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Monitoring moisture in a historic brick wall following the application of internal thermal insulation

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ABSTRACT: This paper monitors the in-situ moisture performance of a solid brick wall following the application of internal insulation using the timber dowel technique. Six internal insulations including thermal paint on lime plaster, aerogel (AG), cork-lime (CL), hemp-lime (HL), calcium silicate board (CSB) and PIR were applied to wall sections.
Improving the thermal performance of buildings reduces building operational energy and its associated negative impact on the environment. However, thermal insulation may increase moisture accumulation in walls undermining their long term durability and lowering their thermal efficiency. Currently, there is a lack of knowledge on the performance of traditional solid walls with respect to heat and moisture and the impact of internal insulation on their hygrothermal behaviour.
The changes in moisture recorded using timber dowels agreed with the moisture recorded using a commercial relative humidity (RH) probes. All the wall sections showed a reduction in moisture content over time as the construction moisture dried. The nature of the insulation significantly determined the wall moisture: after one year, the least vapour permeable and capillary active insulation (PIR, aerogel and paint) had higher moisture contents than the lime based insulation (LP, CL and HL). Moisture gradient across the wall (from the internal surface to wall mid-point) indicate that the lime based materials allow the dissipation of moisture towards the interior surface which is retarded by the low moisture permeability of the paint surface, aerogel and PIR.

KEY WORDS: brick wall; internal insulation; moisture behaviour.

1 INTRODUCTION

Retrofitting insulation to existing buildings can lower energy requirements for heating and cooling reducing both emissions and energy consumption. This has been recognised by the EU and several legislative initiatives have been introduced for building renovation and improving the energy performance of buildings. The building sector is one of the key consumers of energy in Europe using approximately 450Mtoe per annum of which space heating accounts for around 70% of the total energy use [1]. Minimising building energy use has the potential to reduce the adverse environmental impact of the building sector on the environment. Approximately 40% of the existing EU building stock was built prior to 1960 and the introduction of energy specific requirements [1].

External insulation is often the preferred method for upgrading walls however, this approach is not usually appropriate for historic building on account of the architectural and historic significance of their facades. Internal insulation can also impact on the historic character of a building but is commonly considered a preferable alternative. However, there are risks associated with this option, primarily the accumulation of moisture within the wall and consequent structural and material decay. The Sustainable Traditional Buildings Alliance's (STBA) report on the responsible retrofit of buildings notes that there are knowledge gaps on the hygrothermal performance of insulated walls [2].

This paper addresses the moisture risk posed by internal insulation by investigating the in-situ moisture behaviour of a solid brick wall following the application of a range of insulations. When thermally upgrading a wall, the thermal performance of an insulation is a critical factor however, the insulation's effect on moisture accumulation within the wall is even more important as this can undermine the long term durability of the structure. Therefore, it is essential to achieve the optimum balance between energy saving and hygrothermal risk. In some cases, it may be necessary to limit thermal improvement in order to minimise the risk of moisture build-up.

Water is widely regarded as the most prevalent cause of decay in historic buildings. The most important principle is that moisture must not accumulate in a wall over time. Modern buildings are typically constructed using hard impervious materials intended to prevent moisture from entering the building. However, traditional and historic buildings (predating c.1940), function under a different premise, as their breathable fabrics of brick/stone and mortar allow moisture to dry from the wall (both internally and externally) preventing moisture accumulation over time. As a result, traditional and historic constructions are usually more vulnerable to moisture loads than modern buildings [3]

The risk of moisture accumulation in a particular wall is dependent on multiple factors including weather conditions (exposure to driving rain, sunlight, wind) and orientation. Different orientations have different hygrothermal performance depending on direction of prevailing wind and trajectory of the sun [4]. The wall thickness, the properties of constituent materials and the presence of insulation as well as the level of occupancy and the behaviour of occupants conducting water generating tasks such as drying clothes and showering, also determine moisture accumulation in walls.

The application of insulation on the interior of a traditional wall changes the hygrothermal behaviour of the wall and can result in moisture accumulation [5].

Insulation can increase the likelihood of moisture accumulation on account of two primary reasons. First, the reduced permeability of an insulation can impede the wall drying towards the interior. In addition, insulation lowers the wall temperature which reduces the drying capacity of the wall and increases moisture condensation. Consequently, Kunzel and Kiebl (1996) observe that there is no risk free solution to avoid water accumulation [6].

There is no agreement on the most appropriate method to accommodate water when internally insulating solid walls. Two approaches are commonly used when insulating historic structures to avoid moisture accumulation: vapour tight system which prevent moisture entering the wall from the interior and capillary active/vapour open insulation systems that facilitate drying of the wall moisture.

In the vapour tight system, a vapour retarder is installed on the interior side of the insulation to prevent moisture entering the wall. However, vapour tight systems prevent drying towards the interior, do not allow moisture buffering of room humidity and perforations can result in substantial underperformance. The popularity of this type of system is likely on account of the limited selection of insulation materials available over the past number of years [7].

In contrast, capillary active insulation works on the premise that wall moisture can be transported towards the interior by capillarity and the wall allowed to dry.

The moisture behaviour of vapour tight and capillary active insulation systems reported by different authors in traditional structures are inconsistent probably due to the wide variety of insulation materials, walls, sources of moisture ingress and individual circumstances.

A suitable internal insulation system must be tailored to individual specific building requirements taking into account the multiple variables that influence moisture accumulation. As noted by Nielsen et al. (2012), the same refurbishment method might have different outcomes when applied to different buildings [8].

This paper informs on the moisture performance of a number of internal insulation systems (for over 1 year following application) by monitoring their in-situ performance, when applied onto a solid brick wall. Moisture was introduced into the wall in a levelling lime plaster and within the wet insulation materials applied. Authors have both identified that construction moisture can cause long periods of high RH in walls with the associated risks [7, 9]. A long-term monitoring program is in place to investigate the moisture behaviour of the walls over a longer time period.

2 METHODS

2.1 *The building*

The brick walls monitored belong to the Adjutant General’s Building in the Royal Hospital Kilmainham, Dublin (Figures 1 and 2). The building was designed by the internationally renowned architect Francis Johnson (1760-1829) and constructed in 1805. It consists of 770mm brick walls (400mm beneath the windows). The approximate dimensions of the fired-clay bricks are 220*70*95 mm (length*height* width) and the mortar joints are between 25 and 30mm. The exact structure of the walls is unknown however, the wall under the windows is probably a solid, two-brick thick wall in English bond while the remaining wall, also showing English bond on internal elevation, may hold some infill as the wall thickness does not correspond to the brick dimensions. The exterior is a roughcast lime render that was re-rendered in c.2005. The interior plaster was removed approximately 30 years ago and the building treated for timber decay at this time.

Figure 1. Adjutant General’s Building in the Royal Hospital, Kilmainham, Dublin.

Figure 2. Interior of building prior to the application of insulation.

2.2 *The insulation materials*

Insulation was applied in three rooms to the north and west elevations of the first floor as shown in figures 3 and 4. Each insulated wall section had an approximate area of 10m^2 and comprised of three wall parts: above, below and to one side of the window (Figure 3). Six insulation and two lime plaster (control) sections were installed over a 3 month period as set out in table 1. The walls were levelled using lime plaster (table 1) before the application of the insulation. Timber fibre board was also applied but an exterior system was mistakenly used so its moisture behaviour is not included in this paper.

A thermal and moisture survey was undertaken prior to the application of the insulation. The insulation was applied between December 2013 and April 2014. During monitoring, the rooms were heated using oil filled radiators (average internal temperature c.18°C). The west and central rooms were heated from September 2014 until April 2015 while the east room was heated for a longer period (June 2014-April 2015).

The moisture storage and transfer properties of the insulation materials were measured in the laboratory and are included in a paper by the authors [10].

Table 1. Details of lime plaster and insulation materials.

Material	Coat/thickness	Composition weight
Plaster to level all walls	Scud coat c.5-6mm Scratch coat 25-75mm to make wall plumb	2.5:1:0.63 sand:NHL5:water 2.3:1:0.67 sand:NHL3.5:water
Lime plaster (control LP	Floating coat c.12mm Skim coat 3mm	3:1:0.6 sand:NHL3.5:water 1:1:0.5 sand:NHL2:water
Paint on control lime plaster (P)	As above with 3 coats of paint	Emulsion with ceramic additives
Aerogel (AG)	Aerogel and plasterboard w/ foil19.5mm Gypsum skim coat 3mm	Mechanical fixings manufacturer spec
Cork Lime (CL)	2*20mm layers	2.15:1 cork/lime:water
Hemp Lime (HL)	2*20mm layers	1:2.9:3.5 hemp:NHL2:water
Calcium silicate board (CSB)	30mm Proprietary skim coat c.6-7mm	Adhesive as per manufacturer spec Base and finish coat
Thin PIR with foil (PIR)	37.5mm Gypsum skim coat c.3mm	fixings as per manufacturer spec

NHL –Natural Hydraulic Lime.

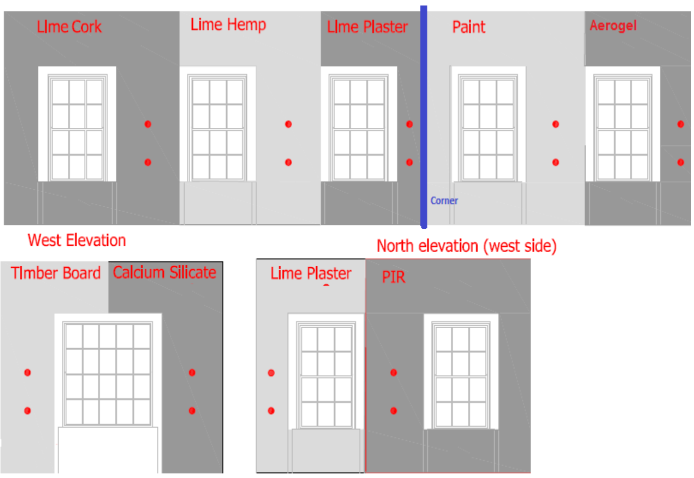

Figure 3. Layout of insulation on west and north elevations.

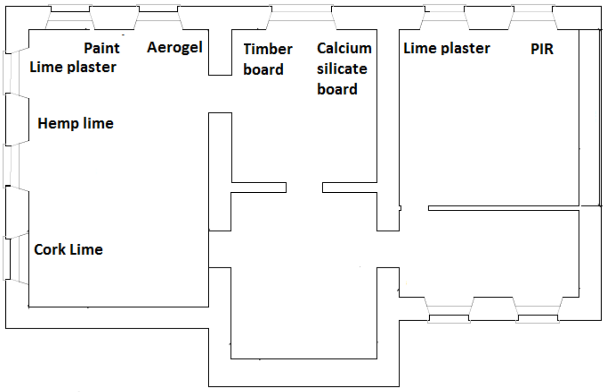

Figure 4. Building plan with location of insulation.

2.3 *In-situ measured moisture properties*

The insulation is present on two elevations (north and west) which are exposed to different meteorological conditions which will affect moisture behaviour in the wall. The prevailing wind direction in Ireland is south-westerly. Consequently, the west elevation will be exposed to higher quantities of wind-driven rain however, it will also undergo further drying from wind and the latter day sun. In contrast, the north elevation will face less wind-driven rain and little direct sunlight.

Moisture measurements were taken one month prior to the application of insulation. Insulation was applied, between December 2013 (M1) and April 2015 (M5), in the following sequence: cork lime, hemp lime, lime plaster, paint on lime plaster, aerogel, PIR and calcium silicate board. Moisture readings were resumed at month 8 (M8) with additional readings at months 11, 13, 15 and 17 so that M17 is one year after completion of the insulation application. The largest initial moisture content was present in the cork lime, hemp lime and to a lesser extent lime plaster owing to their wet application.

2.4 *Measuring of wall moisture using timber dowels*

Relative changes in moisture content were measured using timber dowels inserted in the wall and removed at regular intervals. The moisture content of the timber dowel was measured using a resistance moisture meter (Tramex PTM 6005). Changes in the moisture content of the dowel reflected changes in the moisture content of the wall. The dowel gives a good indication of changes in relative wetness [11]

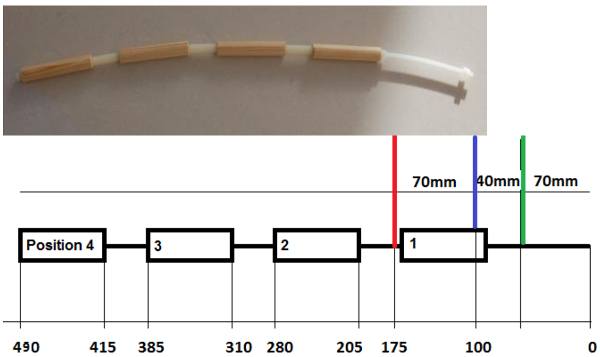

Figure 5. Rod of dowels used to measure the moisture content at different depths in the wall and schematic of rod with dimensions (mm). Green- surface of insulation (wall surface), blue – levelling plaster surface, red – original wall surface.

Rods of dowels were inserted in 14mm diameter cores drilled approximately 420mm into the wall (figure 5). The location of the rods is mapped in figure 3 as red dots. The rod comprised of four sections of pine dowel (length 75mm and diameter 12mm) separated by nylon spacers (length 30mm). This allowed measurement of the moisture content at different depths in the wall. The wall is approximately 840mm thick (770mm external render and brick and c. 70mm levelling lime plaster) with c.40mm of insulation. Dowel position 1 relates to the insulation-plaster interface and positions into the wall 2, 3 and 4 relate to depths of 135-210mm, 240-315mm and 345-420mm. The timber rods are inserted approximately 320mm into the original wall so position 4 is nearly at the mid-point of the original wall. The position slightly varies depending on the thickness of the insulation and levelling plaster. 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 insulations and subsequently reinserted 2 months later.

It is likely that the room environment and probe itself influence the measurement of the wall moisture. Consequently, moisture measurements are relative changes in moisture rather than quantitative values.

2.5 Monitoring of wall RH with probes

The wall temperature and RH were monitored using Lascar EL-USB 2+ temperature and humidity probes inserted into holes drilled in the wall and sealed with tape. The hole depth was c.130mm, extending through the insulation (c.40mm) and levelling plaster (c.70mm) to the interior surface of the brick wall. The RH readings are shown over a 1 month period and show the response of the walls to changing moisture conditions.

3 RESULTS

3.1 Measuring moisture using the timber dowel technique and comparison with commercial RH probes

As discussed in the introduction, the timber dowel technique involves inserting a section of timber dowel snugly in a wall until equilibrium moisture content is achieved between the wall substrate and the timber dowel. The dowel is then removed at intervals and its moisture content measured using an electrical resistance based moisture metre. Previous research by the authors found that the timber dowel does not measure actual wall moisture content but satisfactorily shows relative changes in the wall moisture content [11]

As part of this research, the average readings of the timber dowel were compared to commercial RH probes with the results in table 2. The timber dowel method measures the timber moisture content while the commercial probe measures the RH of the ambient air in a hole in which the probe is inserted.

The average readings of the timber rods at positions 1 and 2 (Figure 5) at month 17 were compared to RH probes inserted into 130mm cores (approximately positioned at the levelling plaster- insulation interface) for one month (M16-M17), 12 months after the application of the insulation. The RH measured depends on moisture conditions but also on the wall temperature as RH increases with decreasing temperature. Therefore, low thermal conductivity insulation results in higher RH as it reduces the wall temperature to a greater extent. For this reason, the relative humidity was converted to absolute humidity (using a formula derived from the ideal gas law) that measures the total moisture present irrespective of wall temperature.

The best agreement between the dowel and RH probe is the PIR board that shows both very high RH for the probe (c.89%) and moisture content in the dowel (13.2%). The remaining probe results are within a small range of relative humidity ((56.5%-63.5%) however both the dowel and probe measurements largely agree on the relative moisture levels. For example, they show that CL and HL have low moisture values compared to the other insulation materials. Additionally, the paint and CSB have the highest moisture readings for both measurement techniques. Despite the small RH range (56.5%-63.5%), the similarity in the trend of moisture content of the insulations using the two measurement techniques provides confidence of a satisfactory level of accuracy on the moisture behaviour.

Table 2. Moisture reading of timber dowel and commercial RH probe

insulation	Average timber dowel % (M17)	RH %	Temp °C	Absolute humidity (kg/m^3)
LP	11.18	56.5	16.3	0.00786
P	11.39	63.5	16.5	0.00894
AG	11.00	62.9	15.3	0.00824
CL	10.94	58.5	15.3	0.00753
HL	10.24	58.9	16.1	0.00809
CSB	11.41	60.8	16.2	0.00841
PIR	13.17	89.2	13.9	0.01072

In addition, previous research by the authors investigated moisture content in the timber dowels in varying RH environments in the laboratory [11]. The results (converted to absolute humidity) are plotted in figure 6 (blue). In this figure, the RHK wall humidity values measured with the probe and timber dowels are shown in red; and the black curves show the typical relationship between environmental relative humidity and timber moisture content (timber pine sorption isotherm). The RHK readings (red) overlaid in a position near the sorption isotherm suggests good agreement in the readings of the probe and timber dowels. The timber moisture readings in the dowel in the walls of the RHK are what would be expected based on the RH measured by the probes in holes in the wall.

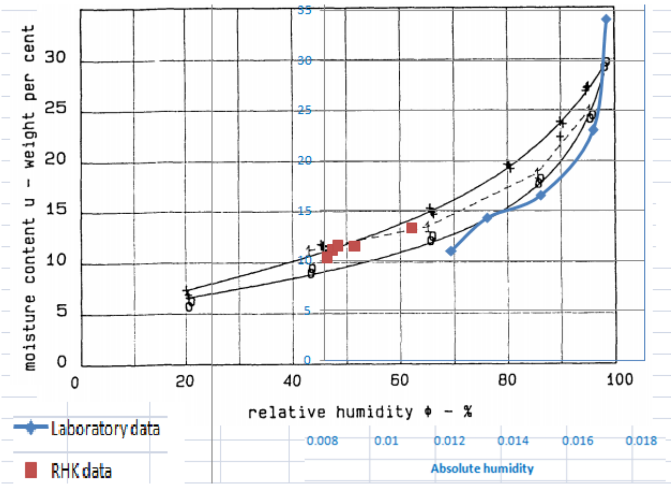

Figure 6. Comparing moisture content in timber dowel and the RH measured using the probe in the RHK wall, with previous laboratory results and timber sorption isotherm.

3.2 Overall trend of moisture in the wall

As discussed in the introduction, moisture movement in the wall is exceptionally complex, with several interactions simultaneously occurring at varying drying, wetting and cooling cycles.

In the case study, significant moisture was introduced into the wall in the levelling plaster and the wet application of insulation. The overall trend of falling moisture content, between M8-M17 (July to April) reflects the drying of this construction moisture. The initial construction moisture content in the wall varied, for each insulated section, on account of moisture introduced by the levelling plaster and/or wet insulation and the sequence of construction. The moisture content at the final stage (at M17) ranged between 10.24-11.39% (except for PIR) which is slightly above the average wall moisture content recorded prior to the application of the insulation (10.3% ranging between 9-11.9%). This suggests that most construction moisture had dried by this time.

The small increase in wall moisture between M11 and M13 however indicates that other sources of moisture are also contributing to the total wall moisture content. Moisture vapour (diffusion and air movement) and rainfall are also contributing to the total moisture content in the wall although likely to a lesser extent than construction moisture.

The effect of the hygric properties of the insulation are evident at months 13, 15 and 17 (M13, M15 and M17), as the least vapour permeable and capillary active materials (PIR, AG and paint) on average show higher moisture contents than the lime based materials (LP, CL and HL).

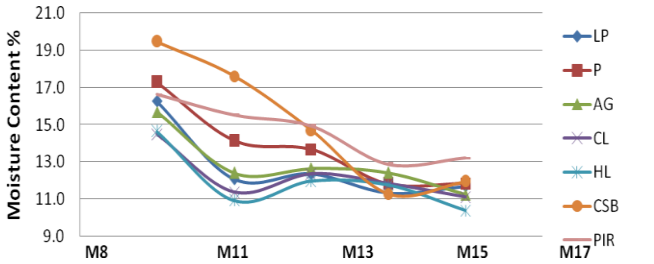

Figure 7. Relative changes in wall moisture content over time, (between month 8 and 17) measured with the dowel method.

In relation to drying, all the walls lost significant moisture between months 8 and 11. It is difficult to compare the drying rate for the walls on account of the varying initial moisture content at M8. However, it is evident that the PIR has the slowest drying rate. The aerogel and paint have similar drying rates to the lime based insulations despite their higher initial moisture content.

The aerogel and paint have similar drying rates to the lime based insulations despite their higher initial moisture content. Typically, drying rates are proportional to the quantity of moisture present so wetter materials will dry at faster rates. The slow drying rate (considering higher initial moisture content) of the least permeable materials (aerogel and paint) is likely inhibited by this characteristic while the good drying rate of the lime based materials (cork-lime and hemp-lime) is benefited by their high water vapour diffusion and capillary activity.

The CSB has a much slower drying rate than expected, although at later ages, particularly between M15-M17 (figure 7), the drying rate is much faster. It is likely that the sensitivity of the CSB to changing environmental conditions may have influenced the moisture content readings.

3.3 Moisture gradient in the wall over time

The moisture profile of the rods in the wall should indicate the direction of moisture transfer in the wall with moisture moving from areas of higher concentration.

The moisture profile of the insulated walls (from the interior to approximately mid-point into the wall) was monitored at 8,11,13,15 and 17 months with timber dowels. As aforementioned, the rods have four sections of timber dowel that are separated from each other by a nylon spacer. Each section of timber dowel indicates moisture content at a different depth in the wall (position 1 relates to the insulation/levelling-plaster interface and positions 2, 3 and 4 relate to depths of 135-210mm, 240-315mm and 345-420mm into the wall respectively- Figure 5). The beginning of the curves in figures 8-10 below relate to position 1 and the end to the midpoint of the wall (position 4).

Two rods were located in each insulated wall. The moisture content of each rod was plotted to give an indication of the moisture profile in the wall. A straight profile refers to less than 1.5% moisture variation at the four positions of the two rods. The angled profile relates to a constant gradient for both rod measurements with a greater than 1.5% difference between position 1 and 4 for at least one of the two rod measurements. The humped profile means that the moisture at the centre points is greater than that at either end by at least 1.5% for both rod measurements. When two distinctly differing profiles were evident for the two rods, both are shown. N/d refers to an undefined profile where the gradient differs for the two rods are inconsistent.

These graphs represent the moisture distribution across the wall rather than the actual moisture content which is not comparable due to varying initial moisture contents.

During application of the levelling plaster and wet insulation, moisture is introduced at the interior side of the wall (dowel position 1 – left hand side (LHS) of curve) and drawn deeper into the brick wall. As moisture dries in both directions, there should be a reduction in moisture content and an equilibrium of water distribution through the wall. If the internal insulation is impermeable, moisture will be forced to dry towards the exterior. Figure 8 shows a simplified visual approximation of the moisture profiles in the wall on account of water introduced during construction.

It is considered that construction moisture makes the greatest contribution towards the total wall moisture at early ages. However other sources of moisture also influence the profiles with rainfall raising moisture from the interior wall position (rod position 4) and internal room humidity transferring moisture from the room side (rod position 1).

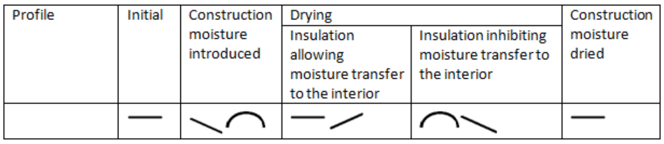

Figure 8. Simplified moisture profiles in the wall considering construction moisture. The beginning of the curves (left hand side) relate to position 1 and the end (right hand side) to the midpoint of the wall (position 4).

The average moisture content (of months 8,11,13,15 and 17) at each position is shown in figure 9 and a visual representation of the moisture profile at each month is shown in figure 10.

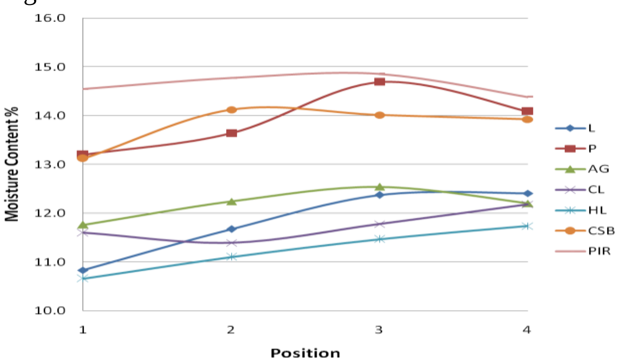

Figure 9. Average moisture content (month 8, 11, 13, 15 and 17) at the different dowel positions (fig 5)

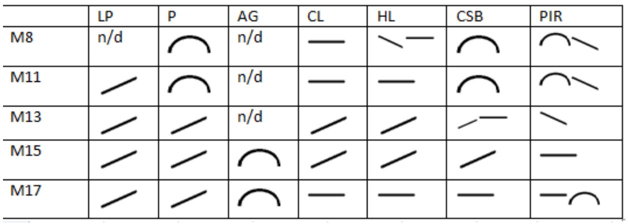

Figure 10. Visual representation of moisture profiles across the wall measured using rods

The lime plaster moisture profiles in figures 9 and 10 indicate that drying is consistently occurring towards the interior which is consistent with its vapour permeable nature. The lime plaster with paint profiles reveal that moisture is moving towards the interior, although its higher moisture content and the small difference in average moisture content between positions 1 and 2 (figure 9) suggest that drying is inhibited at the wall surface by the paint.

All the moisture profiles of the cork-lime and hemp-lime (CL and HL) reflect the good liquid water capillary transfer of these materials: moisture is distributed across the wall on account of the moisture wicking ability of the materials allowing drying towards the interior.

The moisture profiles of the PIR (and aerogel to a lesser extent) largely suggest an inability for moisture to dissipate towards the interior with an accumulation of water near the surface of the original brick wall (humped profile) or evidence of moisture moving towards the exterior. This is attributed to the low capillary transfer and moisture barriers at the internal surface of these insulations.

The CSB has a higher moisture content at the time of measurement (due to construction sequencing it was applied last). The profiles of the CSB at M8 and M11 suggest that construction water is still in the wall and the following measurements (at M13 and M15) indicate that drying is occurring towards the interior facilitated by its highly capillary active nature.

4 CONCLUSION

This paper monitors the in-situ moisture performance of a solid brick wall following the application of internal insulation including thermal paint on lime plaster, aerogel (AG), cork-lime (CL), hemp-lime (HL), calcium silicate board (CSB) and PIR.

Timber dowel and commercial relative humidity (RH) probes provided good agreement of relative changes of moisture content in the wall.

The moisture content of the walls reduced over time as the construction moisture dried. The moisture properties of the insulation influenced this drying. At one year, the least vapour permeable and capillary active insulation (PIR, aerogel and paint) had higher moisture contents than the lime based insulation (LP, CL and HL). The moisture profiles across the wall (from the internal surface to wall mid-point) further illustrated their moisture behaviour with the lime based materials allowing the dissipation of moisture towards the interior while, in contrast, this is retarded by the low moisture permeability of the paint surface, aerogel and PIR.

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