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Measurement of moisture content in solid brick walls using timber dowel

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Abstract Moisture within walls can have a serious detrimental impact on buildings and undermine their long-term durability and integrity. This paper investigates the accuracy of the timber dowel method for measuring wall moisture content in a solid brick wall. The timber dowel is inserted in the wall and removed at intervals and moisture readings obtained using a resistance-based, moisture-meter. The moisture content of timber dowels and the surrounding brick and mortar in a laboratory wall is measured and compared to the moisture content in the timber dowel, brick and mortar in different relative humidity environments (saturated salt solutions). The paper finds that a linear relationship of increasing moisture content in the dowel and laboratory wall is observed. At medium dowel moisture content (dowel moisture content >15 %), the moisture content in the dowel, brick and mortar is similar in both the laboratory wall and the RH environments. At higher moisture content there is a divergence whereby at the same dowel moisture content, the laboratory brick and mortar show higher moisture contents than those achieved in the RH environments. It appears that liquid water present in the wall has difficulty transferring to the dowel and consequently the dowel underestimates at high moisture contents. It is concluded that the dowel gives a good indication of the moisture content in the wall when the dowel readings are not higher than 15 % and indicates changes in relative wetness above this. In-situ monitoring of the moisture content of a nineteenth century brick wall following the application of lime plaster showed expected changes in moisture content. An increase in wall moisture content following the application of the plaster and the wall returned to its original moisture state by 9 months.

Keywords Moisture measurement · Timber dowel · Solid brick wall · Lime plaster

1 Introduction

Moisture within walls can have a serious detrimental impact on buildings and undermine their long-term durability and integrity. High moisture levels in walls can prove harmful by means of several mechanisms including frost and salt damage, distortion of structural elements, decay and corrosion of embedded timber and metal elements and material loss by dissolution. In addition, it promotes biodegradation contributing to problems such as mould growth, staining and poor internal environment. Furthermore, moisture is known to reduce thermal performance and cause deterioration of insulation materials.

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Moisture travels through walls in liquid and vapour form by several independent mechanisms. Water vapour travels by means of diffusion and air movement that are driven by external environmental conditions (temperature, vapour pressure and air pressure differences). Furthermore, rain, groundwater and capillary condensation (water vapour condensing when wall temperature drops below the dew point) lead to liquid water flow in the wall which is driven by either gravity, air and water pressure gradients or by surface diffusion and capillary suction through the pores. Moisture content within walls has proved difficult to measure [1–3]. Numerous variables are unknown including how the probe may influence the measurement environment and the effect of salts [1].

Moisture content can be measured directly using gravimetric analysis or by various indirect methods. Said [4] reviewed in situ moisture measurement methods of walls and categorised them according to measurement principles; resistance, voltage and capacitance methods which are based on electrical properties of materials that vary with the material's moisture content. Thermal-based methods have also been used for moisture measurement. Innovative methods using neutron probes [5, 6], nuclear magnetic resonance (NMR) [7], Medical ECG electrodes [1] and fibre optic sensors [8] have also been used by researchers.

This paper investigates the accuracy of the timber dowel method for measuring wall moisture content. The timber dowel is inserted in the wall and removed at intervals and moisture readings obtained using a resistance-based, moisture-meter.

Initially, the study compares the moisture meter readings of the timber dowels with their moisture content determined by gravimetric analysis and applies a correction factor to the meter reading apparatus so that it accurately reflects the moisture content determined gravimetrically. The underlying principle of the success of the timber dowel method is that equilibrium is achieved between the substrate and the timber dowel. Therefore, the paper measured the moisture content of timber dowels and the surrounding brick and mortar in a laboratory wall. The moisture content in the timber dowel, brick and mortar in different relative humidity environments was also measured. It then determined whether the timber dowel had attained equilibrium moisture content with the wall surrounding it by comparing the moisture content of the materials in the laboratory wall with the moisture content of the materials at different RHs.

Finally, moisture was investigated in situ; the moisture content in a historic, solid brick wall dating from the nineteenth century was monitored using timber dowels prior and following the application of a rendering mortar. This was undertaken to determine the changes in the moisture content of the wall due to the introduction of the wet render and ascertain whether the wall returned to its original moisture state. This research is part of a wider programme investigating the performance of internal insulation.

As previously mentioned, recording resistance is a common indirect method of measuring moisture content. Electrical resistance varies linearly with timber moisture content between 9 and c.27 % RH. Resistance varies depending on the timber species. Calibration factors exist for different timber species however, there is no standard to derive these factors [9] as variables such as speed of growth, origin and storage affect electrical resistance (Ridout [9] referring to Hall 1994). It was therefore necessary to calibrate the resistance moisture meter to the pine dowel used in this research.

The timber dowel method has been successfully used for many years, most commonly in timber construction. Typically, varying sizes and species of timber blocks and rods are inserted into the building fabric and connected by means of wires to a device capable of measuring electrical properties. An early timber probe example is the Duff probe comprising of a rectangular piece of wood coated with conductive silver paint and having electrodes that are connected to a resistance-type moisture meter by wires [10]. The Duff probe can measure moisture content to within 1 % accuracy and has been successfully used by many authors. The Nordtest project utilises wooden probes (connected to an ohmmeter); a popular method applicable to wood and wood based board of known absorption curves [11]. Both Ridout [9] and Brandt and Hansen [12] consider the timber dowel technique reliable with good long term stability. Conversely, Sass and Viles [1] deem that the timber dowel method only allows a rough overview of spatial moisture distribution and is largely dependent on the location of the dowel.

There are less frequent examples of the use of the timber dowel method in building materials other than timber. Ueno and Straube [3] undertook an intensive laboratory and in situ calibration of wood sensors for measuring moisture content. They concluded that wood sensors allow measurement of relative wetness in capillary active materials such as masonry and concrete over long-term (due to slow response times) and that they can distinguish between saturated air and liquid water (liquid moisture appears as above the maximum hygroscopic adsorption of timber). They determined that the accuracy of the dowel at measuring moisture content was ±3 % RH and typically ±5 % RH at 100 % RH for laboratory and in situ conditions, respectively.

Other authors have investigated brick walls [6]; stonemasonry [2]; historic stone walls [1, 5] cellulose-based insulation [13] and straw bales [14–16]. These authors have ascertained that the dowel method is largely successful for building materials in situ. However, this conclusion is not based on the direct measurement of the moisture content of the dowel and the surrounding building material and a comparison with their moisture contents in different RH environments.

The underlying principle of the success of the timber dowel method is that equilibrium is achieved between the substrate and the timber dowel [9, 16]. Ridout [9] suggests that a 6–9 mm dowel will take 3 weeks to attain equilibrium with its environment but will absorb a large proportion of the moisture within the first few days. Furthermore, Ueno and Straube [3] note that the moisture content of wood in direct contact with a capillary active material should rise along with that material although their quantitative levels will be different. According to Ridout [9], a formula can be derived for relating the brick and timber at known moisture contents, but this is dependent on the type of brick and timber. As aforementioned, this research measures moisture content in timber dowels, brick and mortar at different relative humidity. It measures the moisture content of the dowels and the surrounding brick and mortar in a laboratory wall; and then determines whether the dowel had attained equilibrium moisture with the brick and mortar in the wall surrounding it by comparing the moisture content of the materials in the wall with the moisture content of the materials at different RHs.

The pine dowels were made of *Pinus sylvestris* L. and sourced from the UK. The porosity of wood is an important parameter that significantly influences properties such as flow, adsorption and impregnability. Differences in porosity may be due to differences in cell types and quantitative distribution, thickness of cell walls and size of cell cavities. Importantly, as wood is a hygroscopic material, the cell wall adsorbs and desorbs moisture to and from the environment. As a consequence, the cell wall shrinks and swells, and the relative proportions of cell wall and pore space can vary (Olesen 1977 in Ülker [17]). Therefore, some variation in the values of flow and adsorption can be expected however, the pine dowels used were sourced from a single batch; and oven dried with a consistent bulk density of c.0.451–0.510 g/cm^3 falling within the range of pine woods studied by previous authors such as Ülker [17] and Plötze and Niemz [18] who, using a range of methods (mercury intrusion porosimetry—MIP—, green volume and oven dry methods) reported consistent porosity values ranging from 61 to 70 % for bulk densities of 0.444–0.579 g/cm^3 and 65.40–69.71 % (for an average mean density of 0.451 g/cm^3). Plötze and Niemz [18], investigating 30 different European and overseas wood species with MIP, reported that softwoods showed a consistent pore size distribution of micro and mesopores (4.50 % micropores ranging from 80 to 1.8 nm and 16.15 % mesopores of 500–80 nm) and only small differences within the macropores (79 % pores with a radius over 0.5 µm and a characteristic pore radius between 1.5 and 6.0 µm). According to Stamm (1964), Siau (1995), Kollmann (1987) and Wagenführ (2007) in Plötze and Niemz [18], the effective diameter of pit openings for softwoods have been found between 0.02 and 4 µm and the microvoids are found to have typical diameters of 0.3–60 nm. The above suggest that significant cell cavities in the pine dowels are active with respect to flow and adsorption.

2 Materials and methods

2.1 Gravimetric moisture content

Materials including brick, mortar and timber dowels were allowed to achieve equilibrium moisture content with their environment. They were then dried in an oven at 105 °C for 24 h. Moisture content was measured according to Eq. 1

$$MC = ((\text{wet weight} - \text{dry weight})/\text{dry weight}) \times 100\,\%. \quad (1)$$

2.2 Moisture meter reading

A Tramex PTM 6005 resistance moisture meter was used. Pins were inserted approximately 2 mm into the dowel and an average of four readings taken. The apparatus used is a pin meter that uses electrical resistance. After the two probes (pins), are inserted in the wood, a small electrical current passes between them and correlates the electrical resistance to the wood moisture content. As moisture is a good conductor, the wetter the wood, the lower the electrical resistance to the current. Sample characteristics (species, density, thickness and temperature), electrode contact, grain direction, chemicals in the wood, weather conditions, and skill of operator influence readings [19] however, most of these parameters are either constant or fairly consistent in the measurements included in the paper. As the temperature of the wood increases so does its electrical conductance and vice versa, and temperature corrections should be made when using a conductance-type meter on specimens that are warmer than 90 °F or cooler than 70 °F [19]. However, the dowels were placed in the interior of the building which was heated uniformly during the measurements and therefore, it can be assumed that the temperature variations did not adversely affect the readings. The moisture distribution in the wood can also affect readings. For example, high surface moisture from rain or dew, forms a surface layer of high conductivity leading to excessively high readings however, the dowels were inserted in the interior, thus the moisture distribution was mostly consistent and it can be assumed that the variations didn't affect the readings.

2.3 Moisture content in controlled relative humidity environments—absorption and desorption following immersion in liquid water

The moisture content of the different materials in controlled RH environments was determined by placing samples in sealed containers with the appropriate saturated salt solution (Table 1) as specified by Greenspan [20] in ISO 12571:2013 [21] for sorption isotherms. Low relative humidity environments were not considered as a low moisture content in building materials is not considered problematic, and the moisture meter could not take accurate readings below 7 %. A sealed plastic container was used as an enclosed environment. 30 mm timber dowels as well as brick and mortar samples were suspended from the container lid. The lid and suspended material (brick/mortar) were weighed at regular intervals until mass change was <0.1 % of two previous readings. The material (alone) was then weighted and subsequently oven dried and reweighted to establish a dry mass. Three specimens were tested in each RH environment (Table 1).

The above procedure was repeated for brick and mortar previously immersed in liquid water for 10 s so they absorbed approximately 10 % of their weight as liquid water. This was undertaken in order to determine the changes in moisture content in the brick and mortar having been exposed to liquid water (and not just to water vapour); a situation comparable to those in the water-sprayed laboratory wall and in situ (following rain) also subject to this study.

Following immersion in water, the brick and mortar were allowed to stabilise for 4 months (until mass change in successive readings was <0.1 %).

2.4 Measurement of moisture in a laboratory wall

Six, 12 mm cores were drilled in a laboratory wall and pine dowels (12 mm diameter and 30 mm length) inserted. The wall was built with machine pressed, fired-clay brick and lime mortar approximately 10 years ago. The mineral composition of the brick (Fig. 1) and mortar were determined using X-ray diffraction (XRD). The brick consists of quartz,

Table 1 Salts used to create relative humidity environments [21]

Salt	Solubility in water	Relative humidity
Potassium sulphate	11.1 g/100 ml	97.59 ± 0.53
Potassium nitrate	31.6 g/100 ml	94.62 ± 0.66
Potassium chloride	34.4 g/100 ml	85.11 ± 0.29
Sodium chloride	35.9 g/100 ml	75.47 ± 0.14
Potassium iodide	125 g/100 ml	69.9 ± 0.26

The temperature was 20 °C for all the experiments

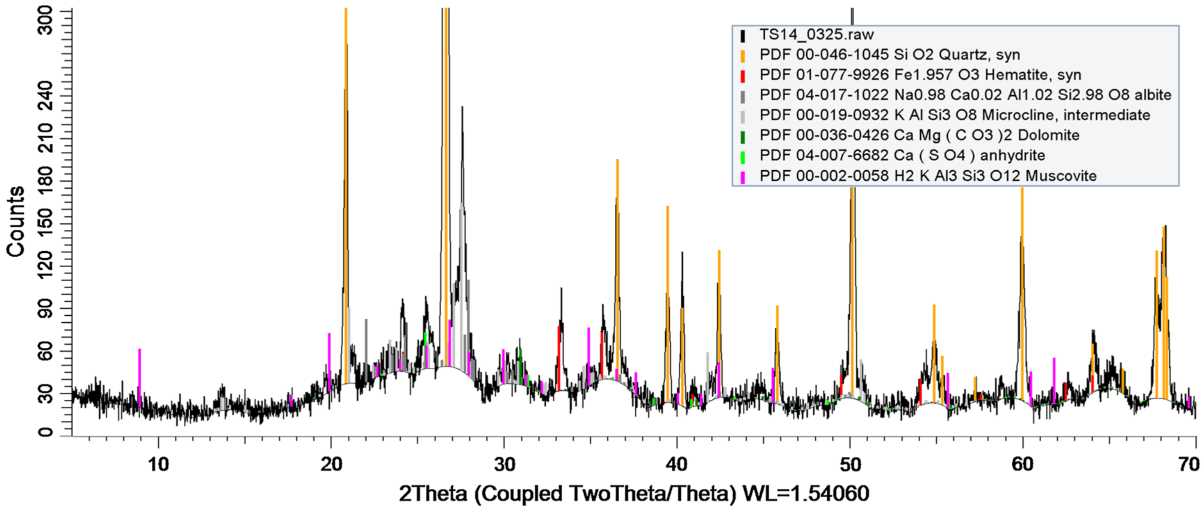

Fig. 1 Mineral composition of laboratory brick determined using XRD

hematite, albite, microcline, dolomite, anhydrite and muscovite. The lime mortar showed the presence of quartz, albite and calcite. No portlandite was present suggesting the lime had fully carbonated.

The wall was sprayed with water intermittently over 8 weeks and periodically surrounded with damp hessian to achieve different moisture conditions (these were subsequently determined to be between approximately 0.2 and 3 % brick moisture content). The external side of the dowel was varnished to ensure moisture in the dowel was absorbed from the surrounding wall rather than during wetting of the wall. On five occasions, 40 mm cores were drilled surrounding the dowels and the moisture content of the dowel, brick and mortar determined gravimetrically.

2.5 In-situ moisture measurement

The moisture content of a nineteenth century brick wall at the Adjutant General's Building in the Royal Hospital Kilmainham, Dublin, was monitored following the application of lime plaster (Fig. 2).

The mineral composition of the brick and lime mortar were determined using XRD. The brick consists of quartz, hematite, spinel, anhydrite and anorthite. The lime mortar binder showed the presence of calcite and portlandite. Quartz, dolomite, albite and muscovite were determined in the mortar aggregate. Gypsum, probably the remains of internal plaster, was also present.

A 14 mm core was drilled approximately 350 mm into the wall and a rod inserted. The rod comprised of four sections of pine dowel (length 75 mm and diameter 12 mm) separated by nylon spacers (length 30 mm). This allowed measurement of the moisture content at different depths in the wall (Fig. 3). The hole was plugged at the end to minimise ambient conditions in the room influencing the moisture content readings. The rod was inserted in the wall for 1 month, removed for the application of the plaster (Table 2) and subsequently reinserted 2 months later. The rods were located between a window and an internal partition wall approximately 1 m (Rod 1) and 2 m (Rod 2) above the ground. The internal room conditions varied from 10 to 20 °C and 40 to 70 % RH.

3 Results and discussion

3.1 Calibration of the moisture meter readings with the moisture content determined by gravimetric analysis

The dowels were placed in the different RH environments (Sect. 2.3) and reached equilibrium moisture content after approximately 14 days (>0.1 % change in weight). Following equilibrium, the moisture content was measured both using the moisture meter and gravimetrically (Fig. 4). Using linear regression, a

Fig. 2 Adjutant General's Building in the Royal Hospital, Kilmainham, Dublin

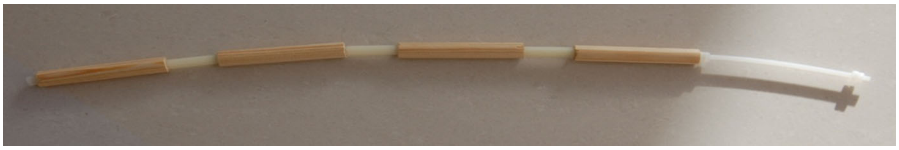

Fig. 3 Rod to measure moisture content at different depths in the wall

Table 2 Composition and depth of plastering mortar applied to the wall

Plaster coat	Coat depth	Composition and proportions
Scud coat	c.5–6 m	2.5:1:0.63 sand:NHL5:water
Scratch coat	25–75 mm	2.3:1:0.67 sand:NHL3.5:water
Floating coat	c.12 mm	3:1:0.60 sand:NHL3.5:water
Skim coat	3 mm	1:1:0.5 sand:NHL2:water

NHL natural hydraulic lime

calibration factor of 1.041 was applied to the meter readings (low standard error of 0.71).

The moisture content of the timber dowels (determined using moisture meter, gravimetric analysis and moisture meter with calibration factor applied) was plotted against varying relative humidity (Fig. 5). As it can be seen from Fig. 5, the results suggest that, using a calibration factor, the moisture meter readings accurately reflects the actual moisture content of the dowel (determined gravimetrically).

3.2 Determination of the moisture in timber dowels and the corresponding brick/mortar moisture content at different RH environments

The dowel, brick and mortar were allowed to reach equilibrium in different RH environments (as set out in Sect. 2.3) and their moisture content was then measured gravimetrically. The adsorption isotherm for each material was plotted (Fig. 6). As expected, the graph shows increasing moisture content with increasing relative humidity and suggest similar S shaped

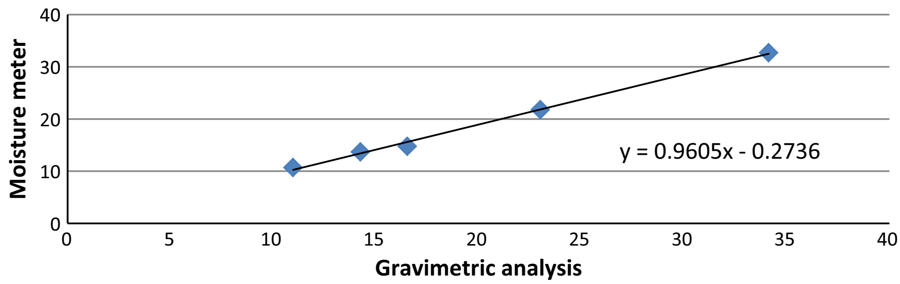

Fig. 4 Moisture content of dowels determined using moisture meter and gravimetric analysis to calculate calibration factor

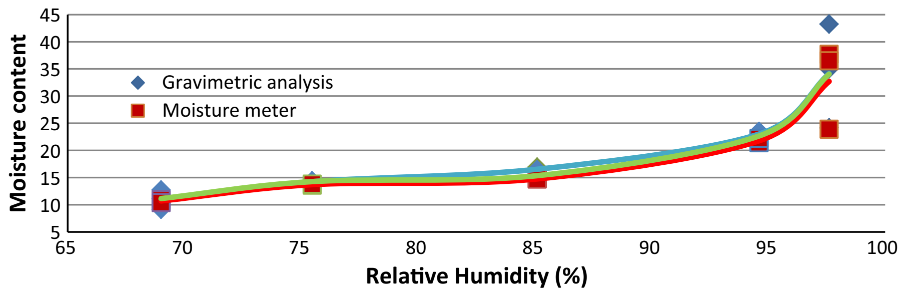

Fig. 5 Moisture content of dowel at varying relative humidity determined using moisture meter, gravimetric analysis and moisture meter with calibration factor applied

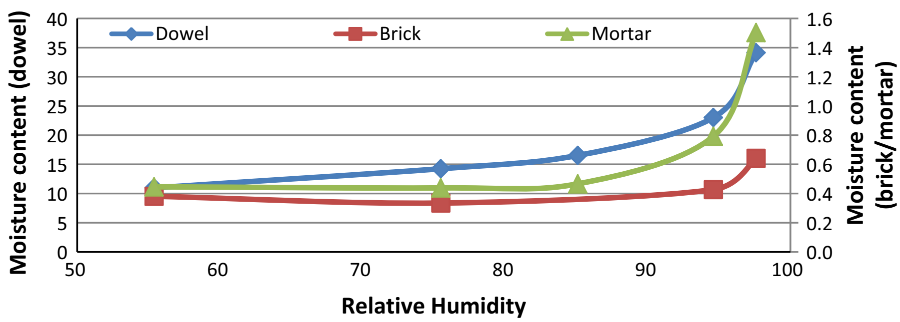

Fig. 6 Moisture content at different RH environments (adsorption isotherms) of the dowel, brick and mortar

curves, characteristic of type II sorption isotherms [22] which are typical of building materials [23].

From Fig. 6, it can be seen that, in comparison to brick and mortar, the pine dowel is a very hygroscopic material. There is a huge increase in moisture content when the dowel is exposed to relative humidity above 90 %. This is on account of the timber reaching its saturation point and the cell walls saturating with bound water.

The brick sorption curve is within the range commonly observed by other authors. Hansen [23] observed moisture content ranging between 0.3 and 0.8 % at high relative humidity (c.98 %).The mortar was observed to have a higher moisture content than the brick particularly as relative humidity increased above 90 %. This agrees with Sass and Viles [1] who hypothesized that this was due to the mortar being more porous.

3.3 Determination of the brick/mortar moisture content in different RHs environments using wet materials

Subsequently, the brick and mortar were immersed in liquid water for 10 s so that they absorbed approximately 10 % of their weight as liquid water. The brick and mortar were then allowed to reach equilibrium in different RHs and their moisture content measured gravimetrically and plotted (Fig. 7). As aforementioned, this allowed to determine changes in moisture content in the brick and mortar having been exposed to

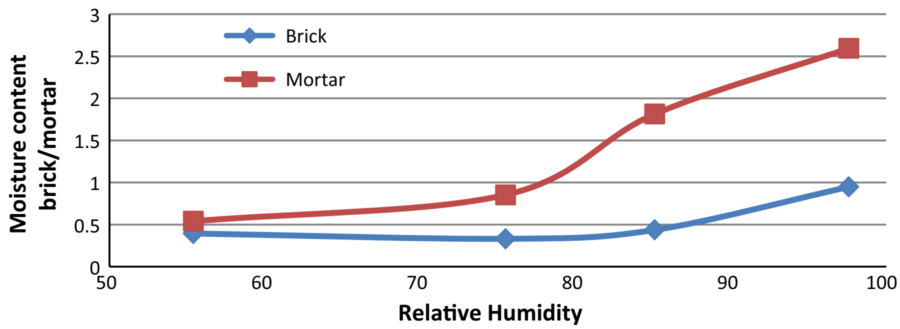

Fig. 7 Moisture content of the brick and mortar, at different RH environments, following immersion in liquid water

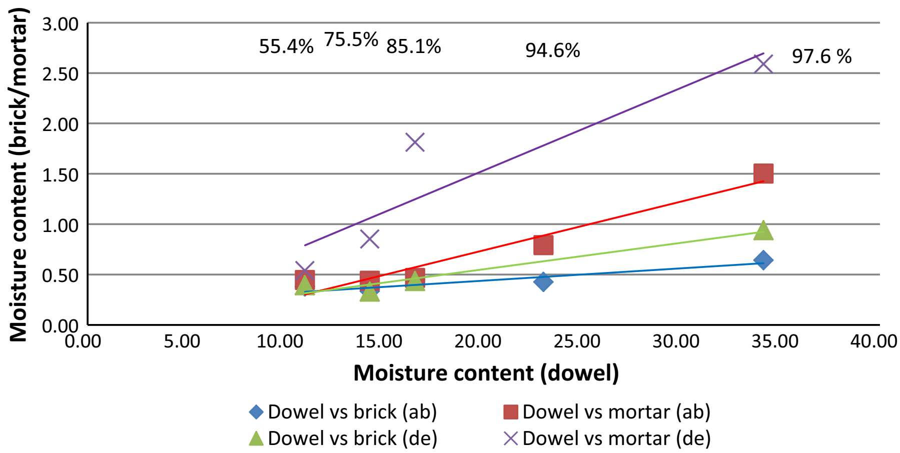

Fig. 8 Linear relationship imposed on the moisture content of the dowel versus brick and dowel versus mortar at varying RH for both dry (adsorption—*ab*) and wet (desorption—*de*, following immersion in water) materials. RH shown in text on the graph

liquid water (as opposed to water vapour); a situation comparable to those in the water-sprayed laboratory wall and the in situ walls following rain.

In order to investigate the relationship between the moisture content in the dowel and that in the brick and mortar, the moisture content of the dry and wet brick and mortar versus the dowel were plotted at different relative humidity as shown in Fig. 8. The results in Fig. 8 show that, on both adsorption and desorption, the mortar has a higher moisture content than the brick. Furthermore, although samples were conditioned at the same RH environments, their moisture content differs at high RH. In particular, the mortars store a significant amount of moisture at high RH. At low RH, the liquid moisture dries from the brick/mortar and both samples (adsorption/desorption) have similar moisture content. At high RH, the moisture content is considerably higher in the samples that were previously immersed in water than in those that were not. This suggests that the brick and mortar are retaining liquid water in their pores that cannot dry in the high RH environment.

3.4 Investigation of whether the dowel moisture content corresponds to the moisture of the wall surrounding it

As aforementioned, a laboratory brick wall with timber dowels inserted was exposed to intermittent episodes of wetting for 8 months. On five occasions during this time, the dowel and surrounding brick/mortar were removed from the wall by coring, and their moisture content determined gravimetrically. The results appear in Fig. 9. A reasonably good linear correlation was found between increasing moisture content in the wall and a corresponding increasing moisture content in the dowel. The linear relationship between the dowel and brick moisture is strong ($R^2 = 0.8$) however, the linear relationship between the mortar and dowel is not as strong ($R^2 = 0.64$). This may be attributed to the inhomogeneity of the mortar samples (varying proportions of binder and aggregate in each sample) or the smaller sample size of the mortar resulting in larger measurement errors.

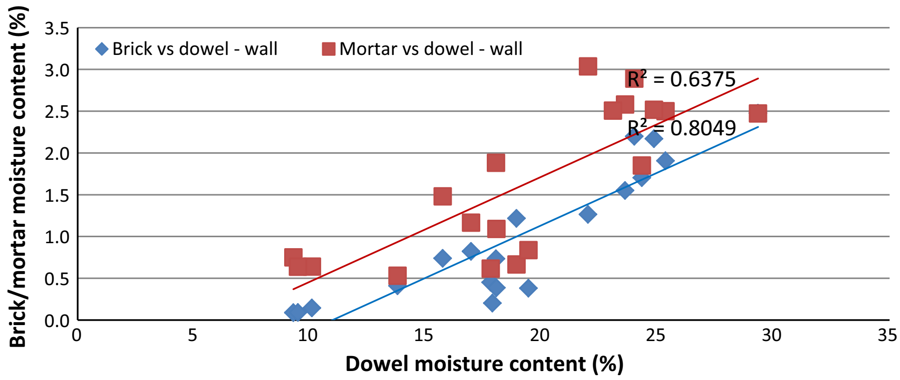

Fig. 9 Moisture content of timber dowel versus that of the brick and mortar surrounding it

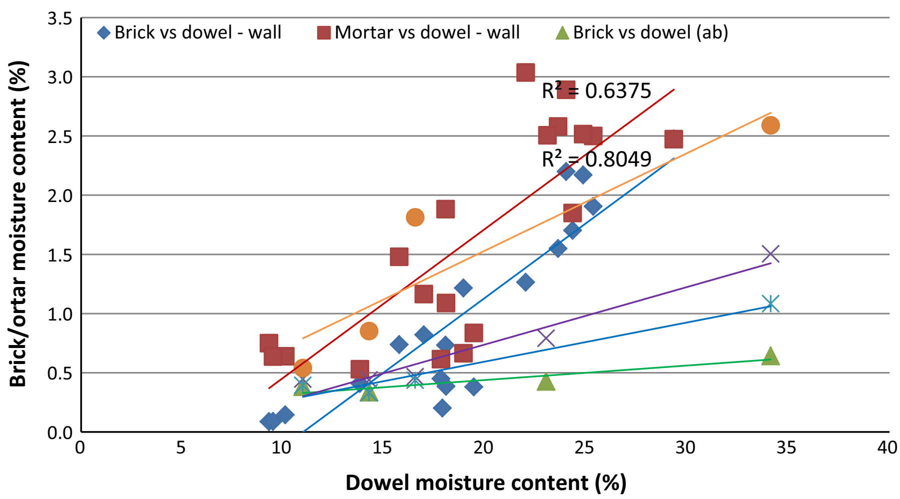

Fig. 10 Comparison between moisture content in the dowel and the moisture in the brick/mortar in the laboratory wall and in the fixed RH environments (Figs. 8, 9 combined)

The results agree with Ridout [9] who reported, on achieving equilibrium, a 3 % moisture content in the brick resulting in approximately 27 % moisture content in the dowel. However, this research yields a linear relationship of increasing moisture content in the two materials (Fig. 9) while Ridout [9] observes a non-linear relationship.

Figure 10 compares the moisture content of the dowel, brick and mortar in the wall (Fig. 9) with their moisture in the different RH environments (created by saturated salt solutions) (Figs. 7, 8). As it can be seen from Fig. 10, at low dowel moisture content (dowel moisture content >15 % relating to RH of approximately 80 %—Fig. 5), the moisture content in the dowel, brick and mortar is similar in both the laboratory wall and the RH environments (saturated salt solutions). However, as moisture content increases, there is a divergence whereby the laboratory brick and mortar show higher moisture contents than those achieved in the RH environments. The only exception is the similar moisture content of the laboratory wall mortar (red line) and desorption mortar (orange line) at both low and high RH.

Figure 11 illustrates the findings in Fig. 10. In the laboratory wall, when the dowel has a moisture content of 14 %, the surrounding brick and mortar have moisture contents of 0.4 and 0.9 %, respectively. Comparatively, in the 75 % fixed relative humidity environments, the dowel's moisture is c.15 % while the brick and mortar moistures are 0.3 and 0.4 % (on adsorption) and 0.3 and 0.9 % (on desorption), respectively.

As illustrated in Fig. 11, when the dowel moisture rises to 25 % in the laboratory wall, the surrounding brick and mortar rise to 1.8 and 2.5 %, respectively. Comparatively, in the 96 % fixed humidity environments, a similar dowel's moisture of c.25 % renders brick and mortar moistures of 0.45 and 0.9 % (on adsorption) and 0.9 and 2.4 % (on desorption), respectively.

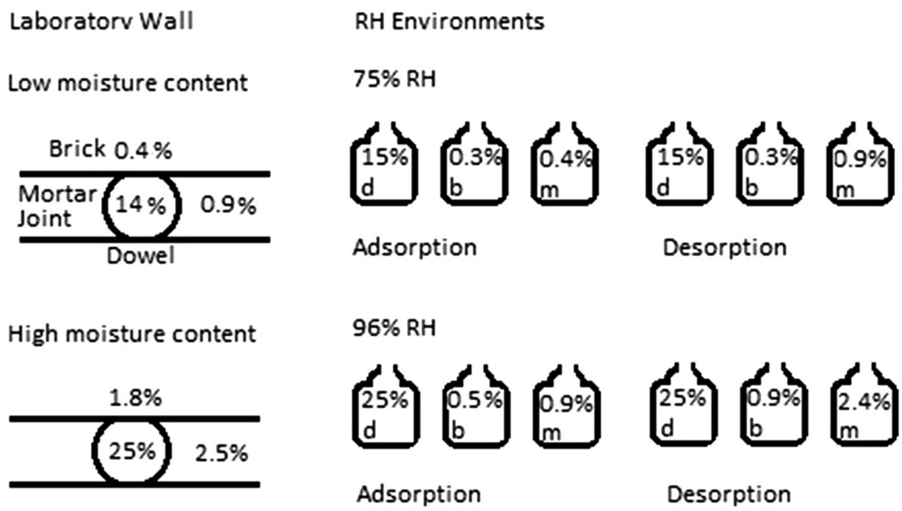

Fig. 11 Approximate moisture content of dowels (*d*), brick (*b*) and mortar (*m*) in the laboratory wall (*left*) and the fixed relative humidity environments (saturated salt solutions—*right*). Low wall moisture content equivalent to 75 % RH environment and high wall moisture content equivalent to 96 % RH environment

This indicates that moisture contents in the laboratory wall and the fixed RH environments are similar when the timber dowel has a moisture content of approximately 14–15 % however, when the dowel moisture rises, the materials in the wall are wetter than those in the set RH environments.

This suggests that either the dowel has not had sufficient time to reach equilibrium moisture with the brick/mortar or that there is liquid water contributing to the moisture in the wall that is not in the dowel. It is unlikely that the dowel did not have time to achieve moisture equilibrium with the brick/mortar as the dowel was in contact with the wall for several months and cores were extracted no sooner than 3 weeks after a wetting episode. Furthermore, similar results by Ridout [9] (3 % moisture content in the brick resulting in approximately 27 % moisture content in the timber dowel) suggest that this is not likely.

Therefore, it is possible that there is liquid water present in the wall that has not transferred to the timber dowel. This is suggested by the good relationship between the wall mortar and desorption mortar (following immersion in liquid water) which clearly has liquid water still present that did not have the opportunity to dry at high RH (Fig. 8). The presence of significant liquid water in the brick/mortar in the wall at moisture content is likely, as the moisture content in the brick/mortar in the wall (2.5/3 %) is far in excess of their moisture content at set 98 % RH (0.64/1.5 %).

Liquid water content in the dowel is unlikely (despite its close contact with the brick) as the moisture content in the wall dowel did not rise above c.29 % (Fig. 10—dowel moisture content) while dowel moisture content in the 97 % RH environment is in excess of this at approximately 34 % (Fig. 6).

The lack of transfer of liquid water from the wall to the dowel may be on account of poor contact between the dowel and surrounding wall material that does not facilitate the transfer of liquid water. This differs from the in situ findings of Ueno and Straube [3] whose timber wafer sensors recorded moisture contents of 45 % on exposure to liquid water in the wall assembly.

The timber dowel satisfactorily shows relative changes in the moisture content of the wall. Furthermore, it gives a good indication of moisture content in the wall when the dowel readings are below 15 % (relating to approximately 80 % RH Sect. 3.1). Although the moisture content in the laboratory wall and fixed relative humidity environments do not directly correspond at high moisture contents (above 80 % RH), it is clear that the dowel can indicate when dangerous conditions are occurring(typically considered over 80 %) and relative changes in wetness in the wall. Considering timber decay, mould etc., moisture

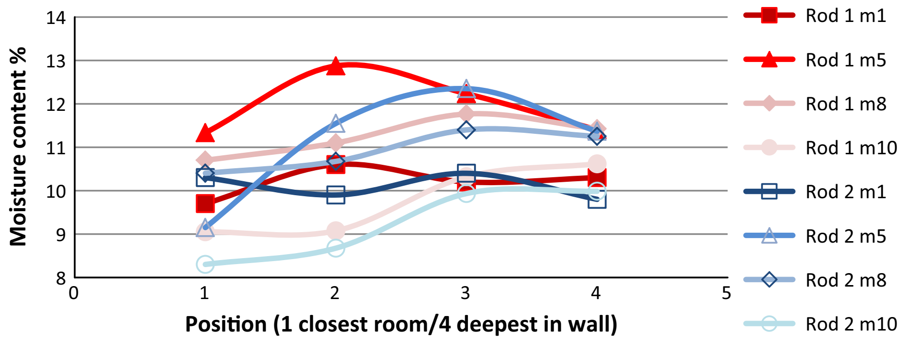

Fig. 12 Moisture content (moisture meter) of dowels in two rods inserted in a historic wall before and following the application of internal lime plaster at 1, 5, 8 and 10 months (m1, m5, m8 and m10). Position 1 relates to the plaster–brick interface and positions 2, 3 and 4 relate to depths of 105–180, 210–285 and 315–390 mm, respectively in the brick wall from the surface of the lime plaster

content in the dowel above 15 % should be an indication of a potential moisture problem within the wall. At this wall moisture level, the moisture meter would give a moisture reading of the dowel of 15.6 % (=15 × 1.041) taking into account the calibration factor.

3.5 In-situ moisture readings from timber dowels inserted in a historic solid brick wall

The variations in moisture content of the dowel rods inserted in the historic brick wall following the application of lime plaster are included in Fig. 12.

The lime plaster was applied in month 2. The moisture content in the wall is shown prior to plaster application at month 1 (m1) and following its application at month 5 (m5), 8 (m8) and 10 (m10). Position 1 relates to the plaster–brick interface and positions 2, 3 and 4 relate to depths of 105–180, 210–285 and 315–390 mm, respectively in the brick wall from the surface of the lime plaster.

Prior to the application of the lime plaster, both rods show a consistent and even moisture distribution through the wall of between 9.5 and 10.5 % moisture content [Rods 1 and 2 at month 1 (m1)].

Lime plaster was applied the following month and the rods reinserted 2 months later. Five months after the plaster application, the rods show an increase in moisture content due to the water introduced in the lime plaster (Rods 1 and 2 at m5). Both rods show similar behaviour; position 1 is closest to the surface and therefore dries quickly showing a lower moisture content. Positions 2 and 3 show high moisture content due to the water introduced by the lime plaster while position 4, deeper in the wall, is consequently less influenced by the water in the lime plaster. At 8 months, both rods show a reduction in moisture content due to drying. The lower moisture content of position 2 compared to position 4 suggests that the rods are drying towards the interior. This is expected as the warmer heated condition of the interior would encourage drying in this direction. At 10 months (Rods 1 and 2 at m10), the interior of the wall is drier than its original state on account of the warm drying environment (heating turned on to dry walls) and the moisture content at positions 3 and 4 in the wall have returned to their original moisture content prior to the application of the plaster.

The moisture content readings of the dowel suggest that the dowel is accurately reflecting changes in moisture content in the wall. The moisture content of the dowel is below 15 % (RH below 80 % as discussed in Sect. 3.3) which suggests that it is not within the range that might prove problematic for the building envelope.

4 Conclusion

Following the application of a calibration factor of 1.041, the resistance moisture meter accurately measured the moisture content of the pine dowel determined by gravimetric analysis.

As well known, moisture content in materials exposed to similar conditions varies depending on the material and its previous moisture exposure (hysteresis in isotherms). In this research, at 96 % RH, the approximate dowel moisture content is 25 % while the brick and mortar show moisture contents of 0.5 and 0.9 % (when exposed to moisture vapour) and 0.9 and 2.4 %, respectively if previously wetted.

The results show that materials exposed to vapour humidity have similar moisture content to those exposed to liquid water in relative humidity environments of approximately 50 % while, at higher humidity, the materials exposed to liquid water (as in situ walls exposed to rain) have greater moisture content. This is attributed to the inability of the materials to dry in the high RH environment.

A timber dowel inserted in a wall satisfactorily shows relative changes in the wall moisture content. A linear relationship of increasing moisture content in the dowel and wall is observed.

Comparing the moisture content of the dowel, brick and mortar in the wall with their moisture in the different RH environments (saturated salt solutions) reveals that at medium dowel moisture content (dowel moisture content >15 %), the moisture content in the dowel, brick and mortar is similar in both the laboratory wall and the RH environments (saturated salt solutions). However, as moisture content increases, there is a divergence whereby at the same dowel moisture content, the laboratory brick and mortar show higher moisture contents than those achieved in the RH environments. It appears that liquid water present in the wall has difficulty transferring to the dowel and consequently the dowel underestimates at high moisture contents.

In-situ monitoring of the moisture content of a brick wall following the application of lime plaster shows expected behaviour. An increase in wall moisture content following the application of the plaster was observed with highest moisture content between 105 and 285 mm, measured from the surface of the wall, 2 months after plaster application. Lower moisture content near the interior and deeper in the wall were on account of the wall drying towards the internal room and lower water migration from the plaster, respectively. The moisture content reduced over time and at 10 months the wall (position 3 and 4) had returned to its original moisture condition.

Accordingly, it is concluded that the dowel gives a good indication of the moisture content in the wall when the dowel readings are not higher than 15 % and indicates changes in relative wetness above 15 %.

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