

3123 Tottenham House Stables Ground Floor
Finishes Rev C 230126

**Approval of Details Application to partially
discharge Condition 20(Floors) of Listed
Building Consent (Ref:18/00195/LBC)**

The Existing consented floor buildup- an Assessment of the current position and the reasoning for modifications.

1 The Existing consented floor buildup is not suitable to receive the Historic Floor Finishes for technical reasons set out below- together with considered options and the considered solution.

2 The Original floor levels- uneven and laid with Falls- are not suitable for the new proposed use of the space and the original historic finishes do not suit the client's requirements for the use of the space- the viable compromise being to install the reinstated historical finish at a lower level with a removable overlay finish.

Why are the Limecrete slabs unsuitable?

The existing consented limecrete slabs are very thin at only 100mm thick. They are proven to crack through in numerous places due to shrinkage and stress cracking from corners and floor boxes. It is a feature of Natural Hydraulic Lime mortar-based slabs, (aka Limecrete), that site mixing and different curing temperatures will mean differing strengths within the same slab design. The slab strength cannot be reliably calculated without sample testing for each slab pour. These slabs are therefore unsuitable to receive the historic finishes, without risk of cracking through both the stones and the joints during service at the 2.5KN/m sq design loadings. This service loading is higher than the normal residential loading of 1.2-1.5 KN/m sq and reflects the client's requirement for ease of location of heavy furniture and access equipment for the high ceilings. The consented slabs are also unreinforced, and movement joints cannot be reliably positioned to prevent cracking.	See BLDA Sheet 240.13 for examples of cracking
---	---

The issue of selection of Limecrete for breatheability (or more precisely- vapour permeability) to protect the historic walls

We are aware that the proposed typical buildups within this application are not vapour permeable. We think that there is strong evidence that the use of limecrete will not necessarily prevent rising damp within the footings of the	See Attached Reports
---	-----------------------------

external walls and would draw attention to a study by Bath university questioning the breathability of limecrete compared to concrete.	See Attached 'Phillips et Al 2019'
We would also point to a further study by UCL showing how the installation of a DPM within a floor adjacent to a very old wall which did not increase rising damp within that wall over a period of three years.	See attached 'In-situ measurements of wall moisture in a historic building in response to the installation of an impermeable floor'
In the case of the external walls, the base of the solid wall is in direct contact with the ground- which together with water within the external ground, presents a greater risk of rising damp within the walls, than that created by the use of an impermeable floor buildup. There is no practical way to insert an effective damp proof course within these historic brick walls which are over 600mm thick, without extensive intervention.	See BLDA Drawing No 240.14 for illustration of this principle
We would also point out, that the typical proposed amended floor edge sections have a vapour permeable strip at the edges which will help to relieve any upwards vapour pressure against the inside face of the external walls within the floor buildup. This feature will provide some of the purported benefits of limecrete without the need for the whole floor slab to be vapour permeable.	See BLDA Drawing No 240.5

Consideration of the alternatives to Limecrete

The structural design performance loading for the floor is set at 2.5KN/m sq to facilitate the client's requirements for the use of the spaces and access loading for the high ceiling heights. This, together with the need to support stone finishes without cracking, means that the substrate supporting the finishes must be capable of being designed and engineered to support these loadings.	
---	--

The obvious alternative to Limecrete, that can be engineered to meet the design criteria, is a Reinforced Concrete (RC) slab, which in this case would be at least 150mm thick to achieve the design loadings. Given the depth needed for the historic finishes on top of the RC slab, (circa 160mm), and the depth of the consented Glapor foamed glass aggregate required to achieve the necessary thermal insulation under the floor, (min 350mm), a RC will mean a deeper excavation of the ground between the walls. The proposed Screed Replacement Tile has the advantage of being very strong, yet thin at 18mm and is ideally engineered to work with the consented Glapor foamed glass aggregate- and will reliably support the stone finishes in large areas without movement joints. It will also minimise extra excavation of the ground between the existing walls. There are numerous examples of the Screed Replacement Tile being used in this way in important historic buildings. (See Table below)	
--	--

Historic uneven floor laid to falls- the reasoning for an overlay solution in these areas

It can be seen from old photographs that the historic floors were laid to falls either to a gulley central to each stall, or to a longitudinal channel and drainage gulley.	See Adam Architecture Drawing 6150 / CE-119
Old survey levels indicate that these falls were in the region of 50-90mm, when related to the external door stone thresholds.	See BLDA Drawing 240.3
It is visible in several photographs that there is a step down onto the historic from the external stone threshold, which varies from 0 to 25mm.	See Adam Architecture Stables Existing Floor Finishes 20.02.2025

If it is accepted that in the new use of the space, that the old historic uneven floor can be reinstated to a flat level -then the lowest point of the old floor could be taken as a reference datum and the reinstated historic finish then can be reinstated at this new level. This then provides the opportunity to install a removeable overlay finish over the historic finish, (laid at this lower level), which is laid to be level with the external threshold stone.	See BLDA Drawing 240.3
The overlay is planned to be laid in such a way that it can be removed at a later date- with no damage to the historic finishes. It would be laid on an easily removed dry granular levelling layer on top of the historic finish below- which could then be brushed and vacuumed clean- leaving no residue.	See detail section on BLDA Drawing 240.3
The total overlay buildup has been designed to fit within the historic falls range of 50-90mm measured from the external door threshold level. This is achieved by the use of a layer of Screed Replacement Tile (SRT) as the basis for the overlay finishes layer.	BLDA Drawing 240.3/ 240.8 for typical floor build ups

How does the overlay floor interact with the retained historic features

Currently- the historic skirtings and fireplaces are removed and will be replaced at the existing historic levels.	
The existing External stone thresholds will be removed and replaced like for like and reinstated to the existing levels. (This has already been consented.)	See BLDA Drawing No 240.8

The overlay top level will be installed just below the inside edge of the stone threshold, Should the overlay be removed at a later date- there will be a nominal 90mm step down from the external threshold. We think that this is reasonable and have considered the alternatives as follows: • Place the historic finish at the original floor level with the overlay over this- this then means that the inward opening external doors would foul the overlay and would require the overlay to be cut back to allow the door to swing inward. This creates a very awkward trip hazard within the floor plan, when the overlay is in position and is not acceptable to the client and the use of the space. • Install the new replacement external stone door thresholds 90mm down to be level with the lower historic finish- then install another stone threshold on top of this, to the same section, so as to be level with the overlay. This means that in the event of reversion to the historic finish level- there is the disruption during removal of the threshold to the external wall fabric, adjustment of the external levels and reconstruction of the bottom section of the door to suit the revised threshold.	See Condition 17 approved package (Ref: 21/02202/DOC)
In the case of internal stone thresholds- there are two cases. Where the existing threshold forms a transition between a space with no overlay and one with overlay- the overlay will be laid to be level with or just below the existing historic threshold level. If the overlay is later removed there will be a nominal 90mm change in level between the threshold and the historic floor In the case of an overlay either side of the historic retained threshold- the threshold would remain installed level with the historic finishes. The overlay would be installed over the historic threshold with a new stone threshold replicating that below.	See BLDA Drawing No 240.9 See BLDA Drawing No 240.9
The stone skirtings- which are replacements to the historic profile- will be installed with the top edge at the historic level- they will made 90mm taller so that the bottom edge is at the revised historic floor level. The overlay will be laid up to the skirting.	See BLDA Drawing No 240.4
The Timber skirtings- which are replacements to the historic profile- will be installed with the top edge at the historic level. The bottom edge will be set such that the overlay tucks underneath it. In the event of the overlay being removed an extension piece of the same thickness will be fitted to the bottom edge and the whole refinished to blend in the horizontal joint.	See BLDA Drawing No 240.5/6

All fixings for the skirtings will be arranged to coincide with brick mortar joints to minimize damage to the historic brickwork.	
The fireplaces, which are mostly new replacements to replace the original ones which have been lost, will be installed such that the hearth stone is flush with the overlay floor finish. If the overlay floor is removed -then the hearth stone edge will be 90mm high in relation to the historic floor level beneath, and be thick enough to allow the historic floor to finish against the hearth stone vertical edge with no exposed bedding.	See BLDA Drawing No 240.7

Where has this Screed Replacement Tile substrate been used in a similar context?

The following are examples where this Screed Replacement Tile system has been used to provide the substrate to support replaced historic finishes in a listed building. A local example is that of GII* St Pauls Church in Chippenham Further examples are at : Church Of St Mary De Crypt, Gloucester, Grade I St Michaels and All Angels, Berwick, Grade I St Mildred's Church, Tenterden, Grade I St Edward's Church, Stow on the Wold – Grade 1	See BLDA Sheet No 240.10/12 See BLDA Sheet 240.11 See BLDA Sheet 240.12
---	--

Citation for published version:

Phillips, G, Briggs, K, McCaig, I & Ball, R 2019, Comparing the moisture permeability of limecrete and concrete floor slabs. in JI Álvarez, JM Fernández, Í Navarro, A Durán & R Sirera (eds), *5th Historic Mortars Conference* . RILEM, pp. 1267-1278, RILEM 5th Historic Mortars Conference, 2019, Pamplona, Spain, 19/06/19.
<<https://www.rilem.net/publication/publication/494>>

Publication date:
2019

Document Version
Peer reviewed version

[Link to publication](#)

The original publication is available at the publisher's web site.
The article is accepted for publication, it is copyrighted by RILEM, and readers must contact RILEM for permission to reprint or use the material in any form.

University of Bath

Alternative formats

If you require this document in an alternative format, please contact:
openaccess@bath.ac.uk

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

Take down policy

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Comparing the moisture permeability of limecrete and concrete floor slabs

Grace A. Phillips¹, Kevin Briggs², Iain McCaig³, Richard J. Ball⁴

(1) University of Bath, gap37@bath.ac.uk, ORCID ID : 0000-0001-5858-6508

(2) University of Bath, ab2kb@bath.ac.uk, ORCID ID: 0000-0003-1738-9692

(3) Historic England, iain.mccaig@historicengland.org.uk

(4) University of Bath, easrjb@bath.ac.uk, ORCID ID : 0000-0002-7413-3944

Abstract

Retrofitting impermeable ground-bearing floor slabs to an old building is thought to ‘drive’ soil moisture up adjoining walls. Historic England has commissioned the University of Bath to conduct research into water vapour and liquid permeation through typical floor slab materials, and their influence on local soil moisture. The project comprises computer modelling to examine the response of soil moisture to slab installation, laboratory tests to analyse moisture movement rates through slab materials, and field monitoring to measure the effect of different slab materials *in situ*. Initial laboratory tests on two materials, concrete and NHL5-based limecrete, used a bespoke modular soil-slab-air apparatus developed to establish evaporation rates through slab materials. Subsequent material characterisation tests were conducted to compare their microstructural properties and moisture transfer characteristics including mercury intrusion porosimetry (MIP), sorptivity tests, and scanning electron microscopy (SEM). Preliminary results showed the NHL5-based limecrete slab was only marginally more permeable than the concrete slab, suggesting that a NHL5-based limecrete slab might be more effective than a concrete slab in reducing water rise in a wall. Further testing of limecrete mixes and *in situ* monitoring is proposed to verify these results.

Introduction

Moisture is a major cause of deterioration of historic building fabric. It drives many deleterious processes including biological growth, the actions of soluble salts, chemical attack and freeze-thaw damage (Cultrone et al. 2007; Feilden 2003a). Therefore, understanding moisture movement and the factors affecting it are important considerations in building conservation. The sketch in Figure 1 shows the main sources and pathways of moisture in and around a building of traditional construction. Internal sources, such as condensation and leaks, can be controlled by regular maintenance, adequate heating, and ventilation (Feilden 2003b). External water sources including precipitation and wind driven rain can be controlled by creating a water shedding building envelope. But a more discreet and equally important

external water source is soil moisture. Although soil moisture levels are influenced by the hydrological characteristics of the site, defective drains and inadequate surface water disposal arrangements often prove to be significant sources. In modern buildings damp proof courses (DPCs) are used to control the capillary rise of moisture in walls, but historic buildings rely on the ability of permeable building fabric to absorb and readily allow evaporation of moisture (Douglas 1998). Therefore, any alterations that might affect the 'hygic balance' (water in = water out) of the building, such as the introduction of a concrete ground-bearing floor slab, require careful consideration.

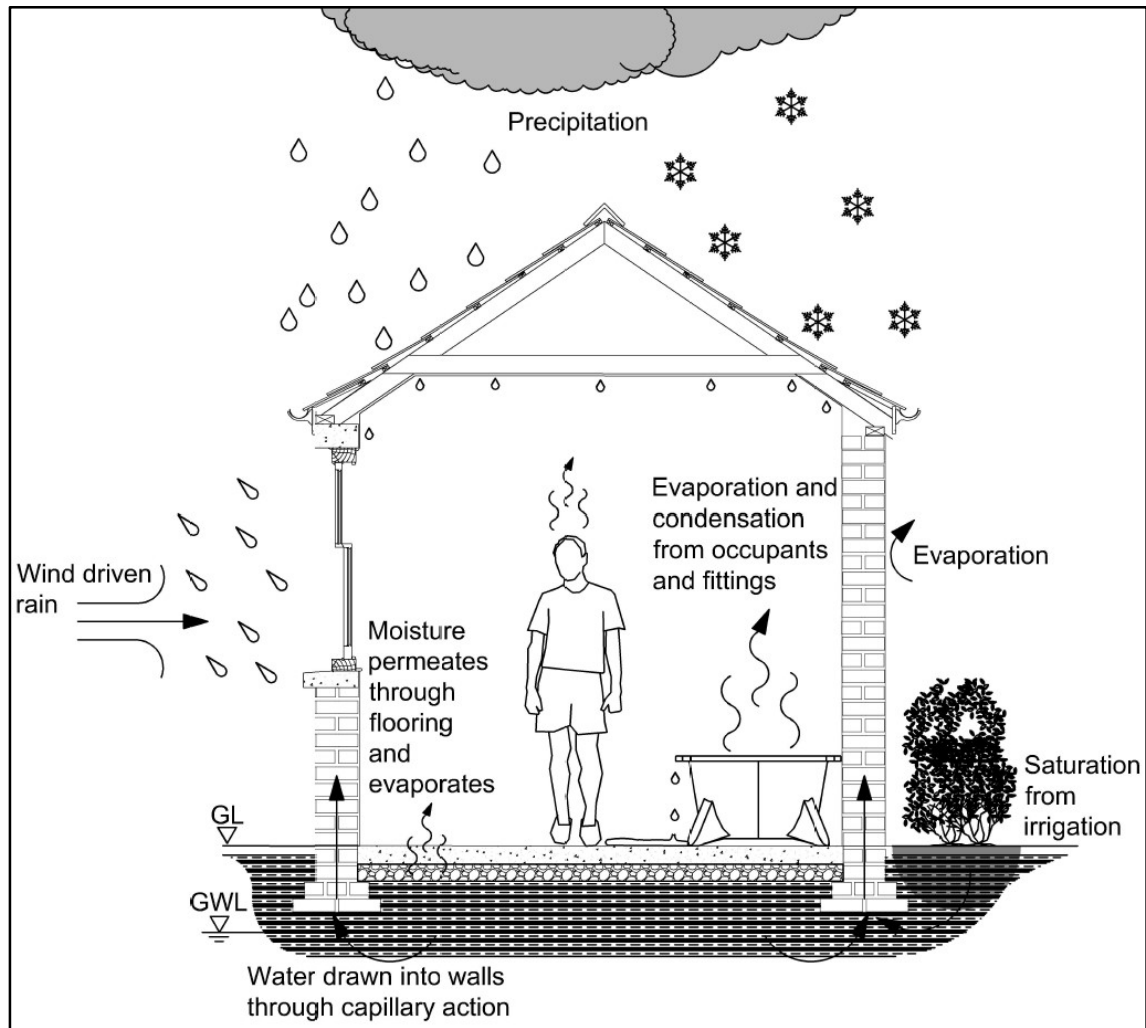


Figure 1 Moisture movement in and around buildings.

Research is being carried out at the University of Bath in collaboration with Historic England to understand the influence of floor slab material (concrete or limecrete) on soil moisture and dampness within the walls of historic buildings. Firstly, modelling was used to explore how the permeability of floor slab materials influenced local ground water flow in the liquid and vapour phases. Secondly, a suite of laboratory tests were carried out to determine the material properties of concrete and limecrete slabs and measure their comparative moisture permeation rates. Lastly, long term field measurements have been taken at two properties to

investigate the *in situ* response of both soil and wall moisture levels to changes in floor materials (Briggs 2017). These measurements are ongoing. This paper focuses on the initial findings from the laboratory element of the project, outlining the experiments and comparing concrete and limecrete slabs with respect to their moisture transport properties. The laboratory tests included a modular soil-slab-air experiment and a range of material characterisation tests. The modular soil-slab-air experiment was developed for the project and was run for a period of at least four weeks per slab in order to measure moisture transfer rates. Subsequent characterisation tests were carried out in order to correlate the slab properties with the observed water movement. These tests included imaging using a scanning electron microscope (SEM), mercury intrusion porosimetry (MIP), sorptivity testing, and mechanical characterisation by compression testing.

Materials

Two materials have been tested in the modular system; concrete and limecrete. The limecrete slab was manufactured using the highest strength classification of commercially available natural hydraulic lime (NHL5). The slab mix designs are shown in Table 1.

Table 1 Material designs for concrete and limecrete slabs tested

	Limecrete	Concrete
Components	NHL (Roundtower NHL5) 6mm to dust aggregate Gravel	Cement 6mm to dust aggregate Gravel
Coarse:fine ratio	0.54	0.4
Binder:aggregate ratio	0.33	0.2
Water ratio	0.50	0.625
Binder:fine aggregate:coarse aggregate ratio	1.00 : 1.95 : 1.05	1.00 : 3.57 : 1.43

The concrete and limecrete were cast as circular slabs, as shown in Figure 2, to fit the modular set-up. Two bolts were cast into the slab to facilitate installation and removal. The concrete and limecrete slabs were of thickness 84mm and 86mm $\pm$ 2mm respectively. They were cast to fit the apparatus, which had an internal diameter of 355mm $\pm$ 1mm with a gap around the perimeter of approximately 10mm. Slabs were installed within 2-4 weeks of casting and had not completely cured.



Figure 2 Cast concrete slab prior to use in the modular slab experiment.

Experimental Set-up and Procedure

Modular Slab Experiment

The set-up for the modular slab experiment is shown in Figure 3. A galvanised steel cylinder was filled with 50mm of gravel, then 80mm of clay soil. The clay was saturated with water. Water evaporating from within the cylinder was replaced by water supplied at a constant pressure head through the use of a Mariotte bottle. The Mariotte bottle was set on scales to log the change in mass with time. A Tinytag temperature and relative humidity (RH) probe was installed at the top of the cylinder to monitor the environment at the surface. The experiment was run for a minimum of four weeks with no soil to determine the free water conditions and then with a bare soil layer for four weeks, as shown in Figure 4, to establish the evaporation rate for a bare soil condition.

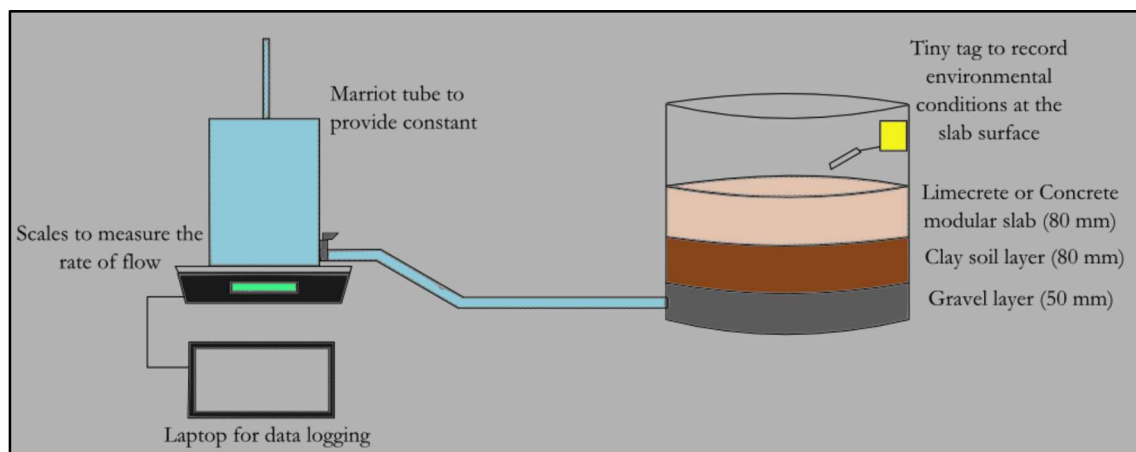


Figure 3 A diagram of the modular soil-slab-air experiment set-up.



Figure 4 Initial saturation of the bare soil surface.

The cast slabs were inserted into the cylinder directly onto the clay soil surface and sealed with silicon rubber around their perimeter. This setup excluded additional elements such as damp proof membranes (DPMs) and so does not directly replicate typical floor systems. However this enables a direct comparison of slab materials to be made without inhibiting moisture transfer to the underside of the slab. Each stage of the test was monitored for a duration of at least four weeks. The limecrete was monitored for the first 12 weeks followed by bare soil for 4 weeks and then the concrete slab for 9 weeks. Following extraction from the apparatus both slabs underwent further analysis.

SEM Imaging

Scanning electron microscopy (SEM) imaging was carried out using a JEOL SEM6480LV to reveal the microstructure and nature of the porosity. The SEM scans a focused beam of electrons on the surface which interact with the sample producing secondary electrons which are detected and the resulting signal used to produce an image. Fracture surfaces from slab samples were coated in gold prior to imaging to prevent surface charging, enabling clearer images to be taken and at higher levels of magnification. Images were taken at x100, x500, x1k, x2k, x4k, x5k, and x10k magnification.

Mercury Intrusion Porosimetry (MIP)

MIP tests provided a quantitative measure of the size distribution of the internal pores. The Pascal 140 and Pascal 440 from Thermo Scientific were both used to carry out the test. The sample is first inserted into the low pressure Pascal 140 which pressurises the mercury, forcing it into the accessible pores. As the pressure increases, the mercury enters into smaller pores. The Pascal 140 increases the pressure up to 400kPa and once the test is completed in the Pascal 140 the sample is transferred to the high pressure Pascal 440. The Pascal 440 increases the pressure up to 400MPa. The results from the 140 and 440 are then combined

providing data over the entire pressure range. Plotting the pore diameter against intruded pore volume is a tool for establishing the critical length of a material. The critical length, 'R_c', is the pore diameter that corresponds to the sample's breakthrough pressure. It is considered the largest particle size that can percolate through a sample.

Compression Tests

Compression tests, carried out to BS 1015-11, elucidated the mechanical properties of the slab material. Blocks of approximate size 40mm x 40mm x 40mm (±4mm) were cut from the slab following testing and the exact measurements to the nearest mm recorded. Six samples cut from each slab were tested to failure using either the 50kN Instron 3369 or the 2000kN Autamax 5 concrete compression equipment and the peak load was recorded. The peak load and applied area were then used to calculate the ultimate compressive strength of the sample. This characteristic is important as slabs require a minimum compressive strength to be suitable for use as a floor slab (NHCB 2018).

Sorptivity Tests

Sorptivity tests enabled the material's capacity to absorb water to be ascertained. This property is important as the absorption provides a supply of water to be transferred and evaporated. The tests were carried out to BS 1015-18. Samples were cut to 40mm x 40mm (±4mm) x approximately 80mm. The samples were dried in a 50°C oven until constant mass was achieved. Samples were then placed within a tray of water on supports such that the sample was immersed in approximately 10mm of water. Samples were weighed and the water height on the sample surface was measured at 10, 40, 90, 160, and 250 minutes.

Results

Water Transfer Rates

The change in mass of the mariotte bottle was recorded at one minute intervals, allowing the water (vapour) transfer rate through the slabs to be easily calculated in gmin⁻¹ or gday⁻¹. The water transfer rate represents the actual evaporation rate from the slab or soil surface, which is less than the potential evaporation rate from a free water surface (Penman 1948). The rate can be converted to ms⁻¹ using equation 1,

$$E(\text{ms}^{-1}) = \frac{E(\text{gday}^{-1})}{86400 \times 10^3 \times \rho \times A} \quad \text{Equation 1}$$

where 'E' is the water transfer rate, 'ρ' is water density for the average air temperature, and 'A' is the area of the slab at 0.088 m². The resulting rates are in Table 2.

Table 2 Actual evaporation rates for each testing configuration

Surface	Average E (gmin ⁻¹)	Average E (gday ⁻¹)	Average Temp. (°C)	ρ (kg/m ³)	Average E (ms ⁻¹)
Free water (gravel)	0.1708	246.0	18.1	998.6	32.39 x10 ⁻⁹
Bare clay surface	0.0754	108.6	19.4	998.3	14.31 x10 ⁻⁹

Limecrete (NHL5) slab	0.0063	9.018	20.1	998.2	1.188×10^{-9}
Concrete slab	0.0041	5.966	20.9	998.0	0.786×10^{-9}

The gravel surface had the greatest water transfer rate and had more than double the water transfer rate of the bare clay surface; this is because the clay restricted the supply of water to the surface for evaporation. The addition of a slab further restricted the supply. The limecrete slab was only marginally less restrictive than the concrete slab. For the limecrete and concrete slabs water transfer rates were smaller than the bare clay soil by 12 and 18 times respectively.

SEM Imaging

The x10k SEM images of the limecrete and concrete are presented in Figure 5 and 6 respectively. Calcium Silicate Hydrate (C-S-H) can be seen in both samples with a greater number of larger needle-like structures in the NHL5 limecrete sample.

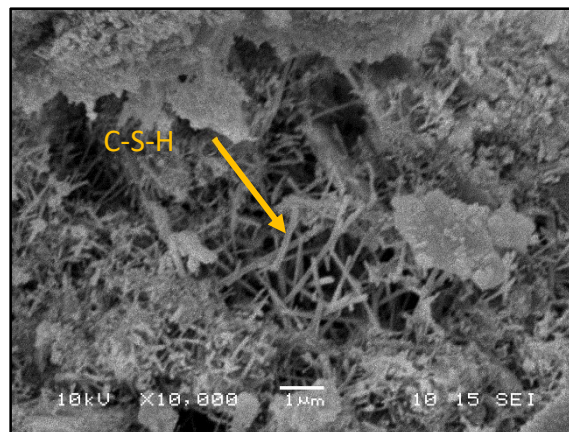


Figure 5 SEM image of the NHL5 limecrete sample showing signs of formed calcium silicate hydrate (C-S-H).

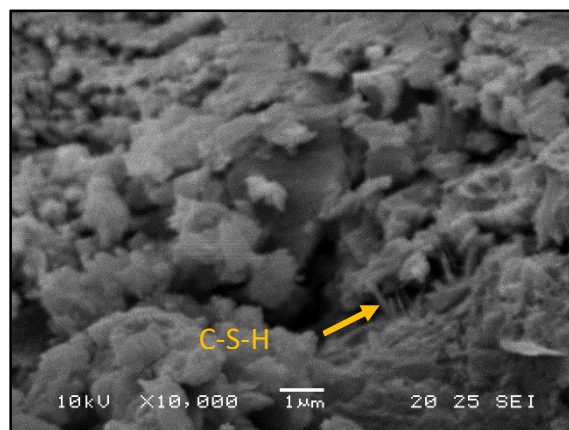


Figure 6 SEM image of the concrete sample showing signs of formed C-S-H.

Mercury Intrusion Porosimetry (MIP)

MIP results are provided in Table 3 and Figure 7. The critical length ' R_c ' for both materials lie within the capillary region; for limecrete it was circa 50nm and the concrete had a bimodal distribution with two peaks at around 75nm and 300nm. For concrete the largest pore diameter of 300nm is the critical length and represents the largest size particle that can percolate through the sample. Through comparing the limecrete and concrete plots in Figure 7 it can be seen that the limecrete had a greater pore volume, as is confirmed by the total pore volume values given in Table 3.

Table 3 MIP results for limecrete and concrete

Case	Bulk Density (g/cm ³)	Total Pore Volume (cm ³ /g)	Total Pore Area (m ² /g)	Porosity by Hg Intrusion (%)	Average Pore Diameter (nm)
Limecrete	2.1319	0.0915	10.236	19.51	35.75
Concrete	2.2096	0.0665	6.716	14.68	39.58

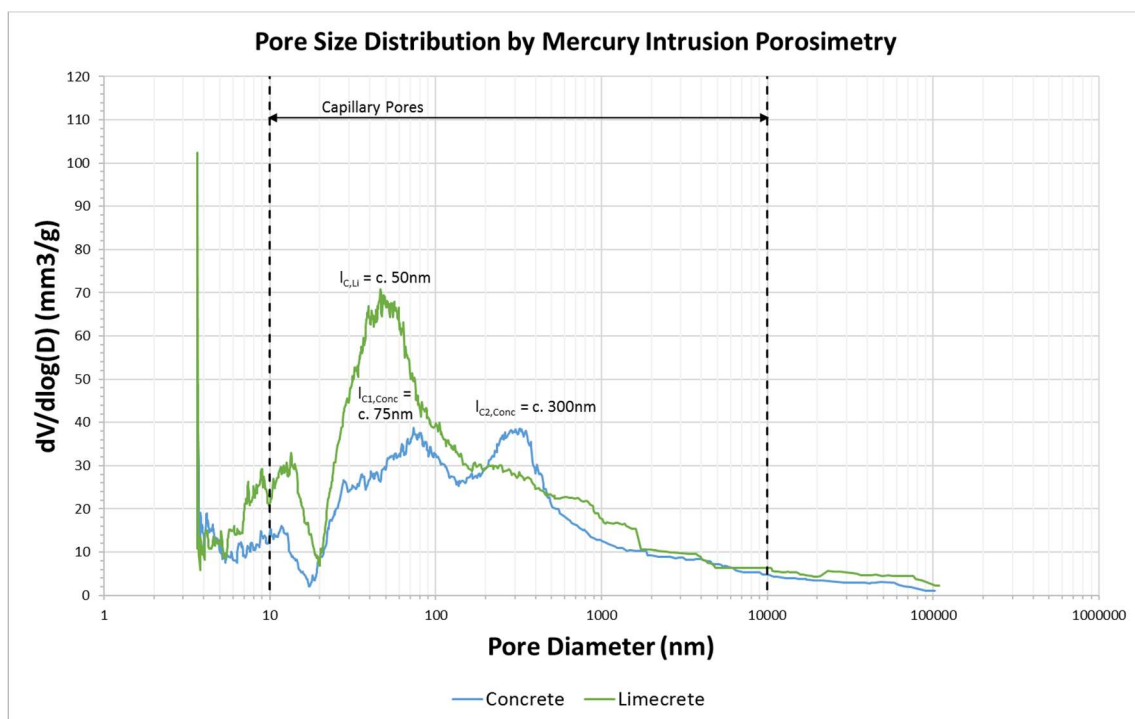


Figure 7 Plot of pore volume measured by MIP, with pore diameter for the limecrete and concrete samples.

Compressive Strength

The results for the compressive tests are given in Table 4. The Limecrete had an average compressive strength of 14.56MPa. The concrete samples exhibited a greater compressive strength of 25.18MPa, however the concrete samples were less consistent, as demonstrated by the larger standard deviation. Any samples that exceeded the 50kN load capacity of the Instron 3369 were tested using the Autamax 5.

Table 4 Compressive strengths for limecrete and concrete samples

Material	Sample	Instrument Capacity	Ultimate Compressive Strength σ_{ULT} (MPa)	Mean Compressive Strength (MPa)	Standard Deviation (MPa)
Limecrete	L1	50kN	15.22	14.56	1.15
	L2a	50kN	13.13		
	L3	50kN	15.51		
	L4	50kN	15.04		
	L5	50kN	12.80		
	L6	50kN	15.69		
Concrete	C1a	2000kN	24.02	25.18	4.90
	C2	2000kN	21.05		
	C3	2000kN	21.86		
	C4	50kN	20.32		
	C5	50kN	31.99		
	C6	50kN	31.85		

Sorptivity

The coefficient of water absorption was calculated for each sample using the equation

$$C = 0.1 \frac{m_{90} - m_{10}}{A\sqrt{t}} \quad \text{Equation 2}$$

where 'C' is the coefficient of water absorption in $\text{kgm}^{-2}\text{min}^{0.5}$, ' m_{90} ' is the sample mass at 90 minutes in kg, ' m_{10} ' is the sample mass at 10 minutes in kg, 'A' is the cross-sectional area in m^2 , and 't' is the time in minutes. Table 5 shows the sorptivity results for two samples of concrete and one sample of limecrete.

Table 5 Sorptivity coefficients for limecrete and concrete

Sample	Material	Mass at 10s, m_{10} (g)	Mass at 90s, m_{90} (g)	Coefficient of water absorption ($\text{kgm}^{-2}\text{min}^{0.5}$)
L3	Limecrete	290.51	294.06	0.023
C2	Concrete	269.60	271.36	0.013
C3	Concrete	299.38	300.93	0.010

Discussion

Water Transfer Rate

Models of ground and wall moisture flow have been developed at the University of Bath. These suggest that the floor slab material will affect the supply of water to the wall base and hence the water available for transfer through the wall. The initial laboratory results showed that the clay had an influence on the rate of water transfer and evaporation and that the presence of a slab further impeded water transfer. The two slab materials tested to date,

NHL5-based limecrete and concrete, exhibited similar water transfer rates with limecrete being marginally more effective at moisture transfer. Further testing including alternative slab compositions and capillary breaks is proposed to ascertain whether the modular slab experiment supports the findings from the model. The authors are also undertaking *in situ* long term monitoring of full scale trials at two historic properties to assess what impact slabs have on wall and soil moisture.

SEM Imaging

The needle-like structures shown in Figure 5 and 6 are calcium-silicate-hydrate (C-S-H) formed from hydrated silicates in both the NHL and cement. In NHLs they grow during the initial hydration phase of hardening, enhancing the material's strength. The morphology of the C-S-H structures in the concrete sample are more consolidated compared to that in the NHL resulting in a denser structure. This is demonstrated by the smaller number of voids visible in Figure 6 than in Figure 5 and the higher bulk density and lower pore volume values for concrete in Table 3.

Mercury Intrusion Porosimetry (MIP)

The bulk density and pore volume values for the concrete showed that it is more dense than the limecrete. Whilst the concrete had a larger critical length and a greater average pore diameter, the limecrete had a greater pore volume, most of which lies within the capillary region. It is this accessible interconnected pore structure that contributes to greater water transfer rates through the limecrete.

Compressive Strength

The compressive strength for the concrete was almost double that of the limecrete. The minimum compressive strength of the limecrete was 12.80MPa which is adequate for classification as a GEN 1 concrete. GEN 1 concrete typically has a compressive strength of 10MPa and the NHBC class this as suitable for use in unreinforced house floors with permanent finishes (Mister Concrete n.d.; EasyMix Concrete UK Ltd n.d.; NHCB 2018). Floor slab compressive strength is only one indication of appropriateness for use and further testing is required before slab mixes are adopted. For example durability testing is required to assess the slab resistance to abrasion, freeze-thaw, and chemical and salt attack.

Sorptivity

The sorptivity of the limecrete was approximately double the concrete's sorptivity. This suggests that the limecrete uptakes water quicker than the concrete, providing more water supply for evaporation at the surface, enabling higher water transfer rates. Further sorptivity testing is proposed to validate these results and compare these slab materials with those used in future tests.

Conclusions

The water transfer rates derived from the bespoke modular soil-slab-air apparatus showed that soil restricts the water supply to the surface for evaporation, and the addition of a slab

restricts the supply further. The water transfer rate of the sample slabs was affected by the sorptivity of the material and the presence of an interconnected pore structure. The NHL5 limecrete slab was found to have a greater sorptivity and pore volume than the concrete slab, and hence it had a greater water transfer rate when tested in the soil-slab-air apparatus. Preliminary results obtained from modelling and laboratory tests suggest that NHL5-based limecrete was marginally more effective than a concrete slab in transferring moisture. However, this has yet to be verified with further testing of different slab compositions, by the long-term monitoring of *in situ* installations, and through representative slab tests including typical construction details such as capillary breaks. Following the successful demonstration of the apparatus detailed in this article, further floor slab systems will be tested to provide a representative range of moisture transport characteristics. Additional studies will explore construction variations such as the inclusion of cracks and construction joints.

Acknowledgements

This study was supported by Historic England and the EPSRC Centre for Decarbonisation of the Built Environment (dCarb) [grant number EB-AR1218]. The authors wish to extend their thanks to David Muddle and David Surgenor for their assistance in the project.

References

- Briggs, K., 2017. Do some floor slab retrofit solutions increase wall damp in historic buildings? Cultrone, G., Sebastián, E., and Huertas, M.O., 2007. Durability of masonry systems: A laboratory study. *Construction and Building Materials*, 21(1), pp.40–51.
- Douglas, J., 1998. The development of ground floor constructions : part IV (damp proofing methods). *Structural Survey*, 16(2), pp.76–80.
- EasyMix Concrete UK Ltd, *Types Of Concrete And Their Strengths - EasyMix Concrete UK Ltd* [Online]. Available from: <https://www.easymixconcrete.com/news/types-of-concrete-and-their-strengths/> [Accessed 18 April 2018].
- Feilden, B.M. (Bernard M., 2003a. Botanical, biological and microbiological causes of decay. In: *Conservation of Historic Buildings*. Abingdon: Architectural Press, pp.133–138.
- Feilden, B.M. (Bernard M., 2003b. Internal environment of historic buildings. In: *Conservation of Historic Buildings*. Abingdon: Architectural Press, pp.173–185.
- Mister Concrete, *Concrete types and their strengths | Mister Concrete* [Online]. Available from: <http://www.misterconcrete.co.uk/concrete-types-and-their-strengths> [Accessed 18 April 2018].
- NHCB, 2018. Concrete and its reinforcement. In: *NHBC Standards 2018*. pp.11–22. Available from: <http://www.nhbc.co.uk/Builders/ProductsandServices/Standardsplus2018/#14> [Accessed 18 April 2018].
- Penman, H.L., 1948. Natural evaporation from open water, bare soil and grass. [Online]. *Proceedings of the Royal Society of London. Series A, Mathematical and physical sciences*,

193(1032), pp.120–45. Available from:
<http://www.ncbi.nlm.nih.gov/pubmed/18865817> [Accessed 19 April 2018].

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

[Kevin Briggs](#) ^{1,*}, [Richard Ball](#) ¹, [Iain McCaig](#) ²

[Author information](#) [Article notes](#) [Copyright and License information](#)

PMCID: PMC10171423 PMID: [37228456](#)

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 3-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

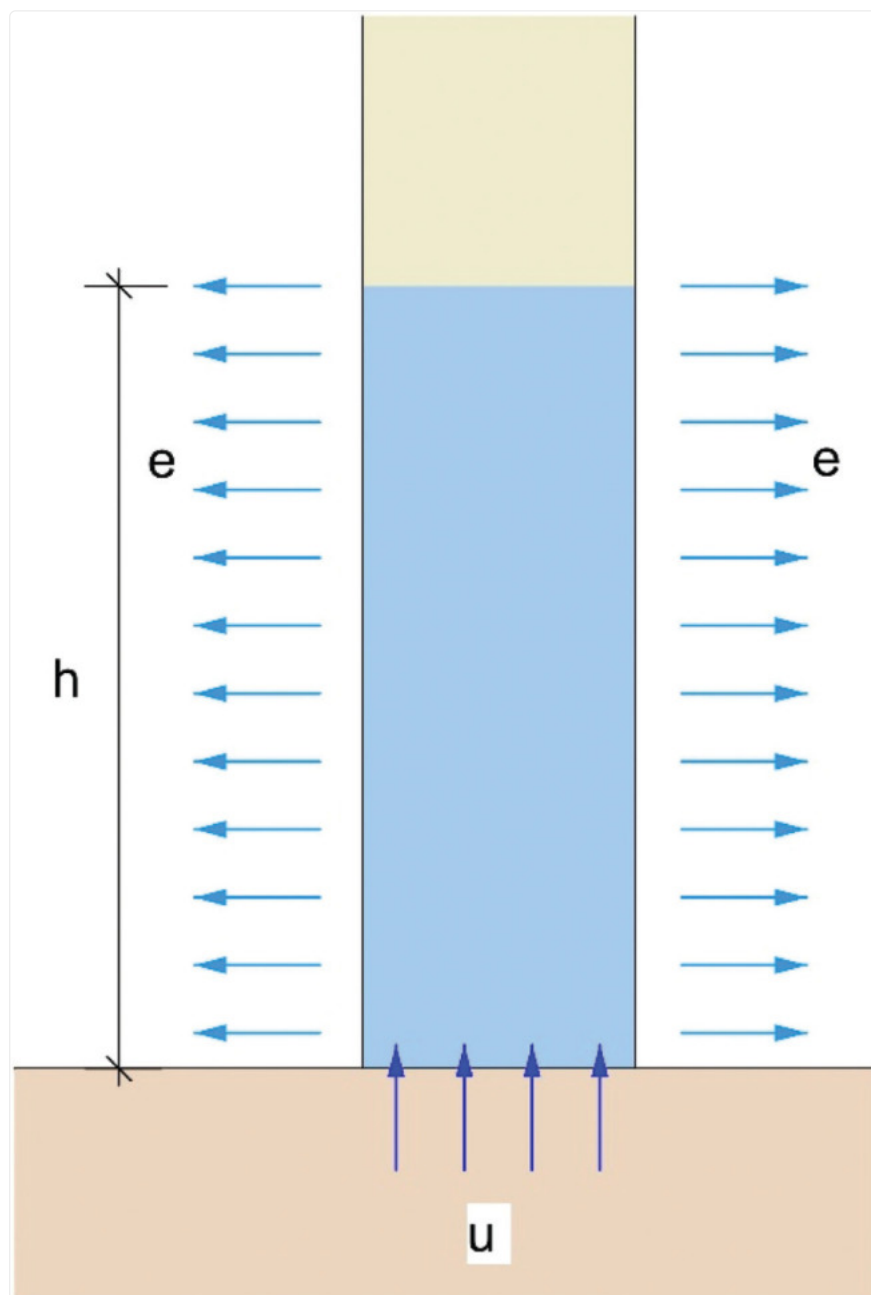
Water movement through the masonry walls of historic buildings is an important process influencing thermal performance, wall deterioration (e.g., salt weathering), decay of built-in timbers, and damage to the internal finishes and environment (e.g., mould) [1]. Therefore, understanding moisture regimes within historic structures is critical to heritage conservation and the appropriate selection of materials for repair or renovation [2].

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 a 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 [3,4], 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 [2,5,6]. 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 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 and Hoff [Z] developed a quantitative representation of the primary processes controlling moisture migration and wall damp rise in a masonry wall (Fig. 1). 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).

Figure 1.



[Open in a new tab](#)

A conceptual model of wall damp rise by Hall and Hoff [Z], with soil moisture uptake (u) and wall evaporation (e) driving the saturated wall height (h), in a wall thickness (b).

The Hall and Hoff [Z] 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 a historic building.

Aim and 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 3-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 ([Fig. 2](#)). Court House is a Grade II listed building originating from the 16th or 17th Century [8]. 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 ([Fig. 3](#)).

Figure 2.



[Open in a new tab](#)

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 3.

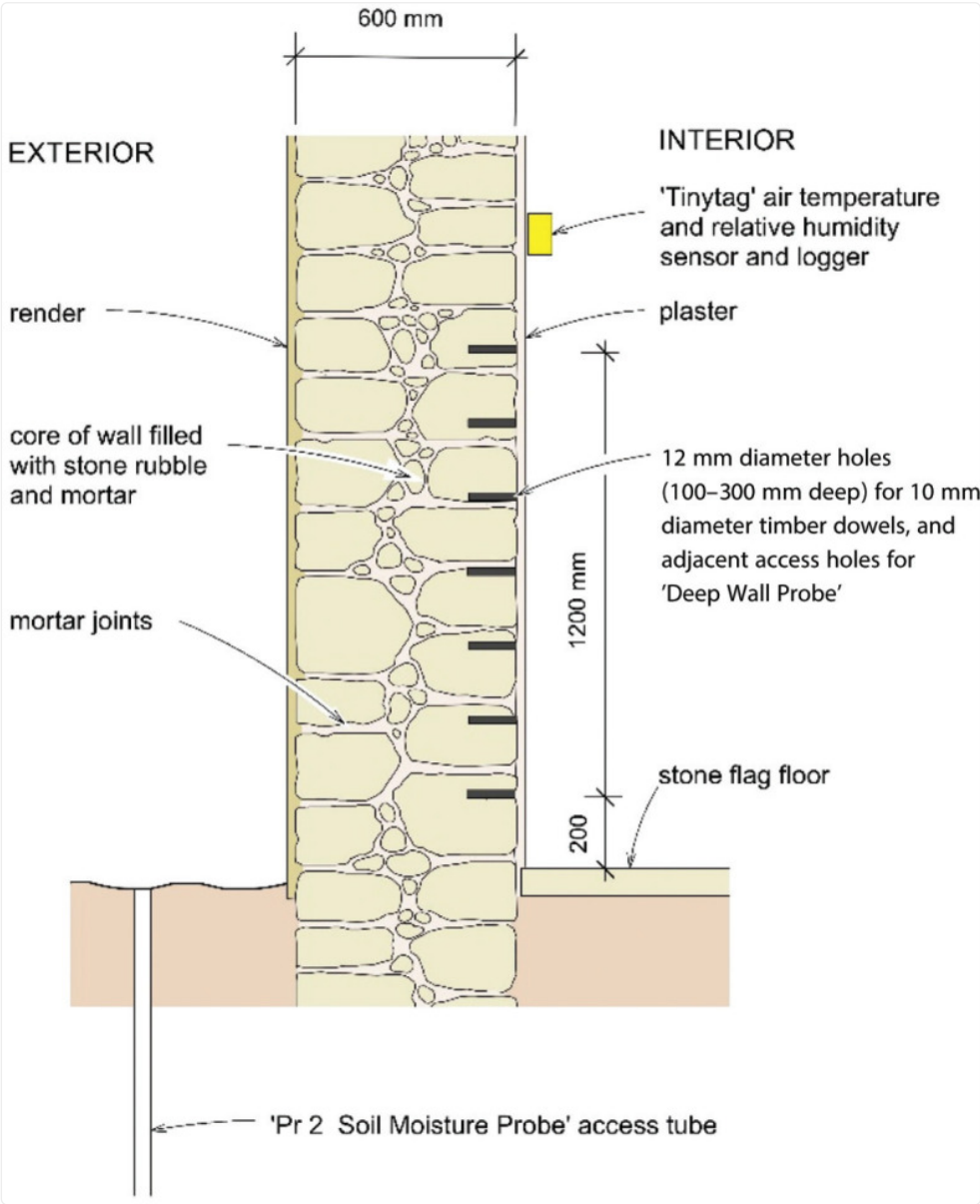


[Open in a new tab](#)

The external face of the pantry wall at Court House.

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 ([Fig.4](#)), in accordance with the conceptual model ([Fig.1](#)). Details of the electronic sensors are shown in [Table 1](#).

Figure 4.



[Open in a new tab](#)

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.

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 ($^{\circ}\text{C}$), humidity (%), rainfall (mm/tip), wind speed (ms^{-1}), wind direction ($^{\circ}$)	Court House (external)	Delta-T Devices, Ltd, Cambridge, UK
Tinytag Plus 2	Internal air temperature ($^{\circ}\text{C}$) and relative humidity (%)	Internal wall at Court House	Gemini Data Loggers, Chichester, UK

Type of instrument	Measurement	Location	Source/references
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

[Open in a new tab](#)

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 (Fig. 3). 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 [9], overlain by organic topsoil. A geological map showed that Court House is located on an outcrop of sandstone from the Mercia Mudstone Group [10] 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, 0.15 mm 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 [11] was installed to measure hourly changes in solar radiation (kWm^{-2}), air temperature ($^{\circ}\text{C}$), humidity (%), rainfall (mm/tip), wind speed (ms^{-1}) and wind direction ($^{\circ}$). A Tinytag Plus 2 datalogger [12] was installed at the top of the internal wall face to measure hourly changes in air temperature ($^{\circ}\text{C}$) and relative humidity (%) directly adjacent to the wall surface.

Soil moisture was measured using a PR2 Soil Moisture Probe [13,14], inserted into a 1 m 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 100 mm radius surrounding the probe. These were logged and converted to volumetric moisture content (θ , %) using a linear relationship for mineral soils:

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

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 ([Fig. 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 [[15](#)]. 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 (°C) and relative humidity (%). The potential evaporation was assumed to be equal to the potential evapotranspiration (*PET*) calculated using the simple equation by Schendel [[16](#)] and appraised for climate modelling by Bormann [[17](#)]:

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

where *PET* is the potential evapotranspiration (mm/day), *T* is the mean daily temperature (°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 SMD is the volume of water per unit area (mm³mm⁻²) that the soil can absorb before reaching field capacity, where the moisture content is in equilibrium and free to drain under gravity [[18](#)]. 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 SMD (*SMD_m*) was derived from the PR2 Profile Probe measurements of volumetric moisture content (*θ*) using the approach described by Smethurst et al. [[19](#)]. The

total SMD_m of the soil profile (0–1 m below ground level) was calculated using

$$SMD_m = \sum_i^n h_i (\theta_{FC} - \theta_i) \quad (3)$$

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 [20] and historic stone walls [21]. Timber dowels absorb moisture over 2 or 3 weeks until they achieve equilibrium with the surrounding wall [22]. Prior to installation, the timber dowels were oven dried at 105 °C for at least 24 h 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:

$$w_m(\%) = \frac{(m_w - m_d)}{m_d} \times 100\% \quad (4)$$

It was possible to calculate the wall moisture changes using the potential evaporative drying measurements, for comparison with the timber dowels measurements. Hall and Hoff [7] derived a conceptual model for rising damp moisture movement within a porous masonry wall without finishes (Fig. 1). 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 and Hoff [7] showed that the steady-state height of water rise (h_{ss}) within a porous wall can be calculated using:

$$h_{ss} = S \left(\frac{b}{2e\theta_w} \right)^{1/2} \quad (5)$$

where S is the sorptivity of the masonry ($\text{mm} \cdot \text{min}^{-1/2}$), e is the evaporation rate ($\text{mm} \cdot \text{min}^{-1}$), θ_w is the moisture content of the wetted part of the wall ($\text{mm}^3 \cdot \text{mm}^{-3}$) 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 ($\text{mm} \cdot \text{min}^{-1}$) 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 $\text{mm} \cdot \text{min}^{-1/2}$ and 0.2, respectively, as used by Hall and Hoff [7].

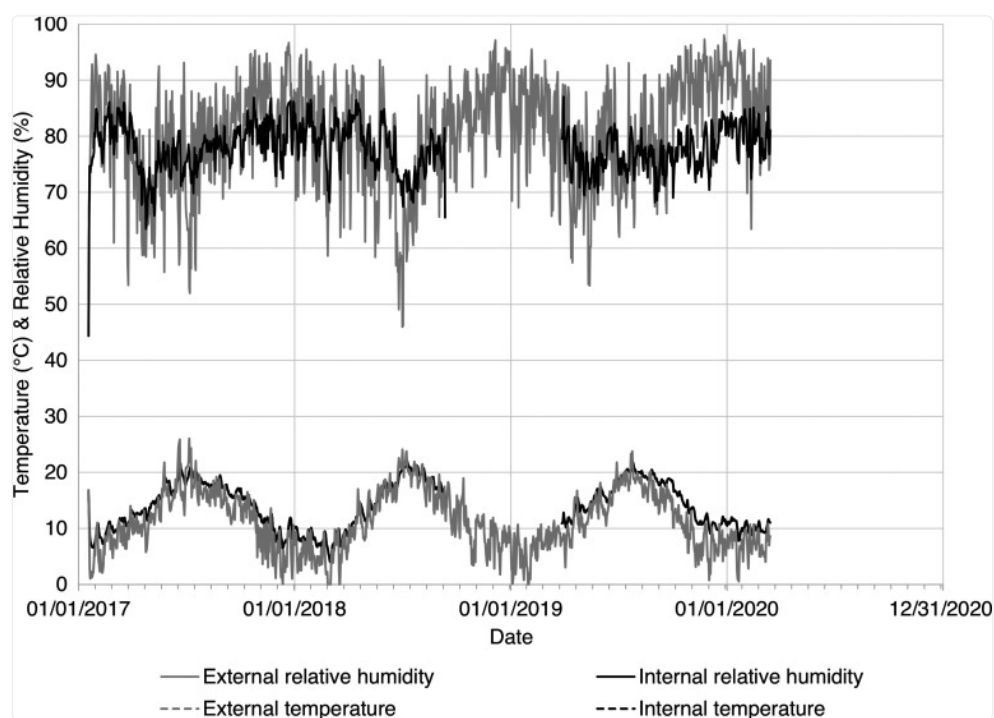
Results

Evaporative drying

The internal and external temperature (°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 [23,24]. 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 (Fig. 6). The calculated cumulative potential evapotranspiration was higher than comparative measurements in southern England [25,26], 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 (Fig. 1) 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 and 2019).

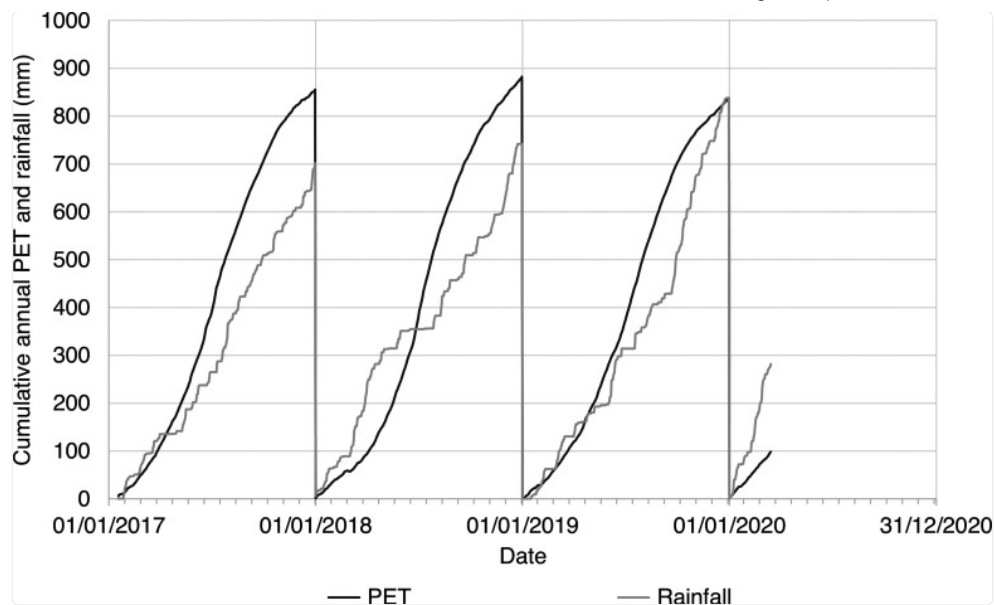
Figure 5.



[Open in a new tab](#)

Daily average temperature (°C) and relative humidity (%) measured internally (Tinytag logger data) and externally (weather station data) at Court House between 2017 and 2020. Note that internal Tinytag data are missing from September 2018 to March 2019 due to instrument damage.

Figure 6.



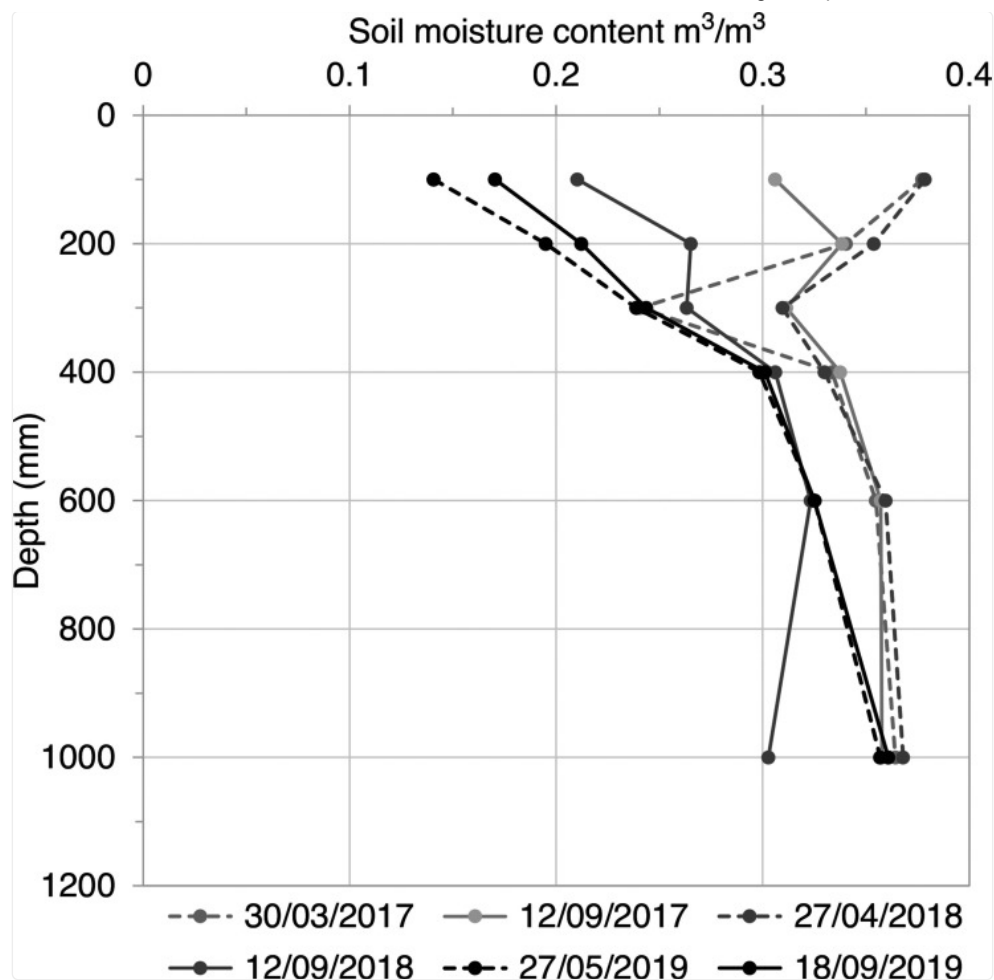
[Open in a new tab](#)

Cumulative annual evapotranspiration (ET₀, mm) and rainfall (mm) measured by the weather station at Court House. Note that the measurements start on 18/01/2017.

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 0.4 m below ground level, as is typical in clay soils with grass vegetation at equivalent latitude [18]. [Figure 7](#) shows that the soil moisture content was often below field capacity ($\theta_{FC} = 38\%$) 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 ([Fig. 1](#)).

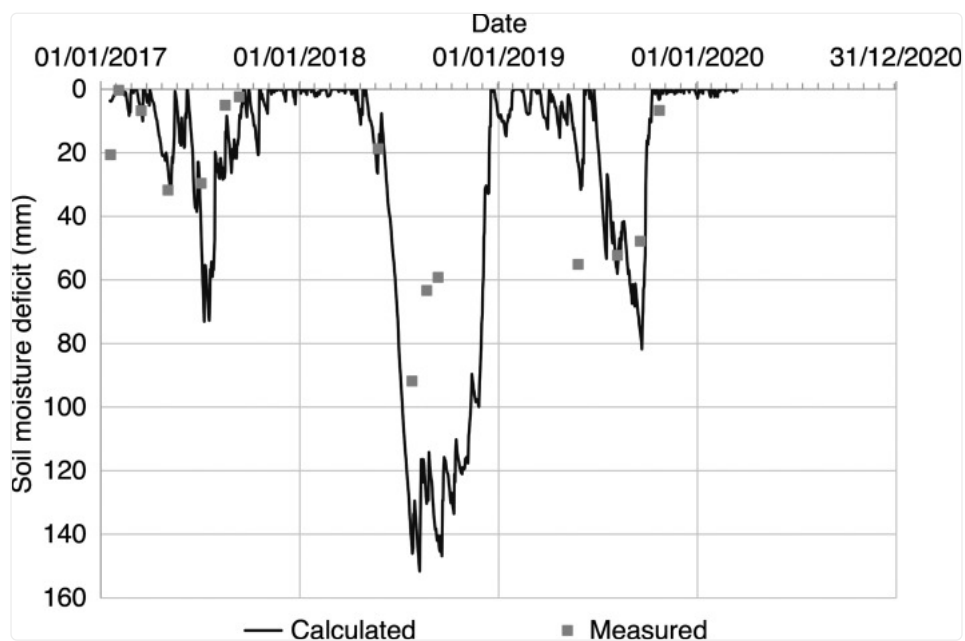
Figure 7.



[Open in a new tab](#)

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

Figure 8.



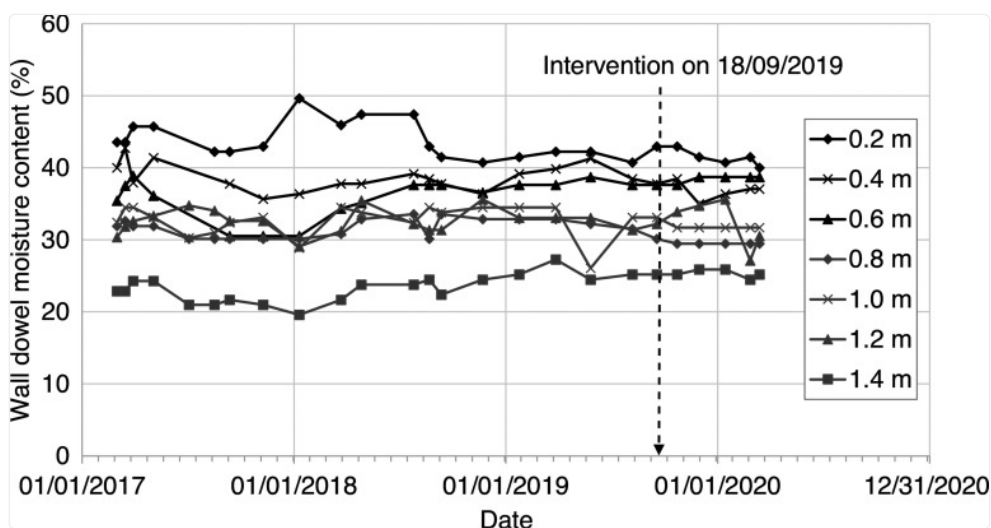
[Open in a new tab](#)

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

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 [Fig. 4](#)) showed that moisture levels rapidly increased beneath the vapour-proof barrier within 2 days of installation in September 2019, showing ground moisture transfer through the floor and into the internal environment of the room.

Figure 9.

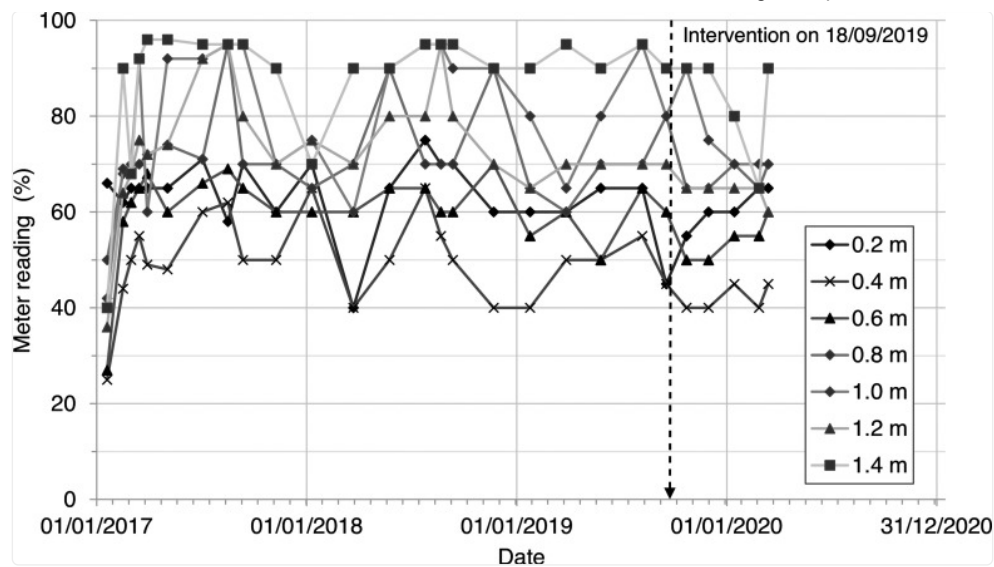


[Open in a new tab](#)

Measurements of timber dowel moisture content (by mass) between 0.2 m and 1.4 m above ground level over a 3-year period between 2017 and 2020, including an intervention to seal the floor on 18/09/2019.

[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 [\[27\]](#). They were not considered to be reliable measurements of wall moisture levels for this study.

Figure 10.

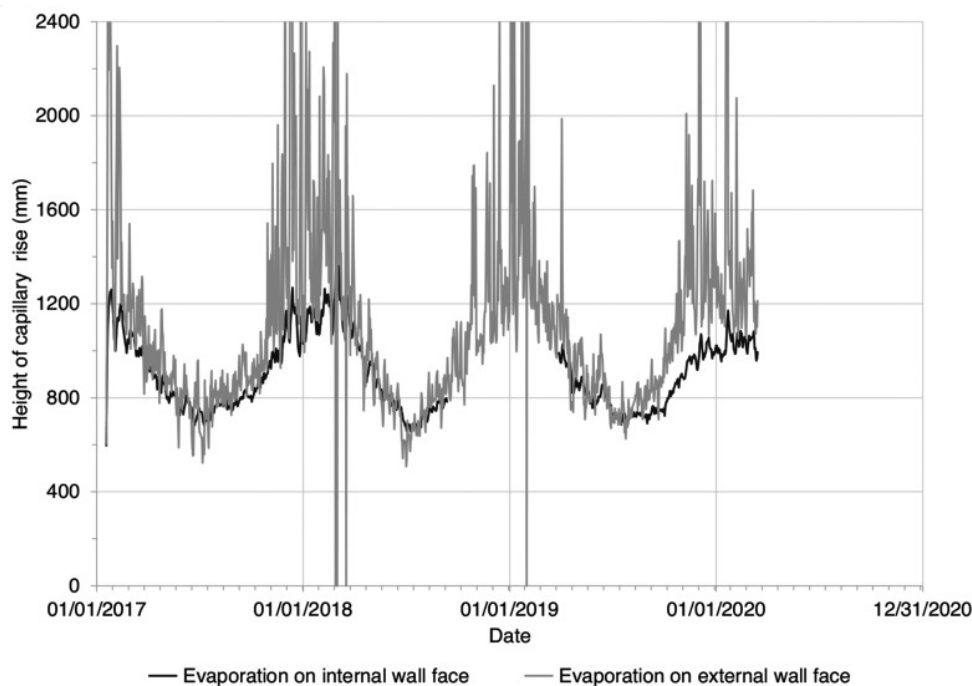


[Open in a new tab](#)

Protimeter Mini Moisture Meter readings measured between 0.2 m and 1.4 m above ground level over a 3-year period between 2017 and 2020, including an intervention to seal the floor on 18/09/2019.

[Figure 11](#) shows the height of wall capillary rise calculated using the Hall and Hoff [7] 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 ([Fig. 8](#)) and seasonally variable evaporative drying on the wall face ([Fig. 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, the 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 ([Fig. 9](#)).

Figure 11.



[Open in a new tab](#)

The height of wall capillary rise calculated using the Hall and Hoff [7] 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.

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 in other clay soils in the south of England [18,19].

3. If an impermeable ground bearing slab was 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 (from visual inspection) seemed to contain a discontinuous pore network between the materials forming the wall. This restricted capillary flow between the wall elements and capillary rise within the wall.

Acknowledgements

The authors would like to thank Alison Henry (Historic England), Kate Leighton (Static Dynamic) and Brian Ridout (Ridout Associates) for helpful discussions. Thanks are also due to former University of Bath staff, David Muddle, David Surgenor and David Williams for help with experimental measurements. Supplementary weather data for the Figures presented in this paper are openly available from the University of Bath Research Data Archive [28] at <https://doi.org/10.15125/BATH-01101>.

Funding

This research was funded by Historic England.

Open data and materials availability statement

The datasets generated during and/or analysed during the current study are available in the repository: <https://doi.org/10.15125/BATH-01101>

Declarations and conflicts of interest

Research ethics statement

The authors declare that research ethics approval for this article was provided by an internal ethics review at the University of Bath.

Consent for publication statement

The author declares that research participants' informed consent to publication of findings – including photos, videos and any personal or identifiable information – was secured prior to publication.

Conflicts of interest statement

The author declares no conflict of interest with this work.

References

- [1]. El-Turki A, Ball RJ, Holmes S, Allen WJ, Allen GC. Environmental cycling and laboratory testing to evaluate the significance of moisture control for lime mortars. *Constr Build Mater*. 2010;24(8):1392–7. doi: 10.1016/j.conbuildmat.2010.01.019. [DOI] [Google Scholar]
- [2]. Franzoni E. Rising damp removal from historical masonries: a still open challenge. *Constr Build Mater*. 2014;54:123–36. doi: 10.1016/j.conbuildmat.2013.12.054. [DOI] [Google Scholar]
- [3]. Trotman P, Sanders C, Harrison H. *Understanding Dampness*. Vol. 640. Berkshire, UK: BRE Bookshop; 2004. [Google Scholar]
- [4]. Historic England. Energy efficiency and historic buildings: insulating solid ground floors. 2016. Version 1.1. Historic England. Available from: <https://historicengland.org.uk/advice/technical-advice/energy-efficiency-and-historic-buildings/>
- [5]. Hall C, Hamilton A, Hoff WD, Viles HA, Eklund JA. Moisture dynamics in walls: response to micro-environment and climate change. *Proc R Soc A: Math Phys Eng Sci*. 2011;467(2125):194–211. doi: 10.1098/rspa.2010.0131. [DOI] [Google Scholar]
- [6]. Hall C, Hoff WD. *Water Transport in Brick, Stone and Concrete*. CRC Press; London, UK: 2021. [Google Scholar]
- [7]. Hall C, Hoff WD. Rising damp: capillary rise dynamics in walls. *Proc R Soc A: Math Phys Eng Sci*. 2007;463(2084):1871–84. doi: 10.1098/rspa.2007.1855. [DOI] [Google Scholar]
- [8]. DataMapWales. Cof Cymru, Listed buildings asset on DataMapWales. 2021. [Accessed 2021]. Accessed from: <https://cadw.gov.wales/advice-support/cof-cymru/search-cadw-records>.
- [9]. Ford J, Kessler H, Cooper AH, Price SJ, Humpage AJ. An Enhanced Classification of Artificial Ground. *Ground British Geological Survey Open Report*; 2010. p. 32. OR/10/036. [Google Scholar]
- [10]. British Geological Survey. *Geological Survey of England and Wales 1:63,360/1:50,000 geological map series, New Series*. Sheet 250, Chepstow. 1981
- [11]. Delta-T. WS-GP1 Weather station, quick start guide. Version 1.0. 2021. Accessed from: <https://delta-t.co.uk/wp-content/uploads/2016/10/WS-GP1-Weather-Station-QSG.pdf>.
- [12]. Gemini. Tinytag Plus 2 Data Sheet. 2021. [Accessed 2021]. Accessed from: <https://www.geminidataloggers.com/data-loggers/tinytag-plus-2/tgp-4017>.
- [13]. Delta-T. User manual for the SDI-12 Profile Probe. Version 4.1. 2016. Accessed from: https://delta-t.co.uk/wp-content/uploads/2016/09/PR2_SDI-12-User_Manual_version_4_1.pdf.
- [14]. Qi Z, Helmers MJ. The conversion of permittivity as measured by a PR2 capacitance probe into soil moisture values for Des Moines loess soils in Iowa. *Soil Use Manag*. 2010;26(1):82–92. doi: 10.1111/j.1475-2743.2009.00256.x. [DOI] [Google Scholar]
- [15]. Amphenol. Protimeter moisture meters. 2021. [Accessed 2021]. Available from: www.protimeter.com.
- [16]. Schendel U. *Vegetationswasserverbrauch und -wasserbedarf*. Kiel: Habilitation; 1967. p. 137. [Google Scholar]
- [17]. Bormann H. Sensitivity analysis of 18 different potential evapotranspiration models to observed climatic change at German climate stations. *Clim Change*. 2011;104(3):729–53. doi: 10.1007/s10584-010-9869-7. [DOI] [Google Scholar]

- [18]. Smethurst JA, Clarke D, Powrie W. Seasonal changes in pore water pressure in a grass-covered cut slope in London Clay. *Geotechnique*. 2006;56(8):523–37. doi: 10.1680/geot.2006.56.8.523. [\[DOI\]](#) [\[Google Scholar\]](#)
- [19]. Smethurst JA, Briggs KM, Powrie W, Ridley A, Butcher DJE. Mechanical and hydrological impacts of tree removal on a clay fill railway embankment. *Géotechnique*. 2015;65(11):869–82. doi: 10.1680/jgeot.14.P.010. [\[DOI\]](#) [\[Google Scholar\]](#)
- [20]. Walker R, Pavia S, Dalton M. Measurement of moisture content in solid brick walls using timber dowel. *Mater Struct*. 2016;49(7):2549–61. doi: 10.1617/s11527-015-0667-6. [\[DOI\]](#) [\[Google Scholar\]](#)
- [21]. Larsen PK. Moisture measurement in tirsted church. *J Archit Conserv*. 2004;10(1):22–35. doi: 10.1080/13556207.2004.10784904. [\[DOI\]](#) [\[Google Scholar\]](#)
- [22]. Ridout B. *Timber Decay in Buildings: The Conservation Approach to Treatment*. London: E & F Spon; 2000. [\[Google Scholar\]](#)
- [23]. Jenkins GJ, Perry MC, Prior MJ. *The Climate of the UK and Recent Trends*. UK Climate Projections; 2009. Project Report. [\[Google Scholar\]](#)
- [24]. Hollis D, McCarthy M, Kendon M, Legg T, Simpson I. HadUK-Grid – a new UK dataset of gridded climate observations. *Geosci Data J*. 2019;6(2):151–9. doi: 10.1002/gdj3.78. [\[DOI\]](#) [\[Google Scholar\]](#)
- [25]. Smethurst JA, Clarke D, Powrie W. Factors controlling the seasonal variation in soil water content and pore water pressures within a lightly vegetated clay slope. *Géotechnique*. 2012;62(5):429–46. doi: 10.1680/geot.10.P.097. [\[DOI\]](#) [\[Google Scholar\]](#)
- [26]. Briggs KM, Smethurst JA, Powrie W, O'Brien AS. Wet winter pore pressures in railway embankments. *Proc Inst Civ Eng Geotech Eng*. 2013;166(5):451–65. doi: 10.1680/geng.11.00106. [\[DOI\]](#) [\[Google Scholar\]](#)
- [27]. Franzoni E, Bandini S. Spontaneous electrical effects in masonry affected by capillary water rise: the role of salts. *Constr Build Mater*. 2012;35:642–6. doi: 10.1016/j.conbuildmat.2012.04.098. [\[DOI\]](#) [\[Google Scholar\]](#)
- [28]. Briggs KM, Ball RJ, McCaig I. Dataset for Daily Weather Data (2017–2020) Measured in Caldicot, Wales. Bath: University of Bath Research Data Archive; 2022. [\[DOI\]](#) [\[Google Scholar\]](#)

Associated Data

This section collects any data citations, data availability statements, or supplementary materials included in this article.

Data Availability Statement

The datasets generated during and/or analysed during the current study are available in the repository: <https://doi.org/10.15125/BATH-01101>

Articles from UCL Open Environment are provided here courtesy of **UCL Press**

ACTIONS

[View on
publisher
site](#)

[PDF
\(1.9 MB\)](#)

[Cite](#)

[Collections](#)

[Permalink](#)

RESOURCES

[Similar articles](#)

[Cited by other articles](#)

[Links to NCBI Databases](#)

ON THIS PAGE

[Abstract](#)

[Introduction](#)

[Aim and objectives](#)

[Method](#)

[Results](#)

[Conclusions](#)

[Acknowledgements](#)

[Funding](#)

[Open data and materials availability statement](#)

[Declarations and conflicts of interest](#)

[References](#)

[Associated Data](#)

FOLLOW N