PRESIDENT'S AWARDS FOR RESEARCH 2016

Shortlisted 2016

Design and Technical

The SPAB Building Performance Survey 2015 Report

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Architecture.com

> This is a meticulously conducted, original and much needed piece of research with some important implications on how relative humidity in wall construction is measured and evaluated.
>
> 2016 Judging Panel

The SPAB Building Performance Survey 2015 Report

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Originating in 2011 the Building Performance Survey is an ongoing research study that uses in situ monitoring to provide information regarding the performance of traditional buildings following energy efficiency refurbishment. The study was originally designed to address the lack of information surrounding the performance of traditional, pre-1919, solid wall, buildings in order to inform and aid decision making with regard to suitable refurbishment measures. Of particular concern was whether certain 'improvement' techniques might lead to the accumulation of moisture within historic building fabric. In 2014 the research was extended to focus specifically on interstitial moisture behavior in the insulated walls of three of the study buildings. The research uses innovative monitoring techniques to provide detailed measurements of interstitial temperature and relative humidity. Multiple analyses of the results are carried out using a number of different methods of vapour quantification. By 2015 sufficient measured evidence had been accumulated to provide confidence in the findings concerning the long-term performance of the insulated solid walls. The 2015 Research Report presents this evidence in graphic and written form, with an analysis that relates this year's findings to those of previous years, in order to draw a picture of long-term moisture behavior. The research finds one wall operating within safe margins, one with a trend of accumulating moisture and another with a moisture profile dominated by the persistent effects of construction moisture. Each of these characteristics can, in part, be ascribed to the refurbishment treatments carried out on the walls. It is thought that this study represents the longest and most comprehensive monitoring of interstitial moisture in the UK to date. It is hoped that this report will be of interest to all those attempting to weigh up the risks and benefits of refurbishing older buildings.

Introduction

Over the past decade, and particularly since the passing of the UK Climate Change Act in 2008, the contribution that buildings make to greenhouse gas emissions have been a source of interest and intervention, both on an individual and governmental level. The question of older buildings – those built with solid walls mostly prior to 1919 – has been a particular concern. Britain has the oldest housing stock in Europe and despite suggestions otherwise the wholesale replacement of these buildings is seen as neither practical nor desirable[1]. Therefore, for the past ten years the question as to the most effective means by which to improve the energy efficiency of this class of buildings has exercised those that are responsible for them: property owners, architects, surveyors, builders and conservationists alike.

The SPAB Building Performance Survey (BPS) was first established in 2011 in order to address the dearth of information surrounding the subject of energy efficiency and traditional buildings. In particular, there was an absence of evidence with regard to the performance of traditional buildings and by extension a lack of understanding as to what constituted effective and risk-free interventions that could be made in the name of energy conservation. Of specific concern were the long-term consequences relating to damage to fabric and occupants' well-being as a result of the application of insulation to building elements and the effects of reductions in ventilation/air infiltration.

Since 2011, the SPAB Building Performance Survey has looked at various aspects of building performance in older, traditionally constructed properties both before and after energy efficiency refurbishment. The survey has measured in seven houses: fabric heat loss, air leakage, indoor air quality, wall moisture behaviour, room comfort and fabric risk conditions. Following refurbishment these measurements were repeated in four of the properties and from 2011 findings have been made available on a yearly basis in the form of SPAB research reports.

In 2014, the Building Performance Survey was extended in order to focus specifically on the question of the long-term performance of moisture in insulated solid walls. The concern is that moisture may accumulate within such a wall depending on the quantities and types of insulation used and its position within the wall build-up. High levels of fabric moisture could lead to uncomfortable living conditions and increased heat losses, and could have serious consequences in the form of mould growth and rot, injurious to human health and a danger to the structural integrity of the building. The solid walls used in this study are part of the original BPS research sample and are constructed of brick (Shrewsbury), granite (Drewsteignton) and cob (Riddlecombe). The brick and granite walls at Shrewsbury and Drewsteignton have been internally insulated with woodfibre and polyisocyanurate (PIR) board respectively. The cob house has external wall insulation in the form of a lime-based insulating render. The investigation is carried out principally through the measurement of interstitial hygrothermal gradients, that is to say, measurements of temperature and relative humidity (RH) made through and either side of the wall section. Measurements were taken from the walls prior to insulation and following refurbishment and have been made continuously in the three properties since 2012. The measurement of water vapour in air is used to provide an indication of the moisture performance of the wall fabric. The use of air as a proxy medium for moisture measurements has a number of advantages. Unlike measurements of moisture via electrical resistivity or capacitance, it is unaffected by salt contamination or the presence of metals. As a quantity %RH is commonly used within fabric risk indices, 80% being the threshold value often quoted for the formation of mould growth.[2] Hence, unlike alternative measurement methods, measurements of %RH provide an immediate indication of risk without the need for interpretation based on the properties of individual materials – which are often unknown. However, the technique relies on high-quality equipment and a thorough and careful method of installation that ensures the sites of measurement are isolated to provide confidence in the findings.

This report sets out in more detail the methodology used to undertake the research work. It then presents the findings of the past year's work and analyses this alongside data collected from the walls over the longer term, since 2012, post-refurbishment. The analysis uses three comparative bases: that of 'Relative Humidity over time'; 'Absolute Humidity over time'; and 'Saturation Margins'. Each is briefly explained prior to the discussion of results. Based on these long-term measurements of the three walls, each with different insulation treatments, conclusions are then drawn with regarding to risks in relation to particular energy efficiency refurbishment approaches.

Further information about the previous year's research surveys can be found in SPAB research reports which can be downloaded from the SPAB website at https://www.spab.org.uk/advice/energy-efficiency/.

Methodology

Interstitial Hygrothermal Gradient Monitoring

Archimetrics has developed the methodology, instrumentation and analysis for Interstitial Hygrothermal Gradient Monitoring (IHGM) to answer questions regarding moisture transfer within building fabric. This bespoke approach, developing electronics, code, instrumentation and analysis techniques, provides a high degree of control and accuracy to monitoring research processes. Four sensor nodes containing precision temperature (±0.4°C) and RH (± 3%) sensors are embedded at varying depths through a wall section. Four separate 32 mm holes are dry core drilled from the interior side with the aim of distributing the sensors evenly through the wall thickness; with sensor 4 closest to external conditions, sensor 1 towards the internal side of the wall and sensors 2 and 3 bisecting the remaining material. If an air layer or material interface is present in the wall build-up, a sensor will be located here. Great care is taken, by use of sleeves, to isolate the sensors and ensure that they are only able to measure conditions within the immediate proximity of the sensor.. Additional sensors are placed on the external wall face in parallel with the embedded wall sensors to measure air temperature, surface temperature, RH, and incident solar radiation. Measurements are also made internally of wall surface temperature, room air temperature and RH. Data from these sensors (15 values) are logged at five-minute intervals by a dedicated ArchiMetrics' monitoring logger mounted in close proximity to the sensor array. See Figure 1 for drawings of the individual installations in the three walls under study and Tables 1 – 3 for wall materials and dimensions (new materials in green) including sensor depth information.

Analysis & Discussion

Direct comparisons between moisture responses at the three properties in the survey are problematic given the differences between the buildings; their locations, wall orientations, materials, sensor positions and general condition. Nevertheless, bearing these differences in mind, it is interesting

Table 1
Interstitial Hygrothermal Gradient sensor positions for Abbeyforegate, Shrewsbury

Build-up - internal – external	Depth of material	Sensor no.	Height from finished floor level	Depth of sensor from internal surface
Lime plaster finish	8 mm	1	1875 mm	8 mm
Woodfibre insulation	40 mm	2	1725 mm	48 mm
Lime plaster	12 mm			
Brick	345 mm	3	1575 mm	195 mm
		4	1425 mm	355 mm
Overall	405mm			

Table 2
Interstitial hygrothermal gradient sensor positions for Mill House, Drewsteignton.

Build-up - internal – external	Depth of material	Sensor no.	Height from finished floor level	Depth of sensor from internal surface
Gypsum skim	3 mm			
Plasterboard	12.5 mm			
Air gap	25 mm	Sensor 1	1730 mm	30 mm
PIR Board	100 mm	Sensor 2	1580 mm	140 mm
Tanking & gypsum	3 mm			
Lime Plaster	20 mm			
Granite	580 mm	Sensor 3	1430 mm	340 mm
		Sensor 4	1280 mm	610 mm
Total	**744 mm**			

Table 3
Interstitial hygrothermal gradient sensor positions and wall build up for The Firs, Riddlecombe.

Build-up - internal – external	Depth of material	Sensor no.	Height from finished floor level	Depth of sensor from internal surface
Lime plaster	20 mm			
Cob	545 mm	Sensor 1	1800 mm	60 mm
		Sensor 2	1600 mm	225 mm
		Sensor 3	1400 mm	395 mm
		Sensor 4	1200 mm	575 mm
Masonry	90 mm			
Lime Render Scat Coat	5 mm			
Insulating Lime render	50 mm			
Lime Render Finish skim	5 mm			
Overall	**715 mm**			

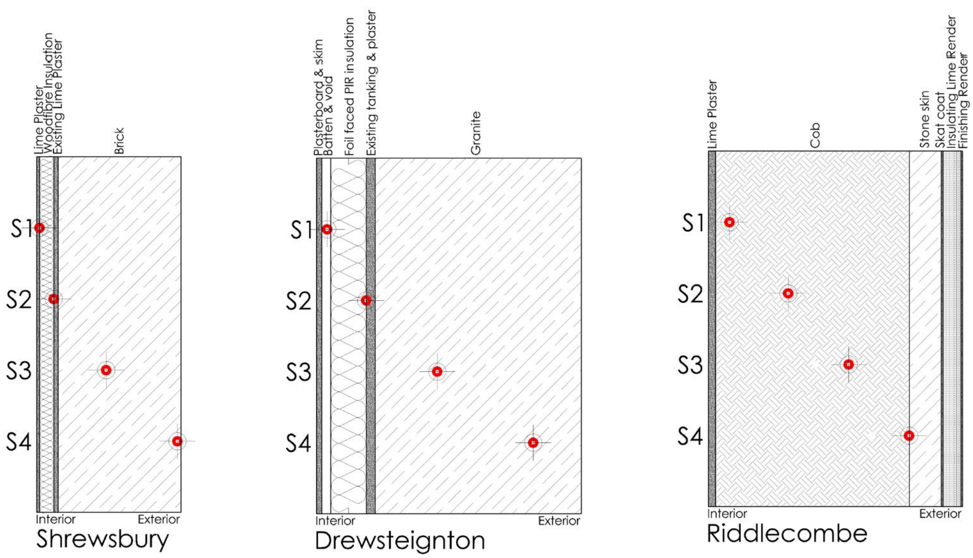


Figure 1
Locations of interstitial hygrothermal gradient sensors in walls at Shrewsbury, Drewsteignton and Riddlecombe, SPAB Building Performance

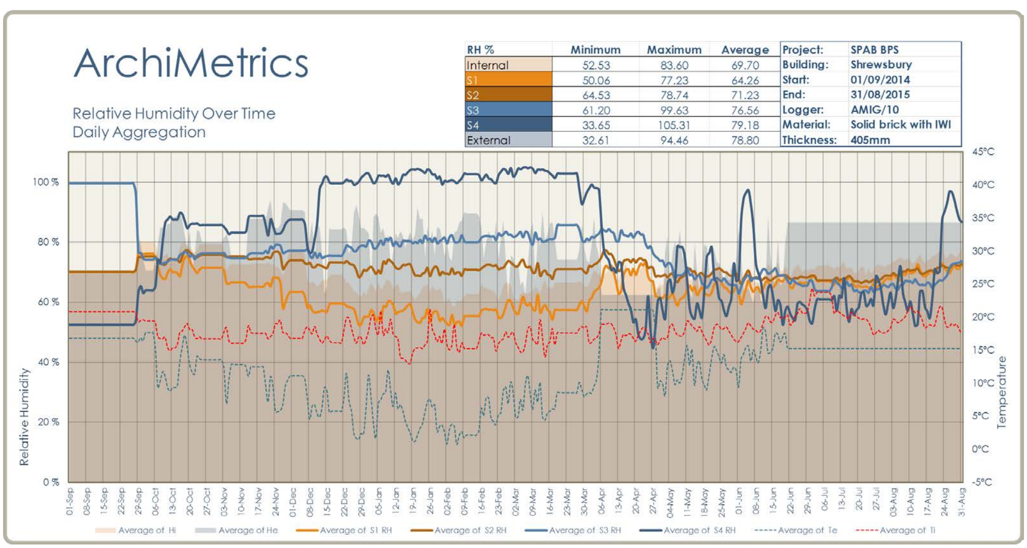


Figure 2
Relative Humidity over time, Abbeyforegate, Shrewsbury 2014 – 2015.

Figure 3
Relative Humidity over time, Mill House, Drewsteignton, 2014 2015.

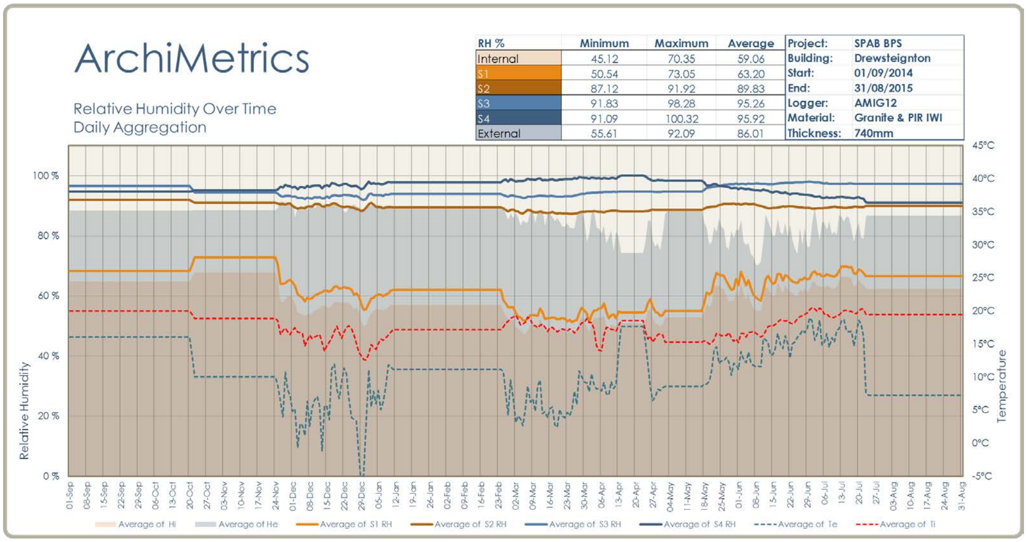
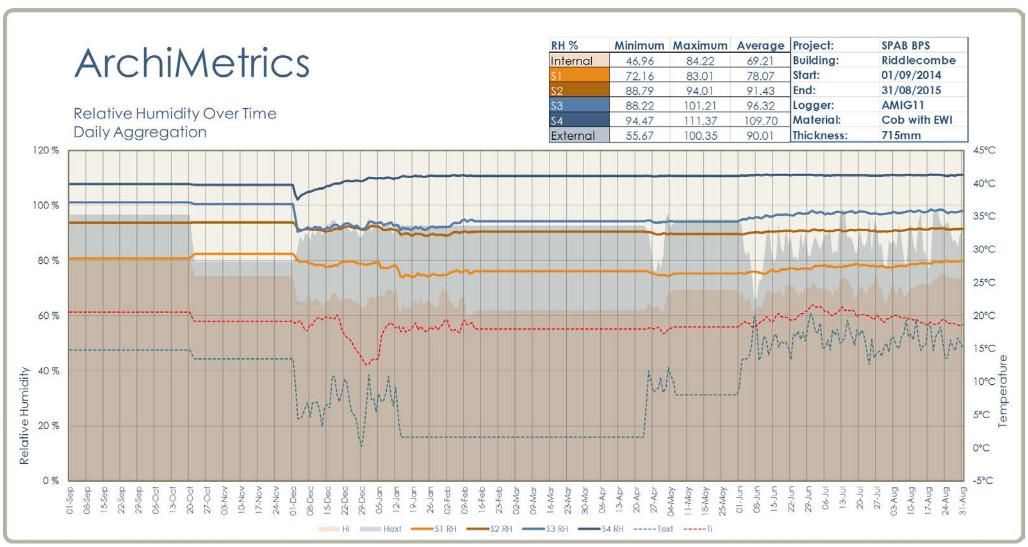


Figure 4
Relative Humidity over time, The Firs, Riddlecombe 2014 – 2015.



to look across the sample at the changes that are taking place in the walls over time for points of similarity and difference.

Relative Humidity

Relative humidity (RH) is a measure of the vapour saturation of air at a particular temperature. It is the ratio, as a percentage, of the actual water vapour pressure and the maximum water vapour pressure air could sustain at the same temperature, i.e. at 100%RH (dewpoint) the air has become saturated and water vapour may begin to condense. High RH (80%+) is one of the conditions required for mould fungus formation.

RH, as its name suggests, is a relational concept, being the relationship between the carrying capacity of air at a particular temperature in relation to the quantity of vapour present. In previous analyses RH reporting has been capped at 100% as this is the upper limit of the concept of relative humidity where air is saturated. However, due to the method by which measurements of RH are derived it is possible to create %RH values over 100%. In this study the electrical capacitance of the surrounding air is measured and this value is translated into an RH value. Wet conditions may create capacitance measurements which return %RH values above that of 100%. Whilst this is a conceptual impossibility in relation to the notion of relative humidity these percentages may, nevertheless, indicate that conditions within surrounding material have exceeded those of dewpoint and surrounding material is more, or less, significantly wet. For this reason we present RH measurements that exceed 100% as a means by which to provide additional suggestions as to the condition of the walls. For the purposes of comparison with preceding years we will also provide an analysis where RH is capped at 100%. 'Over time' analyses of the 2014 – 15 data series will use +100% RH where as comparative tables and sectional averages will use a capped value.

Relative humidity behaviour is presented over time for the three walls within the study (Figs. 2 – 4). Each property is provided with a graphical analysis based on daily aggregated data (an average of the values measured over a 24-hour period – 288 values). The daily aggregation analysis allows for greater differentiation between sensor plots and thus a clearer overview of conditions.

The three walls in the study show very different %RH responses. Shrewsbury is much the most volatile with an extreme range of responses, particularly at sensor 4, in close proximity to external conditions. Also of interest, given this volatility, is the response measured at sensor 2, between the woodfibre insulation and original brick, here values are quite steady throughout the year, despite seasonal changes. %RH measured in the granite wall at Drewsteignton is generally higher than that of Shrewsbury, all three sensors within the masonry part of the wall record values above 80% for the entire year. The exception being sensor 1, located in the air-gap between the plasterboard finish and PIR insulation. Here, %RH measurements track those of internal room conditions. The cob wall at Riddlecombe has the highest annual measurements of %RH of the three walls and displays atypical behaviour where %RH increases over the summer months. Responses are also steadier, more akin to those measured in the granite wall than the thinner brick wall at Shrewsbury.

Figure 2 shows the RH responses measured in and around the test wall at Shrewsbury over the past year. These show moisture vapour behaviour to be broadly consistent with those measured over previous years, post-refurbishment. The %RH responses are quite dynamic and we have ascribed this to the condition of the wall. The wall is quite thin and made of porous brick, it is south-facing so receives direct sunlight as well as the effects of the prevailing weather, with pointing in a poor state of repair. These elements combine to create a changeable picture with regards to heat and air exchange for the wall with a concomitant effect on temperature and moisture behaviour. Of continued note are the extremes of response at sensor 4 located in close proximity to external conditions, 50 mm back from the external wall surface. As with previous years there is a period of time over the winter months where %RH at this location is at, or exceeds, 100%. However, with the move into spring and warmer external temperatures, %RH at sensor 4 falls rapidly and is often the lowest recorded response over the summer months. This pattern, which repeats that of all previous years since measurements began in 2012, shows high %RH in the south-facing wall as a result of cold temperatures, rain and wind-driven rain over the winter months and lower %RH due to heat and direct sun in the spring and summer months.

Figure 3 shows the %RH responses measured in and around the test wall at Drewsteignton 2014 -2015. The granite wall at Drewsteignton provides a contrasting picture compared with that of Shrewsbury, as here the %RH responses are more muted and do not have the volatility of those seen in Shrewsbury's brick wall. This suggests a different quality for the granite wall at Drewsteignton; it is thicker than that of Shrewsbury, constructed from more dense material, it's pointing is in good condition and it has a north-west orientation. This construction is, therefore, less influenced by fluctuations in the weather and %RH responses are more muted as a consequence. An examination of Figure 3 suggests that warmer summer temperatures may have some impact deep within the wall fabric as during these months, while %RH decreases at sensor 4, it increases at sensors 2 and 3. (Sensor 3 is positioned approximately half-way through the granite wall and sensor 2 is at the granite/foil-faced PIR insulation interface.) We have seen this behaviour elsewhere during the summer and have ascribed it to evaporation from damp materials increasing the vapour load of the air. It would seem that whilst a certain quantity of moisture may evaporate from materials this moisture, located further away from the external wall surface and unable to move towards the interior due to the presence of the foil vapour barrier, may not be able to leave the body of the wall during the warmer summer months. The vapour may then become stuck in cycles of evaporation and condensation.

Figure 3 shows the %RH responses measured in and around the wall at Riddlecombe over the past year. In past years this wall has produced the highest %RH values of the three walls in the study and this is still the case for this year. In previous reports we have deemed the high levels of %RH found in the cob wall at Riddlecombe to most likely be the result of construction moisture bound within the earth fabric. Unusual %RH behaviour was observed in this wall as quantities rose during warmer summer months (when %RH is normally lower due to warmer temperatures). We ascribed this phenomenon to the vaporisation of moisture from damp cob material which was particularly noticeable during periods of direct sun on the south-facing wall. This moisture was introduced into the wall during the process of re-rendering when the wall was wetted down prior to the application of the new render. (More discussion of this solar –driven vaporisation is given in the following section on Absolute Humidity.) In 2013 – 14 it was noticeable that rates of %RH diminished during and in spite of the colder winter months. This behaviour is less obvious in the 2014 – 15 data although measurements of %RH at sensor 3 over the summer are raised in comparison with those between December 2014 and February 2015. However, they are on average not as great as those of the previous year.

Table 4 provides details of the annual average %RH values for the four interstitial sensors situated in the monitored walls at Shrewsbury, Drewsteignton and Riddlecombe post-insulation. Blue shading indicates decreases in %RH and orange increases in %RH year-on-year.

The table shows the relative differences in %RH found between the three walls. Over the three years of monitoring Shrewsbury has had the lowest rates of annual average %RH ranging between 64% – 83%. Drewsteignton extends higher up the scale with a range between 63% – 97% and the externally insulated cob wall at Riddlecombe, which had high %RH prior to refurbishment, sits at the top end of the scale with annual average measurements of between 72% – 100%. These %RH values are influenced by construction and condition details, orientation and local climate.

Unlike sensors 1 and 4, responses at sensors 2 and 3 deeper within the walls are of particular interest as the wetting and drying influences of external and internal environments affect these positions less directly. At Shrewsbury there is no change at sensors 2 and 3 from the previous year in the annual average measurements of %RH and only 1 or 2% change since 2012 – 13. At Drewsteignton we see annual average %RH increasing year-on-year at sensors 2 and 3 and the degree of change since 2012 – 13 is greater being 5%. An analysis of the averages from Riddlecombe shows no change at sensor 2 since

2012 -13, and a small (2%) decrease in %RH at sensor 3 from the previous two years. By and large the annual average of measurements of %RH from Shrewsbury indicates that the wall is below the threshold which may indicate conditions conducive to mould growth in bio-utilizable substrates – 80%, unlike those of both Drewsteignton and Riddlecombe.

Figures 5, 6 and 7 show the long-term trends of %RH responses in the three walls. (These are indicated by dashed trend lines, the dotted lines show this year's new analysis of RH beyond 100%). The Shrewsbury trend analysis, Figure 5, shows the lower %RH performance of the wall and the narrower range of the RH trends compared to Drewsteignton and Riddlecombe. This suggests, for the wall in Shrewsbury, a relatively stable and safe (with regards to mould growth) picture for the wall, despite the acute volatility of seasonal responses. At Shrewsbury the trends at sensors 1 and 2 are downward and sensor 4 is static, an upward trend at sensor 3 can be seen. We do not, however, expect this trend to persist as it is the result of the extreme wetting of the substrate that took place deep within the wall during the winter of 2013 -14. More recent data from this year shows that the air in the wall at this location has 'recovered' from this event and returned to lower %RH.

In Figure 6 for Drewsteignton the year on year rise in %RH in the centre of the wall can be seen as a long-term trend at sensors 2 and 3. The trends on sensors 1 and 4 at the periphery of the wall are downward. These are likely to be more strongly influenced by seasonal events and these decreases may reflect the warmer conditions experienced in 2014 – 15 compared with those of previous years. It is telling that, given the trends at sensors 1 and 4, those seen at sensors 2 and 3, more deeply embedded in the core of

Table 4
Annual Average %RH for all Interstitial Sensors 2012 – 2015.

Annual Average RH	Sensor 1	Sensor 2	Sensor 3	Sensor 4
Shrewsbury				
2012 – 2013	66%	72%	75%	83%
2013 – 2014	66%	71%	77%	81%
2014 – 2015	64%	71%	77%	79%
Difference 2012 – 2015	-2.00%	-1.00%	2.00%	-4.00%
Drewsteignton				
2012 – 2013	68%	85%	90%	96%
2013 – 2014	64%	87%	92%	97%
2014 – 2015	63%	90%	95%	96%
Difference 2012 – 2015	-5.00%	5.00%	5.00%	0.00%
Riddlecombe				
2012	72%	91%	98%	100%
2013 – 2014	78%	91%	99%	100%
2014 – 2015	78%	91%	96%	100%
Difference 2012 – 2015	6.00%	0.00%	-2.00%	0.00%

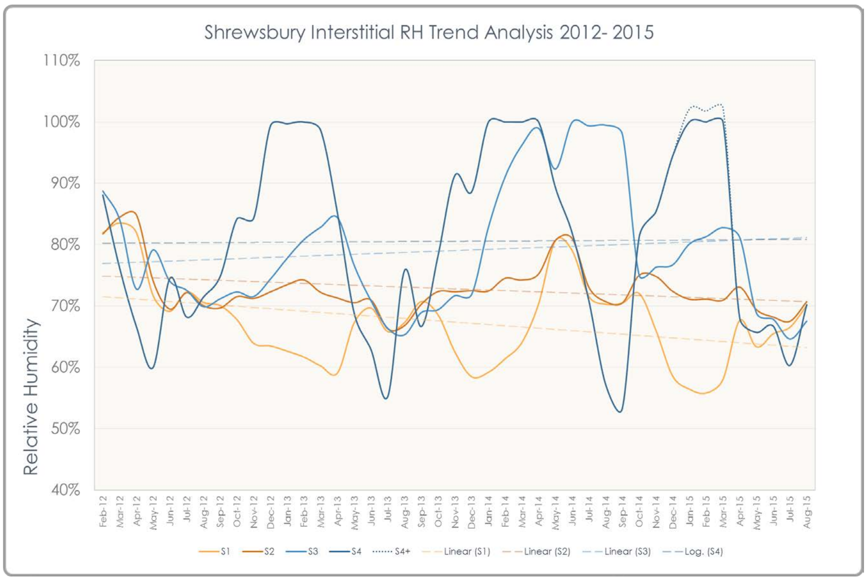


Figure 5
Relative Humidity Trends over time, Shrewsbury 2012 – 2015.

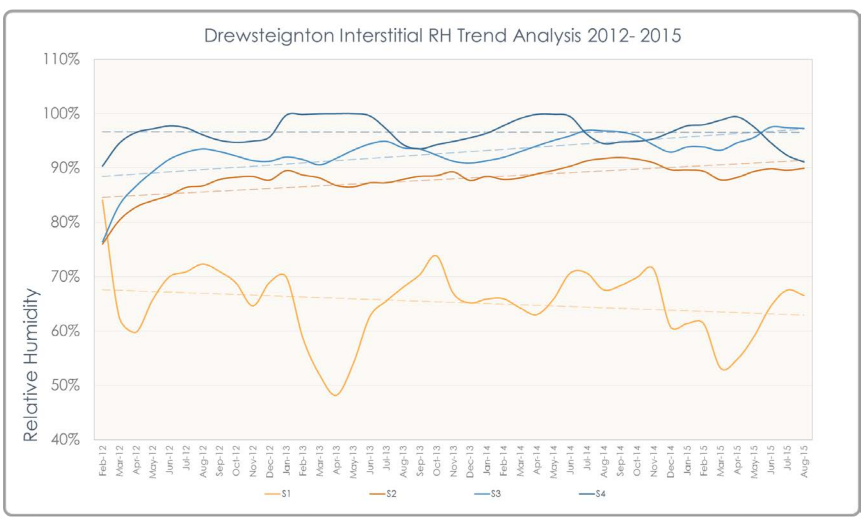


Figure 6
Relative Humidity Trends over time, Drewsteignton 2012 – 2015.

Figure 7
Relative Humidity Trends over time, Riddlecombe, 2012 – 2015.

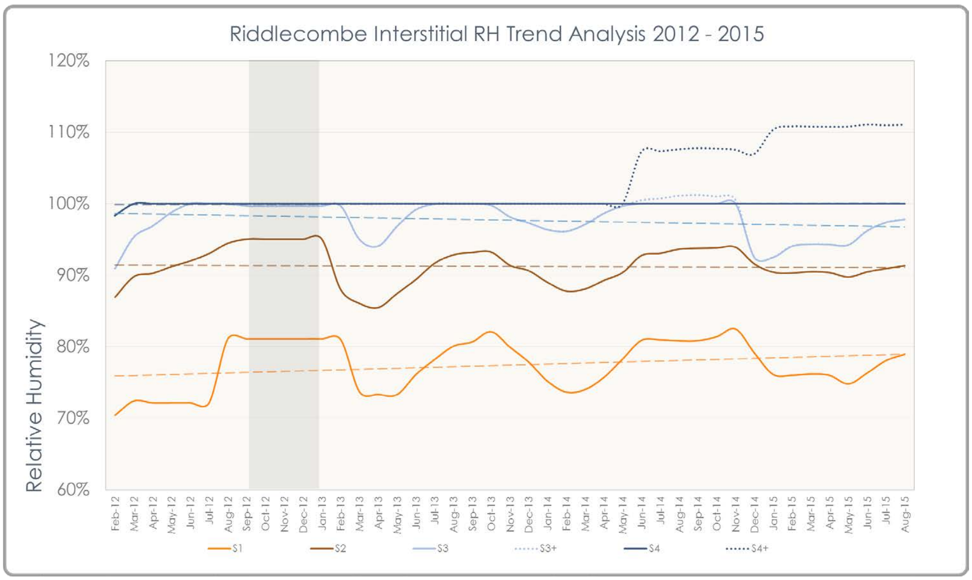
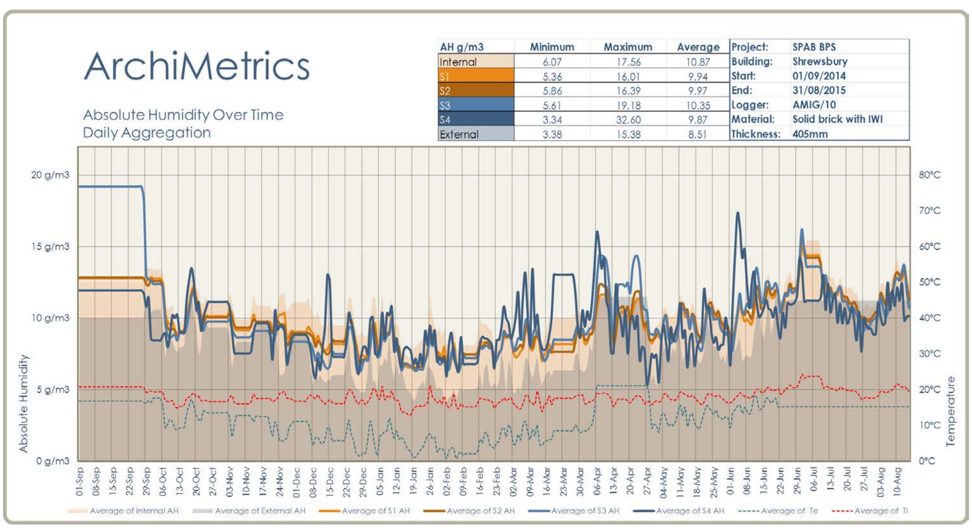


Figure 8
Absolute Humidity over time, Abbeyforegate, Shrewsbury 2014 – 2015.



AH g/m3	Minimum	Maximum	Average	Project:	SPAB BPS
Internal	6.07	17.56	10.87	Building:	Shrewsbury
S1	5.36	16.01	9.94	Start:	01/09/2014
S2	5.86	16.39	9.97	End:	31/08/2015
S3	5.61	19.18	10.35	Logger:	AMIG/10
S4	3.34	32.60	9.87	Material:	Solid brick with IWI
External	3.38	15.38	8.51	Thickness:	405mm

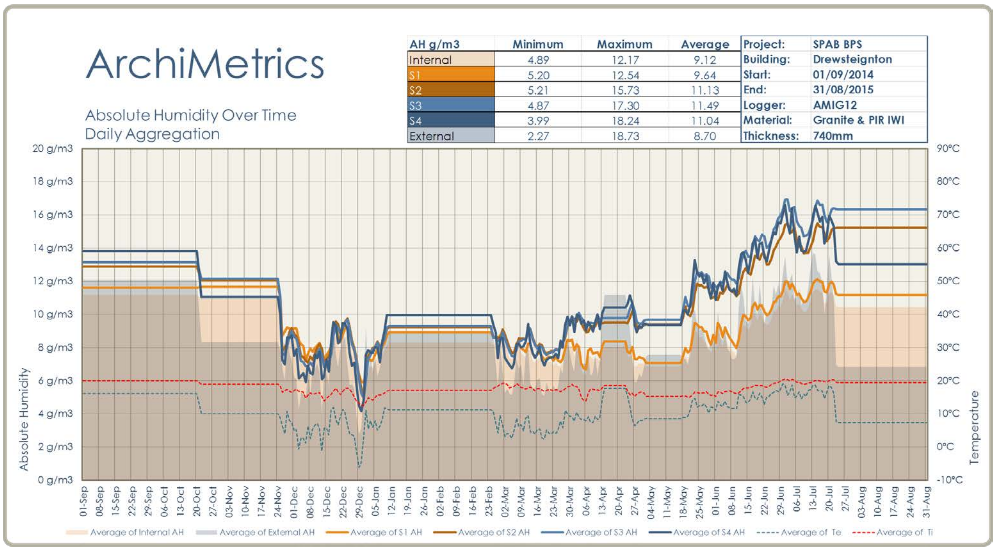


Figure 9
Absolute Humidity over time, Mill House, Drewsteignton 2014 – 2015.

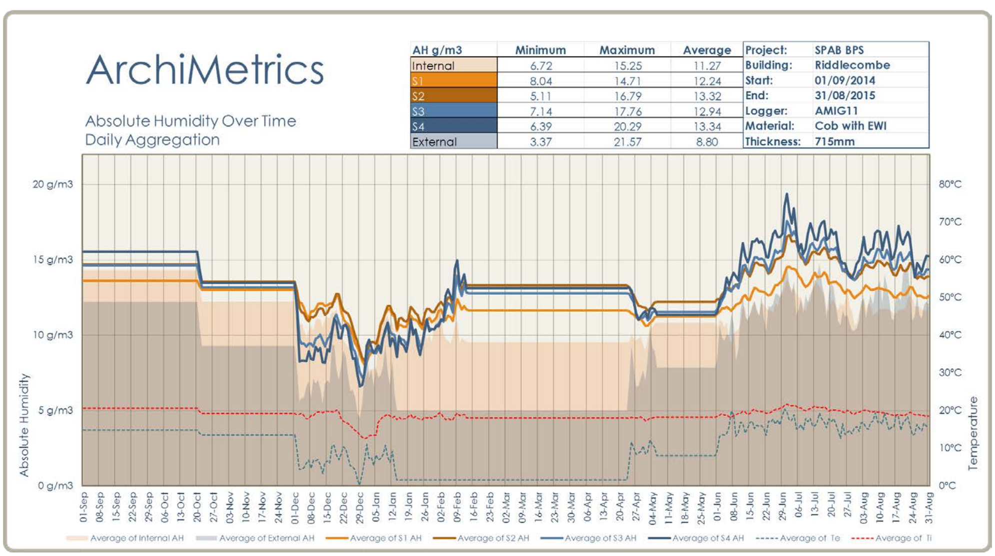


Figure 10
Absolute Humidity over time, The Firs, Riddlecombe, 2014 – 2015.

the wall, continue to climb. This suggests that currently drying influences within the environment are unable to penetrate conditions deeper within the wall to reduce %RH by drying the air and surrounding substrate, hence a rising trend.

Like Drewsteignton, the trends of %RH at Riddlecombe are high, well above the 80% threshold for mould growth, Figure 7. However, unlike Drewsteignton, the trend within the centre of the wall at Riddlecombe, at sensors 2 and 3, is one of falling RH. The trend for sensor 4, towards the external side of the wall, static at 100%, indicates perpetual saturation of the air and this persistence implies a wet substrate at this location. The high measurements of %RH at sensors 2 and 3 also suggest damp material but the decrease found over time here may imply that this material is drying out through solar driven vaporisation, albeit slowly. The upward trend at sensor 1 may also be a response to the drying taking place deeper within the wall as vapour travels back toward the internal wall surface, the area of lower vapour concentration.

Absolute Humidity

Absolute humidity (AH) is a measure of the quantity of vapour in air over a particular volume – g/m^3. It provides an indication of the weight of vapour present at a particular location at a particular point in time and thus is a way of identifying vapour trends within building fabric. However, whether this vapour presents a risk to fabric is usually determined in relation to vapour saturation and measured as relative humidity (RH).

Absolute humidity behaviour is presented over time for the three walls within the study (Figs 8 – 10). Each property is provided with a graphical analysis based on daily aggregated data (an average of the values measured over a 24-hour period – 288 values). The daily aggregation analysis allows for greater differentiation between sensor plots and thus a clearer overview of conditions. Unsurprisingly, there are certain similarities between the AH behaviour seen in Figures 8 – 10 and the %RH over time analysis. Both analyses are measures of vapour quantities; one relative to temperature and the other as an absolute weight. Quantities of vapour between the three walls follow that indicated by the %RH analysis, that is Shrewsbury has the lowest weights of vapour, whereas Drewsteignton and Riddlecombe have higher weights, with Riddlecombe being the highest of the three. Shrewsbury also has a much greater range of responses, seen at sensor 4, than the other two walls, where AH is on average higher and the range of measurements smaller. In all three analyses weights of vapour increase during the summer months, this is normal as atmospheric vapour also increases over this period due to warmer temperatures and the ability of warm air to hold a greater quantity of moisture as vapour. However, it is noticeable that sensor gradients over the summer months for the walls in both Drewsteignton and Riddlecombe indicate weights of vapour higher than those of the external atmosphere. This suggests additional sources of vapour affecting conditions within the wall above and beyond that of internal and external air.

At Drewsteignton it has been suggested that over the summer the interior of the granite wall experiences cycles of evaporation and condensation with moisture unable to progress towards an evaporative surface partly due to the presence of the impermeable foil-faced membrane of the PIR board. At Riddlecombe the previously observed relationship between vapour production and warmer temperatures, particularly during periods of direct solar radiation falling upon the south-facing wall, is found, Figure 11. In this example, taken from a week in late July 2015, we can see drying taking place as a result of vaporisation due to solar radiation. Despite the high weights of vapour being measured over this time we can see the wall is drying as over the week quantities of vapour measured at sensors 3 and 4 fall (particularly noticeable in the more muted responses at sensor 3). The assumption is that vapour is dispersed from these locations by diffusion.

Table 5 provides details of the annual average AH values for the four interstitial sensors situated in the monitored walls at Shrewsbury, Drewsteignton and Riddlecombe post-insulation. Blue shading indicates decreases in AH and orange increases in AH year-on-year.

All the three walls in the study show largely the same general trend of year-on-year increases in average weights of vapour. As has been demonstrated weights of vapour increase (to different degrees) through the individual wall sections in line with general increases in atmospheric vapour. The weather since post-refurbishment monitoring began in 2012 has been characterised by record-breaking rainfall and warm temperatures. 2012 saw a very wet spring and summer and had the second highest annual rainfall since 1910. 2013 had a cold and late spring followed by a very warm summer with a heat wave in July then severe storms with strong winds over the winter.

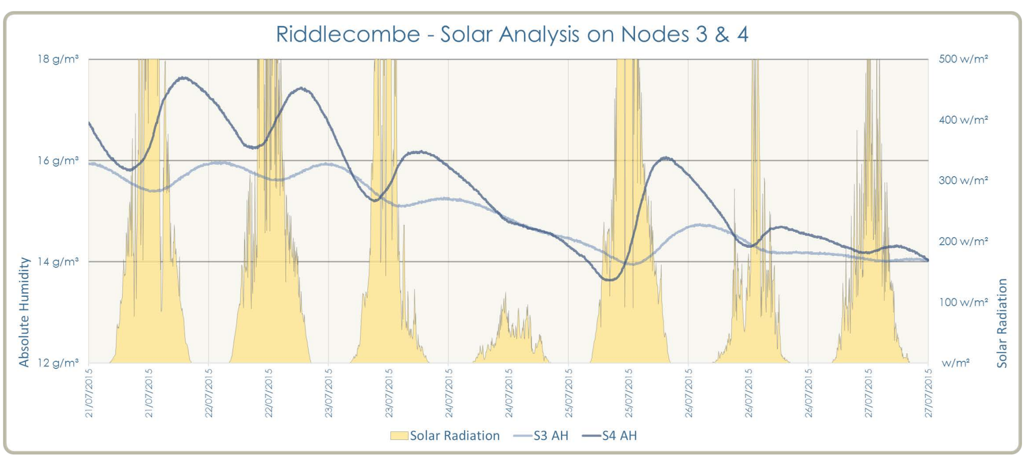


Figure 11
Solar Analysis – Absolute Humidity sensors 3 and 4 over time, Riddlecombe, July 2015.

Table 5
Annual Average AH g/m³ for all Interstitial Sensors 2012 – 2014.

Annual Average AH	Sensor 1	Sensor 2	Sensor 3	Sensor 4
Shrewsbury				
2012 – 2013	9.01 g/m³	8.80 g/m³	8.95 g/m³	9.18 g/m³
2013 – 2014	9.56 g/m³	9.42 g/m³	9.69 g/m³	9.65 g/m³
2014 – 2015	9.94 g/m³	9.92 g/m³	10.35 g/m³	9.81 g/m³
Difference 2012 – 2015	0.93 g/m³	1.12 g/m³	1.4 g/m³	0.63 g/m³
Drewsteignton				
2012 – 2013	8.53 g/m³	8.76 g/m³	8.96 g/m³	9.13 g/m³
2013 – 2014	9.24 g/m³	10.04 g/m³	10.24 g/m³	10.17 g/m³
2014 – 2015	9.64 g/m³	11.13 g/m³	11.49 g/m³	11.04 g/m³
Difference 2012 – 2015	1.11 g/m³	2.37 g/m³	2.53 g/m³	1.91 g/m³
Riddlecombe				
2012	9.47 g/m³	12.66 g/m³	12.74 g/m³	12.27 g/m³
2013 – 2014	12.10 g/m³	12.96 g/m³	12.72 g/m³	11.75 g/m³
2014 – 2015	12.24 g/m³	13.32 g/m³	12.91 g/m³	12.15 g/m³
Difference 2012 – 2015	2.77 g/m³	0.66 g/m³	0.17 g/m³	-0.12 g/m³

2014 was the warmest year on record (since 1659) and also much wetter than average, being the fourth wettest year since 1910. It seems probable therefore that the general increase in weights of vapour in the walls are a reflection of conditions that have caused exceptional wetting of substrates (including the effects of wind-driven rain and unseasonably high rainfall) combined with periods of higher than average warm, sunny weather which aid the vaporisation of moisture from materials.

However, a comparison of the difference between 2012 – 13 and 2014 -15 weights of vapour at each of the sensor locations shows different degrees of change and may reveal more individuated drivers for each wall. Weights of vapour measured through the section at Drewsteignton have increased more than those of Shrewsbury. Deep in the wall, at sensors 2 and 3, there is roughly a two-fold increase in the rise in AH measured on average compared with that of Shrewsbury. Both these increases are greater than those found for Riddlecombe, which has smaller gains of weights of vapour at sensors 2 and 3 and indeed a reduction in AH this year at sensor 4. The exception to this is the annual average AH measured at sensor 1 at Riddlecombe which shows the greatest increase of all the sensors in the three walls.

We might speculate that AH trends in the south-facing porous wall at Shrewsbury broadly reflect those of atmospheric conditions over the past few years where there has been both greater moisture availability from the wet and windy weather and also extra drying capacity as a result of high temperatures. The additional increases in weights of vapour seen at Drewsteignton, over and above those at Shrewsbury, may indicate that whilst atmospheric moisture has increased the wall has been less able to benefit from the drying available over the summer months due to the thicker, more inert, north-west facing nature of the granite construction. Riddlecombe sits apart from the other two examples with an extreme range of differences calculated for the four sensors. This suggests, perhaps, different influences within this wall from those of the immediate atmosphere. The vapour picture at Riddlecombe may be dominated not by atmospheric moisture but by water added to the cob material during the re-rendering process (hence the highest AH values of the three walls). Thus, the smaller changes we see here are a result of this moisture drying in the summer through the action of direct sun on the south-facing wall, which might also account for the significant gain seen at sensor 1 as vapour evaporates to the interior as part of this drying process.

Saturation Margins

'Dewpoint' is the temperature at which air reaches vapour saturation. The difference between the measured temperature and dewpoint temperature we term the 'saturation margin' and represents the temperature drop required for condensation to begin at the measured locations within the wall. Figure 12 illustrates this principle. In previous reports we have used the term 'dewpoint margin' as a means by which to quantify the risk of interstitial condensation. The term 'saturation margin' shifts the emphasis of this concept to point to the condition of wall material as well as the possibility of condensation. A narrow saturation margin is an indication that the air within the wall material is close to saturation, 100% RH. We may measure high RH values due to wetting from wind-driven rain, vaporisation from wet materials as a result of built-in construction moisture, the failure of rainwater goods and/or vapour control layers or just the inability, over time, for a wall to evaporate its moisture load. The term 'saturation margin' moves us away from the dewpoint/condensation risk paradigm which sees only internal water vapour moved by diffusion and condensed by cold temperatures as the sole moisture risk to buildings. 'Saturation' in this context refers to the state of air, but it also hints at the condition of surrounding fabric which may well be wet as a result of influences other than those of internally-driven vapour diffusion and condensation. Nevertheless, due to cycles of condensation and evaporation, this wet material can contribute to the wetting and drying of building fabric. Some moisture may be expected within building fabric, particularly towards the outside of the building envelope in proximity to cold external conditions during winter months. It is generally considered that this is acceptable if any interstitial moisture can dry out without accumulating over longer periods of time.

In this report pre- and post-insulation saturation margins are compared. The pre-insulation margins are calculated from a short data series collected during the coldest part of the year, February 2011. To this extent these could be seen as ‘worse case’, i.e. the margins will be narrow due to cold temperatures. (In winter %RH is likely to increase due to colder external temperatures and therefore dewpoint towards the external side of the wall is more likely to be reached. Some reduction of the saturation margin is to be expected particularly in an internally-insulated wall as the insulation also deprives the majority of the wall fabric of heat from the interior during the winter heating season.) Saturation margins for the walls in this study post-insulation are calculated from a full year of data and are therefore representative of both colder winter conditions and warmer summer months where margins may be much greater. The post-insulation saturation margins will be increased by the inclusion of summer data and thus any narrowing of saturation margins post-insulation in comparison with those pre-insulation can be deemed to be of substance. Dewpoint temperatures are presented in the form of hygrothermal sections, plots of averages of measured temperature and dewpoint temperatures for each of the walls on an annual basis (Figs. 13 – 15). Saturation margins are shown over time as plots for each individual sensor (Figs. 16 – 18)

As might be expected based on the %RH findings for the three walls, the brick wall at Shrewsbury has the widest saturation margins,

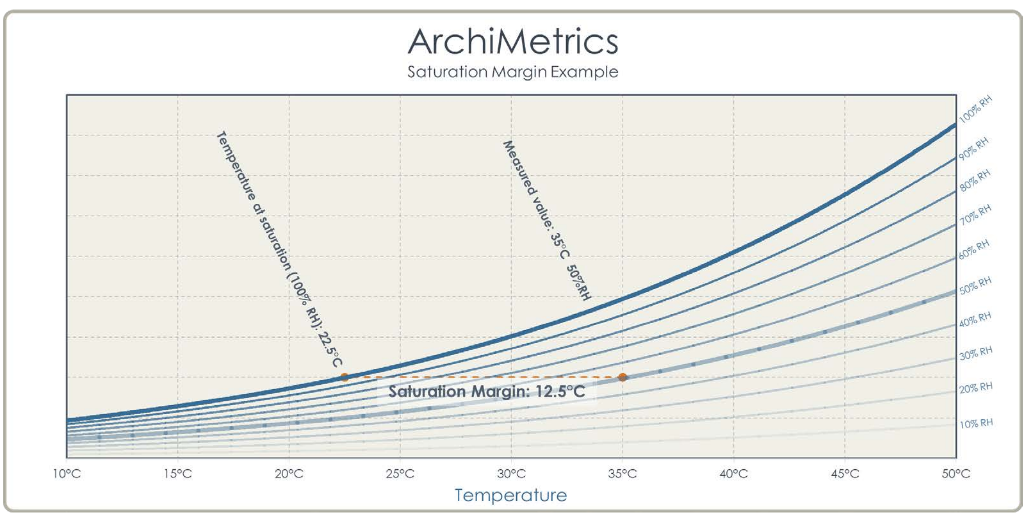


Figure 12
Illustration of Saturation Margin principle

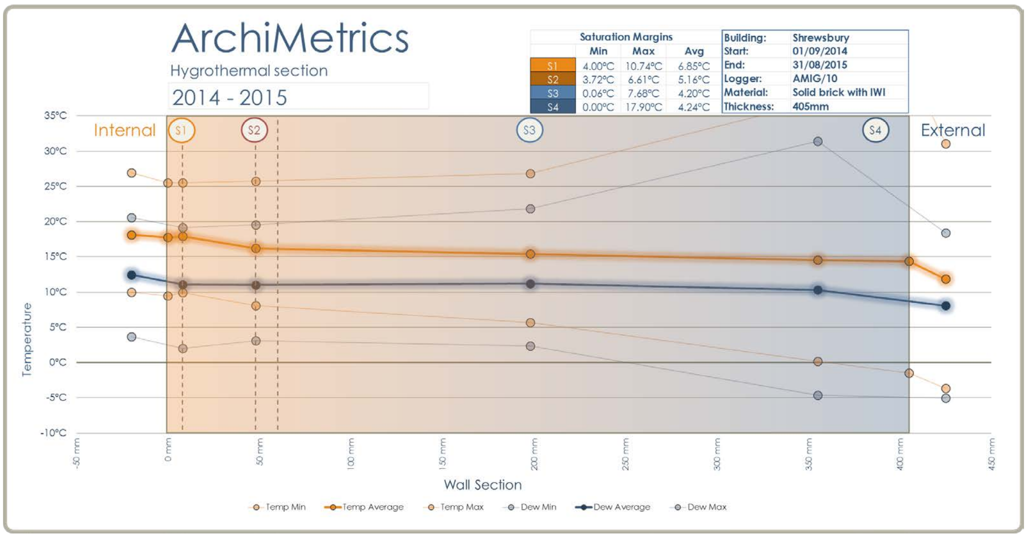


Figure 13
Hygrothermal Section, Abbeyforegate, Shrewsbury 2014 – 2015 (capped).

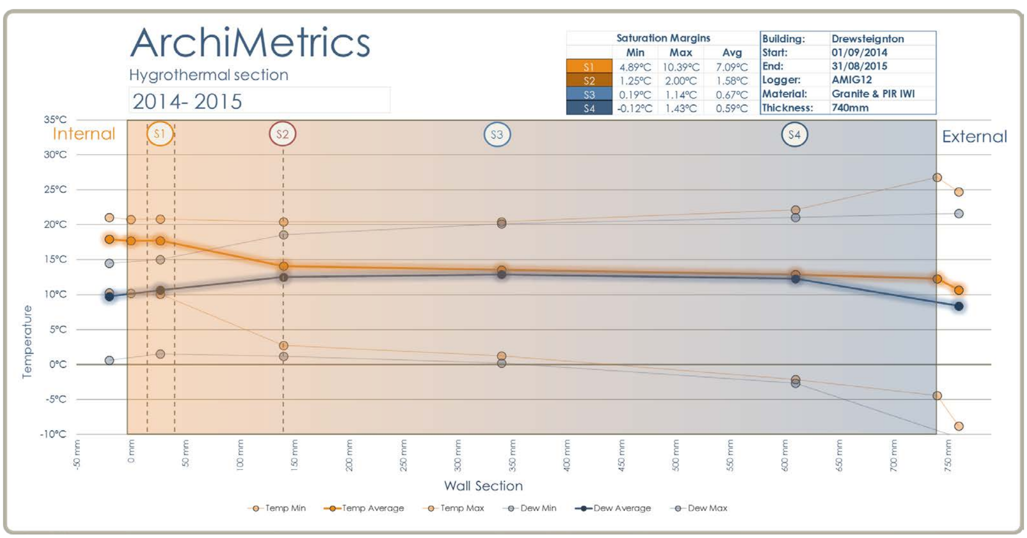


Figure 14
Hygrothermal Section, Mill House, Drewsteignton, 2014 – 2015 (capped).

Figure 15
Hygrothermal Section,
The Firs, Riddlecombe,
2014 – 2015.

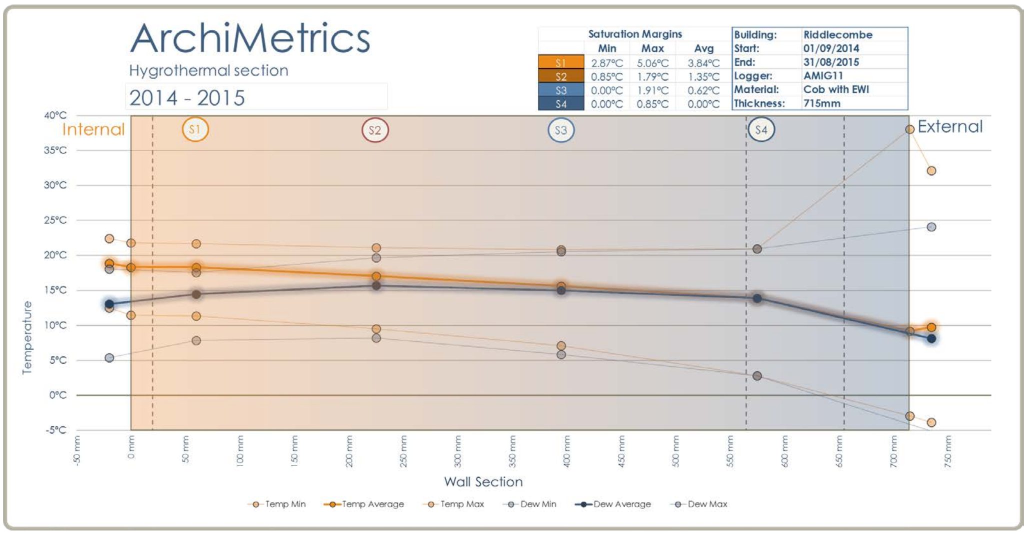
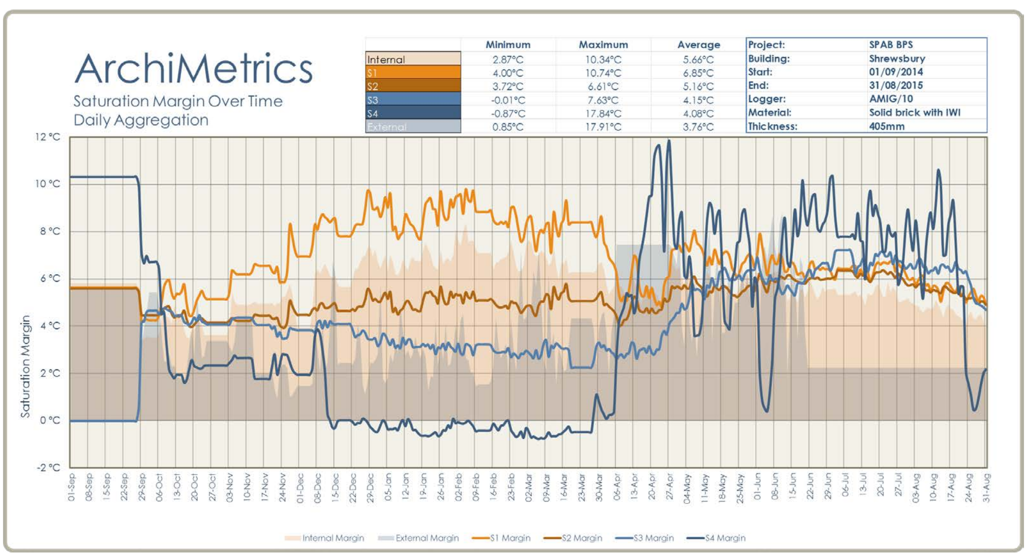


Figure 16
Saturation Margin over
time, Abbeyforegate,
Shrewsbury
2014 – 2015.



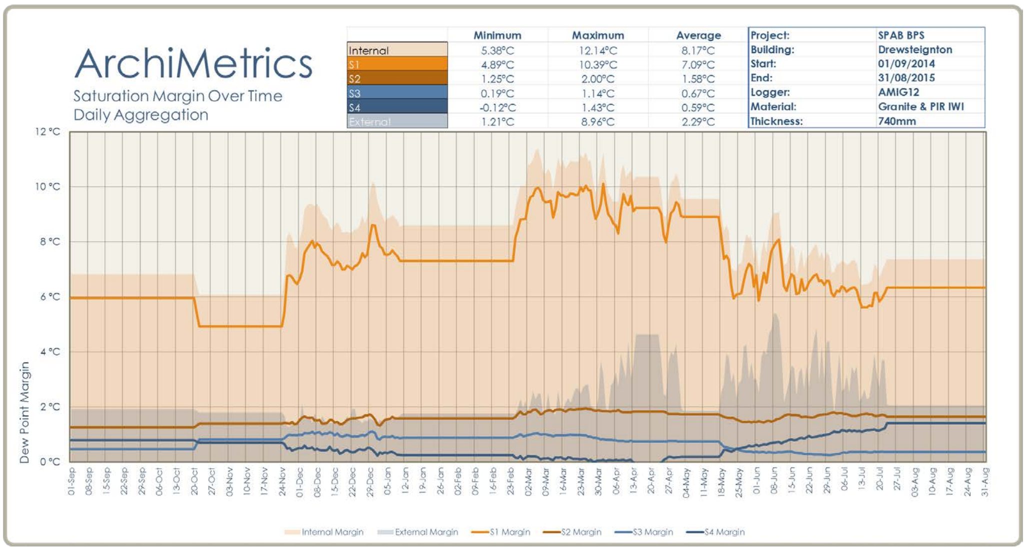


Figure 17
Saturation Margin Over Time, Mill House, Drewsteignton, 2014 – 2015.

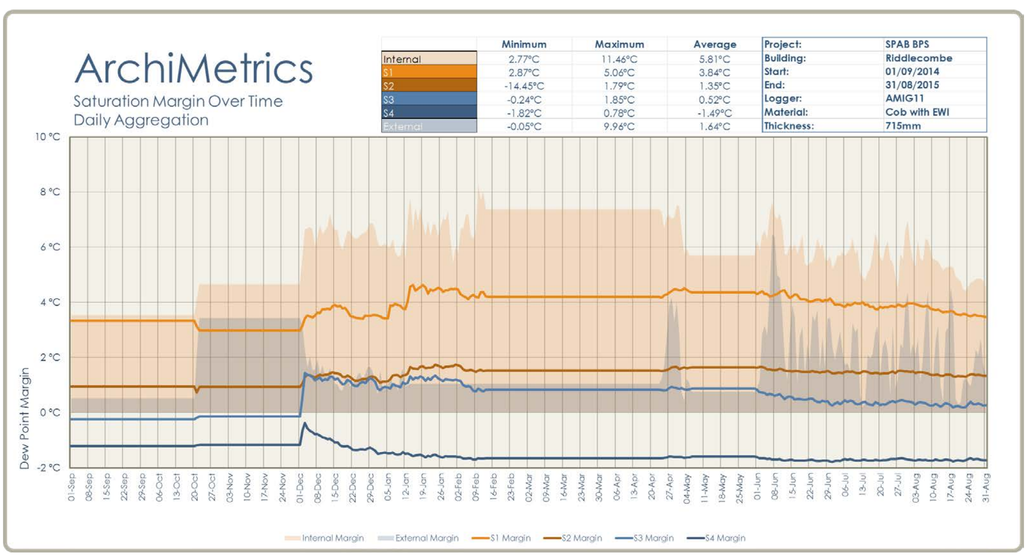


Figure 18
Saturation Margin over time, The Firs, Riddlecombe, 2014 – 2015.

indicating that on average this wall is several degrees away from dewpoint through the year. In contrast, Figure 14, for the granite wall at Drewsteignton, shows, on average, near convergence of the temperature and dewpoint gradients at sensors 2, 3 and 4, through the masonry section of the wall throughout the year. There is complete convergence at sensor 4 for the cob wall at Riddlecombe indicating saturation conditions at this location for this wall and only a narrow margin of temperature and dewpoint difference at next sensor location, sensor 3. The plots of saturation margins overtime (Figs. 16 – 18) show how close the air in particular parts of the various walls is to saturation at specific times of year. There is a period over winter where sensor 4, at Shrewsbury, is influenced by the wet and cold conditions and records negative saturation margins. Importantly, however, these margins show a rapid improvement over the spring and summer months when the wall material is able to evaporate moisture leading to 'safe' margins of 4 – 5°C degrees for the wall when factored on an annual basis. The wall at Drewsteignton looks very different. There is no period of time over the year that provide negative margins but all three sensors embedded within the granite section of the wall show margins of below 2°C for the entire period of the year. Whilst there is a slight improvement in margins at sensors 2 and 4 over the warmer summer, margins decrease at sensor 3 at the centre of the wall. Sensors 2, 3 and 4 in the cob wall at Riddlecombe also do not go above 2°C during the whole year and indeed margins at sensor 4 arenegative through the whole period, without the recovery seen in the brick wall at Shrewsbury. Margins also narrow during the warmer summer months, as they do at sensor 3 in the wall at Drewsteignton.

Table 6 shows the annual average saturation margins for the three walls in the survey. Blue shading indicates decreases in saturation margins and orange shading increases in margins year-on-year.

The saturation margin quantifies the temperature drop required for dewpoint conditions to be reached within the wall. It can be used as an indication of risk, that is the risk of air in the wall being at saturation (100% RH or dewpoint). This may also, at times, be an indication of wet fabric in proximity to the measurement sensor. Table 6 shows saturation margins as annual averages and so indicates the general condition of the wall in relation to proximity to dewpoint. From this it can be seen that, following both the RH and AH vapour trends, post-insulation margins at Shrewsbury are greater than those at Drewsteignton and Riddlecombe, indicating on average drier and 'safer' conditions as a greater temperature drop is required before dewpoint may be reached. Saturation margins at Drewsteignton and Riddlecombe are much narrower post-insulation, particularly at sensor positions 2, 3 and 4 away from the internal wall face and the benefit of interior heating during the colder winter months. In both these walls, at sensors 3 and 4, saturation margins are below that of 1°C and given that these are average values we can speculate that temperature drops of this order occur frequently particularly over the winter time suggesting these walls are at greater risk from periods of saturated air. Indeed averages from sensor 4 at Riddlecombe over the past two monitoring years show dewpoint as the predominant condition suggesting that material here is likely to be wet.

The trend in these margins as indicated by the shading in the table also follows those indicated by an analysis of RH (this is to be expected as saturation margins are calculated from measurements of %RH). There has been a general increase in the margins for the wall at Shrewsbury reflecting warmer temperatures and fewer instances of driving rain leading to a reduction in wetting and also more effective drying over the past year. These factors, to a lesser extent can perhaps also be seen at play in the wall at Drewsteignton where margins at the periphery have slightly increased. In contrast those at the centre of the wall, sensors 2 and 3, continue to reduce in line with the trend of rising RH found for this part of the wall suggesting that the moisture risk is increasing in the middle of the wall and immediately behind the PIR insulation. Riddlecombe has the narrowest margins of

Annual Average Sat. Margins	**Sensor 1**	**Sensor 2**	**Sensor 3**	**Sensor 4**
Shrewsbury				
2011	6.46°C	6.41°C	5.12°C	3.96°C
2012 – 2013	6.34°C	5.08°C	4.3°C	3.08°C
2013 – 2014	6.33°C	5.00°C	4.08°C	3.45°C
2014 – 2015	6.85°C	5.16°C	4.20°C	4.24°C
Drewsteignton				
2011	5.3°C	4.82°C	3.53°C	2.38°C
2012 – 2013	5.6°C	2.23°C	1.53°C	0.57°C
2013 – 2014	6.9°C	1.97°C	1.14°C	0.49°C
2014 – 2015	7.09°C	1.58°C	0.67°C	0.59°C
Riddlecombe				
2011	5.57°C	3.22°C	2.06°C	0.6°C
2012	5.19°C	1.4°C	0.35°C	0.03°C
2013 – 2014	3.97°C	1.55°C	0.23°C	0.00°C
2014 – 2015	3.84°C	1.35°C	0.62°C	0.00°C

Table 6
Annual Average Saturation Margins for all Interstitial Sensors 2011 – 2015.

all and no margin at all at sensor 4. In this sense there is nothing to quantify here in terms of how close the air is to saturation – it appears to be permanently saturated. Whilst margins at sensors 2 and 3 are quite small indicating a greater risk of saturation at these locations, there may also be a slight but encouraging trend if one accepts the premise that the vapour load is largely the result of the vaporisation of construction moisture. In these circumstances the increase in the margin measured at sensor 3 and the decrease in margins at sensors 1 and 2 as a result of vapour movement may indicate that moisture bound in to the centre of the walls is slowly beginning to dry out. Therefore, whilst the risk of saturation is still high in this wall we might be able to expect this to decrease over time.

Summary and conclusions

Since 2011, the three walls in the SPAB Building Performance Survey have been subject to long-term interstitial hygrothermal gradient monitoring (IHGM) – measurements of temperature and relative humidity (RH) made through and either side of a wall section.. As this research continues the value of long-term detailed measurements becomes increasingly apparent. Certain trends and tendencies are revealed as more or less significant depending on the different, and at times competing, influences on the moisture profiles of the walls.

The thinner, south-facing porous brick wall at Shrewsbury is insulated internally with 40 mm of woodfibre board with a lime plaster finish. Of the three walls under study, it has the lowest rates of %RH, AH g/m^3 and the widest saturation margins. Vapour responses in this wall are very dynamic and at times quite extreme and this is due to the nature and orientation of the construction. The external side of the wall quickly becomes wet and during periods of driving rain and this moisture can penetrate towards the centre of the wall. However, the wall also dries out rapidly due to heat from direct (and diffuse) solar radiation and plentiful air exchange through the substrate. It is noticeable that despite this volatility overall the wall operates below the 80% RH threshold for mould growth and has the narrowest range of annual averaged RH responses of the three walls. It is possible that the hygroscopic qualities of the woodfibre insulation added to the wall makes a positive contribution to this vapour profile by 'buffering' humidity and flattening out RH responses especially around the sensor 2 location. It is also possible that the quantity of insulation installed, which reduced the measured *in situ* U-value from 1.48 W/m^2K to 0.48 W/m^2K, ensures that whilst the passage of heat through the wall is reduced sufficient heat still travels from interior to exterior during colder winter periods to provide a safe margin between the measured air temperature and dewpoint temperature.[3]

The wall at Drewsteignton in Devon is quite different being a north-west-facing, 600mm thick granite construction internally insulated with 100mm of PIR board finished with a plaster-board dry lining. In this wall we find higher measurements of %RH, AH g/m^3 and narrower saturation margins, °C. Within the original masonry element of the wall, on the cold side of the insulation, there are on average measurements of %RH above 80%, the threshold for mould growth. We also find, over the past three years, a trend of rising humidity within the centre of the wall which year-on-year moves this part of the wall closer to saturation conditions. As this trend has continued over a number of years now, we can perhaps surmise that the high vapour within the wall is not solely a response to atmospheric conditions but is also a function of certain qualities of the construction that might limit or inhibit drying in this wall. This may be down to the heavyweight nature of the wall and its aspect, but vapour profiles have climbed since the wall was insulated and have not returned to pre-insulation levels, suggesting that the insulation itself maybe having some impact on the wall's performance. The greater quantity of more thermal resistive insulation (which reduced the *in situ* U-value measured from this construction from 1.20 W/m^2K to 0.16 W/m^2K) in comparison with that of Shrewsbury, ensures that less heat passes into the cold side of the masonry during the winter period, thus saturation margins are lower. Thus, air is more likely to become saturated and remain saturated for longer periods, limiting drying potential. The foil-facing of the PIR board acts as a barrier to moisture, therefore the movement of moisture in this wall is restricted and its access to a potential evaporative surface is limited as moisture can no longer move to the interior side of the wall.

The south-facing 655 mm cob wall at Riddlecombe is externally insulated with 60 mm of a lime-based external insulating render that incorporates perlite. Riddlecombe has the highest vapour profiles, %RH and AH g/m^3, of the three walls in the study. It also has the smallest or no saturation margins °C. Responses measured in this wall differ from those of the other two walls in the study largely we believe because the most significant factor with regard to vapour behaviour here is construction water. Findings of unseasonal, persistent and rising %RH over summer months suggested substantial vaporisation of moisture within the earth wall material occurring as a result of the heating of the wall by solar radiation, something which this year's solar analysis, Figure 11, has confirmed. The question remains whether this wall is able to reduce its internal moisture load via vaporisation and evaporation? For the first time this year we see a reduced annual average measurement of %RH at sensor 3 and a wider saturation margin implying that residual material moisture at this location may have fallen. This year measurements of vapour at sensors 1 and 2, towards the internal side of the wall, have increased and this may be due to the movement of vapour from the centre of the wall towards the internal wall surface. Over the three years it is now also possible to see a trend of %RH reduction at both sensors 2 and 3 over time, which also implies a possible gradual drying of the interior wall material. This drying is taking place very slowly, possibly inhibited by the thickness of the external render and the very air-tight cob construction. However, this wall also shows very high records of %RH and a static 0°C saturation margin over the whole three years towards the external side of the wall at sensor 4, indicating that the wall continues to be wet at this location.

In conclusion, we find that as well as the influences of external and internal climate the performance of these walls is conditioned by their individual material components and context, including changes made to the fabric in pursuit of energy efficiency. Interstitial condensation has been a particular concern with regard to the internal insulation of solid walls as the application of insulation to the internal face of the wall inevitably deprives the wall of heat during the heating season, thus making dewpoint conditions more likely to occur on the cold side of the wall. Conventional treatments for this potential problem come in the form of a vapour control layer (VCL) installed in tandem with insulation which excludes or limits the passage of internally generated vapour through the wall. There is no formal VCL within the wall build up at Shrewsbury (although the lime plaster and woodfibre insulation may condition vapour movement through the wall), yet this internally insulted wall has stable vapour responses that operate within safe limits. In contrast the VCL at Drewsteignton may be one of the causes of the high and rising humidity measured in this internally insulated wall. The externally insulated wall at Riddlecombe is different again as here we see the effects of moisture deliberately added to a wall and the extreme effects this can have on moisture profiles as well as the prolonged period of time over which any necessary drying may take place.

These three examples show there are other important factors that can arise as a result of wall insulation aside from the threat of interstitial condensation caused by internal vapour diffusion. The risks from moisture in these solid walls more often than not originate from the exterior in the form of atmospheric moisture (rain, wind-driven rain, ground water etc) or can be of human origin in the case of Riddlecombe. In these circumstances, as with that of interstitial condensation, the crucial question is can the fabric moderate these influences over time to keep moisture within safe and comfortable limits with regard to structural stability, human health and a pleasant living environment? In Shrewsbury we have an example where the competing demands to keep heat in do not, so far, appear to have compromised the ability of the wall to dry excess moisture. The examples of Drewsteignton and Riddlecombe are less resolved. Some slow improvement in humidity levels has been found for the cob wall at Riddlecombe. Drewsteignton, with its increasing vapour profile, seems more unsatisfactory.

This research may not offer definitive proof as to the suitability of certain techniques and materials with regard to the insulation of solid walls. It does, however, through the practice of long-term detailed measurement, indicate trends for moisture behavior in particular walls. The analysis provides explanations for the particular drivers that may condition moisture behaviours and an explanation as to why these might differ between the three walls under study.

It is thought that this research represents the earliest and hence, thus far, the longest measured study of the effects of insulation on solid walls in the country. Modelling suggests that the risks to these walls may only emerge after significant periods of time have elapsed, perhaps decades, as it is these durations that are required for moisture to accumulate within fabric to levels that represent a risk.[4] Measured over the past four years and conditioned, as they are, by the individual circumstances of the three buildings, the results from the SPAB BPS suggest that some insulation strategies represent a greater risk to particular building forms. In the absence of definitive proof such evidence is of important value for those who wish to adopt a precautionary principle with regard to improving the energy efficiency of older properties. This study demonstrates that it is possible to make positive changes to the energy efficiency of solid walls through the application of solid wall insulation but that an approach that favours limited improvements to heat loss through fabric and more vapour-open materials may introduce less risk than alternative strategies.

Endnotes

1 B. Boardman et al's publication *40% House* being perhaps the most well know document to suggest large-scale demolition of this class of buildings, (2005). 40% House. Oxford: University of Oxford Environmental Change Institute.

2 Department for Communities and Local Government. (2010). *Approved document F: Ventilation.* London: NBS and *Altamirano-Medina H., Mumovic D., Davies M., Ridley I., Oreszczyn T. (2009). Guidelines To Avoid Mould Growth In Buildings, Advanced Buildings Energy Research, 3, 221-236.* being two examples of such documents.

3 The pre and post insulation measured in situ U-values for the three walls are given in the *SPAB Building Performance Survey Report 2011*. It is important that these U-values have been measured rather than derived from the standard calculating method as this method has been shown to have limitations with regard to the estimation of heat loss for solid walls, see previous SPAB research; *The SPAB U-value Report 2010* (rev. 2012), Dr P. Baker *Technical Paper 10: U-values and traditional buildings*. Edinburgh: Historic Scotland and recent research by the Building Research Establishment.

4 See *Responsible Retrofit of Traditional Buildings Report,* Sustainable Traditional Buildings Alliance STBA, (Department of Energy and Climate Change) 2012.

Acknowledgements

The SPAB would like to thank the owners of the properties used in the SPAB Building Performance Survey: James Ayres, Jason & Doe Fitzsimmons and Sebastian & Rosemary Payne. We are also grateful to Paul Bedford and Stephen Bull of the SPAB Technical Panel, and Dr Chris Sanders and Dr Paul Baker of Glasgow Caledonian University for their assistance in the preparation of this document. We would particularly like to thank Historic England for its support of the monitoring and reporting work via its HERITAGE PROTECTION COMMISSIONS grant.

This research is conducted on behalf of the SPAB by ArchiMetrics Ltd.

Supported by:

Historic England

RIBA President's Awards for Research 2016 – Shortlisted

Edited by Dr Kat Martindale