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In-situ measurements of wall moisture in a historic building in response to the installation of an impermeable floor

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Abstract

When impermeable ground bearing slabs are installed in old buildings without a damp-proof course, it is a common belief of conservation practitioners that ground moisture will be 'driven' up adjacent walls by capillary action. However, there is limited evidence to test this hypothesis.

An experiment was used to determine if the installation of a vapour-proof barrier above a flagstone floor in a historic building would increase moisture content levels in an adjacent stone rubble wall. This was achieved by undertaking measurements of wall, soil and atmospheric moisture content over a three-year period. Measurements taken using timber dowels showed that the moisture content within the wall did not vary in response to wall evaporation rates and did not increase following the installation of a vapour-proof barrier above the floor. This indicates that the moisture levels in the rubble wall were not influenced by changes in the vapour-permeability of the floor.

Keywords

Masonry, wall moisture, historic building, conservation, renovation, capillary rise, evaporation, timber dowel, soil moisture deficit

Introduction

Water movement through the masonry walls of historic buildings is an important process influencing thermal performance, wall deterioration (e.g. salt weathering), decay of built-in timbers, and damage to the internal finishes and environment (e.g. mould)(El-Turki *et al*., 2010). Therefore, understanding moisture regimes within historic structures is critical to heritage conservation and the appropriate selection of materials for repair or renovation (Franzoni, 2014).

Relatively impermeable concrete ground-bearing slabs are sometimes installed in historic buildings during renovation, but it is unclear if this adversely alters the moisture dynamics of the building. It is believed by many conservation practitioners that if an impermeable ground bearing slab is installed in an historic building during renovation, and particularly those which do not contain a damp proof course, ground moisture will be 'driven' up adjacent walls through capillary action. Although there are references to this phenomenon in the technical literature (Trotman et all., 2004; Historic England, 2016), there is limited evidence based on long-term monitoring.

Water transport in buildings and building materials is site specific and complex, but is generally dominated by capillary forces and unsaturated flow within the pores of building materials (Franzoni, 2014; Hall *et al*., 2011; Hall & Hoff, 2021). It can be difficult to model unsaturated flow through historic masonry walls because it is not always possible to intrusively characterise the physical properties of the wall materials, their heterogeneity and the interfaces between the different

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materials forming the wall. However, it is possible to measure and model the primary processes influencing the supply and removal of water within walls, to consider the behaviour of the wall as a system. Hall & Hoff (2007) developed a quantitative representation of the primary processes controlling moisture migration and wall damp rise in a masonry wall (Figure 3). This shows that ground moisture (*u*) is absorbed at the base of a homogenous, porous wall of thickness *b*. To ensure the conservation of mass, a state of dynamic equilibrium is established if the height of the wetted part of the wall (*h*) varies in response to the evaporation rate on the wall surface (*e*).

The Hall & Hoff (2007) conceptual model describes the primary process of moisture migration through porous building materials. However, the wall moisture dynamics in a historic building is further complicated by in situ conditions that are difficult to quantify, measure and model. This includes, but is not limited to (i) the heterogeneous nature of old masonry walls, and (ii) the moisture storage and conductivity properties of the materials forming the wall. Therefore, in situ monitoring was identified as the most effective method to measure the response of a masonry wall to the installation of an impermeable floor barrier in an historic building.

Aim & objectives

The aim was to determine if moisture levels in the external wall of a historic building were responsive to seasonal potential evaporation rates and if these were influenced by the installation of an impermeable ground bearing slab. The first objective was to determine whether seasonal changes in soil moisture content and evaporative drying influenced moisture levels within the wall. The second objective was to simulate the installation of an impermeable ground bearing slab by sealing the floor with a vapour-proof barrier and measuring changes in wall moisture levels due to the intervention.

Method

The monitoring programme

A three-year monitoring programme was undertaken to measure moisture levels in a 600 mm thick, composite rubble-core masonry wall at Court House; a private residential property in Caldicot, Wales (Figure 1). Court House is a Grade II listed building originating from the 16th or 17th Century (DataMapWales, 2021). The masonry wall was located on the north elevation of the house and formed the external wall of an unheated, flagstone-floored room that was used as a pantry during the monitoring period (Figure 2).

The monitoring programme included measurements of soil moisture levels at the base of the wall, the evaporative drying on the wall faces and the moisture levels within the wall (Figure 4), in accordance with the conceptual model (Figure 3). Details of the electronic sensors are shown in Table 1.

The internal structure of the wall was unknown, but walls elsewhere in the property were formed from an inner and outer leaf of stone rubble bedded in lime mortar, with a mortar and rubble-filled core. The wall was rough cast cement rendered and painted on the external face (Figure 2). It was plastered with a lime-based material and painted on the internal face. A shallow excavation at the property showed that the ground consisted of clay soil mixed with made ground and infilled ground (Ford *et al*., 2010), overlain by organic topsoil. A geological map showed that Court House is located on an outcrop of Sandstone from the Mercia Mudstone Group (British Geological Survey, 1981) but this was not observed in the ground excavation.

The instrument installation and monitoring began in January 2017. Site visits to measure soil and wall moisture levels were undertaken at approximately monthly intervals between January 2017 and March 2020. A vapour-proof, 0.15mm thick polyethylene sheet was laid over the floor along the length of the pantry wall and sealed at the edges with tape on 18th September 2019, to simulate the installation of an impermeable ground bearing slab. Supporting laboratory experiments showed that the polyethylene sheet was less permeable than a concrete slab. It therefore simulated a worst case scenario in terms of creating an impermeable floor. A Tinytag logger was installed beneath the polyethylene sheet to measure the time required to reach a constant humidity (%) reading.

Instrumentation and measurement

Figure 4 shows the layout of instrumentation installed at Court House. Evaporative conditions on the internal and external wall faces were continually measured and logged. Externally, a WS-GP1 weather station (Delta-T, 2021) was installed to measure hourly changes in solar radiation (kWm^{-2}), air temperature (^oC), humidity (%), rainfall (mm/tip), wind speed (ms^{-1}), wind direction (^{o}). A Tinytag Plus 2 datalogger (Gemini, 2021) was installed at the top of the internal wall face to measure hourly changes in air temperature (^oC) and relative humidity (%) directly adjacent to the wall surface.

Soil moisture was measured using a PR2 Soil Moisture Probe (Delta-T, 2016; Qi & Helmers, 2010), inserted into a 1m long access tube at approximately monthly intervals. The probe has electronic sensors fixed to a 25 mm diameter polycarbonate rod at fixed intervals of 0.1 m, 0.2 m, 0.3 m, 0.4 m, 0.6 m and 1 m below ground level. The sensing elements measure the permittivity (ε) of the soil in a 100mm radius surrounding the probe. These were logged and converted to volumetric moisture content (ϑ, %) using a linear relationship for mineral soils:

$$\theta = \frac{\sqrt{\varepsilon} - 1.6}{8.4} \quad (1)$$

Changes in wall moisture were measured indirectly at approximately monthly intervals using (i) timber dowels and (ii) a commercial moisture meter. Seven, 130 mm long, 12 mm diameter holes were drilled into the internal face of the pantry wall in a vertical array at 0.2 m spacing between 0.2 m and 1.4 m above ground level (Figure 4). Pine dowels (10 mm diameter) were installed into these holes and sealed with plumber's putty. Weight measurements of the dowels were then taken on site at approximately monthly intervals, to determine changes in their gravimetric moisture content (%). Calibration of the timber dowels showed that they took approximately 14 days to reach equilibrium and provided a good indicator of relative changes in wall moisture, however absolute values at dowel moisture contents > 15% may be underestimated.

At approximately monthly intervals, 'deep wall probes' were inserted into the wall to measure wall moisture using a Protimeter Mini moisture meter (Amphenol, 2021). The deep wall probes were inserted into seven pairs of 75 mm deep, 6 mm diameter holes that were drilled 40 mm horizontally apart, directly adjacent to the larger diameter holes which contained the timber dowels, again between 0.2 m and 1.4 m above ground level. These holes were also sealed with plumber's putty. The Protimeter Mini moisture meter provides a 'wood moisture equivalent' reading (6 - 90%) based on the electrical resistance measured between the probes. The calibration for the Protimeter Mini moisture meter was not readily available from the manufacturer, so the meter readings were treated as an approximate measure of relative changes in wall moisture.

Interpretation of potential evaporative drying

An approximation for the potential evaporative conditions on the external and internal wall faces were calculated from the weather station and Tinytag measurements of air temperature (^{o}C) and relative humidity (%). The potential evaporation was assumed to be equal to the potential evapotranspiration (*PET*) calculated using the simple equation by Schendel (1967) and appraised for climate modelling by Bormann (2011):

$$PET = \frac{16 \cdot T}{RH} \qquad (2)$$

where *PET* is the potential evapotranspiration (mm/day), *T* is the mean daily temperature (^{o}C) and *RH* is the mean daily relative humidity (%).

Interpretation of soil moisture

The soil moisture levels at the property were calculated from (i) the weather station data and (ii) direct measurements of the soil moisture content profile. Using both approaches it was possible to calculate a soil moisture deficit (SMD) for the soil profile between 0 m and 1 m below ground level.

The soil moisture deficit (SMD) is the volume of water per unit area (mm^3mm^{-2}) that the soil can absorb before reaching field capacity, where the moisture content is in equilibrium and free to drain under gravity (Smethurst *et al*., 2006). The daily SMD can be calculated from a soil water balance of daily rainfall infiltration and potential evapotranspiration; bounded by SMD equal to zero when the soil is at field capacity and water cannot infiltrate the soil surface. The daily SMD at Court House was calculated using the rainfall, temperature and relative humidity measurements from the weather station, with the PET calculated using Equation 2.

The measured soil moisture deficit (SMD_m) was derived from the PR2 Profile Probe measurements of volumetric moisture content (ϑ) using the approach described by Smethurst *et al*., (2015). The total SMD_m of the soil profile (0 m - 1 m below ground level) was calculated using

$$SMD_m = \sum_{i}^{n} h_i(\theta_{FC} - \theta_i) \qquad (3)$$

where θ_i is the measured volumetric moisture content in each soil layer (n), of thickness h_i. A volumetric moisture content of 38% was assumed at field capacity (θ_{FC}), based on the wettest soil profiles measured.

Interpretation of wall moisture

Timber dowels have been used to successfully measure in situ moisture changes in solid brick walls (Walker *et al*., 2016) and historic stone walls (Larsen, 2004). Timber dowels absorb moisture over two or three weeks until they achieve equilibrium with the surrounding wall (Ridout, 2000). Prior to installation, the timber dowels were oven dried at 105 ^{o}C for at least 24 hours to determine the dry mass (m_d). The timber dowels were then weighed at monthly intervals to measure the wet mass (m_w) and enable calculation of the relative changes in gravimetric moisture content (w_m) using:

$$w_m(\%) = \frac{(m_w - m_d)}{m_d} \times 100\%$$

(4)

It was possible to calculate the wall moisture changes using the potential evaporative drying measurements, for comparison with the timber dowels measurements. Hall & Hoff (2007) derived a conceptual model for rising damp moisture movement within a porous masonry wall without finishes (Figure 3). From this they developed a one-dimensional model of capillary rise dynamics based on sharp front theory. The model shows that water will rise within the pores of a wall via capillary action, if the wall has interconnected pore space and water is available at the base of the wall. Hall & Hoff (2007) showed that the steady-state height of water rise (h_{ss}) within a porous wall can be calculated using:

$$h_{ss} = S\left(\frac{b}{2e\theta_w}\right)^{1/2}$$

(5)

Where S is the sorptivity of the masonry (mm.min$^{-1/2}$), e is the evaporation rate (mm.min^{-1}), ϑ_w is the moisture content of the wetted part of the wall (mm^3.mm^{-3}) and b is the wall thickness (mm). Equation 5 was used to calculate the daily, steady-state height of water rise using the daily average *PET* (mm.min^{-1}) measured at Court House on both the internal and external wall faces. The wall thickness (b) was 600 mm. The sorptivity (S) and moisture content of the wetted part of the wall (ϑ_w) were not measured, but were assumed to be 1.0 mm.min$^{-1/2}$ and 0.2 respectively, as used by Hall & Hoff (2007).

Results

Evaporative drying

The internal and external temperature (^{o}C) and relative humidity (%) data showed potential evaporative drying during the summer months, followed by reduced drying through the winter months. These seasonal changes are typical of the temperate UK climate (Jenkins *et al*., 2009; Hollis *et al*., 2019). Figure 5 shows increased temperature and reduced relative humidity in the summer months (April to September), relative to the cooler, more humid winter months (October to March). A comparison of annual cumulative potential evapotranspiration (*PET*, mm) and rainfall (mm) shows that *PET* was greatest in the summer months and least in the winter months, with consistent total, annual cumulative *PET* (Figure 6). The calculated cumulative potential evapotranspiration was higher than comparative measurements in southern England (Smethurst *et al*., 2012; Briggs *et al*., 2013), due to the simple *PET* model used (Equation 2). Figure 6 shows that 2018 was both wetter (January to June) and drier (July to December) than in 2017 and 2019. According to the conceptual model of wall damp rise (Figure 3) and Equation 5, these evaporative conditions would lead to greater annual variation in the wall damp rise (mm) in 2018 than in the preceding or succeeding years (2017 & 2019).

Soil moisture

Figure 7 shows soil moisture content profiles measured at the end of winter and the end of summer between 2017 and 2019. The greatest variation in soil moisture content occurred in the near surface, up to 0.4m below ground level, as is typical in clay soils with grass vegetation at equivalent latitude (Smethurst et al., 2006). Figure 7 shows that the soil moisture content was often below field capacity (ϑ_{FC} = 38%) and that a supply of water was not consistently available at the base of the masonry wall. Figure 8 shows that soil moisture was available at the base of the masonry wall during the winter months (i.e. SMD = 0), while there was a soil moisture deficit (i.e. SMD > 0) during the

summer months. This shows that the availability of soil moisture varied seasonally and was not constant, as was assumed in the conceptual model (Figure 3).

Wall moisture

Figure 9 shows the dowel moisture (mass) content values taken at approximately monthly intervals between March 2017 and March 2020. The measurements show that the dowel was close to 50% moisture content at the base of the wall and consistently greater than higher up the wall. The data show that the moisture level of the dowels, and by implication the wall, did not vary in response to seasonal evaporation rates. Nor did the dowel moisture levels immediately increase in response to the sealing of the flagstone floor. Measurements with a Tinytag logger (not shown in Figure 4) showed that moisture levels rapidly increased beneath the vapour-proof barrier within two days of installation in September 2019, showing ground moisture transfer through the floor and into the internal environment of the room.

Figure 10 shows the wall moisture levels measured using the moisture meter with a deep wall probe. The wall moisture probe showed consistently lower meter readings at the base of the wall relative to the upper part of the wall. The meter readings were erratic and did not show a temporal trend. It is possible that the meter readings were responding to changes in the internal air temperature and humidity or were influenced by the distribution of salts within the wall (Franzoni & Bandini, 2012). They were not considered to be reliable measurements of wall moisture levels for this study.

Figure 11 shows the height of wall capillary rise calculated using the Hall & Hoff (2007) sharp front model, assuming (i) the supply of water at the base of the wall (ii) potential evaporative drying measured on the internal and external wall faces at Court House and (iii) a porous masonry wall with interconnected pores and without finishes. This shows that prior to the installation of the vapour-proof barrier, given the model assumptions, the capillary rise should have varied between 800 mm (summer) and 1200 mm (winter) above ground level. However, the historic masonry wall was not subject to capillary rise, despite the supply of water at the wall base (Figure 8) and seasonally variable evaporative drying on the wall face (Figure 6). Inspection of the wall showed that the wall was formed from porous materials, but with large voids and discontinuities that would inhibit capillary flow. Therefore, fabric of the wall itself did not facilitate water being ‘driven up’ by capillary action. This was confirmed by the measurements showing that the wall moisture levels did not vary seasonally, nor did they vary in response to the installation of a vapour-proof barrier to seal the floor (Figure 9).

Pre-existing moisture damage was observed on the internal plaster surface of the lower part of the wall (approx. 200 mm above ground level) prior to instrumentation, but the moisture levels did not vary at this location during the monitoring period. It is possible that localised capillary rise occurred within the plaster and caused the damage. However, this did not affect the core of the wall, nor was the base of the wall influenced by the installation of the vapour-proof barrier during the monitoring period.

Conclusions

Instrumentation was installed in a historic building to measure changes in wall moisture content and to measure the response of the wall to vapour-sealing of the ground floor. The monitoring programme was based on a conceptual model of capillary rise within the pores of the wall, driven by evaporative drying on the wall surface.

The following conclusions can be drawn from the results presented:

1) The rubble-fill, masonry wall at Court House was not susceptible to wall moisture fluctuations due to capillary rise, driven by evaporative drying. The moisture levels in the wall did not vary in response to changes in potential evaporative drying on the internal and external faces of the wall, despite the availability of soil moisture at the base of the wall during the winter months.

2) Measurements of soil moisture content showed that the supply of water from the soil is seasonally variable. Water is often not available for capillary rise within the pores of a wall during the drier summer months, when soil moisture levels are below field capacity. The supply of water for capillary uptake within a wall is greatest during the winter months, when the ground is more likely to be close to, or at field capacity. This seasonal variation is comparable to measurements at other locations in the south of England (Smethurst *et al*., 2006; Smethurst *et al*., 2015)

3) If an impermeable ground bearing slab were installed in this building, ground moisture would not necessarily be 'driven' up adjacent walls. Measurements beneath the vapour-proof barrier confirmed that moisture was moving through the flagstone floor, but this did not increase the wall moisture. Sealing of the flagstone floor using a vapour-proof barrier did not increase the moisture levels within the rubble-fill, masonry wall at Court House.

4) The in situ measurements of wall moisture at Court House contradicted predictions based on a theoretical model of capillary rise for an idealised wall. This is because the heterogeneous fabric of the rubble-fill wall contained a discontinuous pore network and therefore restricted capillary flow and capillary rise within the wall.

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Supplementary weather data for the Figures presented in this paper are openly available from the University of Bath Research Data Archive (Briggs *et al*., 2021) at https://doi.org/10.15125/BATH-01101.

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Figures & Tables

Internal wall face data are missing for September 2018 to March 2019. Extreme capillary rise values for the external wall face have been omitted for clarity.

Table 1: A summary of electronic sensors installed at Court House.

Figures

Figure 1: Court House is located in Caldicot, Wales. © Crown copyright and database rights 2021 Ordnance Survey (100025252) using Digimap Ordnance Survey Collection, https://digimap.edina.ac.uk/

Figure 2: The external face of the pantry wall at Court House showing a rubble wall formed of Sandstone and Limestone blocks with a cement-based, three-coat render system.

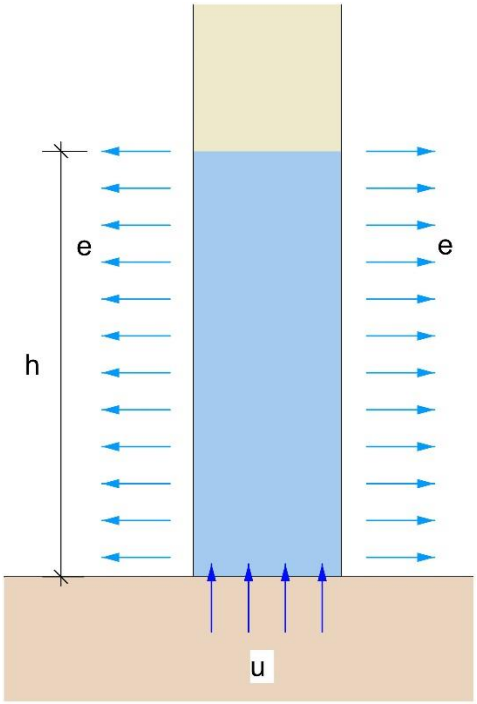

Figure 3: A conceptual model of wall damp rise by Hall and Hoff (2007), with soil moisture uptake (*u*) and wall evaporation (*e*) driving the saturated wall height (*h*), in a wall of thickness *b*.

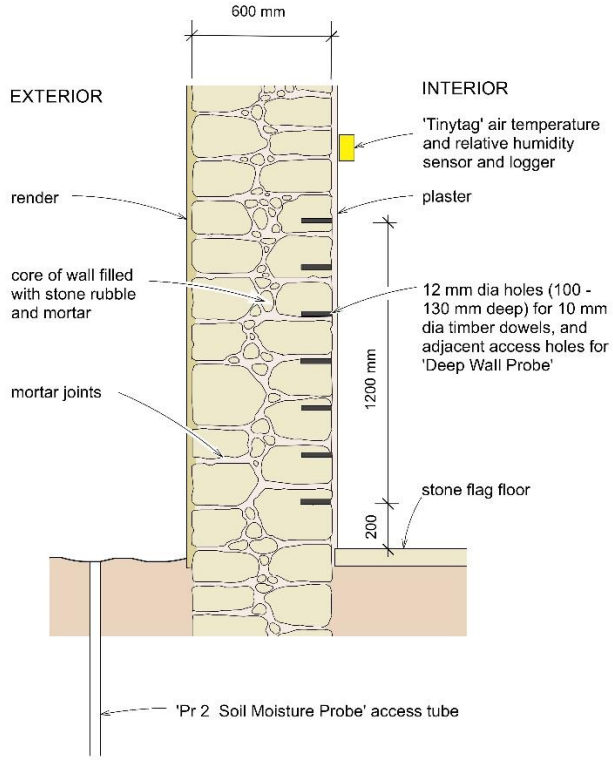

Figure 4: Instrumentation installed in a 600 mm thick, rubble-core masonry wall at Courth House to measure wall moisture (%) , soil moisture (%) and evaporative drying on the wall face.

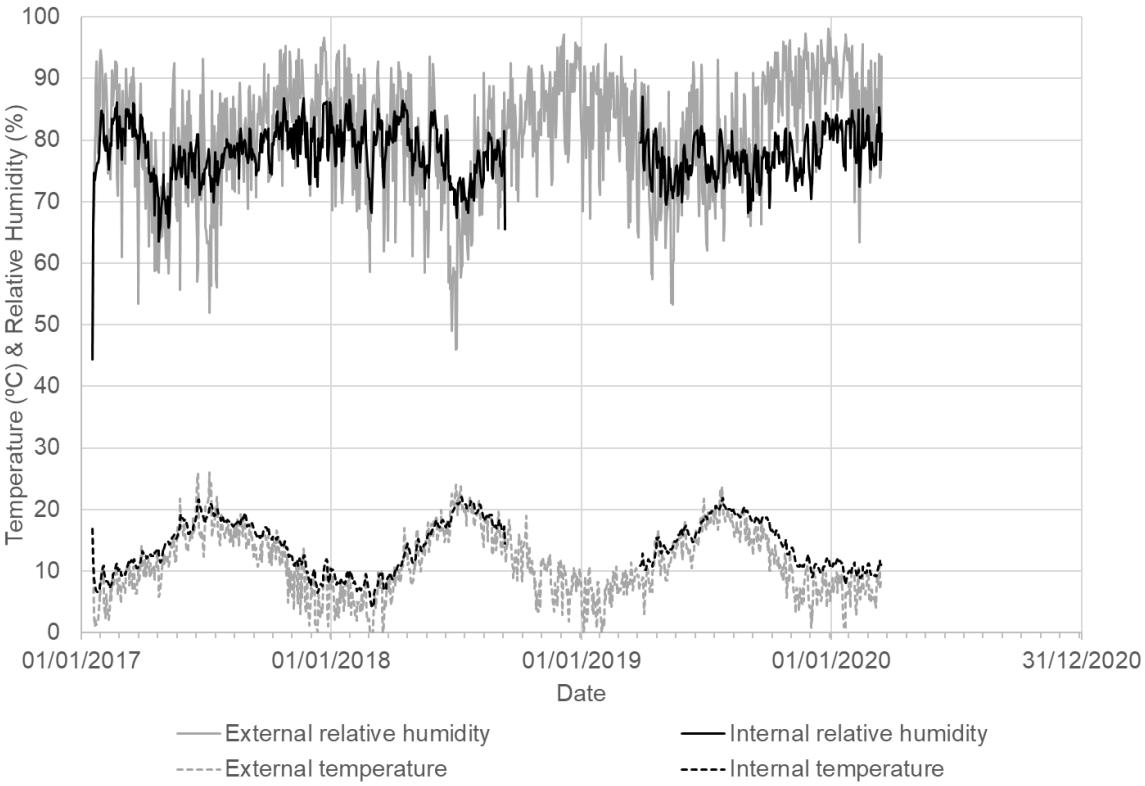

Figure 5: Daily average temperature (^{o}C) and relative humidity (%) measured internally (Tiny Tag logger data) and externally (weather station data) at Court House between 2017 and 2020. Note that internal Tiny Tag data are missing from September 2018 to March 2019 due to instrument damage.

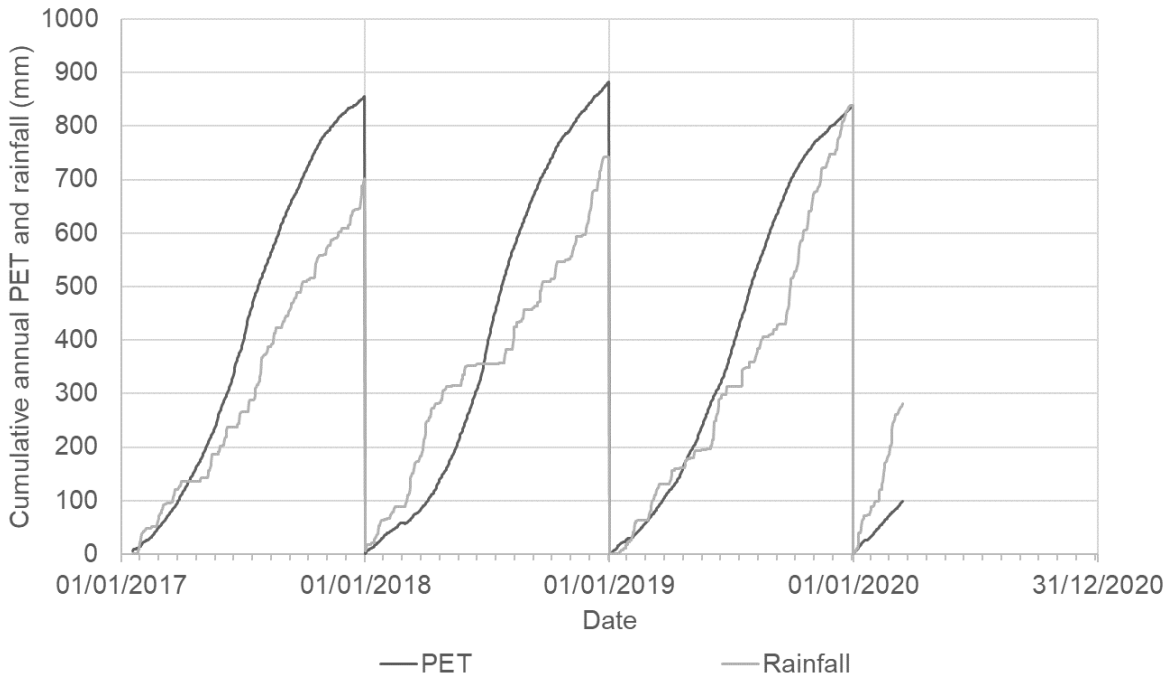

Figure 6: Cumulative annual potential evapotranspiration (*PET*, mm) and rainfall (mm) measured by the weather station at Court House. Note that the measurements start on 18/01/2017.

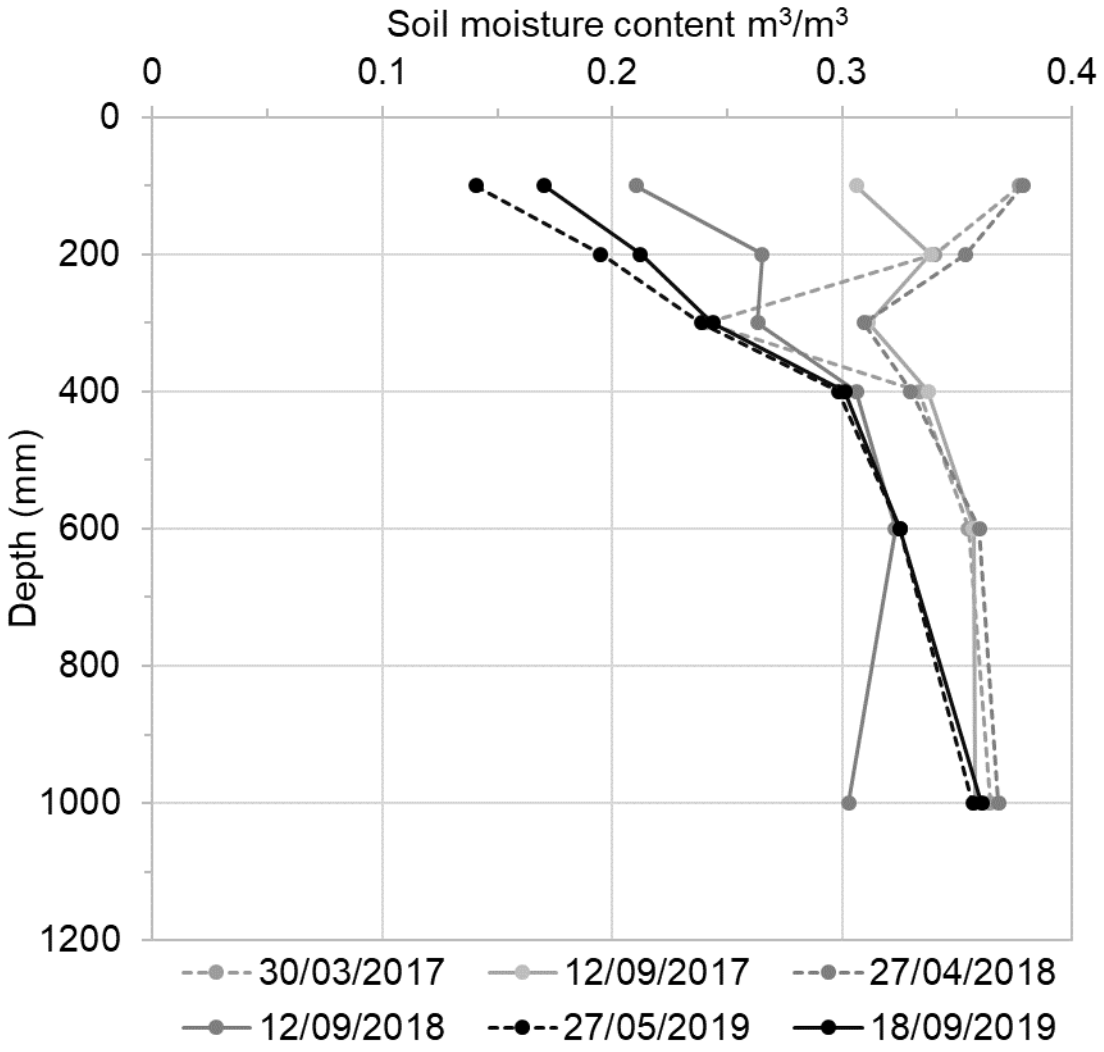

Figure 7: Soil moisture content profiles measured at the end of winter (April/May) and the end of summer (July/September) at Court House.

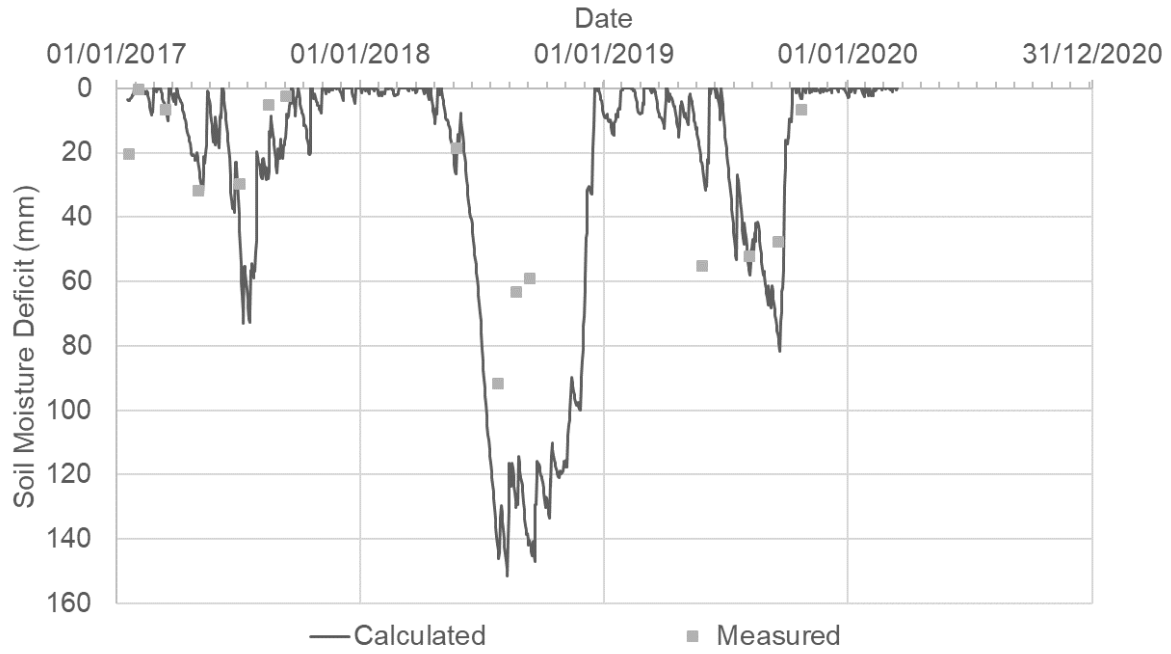

Figure 8: Soil Moisture Deficit (mm) at Court House (i) calculated using daily weather station data and (ii) measured using a PR2 soil moisture probe (up to 1m below ground level).

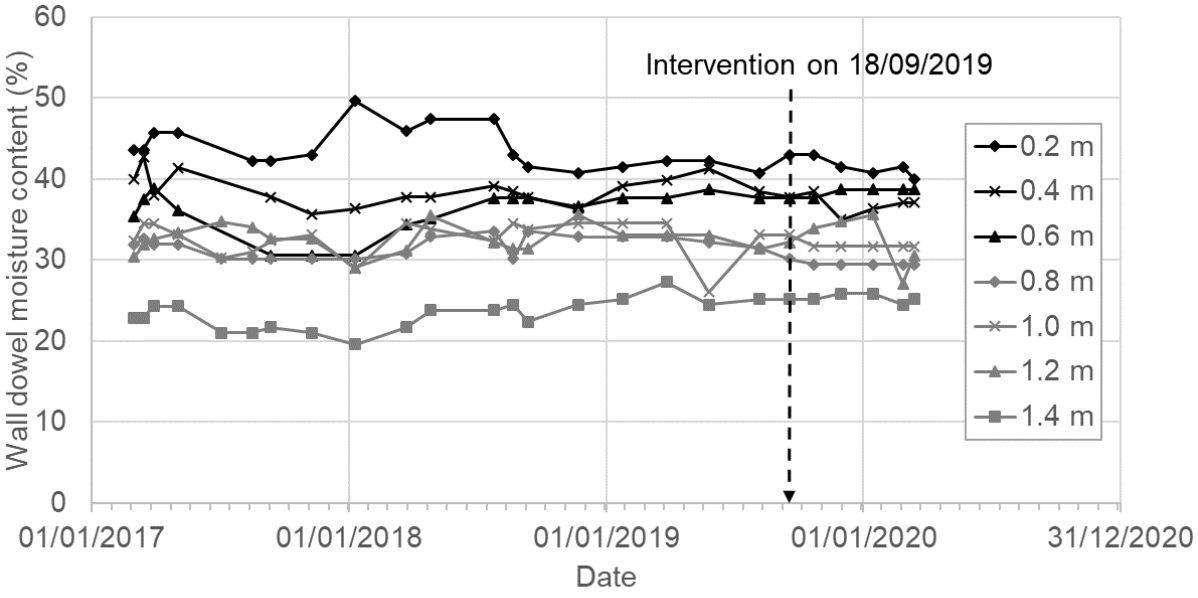

Figure 9: Measurements of timber dowel moisture content (by mass) between 0.2m and 1.4m above ground level over a three-year period between 2017 and 2020, including an intervention to seal the floor on 18/09/2019.

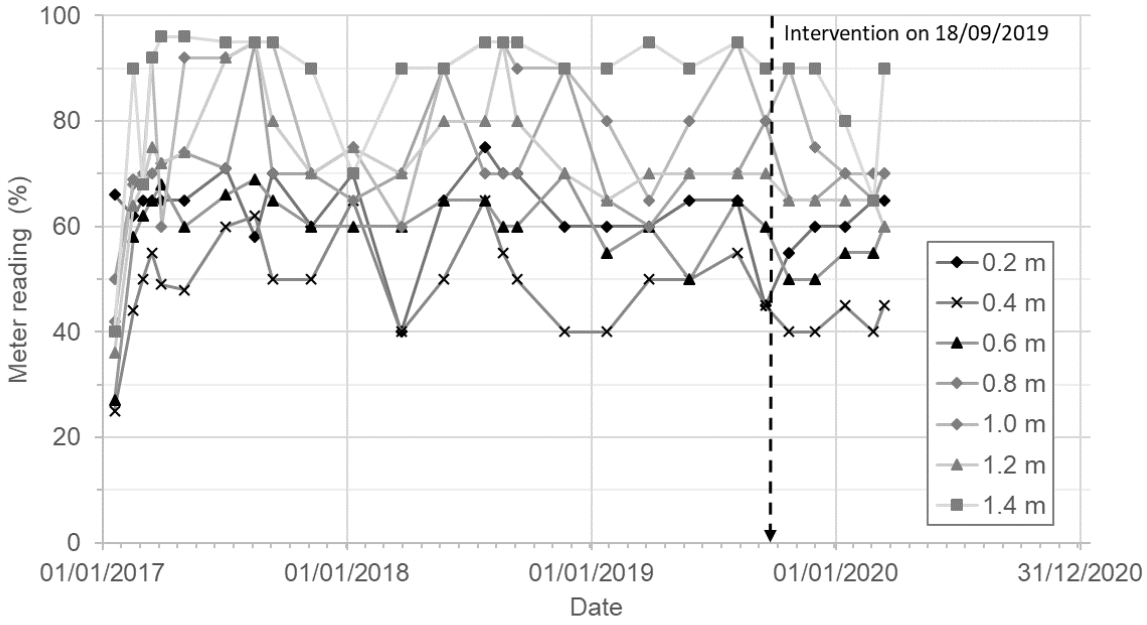

Figure 10: Protimeter Mini moisture meter readings of wood moisture equivalent (WME) measured between 0.2m and 1.4m above ground level over a three-year period between 2017 and 2020, including an intervention to seal the floor on 18/09/2019.

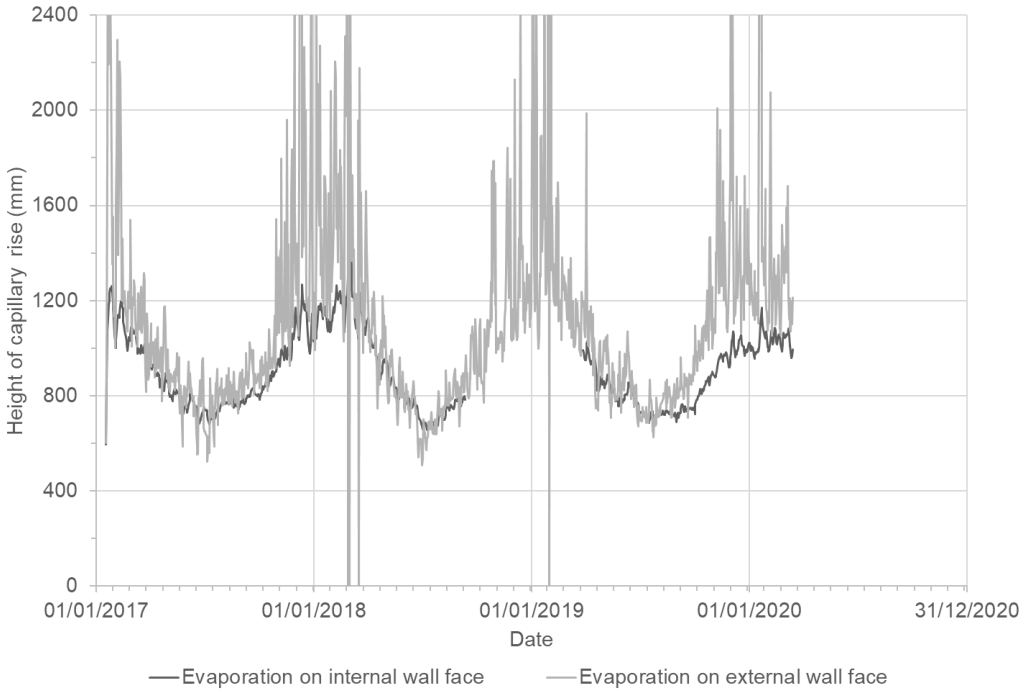

Figure 11: The height of wall capillary rise calculated using the Hall & Hoff (2007) sharp front model using PET derived from temperature and relative humidity data measured (i) On the internal wall face and (ii) On the external wall face. Note: Internal wall face data are missing for September 2018 to March 2019. Extreme capillary rise values for the external wall face have been omitted for clarity.

Table 1: A summary of electronic sensors installed at Court House.

Type of instrument	**Measurement**	**Location**	**Source/references**
WS-GP1 weather station	Solar radiation (kWm^{-2}), air temperature (^oC), humidity (%), rainfall (mm/tip), wind speed (ms^{-1}), wind direction (^{o})	Court House (external)	Delta-T Devices, ltd, Cambridge, UK
Tinytag Plus 2	Internal air temperature (^oC) & relative humidity (%)	Internal wall at Court House	Gemini Data Loggers, Chichester, UK
Protimeter Mini, with deep wall probe	Wall moisture 'wood moisture equivalent' (via resistance)(%)	Holes drilled into internal wall face at Court House (0.2 m - 1.4 m above ground level)	Amphenol Advanced Sensors, Taunton, UK
PR2 Profile Probe	Soil moisture (m^3m^{-3})	Court House (0 m - 1 m below ground level)	Delta-T Devices, ltd, Cambridge, UK

Response to reviewer comments: In-situ measurements of wall moisture in a historic building in response to the installation of an impermeable floor

Introduction

Overall, the hypothesis is clearly formulated but the argumentation is not very stringent. How damp and moisture may promote the decay of construction building materials and how it affects the health of occupants is not well justified.

Response – The paper isn't specifically about the decay of building materials or the health of occupants, but these two issues did contribute to the need for the study because moisture within walls can be a contributor both. We have added citations to others showning evidence. Hall et al (2011) and Hall & Hoff (2021) show photos of damage to masonry walls while the review by Franzoni (2014) includes evidence for occupant health and the degradation of building materials.

The data and results are interesting but the description of the building materials (e.g. limestone, sandstone ashlars? gypsum, lime or cement plaster?, painting layer, etc) and their petrophysical properties, are specific to this case study but these were not well described nor measured and hence maybe not statistically significant.

Response – Thank you for raising this as it hadn't been fully explained in the draft manuscript. Yes the wall is heterogeneous in terms of composition (a photo has been added). It is difficult to quantify the moisture storage and conductivity of these materials, particularly to capture the in-situ variability of each material and also to understand their interactions when forming a composite wall with unconnected pores. From our understanding it is difficult to model flow through composite materials in this way. For this reason, we chose a very simple conceptual model with parameters that we could measure. This lead to our decision to pursue in-situ monitoring as our method, to understand the behaviour of the wall as a system. The text in the introduction has been updated to reflect this.

From the title of this article 'The influence of ground slab permeability on wall moisture in a historic building' the reader expects to have more accurate and representative results to establish that influence'. However, the paper deals mostly with the methodology used to establish this in a very particular case in which the type of building materials and underlying ground where the building is settled is very specific to this study. Different outcomes could have been obtained for other types of materials where the physical properties should be known either by measurements or at least by references.

Response – Yes this is true. The title has been altered to reflect this. The in-situ conditions at the property were complex and site-specific, so the study is not easy to generalise. However, the results do show that capillary rise did not occur in the wall, despite the availability of water at the wall base during the winter months. So we believe it is a contribution to the in-situ evidence for similar wall types.

The second paragraph of the Introduction section that describes the hypothesis and related physical factors involved should be better deliberated. The factors that might influence the occurrence or severity of rising damp in the walls that may happen due to a lack of damp proof course and the installation of impermeable ground bearing slab installed in a historic building during renovation and

how this may alter the moisture dynamic of the building should be better addressed. Despite the limited evidence-based on long-term monitoring, the authors mention that there are references to this phenomenon. The provision of those 'technical and product literature' references would be useful.

Response – Two citations from the technical literature have been added.

Aim & Objectives

Method

Some info about the physico-chemical properties and context of the building structure, location, and weather would provide a more consistent and realistic interpretation of results.

Response – We weren't able to take samples from the wall and measure the physico-chemical properties of the materials forming the wall. We didn't undertake an overall building survey. The text includes details of the weather conditions, that are typical of the temperate UK climate (with citations added).

Among other factors, such as climate, weather, or geological features, rising damp will depend on the type and petrophysical properties of surrounding materials, i.e. of both the soil (ground) and building materials (walls) which will condition the capillary forces mentioned by the authors. The influence of their physical properties, such as open porosity, pore size distribution, tortuosity, capillarity coefficient, etc. should be mentioned and discussed. This is important since the final consequences (including rising damp) may be very different depending on the type of materials and hence on the type and kinetics of water transport and the eventual mechanisms of decay (e.g. freezing-thaw, salt crystallisation, etc). The paper doesn't provide information on the hygrothermal properties of the existing building materials considered in the analysis. A geological map is mentioned (please add a reference), but there is no information on the hygrothermal properties of the materials used in this house for the wall and floor.

Response – The conclusion of the paper is that the capillary forces are not causing moisture flow because the capillaries/pores are not connected. Hence any properties to describe flow through porous materials that is based on a continuum will not be applicable. So properties such as the open porosity, pore size distribution, tortuosity, capillarity coefficient will not be helpful for understanding the flow. They were also not measured and it would be difficult to know how to measure them to represent the whole wall and the composite nature of the various layers. For these reasons, we chose in-situ monitoring to gain information about the wall as a system, rather than measuring the individual elements/materials forming the wall, which we could not do.

The paper includes the bedrock geology at the site and the overlying layers of fill material. The term fill has been changed to 'made ground' and 'infilled ground' to align with the British Geological Survey definition. A citation for the geology has been added.

Even though in the 'Methods' section (which should be better named as 'Materials and Methods'), it was already explained in the Level of Validity query, that the methodology is thoroughly described but some important information is still missing, such as the description of installation of impermeable layer, etc. (see these comments above).

Response – Information has been added to describe the impermeable layer as a vapour-proof, 0.15mm thick polyethylene sheet that was taped to the floor.

In the 'Methods' section (second paragraph) briefly specify what type of 'instruments'? e.g. data loggers? sensors? The 'Instrumentation' subsection should be specified that the moisture meters are not directly measuring 'moisture' when inserted through the building materials of the wall; these are moisture equivalent measurements WME (%) using electric resistance mode (pin mode).

Response – The instruments are shown in Table 1, as in the text. The paragraph has been re-phrased to cover all types of measurement, not just those with instruments. The 'instrumentation' heading has been changed to 'Instrumentation and measurement' to reflect the content of this section. Text has been added to clarify that the dowel and moisture meter measurements are indirect measurements of changes in wall moisture.

The figure captions are properly described but the quality of some images and pictures (e.g. Fig. 1 and Fig.2) is not good enough or relevant to provide the necessary information (e.g. image of the external view of the building is missing; Fig.2. is blurry and building materials cannot easily being distinguished, etc.).

Response – The internal photo is blurry and has been removed. We don't have a replacement photo, but the layout of the instrumentation is shown schematically in Figure 4. Figure 2 has been replaced by a photo of the external face of the wall, after removal of the external render as part of building works at the property.

The concrete slab is represented by the installation of a polyethylene sheet; however, there is no comparison between the two:

- *In the method section, please add information on the hygrothermal properties of both, at least on the vapour resistance.*
- *It is likely that the polyethylene sheet has a lower vapour resistance than the slab; also, construction moisture is not considered in the analysis. In the discussion section, please add a discussion point on the difference between the two.*
- *The title refers to "ground slab permeability "; it is more appropriate to rename it to "ground floor vapour permeability"*
- *Is the polyethylene sheet appropriate to represent a concrete slab? Some vapour accumulated initially, but there is not information on the moisture levels under the polyethylene sheet in the long-term, nor any discussion on where the initial vapour might have transferred to (absorbed by the floor material? Through the polyethylene sheet?)*

Response – Yes a good point. It isn't a slab. We are undertaking laboratory testing of different slab materials. The results show that the vapour permeability of a properly sealed concrete slab is very low. The vapour permeability of a polyethylene sheet is even lower and would therefore represent a 'worst case' in terms of creating a barrier to moisture movement. We have changed the title to reflect the fact that a sheet was used, rather than a slab.

Why were monthly intervals considered? For some of the methods considered, a more frequent sampling is possible, and this could have been beneficial for the analysis. Also, other measurements could have been considered for this analysis.

It was a limitation of the field experiment in terms of time and access. We could only go to site at monthly intervals. Our approach was consistent with other studies (e.g. Walker et al., 2016).

Are all the measurement points presented? A Tinytag logger was mentioned in the results section, but it is not clear if it's the indoor logger or a new logger beneath the polyethylene sheet .

Yes it is a new logger that had not been previously mentioned. Text has been added to the method to clarify that this logger was used: “A Tinytag logger was installed beneath the polyethylene sheet to measure the time required to reach a constant humidity (%) reading. “

Introduce this comparative analysis in the methodology. E.g. "The wall moisture changes were then calculated using the potential evaporative drying measurements, and the results of this calculation were compared with the wall moisture measurements".

Response – Thank you, this wasn’t explicit in the first draft. The text in “Interpretation of wall moisture” has been altered to make this more explicit and link to the results.

Results

The interpretation of results is also unsound, and a better discussion of results is missing to draw a solid conclusion. Nevertheless, some important useful methods applied in this research are not clearly described (e.g. explanation on how the impermeable layer was installed and fitted (sealed) onto the ground; how the collected samples for gravimetry analyses were preserved to avoid dehydration until analyses were performed in the lab; the identification for the location of the drills to introduce the timber dowels and deep wall probes, etc.).

Response – The text has been updated to describe how the sheet was installed (with tape) and that the mass of the dowels was measure on-site. The drilled holes are shown in the cross-section in Figure 4.

As mentioned above, the final hydric, capillary, and evaporation behavior, water transport, and mechanisms of decay of building materials that could happen or not or being more or less severe, will be conditioned, among other factors by the local climate and weather and type of petrophysical properties of building materials and soil/ground/rocks where they're settled. More information of materials’ properties obtained from measurements or at least references would be important to better discussion and conclusions from results; e.g. Type and main physical properties of the buildings materials and soil/ground of this historic building? Are these frequently used in the UK, England, other countries? Are the type of soil and location-ground settlement representative of many historic buildings in the UK, other countries? In this case study, it seems that the ground underneath the building is clay soil (mixed with 'fill'?? this term should be clarified) which is mostly impermeable; the influence of this for example should have also been discussed. There should be references providing generic petrophysical characteristics of the sandstone rock geological formation underneath that would be relevant and important to mention and discuss here (eg. open porosity, capillarity rates, etc). Also regarding the building materials; are the stone ashlars of the building also sandstone?

Response - The local climate was measured with a weather station. The results are typical of the seasonal temperate climate in Wales and the UK. It would be possible to compare these values to long-term averages (LTAs) but the results would not contribute to the results or conclusions of the case study. Fill has been changed to made ground, to align with the termed used by the British Geological Survey. A citation has been added. In terms of the geology, we could include general information about open porosity and capillarity rates, but from my experience these will not be enough to reliably model the flow through these materials. Also, the bedrock geology was not encountered during excavation, so the moisture supply and flow will be from the near-surface topsoil layers (and made ground). Not only do we not have that information, it would not give us any further insight into the results than was provided by the measurements (e.g. see the approach used in the Smethurst citation).

Additionally, a discussion about the climate and the weather during the monitoring period would have been relevant e.g the discussion on evaporating drying is missing a link/references to climate/historic weather conditions of this particular UK region and future implications (also for other climates/regions in other countries); discussion the orientation of the building, seasonally rainfall? predominant rain/ wind direction? etc.

Response – We could include information on the long-term average (LTA) values for this site but that is not the focus of the paper. Nor is the paper about climate change or future implications. The weather data are there to test the Hall & Hoff model and the influence of sealing the floor. Other implications would not be well-served by this case study. However, to allow comparison with long-term (+10 years) weather data, citations for two sites in southern England have been added for readers interested in this comparison.

In figure 10, it would be best to refer to WME (wood moisture equivalent); the text already explains the limitations of this reading. Also, if this chart presents unreliable measurements (as mentioned in the text), what is the value of having it in this paper

Response – Thank you for the suggestion. WME has been added to the caption. These measurements were not useful, but we decided to include them because there is evidence that some practitioners use this method to measure wall moisture levels. This Figure shows that at Court House these measurements were not reliable. So we would like to keep the Figure in the paper.

The available ground moisture is measured considering the soil moisture deficit; please add information on how this compares with other locations. Is this a location with particularly low water table or is this representative of an average ground moisture?

Response – Soil moisture is different to the ground water level. It is hard to say what an average ground moisture looks like, but this is comparable to profiles showing seasonal variation in the near-surface soil, to approximately 0.4-0.5mbgl (e.g. Smethurst et al., 2006). I have added a citation. The purpose of the measurements was to measure the availability of water at the base of this specific wall, to then compare with the wall moisture, rather than to characterise general conditions so I haven't added text to discuss this.

Discussion

The discussion about why meter readings were erratic and did not show a temporal trend in contrast to gravimetric analyses that is mentioned at the end of the Results section should be better discussed and moved to the corresponding Discussion of Results section.

Response – Neither the gravimetric (wall dowel) measurements or the meter readings showed a temporal trend. The text includes possible reasons for the erratic readings, with a citation. But we did not undertake supporting laboratory calibrations ourselves as the Protimeter Mini wasn't a reliable tool for this experiment.

Most of the text found in the discussion consists of the results of a sharp-front model on capillary rise and the comparison with measurements. Please move this part to the result section.

Response- Thank you. Agreed. The text has been moved to the results.

Is the timeframe of this analysis long enough? The conclusion refer to long-term changes, but moisture can build up in years, and three years is possibly not long enough.

In this case we define the monitoring period as 'long-term', but yes the measurements could be extended. The term "long-term" doesn't have a fixed definition. It also isn't essential to the story of the paper, so the term has been removed.

Is this measurement method the most appropriate? How could this methodology be improved for more conclusive results? How have other researchers tackled similar problems?

Response – The literature review showed that the most reliable measurements of wall moisture were from timber dowels, hence why we used them in this study. The measurements of weather and soil moisture were undertaken using reliable approaches used by other authors and cited in the text (e.g. Smethurst et al., 2006 and Smethurst et al., 2015). Text has been added to the conclusion to highlight that the soil moisture measurements are consistent with those undertaken by others.

What can be the causes of discrepancy between model and measurements? Is there something that the model is missing?

Response – In this instance the model is testing whether moisture movement is due to capillary flow of water from the ground. The results suggest that this capillary flow is not occurring. This is due to the heterogeneous composition of the wall, with pores that are not connected. If the material porosity was fully defined, more complex models of liquid and vapour water flow would also simulate capillary flow (if the pores were assumed to be continuous). But the in-situ wall moisture data and inspection of the wall composition shows that this is unlikely to be the case.

Conclusions

Regarding the following statement posed in the abstract and conclusions: 'moisture content within the wall did not increase following the installation of a vapour-proof barrier above the floor. This indicates that the moisture levels in the rubble wall were not driven by capillary rise.' :

There are no consistent results and neither a thoughtful interpretation of these to assure this. Several questions should be important to address and discuss, such as: 'where is the moisture coming from'? Why the moisture content measured from the timber dowels is there if the source is not capillary rise?' Why is there more moisture content at the base of the wall compared to higher height? This and other arguments would enrich the content of the manuscript and the quality of the research. Some clarifications would be useful to avoid some contradictory interpretation of results

Response – We do not have a clear answer to this question as we did not design the experiment to explore wall moisture distribution, but instead to explore changes in wall moisture in response to the intervention. In our experience, the moisture content of walls in historic buildings is usually greater at the base than further up (unless there is a roofing, guttering or plumbing defect). At

Court House there may have been some water uptake at the base of the wall from the adjacent soil during wet weather, but because of the composite construction and lack of capillary pathways its ability to rise was limited. Alternatively, the moisture distribution in the wall may reflect moisture equilibrium with the room by a process of diffusion rather than capillary rise (which was shown to be not occurring).