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Measuring Moisture Content in Historic Building Materials

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Front cover: Assessing the moisture content of timber dowels using an electrical resistance moisture meter.

SUMMARY

This report presents some preliminary results from an ongoing programme of research to gain a better practical understanding of the limitations of various techniques for assessing moisture in historic building materials. This task has become more urgent as a changing climate increases the risk from flooding. The topics considered include:

- variation in moisture distribution within historic brick walls.
- how this variation may be overcome to provide a useful and repeatable moisture content approximation.
- unfamiliar limitations of resistance moisture meters for wood.

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1. INTRODUCTION

Water is responsible for many forms of deterioration in a wide range of materials.

Therefore, the ability to assess moisture contents and identify sources of moisture is of considerable importance in the conservation of historic buildings. Excess moisture can accumulate in building fabric because of occupancy, building and services defects, or more extensive problems such as fire or flood. Whatever the cause, assessing moisture content can help in diagnosing faults, assessing risks of decay and deterioration, and monitoring drying after remedial measures have been implemented.

Most efforts to develop convenient moisture measuring and monitoring techniques for building materials have been developed for wood or concrete (though the familiar moisture meters for wood have unexpected limitations that are discussed later in this report). In contrast, instruments for the accurate, convenient and non-destructive measurement of moisture in brick and stonework have proved particularly difficult to devise.

2. MOISTURE DISTRIBUTION IN WALLS

Wall moisture contents are often measured with some type of meter, but it is difficult to establish an exploitable relationship between moisture content and some measurable property of the material. Most meters produce a reading that is more or less inaccurate, generally unrepeatable, and of scant use for ongoing assessment. An alternative approach is to remove small samples of material from the wall and to evaluate these by the oven/balance method according to the following formula:

$$\%\ \text{Moisture content} = \frac{\text{wet weight} - \text{dry weight}}{\text{dry weight}} \times 100$$

Destructive sampling should theoretically give good results because it produces absolute moisture contents provided (a) that samples are carefully taken, (b) there is no moisture loss during transit, and (c) weighing equipment is reasonably accurate. However, sampling is dependent on wall material variability and moisture distribution. One half of a brick might be wetter than the other and both may be wetter of drier than the surrounding mortar. The moisture content of the sample would then depend on its size and the proportion of brick to mortar it contained.

2.1 Moisture variability

A preliminary investigation of moisture variability was made using a section of a Victorian ground floor wall that was being demolished in Pershore, Worcestershire. Large samples (half brick sized) were used, rather than the 2 or 3 grams normally removed with a masonry bit, so a greater wall area could be assessed.

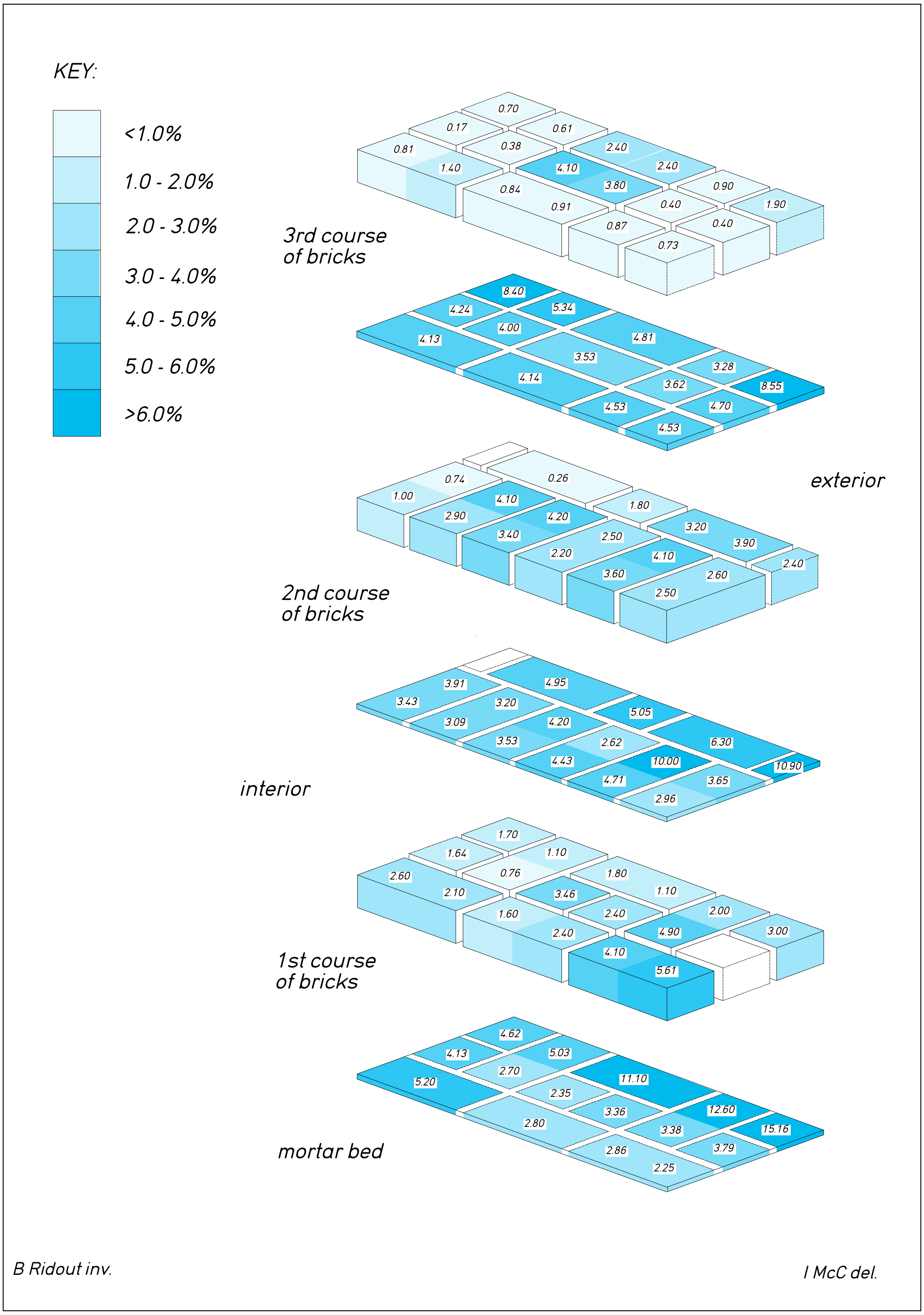


Figure 1: Absolute moisture content of bricks and mortar in section of wall.

A section of wall 1½ bricks thick, 3 courses deep and 3 stretchers long, was carefully dismantled. The position of each brick was recorded and numbered on a drawing. Bricks were cut in half with a bolster chisel and the horizontal lime mortar layers between courses were similarly recorded and retained. All the samples were weighed on site with a beam balance (to 0.01 g) and placed in labelled bags. Moisture contents were calculated by the oven balance method (drying at 65°C for 12 hours). The distribution of moisture is shown in Figure 1.

The moisture content of each brick was then tabulated with the moisture content of each mortar layer from its underside. The 51 resulting moisture pairs are compared in Figure 2.

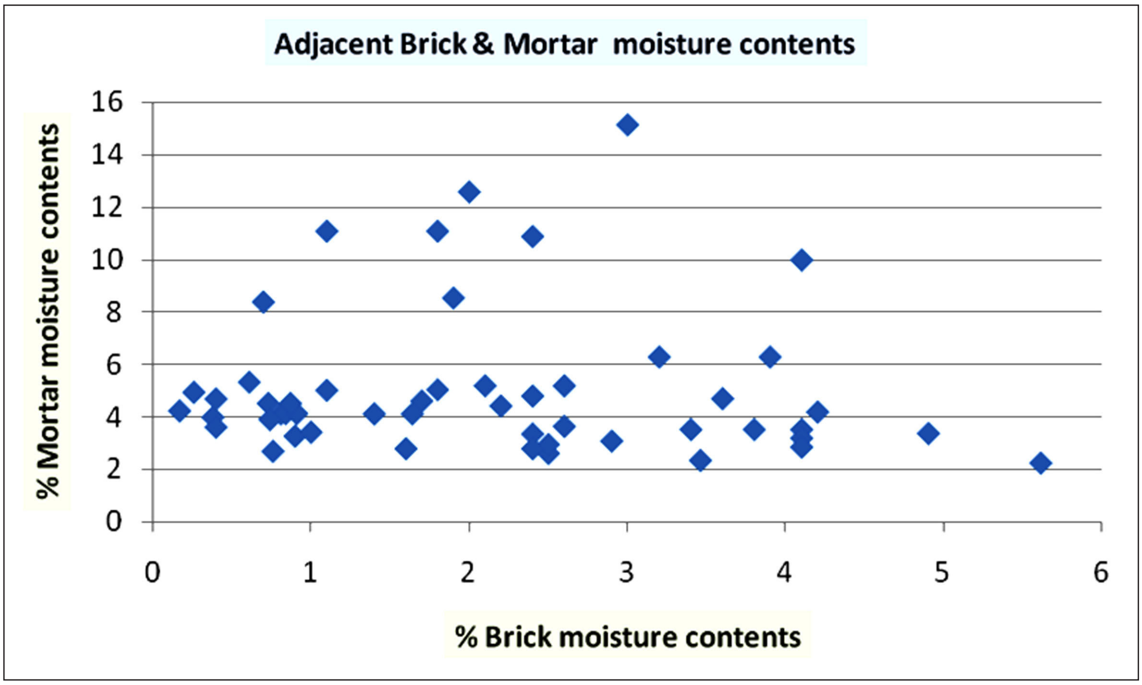


Figure 2: Adjacent brick and mortar moisture contents. © Ridout Associates

These results are informative. Most of the lime mortar moisture contents were within a band of about 2% to 6.5%, which is dry to damp, but there were 8 outliers that were wet. If these 8 wet outliers are ignored, just to make a general comparison more visually obvious with the majority of paired moisture contents (43), then it can be seen in Figure 3 that dryness or dampness in mortar can be independent of brick moisture content. A dry brick moisture content of 1% or a damp brick moisture content of 5% may both be adjacent to mortar with a moisture content of 3–4%. Presumably a change from dry to damp in the brick does not influence mortar moisture contents because extra moisture remains held by capillary forces within the brick and is not transferred to the random structure of the mortar.

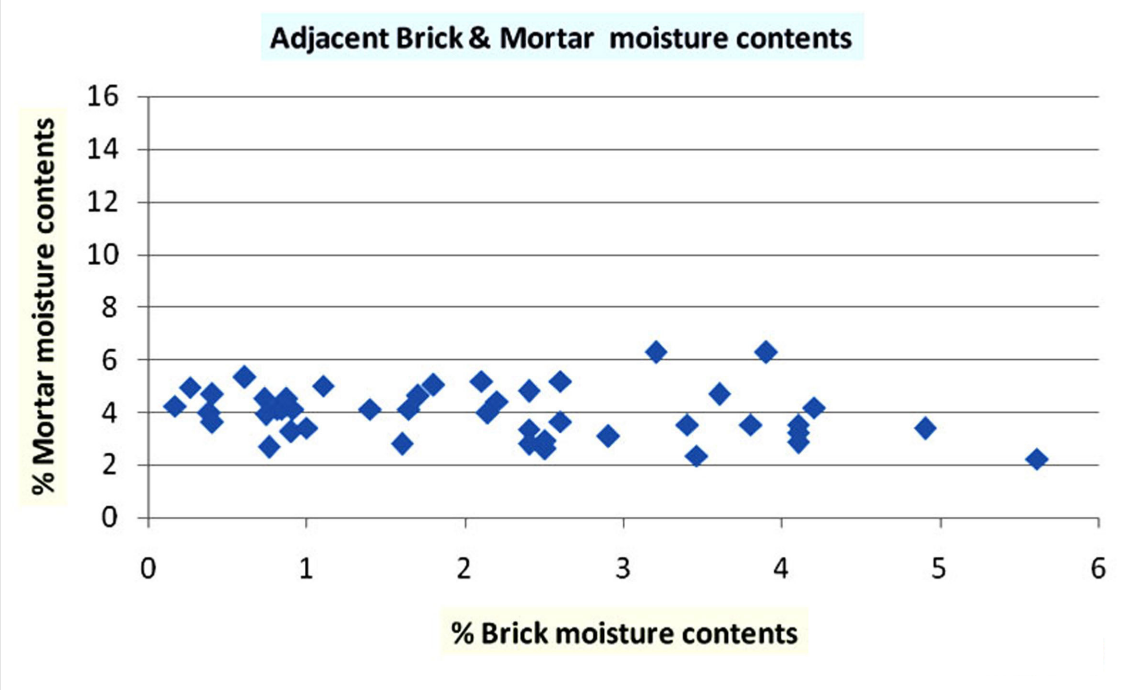


Figure 3: Adjacent brick and mortar moisture contents (with outliers removed). © Ridout Associates

The high readings in Figure 2 (not shown in Figure 3) are mostly from the outer skin of the wall and again they demonstrate the difference in moisture uptake between brick and mortar. It would seem that even a large uptake of moisture by the mortar joint may have little impact on the far more massive bricks.

The practical implications of this are that graivimetric assessment of wall samples removed with a drill can give a broad indication of wall moisture contents, but only if several samples are taken. The problem becomes more acute if sampling is undertaken through wall plaster, as is usually the case for fire or flood damage. The dust removed may be either brick or mortar, but more commonly some mixture of the two. If a brick has a moisture content of 3% and the mortar below has a moisture content of 15% (as shown by one result in Figure 2) then the removed sample will range from dry to wet depending on the proportion of brick to mortar it contains.

2.2 Equilibrium humidities and reference materials

Material variability can be overcome by assessing its ***wetting potential***, in other words the environment that a section of wall will maintain. Humidity measurements taken within holes drilled into a wall have become generally popular for monitoring drying following flooding. Unfortunately, there is a tendency to rely on relative humidity readings alone without taking account of temperature. The results obtained can be substantially misleading because there is an inverse relationship between temperature and humidity, so dry air that is quite dry can have a high relative humidity if the temperature is low. The way to avoid this mistake is to convert temperature/relative humidity readings into air moisture content, but there is still the problem that a wide range of moisture contents in the material will produce the maximum of 100% relative humidity (although the equipment may read higher). A further difficulty is that humidity sensors are inherently inaccurate, particularly above 90%, so that any calculated air moisture contents, dew points, or vapour pressures may not be sensible or comparable.

The pitfalls in converting humidity data can be avoided by measuring the moisture content of sensors made from material with known characteristics which have been inserted into holes drilled in the wall and allowed to equilibrate. Softwood dowel rods, 8–12 mm in diameter, have proved useful for this purpose.

Some wooden wall sensors have been designed to be isolated from the sides of the hole into which they are inserted to avoid the uptake of salt laden water which would alter the electrical resistance of the sensor. Salt contamination from ground water or the wall material itself has been a constant problem in the development of moisture meters. These salts may be mobilised by water movement within a wall, and the incautious investigator with a resistance or capacitance moisture meter might conclude that there was a significant damp problem when only a small amount of water was present. However, salt contamination is usually only a problem at the bases of walls or in exceptional environments and trials using the Historic England segmented dowel rod sensor shown in Figures 4a–e have provided accurate and repeatable readings.

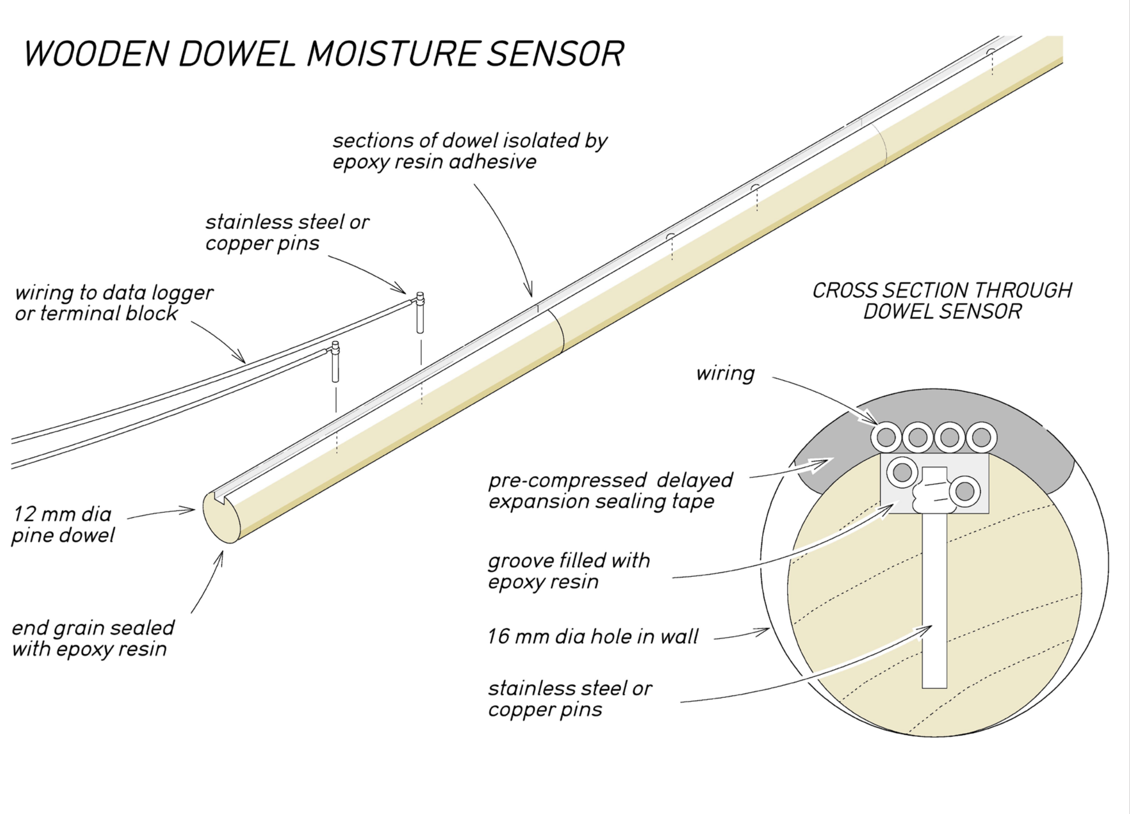
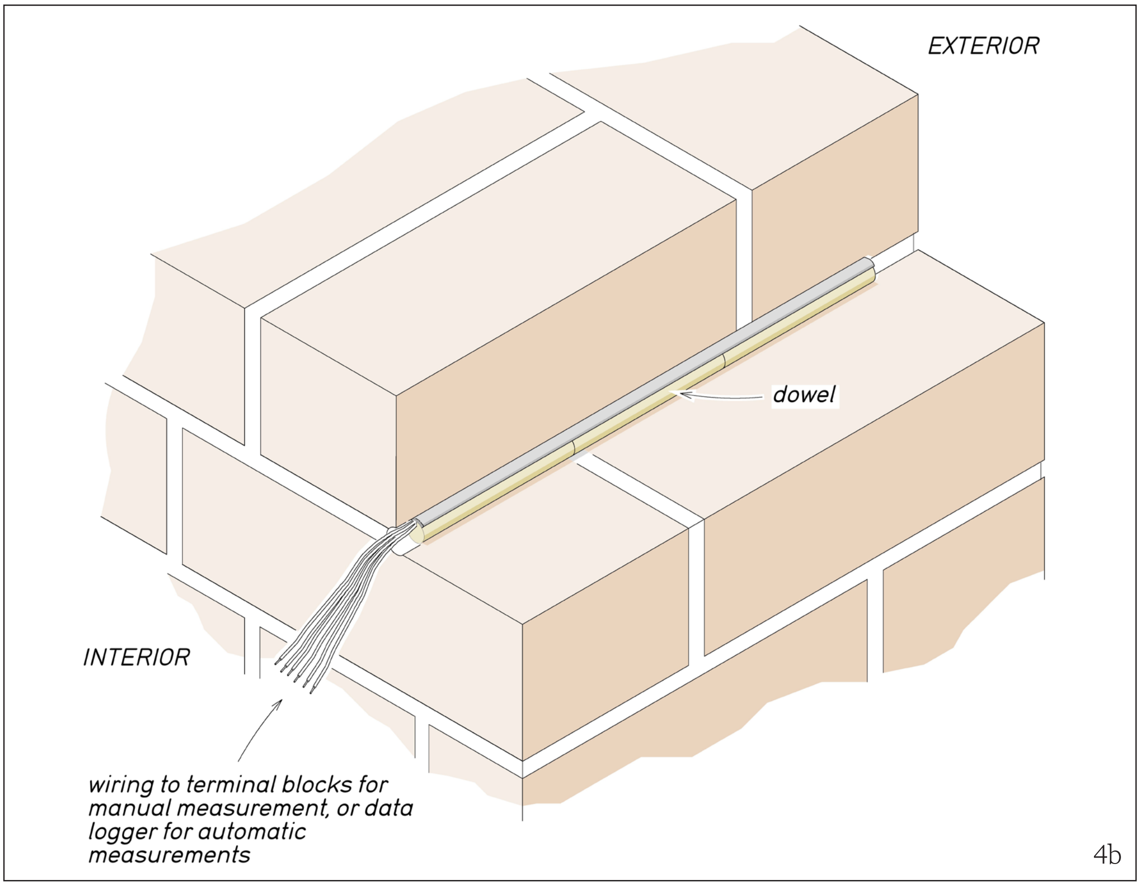


Figure 4a: Segmented timber dowel.



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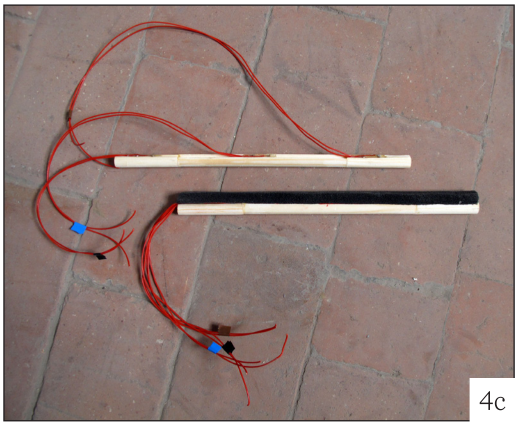

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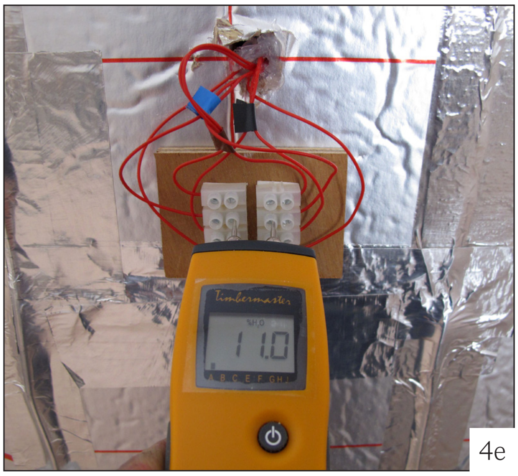

4e

Figure 4b: Diagram showing position of segmented timber dowel in wall.

Figure 4c: Segmented timber dowel.

Figure 4d: Inserting segmented timber dowel into hole drilled in wall.

Figure 4e: Remote measurement of timber dowel moisture content using a resistance-type moisture meter.

An alternative way to assess the moisture contents of the wooden sensors (while avoiding potential inaccuracies caused by salt contamination) is by gravimetric measurement using the oven/balance method. In this case the dowel may be left in a wall for about four weeks to equilibrate. It is then removed and cut into sections which are weighed, dried at 105°C ± 5° for 12 hours, and weighed again. Omitting the remote resistance readings simplifies the sensor design because each needs only be a dowel inserted into a hole drilled into the wall. Sensors can be replaced using the same holes at the end of each monitoring period. (N.B. The diameter of the holes must be large enough to allow for the swelling of the dowels as their moisture content increases, otherwise they will become jammed and impossible to remove).

This method has proved particularly useful for measuring the rates of drying in walls following fire and flooding. It also provides a good indication of moisture profiles across the thickness of the wall. The methodology is consistent, simple and inexpensive. It also avoids the use of more costly apparatus which could be lost or damaged on a building site or one where there is public access.

Repeatability is the overriding consideration since, as discussed above; accuracy is always going to be limited by the variability of the materials. Figure 5 demonstrates this by showing the relationship between timber dowel readings and the dust removed from the holes during drilling.

When the dowel in Figure 5 shows that the wall is dry (mc about 15%) then the masonry sample is also dry (mc below 3%). But when the wall is wet there is little correspondance between the moisture contents of the dowel rods and the dust samples because the latter give a poor indictation of the wall's wetting potential..

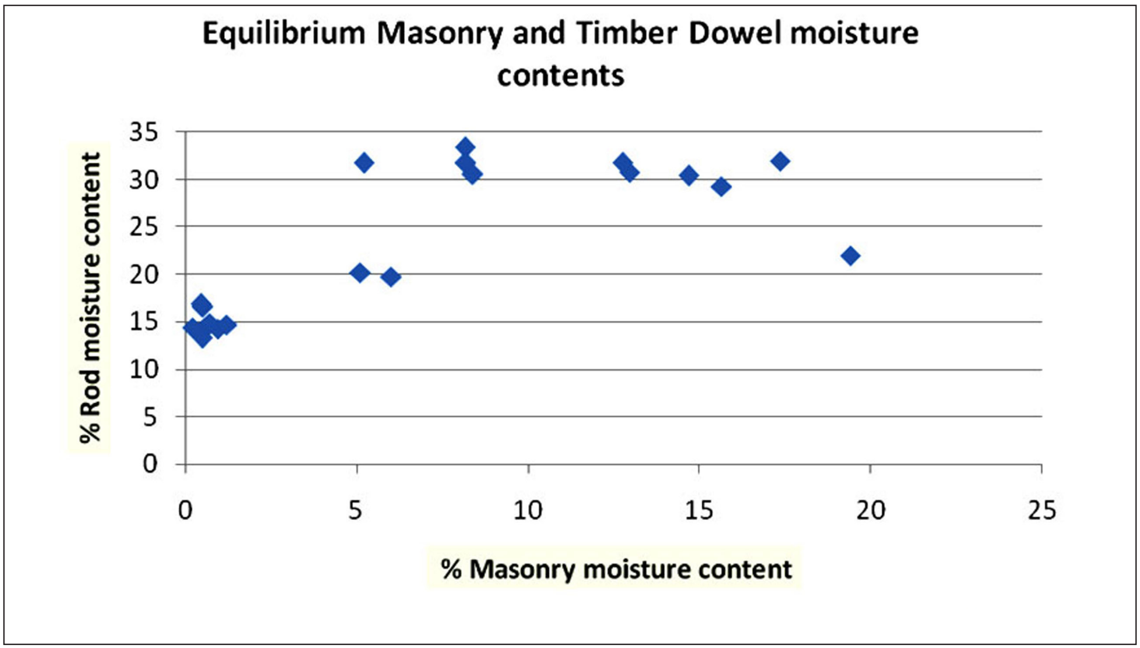

Figure 5: Equilibrium masonry and timber dowel moisture contents.
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3. HOW USEFUL ARE RESISTANCE MOISTURE METERS FOR TIMBER?

3.1 Samples from Ditherington Flax Mill and High Bickington Church Tower

Resistance moisture meters work for timber because it is possible to derive a linear relationship between moisture content and electrical resistance between about 8%, (below which the resistance is too high to measure conveniently) and around 28% (fibre saturation) when the relationship breaks down. These meters can accurately measure resistance but the calibration is dependent on the moisture content / resistance curve that each meter manufacturer applies. The accuracy at the upper half of the range has not received much attention because the meters were primarily developed for use with drying kilns and in clean new timber.

Most surveyors have a moisture meter and assume that it measures moisture. The manufacturers of the instruments have seen a good marketing opportunity, and some meters will give readings over a scale that might be as low as 6% or as high as 50% or more – but what do these readings mean? This question is important because surveyors draw conclusions about the risk of infestation or decay from the results. It is also of importance where timber moisture changes are being monitored as part of an environmental assessment. Readings taken from wood are generally assumed to be reasonably accurate. But how accurate are they?

3.2 Moisture readings between about 9% and 18%

In 2000 the Technical Research Centre in Finland (VTT) published the results of an extensive European project to test the reliability and performance of moisture meters. Their study used 16 resistance-type meters and 6 capacitance meters on 2700 samples of timber from 7 species, including our commonest construction softwood Scots pine (***Pinus sylvestris)***. Samples were conditioned for 1 year to moisture ranges of 8–10%, 12–14% and 16–18 %.

Their industrial tests were performed in accordance with the European Standard (EN 13183-2) which indicates measuring at 0.3 times the depth of the timber at 0.3m from either end and 0.3 times the width from one edge. While this is useful for a drying kiln it is meaningless for a surveyor. However, the results are important and they reached the following conclusions:

- Sapwood, heartwood and density made no difference to the resistance value.
- Probe orientation had no effect.
- Electrode separation distance had no effect, however tip profile did.
- All resistance meters showed systematic variations from absolute readings because of incorrect moisture content – resistance curves used by the manufacturers.
- The accuracy of the readings was about ±2.5%–±5% for the resistance meters.

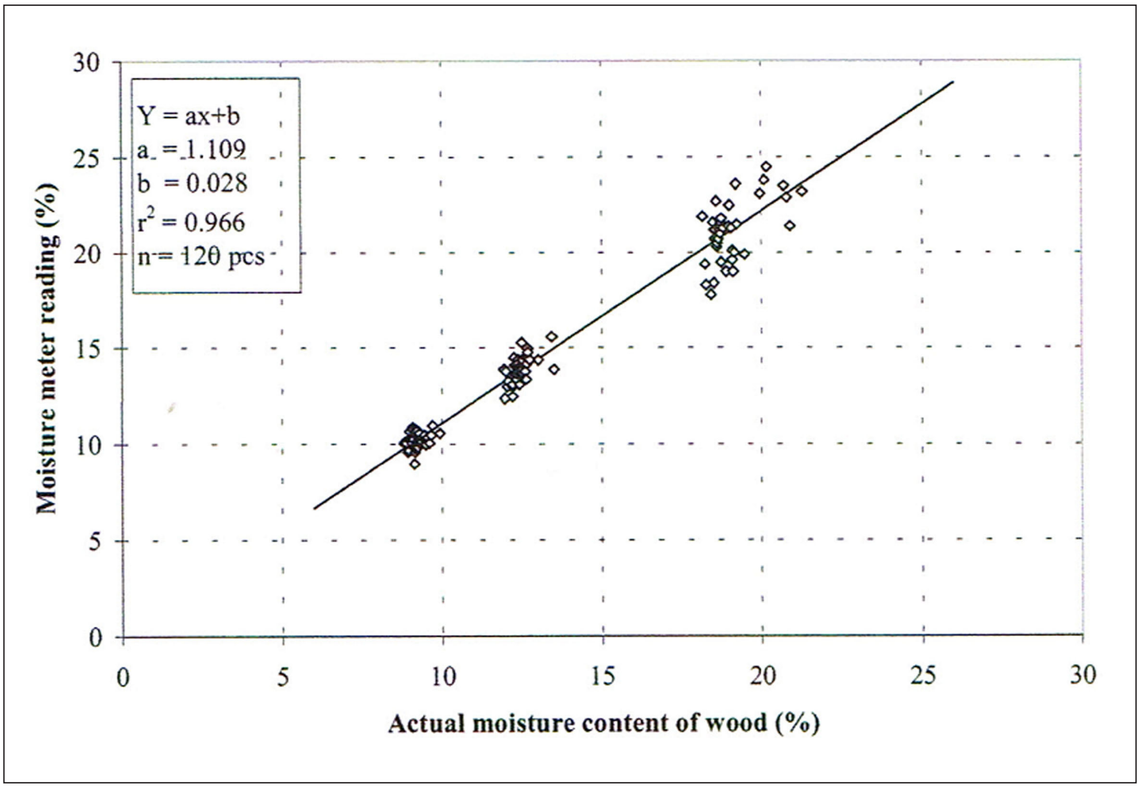

Figure 6: Regression of moisture meter readings against actual moisture content of timber. © Ridout Associates

The document presents a graph (Figure 6) showing the regression of moisture readings against absolute moisture content (calculated line of best fit that minimises individual variation). These tests were performed using pieces of clean and uncontaminated timber so that they would not produce the additional potential inaccuracies we might find in old building components or dowel rods left in a wall.

The dry end of the range shown in Figure 6 is reasonably consistent, but if the actual moisture content of the timber was about 18% then a surveyor might obtain a reading of 17%–23%, which the meter manufacturer's leaflet might tell him was either damp or liable to decay.

Tests undertaken with clean pieces of timber may not reflect materials in an old building. Known causes of variation, which can be compensated for, are timber species and temperature. Nevertheless, the accuracy of the meter is generally accepted by the surveyor.

Figure 7 shows results obtained from dowel rods inserted for four weeks into walls at Ditherington Flax Mill. Each dowel rod section was measured at its centre with a Protimeter that had been tested against the manufacturers calibration check and set to scale A, which was appropriate for pine. Sections were weighed on site and then dried overnight at 105°C.

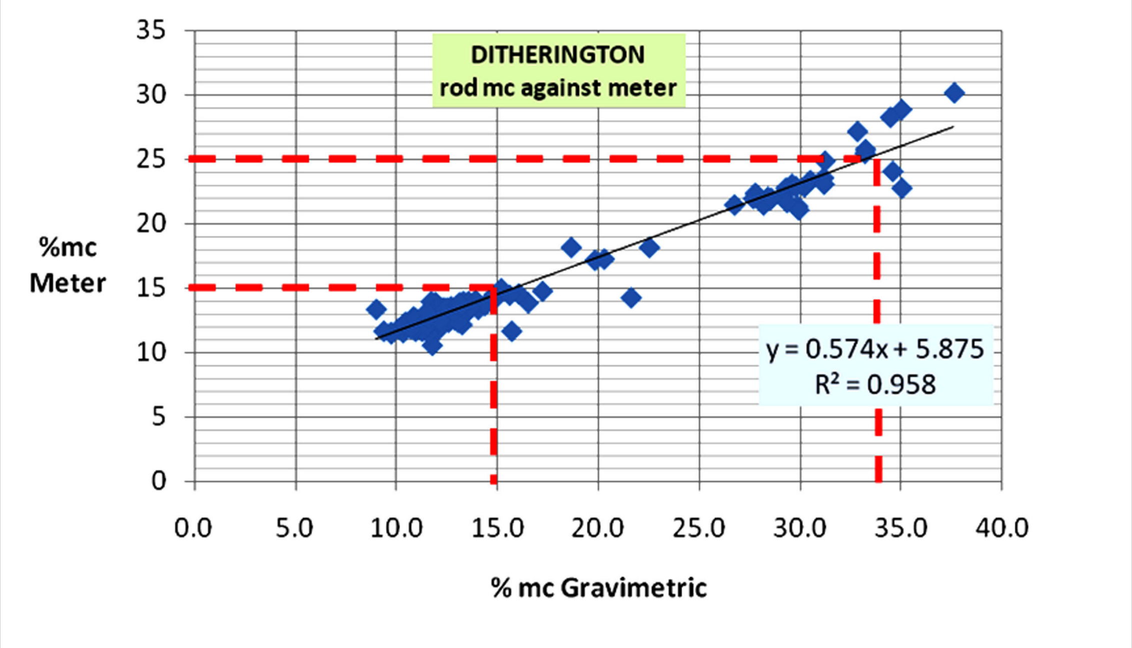

Figure 7: Ditherington Flax Mill. Moisture meter readings against actual moisture content of timber dowels. © Ridout Associates

The fit of the regression line is excellent (the nearer R^2 is to 1 the better the fit) showing that there is a clear relationship between the moisture meter reading and the actual moisture content. However, the meter underestimates the moisture content by an increasing amount above about 15%. This probably does not matter much until the reading is around 20% when the consequences of the inaccuracy could become significant: a timber that is theoretically not wet enough for fungi to attack might start to decay.

3.3 Moisture contents above about 18%

Moisture levels in walls that produce high moisture contents in timber might also mobilise contaminating salts and cause readings from a moisture meter to be substantially elevated. There was an opportunity to explore this possibility with a set of 10mm diameter dowel rods removed from the walls of the tower at High Bickington Church, Devon. The dowels were 500 mm long and several were coated with mould. They were cut into sections of similar length and their moisture contents measured with a Protimeter 25 mm from either end of each section, first on one side then in similar positions on the opposite side. This was done because the contact surface between dowel and masonry was unknown, and no attempt had been made during transit to keep each cut section the same way up. If measurements were affected by contaminants transferred from the damp wall, one side of the dowel section would give much higher readings than the other. The wood temperature was 18°C when measured. Pairs of readings are presented in Table 1. The first section of each dowel protruded from the wall, into the tower interior, by an unknown amount. As this would have had an undeterminable effect on their total moisture content, these sections were excluded from the assessment.

TABLE 1: A COMPARISON OF MOISTURE READINGS FROM EACH SIDE OF EACH DOWEL SECTION

The first pair is on one side (eg. 2a & 2b). The shallowest section is .2 (eg. 1.2) and the deepest is .4 (eg. 1.4)

Section no	1a	1b	2a	2b	Section no	1a	1b	2a	2b
1.2	44.4	44.8	42.0	45.7	**2.2**	20.2	24.6	24.0	24.9
1.3	39.9	39.4	44.8	40.3	**2.3**	30.1	24.2	31.7	24.3
1.4	43.8	36.0	52.7	50.1	**2.4**	35.1	37.0	35.4	35.7
3.2	49.5	48.0	46.0	47.9	**4.2**	24.3	22.2	25.2	20.6
3.3	40.8	45.5	44.5	43.4	**4.3**	37.9	31.6	28.0	37.5
3.4	41.9	41.3	45.1	44.8	**4.4**	38.8	64.9	49.2	60.8
5.2	30.7	25.5	33.6	27.1	**6.2**	30.1	27.8	25.1	24.2
5.3	33.9	37.4	35.0	31.7	**6.3**	27.5	31.9	24.7	27.4
5.4	25.1	25.5	24.9	25.1	**6.4**	27.1	25.6	24.4	24.0
7.2	22.8	22.4	23.7	21.7	**8.2**	21.8	20.7	22.5	21.5
7.3	24.2	22.9	24.6	23.0	**8.3**	21.9	22.2	22.1	22.4
7.4	24.8	24.6	24.7	24.3	**8.4**	22.7	22.2	23.0	21.1
9.2	27.1	28.5	26.3	28.9	**10.2**	21.8	21.3	21.1	21.7
9.3	26.0	25.9	24.2	24.9	**10.3**	23.0	23.2	22.9	22.8
9.4	24.5	26.0	24.7	25.6	**10.4**	23.6	22.1	23.3	21.6
11.2	27.1	23.8	25.9	24.0	**12.2**	43.4	47.4	41.2	40.1
11.3	24.0	24.3	24.5	25.3	**12.3**	40.5	40.4	46.4	41.2
11.4	25.0	26.2	24.6	26.9	**12.4**	44.3	36.4	40.8	39.4
13.2	24.8	31.5	23.5	31.8					
13.3	26.5	28.7	25.2	25.0					
13.4	23.5	24.4	25.5	24.4					

Paired readings across the columns show variation within each rod section, but they are mostly rather consistent and without substantial differences. With the possible exception of rod sections 1.4 and 4.4, there is little to suggest that one surface of any section is more contaminated than the other. Sections 1.4 and 4.4 are also the deepest and the wettest so that the difference in moisture readings from one end to the other (4.4: 1a & 2a compared with 1b & 2b) is most likely to reflect end grain absorption (Table 2). The rods could, therefore, be used to compare meter readings with absolute moisture contents. Readings down the columns in Table 1 show that rod moisture contents remain rather consistent along the rod length. This is all useful until we plot the actual moisture contents of each section.

Absolute moisture contents determined by the oven/balance method are plotted against meter readings for each section in Figure 8. The contribution to variation from end grain absorption is assessed by removing data from the deepest rod sections. This result is shown in Figure 9, where the only change is the loss of a few very high moisture contents.

Figure 8 shows that a meter reading of about 35% can represent an actual moisture content ranging from 30% to 84% (follow red line across graph). The high reading was caused by end grain absorption.

Figure 9 shows that even where there is no end grain absorption a meter reading of 24% might actually represent a moisture content of about 22.5–39%. This is more worrying because decay fungi would not grow at 22%, but they certainly would at 39%.

Figure 10 shows the lower end of the range in greater detail. The regression line (line of best fit) is reasonably accurate but the individual variation is considerable. The red line shows that a moisture content of around 27.5% might give a meter reading of between 20% and 34%.

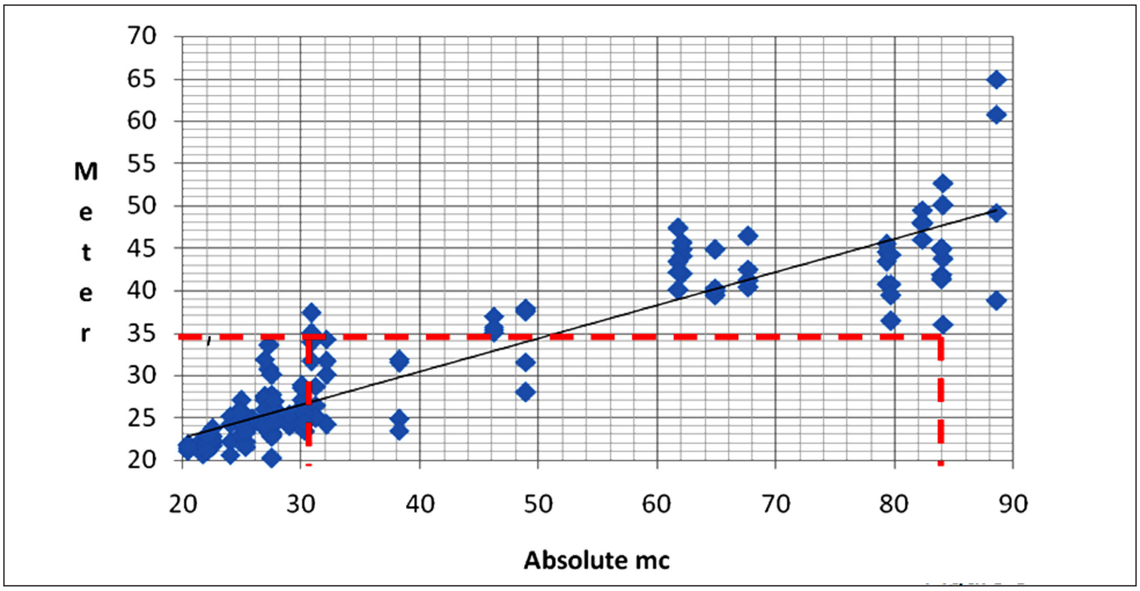

Figure 8: High Bickington Chuirch. Moisture meter readings against actual moisture content of timber dowels. © Ridout Associates

These results show that a meter becomes progressively less accurate above about 22%, and entirely unreliable as the wood approaches and exceeds fibre saturation. The regression line in Figure 10 shows that the meter could give a reasonable approximation of the true moisture content. But if the surveyor is only taking a few spot readings, then these might be substantially inaccurate.

The actual moisture content results are shown in Table 2.

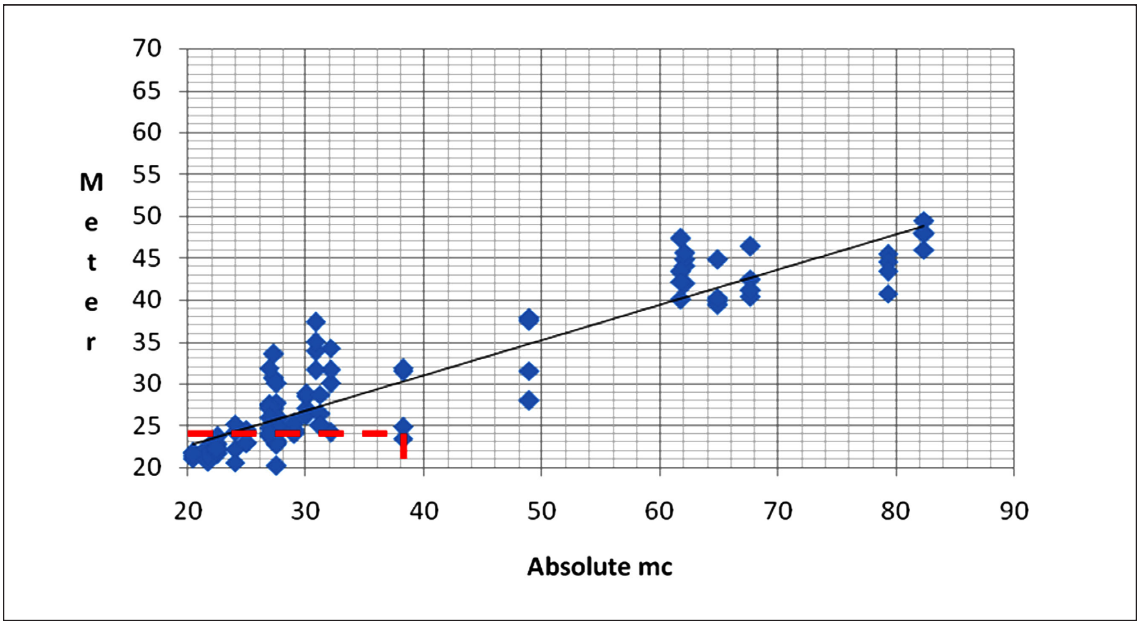

Figure 9: High Bickington Church. Moisture meter readings against actual moisture content of timber dowels. © Ridout Associates

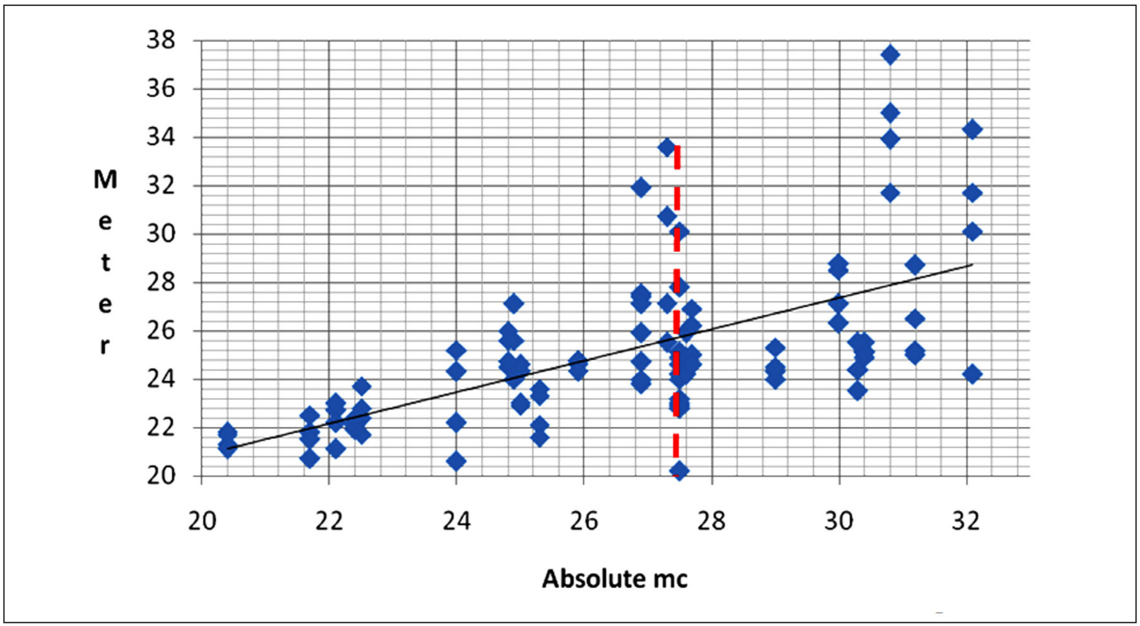

Figure 10: High Bickington Church. Moisture meter readings against actual moisture content of timber dowels. © Ridout Associates

TABLE 2: MOISTURE CONTENTS CALCULATED FROM WEIGHT LOSS AFTER DRYING OVERNIGHT AT 105°C

Rod	%mc		Rod	%mc		Rod	%mc		Rod	%mc
1.1	26.2		5.1	18.3		8.1	13.5		11.1	19.4
1.2	62.1		5.2	27.3		8.2	21.7		11.2	26.9
1.3	64.9		5.3	30.8		8.3	22.4		11.3	29.0
1.4	84.1		5.4	30.4		8.4	22.1		11.4	27.7
2.1	16.9		6.1	21.9		9.1	19.3		12.1	14.9
2.2	27.5		6.2	27.5		9.2	30.0		12.2	61.8
2.3	32.1		6.3	26.9		9.3	27.6		12.3	67.7
2.4	46.2		6.4	24.9		9.4	24.8		12.4	79.7
3.1	33.8		7.1	18.6		10.1	18.3		13.1	22.4
3.2	82.4		7.2	22.5		10.2	20.4		13.2	38.2
3.3	79.3		7.3	25.0		10.3	23.5		13.3	31.2
3.4	84.0		7.4	25.9		10.4	25.3		13.4	30.3
4.1	17.4									
4.2	24.0									
4.3	48.9									
4.4	88.6									

The table shows that the moisture contents of the shallowest sections (eg 1.1) are lower than the remainder because they were partially exposed in the room and influenced by interior conditions. Moisture contents along the dowels (eg 1.2–1.4) are generally fairly consistent and the end section is only considerably wetter than the shallower sections at high wall moisture contents (eg 4.2 compared with 4.4).

3.4 Laboratory assessment

Some sections of Scots pine batten 50mm x 20mm x 20mm were cut and submerged in water for two weeks to ensure that they were fully saturated. They were then blotted to remove excess moisture, weighed, and moisture content readings were taken at 1cm distance from either end on each face. The meter was a Protimeter checked with the manufacturers calibration test, the scale was set to pine (scale A) and the wood temperature was 21°C.

The process was repeated every few hours until moisture readings indicated air dry conditions of around 12%. Samples were stood on end on a metal plate at room temperature. End grain was not sealed and the sections were not always the same way up. Then the sections were oven dried overnight at 107°C to provide a dry weight. The actual moisture content at each stage was then calculated. This procedure generated a data set of 432 moisture meter readings and these are plotted against absolute moisture contents in Figure 11.

The results are similar to those obtained from the rods. The moisture meter generally underestimates actual moisture contents from about 15% to fibre saturation and readings become highly erratic at higher moisture contents.

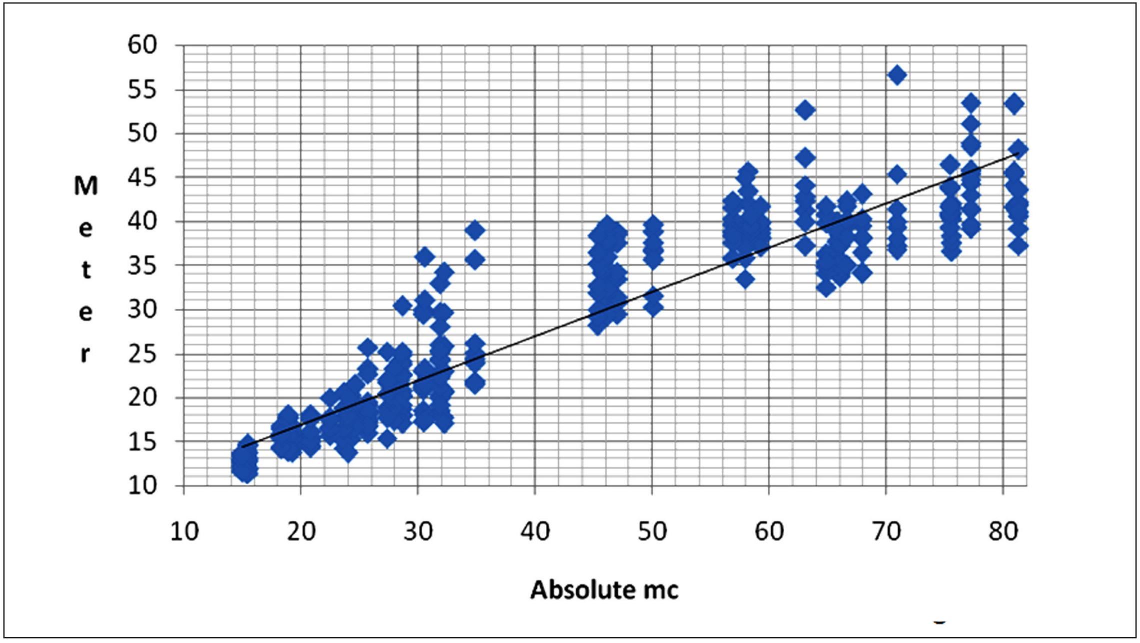

Figure 10: High Bickington Church. Moisture meter readings against actual moisture content of timber dowels. © Ridout Associates

4. CONCLUSIONS

There cannot be a sensible answer to the question ‘how wet is a wall’ but ‘wetting potential’ can be assessed and gives a useful insight into wetting and drying provided that the method used is reliable and repeatable. Wetting potential indicates the environment that the walls migh produce in a room.

Wall monitoring with rods is useful indicator of wetting potential and our results suggest:

- End grain absorption along the rod is only apparent to any great extent when the wall is very wet.

- We have not yet found evidence that contact with masonry causes inaccuracies because of surface contamination.

- Rods may be used sacrificially, with moisture contents assessed by the oven balance method. Alternatively, reasonably consistent readings can be obtained with a resistance moisture meter. For long-term moisture monitoring in damp walls, readings can be obtained from rods via fixed electrodes connected either to a terminal block where measurements can be taken with a resistance moisture meter, or to a data logger.

Moisture meters are reasonably accurate up to about 22%, but from there until fibre saturation point the accuracy diminishes considerably. Once free water forms in the wood cells the readings become entirely unreliable.

The problem is probably not the meter (although manufacturers’ calibration curves are reported to vary) but the natural variation within the timber. Many of the readings along a rod or batten are reasonably consistent, but there always seem some that differ significantly at higher moisture contents. Any timber moisture assessment in a building should include numerous readings

There is a popular assumption amongst surveyors that decay will occur at timber moisture contents of around 20%. This is certainly much too low, but the inaccuracy in meter readings suggests that this ‘rule of thumb’ is useful.

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