not of concern in terms of serious decay of the straw how long can they be maintained before serious decay does occur? It is feasible that like timber the risk of colonization by serious decay fungi such as dry rot is only an issue when unfavourable conditions are maintained in the longer term.

The objective of the study presented in this paper was to understand the risk of degradation and mould growth arising from the naturally present spores and fungi on wheat straw taken straight from a bale. Cyclically exposing such specimens to high levels of relative humidity suggests that mould growth of this type may be limited by resource availability. However, risk of degradation resulting from long-term exposure to elevated moisture levels remains uncertain.

Further study is planned to help understand the risk posed by fungi known to cause serious degradation in buildings and cellulose materials. Timber in buildings is at risk of serious decay from wet and dry rot when it becomes wet. Untreated timber is very commonly used in conjunction with straw bale insulation in buildings and is a cellulose based material. It is suggested that if elevated levels of moisture were to occur in a straw bale building the risk of wet and dry rot of the straw may be significant.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the support of the Executive Agency for Competitiveness & Innovation (EACI) Eco-innovation project funding for the work outlined in this paper.

References

[1] Magwood, C. et al., More straw bale building: a complete guide to designing and building with straw. New Society Publishing; 2005.

Commented [PW6]: Needs full reference (all authors names)

[2] Holzhueter, K. & Itonga, K. The hygrothermal environment and potential for mould growth within a straw bale wall. Journal of Asian Architecture and Building Engineering, 2010; 9(2), 495-499.

[3] Yates, T. et al. Cellulose-based building materials: use, performance and risk, IHS BRE Press on behalf of NHBC Foundation; 2013.

[4] Goodhew, S. et al. 2010, Briefing: Challenges related to straw bale construction, *Proceedings of the ICE - Engineering Sustainability*, 163(4), 185 –189

[5] Lawrence, M. et al. Determining moisture levels in straw bale construction. Construction and Building Materials. 2009; 23, 2763-2768.

[6] Hofbauer, W. 2005, Toxic mould versus façade jungle – a comparison of undesirable biological growth on indoor surfaces and outdoor building coatings, *Proceedings of the International Conference on Indoor Air Quality and Climate*, Beijing, China

[7] Hofbauer, W. et al. 2008, Mould resistance assessment of building materials - Material specific isopleth-systems for practical application. *11th International Conference on Indoor Air Quality and Climate*, Copenhagen, Denmark. Paper ID: 465

[8] Sedlbauer, K. et al. 2011, Material specific isopleth-systems as valuable tools for the assessment of the durability of building materials against mould infestation – The "isopleth-traffic light". *International conference on building materials and components*, Porto, Portugal

[9] Goodhew, S. et al. 2004, An investigation of the moisture content in the walls of a straw-bale building, *Building and Environment* 39(12): 1443-1451

[10] Carfrae, J. et al. 2011, Development of a cost effective probe for the long term monitoring of straw bale buildings, *Building and Environment 46(1): 156-164.*

[11] Ingold, C. & Hudson, H. 1993, The biology of fungi (6^{th} edition), *Chapman and Hall.*

[12] TRADA, 2004, Timber: fungi and insect pests, *Wood information sheet,* 2/3(32)

[13] BS EN ISO 12570:2000. Hygrothermal performance of building materials and products – Determination of moisture content by drying at elevated temperature. British Standards Institution; 2000

[14] Lacey J. The microflora of straw and its assessment. In: Grossbard E, editor. Straw decay and its effect on disposal and utilization: Wiley-Interscience; 1979, 57-64.

[15] Harper S, Lynch J. The chemical components and decomposition of wheat straw leaves, internodes and nodes. Journal of the science of food and agriculture. 1981; 1057-1062.

[16] Knapp E, Elliott L, Campbell G. Microbial respiration and growth during the decomposition of wheat straw. Soil biology and biochemistry; 1982, 15(3): 319-323.

[17] Reinertsen S, Elliott L, Cochran V, Campbell G. Role of available carbon and nitrogen in determining the rate of wheat straw decomposition. Soil biology and biochemistry; 1983, 16(5): 459-464.

[18] Cochran V, Horton K, Cole C. An estimation of microbial death rate and limitations of N or C during wheat straw decomposition. Soil biology and biochemistry; 1987, 20(3): 293-298.

[19] Lynch J. Straw residues as subrates for growth and product formation by soil micro-organisms. In: Grossbard E, editor. Straw decay and its effect on disposal and utilization: Wiley-Interscience; 1979, 47-56.

[20] Zadrazil F. Influence of CO_2 concentration on the mycelium growth of tree pleurotus species. European Journal of Applied Microbiology; 1975, 1: 327-335.

[21] Angers D, Recous S. Decomposition of wheat straw and residues as affected by particle size. Plant and soil; 1997, 189: 197-203.

[22] Summers M, Blunk S, Jenkins B. Moisture and thermal conditions for the degradation of rice straw. American Society of Agricultural Engineers (ASAE) Annual International Meeting; 2002, Paper no. 026153.

Figure 1

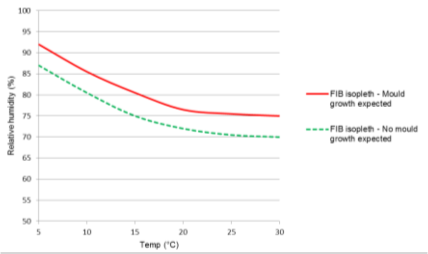

Figure 2

Commented [PW7]: Needs to much bigger

Figure 3

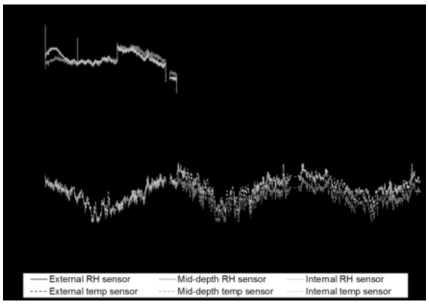

Figure 4

Commented [PW8]: Needs to much bigger to be able to read

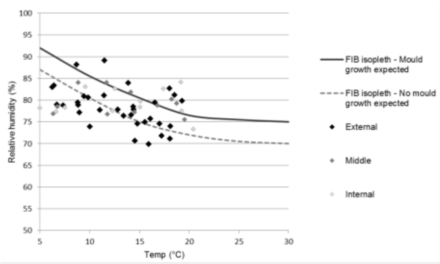

Figure 5

Commented [PW9]: ditto

Figure 6

Figure 7

Figure 8

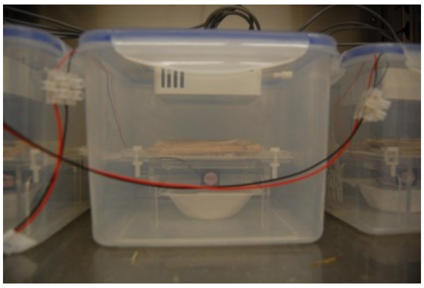

Figure 9

Commented [PW10]: label different elements mentioned in text

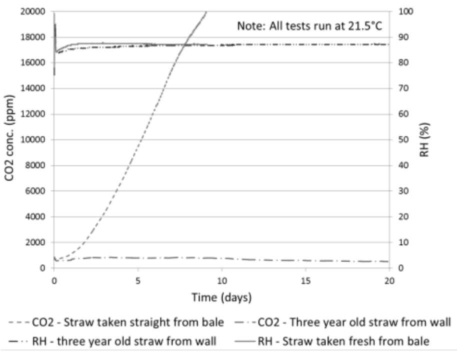

Figure 10

Commented [PW11]: font too small (as above). Need to subscript '2'

Figure 11

Figure 12

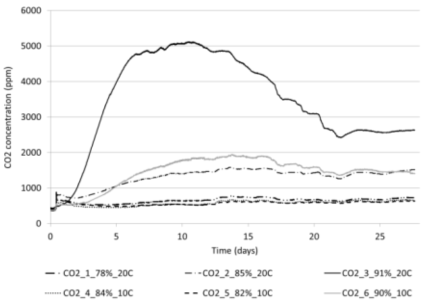

Figure 13

Commented [PW12]: too small. Subscripts needed

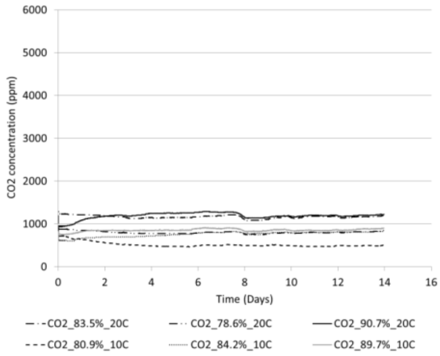

Figure 14

Commented [PW13]: ditto