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DETERMINING MOISTURE LEVELS IN STRAW BALE CONSTRUCTION

Mike Lawrence, Andrew Heath, Pete Walker

*BRE Centre for Innovative Construction Materials, Department of Architecture &
Civil Engineering, University of Bath, UK*

Abstract

The use of straw bales for the construction of buildings in the UK has to date generally been limited to the self-build fringe sector. In order to bring this form of construction into the mainstream sector, to benefit from its inherent low carbon and high insulation characteristics, it is necessary to guarantee the long-term durability of the straw. Maintaining low moisture levels is critical to the long-term resistance of straw to biological decomposition. This paper presents results from a study on moisture monitoring in straw bale construction, and includes the development of an empirical equation which relates straw moisture content to surrounding microclimate relative humidity and temperature. This knowledge allows continuous non-invasive condition monitoring of the straw in on-going research work and potentially as part of future managed maintenance of straw bale buildings.

Keywords

Straw bales, moisture content, relative humidity, sorption isotherm

Main Text

1. Introduction

Straw bales have been used in the construction of buildings since the late C19th [1,2,3]. Over the last 15 years interest in the use of straw in mainstream construction (figure 1) has developed for a number of reasons.

Figure 1: Media centre in Bristol constructed using ModCell pre-fabricated straw bale panels

- Straw has excellent thermal insulation properties [4]
- Straw has excellent sound insulation properties [5]
- The production of straw is a low energy process compared with other building materials [4]
- Straw sequesters carbon dioxide (CO₂) by photosynthesis, thereby reducing atmospheric CO₂.

These characteristics offer the potential to construct buildings with a zero carbon footprint as required by the Code for Sustainable Homes. [6]

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

In order to satisfy the concerns of designers, engineers and users as well as to meet local building regulations research has been conducted into fire resistance [7,8,9], vermin resistance [2, 10], structural performance [11, 12, 13, 14, 15, 16, 17, 18] and resistance to decay [19, 20, 21, 22, 23].

This paper concerns itself with the need to monitor the condition of straw which is sealed within the structure of a building. The moisture content of straw is the decisive factor in determining the rate of decomposition of straw. The experiment described below was designed to establish an empirical mathematical relationship between the moisture content of wheat straw and the relative humidity within the straw to estimate the moisture content of the straw without the use of invasive techniques. Straw specimens were exposed to different RH levels, and moisture content determined by the gravimetric method in order to produce a sorption isotherm. These data were compared with data from other sources, and an empirical relationship was developed.

2. Moisture Content Determination

Moisture is a problem in all forms of construction, and the concern in straw bale buildings is exacerbated by the fact that straw will decay when kept in a high moisture environment (Fig. 2). Hidden from view, the routine visual inspection of the straw as part of maintenance work is not possible.

Figure 2: Straw behind a rendered wall kept in high moisture conditions

The Canada Mortgage and Housing Corporation (CMHC) has probably conducted the greatest amount of research into straw bale housing with 11 reports currently available on their website (<http://www.cmhc-schl.gc.ca/en/>). The CMHC is directly involved in the financing of the construction and purchase of straw bale domestic dwellings on a relatively large scale. The greater proportion of their studies are in the area of moisture control and measurement, which is the area seen as being the

most problematic from the point of view of durability. Their studies [19, 20, 21, 22, 23], conclude that straw will only deteriorate when the moisture level exceeds about 25% (of dry weight of straw).

The weight of water present in straw expressed as a percentage of the weight of dry straw is the measure used for moisture content. A moisture content of less than 15% is generally accepted as rendering the straw safe from degradation by decomposition [24]. However, this level can be exceeded for limited periods without causing degradation [24]. Steen et al [3] suggest that the ideal moisture content is less than 14%, although the New Mexico standards list 20% as acceptable. They further state that the threshold of biological activity that results in decay is generally thought to be 14 - 16%. Tests on rice and wheat straw [25] have shown that moisture contents as high as 27% can be supported before initiation of significant micro-organism growth and decomposition. However, Summers [26] has suggested that moisture levels greater than 25% should be avoided to provide a margin of safety. In comparison, many fungi and bacteria associated with straw deterioration cannot survive at temperatures below 10°C, and the optimum temperature range for growth is 20°C to 70°C.

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

2.1 Direct measurement

The simplest and most reliable method of measuring moisture content is to weigh a sample of the material, dry it in an oven at 105°C and then re-weigh it. The weight loss represents the amount of water present in the initial sample, and this can be expressed as a percentage of the dry weight of straw to give a true moisture content measurement. Drying at 105°C is sufficient to drive off the moisture without causing

breakdown of organic material. For in-service monitoring the moisture content of a rendered straw bale wall, this method presents obvious difficulties:

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

2.2 Indirect measurement

There is a direct relationship between the moisture content of straw and the temperature and relative humidity (RH) of the surrounding environment [27]. The higher the temperature, the lower the moisture content of the straw for a given RH. It is therefore possible to measure the moisture content of straw indirectly by measuring the relative humidity within the straw, provided a mathematical relationship between the two can be established.

Hedlin [28] developed an equation to predict the sorption moisture content of five different grain straws at 70°F (21.1°C) based on earlier work by Malmquist [29, 30]:

$$\varphi = \frac{1 - K \left(1 - \frac{C}{C_s} \right)}{1 + \left[\frac{\frac{C_s}{C} - 1}{n} \right]^{\frac{3}{i}}}$$

C_s is defined as the fibre saturation moisture content,

C is the equilibrium moisture content at relative humidity φ . n , K_c and i are constants

where $n = C_s / C_{50\% RH}$

This equation was also compared with data taken at 14 different RH levels for oats, barley, flax and two types of wheat, and was found to represent the data closely.

According to Perry & Green [31] the lowering of the saturation vapour pressure through the reduction of temperature allows water vapour molecules to condense into capillaries with wider diameters than at the higher temperature. The range of capillary sizes available to capillary condensation therefore increases. The effect of this is that the sorption isotherm of porous materials such as straw is independent of temperature in the range 15°C to 50°C. Because progressive decomposition occurs in the temperature range 20°C – 70°C [25], slight variations in the isotherm occurring below 15°C can be ignored for the purposes of this study. Since air temperatures in straw bale walls in the UK are unlikely to exceed 50°C, variations in the isotherm between 50°C and 70°C can similarly be ignored.

2.2.1 Electronic RH/Temperature sensors

Theoretically, electronic RH and Temperature (RH/T) sensors are able to measure the temperature and RH of the air in a small localised volume of straw within a bale. This allows a temperature and RH profile to be measured through the depth of the straw bale. Knowing the shape of this profile would allow a greater understanding of the way in which moisture is stored, retained and moves through a straw bale. Straube & Schumacher, [32] installed RH/T sensors at the top, middle and bottom of a number of straw bale walls positioned at the interior, middle and exterior of the wall thickness.

The data gathered demonstrated that there was a relationship between exterior wetting (through rainfall or other means) and the RH inside the straw bales. The rate at which straw bale walls dried out was also able to be measured, as was the

influence of high RH at the interior on the RH within the straw bales. The moisture content of the straw was not measured.

2.2.2 Straw Bale moisture probes

Straw bale moisture probes are used by farmers to measure the moisture content of straw bales. These meters have been adopted by straw bale builders for quality control of the selection of straw bales for use in construction.

2.2.3 Timber moisture meters

Timber based moisture meters to measure moisture levels in straw bales appear to have been first developed by Gonzalez [33]. The design consists of a timber disc with two wires screwed to it, fixed in the centre of a ventilated 22mm diameter pvc tubing with wires running out through two holes in the endcap. The ventilated tube provides mechanical protection to the disc and avoids direct contact with the straw. The resultant moisture content reading is assumed to equate to that of the straw.

Goodhew et al [34] used moisture probes of this type in a study of a straw bale building. A calibration was conducted which found that the sensors produced a figure which was 1% higher than the measured straw figure, which is to say that an 11% meter reading equated to a 10% straw moisture content.

The electrical resistance of wood at any given moisture content (MC) decreases as the temperature increases and the effect of temperature is greater the higher the MC. With moisture contents below 15% a timber moisture meter overestimates the MC by about 7% for every 8°C below 20°C. Thus at 12°C a reading of 15% represents an actual MC of 14%.

Jolly [22] monitored several houses using both RH meters and timber moisture meters. The RH meter used was adapted from 'Micronta RH meter'. The sensors were removed from the unit and inserted 200mm into a perforated CPVC 17mm pipe (Fig. 3). They were reattached to the display by means of wires allowing continuous monitoring of RH and temperature.

Figure 3: Straw Bale Moisture RH sensor as used by Jolly [22]

The timber moisture meter used balsa wood and white pine inserted into a perforated CPVC 17mm pipe. Wood moisture meter contacts were inserted into the end cap of the assembly connected to the wood by means of wires (Fig. 4).

Figure 4: Wood Block moisture sensor as used by Jolly [22]

Jolly concluded from his work that:

1. Extreme diurnal variations in RH (with spikes as high as 98%) do not seem indicative of straw degradation. Moisture content values correlated most closely with the minimum daily RH value. Prolonged high RH values (over 85%) generally indicate a problem.
2. The maximum recorded in wall (*timber moisture content*) reading was 14%-17% (unadjusted). Readings at this level were described by Jolly as being indicative of borderline to unacceptable conditions in two Alberta structures.

2.3 Summary of literature

The use of direct measurement by gravimetric techniques is problematic with sealed walls, since it is both invasive and destructive. Straw bale moisture probes are also invasive. The sorption isotherms of timber are different from those of straw making comparison between the two problematic. RH/T sensors offer the potential for continuous monitoring the condition of straw provided the relationship between RH and moisture content is established.

3. Experimental Study

3.1 Methodology

The objective of this study was to establish a relationship between RH measurements taken of the atmosphere immediately surrounding straw with the moisture content of that straw. Although isotherms have been published for wheat straw in the USA [28], a series of tests were conducted to confirm their findings. These data were then analysed in order to develop an model that could be used to predict the moisture content of wheat straw based on measurements of relative humidity.

The isotherm relations for wheat straw samples were determined by placing samples in a scientific oven, set at different RH levels using saturated salt solutions contained within sealed boxes. Procedure followed BS EN ISO 12571:2000 [35]. The experimental set up is illustrated in figure 5.

Figure 5: Experimental set-up used for the measurement of the isotherms.

The straw was placed on perforated shelves over the salt solutions. Details of the saturated salt solutions and test temperatures are set out in Table 1. The wheat straw was grown inorganically (with the aid of fertilizers and herbicides) and was sourced from a farm in Gloucestershire, England through a straw merchant. The study was limited to wheat straw as this is preferred material for construction. The specimens weighed approximately 20g, were 35mm diameter and 185mm long, tied at a density of 125kg/m^3 to replicate that of straw bales at 125kg/m^3 . Three specimens were tested in each series. RH and temperature sensors were placed in each container to monitor RH and temperature. The RH sensors were manufactured by Humirel model #HTM1735LF with a humidity operating range of 0 to 100%, calibrated to $\pm 2\%$ RH @ 55% RH, 34 x 13 x 13mm. Temperature sensors were manufactured by Grant Instruments #CM-U-VL-0 general purpose thermistor, 50mm long and 3.2mm in diameter.

Table 1: Relative air humidities above saturated solutions in equilibrium (taken from BS EN ISO 12571:2000 [35])

Specimens were oven dried to establish a dry mass, and then placed in sealed containers with the appropriate saturated salt solution in the oven. They were removed and weighed at 24 hour intervals after 7 days had elapsed, and at 24 hour intervals thereafter until mass change was less than 0.1% of two previous readings.

Figure 6 shows a specimen at the end of the testing cycle that had been kept at a RH of 98%. Note the expansion in volume that has occurred and the formation of mould on the surface of the straw.

Figure 6: Specimen kept at 98%RH showing volume expansion and mould growth.

3.2 Experimental results

Results of the test measurements are presented in Table 2. These data show that the MC reduces with increased temperature over the range 5°C to 26°C by between 1% and 2% over most RH levels, but increases at the highest level of 98%. This does not bear out Perry & Green's theory, although the differences are not so great as to invalidate the principle of ignoring the effect of temperature for a first approximation assessment. An equation created to predict MC levels based on RH measurements would tend to over-estimate MC levels by up to 1-2% as temperatures increased within the sensitive range of 15°C to 70°C. This effectively means that such an equation has an inherent factor of safety. The data taken at 20°C are presented together with comparable data from Hedlin [28] in Fig. 7

Table 2: Equilibrium moisture content (%dry basis) of wheat straw at different temperature and relative humidity values

Figure 7: Moisture content vs Relative Humidity at 20°C (Experimental and Hedlin [28])

3.3 Analysis

The equations developed by Malmquist and Hedlin are problematic for the purposes of predicting the moisture content of straw when only the relative humidity is known.

Hedlin's equation defines relative humidity in terms of moisture content. Since the requirement is to define relative humidity as a function of moisture content, the terms of this equation need to be rearranged. The equation can be simplified if the effect of temperature is ignored as demonstrated by Perry & Green [31]. The simplified equation can be shown as:

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

Where K_m used in this equation is $1-K$ used in the Hedlin Equation

Fig. 8 shows the data shown in Fig. 7 together with graphs using the above equation and that proposed by Hedlin.

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 [36] 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 . [28]. The constants used in these equations, empirically determined by Hedlin, are:

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

Figure 8: Proposed equation compared with experimental data and data and equation proposed by Hedlin [28]

It can be seen that the proposed equation closely maps Hedlin's equation, and both of them closely represent both sets of experimental data. The equation shows that RH of 85% equates to moisture content of 25%, which is the level above which the literature suggests that degradation will commence. The figure of 85% agrees with the observations made by Jolly that prolonged RH levels greater than 85% generally indicate a problem.

The embedding of RH/T sensors within straw bale walls can be done at a cost of ~£10 per sensor, thereby allowing occasional or constant monitoring of the localised condition of the straw. With sensors located in areas where walls are most likely to be subject to water ingress (base of walls, walls subject to heavy weather conditions) it is possible to measure performance experimentally and monitor the condition of straw in existing buildings. This will undoubtedly contribute to the raising of confidence levels in the long term use of straw as a construction material.

4 Conclusions

In order to ensure the durability of straw bale walls in built structures, it is useful to monitor the moisture content of the straw. Measurement of the moisture content by direct means is invasive and not a practical solution on an ongoing basis.

Measurement of the relative humidity inside a straw bale can be performed in an economical, non-invasive way through the implantation of sensors within the straw bales at the time of construction or through small-scale intervention post-construction. The equation proposed in this paper allows the conversion of relative

humidity readings into moisture content to be made reliably thereby ensuring high confidence levels in the condition of the straw.

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TABLES:

Table 1: Relative air humidities above saturated solutions in equilibrium (taken from BS EN ISO 12571:2000)

Temp °C	Relative humidity %				
	MgCl ₂	Mg(NO ₃) ₂	NaCl	(NH ₄) ₂ SO ₄	K ₂ SO ₄
5	33.60 ±0.28	58.86 ±0.43	75.65 ±0.27	82.77 ±0.68	98.48 ±0.91
10	33.47 ±0.24	57.36 ±0.33	76.67 ±0.22	82.06 ±0.51	98.18 ±0.76
15	33.30 ±0.21	55.87 ±0.27	75.61 ±0.18	81.70 ±0.38	97.89 ±0.63
20	33.07 ±0.18	54.38 ±0.23	75.41 ±0.14	81.34 ±0.31	97.59 ±0.53
25	32.78 ±0.16	52.89 ±0.22	75.29 ±0.12	80.99 ±0.28	97.30 ±0.45
30	32.44 ±0.14	51.40 ±0.24	75.09 ±0.11	80.63 ±0.30	97.00 ±0.40

Table 2: Equilibrium moisture content (%dry basis) of wheat straw at different temperature and relative humidity values

Sample	Temp °C	5		10		15		20		26	
	Saturated solution	Straw MC	RH%	Straw MC	RH%	Straw MC	RH%	Straw MC	RH%	Straw MC	RH%
1	MgCl ₂	7.97	33.6	7.14	33.5	6.57	33.3	6.44	33.1	5.80	32.8
3	Mg(NO ₃) ₂	14.82	58.9	14.38	57.4	13.83	55.9	11.78	54.4	13.17	52.9
2	NaCl	14.84	76.7	14.58	75.6	14.36	75.6	14.13	75.4	13.42	75.3
4	(NH ₄) ₂ SO ₄	18.53	82.8	18.32	82.1	18.01	81.7	17.60	81.3	17.05	81.0
5	K ₂ SO ₄	48.44	98.5	47.15	98.2	46.51	97.9	49.34	97.6	51.49	97.3

FIGURES:



Figure 1: Media centre in Bristol constructed using ModCell pre-fabricated straw bale panels



Figure 2: Straw behind a rendered wall kept in high moisture conditions

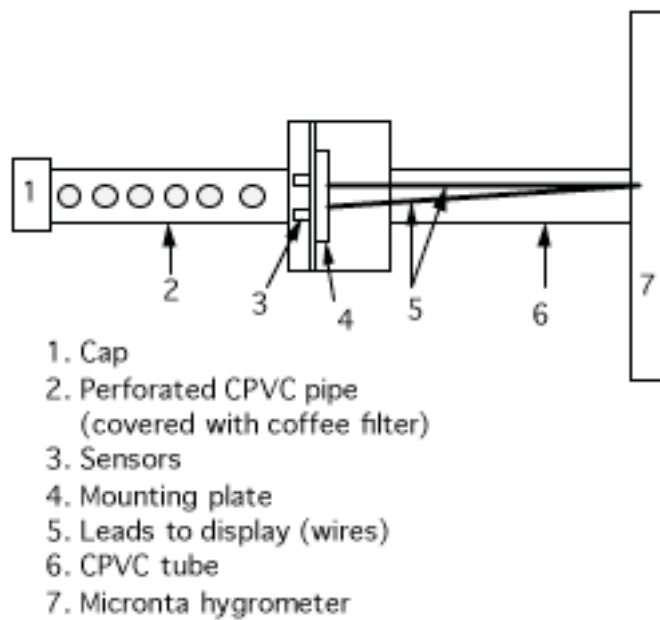


Figure 3: Micronta Straw Bale Moisture RH sensor as used by Jolly [22]

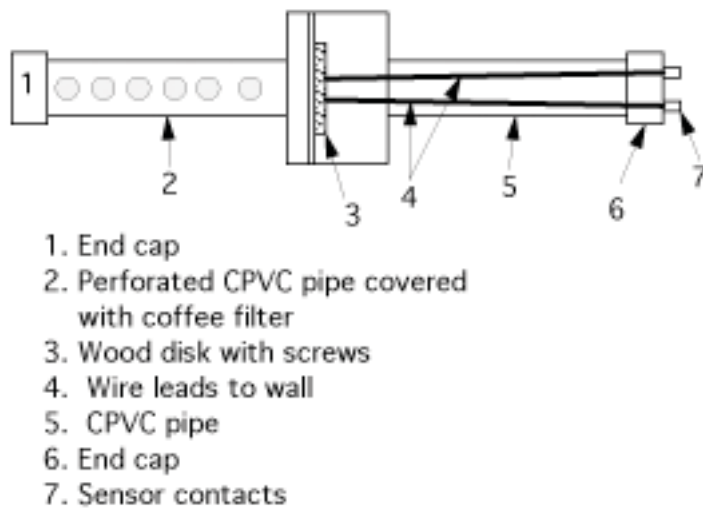


Figure 4: Wood Block moisture sensor as used by Jolly [22]

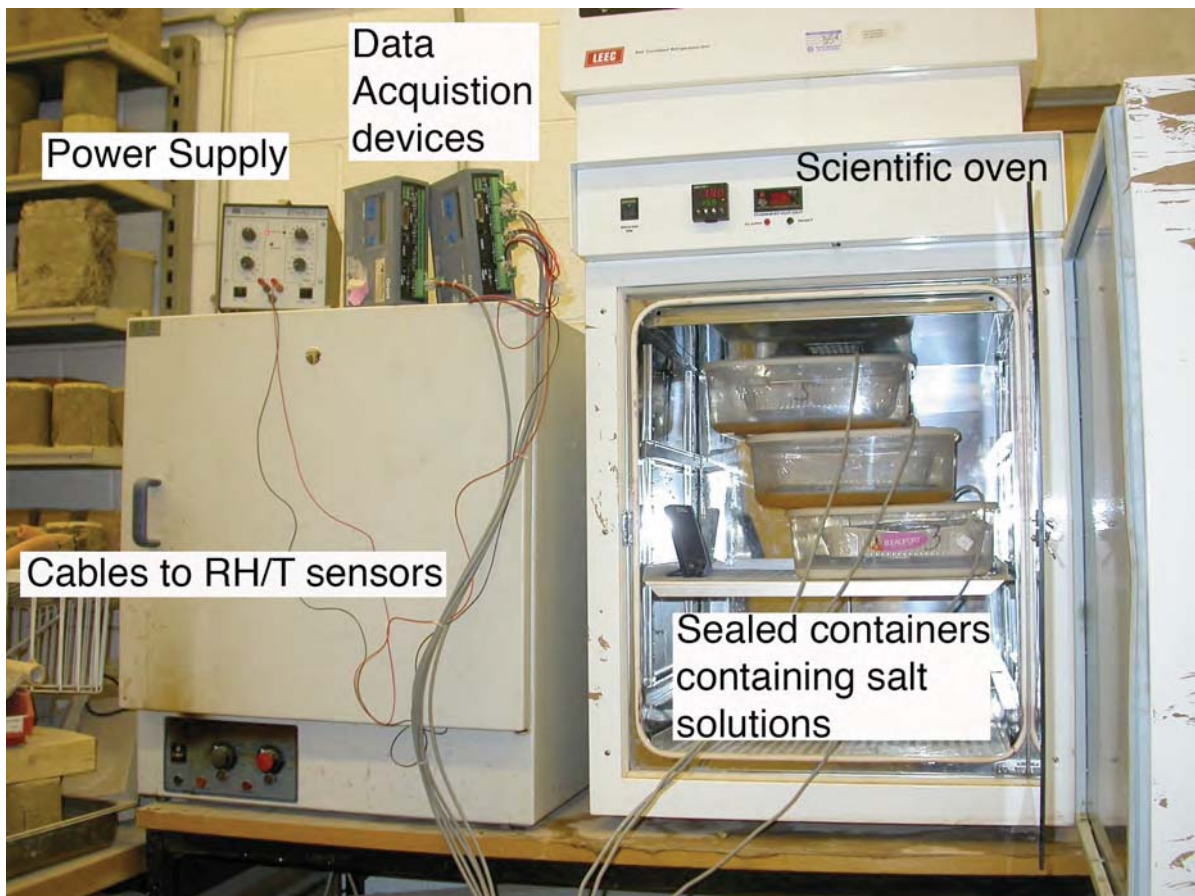


Figure 5: Experimental set-up used for the measurement of the isotherms.



Figure 6: Specimen kept at 98%RH showing volume expansion and mould growth.

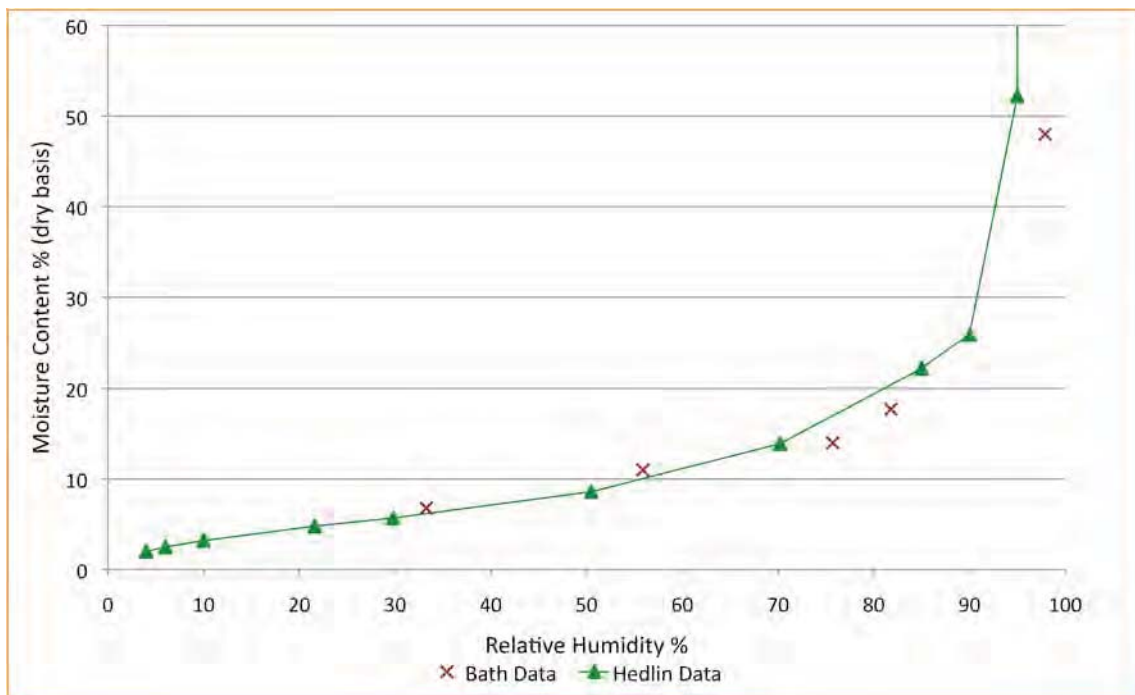


Figure 7: Moisture content vs relative humidity at 20°C (Experimental and Hedlin [28])

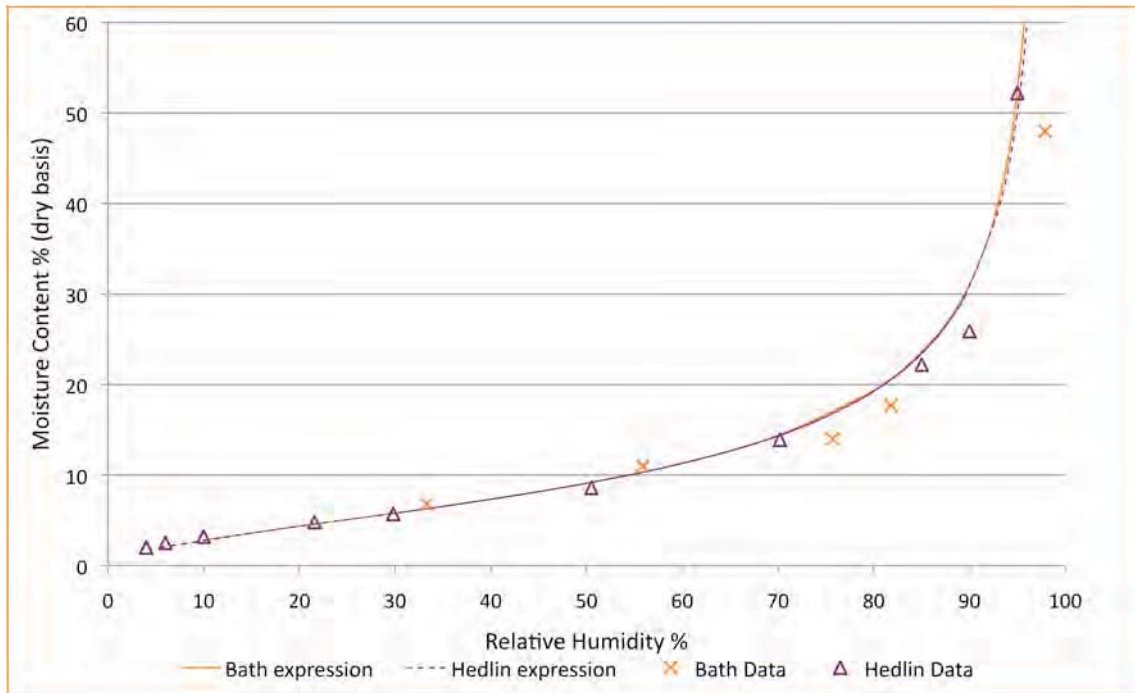


Figure 8: Proposed equation compared with experimental data and data and equation proposed by Hedlin [28]