Historic England

SPAB Building Performance Survey 2013

Interim Report
October 2013

Dr Caroline Rye, Cameron Scott and Diane Hubbard
Society for the Protection of Ancient Buildings
Supported by Historic England

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THE SPAB RESEARCH REPORT 2

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Foreword

This report is the third in a series which details the interim findings of the SPAB's Building Performance Survey, a research project that looks at the performance of a number of traditional buildings both before and after refurbishment designed to improve energy efficiency. This report is the second to provide details of post-refurbishment performance in four of the buildings within the survey. The report is in two parts: The first part sets out the background to the project, provides an update of progress and is followed by a summary discussion of findings so far. The second part, called Appendix A, is formed of individual documents that report in detail from the four refurbished properties studied over the past year. Further background information, including details of the monitoring procedures and data processing used in the study can be found in the first version of this report, *SPAB Research Report 2: The SPAB Building Performance Survey 2011 Interim Report*.

The SPAB would like to thank all the owners of the properties used in the SPAB Building Performance Survey and particularly James Ayres, Jason Fitzsimmons, Sebastian Payne and the Andrews family whose houses are the focus of this particular report. We are also grateful to Paul Bedford, Stafford Holmes and Stephen Bull of the SPAB Technical Panel and Dr Paul Baker and Dr Chris Sanders of Glasgow Caledonian University for their assistance in the preparation of this document. In addition we would like to give particular thanks to the Dartmoor National Park Authority for their continued support throughout this project through their Dartmoor Sustainable Development Fund and also to English Heritage for their support of the 2012 monitoring and reporting work.

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1. INTRODUCTION

In the winter of 2011 the SPAB embarked upon a research study to assess the performance of seven traditional buildings that were subject to various energy efficiency refurbishment methods. Measuring across a range of parameters, the study looks at the ways the energy performance and environmental behaviour of traditionally-built dwellings may be affected by this refurbishment. Specifically the study looks at:

- Fabric heat loss through the U-value measurement of wall elements both in the form of *in situ* and calculated U-values,
- Air infiltration through air permeability testing and thermographic survey,
- Moisture behaviour; room and wall moisture including wall surface, sub-surface and interstitial moisture via hygrothermal monitoring and
- Indoor air quality, comfort levels and fabric risk through the measurement of CO_2, interior temperature and relative humidity.

During a two week period between January and April 2011 measurements were taken of the seven properties whilst in an 'unimproved' condition. Following this pre-refurbishment assessment, in 2012, we returned to four of the properties that had completed their refurbishment work to repeat our measurements and install long term interstitial hygrothermal gradient monitoring (IHGM - measurements of temperature and relative humidity through, and either side of, a wall section). The previous 2012 edition of this report, *SPAB Research Report 2: The SPAB Building Performance Survey 2012 Interim Report,* provided details of fabric heat loss, air permeability, moisture behaviour, indoor air quality and comfort/risk conditions in three buildings; Shrewsbury, Drewsteignton and Riddlecombe[1]. This 2013 Interim report provides findings from the long-term on-going IHGM monitoring at

these three properties as well as findings from the post-refurbishment measurements of fabric heat loss, air permeability, moisture behaviour, indoor air quality and comfort/risk conditions for the property in Skipton.

[1] In 2013, following findings, in 2012, of high moisture levels in the cob wall of the house at Riddlecombe an expanded study of this property was initiated in collaboration with English Heritage and the Devon Earth Building Association. Details of the results of this work will be reported in a separate case study publication.

2. PROJECT BACKGROUND AND UPDATE

All the buildings included in the Building Performance Survey conform to the definition of a 'traditional building' provided by, amongst others, English Heritage[2] that is to say they are of pre-1919 origin and consist of solid walls built of permeable materials without the use of a damp-proof course or similar moisture breaks or barriers. The buildings span a variety of materials including brick, sandstone, limestone, granite, slate-stone and cob and are quite widely distributed within England, with a cluster concentrated within the south-west as a reflection of the funding provided by the Dartmoor National Park Authority (Figure 1).

Figure 1. Map showing distribution of the SPAB Building Performance Survey Properties.

The properties were chosen as they were all intended to be refurbished within the timespan of the project and although this refurbishment work may not have been exclusively driven by the desire to improve energy performance and comfort levels, this was articulated as one of the primary motivating forces for the changes planned for the individual buildings. The refurbishment work planned for, or undertaken, on most of these properties, with the exception of Drewsteignton, has been the responsibility of their owners or agents, such as surveyors or architects, acting on behalf of the owners.

[2] This definition is given in English Heritage's publication *Energy Efficiency and Historic Buildings* (p. 17) and can also be found in the Building Regulation's Approved Document Part L1B & L2B *Conservation of Fuel and Power 2010*, 3.8,c and the *Scottish Building Regulations Technical Handbooks.*

In the winter of 2011, whilst embarking on this study, most home-owners expected to have completed their refurbishment work within a 12 month period. However, by the following winter, 2012, only three of the seven buildings had reached some form of completion sufficient to allow post-refurbishment measurements to be carried out. Work in many of the properties has carried on in varying degrees through 2012 and 2013, particularly where extensions have been included as part of the work programme. In 2013 wall finishes at Skipton had dried out sufficiently to allow measurements of in situ U-values and surface and sub-surface moisture to take place and it is only now, in October 2013, that the property is in a condition to allow a second air permeability test to be completed. The property at Drewsteignton is undergoing a major re-building of the modern 1970s extension at the rear of the property. This work is on-going. However, for monitoring purposes, in 2012, the owners allowed us to insulate a section of the solid granite wall in the office room of the property using PIR insulation. This location, in the older part of the dwelling, coincides with the site of the pre-refurbishment measurements made at this house and since 2012 has been the site for the long-term IHGM monitoring.

3. RESULTS AND DISCUSSION

A summary of the results of the post-refurbishment monitoring at - Shrewsbury, Riddlecombe, Drewsteignton and Skipton - including comparisons between the four properties and with findings from the pre-refurbishment monitoring carried out in 2011, is provided below. Appendix A contains individual reports from each of the four properties with a detailed commentary and further comparisons on the findings from the monitoring at each building over the past 12 months. For details of previous monitoring including pre-refurbishment results please consult the earlier versions of this report published in 2011 and 2012.

Fabric Heat Loss (U-values)

Following the refurbishment of the walls at the four properties; Shrewsbury, Riddlecombe, Drewsteignton and Skipton, reductions in heat loss measured and calculated as U-values have been noted at all cases. Three of the properties have added internal wall insulation (IWI); Shrewsbury in the form of 40mm of woodfibre board, Skipton via 40mm of hemp/lime plaster and the test wall at Drewsteignton following the application of 100mm of polyisocyanurate (PIR) insulation. The cob wall at Riddlecombe has been externally insulated using 50mm of lime-based insulating render. The measured and calculated U-values for the walls, both pre and post-refurbishment, and are given in Table 1 along with the changes in U-values quantified as percentages.

Location	2011 Measured Un-insulated W/m^2K	2012/13 Measured Insulated W/m^2K	% Reduction	2011 Calculated Un-insulated W/m^2K	2012/13 Calculated Insulated W/m^2K	% Reduction
Shrewsbury South wall	1.48	0.48	68%	1.52	0.59	61%
Shrewsbury West wall	2.06	0.63	70%	1.71	0.62	64%
Drewsteignton	1.24	0.16	87%	2.45	0.19	**93%**
Riddlecombe	0.76	0.72	4%	0.95	0.56	**41%**
Skipton (low)	1.63	0.97	40%	2.31	1.72	26%
Skipton (high)	1.62	1.04	36%	2.31	1.72	26%

Table 1. Measured and Calculated U-values and % Reductions of pre and post-refurbishment walls from the SPAB Building Performance Survey.

The results presented in Table 1 are from walls of different widths made of different materials and refurbished with different insulation products applied at different thicknesses, therefore no direct comparisons between these figures can be made. However, the percentage reductions in each case are of interest. Both the internally insulated walls at Shrewsbury and Drewsteignton have seen considerable reductions in measured heat loss, at Shrewsbury this reduction has been in the order of 68% and 70% and at Drewsteignton an 87% reduction in heat loss is recorded. The wall insulated with hemp/lime plaster at Skipton shows a smaller average percentage reduction for heat loss of 38% which is understandable as this product is not exclusively an insulating one but combines the roles of an internal finish with some thermal benefit. The external render used at Riddlecombe is similar to that of Skipton in that the product combines a finish with some insulative properties, however, the lime render used at Riddlecombe has only measured a 4% reduction in heat loss for the wall at this location. The superior percentage reduction for the wall at Drewsteignton compared with that of the other internally insulated walls is a result of the additional width of insulation material used at Drewsteignton, 100mm as opposed to 40mm and the lower conductivity of the PIR board, 0.022 W/mK in comparison with that of 0.039 W/mK for woodfibre board and 0.2 W/mK, the conductivity given by the manufacturers for hemp/lime plaster.

In Table 1, with the exception of the west wall at Shrewsbury, the U-values calculated for the walls pre-insulation follow a common trend; there is a tendency for a calculated U-value to overestimate the thermal transmissivity of the wall[3]. Following insulation, of the six sample walls in Table 1, the calculated U-value for the wall at Riddlecombe is the only significant occasion when a calculated U-value is lower than that of a measured value. Therefore, once again, the tendency, post refurbishment, is that the measured *in situ* U-value seems to be of a lower number value than its calculated equivalent, probably as a result of the heat loss, or inversely the thermal resistance of the original part of the wall, not being fully accounted for within a calculated U-value. However, the pattern of discrepancy between measured and calculated pre and post insulation U-values is not consistent. That is to say, if a wall exhibits a significant difference between the two forms of U-value quantification before insulation the same difference is not necessarily replicated in this wall post insulation.

Location	**2011 Measured Un-insulated W/m^2K**	**2011 Calculated Un-insulated W/m^2K**	**% Difference**	**2012/13 Measured Insulated W/m^2K**	**2012/13 Calculated Insulated W/m^2K**	**% Difference**
Shrewsbury South wall	1.48	1.52	3%	0.48	0.59	19%
Shrewsbury West wall	2.06	1.71	17%	0.63	0.62	2%
Drewsteignton	1.24	2.45	49%	0.16	0.19	16%
Riddlecombe	0.76	0.95	20%	0.72	0.56	22%
Skipton (low)	1.63	2.31	29%	0.97	1.72	44%
Skipton (high)	1.62	2.31	30%	1.04	1.72	40%

Table 2. Percentage Difference between measured and calculated U-values in pre and post-refurbishment walls from the SPAB Building Performance Survey.

For example, in Table 2, the wall at Drewsteignton displays the greatest percentage difference between measured and calculated U-values prior to insulation, 49%. Yet this difference is reduced to 16% post insulation most likely as the result of the over-riding contribution made to the thermal transmissivity of this wall by the insulating layer. This insulation is of known quantity and conductivity and therefore its contribution to thermal performance can be accurately reflected in a calculated U-value. If this insulating layer also represents a significant contribution to the overall performance of the wall, as is suggested by the percentage reduction in U-value measured for this wall of 87% (Table 1) the calculation is more likely to be aligned with the measured U-value for this wall post-insulation. However, at another location,

[3] See Rye, C. Scott, C. (2010). *The SPAB Research Report 1: The U-value Report*. Revised 2011. London: The Society for the Protection of Ancient Buildings and Baker, P. (2011). *Technical Paper 10 - U-values and Traditional Buildings*, Edinburgh: Historic Scotland

Skipton, this pre and post measured and calculated U-value discrepancy is reversed, here there is closer correlation between measured and calculated U-values pre-insulation, albeit in the order of a 30% difference, but this difference post insulation increases to around 42%. Therefore, in contrast to what was suggested in the previous version of this report, 2012, it is not always the case that there will be better correlation between measured and calculated U-values for solid walls post insulation as the degree of correlation is determined by a number of factors: principally the contribution of the insulating layer to the overall thermal transmissivity of the wall. Therefore, in the case of the wall at Skipton, the measured improvement in wall U-value pre and post insulation is much smaller than that found at Drewsteignton, around 38%. Thus, the contribution of the insulating hemp/lime plaster layer, which may also not be fully dry, in the build up of the wall at Skipton may be roughly less than half of that of other components within the wall. This may explain why there is still quite a large discrepancy between the measured and calculated U-values post refurbishment at Skipton, as the thermal performance of the original wall still exerts a significant influence on overall thermal transmissivity and this contribution continues to be underestimated within the calculation. Furthermore, as the discrepancy between the measured and calculated U-values for the insulated wall at Skipton is even greater than that found between measured and calculated U-values prior to insulation (42% compared to 30%) this also suggests that the thermal conductivity of the additional insulating layer, the hemp/lime plaster, may not be particularly well defined within the calculation.

Riddlecombe is the only example within Tables 1 and 2 where the post insulation calculated U-value is lower than that of the measured U-value and where very little change is seen between pre and post measured in situ U-values; 0.76 - 0.72 W/m^{2}K. In the winter of 2013 an additional in situ U-value was measured on another ground floor wall at Riddlecombe of equivalent thickness and construction, this measurement returned a U-value of 0.46 W/m^{2}K much closer to the post-insulation U-value calculated for this wall build-up, 0.56 W/m^{2}K and an improvement upon the U-value measured from the office wall of 0.72 W/m^{2}K (Table 2). As was detailed in previous versions of the Building Performance Survey Report (*SPAB Research Report 2: 2011 & 2012*) the office wall was suspected of having a raised moisture content and high and rising interstitial %RH. Monitoring carried out over 2012 - 2013 has found that these conditions have persisted and indeed worsened within the measured section of wall (more details about this can be found in the Moisture section of this report). Therefore the thermal performance of the wall maybe compromised by the high moisture content of the cob material which will make the element more thermally conductive.

Air Permeability

White House Farm at Skipton was the only property to have progressed sufficiently to have the post refurbishment air permeability testing and thermographic survey carried out during 2013, with testing carried out on 10 October 2013. Post-refurbishment tests had previously been carried out at 116

Abbeyforegate, Shrewsbury and The Firs, Riddlecombe during 2012 on 15 February and 17 February respectively.

	Units	Shrewsbury		Riddlecombe		Skipton	
		2011 Pre-refurbishment	**2012 Post-refurbishme**	2011 Pre-refurbishment	**2012 Post-refurbishme**	2011 Pre-refurbishment	**2013 Post-refurbishme**
Whole dwelling							
Internal floor area	m^2	60	**60**	86	**86**	190	**298**
Habitable	m^3	134	**134**	189	**189**	458	**718**
Dwelling	m^2	185	**185**	245	**245**	401	**567**
Measured air flow	m^3h^{-1} @50	2106	**1570**	1355	**1308**	6789	**6181**
Air permeability test result	$m^3h^{-1}m^{-2}$ @50 Pa	11.4	**8.5**	5.5	**5.4**	16.9	**10.9**
Air changes per hour @ 50Pa	ach @50 Pa	15.7	**11.7**	7.2	**6.9**	14.8	**8.6**
Estimated ach through infiltration	ach	0.8	**0.6**	0.4	**0.3**	0.7	**0.4**
Part of dwelling							
Description		Extension		Original cottage			
Internal floor area	m^2	17	**17**	54	**54**		
Habitable	m^3	41	**41**	124	**124**		
Envelope area	m^2	81	**81**	184	**184**		
Measured air flow	m^3h^{-1} @50	520	**459**	927	**924**		
Air permeability test result at	$m^3h^{-1}m^{-2}$ @50 Pa	6.4	**5.6**	5.0	**5.0**		
Air changes per hour @ 50Pa	ach @50 Pa	12.8	**11.3**	7.5	**7.5**		

Table 3. Comparison of air permeability results for Shrewsbury, Riddlecombe and Skipton before and after refurbishment. Note: The 2011 test on Skipton was not carried out on the full area of the dwelling.

Air Infiltration

The results of the post refurbishment air permeability testing for Shrewsbury, Riddlecombe and Skipton are summarized in Table 3. The air permeability result for Skipton is 10.9 $m^3h^{-1}m^2$ @ 50 Pa, which is slightly above the limiting air permeability under Approved Document L1A 2010 for new build dwellings (10 $m^3h^{-1}m^2$ @ 50 Pa). For Shrewsbury and Riddlecombe, the post refurbishment test results are 8.5 $m^3h^{-1}m^2$ @ 50 Pa and 5.4 $m^3h^{-1}m^2$ @ 50 Pa respectively, both below the limiting air permeability for new build dwellings. At Skipton it should be noted the pre-refurbishment test was carried out in February 2011 and the post refurbishment test in October 2013. Stephen[4] identifies there can be a seasonal variation in airtightness, with an increase in infiltration in the winter. All other air permeability tests for the SPAB Building Performance Survey have been carried out between January and March in order to eliminate this potential variation.

The post refurbishment air permeability tests for Shrewsbury and Skipton display a significant improvement from the pre-refurbishment results in 2011 (from 11.4 $m^3h^{-1}m^2$ @ 50 Pa to 8.5 $m^3h^{-1}m^2$ @ 50 Pa and 16.9 $m^3h^{-1}m^2$ @ 50 Pa to 10.9 $m^3h^{-1}m^2$ @ 50 Pa respectively). It should be noted that at Skipton, the pre-refurbishment test was not for the building as a whole – a modern addition which was due to be demolished was excluded, together with one bedroom in the farmhouse and the utility room, which was to be remodeled. The post-refurbishment test was for the whole building. For Shrewsbury and Skipton, the air permeability result reflects the state of the dwelling at the time of the 2011 test, with the exterior wall of the first floor room unplastered at Shrewsbury and the plaster removed from the Dining Room walls at Skipton and the upgrading subsequently carried out in both properties. There were still items requiring completion in both properties at the time of the post-refurbishment test which adversely affect the air permeability result, such as the open stone and block work around the doorway between the main bedroom and its bathroom and the missing window sills in the new addition at Skipton. At Shrewsbury, the items requiring completion were an exterior ground floor wall requiring plastering over insulation, missing windows sill to the first floor window and floor repairs. There is therefore merit in considering a further test for both of these properties after completion of these items.

For Riddlecombe, the improvement in air permeability between the pre and post-refurbishment tests is less significant (5.5 $m^3h^{-1}m^2$ @ 50 Pa to 5.4 $m^3h^{-1}m^2$ @ 50 Pa) due to the building already being relatively airtight and the limited scope of the draught proofing measures.

[4] Stephen, R. (2000) Airtightness in UK dwellings IP1/00. Watford: BRE p4

At both Shrewsbury and Riddlecombe in 2012, an attempt was made to separately test the original and newer components of the building. At Riddlecombe, this identified the older portion had a slightly better air permeability than the building as a whole (5.0 $m^3h^{-1}m^2$ @ 50 Pa compared to 5.4 $m^3h^{-1}m^2$ @ 50 Pa) and the addition at Shrewsbury had a superior result to the dwelling as a whole (5.6 $m^3h^{-1}m^2$ @ 50 Pa compared to 8.5 $m^3h^{-1}m^2$ @ 50 Pa). It was not possible to carry out a similar examination at Skipton because of the open-plan nature of the dwelling layout after refurbishment. However it should be noted there were significant infiltration points identified within the new addition during the thermographic survey under pressure test conditions. At Shrewsbury, it was possible to identify the effect of the secondary glazing installed as part of the refurbishment. It was closed during the testing, but when opened (leaving single-glazed windows), an increase in air flow through the whole property of 11% was noted.

The air change rate at Skipton reduced from 14.8 ach @ 50 Pa pre-refurbishment to 8.6 ach @ 50 Pa post-refurbishment. Translating these results to air changes per hour at ambient pressure, the 2013 test result gives a figure of just over 0.4 ach, compared to 0.7 ach in 2011. It is generally viewed that occupants and their activities require a ventilation rate of 0.4 - 0.5 ach. However this is a relatively large dwelling for 5 occupants and has ample automatic intermittent extract ventilation from the kitchen and bathrooms, so indoor air quality issues would not be anticipated. For Riddlecombe, the air change rate is lower (6.9 ach @ 50Pa, giving an air change rate at ambient pressure of just over 0.3 ach) and, compounded with a higher occupation density of 5 occupants in an 86m^2 dwelling, may present a problem without further means of ventilation in place.

Though flues are excluded from the standard test procedure some of the flues in the test properties have been examined. The two flues at Skipton have the same wood burning stoves in place for both the pre and post-refurbishment tests. One of the flues at Riddlecombe was tested as an open flue in 2012, when its wood burning stove had been temporarily removed, providing a relatively low additional air flow under the test conditions of 158 m^3h^{-1} @ 50 Pa[5]. This represents an increase in air flow through the whole dwelling of 12%. The air flow measured at Shrewsbury from the living room fireplace was substantially higher than at Riddlecombe (880 m^3h^{-1} @ 50 Pa) and provided an increase in airflow through the property as a whole under the test conditions of 56% (compared to 47% in 2011). This result highlights the fact that as the airtightness of a building improves, air flow relating to remaining flues becomes increasingly important. It should be noted the measured result under the test conditions will not relate directly to the air flows through chimneys, but offers a simple comparison.

[5] Hubbard, D.C. 2012. *Chimney balloons – a solution for rural fuel poverty?* Commissioned by Sustainable and Energy Network, Staveley (SENS) through the Department of Energy and Climate Change Local Energy Assessment Fund (LEAF). Unpublished document.

Thermographic survey

The interiors of all three properties were examined for the post-refurbishment survey whilst each dwelling was depressurised. For Riddlecombe and Shrewsbury, images were also taken of the exterior of the property. At Riddlecombe, the position of the stone plinth at the base of the cob wall could be identified from images. At Shrewsbury the un-used chimney flue could be clearly identified from the outside of the building, due to the warm air being drawn from the living space, together with the location of thermal bridges and heating pipes and radiators. In the case of Skipton, a thermographic survey of the building exterior did not prove possible because of the weather conditions before and at the time of the survey.

With respect to the building interior, common to all three properties were issues relating to ingress at the junction of walls and ceilings to beams, at sills, around loft hatches and ingress evident through floors. The problems around beams and sills could have been addressed through the use of air tightness tapes and specialist joint fillers during the refurbishment work. At Skipton, air tightness problems appeared to be more widespread in the new addition, but still apparent at beams and sills.

Ingress through closed windows and around casements was evident at Shrewsbury (around older windows in the addition which are due to be replaced) and through some windows/doors at Skipton, despite these only being recently installed.

At Skipton, it is possible to make comparison between the new addition to the property and the original farmhouse during the 2013 post-refurbishment test. Both old and new show similar maximum wall temperatures (the building was heated to an approximately even temperature throughout). The older part of the building shows a more consistent temp of exterior wall with only around a 1^{o}C temperature variation, whereas the new addition had localised temperature reductions of up to 3^{o}C across the general wall surface under depressurisation conditions.

Surface and Sub-Surface Moisture

The following observations concern moisture readings taken at the interior surface and sub-surface of the walls at Shrewsbury, Drewsteignton, Riddlecombe and Skipton (Figures 2 - 5). In general all four walls, post-refurbishment, have seen a decline in moisture readings at both surface and sub-surface levels. The two walls, Shrewsbury and Drewsteignton (Figures 2 and 3) that have been subject to internal wall insulation in the form of sheet materials, PIR and Woodfibre board, show similar patterns of behaviour. Previously, in 2011, the surfaces of these two walls appeared to be fairly stable and dry (there is a brief deflection mid-way up the plot for the wall in Shrewsbury which has been accounted for as the effect of water moving into the interior surface along a lintel). The 2011 plots for the sub-surfaces of these walls, about 40mm back, were a little more dynamic and indicated the influence of ground water at the base of the walls. The measurements taken in 2012 show both the plots of surface and sub-surface moisture occupying the 'dry' end of the nominal moisture scale. This indicates something about the limitation of these methods of measurement as a means by which to assess moisture risk in internally insulated solid walls. The internal surface and sub-surface of the walls at Shrewsbury and Drewsteignton are drier as this is where a new insulating layer of dry sheet material has been applied. The affect of this build-up to the internal face of the wall is to move the zone of moisture measurement away from the original masonry part of the wall. It is in the solid masonry part of these walls that we have previously seen fluctuating moisture readings indicating a dynamic environment influenced by external forces such as ground water and/or rain, therefore, whilst it is true to say that the internal leaves of these walls appear to be slightly drier this is not necessarily the case for the walls as a whole.

The other wall in the study that has been internally insulated using a hemp/lime plaster is the wall at Skipton. In comparison with the other IWI walls which have been insulated with sheet material the surface and sub-surface measurements of moisture at Skipton show some differentiation (Figure 4). The differentiation may reflect the fact that the sub-surface material is still in the process of drying but also, as the plaster is directly coupled to the masonry in this instance, rather than measuring the dry sheet material, there is some influence of the masonry component in the measurements gathered 40mm back from the wall surface at the sub-surface level. However, the 2013 post refurbishment measurements do indicate that in comparison with the measurements taken pre-refurbishment in 2011 the surface and sub-surface of the wall at Skipton has, at least nominally, become 'drier'. And in addition the influence of ground water at the base of the wall and possibly water tracking in to the internal wall face under the window cill is less significant at the surface and sub-surface level than it was prior to refurbishment.

The graph for Riddlecombe, an externally insulated wall, is somewhat different but also shows the general declining trend for surface and sub-surface moisture (Figure 5). At this property the vapour permeability of both the internal and external finishes of the walls has, in theory, been increased by the application of lime-based finishes and both the moisture buffering and evaporation potential of these materials could account for the improvement in moisture readings taken here in 2012. This improvement is particularly pronounced for the lower part of the wall and it should be noted that the stone plinth (300mm) upon which the cob wall sits has received an additional coat of stabilising mortar to both its interior and exterior face which could alter moisture readings for this part of the wall. Also of note, however, is that above 1400mm readings for sub-surface moisture at Riddlecombe return to those previously recorded, pre-refurbishment, in 2011. This suggests that beyond the internal wall surface moisture conditions deeper within the wall have not really altered as a result of the refurbishment work. This may be a reflection of the fact that high %RH and possibly high moisture levels within this wall continue to be a feature of the wall at Riddlecombe.

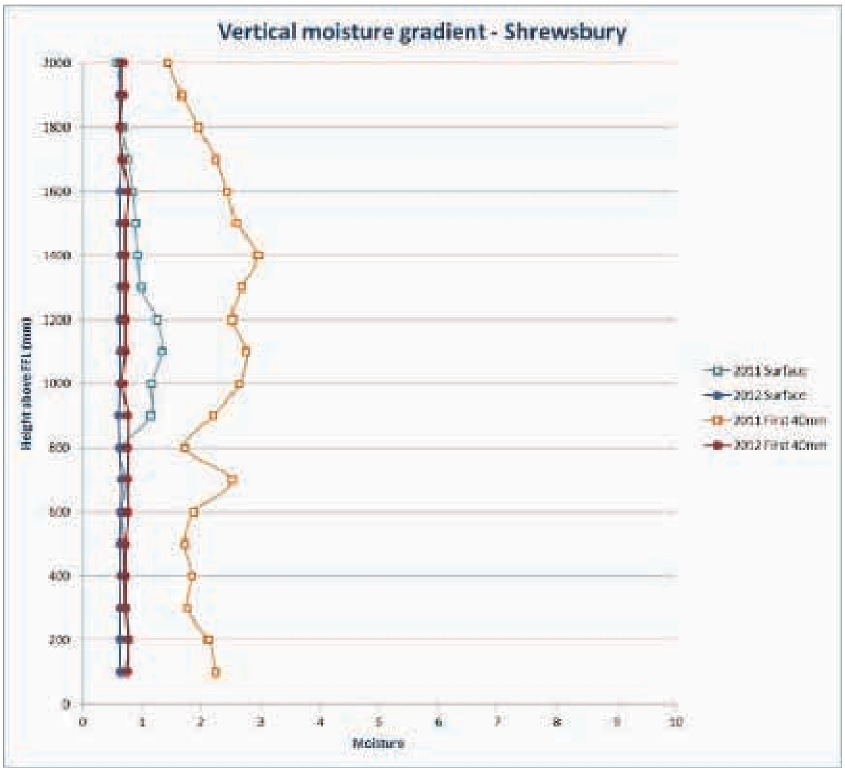


Figure 2. Pre and post refurbishment measurements of surface & sub-surface moisture at Abbeyforegate, Shrewsbury, 2011 & 2012.

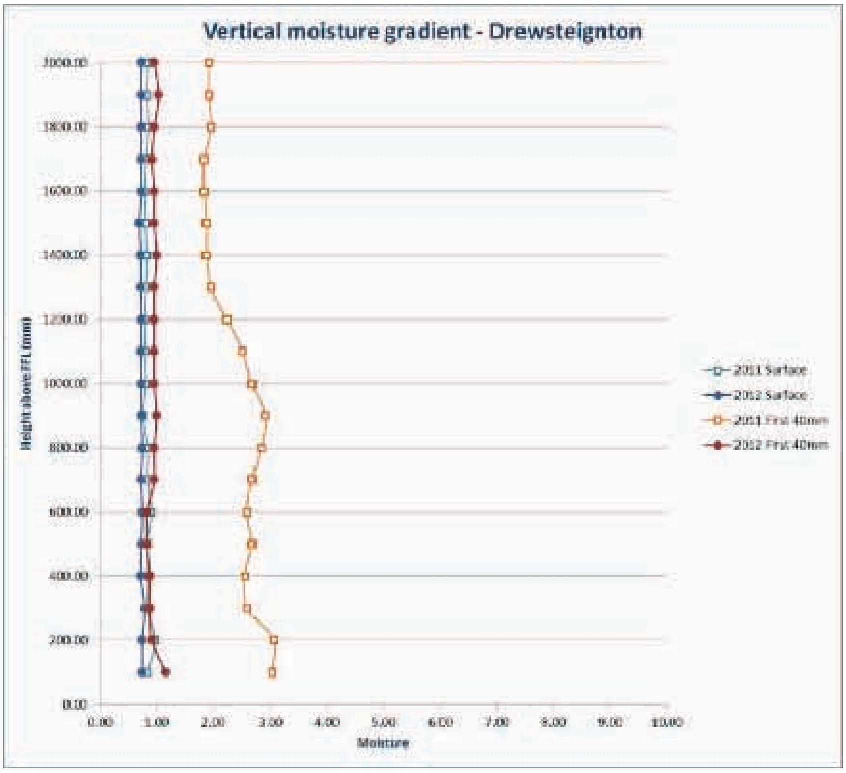


Figure 3. Pre and post refurbishment measurements of surface & sub-surface moisture at Mill House Test Wall, Drewsteignton, 2011 & 2012

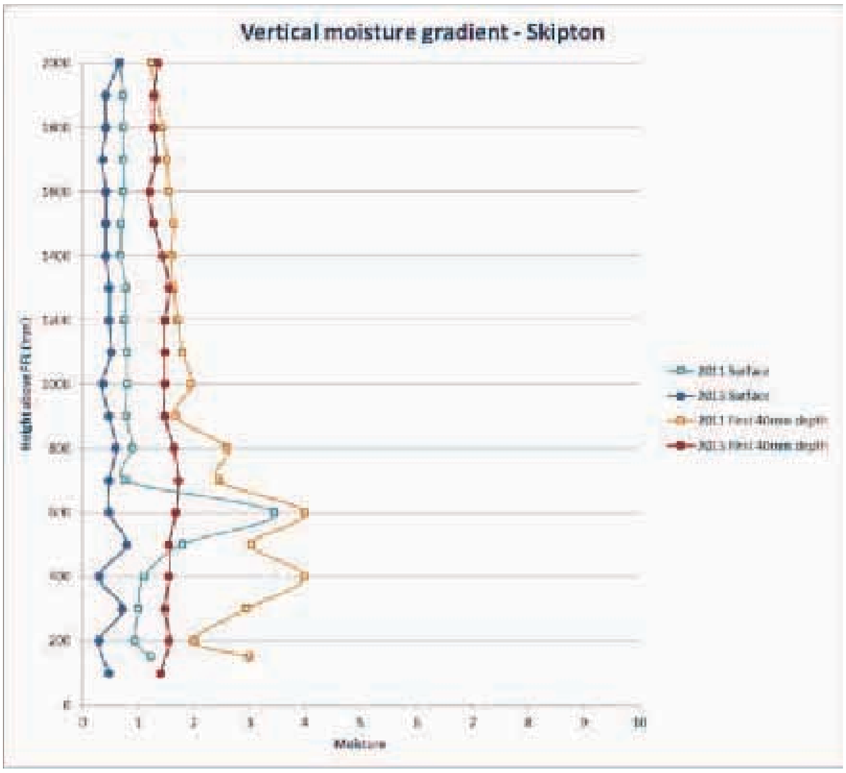


Figure 4. Pre and post refurbishment measurements of surface & sub-surface moisture at White House Farm, Skipton 2011 & 2013.

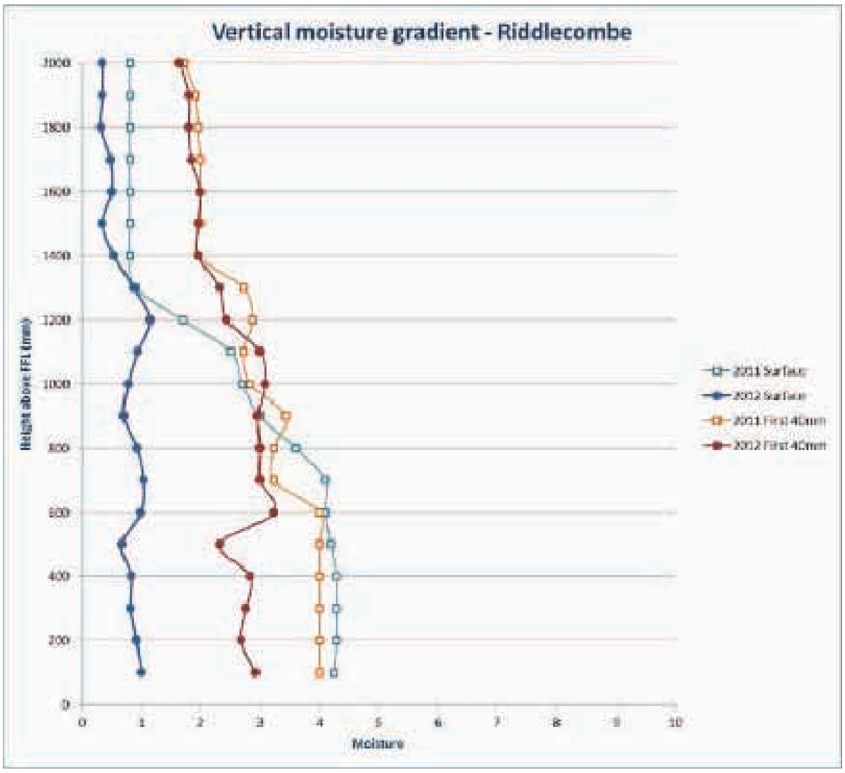


Figure 5. Pre and post refurbishment measurements of surface & sub-surface moisture at The Firs, Riddlecombe, 2011 & 2012.

Interstitial Hygrothermal Conditions

Interstitial hygrothermal conditions within the walls of the four buildings are examined in a number of ways; an analysis of %RH and absolute humidity within the walls over time, cross-sectional averages of absolute humidity, temperature and dewpoint over the reporting period and also the dewpoint margins (the temperature drop required for condensation to occur at a certain location) over time. Figures 38, 58, 71 and 78 provide details of the positions and depths of the measurement sensors within the wall sections for the individual properties.

Relative Humidity Over Time

Figures 6-9 plot %RH readings from four interstitial wall sensors, numbered 1-4 from the internal to the external side of the wall, along with measurements of internal and external temperature and %RH over time for the each of the four walls in this study. Figures 6-8 represent approximately a year's worth of data collected from Shrewsbury, Drewsteignton and Skipton, whereas the graph for Riddlecombe, Figure 9, is for a shorter six month period. Figures 6-8 all show a distinction between summer and winter measurements although this is most pronounced in the walls at Shrewsbury and Skipton. In Figures 6 and 7, the graphs follow a pattern of two distinct summer and winter arrangements of %RH distribution through the wall. %RH indicates the proportion of vapour held within air at a certain temperature in relation to saturation or dewpoint and is a temperature dependent quantity. During the warmer spring and summer months levels of %RH at all four wall sensors are similar as the temperature difference across the wall is less acute due to similar internal and external temperatures. Moving into winter however, due the affect of central heating and an increased internal/external temperature gradient, there is greater differentiation in the %RH values measured by the four sensors through the wall section. By and large, lower %RH is found towards the warmer internal side of the wall and %RH increases in proximity to colder external conditions.

Another characteristic shared by the walls at Shrewsbury and Skipton (Figures 6 and 7) in comparison with those at Drewsteignton and Riddlecombe is seen in the nature of the gradients plotted for each if the interstitial sensors which in turn communicates something of the qualities of these walls. The %RH responses measured at Shrewsbury and Skipton are that much more volatile than those plotted for the Devon buildings indicating walls that are more open and porous in structure and therefore subject to greater and more rapid changes in condition. Both these walls are south-facing, however extremes of temperature do not seem to be a determining factor in this behaviour as the wall at Riddlecombe is also south-facing. Therefore it is more likely to be a reflection of the amount of air that is passing in and around the structure. It has been observed that the pointing of the brick wall at Shrewsbury is in quite a poor state of repair, and the wall at Skipton is a rubble core construction with considerable voids both these lead to the opportunity for multiple air pathways within the body of the wall. The walls at Drewsteignton and

Riddlecombe are of granite and cob respectively, the manner of their construction is that much compact and homogenous with no evidence of any voids (walls are core drilled to install the interstitial sensor arrays and in this way the manner and quality of their construction can be discerned).

The walls at Drewsteignton and Riddlecombe (Figures 8 and 9) also share another feature, that is both these locations exhibit a trend of rising %RH over the reported monitoring period (12 months for Drewsteignton, 6 month at Riddlecombe). This is particularly clear in Figure 9 when measurements of %RH at sensor 4, the sensor closest to the external side of the wall at Riddlecombe, reaches 100% RH within a matter of weeks from the commencement of the graph and is followed, sixteen weeks later by sensor 3 and all four gradients have a mostly upward trajectory for the entire duration of the graph. At Drewsteignton, Figure 8, the trend is less obvious and there is also a period of time over the summer where measurements of %RH decline at sensors 3 and 4, however, over the full reporting period the predominate trend is one of increasing %RH with the exception of measurement from sensor 1 positioned in the air gap behind the plasterboard drylining of this wall which tracks internal room %RH conditions. Towards the end of the graph for Drewsteignton, in January 2013, sensor 4 reaches 100% RH. There is however a significant difference between these two walls in that peaks of %RH occur in opposing seasons suggesting two different and possibly opposing driving forces for this behaviour. By and large, and this can be seen in the other walls in this study (Figures 6 and 7) %RH increases and peaks during the winter when colder external temperatures cause the %RH to rise particularly within the colder, external side of the wall leaf. However, at Riddlecombe the rising trend, including peaks at 100%, occurs over the warmer summer months and it is thought that this may be due to vaporisation or sweating behaviour from the cob material that has a high moisture content due to the failing external cement render that previously covered the building and water introduced into the wall as part of the re-rendering process. (This phenomenon is explored in more detail in the individual report on Riddlecombe in Appendix A, pps. 102-121). Continued measurements of this wall into the winter period, 2013-14, should be able to shed more light on the high %RH measured in this wall and whether this is a seasonal and ultimately diminishing trend or a cause for concern over the longer term. However, measurements of %RH at Drewsteignton reveal a trend of rising %RH that occurs over a 12 month period, when normally perhaps one might expect any rise in %RH as a result of colder temperatures to be reversed during the warm summer. Both Drewsteignton and Riddlecombe also show higher interstitial %RH values where average %RH values measured at sensors 2-4 in both walls all exceed 80% the value often quoted as the threshold for mould growth conditions. In contrast, only measurements from sensor 4 exceed 80% RH in the walls at Shrewsbury and Skipton, averaging 83.49% and 81.43 respectively whereas averages for sensor 4 are much higher at Drewsteignton, 96.01% and at Riddlecombe, 99.82%.

The graph for Skipton, Figure 7, shows a contrasting trend of downward %RH over the reported monitoring period. This could be a reflection of the generally warmer conditions experienced in the summer of 2013 where external as well as interstitial %RH (sensors 4-2) is shown to be lower than that of the previous summer, combined with the drying that is occurring to the internal wall finishes measured by sensor 1. The wall at Skipton also shows moments of vaporisation behaviour, similar, if less pronounced to that seen at Riddlecombe as well as the affect of its fissured construction in that responses to external conditions mapped at sensor 2 are sometime more pronounced than those plotted for sensor 3, the sensor that is physically closer to the outside possibly as a result of erratic air-pathways through the wall. At Shrewsbury the extended period of peak 100% RH measured at sensor 4 seems at first glance to be alarming, however this peak should be read within the context of responses over an annual cycle which show that %RH reduces at the onset of warmer spring weather and averages 83.49%. It is also worth noting that unlike the other walls in this sensor 4 at this location is placed in much closer proximity to external conditions, 30mm back from the external wall face and this, combined with the generally open and porous nature of this wall, as previously observed results in extreme responses. Given the potentially volatile nature of the wall, including its south-facing aspect, %RH measurements made at this location are, with the exception of sensor 4, remarkably stable.

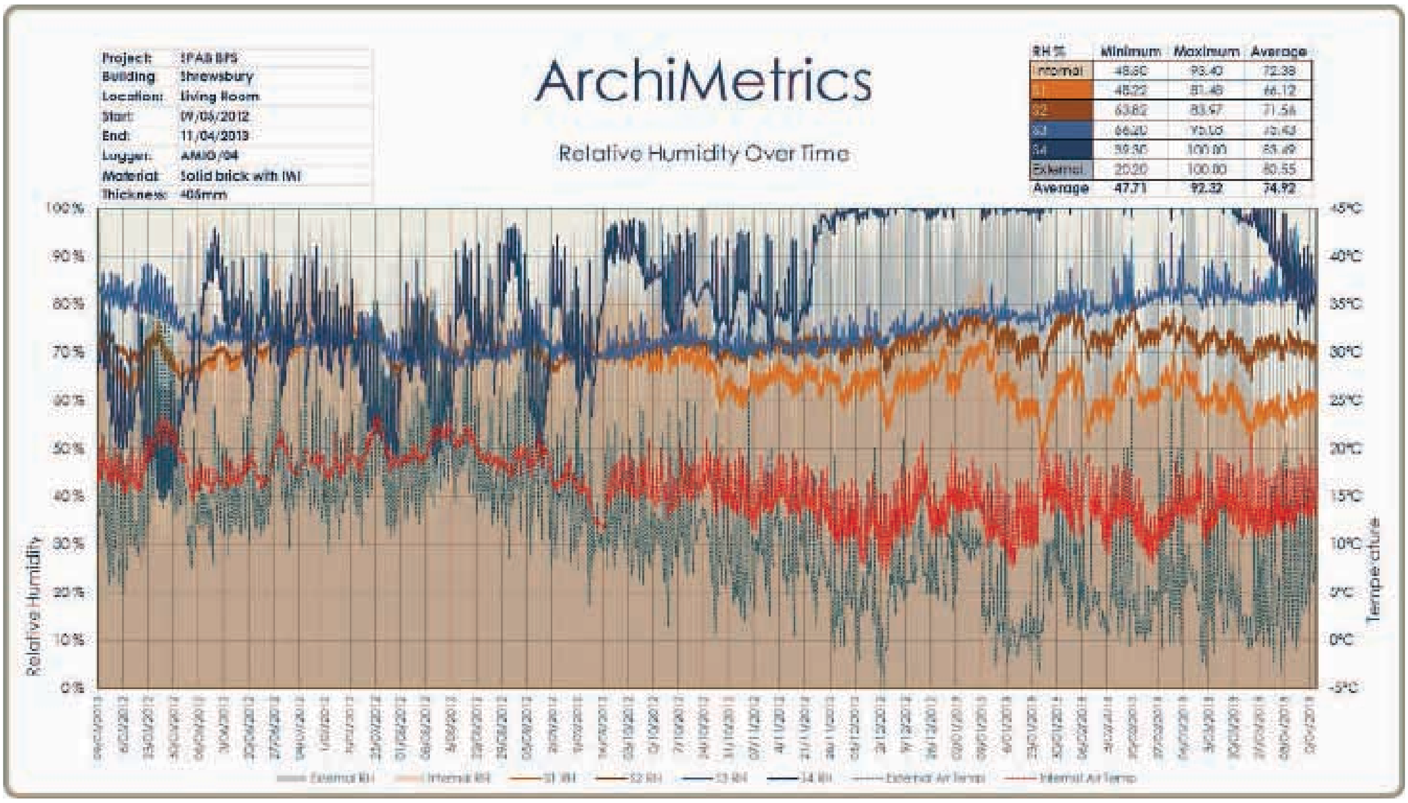


Figure 6: Relative Humidity over time, Abbeyforegate, Shrewsbury 2012 - 2013.

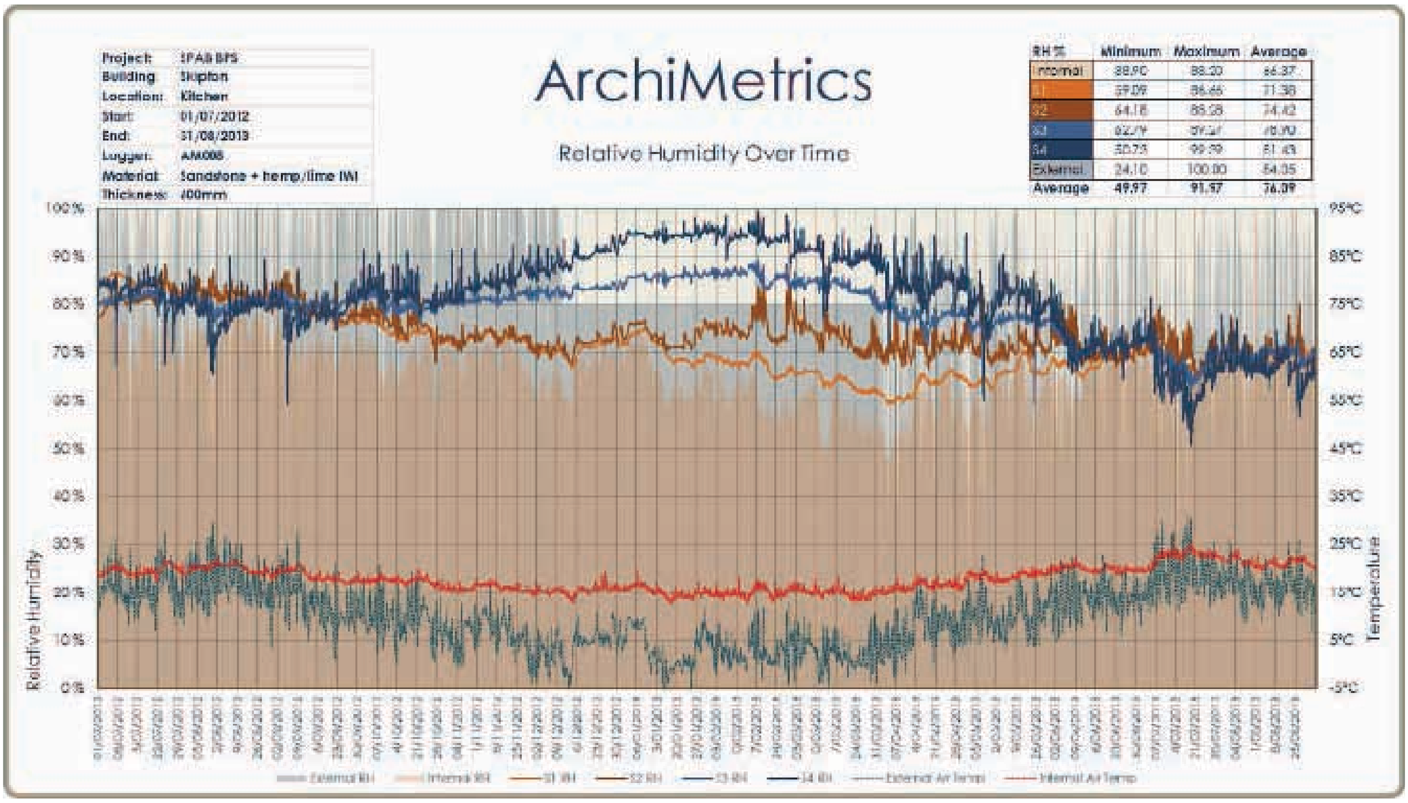


Figure 7. Relative Humidity over time, White House Farm, Skipton, 2012 -13.

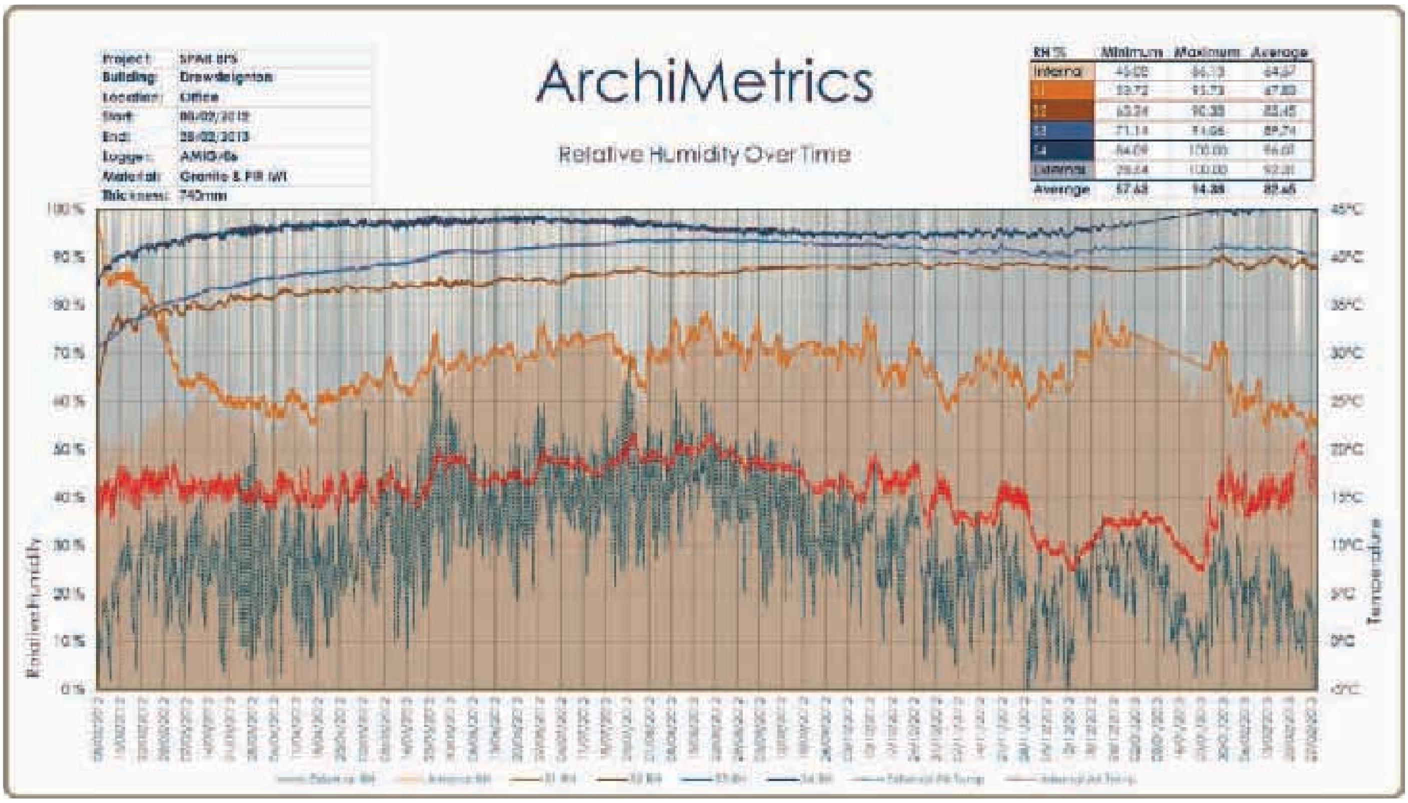


Figure 8: Relative Humidity over time, Mill House, Drewsteignton 2012 - 2013.

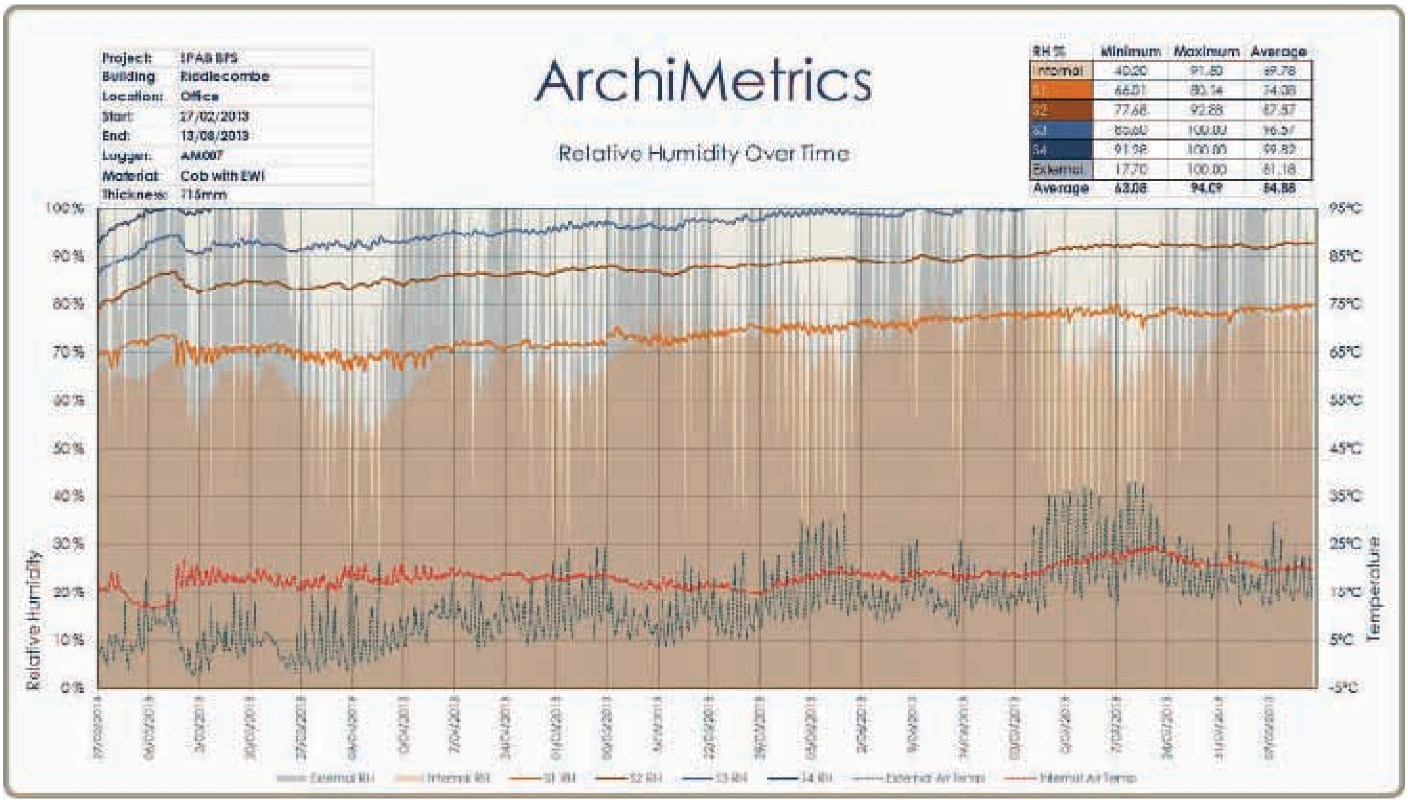


Figure 9: Relative Humidity over time, The Firs, Riddlecombe Feb - Aug 2013.

Absolute Humidity Over Time

Figures 10-13 plot, over time, absolute humidity, a measure of the weight of vapour by volume (g/m^3) for the interstitial wall sensors, along with measurements of internal and external temperature and absolute humidity for the each of the four walls in this study. Figures 10-12 represent approximately a year's worth of data collected from the walls at Shrewsbury, Drewsteignton and Skipton, whereas the graph for Riddlecombe, Figure 13, is for a shorter, six month period. For purposes of clarity, Figure 10, for Shrewsbury, provides plots just from sensors 1-3, as responses from sensor 4 are so volatile (see %RH discussion above) they tend to obscure the behaviour of the rest of the sensors in the wall. The individual reports on each property provide additional graphs of the absolute humidity over time responses of each wall.

All four Figures (10-13) show the same general pattern of behaviour, that is to say that as atmospheric absolute humidity increases in the warmer summer months (due to the ability of warmer air to contain more vapour) a similar rise in absolute humidity occurs within wall fabric. Following this logic we can also see that weights of vapour within the walls are at their highest in proximity to a source of heat. During the summer the highest weights are recorded towards the exterior side of the wall, at sensor 4 and diminish in proximity to this heat but in winter this hierarchy is reversed and with the onset of central heating sensor 1 tops the range of absolute humidity readings through the wall section. This behaviour is particularly visible in the walls at Shrewsbury and Skipton (Figures 10 and 11) but less defined at Drewsteignton, Figure 12, where it is only from January 2013 onwards that this arrangement is seen. (The peak absolute humidity at sensor 1 seen early on in Figure 12 is as a result of the drying of the gypsum skim on the plasterboard drylining). Drewsteignton also differs from the walls at Shrewsbury and Skipton in another way in that it seems to reverse a dispersal pattern. At Shrewsbury and Skipton measurements of the weight of vapour through the wall are more dispersed and differentiated during the winter, presumably, as with %RH, as a result of a greater temperature gradient through the wall section. However, at Drewsteignton a greater differentiation between g/m^3 of vapour is found in the summer and measurements of the weight of vapour through the wall section become more aligned in wintertime.

Although the graph for Riddlecombe, Figure 13, covers a shorter time period the increase in absolute humidity here also follows the seasonal pattern and increases with increasing external temperatures/external absolute humidity. There is, however, a significant difference in the plots of absolute humidity for the wall at Riddlecombe compared with those at the other locations. By and large, plots of absolute humidity in the other walls broadly match, sit between or fractionally surmount, those of internal and external levels of absolute humidity showing a close correlation between internal/external and interstitial conditions. At Riddlecombe plots of interstitial absolute humidity are detached from and significantly higher than those of external humidity and also internal absolute humidity from May 2013 onwards. This suggests that there is an additional factor or factors driving quantities of vapour in this cob wall independent of ambient internal and external vapour conditions. In the previous discussion on %RH and in the individual report on Riddlecombe it is suggested that excess moisture is contained within the cob as a result of a past failing external render as well as water added to the wall during the re-rendering process and this is vaporising during periods of warm temperatures as sun falls on the south-facing wall. This might explain the detachment seen between internal and external vapour conditions and those within the wall, as the moisture within the cob material provides an additional and independent source of vapour.

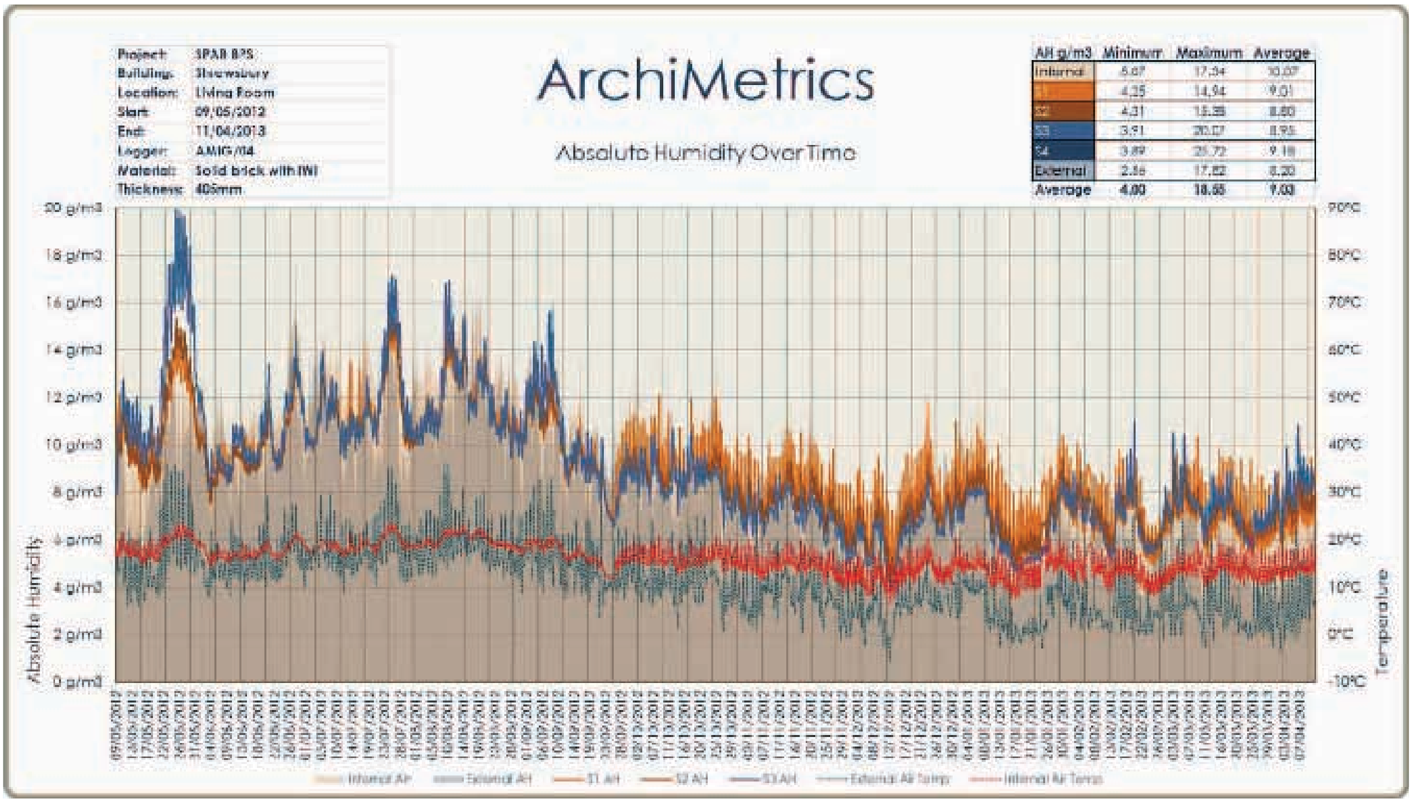


Figure 10: Absolute Humidity over time, Sensors 1 - 3, Abbeyforegate, Shrewsbury 2012 - 2013.

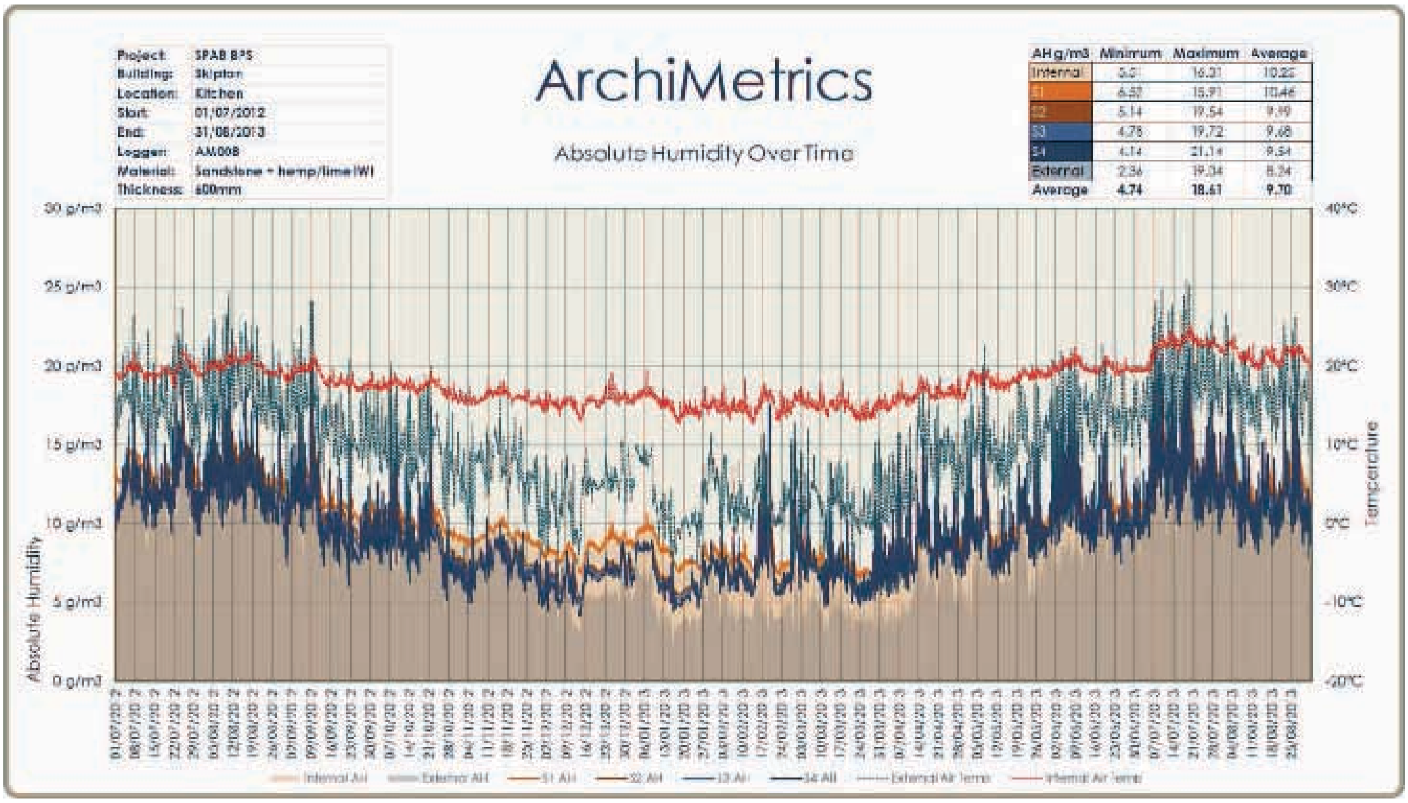


Figure 11: Absolute Humidity over time, Sensors 1 - 4, White House Farm, Skipton, 2012 -13.

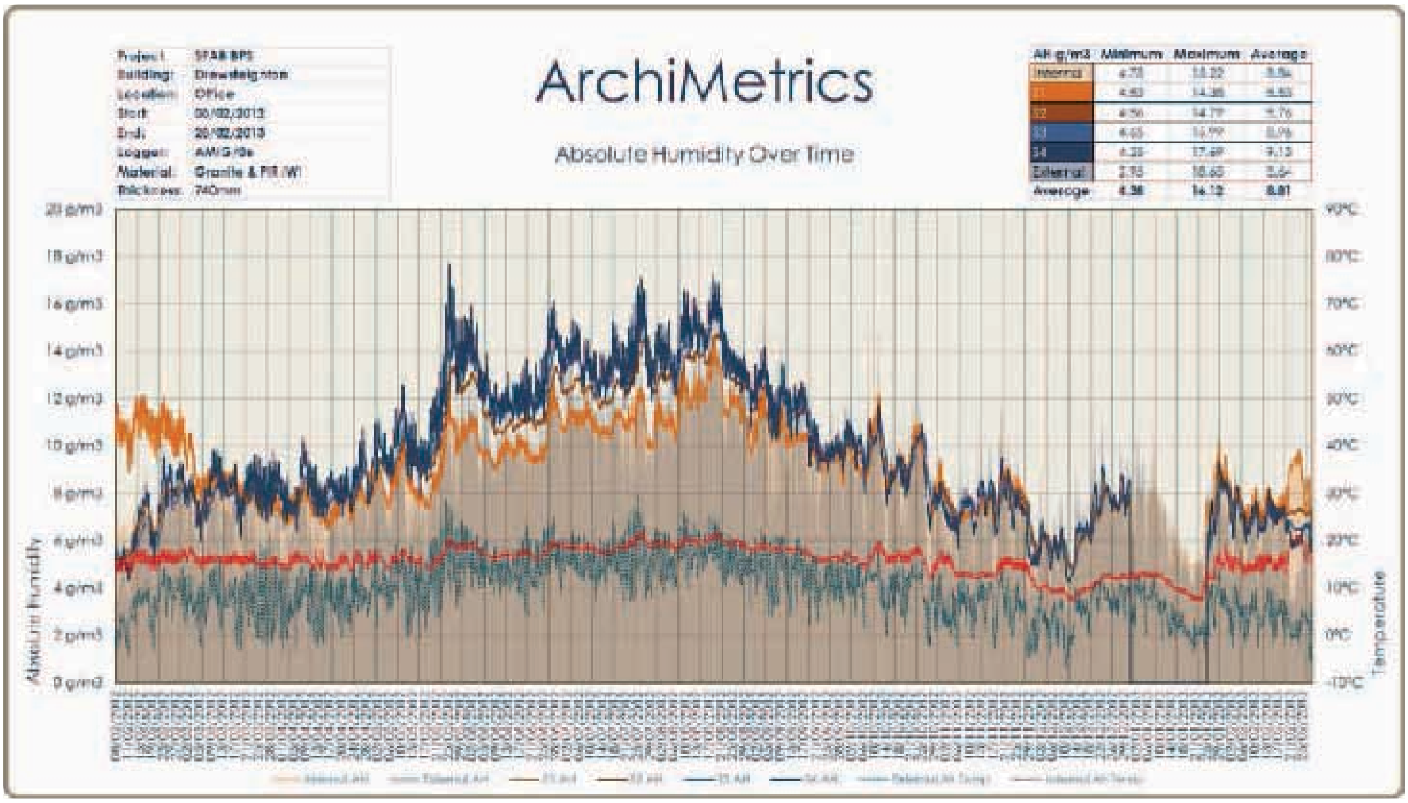


Figure 12: Absolute Humidity over time, Sensors 1 - 4, Mill House, Drewsteignton 2012 - 2013.

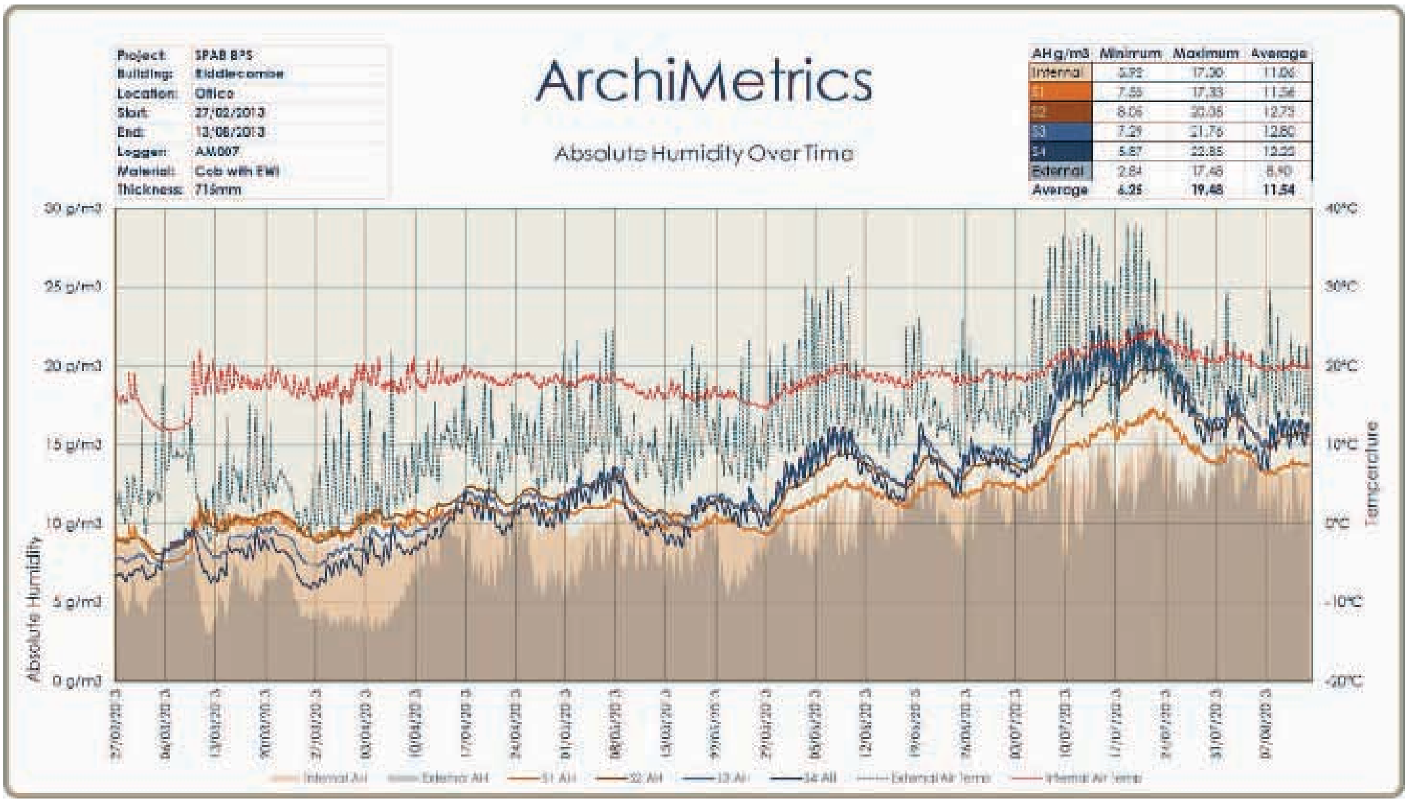


Figure 13: Absolute Humidity over time, Sensors 1 - 4, The Firs, Riddlecombe February - August 2013.

Average Absolute Humidity

In Figures 14-17 the average absolute humidity values through and either side of the four wall sections under study have been plotted along with the maximum and minimum values recorded over the reported monitoring period. These result in more or less flat gradients, showing more or less similar quantities of vapour through the wall sections with the exception of Riddlecombe, Figure 17.

Location	**Sensor 1**	**Sensor 2**	**Sensor 3**	**Sensor 4**	**Average Interstitial AH g/m^3**	**Average AH (inc. internal and external AH) g/m^3**
Shrewsbury	9.01	8.80	8.95	**9.18**	8.99	9.04
Skipton	**10.46**	9.99	9.68	9.54	9.92	9.07
Drewsteignton	8.53	8.76	8.96	**9.13**	8.88	8.81
Riddlecombe	11.56	12.73	**12.80**	12.22	12.33	11.54

Table 4. Absolute Humidity Averages, SPAB Building Performance Survey 2013.

As can be seen from the compilation of data given in Table 4, on average the walls at Skipton and Riddlecombe contain the highest weights of vapour g/m^3, although the weight of vapour in Riddlecombe far exceeds that of Skipton in relation to the other two walls in the study, being approximately 38% greater than that of the walls at Shrewsbury and Drewsteignton, as oppose to just 11% greater in the wall at Skipton. The walls at Drewsteignton and Shrewsbury bear very similar averaged quantities of vapour, and these in turn closely match averages calculated for the walls which also include internal and external absolute humidities. This suggests that there is a close relationship between the ambient vapour conditions surrounding these walls and the vapour behaviour within the wall itself. In Table 4 the highest averaged measurements of weight of vapour through each wall section is marked in bold, this shows that for the walls at Shrewsbury and Drewsteignton the highest averaged weight of vapour is found at sensor 4, at the exterior side of the walls, but for Skipton this is located at sensor 1 close to the internal wall face. It is suggested that this is a reflection of the wet hemp/lime finishes which are in the process of drying during the reported monitoring period and that this in turn influences the overall average weight of interstitial vapour recorded for this wall and explains why this is raised in relation to the average which takes account of internal and external conditions. However, the discrepancy between the average interstitial absolute humidity recorded at Riddlecombe and this same quantity including internal and external conditions is less easily explained unless, as is suggested elsewhere, there is an additional source of vapour that influences this wall, possibly in the form of additional moisture bound within the cob.

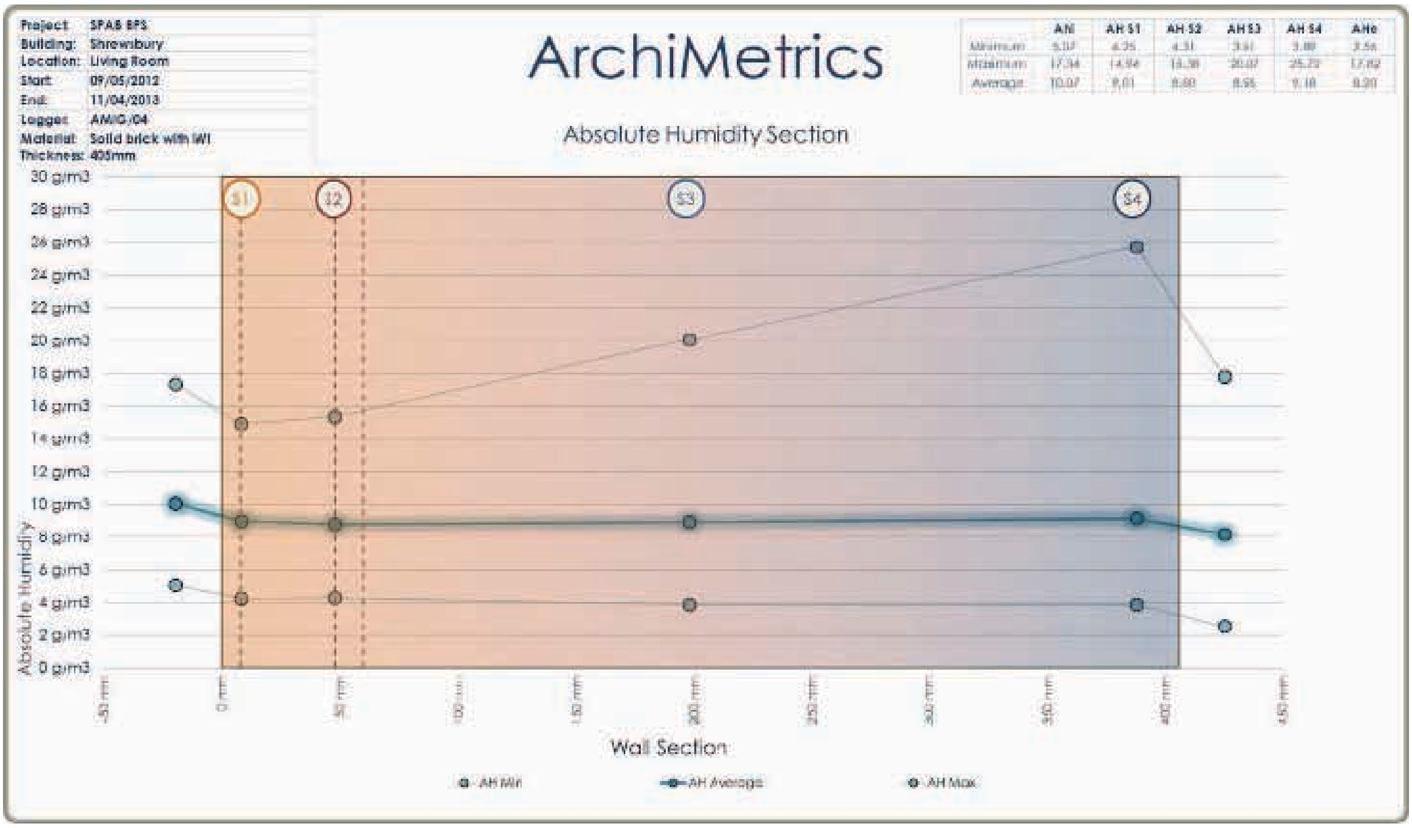


Figure 14: Absolute Humidity Section, Abbeyforegate, Shrewsbury 2012 - 2013

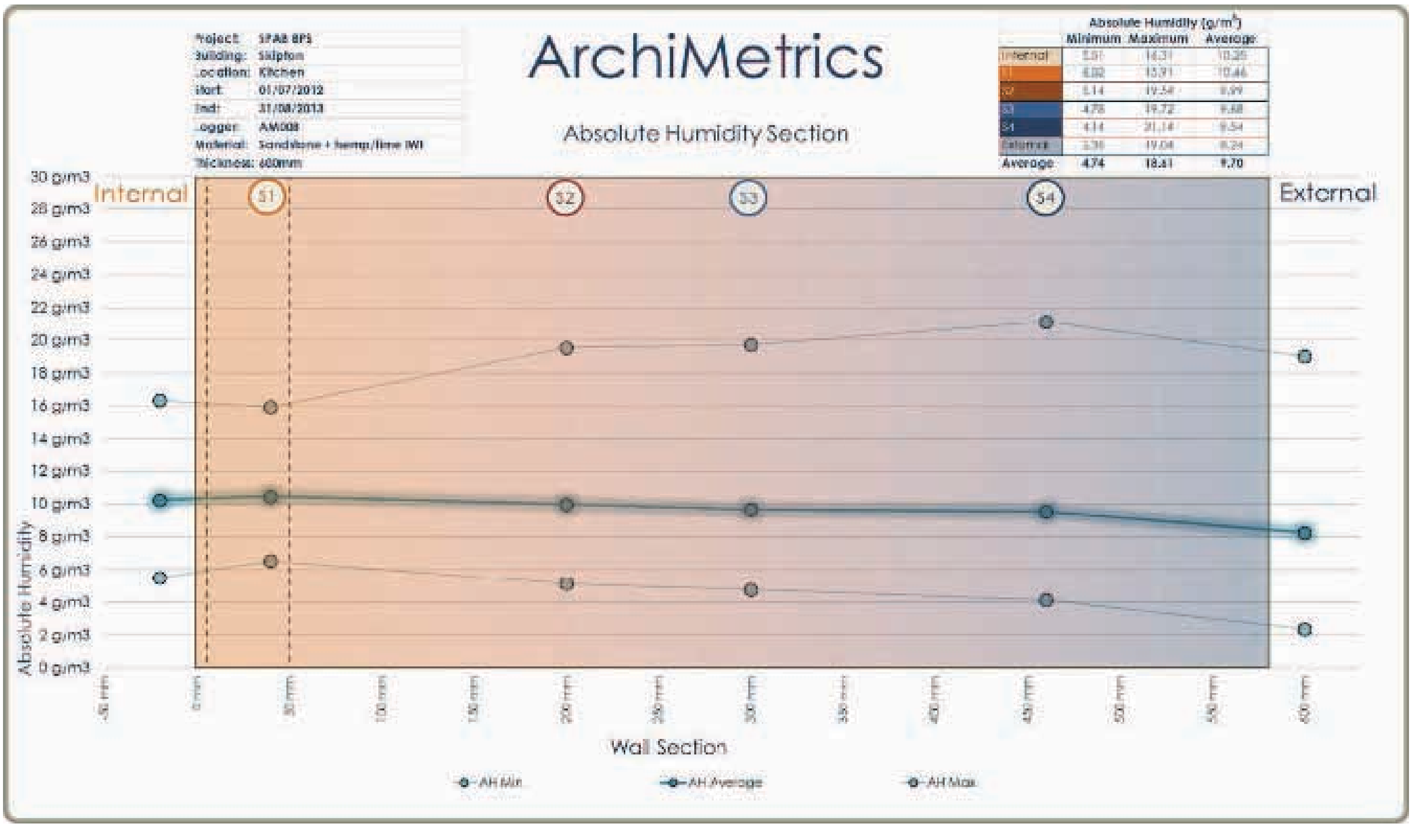


Figure 15: Absolute Humidity Section, White House Farm, Skipton, 2012 -13.

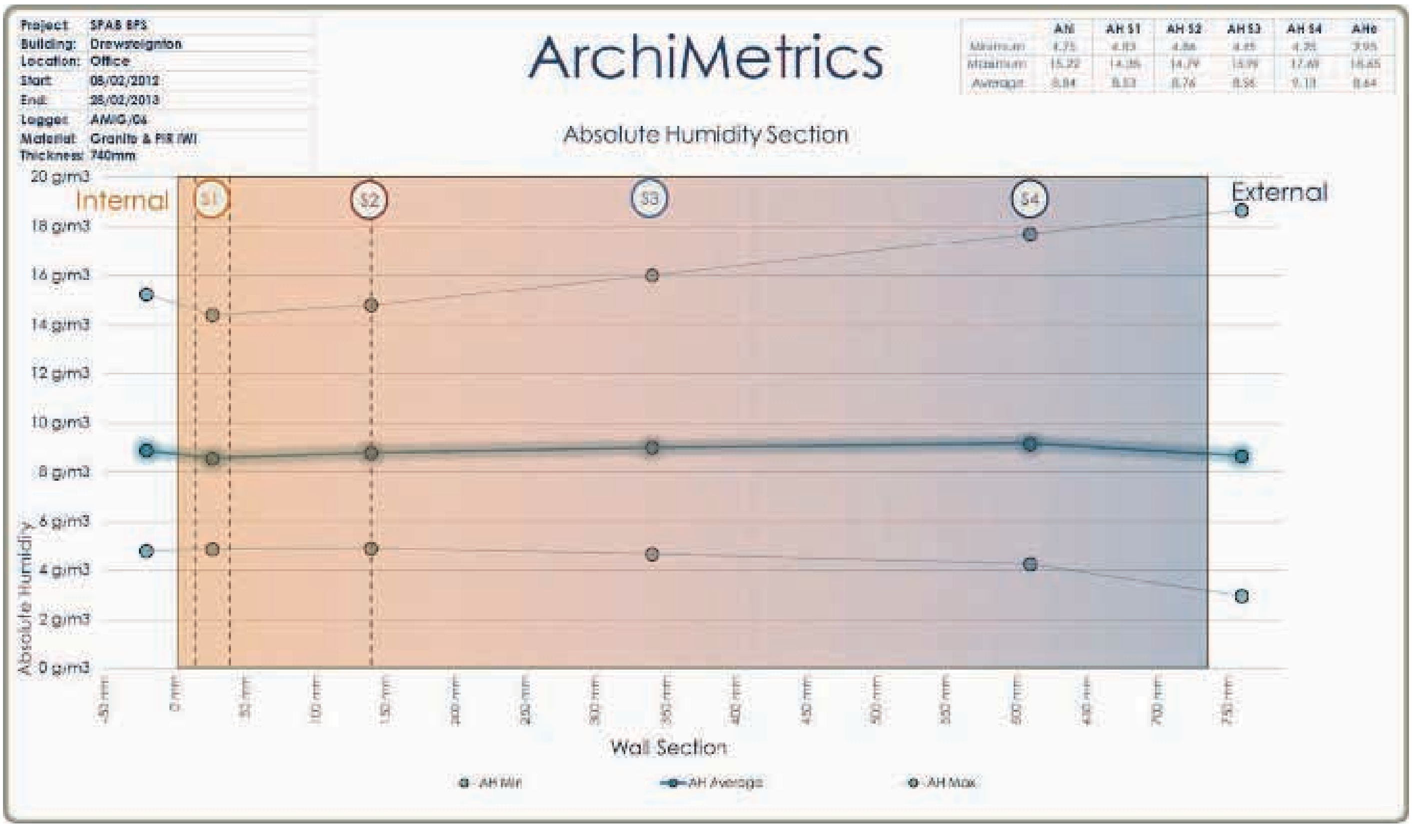


Figure 16: Absolute Humidity Section, Mill House, Drewsteignton 2012 - 2013

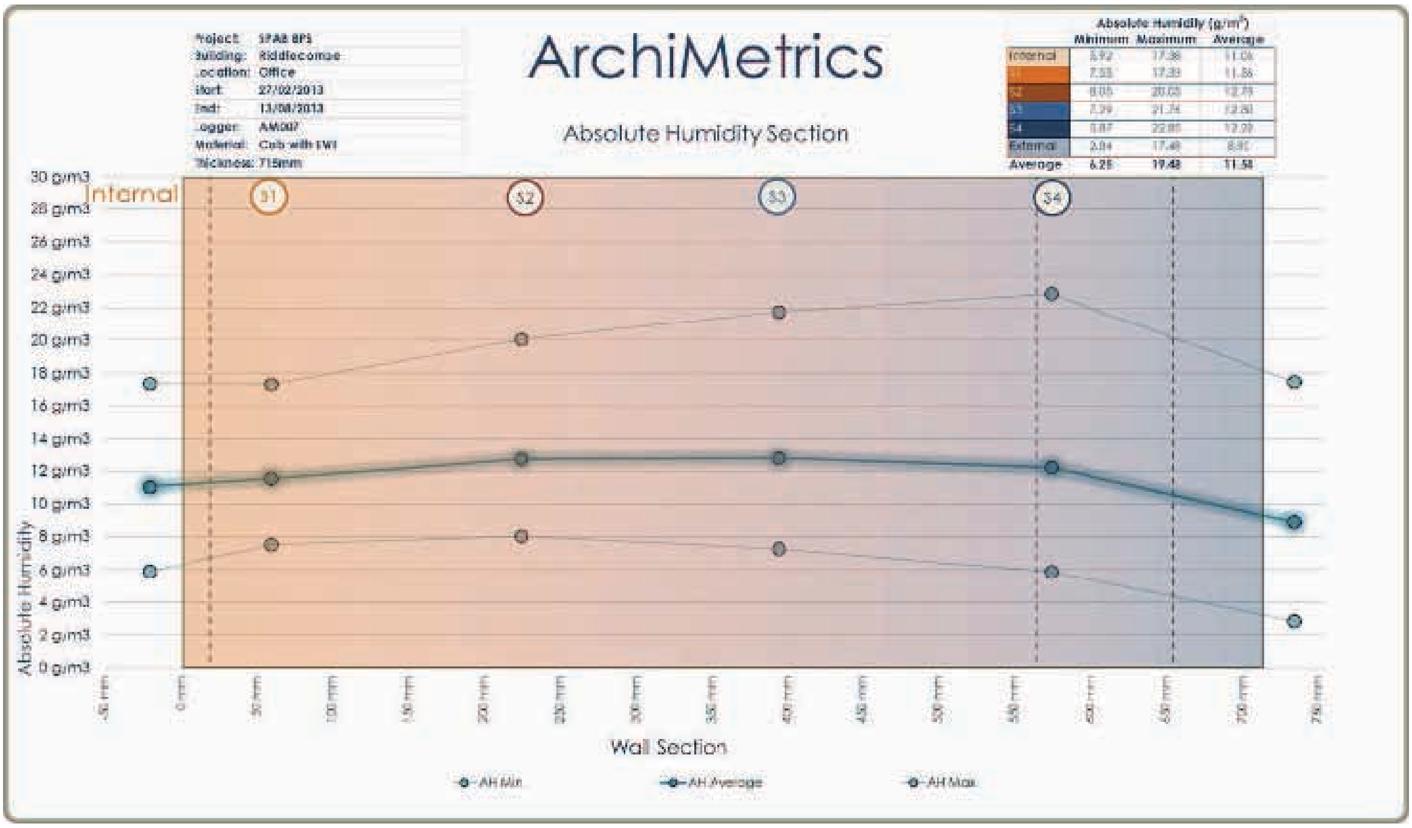


Figure 17: Absolute Humidity Section, The Firs, Riddlecombe February - August 2013.

Hygrothermal Section

Figures 18-21 provide plots of temperature and dewpoint gradients for the four wall sections under examination in this report. In the temperature gradients for the walls that have been insulated internally (Shrewsbury, Skipton and Drewsteignton) it is possible to see the different thermal resistance of this layer, compared with that of the masonry part of the wall, reflected in the steeper gradient which passes through the insulation. The pitch of this gradient reflects the degree of impact this insulating layer has had on the overall U-value of the wall post-refurbishment i.e. it is at its steepest at Drewsteignton, Figure 20, where the addition of 100mm PIR resulted in an measured 87% decrease in heat loss through this wall. The gradients are less pronounced at Shrewsbury and Skipton where the thinner 40mm addition of IWI resulted in reductions of 69% and 38% respectively. Beyond this insulating layer these internally insulated walls all share another characteristic which is a flattening of the temperature gradient as it passes through the remaining masonry part of the wall, here walls at Drewsteignton and Shrewsbury only seem to have a 1-2˚C temperature difference across their masonry sections, whereas the wall at Skipton looks to have a slightly greater difference of between 4-5 ˚C, once again as a reflection of the different proportions of heat loss reduction that have occurred in these walls. The temperature gradient within the masonry section at Skipton also differs from that of Drewsteignton and Shrewsbury in that at these locations the flattened gradient also follows the same pitch between sensor positions indicating a similar rate of heat loss throughout this part of the wall section. As has been observed elsewhere the wall at Skipton is a rubble core construction and as such is more diverse in its materials and contains considerable voiding particularly at the centre of the wall. In pre-refurbishment measurements the affect of this rubble core and alterations in thermal conductivity/resistivity as a result of the wall's disparate construction was seen in changes of pitch between measurement points particularly the measurement that straddled the rubble core. This characteristic is still visible, if somewhat muted by the flattened temperature gradient, in Figure 19 post-refurbishment.

The plots of the maximum temperature gradients through the four walls naturally all show reverse heat flow occurring through the sections but this is most pronounced, understandably, for the south-facing walls that have been internally insulated at Shrewsbury and Skipton. While the maximum external surface temperatures plotted for the west-facing wall at Drewsteignton are roughly 10-15˚C lower than those of the south-facing walls.

The dewpoint gradients plotted for these walls derive from measurements of %RH and show the nominal temperature drop required for dewpoint to occur at certain points within the wall. For Shrewsbury, Skipton and Drewsteignton these gradients are, more or less, flat and sit around 10˚C. At Riddlecombe, which is found to have higher levels of vapour within its structure, the average dewpoint gradient is raised above 10˚C and is convexed and peaks within the centre of the wall echoing the section plot of average absolute humidity found in Figure 17. For all four walls the margin between the temperature gradient and the dewpoint gradient narrows towards the colder external side of the wall as colder temperatures cause an increase in %RH. However, in Figures 18 and 19, Shrewsbury and Skipton, there is a gap between these two gradients showing that, over an annual cycle, on average, a temperature drop of roughly 3˚C is required before saturation point is reached at sensor 4. Therefore possibly there is no significant risk of extended periods of condensation within these two walls. This is in contrast to the wall at Drewsteignton, Figure 20, where temperature and dewpoint gradients at sensor 4 are seen to be in close proximity to one another, the margin of difference being 0.57˚C. As well as the wall at Riddlecombe, Figure 21, where at sensor 4 and sensor 3 they are affectively coincidental with margins of 0.03˚C and 0.54˚C respectively. This would seem to suggest that these walls, which were also found to both exhibit the trend of rising %RH, may be at greater threat from condensation over the long term.

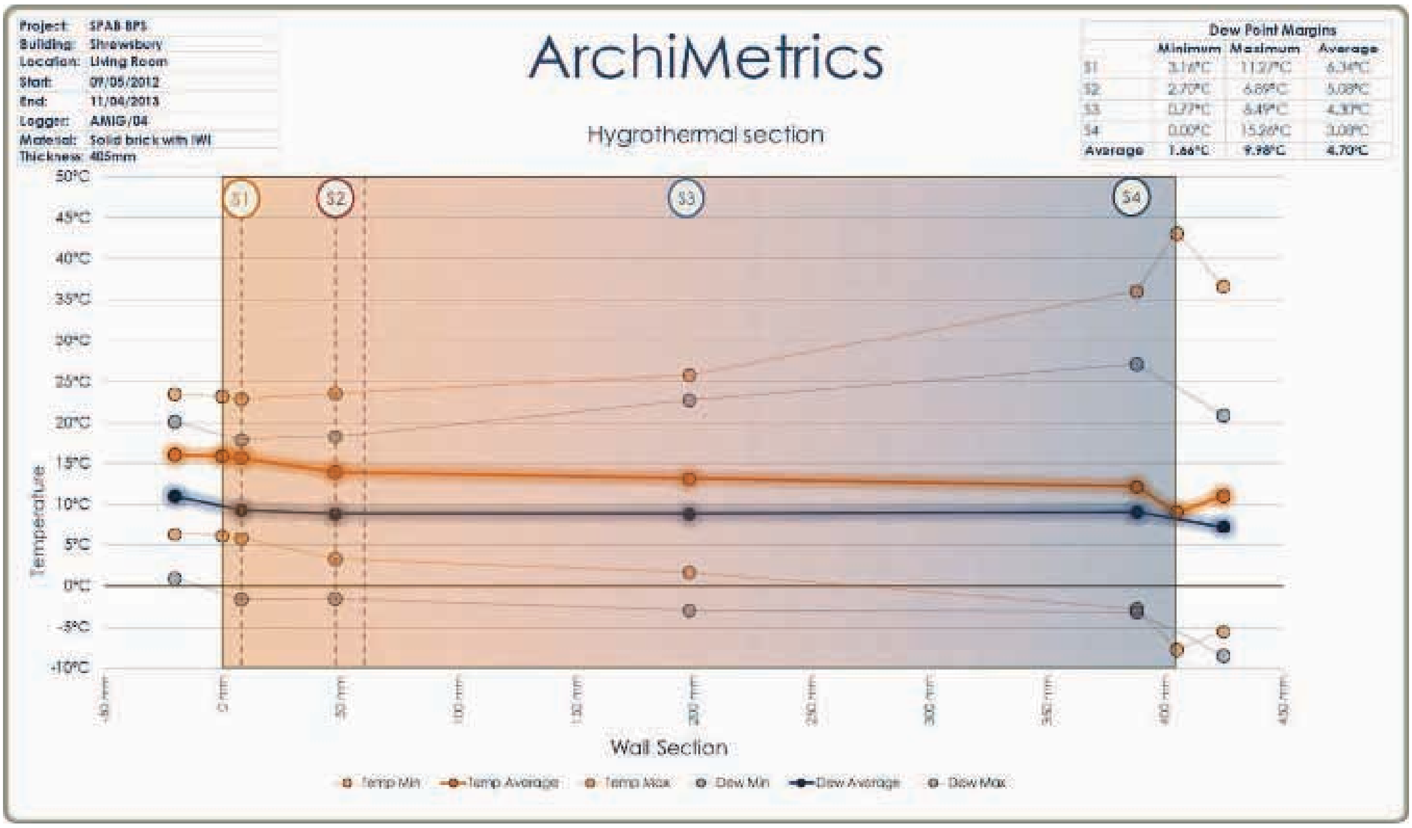


Figure 18: Hygrothermal Section, Abbeyforegate, Shrewsbury May 2012 - April 2013.

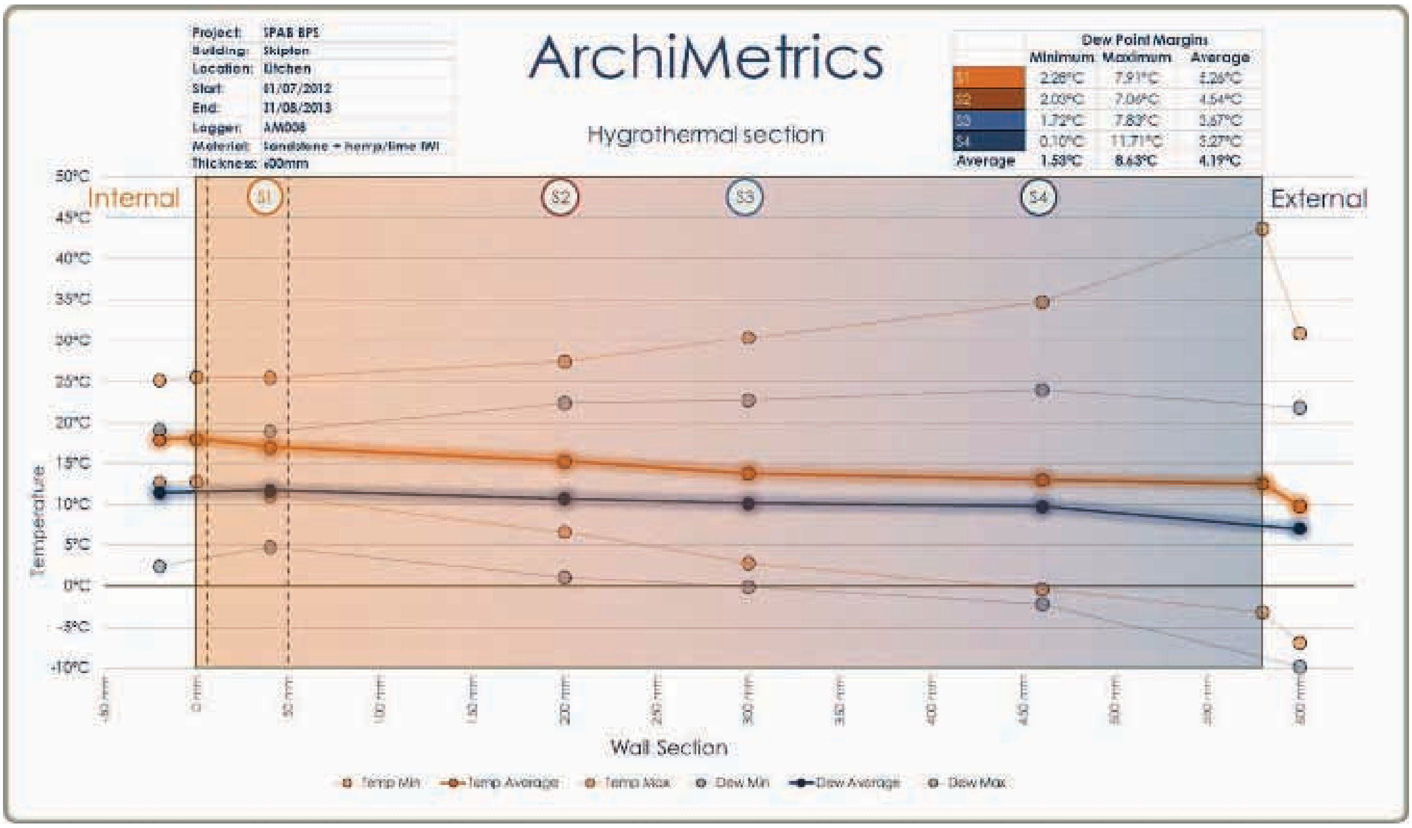


Figure 19: Hygrothermal Section, White House Farm, Skipton, July 2012 - August 2013.

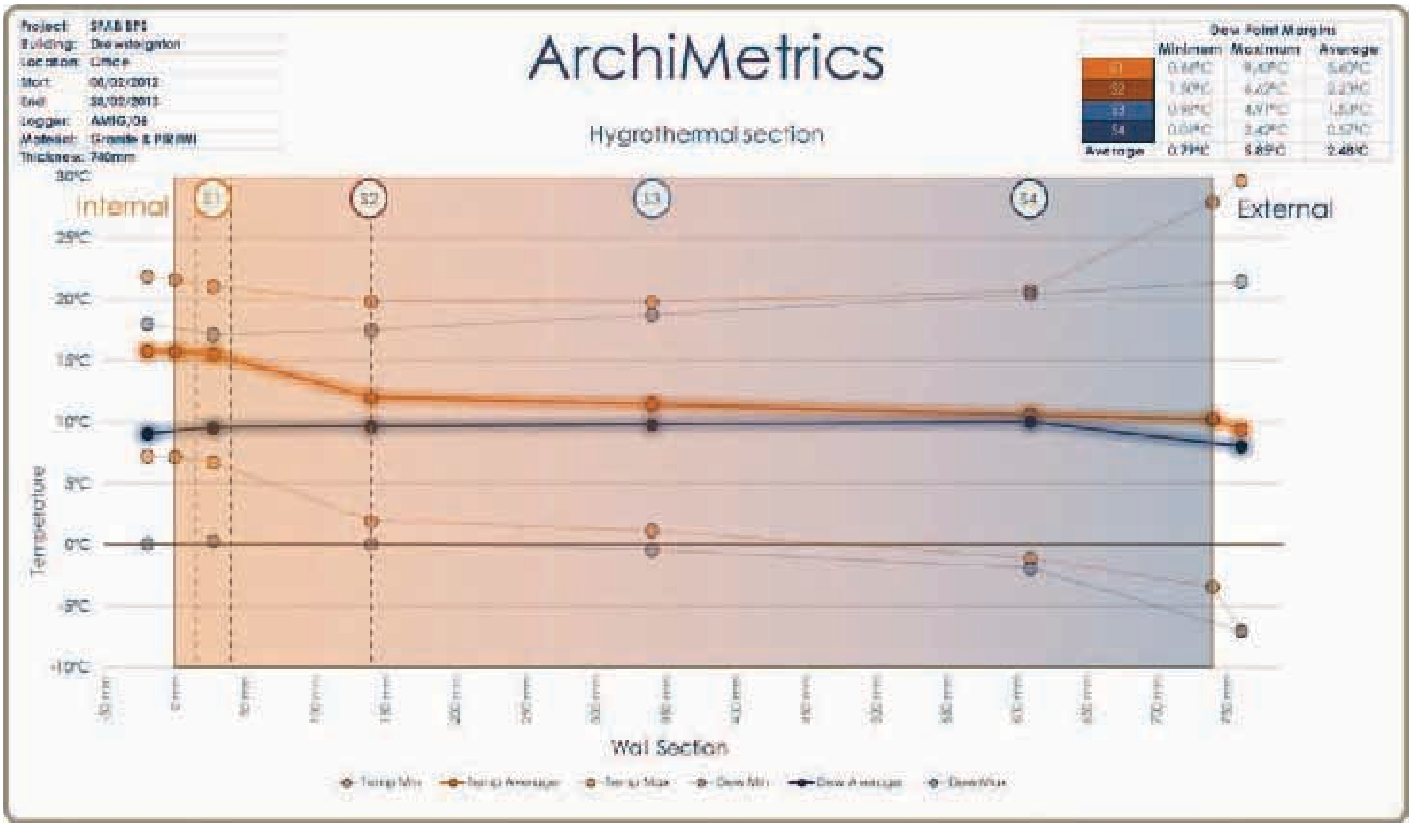


Figure 20: Hygrothermal Section, Mill House, Drewsteignton February 2012 - February 2013

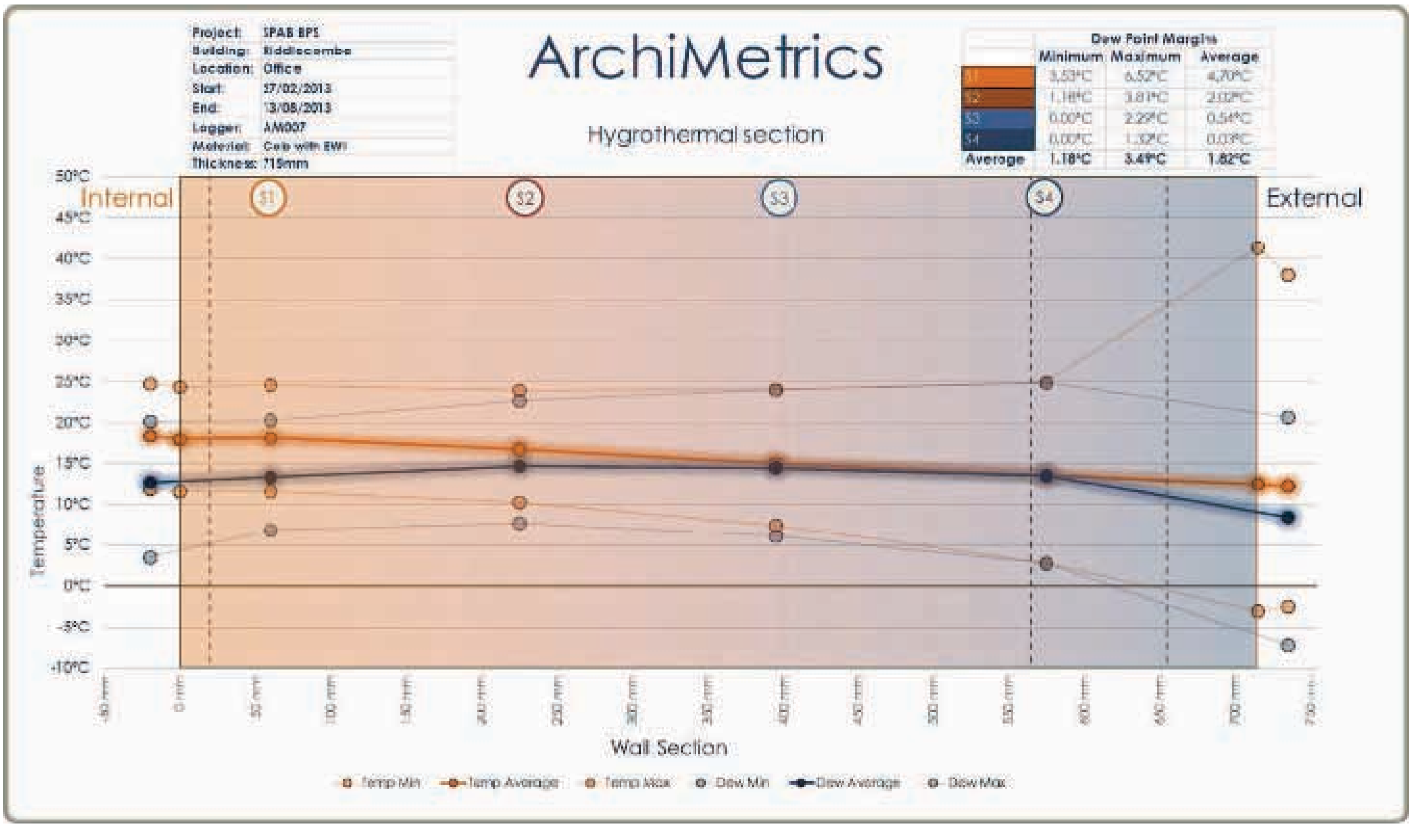


Figure 21: Hygrothermal Section, The Firs, Riddlecombe February - August 2013.

Dewpoint Margin Over Time

Figures 22-25 allow an examination of dewpoint margins for the four walls over time and thereby indicate when the walls are at greatest risk of condensation occurring. As dewpoint is a function of %RH these graphs reflect an inverse response to those found in the %RH over time figures, Figures 6-9, i.e. as %RH increases dewpoint margins decrease. Therefore the period of near 100% RH measured at sensor 4 in Shrewsbury over the winter (Figure 22) translates to a margin of or around 0˚C indicating a period of likely condensation in close proximity to the external wall face over this time. However, despite the open and volatile nature of this wall the dewpoint margins found within the rest of the section are reassuring large and quite steady, averaging between 6.34-4.30 ˚C and the 0˚C margin for sensor 4 does not reflect the walls predominant state, the average margin here being 3.06˚C. Similarly, the margins plotted over time for the walls at Drewsteignton and Riddlecombe reflect the rising trend of %RH found for these walls. At Drewsteignton the margin at sensor 4 reaches 0˚C in January 2013 and this also occurs at Riddlecombe at sensor 4 and then later in the reporting period at sensor 3, albeit counter intuitively in mid-summer when %RH might be expected to be at its lowest. The only wall of the four in the survey that has not recorded a margin of 0˚C at any point within the reported monitoring period is that of Skipton. Here sensor 4 is positioned quite far back from the external wall face, 255mm, as opposed to the sensor at Drewsteignton which is 134mm back and at Shrewsbury which is only 20mm away from external conditions. It may be that the distance of this separation from the cold external conditions means that no incidence of vapour saturation has been recorded for this wall.

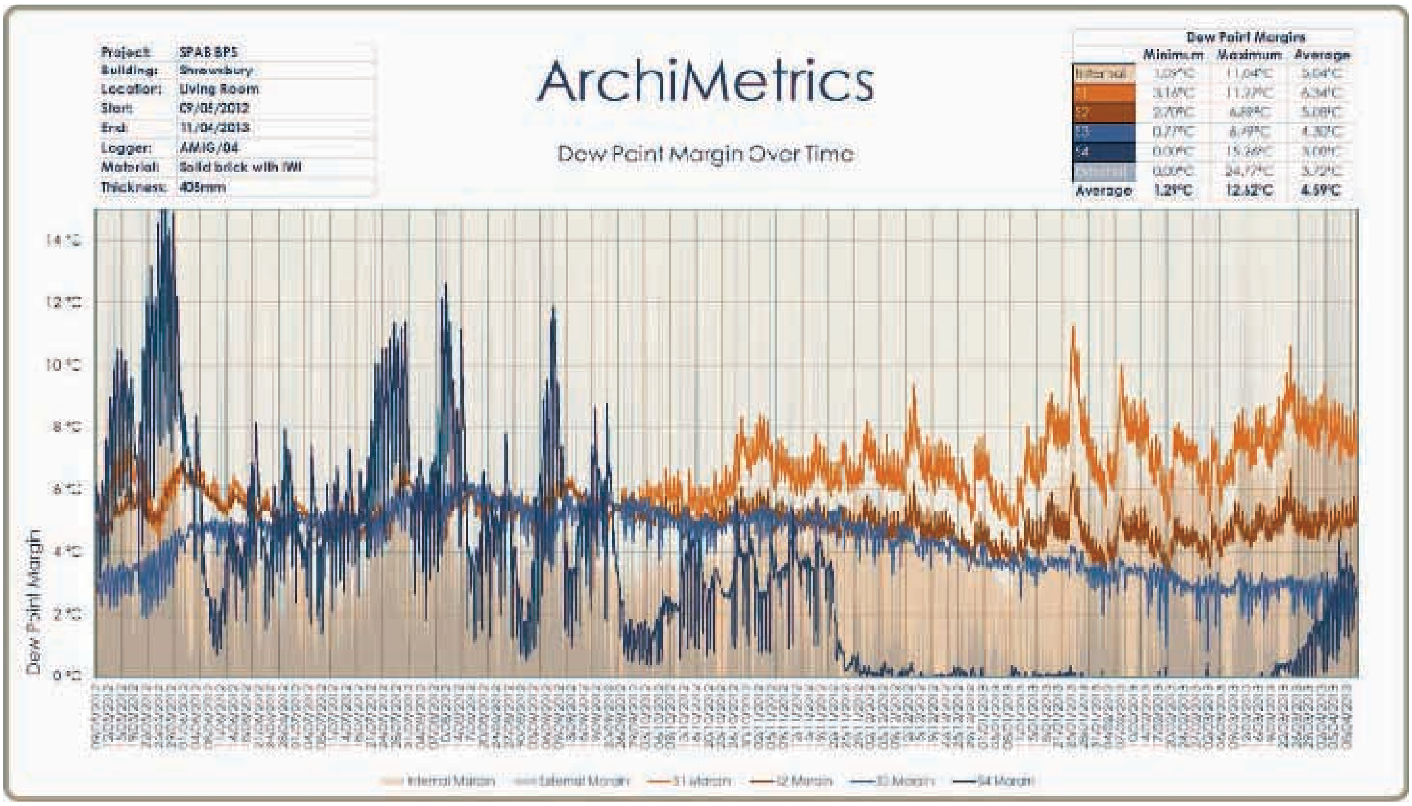


Figure 22: Dewpoint Margin over time, Abbeyforegate, Shrewsbury 2012 - 2013.

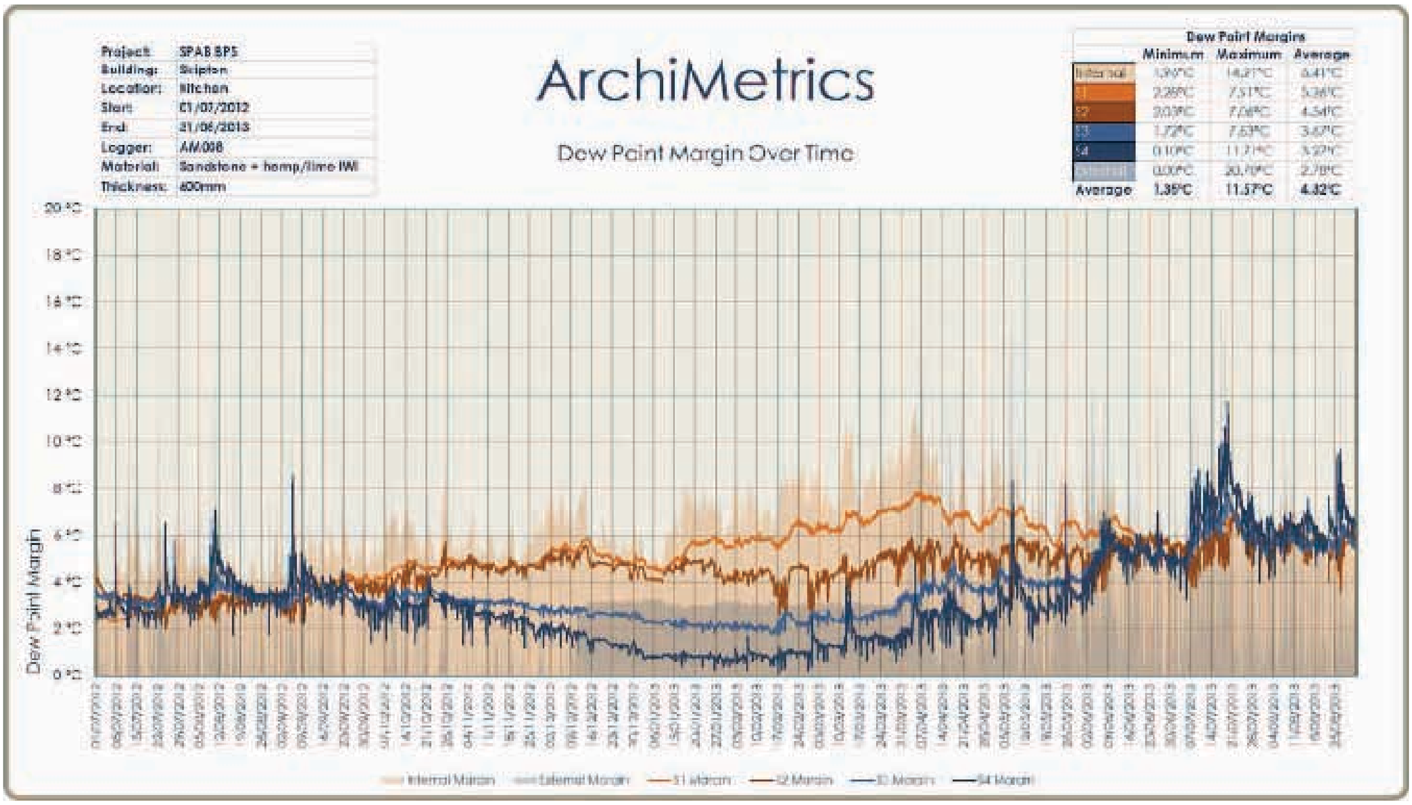


Figure 23: Dewpoint Margin over time, White House Farm, Skipton, 2012 -13.

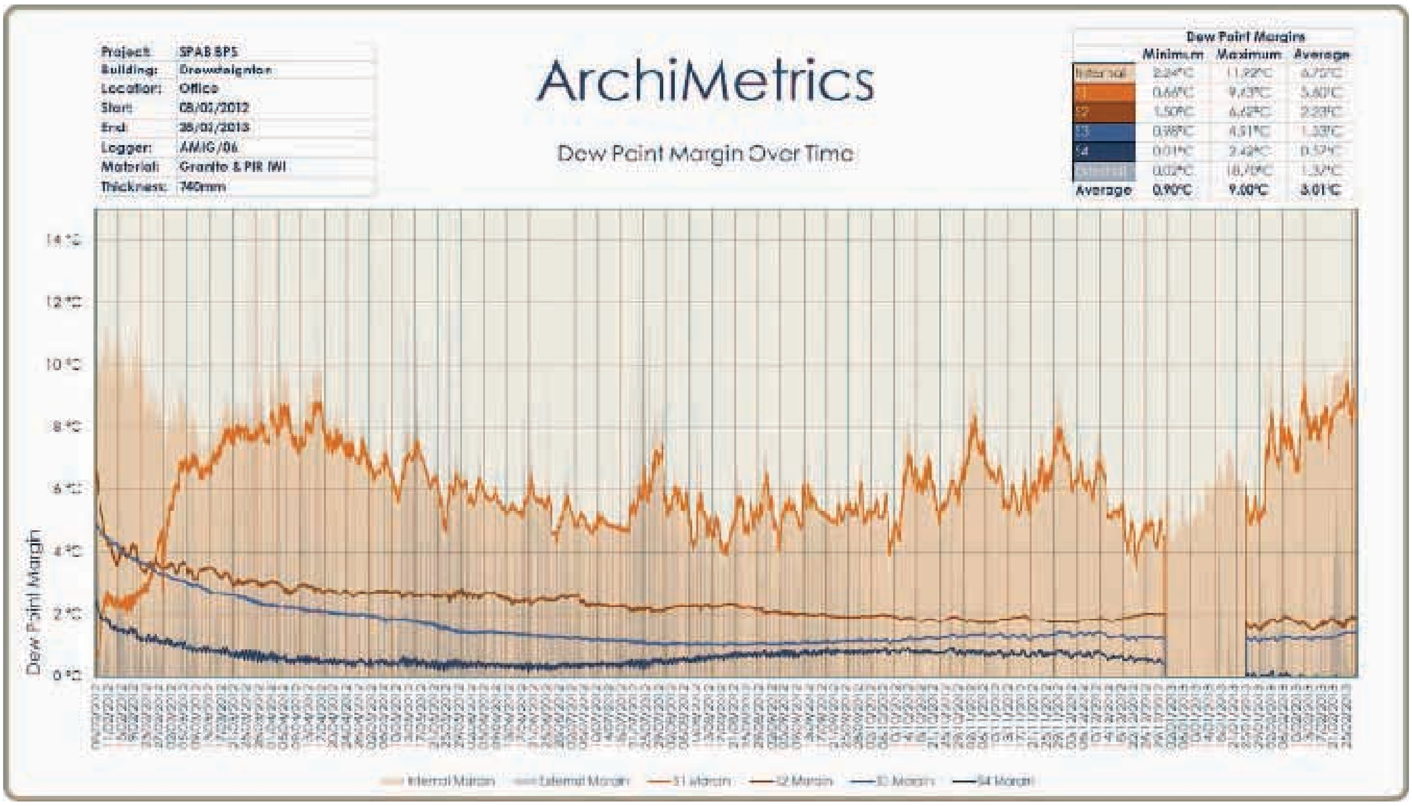


Figure 24: Dewpoint Margin over time, Mill House, Drewsteignton 2012 - 2013.

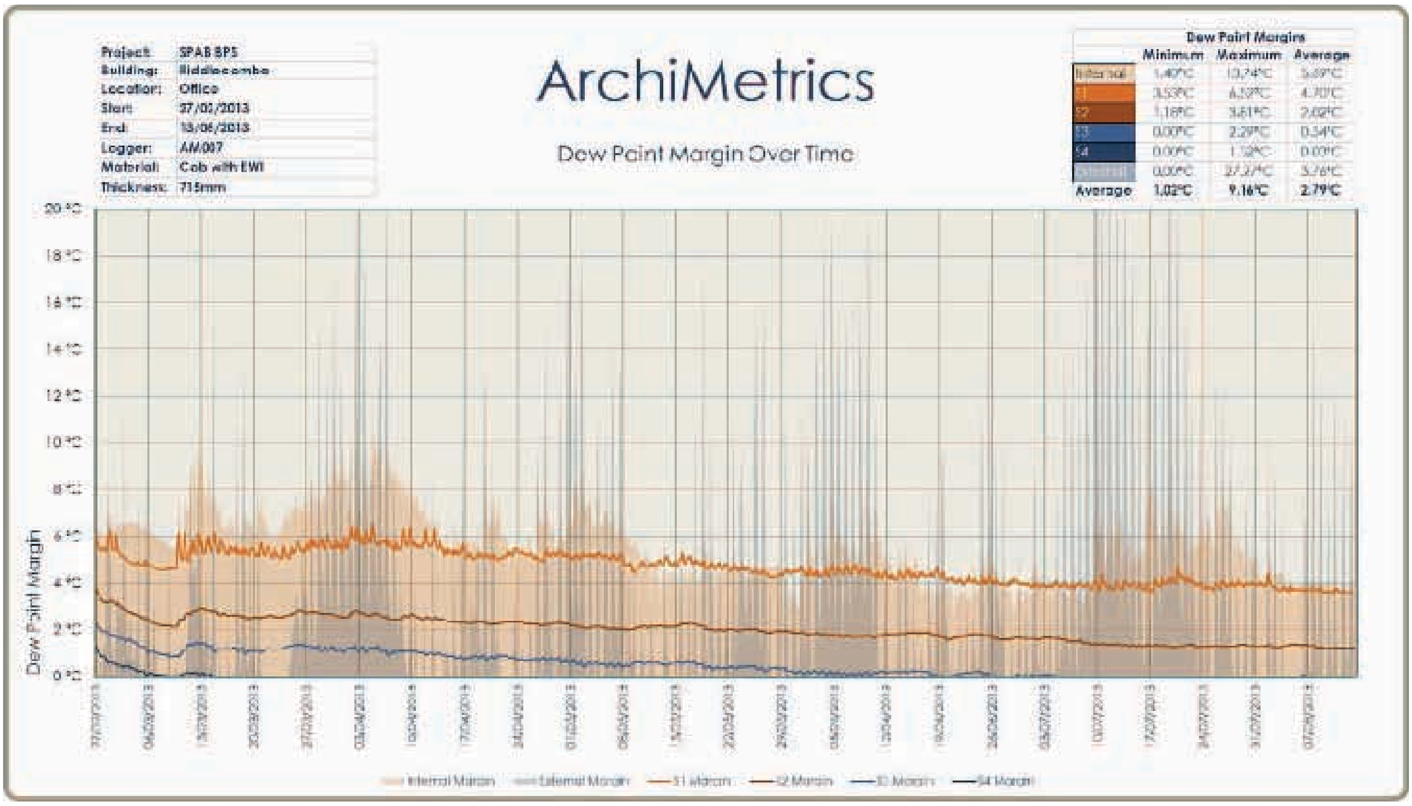


Figure 25: Dewpoint Margin over time, The Firs, Riddlecombe February - August 2013.

Indoor Air Quality

Figures 26-29 provide plots of CO_2, temperature and %RH for the four houses post-refurbishment. Figures 27-29 cover roughly a 3 week monitoring period whereas the graph for Shrewsbury, Figure 26, is for a longer two and a half month period. Table 5 provides averaged values for indoor conditions within the four buildings pre- and post-refurbishment, the data in the table is averaged over a 2-3 week period for all locations for comparative purposes.

The pre- and post-refurbishment figures recorded for Drewsteignton show little change and this is because no substantial refurbishment work has taken place on this part of the building therefore conditions, by and large, remain unaltered. At the other three properties it can be seen that while the average levels of CO_2 post refurbishment all lie within the range deemed 'acceptable', i.e. below 1000 ppm as defined by CIBSE, this only describes the average condition of these rooms therefore a better indication of air quality is found through an examination of peak measurements at each property. Here we can see that the air quality at Riddlecombe, Figure 29, is appreciably poorer than at the other locations frequently peaking above 1500 ppm and even 2000 ppm, the maximum recorded quantity being 2824 ppm. Whereas the only other property which exhibits peaks above 1000 ppm is Shrewsbury and here the maximum quantity is 1326 ppm and at Skipton and Drewsteignton records never exceed 1000 ppm. The poor air quality measured in the office at Riddlecombe has previously been ascribed to a combination of low air permeability, high occupancy and low volume areas for the house. Also, perhaps surprisingly, levels of CO_2 at Shrewsbury, Skipton and Riddlecombe post refurbishment are all slightly lower than those recorded pre-refurbishment in 2011. This is surprising because measured air permeability at all three properties has reduced and one might expect that reductions in air permeability/air change rates may result in an increase in measured CO_2 in these rooms. Measurements of CO_2 are, of course, determined by a combination of air infiltration/ventilation, room scale and occupancy. It may be therefore that these reduced quantities of averaged measurements of CO_2 reflect slightly lower room occupancy over the reported period. And/or in the case of Skipton they may be a reflection of the enlargement that has taken place to the kitchen/dining area at this property where the greater area and volume of the room results in lower concentrations of CO_2. At Shrewsbury measurements have taken place in a small room which contains a substantial flue it was suggested in the previous version of this report, 2012, that improvements to air tightness at this property could have the effect of increasing the influence of this uncapped flue within the room and this may explain the reduced CO2 measurements at this location. A stove has subsequently been fitted at this property which will most likely have altered the air permeability and in turn may have now reversed this affect.

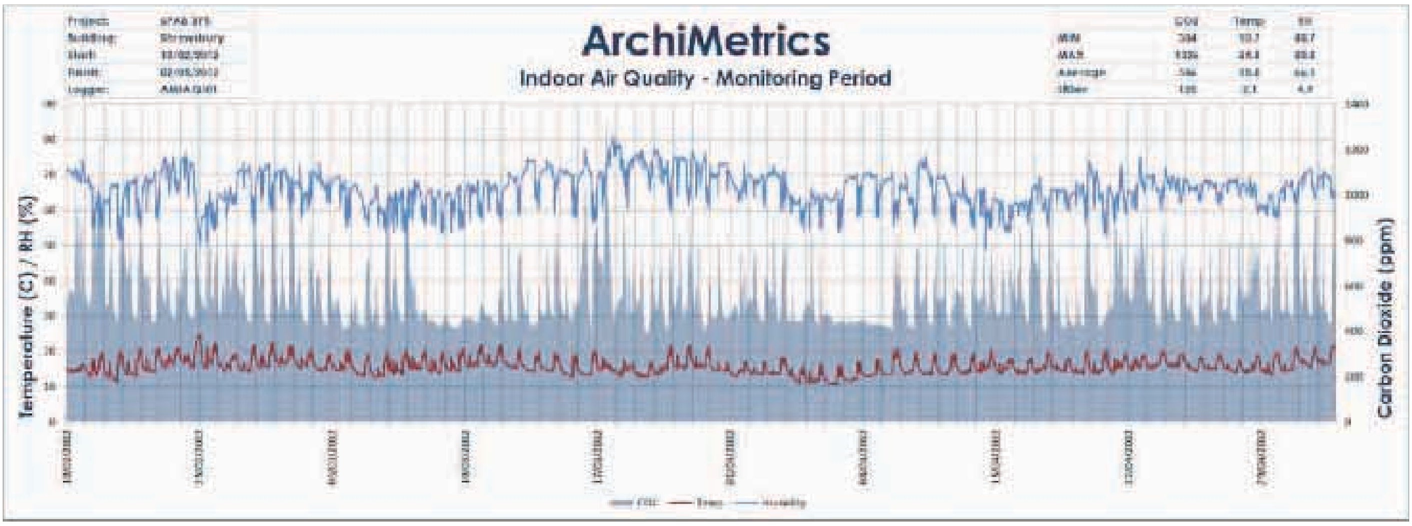


Figure 26. Indoor Air Quality (CO_2, temperature and RH) Abbeyforegate, Shrewsbury, 2012.

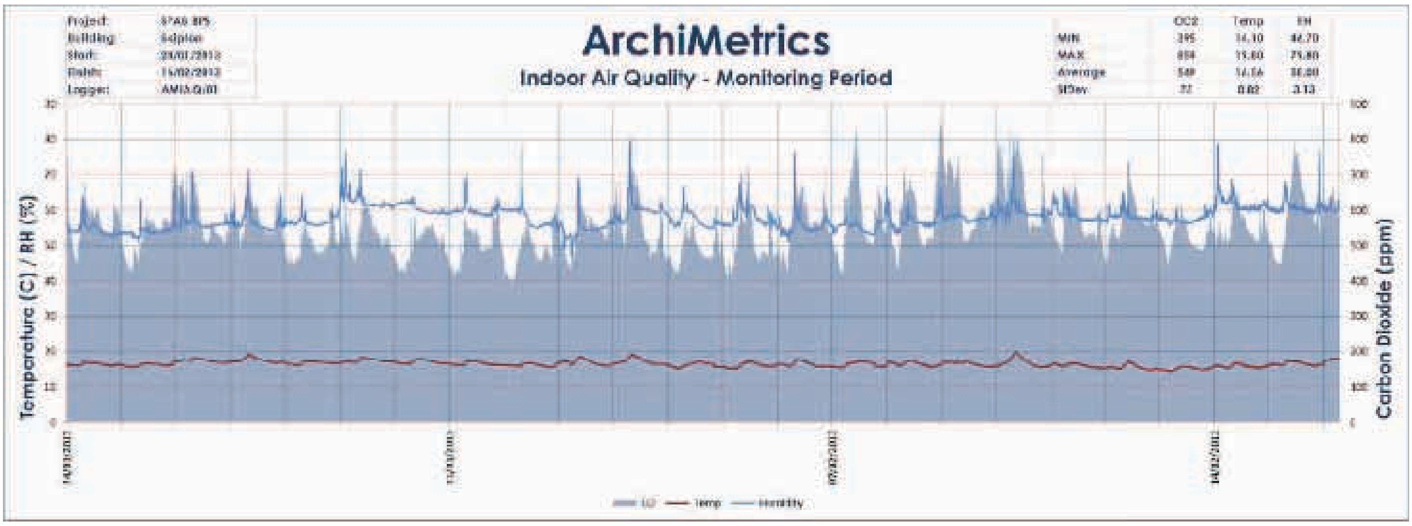


Figure 27. Indoor Air Quality (CO_2, temperature and RH) White House Farm, Skipton 2013.

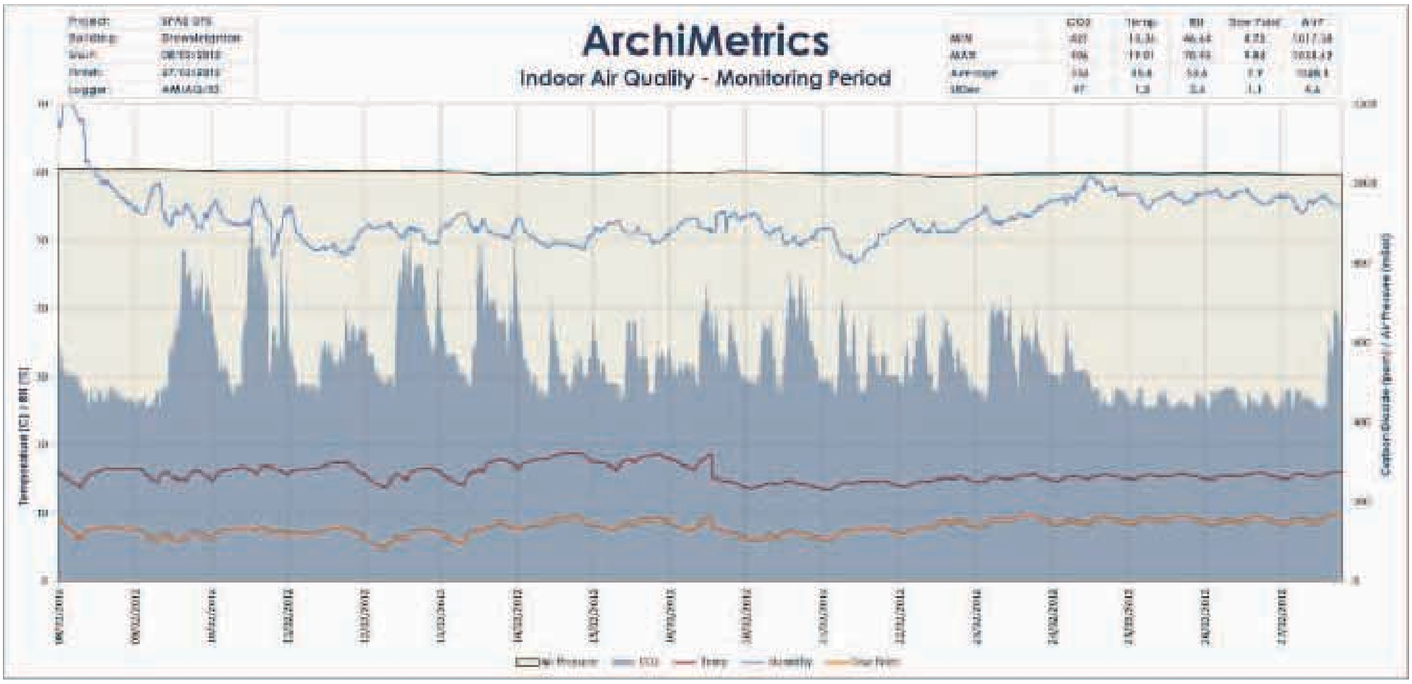


Figure 28. Indoor Air Quality (CO_2, temperature, RH, dewpoint and air pressure) Mill House, Drewsteignton, 2012.

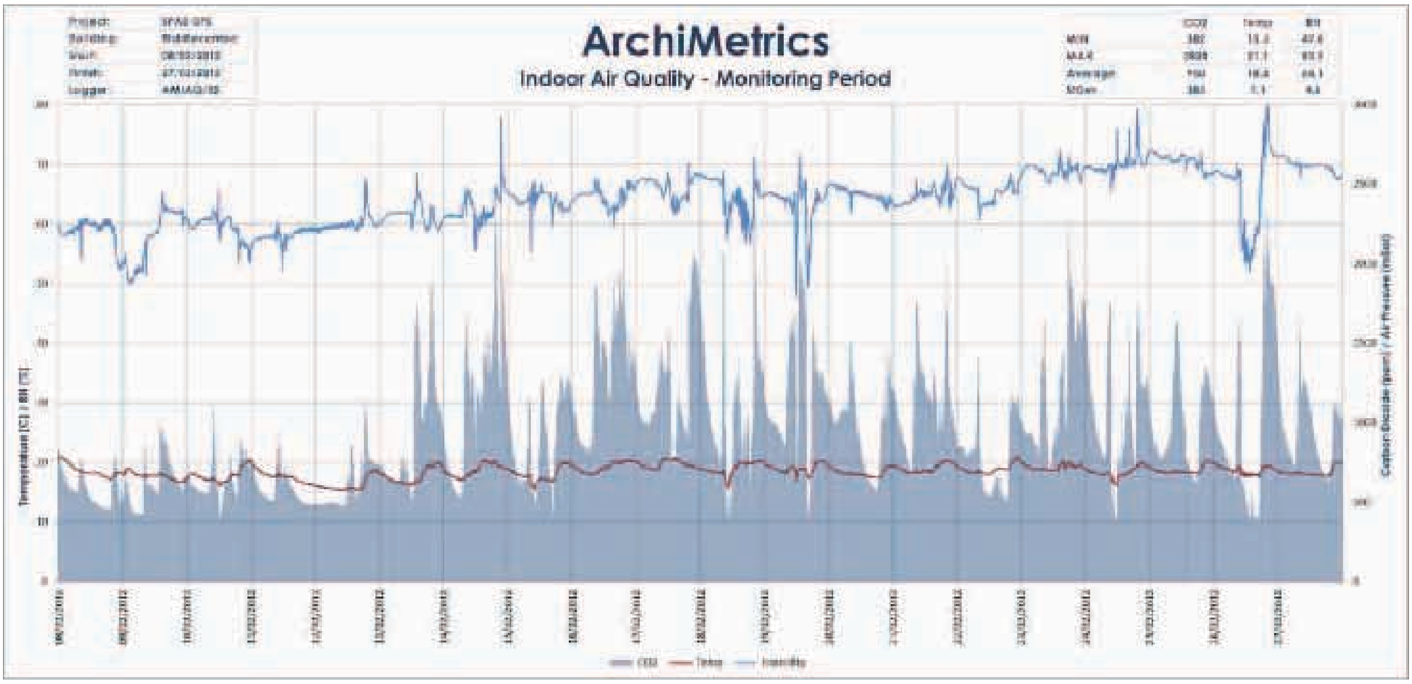


Figure 29. Indoor Air Quality (CO_2, temperature and RH), The Firs, Riddlecombe, 2012.

Property	Pre-refurbishment Averages			Post-refurbishment Averages		
	CO_2 (ppm)	Temp (˚C)	RH (%)	CO_2 (ppm)	Temp (˚C)	RH (%)
Shrewsbury	702	15	50.6	595	17	66.1
Skipton	554.5	16.2	63.3	540	16.56	58
Drewsteignton	581	16.8	55.13	553	15.8	59.7
Riddlecombe	1097.5	19.5	60.4	950	18.4	64.1

Table 5. Comparison of Average Pre and Post-refurbishment conditions: Indoor Air Quality (CO_2, temperature and RH), SPAB Building Performance Survey 2013.

Comfort and Fabric Risk

Figures 30-33 show individual indoor temperature and relative humidity readings plotted against an index of human comfort and fabric risk for the properties at Shrewsbury, Skipton, Drewsteignton and Riddlecombe post refurbishment. Table 6 provides averages of temperature and %RH measurements from the monitored rooms pre and post-refurbishment. The data for the pre-refurbishment Comfort/Risk analysis was gathered over a short period of time, normally between 2-3 weeks at each location. Post-refurbishment measurements were undertaken over considerably longer time periods. The duration of data gathering in each case is given against the pre and post refurbishment results for each property.

As can be seen from Table 6, average post-refurbishment temperatures have risen in all cases in comparison with room air temperatures prior to refurbishment. However this may just be a reflection of the fact that the post refurbishment data was gathered over a longer and warmer period of time, whereas pre-refurbishment measurements were all conducted in the winter months. Relative Humidity measurements at each location have also increased post refurbishment and this is perhaps slightly counter intuitive as higher temperatures should, in general, result in lower %RH, however, once again this increase may just be a reflection of the larger data sets. It may also reflect the influence of the application of new internal wet finishes where each house in this study experienced the application of new plaster in the rooms being monitored (and in some case elsewhere within the property). The drying of these wet finishes can certainly be seen in %RH and absolute humidity findings for some of the locations; Drewsteignton, Skipton (Figures 8 and 7) therefore the additional moisture within the internal room atmosphere particularly at the start of the post-refurbishment monitoring periods may be a reason why post refurbishment %RH has been found to be higher than pre-refurbishment values.

Individual indoor temperature and relative humidity readings are plotted against an index of human comfort and fabric risk for the four properties (Figures 30-33). With regards to the Comfort polygons, we can see that while the majority of temperatures and %RH measurements at all four properties fall within the 'acceptable' and 'ideal' Comfort polygons a proportion of post-refurbishment temperature measurements fall below this range at Shrewsbury, Skipton and Drewsteignton. However, it should be noted that at these three locations, pre-refurbishment, the majority of temperatures recorded over the (shorter) monitoring period were located below the 'acceptable' range therefore an improvement in conditions at least when measured over the longer term, seems to have taken place. However, by and large the post-refurbishment temperature averages for these three buildings are slightly lower than the range often identified as comfortable of about 18˚C-24˚C. To what extent this is a reflection of personal choice and/or longer duration monitoring is difficult to know. As has been previously explained no substantive changes have taken place within the monitored room at Drewsteignton, which is used as a study, therefore these temperatures are most likely a reflection of the longer monitoring period and may be also the preferred conditions of the occupant. The average measured post-refurbishment temperature at Skipton, 17.85˚C is only fractionally lower than 18˚C and may also reflect the means by which heat is delivered into this space, via underfloor heating which often results in lower air temperatures but nevertheless provides a perception of comfort on behalf of occupants. Conditions at Riddlecombe are interesting in this context as the temperature here, post-refurbishment, has only increased very slightly by 0.5˚C. This suggests that internal temperatures remain less affected by warmer external temperatures due to the thermal inertia of the cob wall and the small window in the room which admits little solar gain.

Previously, in 2011, measurements of room %RH in any of the properties under survey rarely crossed the limiting isopleths given for mould growth, where LIM0 represents an optimal substrate, LIM1 being biodegradable materials and LIM2 representing porous materials [6]. In Figures 30 - 33, post refurbishment we now find a proportion of measurements that intersect with these isopleths although Shrewsbury it would seem remains at very little risk. At the other three properties all three isopleths are crossed by a number of measurements although at Skipton and Drewsteignton this is a very small proportion overall. At Riddlecombe, the location that records high levels of interstitial %RH, indoor conditions also have the highest quantity of room %RH and this is reflected in a greater proportion of indices which cross and surmount all three LIMs. However, it should be noted that there is no indication of mould growth on the internal surfaces of the walls at Riddlecombe, perhaps due to a mould retarding limewash finish, although there is some indication that conditions for such a thing may be favourable.

[6] Sedlbauer, K. (2001). Prediction of mould fungus formation on the surface of and inside building components. Fraunhofer Institute for Building Physics.

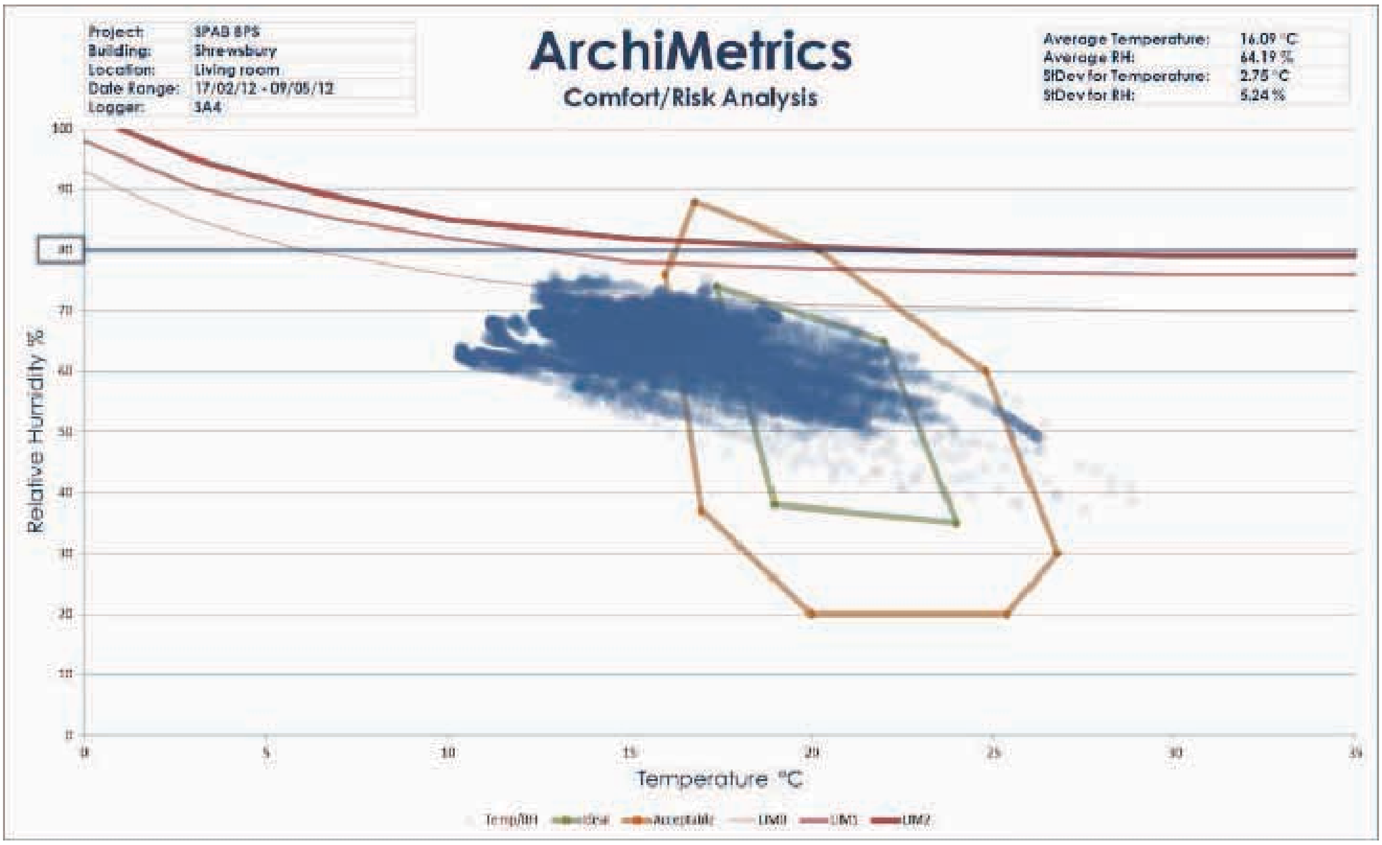


Figure 30. Comfort/Risk Analysis for Abbeyforegate, Shrewsbury, 2012.

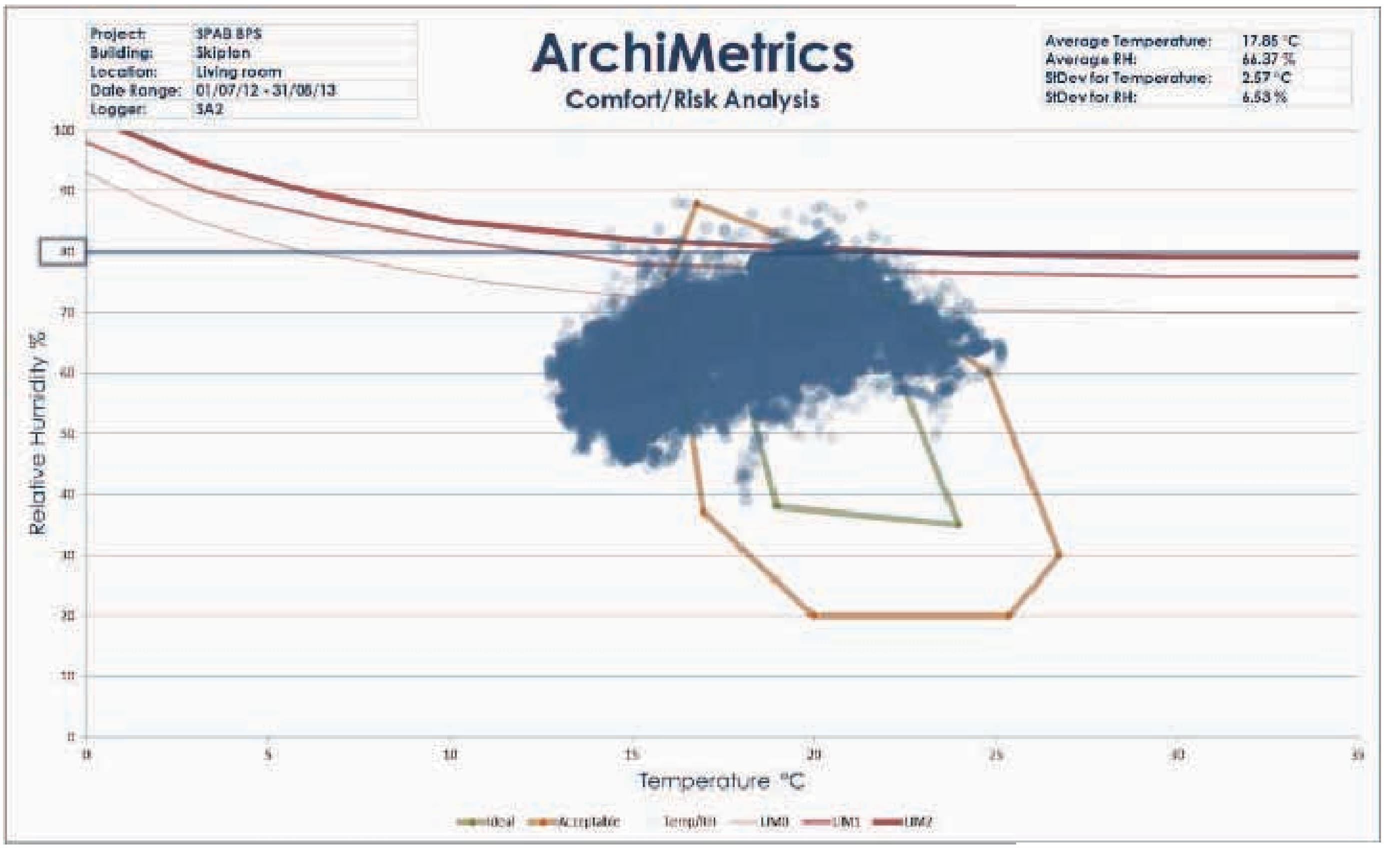


Figure 31. Comfort/Risk Analysis for White House Farm, Skipton, 2012 - 13.

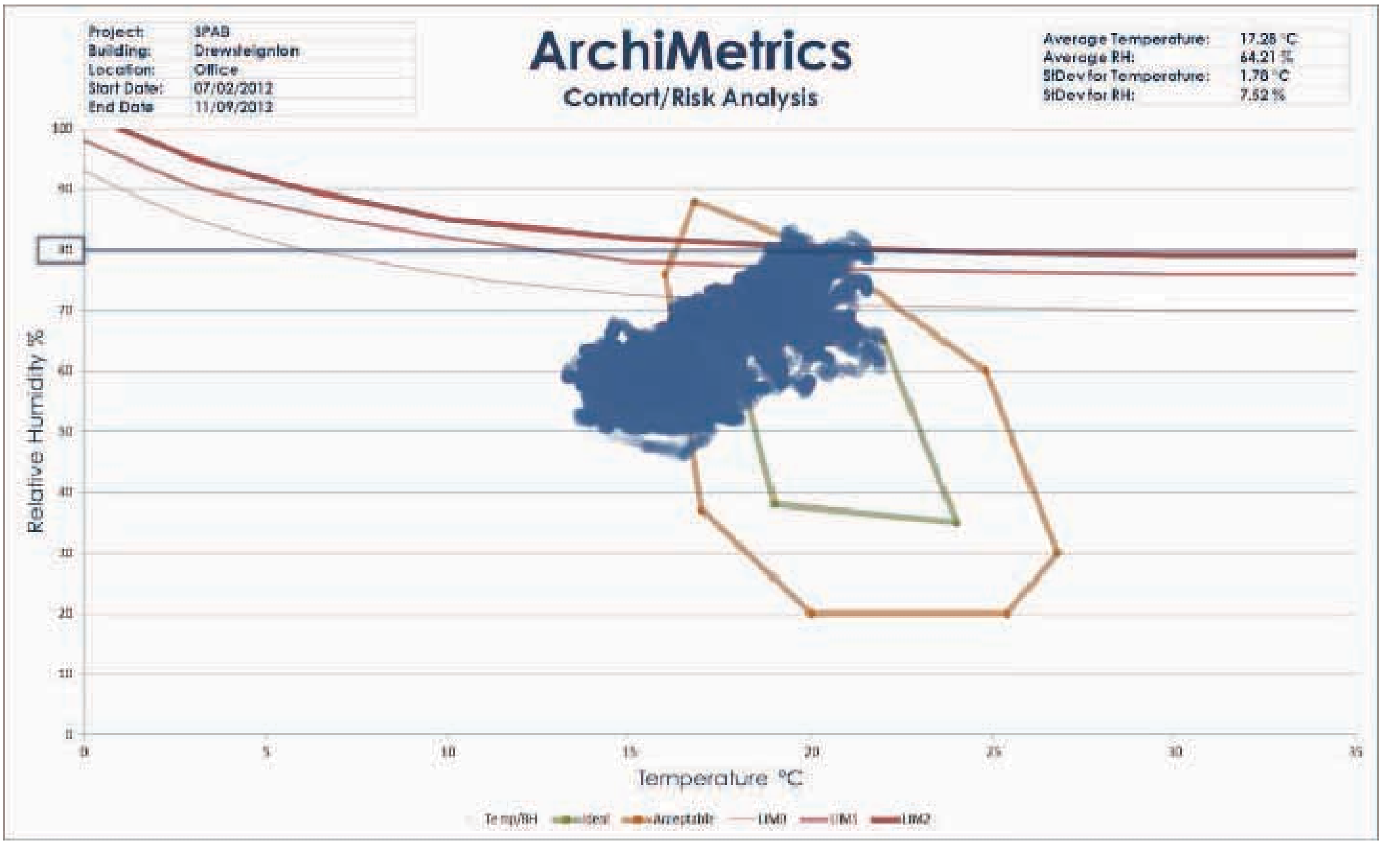


Figure 32. Comfort/Risk Analysis for Mill House, Drewsteignton, 2012.

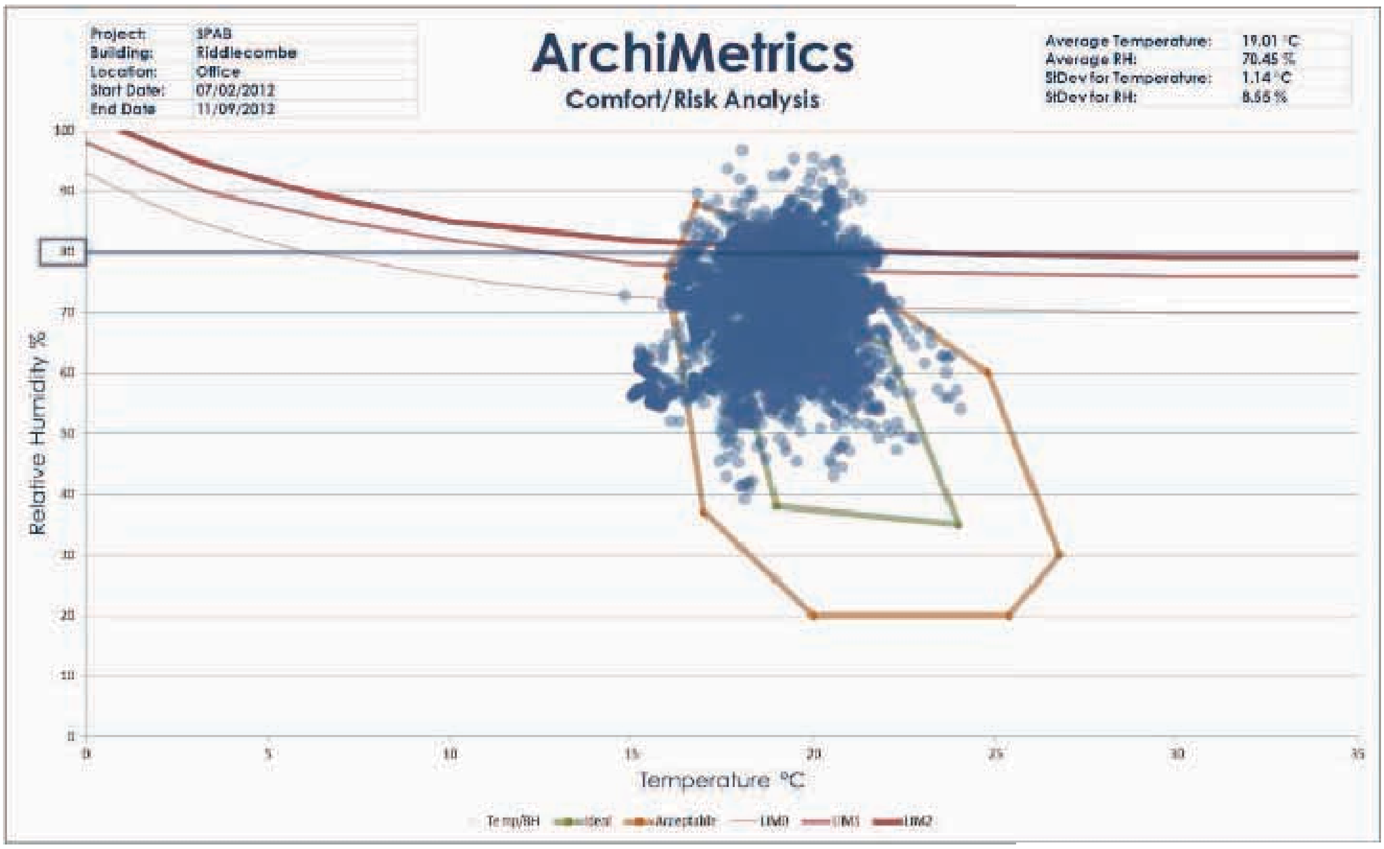


Figure 33. Comfort/Risk Analysis for The Firs, Riddlecombe, 2012.

Location	Dates	Temperature ˚C	Relative Humidity %
Shrewsbury (Pre)	27/01/11 -17/02/11	14.35	57.69%
Shrewsbury (Post)	17/02/12 - 09/05/12	16.09	64.19%
Skipton (Pre)	10/02/11 - 24/02/11	16.20	63.30%
Skipton (Post)	01/07/12 - 31/08/13	17.85	66.37%
Drewsteignton (Pre)	04/03/11 - 21/03/11	15.75	54.25%
Drewsteignton (Post)	07/02/12 -11/09/12 -	17.28	64.21%
Riddlecombe (Pre)	25/02/11 - 13/03/11	18.50	59.44%
Riddlecombe (Post)	07/02/12 - 11/09/12	19.01	70.45%

Table 6. Averaged Room Temperatures and %RH Pre and Post-Refurbishment, SPAB, Building Performance Survey 2013.

4. CONCLUSIONS

From the post-refurbishment monitoring undertaken in 2012 and 2013 at the properties in Shrewsbury, Skipton, Riddlecombe and Drewsteignton it is possible to identify some interesting trends developing. However, it should be emphasised, that because of the differences between the buildings under discussion, as well as their different refurbishment treatments, direct comparisons between them are problematic.

Furthermore, monitoring is still on-going at three of the properties; Shrewsbury, Drewsteignton and Riddlecombe and the findings contained within this report relate to a relatively short period that extends from February to September 2012 (or February to May in the case of Shrewsbury). Therefore, the purpose of this report is to provide some broad indications of trends and tendencies in the hope that, as the monitoring continues, these will be brought into focus by additional data and be supplemented by information collected from the other buildings within the Building Performance Survey that are yet to have refurbishment work completed.

From the measurements of U-values it is possible to see substantial reductions in fabric heat loss through wall elements due to the application of insulation at three of the four properties. The installation of 100mm of PIR internal wall insulation on the test wall at Drewsteignton resulted in a 87% reduction in the measured U-value for this wall, whilst smaller quantities of less thermally resistive insulation material also made considerable differences at both Shrewsbury, a 69% reduction from 40mm of woodfibre insulation, and 38% at Skipton from 40mm of hemp/lime plaster. The only location that didn't record any significant change in measured U-values pre and post insulation was the cob wall at Riddlecombe insulated with an external insulating render where only a 4% reduction in heat loss was measured. It is thought that this is possibly a result of the high moisture content of this wall. Previously it has been thought that the discrepancy between measured and calculated U-values for solid walls would reduce following the application of a known quantity of insulating material. However, an examination of Table 2 shows that, within this sample of walls, the discrepancy between the two forms of U-value quantification both pre and post insulation overall remains very similar. The discrepancy is reduced, meaning a calculated U-value becomes more aligned with a measured U-value, when the effect of the new insulating layer dominates within the thermal profile of the wall i.e. the 100mm of PIR at Drewsteignton. For other walls, with less heat loss reduction as a result of insulation, i.e. Skipton 38%, a large discrepancy between measured and calculated U-values remains, where the calculated U-value overestimates heat loss.

The air permeability of the three properties tested thus far - Shrewsbury, Skipton and Drewsteignton - has reduced following refurbishment. In the case of Shrewsbury infiltration has been reduced by 23% and this has been significantly aided by the installation of secondary glazing on the first two floors. At Skipton the reduction is greater, 42% although the envelope that was measured was different pre- and post-refurbishment for practical reasons. The improvement is much less significant for Riddlecombe which, at the time of re-testing, only measured a 3.6% reduction to infiltration. It should be noted that the house at Riddlecombe had already been found to have a low rate of permeability pre-refurbishment in 2011 and now has an the air change rate at 50Pa of 6.9 air changes per hour (ach) which may be considered less than desirable.

Refurbishment measurements undertaken on all four properties seem to have improved moisture conditions at the interior surface of the walls. At Shrewsbury and Drewsteignton this is a function of the addition of sheet material insulation to the internal face of the wall moving the surface and sub-surface measurement range away from the solid masonry part of the wall. The masonry element of the wall built without a cavity or damp-proof course is still likely to be influenced by external conditions such as rain and ground water. At Skipton and Riddlecombe the use of lime finishes on the interior surface of the wall seems to have contributed to a more stable moisture scenario at the internal face particularly at the base of the wall. However, above the limit of capillary rise, roughly 1200-1400 mm above finished floor level, surface and sub-surface measurements, although nominally 'drier', become more aligned with pre-refurbishment measurements. This may indicate that the moisture profiles measured at the surface and sub-surface of these walls more are influenced by conditions deeper within the substrates than those walls which are internally insulated with sheet materials.

Location	Dewpoint Margins					
	Pre-Refurbishment (short term)		Post-Refurbishment (short term)		Post-Refurbishment (long term)	
	Ave ˚C	S4˚C	Ave ˚C	S4˚C	Ave ˚C	S4˚C
Shrewsbury	5.49	3.96	3.81	0.0	4.7	3.08
Skipton	4.34	2.49	3.29	0.87	4.19	3.27
Drewsteignton	4.01	2.38	3.51	0.90	2.48	0.57
Riddlecombe	2.86	0.6	2.36	0.33	1.82	0.03

Table 7. Short and Long Term Pre and Post-Refurbishment Dewpoint Margins, SPAB, Building Performance Survey, 2013.

Dewpoint margins have been calculated for the walls post refurbishment on a short and long term basis, Table 7. Pre-refurbishment hygrothermal measurements within the wall section were undertaken over a short time period, 2 - 3 weeks during the winter months, therefore, whilst post-refurbishment measurements have been carried out over a much longer time period two sets of post-refurbishment margins have been calculated for comparative purposes. All walls, with the exception of Skipton, have seen a reduction in both their short and long term dewpoint margins following insulation. The short-term margins will be particularly determined by the external conditions and therefore these reduced margins may be explained by colder conditions during the winter of the post-refurbishment measurement period. However, the performance of the wall over the long term, post-refurbishment, gives an indication of the change in dewpoint margins conditioned by both summer and winter conditions and here also we find a reduction in comparison to the pre-refurbishment margins. This suggests, that in the case of the three internally insulated walls; Shrewsbury, Skipton and Drewsteignton the dewpoint margin may be reduced due to the cooling of masonry fabric on the cold side of the insulation. At Riddlecombe, an externally insulated building, the reason for the reduction in dewpoint margin is possible a result of the vaporisation of moist cob material as a result of past building failures and trapped construction moisture.

The previous edition of this report found possible trends of rising %RH in two of the walls under study; Drewsteignton and Riddlecombe. Longer term monitoring has provided more evidence of this trend although the cause of this behaviour is likely to be very different in both walls. The wall at Drewsteignton has seen a significant reduction in heat loss leading to cooler masonry on the cold side of the insulation and a reduction in the dewpoint margin for the wall overall. In addition, the insulation material incorporates a virtually impermeable barrier in the form of aluminum foil bonded to both surfaces. Increases in %RH measured for this wall may be a result of the lowering of dewpoint affording an increased incidence of condensation and restrictions to the migration of vapour due to these impermeable layers. At Riddlecombe the rising trend of %RH is most pronounced over the summer months suggesting cycles of vaporisation from the damp cob material and the possible failure of this vapour to migrate through the wall material quickly.

In contrast the walls at Shrewsbury and Skipton show steady or declining %RH possibly indicating that the quantity and type of materials used to insulate these walls have not excessively cooled the masonry element and are able to moderate vapour balances between the wall and internal and external conditions. The hygrothermal performance of walls is driven by a combination of internal and external conditions; longer term monitoring enables us to identify to what extent this performance is determined by specific weather conditions, heating regimes, vapour control layers and the inherent qualities of specific wall materials.

With regards to indoor air quality and indoor conditions in general these do not seem to be significantly changed as a result of the refurbishment work. Levels of measured CO_2 have fallen at all four properties post-refurbishment where the average recorded at Riddlecombe remains on the cusp of acceptable at 950 ppm. Indoor air temperature and %RH have both risen post-refurbishment, the %RH measurements possibly reflecting the drying of wet internal finishes. The longer term measurements post-refurbishment also show occasions where internal room conditions may be conducive to mould growth on a variety of more or less biologically active substrates. However, this risk seems very minor and there in no indication of such growth at any property within the study.

Monitoring of interstitial temperature and RH along with internal and external conditions is on-going in three properties; Shrewsbury, Drewsteignton and Riddlecombe. This extended monitoring will allow us to clarify trends and further define links between long term performance responses and the energy efficiency refurbishment work undertaken at the properties. The results of this research work will be published on an annual basis in the form of the SPAB Building Performance Survey report.

116 Abbeyforegate, Shrewsbury.

2013

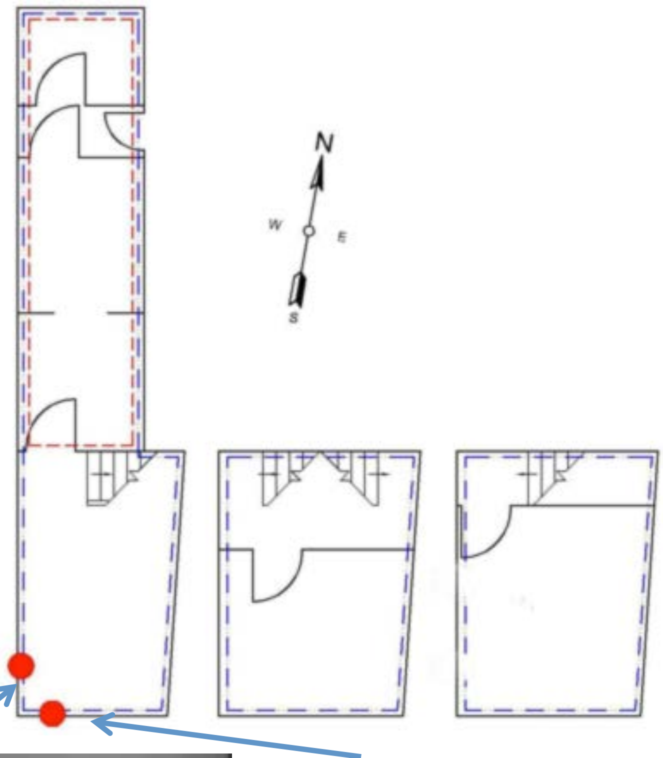
Description: End of terrace (originally mid-terrace) house, 2 storeys with attic dormer. Dating from 1820 but with earlier core. Brick with plain tiled roof, with elements of timber-framing and a modern single storey extension at rear accommodating a kitchen and bathroom.

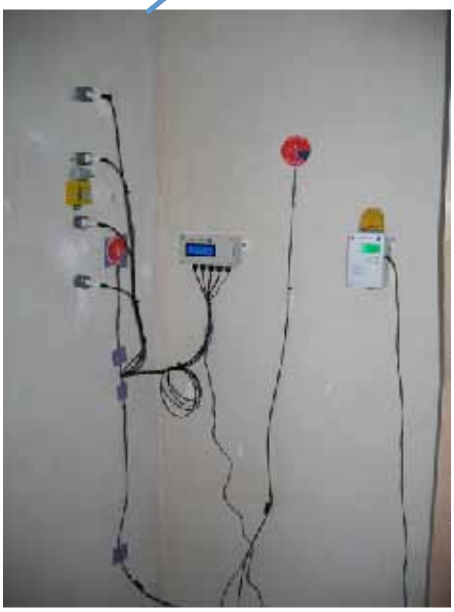
Refurbishment: Between February 2011 - December 2012 the following refurbishment work was undertaken at Abbeyforegate: internal insulation of all external walls on the ground and first floor with woodfibre board (excluding the rear single storey extension) and fitting of secondary double-glazing to ground and first floor sash windows on the front elevation. In 2013 a wood burning stove was fitted in the ground floor sitting room and the flue lined and backfilled with vermiculite.

Occupancy: 1 person.

Floor Area: $60m^2$

Figure 34 – Plan of 116 Abbeyforegate, Shrewsbury, with ground floor on left hand side. The red dots indicate the locations of the monitoring equipment. The air permeability test perimeter is show in blue, with the secondary test zone shown in red.





Figures 35 - 36. Showing positions of in situ monitoring equipment at 116 Abbeyforegate, Shrewsbury, 2012.

MOISTURE

Interstitial Hygrothermal Conditions

Measurements of temperature and relative humidity (%RH) are being made through a section of south-facing brick wall of the living room at Abbeyforegate (Figures 37 and 38). Combined temperature and relative humidity sensors are located at four points within the wall at the heights and depths given in Table 8. In addition to these measurements ambient conditions (temperature and %RH) is measured, internally and externally on either side of the wall in close proximity to the interstitial sensors. Data from all these sensors, for the period 9th May 2012 - 11th April 2013, has been collected and used as the basis for the following analysis.

Figure 37. Interstitial, U-value and IAQ monitoring set up at Abbeyforegate, Shrewsbury, 2012.

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	8mm
Woodfibre insulation	40 mm	2	1725 mm	48mm
Lime plaster	12 mm			
Brick	345 mm	3	1575 mm	195 mm
		4	1425 mm	385 mm
Overall	405mm			

Table 8. Interstitial hygrothermal gradient sensor positions for Abbeyforegate, Shrewsbury, 2012- 2013.

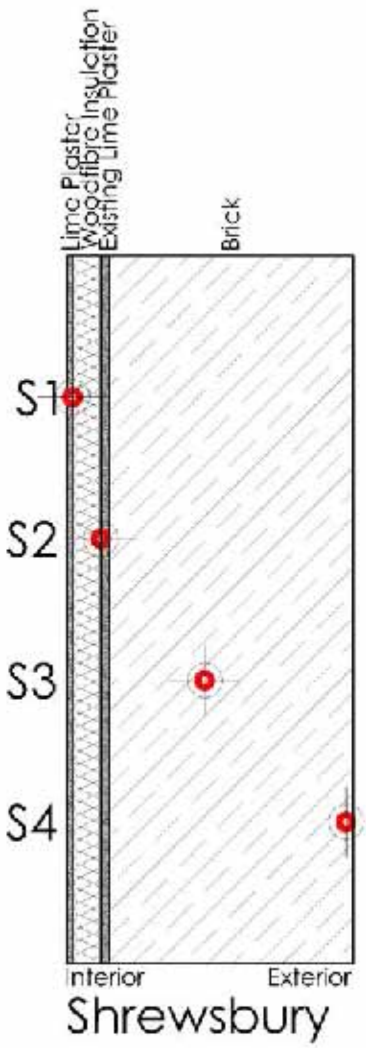


Figure 38: Wall Section showing position of sensors, for Abbeyforegate, Shrewsbury, 2012 - 2013.

Relative Humidity Over Time

Figure 6 plots levels of %RH recorded by the interstitial and internal and external sensors over time, from 9th May 2012 - 11th April 2013 and show a number of interesting trends. There are two distinct periods of 'behaviour'; that is to say a summer pattern and winter pattern seen in the wall. Values measured over the warmer spring and summer months show %RH values are more closely aligned through the depth of the wall whereas these values become more differentiated during the colder autumn and winter months where the affect of central heating and greater internal and external temperature difference creates a range of %RH measurements of increasing value in relation to proximity to external conditions.

Whilst the %RH values recorded at sensors, 1, 2 & 3 remain within a fairly narrow band, roughly between 60 - 80% those plotted for sensor 4, close to the external surface of the wall, are much more volatile and for a period of time, in February 2013, reach 100% RH indicating the possibility of condensation or saturated brick at this point in the wall. However, towards the end of the reporting period, from March onward levels of %RH at sensor 4 begin to fall and return to below 80%. Sensor 4 is located in proximity to the external wall surface, approximately 20mm back from the wall face. It has been previously noted that, due to the porous nature of the materials found at Shrewsbury and possibly the poor condition of the pointing, that the wall has an 'open' quality, that is to say it is significantly affected by different weather patterns and external conditions. The difference between this structure and, for example, the granite wall at Drewsteignton is demonstrated by the quality of the different %RH gradients plotted for the individual sensors for each wall seen in Figures 6 and 8. In general, the sensor responses at Shrewsbury are much more volatile showing rapid fluctuations in conditions even quite deep within the wall compared with the smoother more placid gradients recorded at Drewsteignton. This volatility is particularly of note in the plot of sensor 4 %RH responses over the reporting period and this is because of its extreme proximity to external conditions where it experiences rapid wetting and drying close to the face of the external south-facing wall. Whilst it is, therefore, perhaps not surprising that during the coldest period of the year dewpoint is reached close to the external wall surface it is also important to note that this is a temporary occurrence and that %RH returns to levels below 80% once conditions begin to warm up in early Spring.

With the exception of sensor 4, %RH responses throughout the wall section are very steady despite the open and porous nature of the wall and on average remain below 80%, the threshold often given for the formation of mould fungus. Neither do they, overall, exhibit a rising trend of %RH throughout the wall section as a whole, unlike those measured at Drewsteignton and Riddlecombe. Readings from sensor 2, installed between the woodfibre insulation and the brickwork are particularly interesting in this regard as these are particularly stable, only varying between 63.82 - 83.97 %RH throughout the whole period, with an average value of 71.56%. It might be suggested that this steady %RH response may be as a consequence of the hygroscopic properties of the woodfibre board which, via its moisture buffering capabilities, might serve to even out fluctuating humidity responses in this part of the wall.

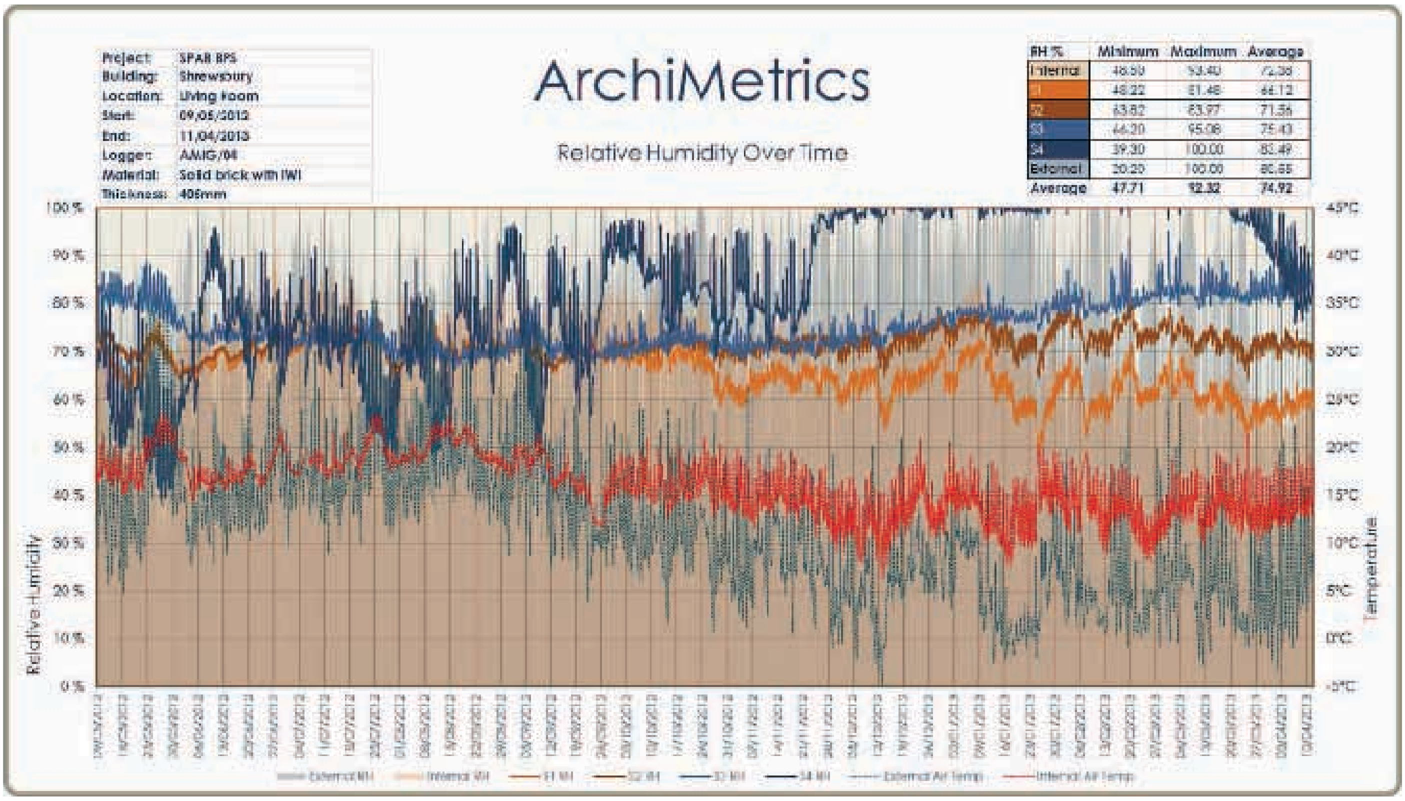


Figure 6: Relative Humidity over time, Abbeyforegate, Shrewsbury 2012 - 2013.

Absolute Humidity Over Time

Figures 39 and 10 show plots of absolute humidity over time for the insulated brick wall at Shrewsbury (Figure 10 is given for clarity to show plots from sensors 1 -3 which are obscured by the plot from sensor 4 in Figure 39). These show that humidity rises within the wall, tracking ambient conditions, over the warmer summer months as warmer temperatures enable more vapour to be held in the air. Once again the same volatility is seen in responses at sensor 4 (Figure 39) as a result of its position in close proximity to the external environment leading to rapid cycles of wetting and drying. In general the weight of vapour through the wall is quite evenly distributed and is on average lower than that found for the granite wall at Drewsteignton. Figure 10 shows two distinct summer and winter phases where greater quantities of vapour are recorded towards the exterior side of the wall over the summer but once the interior space of the house becomes heated during the winter months the weight of vapour is higher toward the internal side of the wall. The winter months therefore show the expected pattern with regard to vapour flow where vapour diffuses through the wall from an area of high pressure to one of lower pressure. Figure 39 (including sensor 4) also illustrates an interesting phenomenon which occurs during a period of very cold temperatures between 13th and 21st January. The gradient for sensor 4 becomes uncharacteristically static and shows the exterior wall face to be the driest point of all four sensing positions. This period also coincides with high %RH, 100%, measurements at this location (Figure 6). This is during a period of snow fall in the area, when the vapour carried in the atmosphere is very low but despite this, due to the extremely low temperatures, dewpoint is frequently reached. Therefore whilst this part of the wall is 'dry' from a vapour point of view it is also at dewpoint and therefore likely to be 'at risk' from a small amount of liquid condensation.

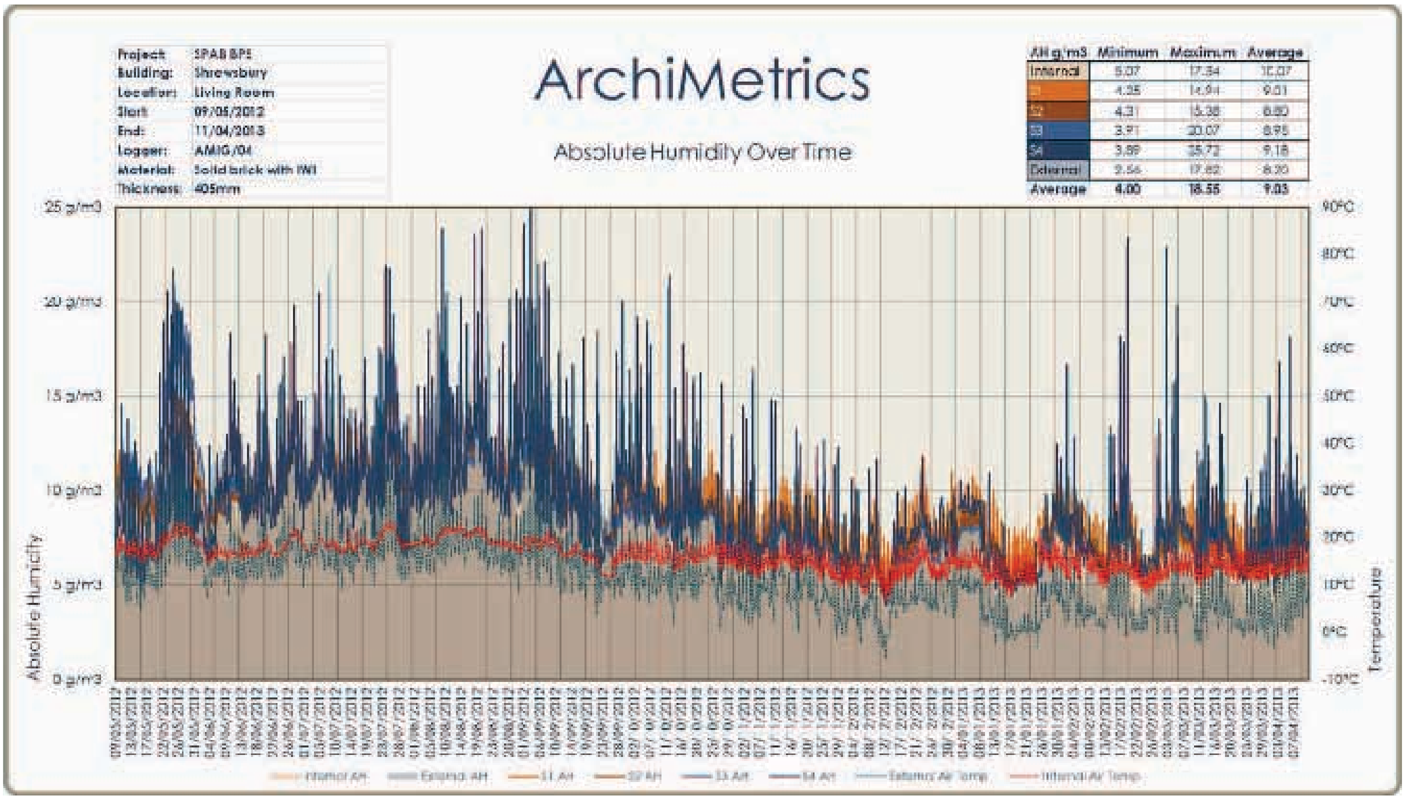


Figure 39: Absolute Humidity over time, Sensors 1 - 4, Abbeyforegate, Shrewsbury 2012 - 2013

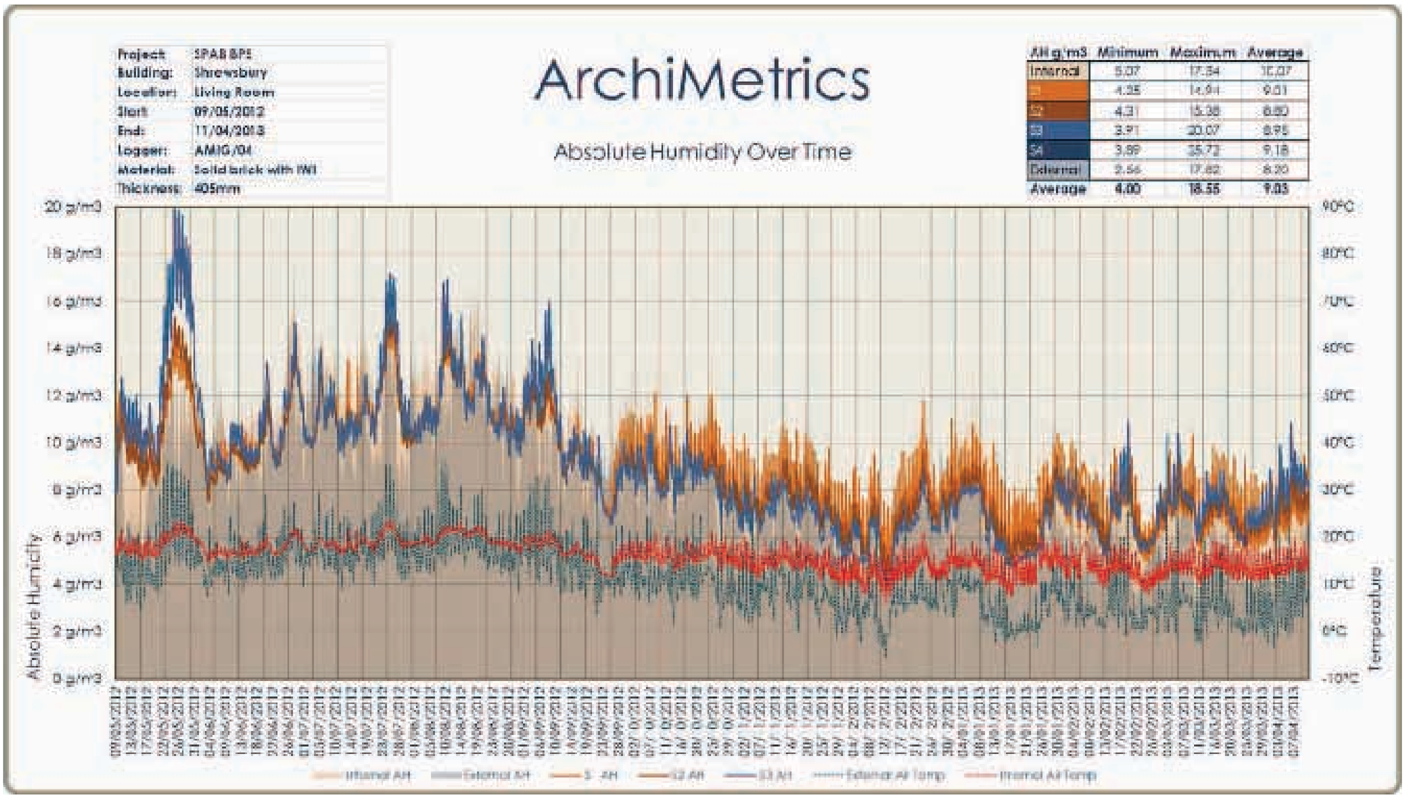


Figure 10: Absolute Humidity over time, Sensors 1 - 3, Abbeyforegate, Shrewsbury 2012 - 2013

Average Absolute Humidity

The absolute humidity section for Shrewsbury, Figure 14, provides an indication of the average g/m^3 of vapour either side of and through the wall section at Shrewsbury over the period 9th May 2012 - 11th April 2013. The graph presents a virtually flat line through the wall and an examination of the average values calculated for sensors 2, 3 and 4 (given in the table in the top right corner of Figure 14) shows a slight increase in average quantities of vapour towards the external wall leaf. This may suggest that, despite the distribution of vapour seen for the winter months in Figure 10, where vapour was higher at the internal wall leaf, the predominant condition of the wall over the reporting period is one of slightly increased weights of vapour towards the exterior side of the wall.

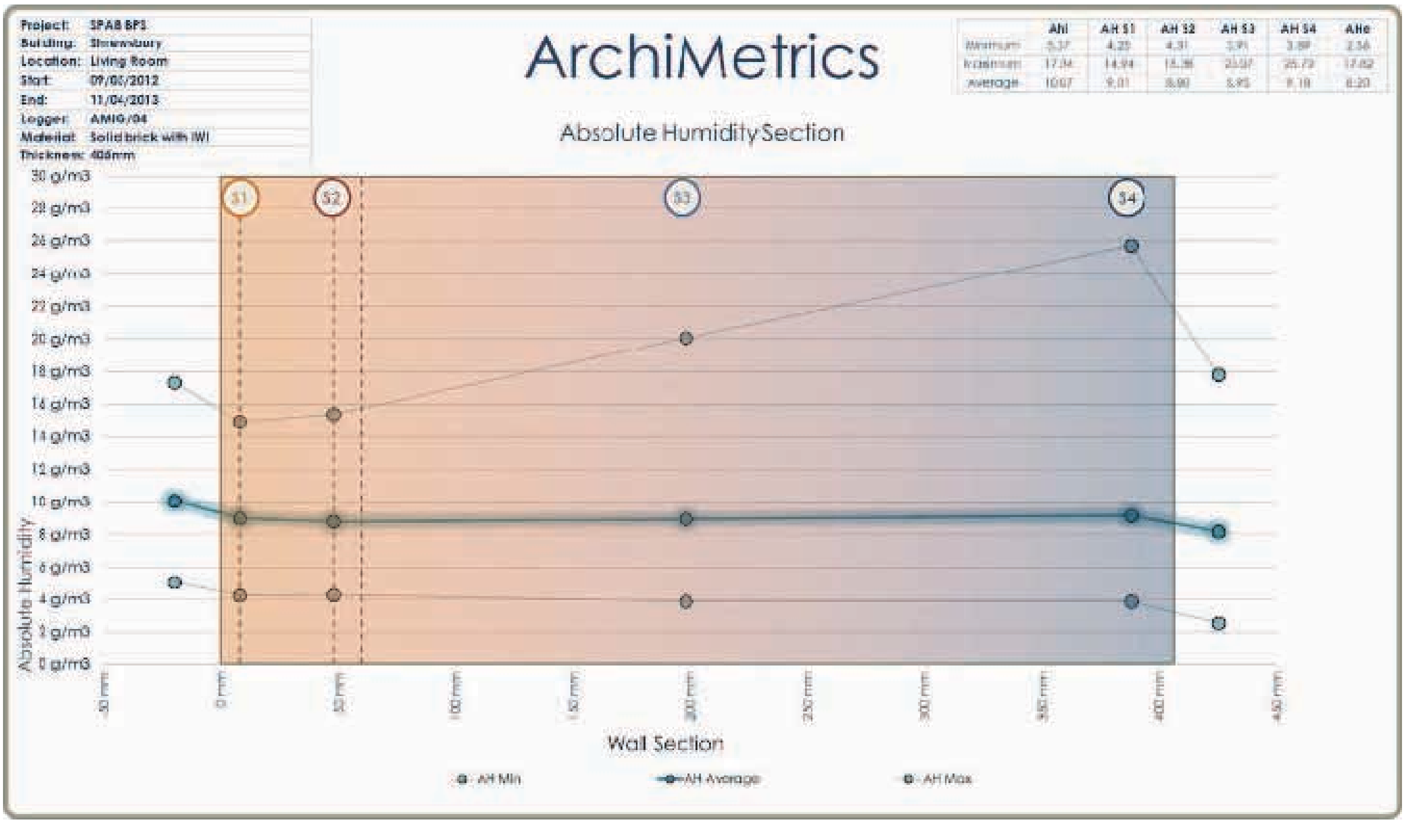


Figure 14: Absolute Humidity Section, Abbeyforegate, Shrewsbury 2012 - 2013

Hygrothermal Section

The dewpoint behaviour of the wall averaged over the reporting period is illustrated in Figure 18. This shows that the narrowest dewpoint margin (that is the temperature drop required for dewpoint to occur at a certain point) is understandably located towards the coldest part of the wall element at sensor 4, the average ˚C margin here being 3.06˚C. The average dewpoint margin calculated from data from all four sensors in the wall for this period is 4.70˚C. Prior to refurbishment, the average dewpoint margin for the wall section was 5.49˚C and 3.96˚C specifically at the 4th sensor. Therefore, the addition of 40mm of woodfibre internal wall insulation has not resulted in a significant reduction in these dewpoint margins despite lowering the quantity of heat transferred into the wall during the cold winter heating season. The plots of maximum temperatures recorded over the period are also of interest. These show the affect of solar radiation on the south-facing wall resulting in periods of reverse heat flow in the wall fabric. This reverse heat flow will be of benefit on sunny days during the winter heating season as the transmission of heat from the interior to the exterior will be slowed by the warming of the external fabric by solar radiation.

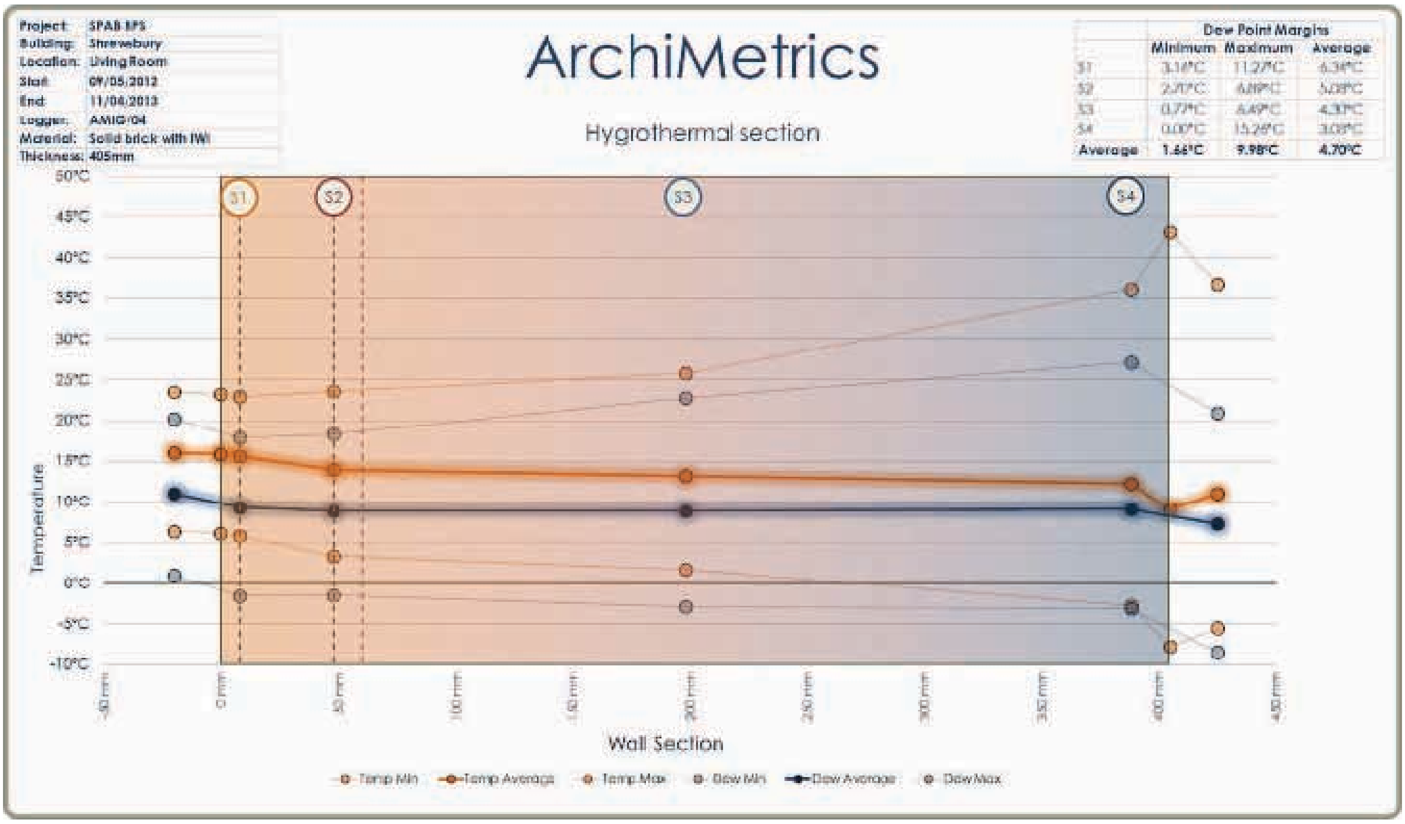


Figure 18: Hygrothermal Section, Abbeyforegate, Shrewsbury 2012 - 2013.

Dewpoint Margin Over Time

Figure 22 presents a plot of dewpoint margins over time for the wall at Shrewsbury. Like the previous Figures, Figure 6 for %RH and Figure 10 for absolute humidity, this graph shows responses at sensor 4 to be quite volatile and distinct from the more closely group plots from sensors 1 -3. This is not surprising as dewpoint is a factor of quantity of vapour and the surrounding temperature therefore the plots shown from sensors in Figure 22 have a direct relationship with vapour and %RH and mirror the findings shown in Figures 6 and 10. This is most clearly seen in the plot for sensor 4 between the period 22nd November 2012 - 19th March 2013 where the dewpoint margin is around or at 0˚C and corresponds, naturally, with the findings of 100%RH over the same period at sensor 4 indicating the likelihood of condensation. However, whilst this may seem alarming and might suggest that the external wall face is at the risk of some frost damage during periods of extreme cold, the risk of condensation needs to be reviewed over an annual cycle. The previous Figure, Figure 18, showed that over the reporting year on average the dewpoint margin at sensor 4 was 3.06˚C, for this to be the case there must have been periods of time over the 12 months where this part of wall was well below 100% and free from condensation and that on average this is the predominant condition of the wall. It should also be remembered in this context that sensor 4 is positioned very close to the external wall face (20mm back) situated within quite open and porous materials. Therefore, it is not surprising that extremes of temperature and weather will have a profound affect at this location and that extremes of cold leading to condensation will also be tempered by extremes of heat resulting in a dewpoint margin overall that suggests the wall is at little risk from prolonged condensation. With regard to the risk of prolonged condensation, the behaviour deeper within the interstices of the wall is of more interest as here, away from the direct influence of internal or external conditions, the opportunities for the dispersal of vapour may be decreased. In this respect, and has been previously noted in the discussion concerning %RH over time, the wall at Shrewsbury appears to be functioning well with levels %RH below risk thresholds and this is reflected in Figure 22 in the 'healthy' dewpoint margins recorded for sensors 1 - 3; 6.34˚C, 5.08˚C and 4.30˚C respectively.

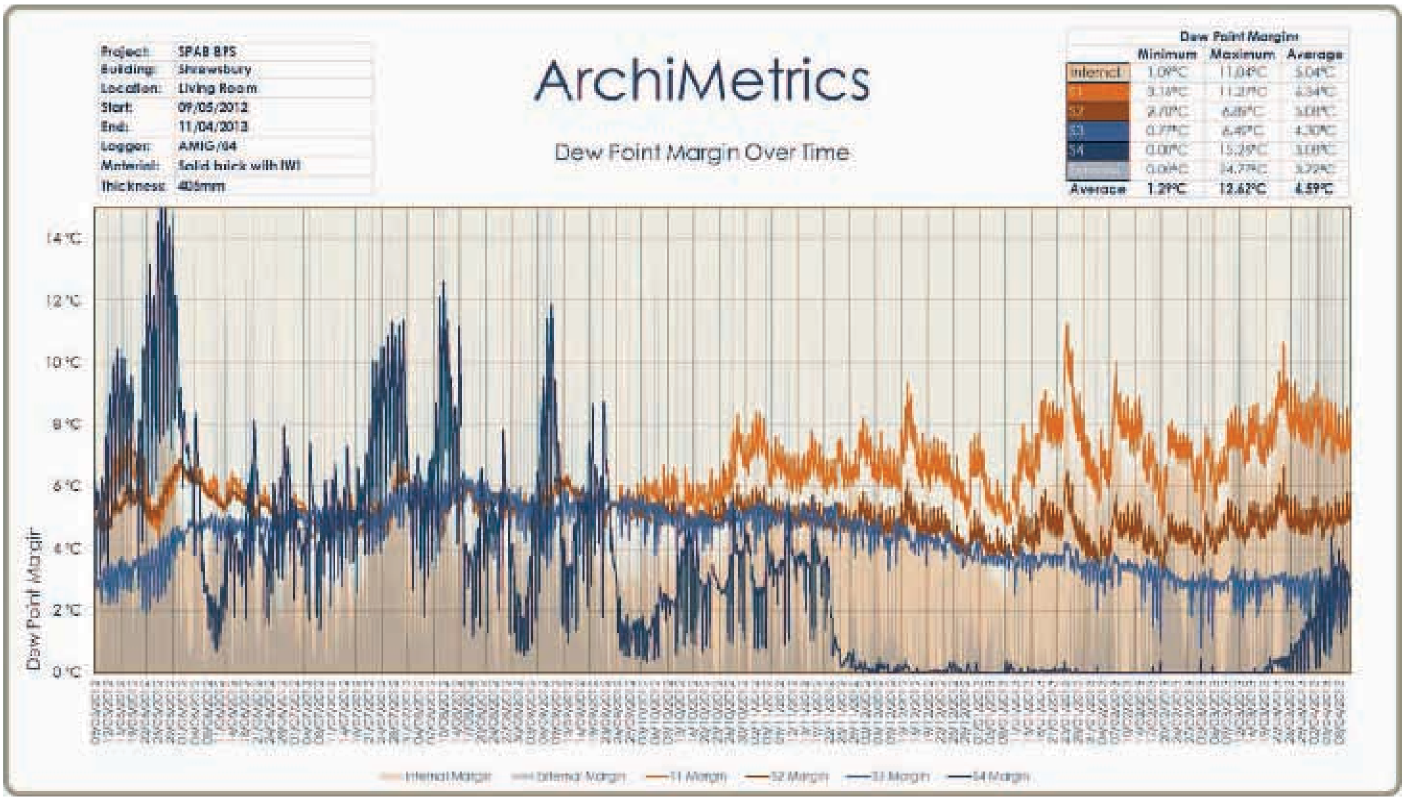


Figure 22: Dewpoint Margin over time, Abbeyforegate, Shrewsbury 2012 - 2013.

White House Farm, Stirton, Skipton
2013

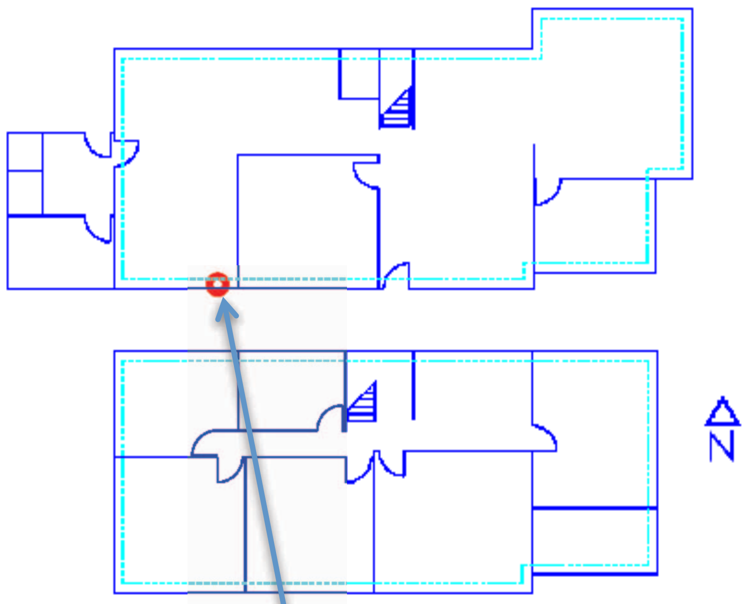
Description: Grade II listed farmhouse dating from 1790 of local squared sandstone rubble construction with slate stone roof. The walls comprised principally of gritstone set in a lime mortar and contain a distinct rubble core comprising of other stone types including flint. The original building has been extended twice; a nineteenth century extension full depth to the left side of the original and a 1957 addition in brick and render half depth to the right of the original. The property has functioned as two separate dwellings but was reinstated as a single dwelling in March 2010.

Refurbishment work at White House Farm commenced in 2011 and has included; the replacement of all windows with new timber double glazed units, the insulation of the whole of the ground floor using LECA and the incorporation of underfloor heating into a limecrete sub-floor, the dwelling has been re-roofed including a new breathable membrane and the roof insulated with sheeps wool insulation and the solid stone external walls have been insulated internally with a hemp/lime insulating plaster finished with a lime plaster. The modern extension at the east end of the property has been demolished and been replaced with a modern stone clad cavity construction built to current Part L1A regulations.

Occupancy: Family of 5

Floor Area: 298m^2 (including new extensions)

Figure 40. Plan of White House Farm, Skipton, with ground floor plan on LHS. The red dot indicates the location of monitoring equipment. The air permeability test area is shown in light blue, with a secondary test zone in red.



Figures 41 & 42. Positions of in situ monitoring equipment at White House Farm, Skipton, 2013.

U-VALUES

Between 25th January and 21st March 2013 two *in situ* U-value measurements were taken on the south wall of the ground floor kitchen (Figures 40 - 42). This position differs, for practical reasons, from those of the previous measurements, which were taken on the bedroom wall immediately above the kitchen. However, the wall construction and thicknesses are the same at both locations and therefore a similar thermal performance may be assumed.

Two U-values were measured from the wall, one lower down at 1000mm above finished floor level and another higher up at 1500mm (Figures 43 and 44). The lower measurement resulted in a U-value of 0.97 W/m2k and the other, slightly higher up the wall, produced the figure 1.04 W/m^{2}K. Percentage error figures have been calculated for both U-values; the 0.97 W/m^{2}K U-value has an error of 7.67% and therefore a potential range of 0.90 - 1.04 W/m^{2}K while the U-value 1.04 W/m^{2}K has an error percentage of 7.58% and a range between 0.96 - 1.12 W/m^{2}K. As can be seen from these two ranges the U-values 0.97 W/m^{2}K and W/m^{2}K sit within the upper and lower end of one another's potential U-value range as determined by their percentage errors and therefore may be considered as consistent. The average of the two measured post-refurbishment U-values is 1.00 W/m^{2}K.

The results of both the pre-refurbishment and post refurbishment U-values, along with accompanying standard U-value calculations made following the BR 443 method are shown in Table 9.

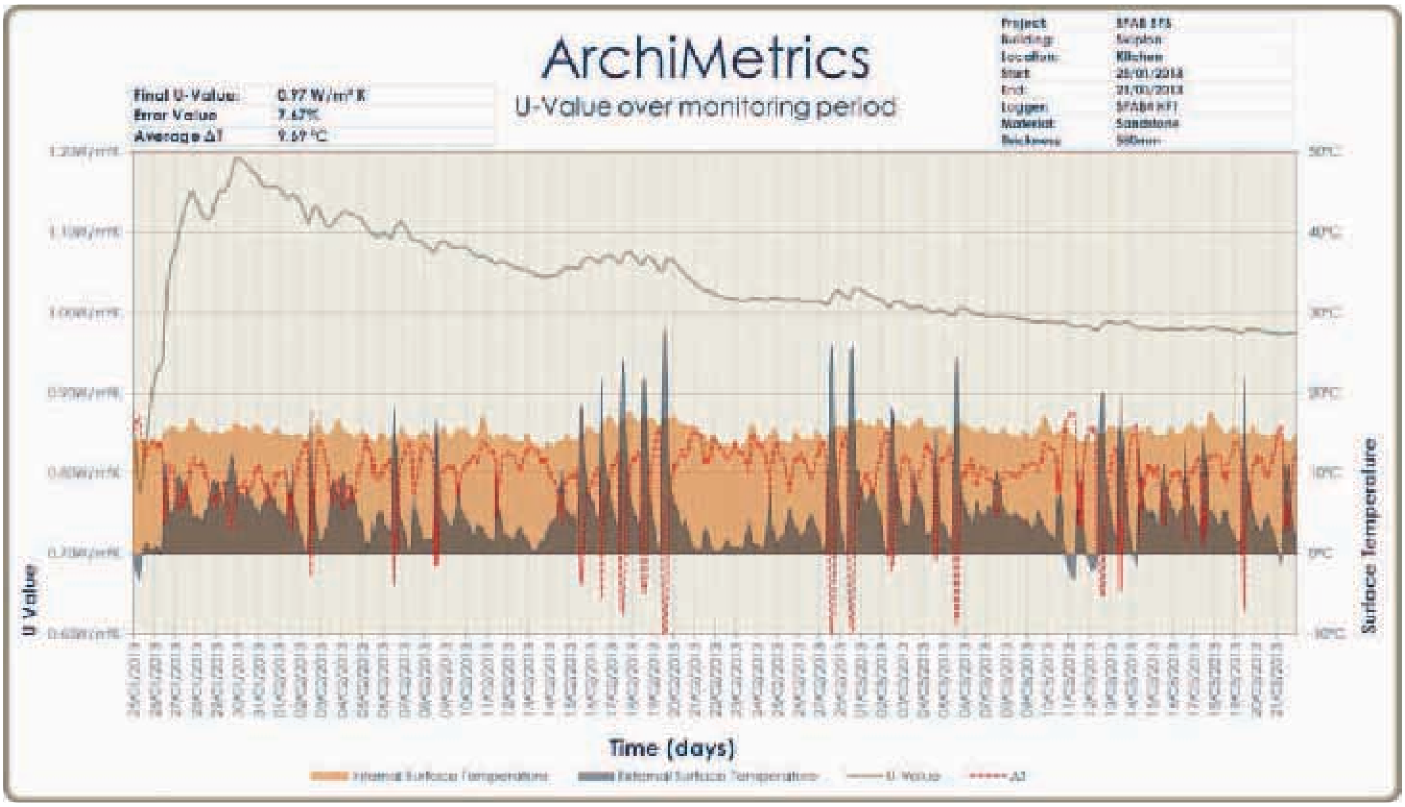


Figure 43. U-value over time (lower) White House Farm, Skipton, Jan. - March 2013.

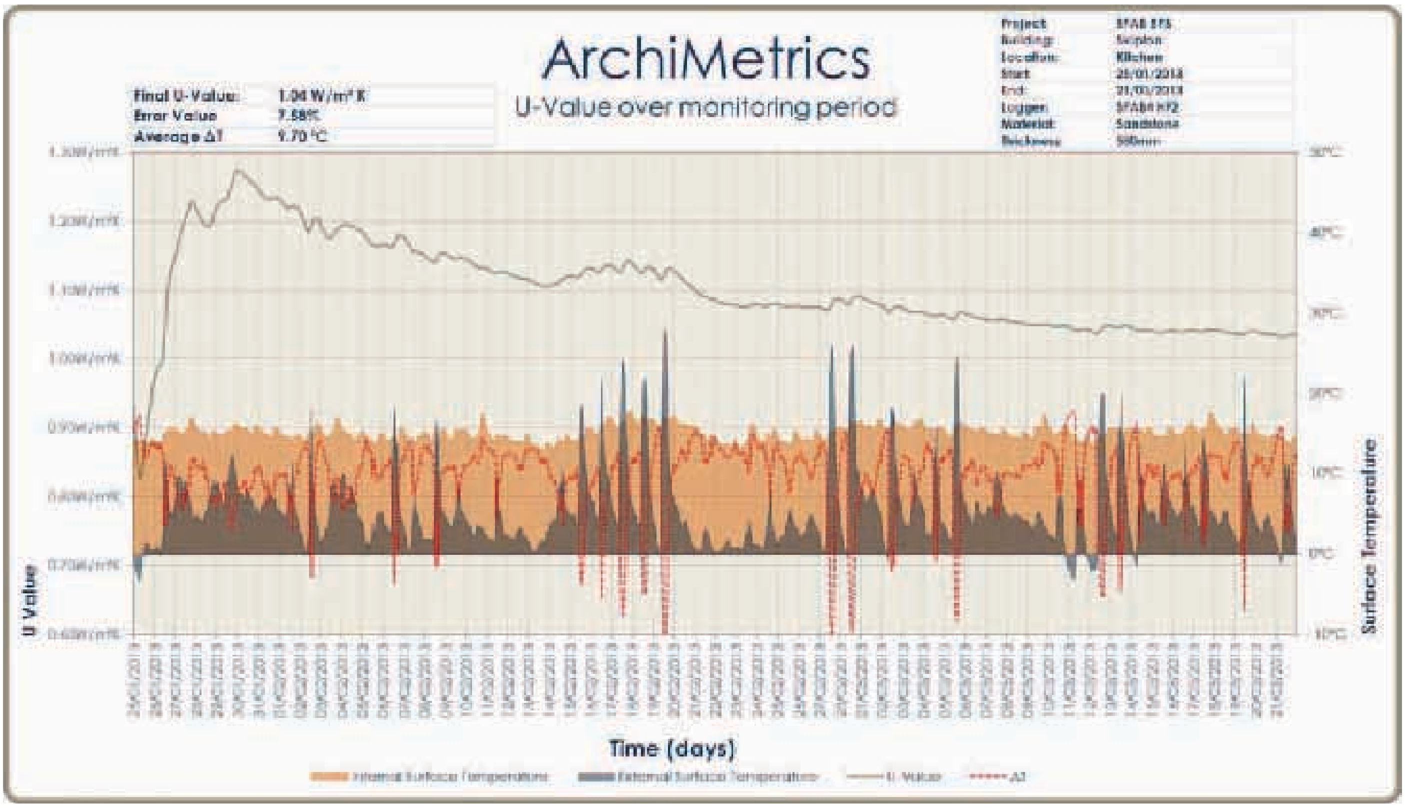


Figure 44. U-value over time (upper) White House Farm, Skipton, Jan. - March 2013.

Un-insulated 2011				**Insulated 2013**			
South Wall 1st Floor Bedroom Low - 1200mm from ffl				South Wall Grd Floor Kitchen Low - 1000mm from ffl			
Materials & Build Up internal - external	**mm**	***In situ* U value W/m²K**	**Calculated U-value W/m²K**	**Materials & Build Up** internal - external	**mm**	***In situ* U-value W/m²K**	**Calculated U-value W/m²K**
Cement skim	26			Lime Plaster	5		
Lime Plaster	6			Hemp/Lime Plaster	35		
Grit Stone Rubble	540			Grit Stone Rubble	540		
Total	**572**	**1.63**	**2.31**	**Total**	**580**	**0.97**	**1.72**
South Wall 1st Floor Bedroom High - 1700mm from ffl				South Wall Grd Floor Kitchen High - 1500mm from ffl			
Cement skim	26			Lime Plaster	5		
Lime Plaster	6			Hemp/Lime Plaster	35		
Grit Stone Rubble	540			Grit Stone Rubble	540		
Total	**572**	**1.62**	**2.31**	**Total**	**580**	**1.04**	**1.72**
Averaged Totals	**572**	**1.625**	**2.31**	**Averaged Totals**	**580**	**1.00**	**1.72**

Table 9. In situ and calculated U-value results for White House Farm, Skipton 2011 & 2013.

Both the pre and post refurbishment U-value measurements are quite consistent and using averages of the pre and post measured U-values (1.625 W/m^{2}K and 1.00 W/m^{2}K) a 38% improvement in the thermal resistivity of the external wall at Skipton is found. The same comparison, using pre and post refurbishment calculated U-values for the wall at Skipton, shows a theoretical reduction in heat loss of 26%. There is discrepancy between the measured and calculated U-values for the wall at Skipton pre-refurbishment, in 2011, of 0.69 W/m^{2}K which is matched almost exactly by the post-refurbishment 2013 measured/calculated discrepancy of 0.72 W/m^{2}K. The possible reasons for the discrepancy between measured and calculated U-values for solid walls is dealt with in some detail in another SPAB Research Report, Research Report 1: The U-value Report 2012, as well as being discussed in relation to the pre-refurbishment U-value findings in the 2011 edition of Research Report 2: Building Performance Survey: Interim Report. In this context it is interesting to note that if the U-value calculation for the stone wall at

Skipton allows for a 60:40 stone to mortar ratio this moves the calculated U-value more in-line with the measured U-values. This ratio has been suggested by Dr Paul Baker in work for Historic Scotland on solid wall U-values[7], and when included for the wall at Skipton the pre-refurbishment U-values reduces from 2.13 W/m^2K to 1.54 W/m^2K (lower than the measured U-value) and the 2013 post-refurbishment calculation changes from 1.72 W/m^2K to 1.25 W/m^2K.

In some situations, for example the insulated wall at Drewsteignton, a better correlation between measured and calculated wall U-values is found for the wall post-refurbishment. This can be explained in cases where proportionally the greatest determinant of the overall thermal transmissivity of the wall is the insulating layer. In situations where the insulation makes the single most significant contribution to the thermal resistance of the wall by identifying this material, its thickness and conductivity (usually known and tested qualities) a calculation can be provided which has close correspondence with a measured U-value. However, in the case of the wall in Skipton, such a correlation is not seen because, whilst the addition of the insulating hemp/lime plaster seems to have created some thermal benefit for this wall (a 38% reduction in measured heat loss) as a relatively thin layer with mildly insulating properties other materials within the build up continue to be of consequence for the overall thermal profile of the wall.

AIR PERMEABILITY

Air permeability testing was carried out on the complete habitable volume at White House Farm on 10 October 2013, solely using depressurisation due to concerns over any impact pressurisation would have on the two loose fitting loft hatches in the dwelling and potential impact on decor. The building has been remodelled and has an open-plan layout which does not permit the separate tests on the original dwelling and new addition (Figure 40). At the time of testing, the refurbishment of the dwelling was virtually complete apart from minor details. The ground floor of the new extension requiring finishing, with detailing such as internal doors and window sills yet to be fitted.

The test area is identified in Figure 40. Interior and exterior conditions at the time of testing are noted in Table 10 and the results of the whole dwelling air permeability test are shown in Table 11

Date of Test:	10 October 2013
Prevailing weather conditions at time of test:	Dry. Sunny. 10-50% cloud cover. Wind speed (approx. 11.30 am) 1.1ms^{-1} mean, 3.6ms^{-1} max External conditions at rear of dwelling: 8.3°C 72% RH (11.30am approx.)
Conditions inside dwelling:	Kitchen: 19.5°C 59% RH (approx. 10.45am)

Table 10. Interior and exterior conditions for air permeability test at White House Farm, Stirton, Skipton.

[7] Baker, P. (2011). *Technical Paper 10 - U-values and Traditional Buildings*, Edinburgh: Historic Scotland

	Units	Results	Comments
Whole dwelling			
Internal floor area (ground and first floors)	m^2	298	
Habitable building volume	m^3	718	
Dwelling envelope area i.e. surface area of living space	m^2	567	
Measured air flow	m^3h^{-1} @50 Pa	6181	
Air permeability test result at 50Pa	$m^3h^{-1}m^{-2}$ @50 Pa	10.9	m^3 of air per hour per m^2 of surface area of the living space.
Air changes per hour at 50Pa	ach@50 Pa	8.6	The number of times the complete volume of air in the property is changed per hour at the test pressure.

Table 11. Results for whole house air permeability test at White House Farm, Stirton, Skipton.

The air flow measured under the test conditions was 6181 m^3h^{-1}. Relating this result to the total surface area of the property, Table 11 shows the post-refurbishment air permeability of White House Farm is 10.9 $m^3h^{-1}m^{-2}$ @ 50 Pa, which is just above the limiting air permeability of 10 $m^3h^{-1}m^{-2}$ @50 Pa under Approved Document L1A 2010 for new dwellings. There were some notable areas of infiltration during the test process, particularly around the doorway into the en suite bathroom from the main bedroom which has yet to be plastered (Figure 45). In addition, there is a hole in the north wall adjacent to the stairs formed by a now redundant timber socket. There was noticeable air movement here under ambient conditions and this was excluded from the test as it will shortly be filled.

Relating the air flow to the building volume, the air change rate at 50 Pa pressure difference is 8.6 ach, representing the number of times per hour the total volume of air in the dwelling will change at this pressure. From Sherman[8], under normal conditions this would represent an air change rate of around 0.4 ach, which is around the level considered necessary for building occupants and their activities.

[8] from Ridley, I. et al, The impact of replacement windows on air infiltration and indoor air quality in buildings. International Journal of Ventilation 1(3) pp 209-218.

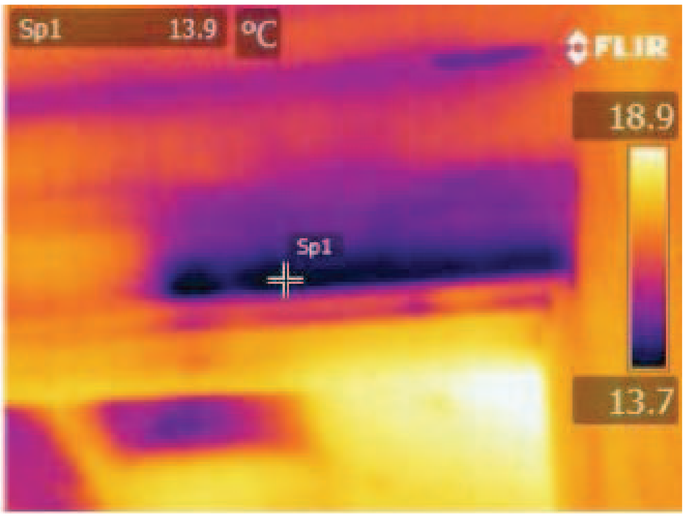


Figure 45. White House Farm, Stirton, Skipton - doorway into bathroom from main bedroom.

THERMOGRAPHIC SURVEY

A thermographic survey of the interior of White House Farm was carried out on 10 October 2013 in conjunction with the air permeability testing. No images of the exterior of the property were taken for the following reasons: The period before testing was relatively mild, though overnight temperatures were lower than 8°C. There was significant solar gain to the southern fa□ade of the property on the morning of the test. Due to these factors, images would have probably reflected environmental conditions rather than building performance. The external conditions may also influence images taken internally, so the focus of the thermographic survey has been on drawing comparisons between the original dwelling and the recent addition, since the temperature is relatively even throughout the property.

It should be noted the temperatures represented by a particular colour change from image to image and these should be cross-referenced against the temperature scale on each image. The temperatures displayed in the top left hand corner of the image are the surface temperatures measured at the centre of the relevant image cross hair. The thermal imaging camera has had an emissivity set which is appropriate for examining the general building fabric. This does however mean that where the surface properties of a material are significantly different (e.g. glossy window frames or reflective door furniture), the temperatures these items display in an image may be deceptive.

Examining the older building fabric, it is possible to see the underlying external wall structure (Figure 46). It should be noted there is approx. 1°C temperature difference between the coolest and warmest parts of this wall area.

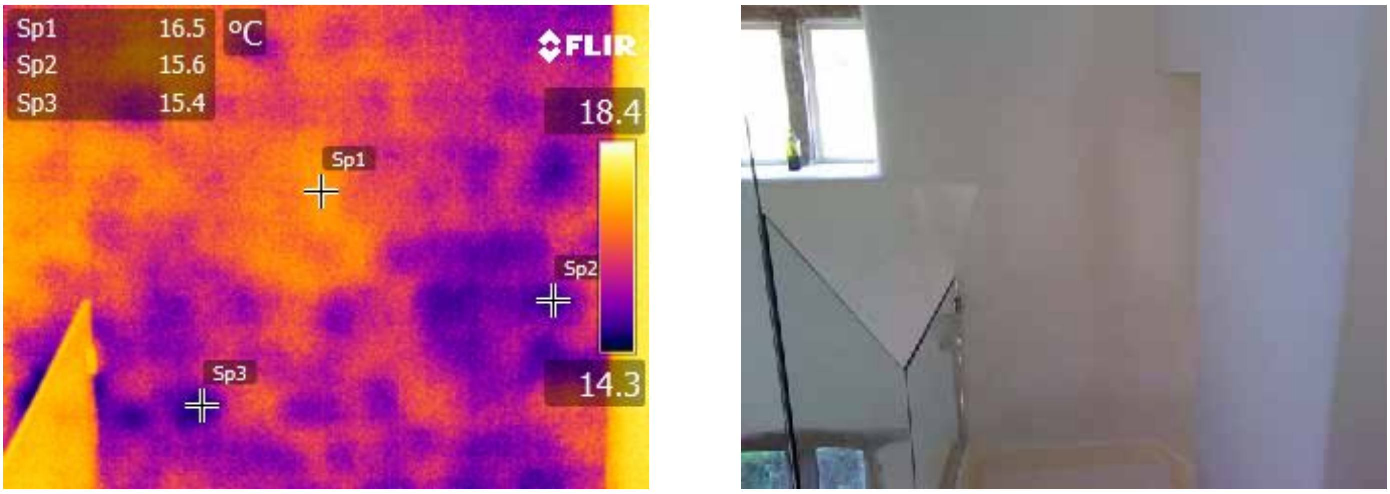


Figure 46. White House Farm, Stirton, Skipton – North exterior wall on staircase.

The stone mullions show they are the main thermal bridges and the key leakage points displayed in the older portion of the dwelling are around beams, missing pointing at sills and around window / roof light casements (Figures 47 - 49). In some areas, where floor coverings are not fitted, ingress can be seen between floorboards (e.g. on the staircase).

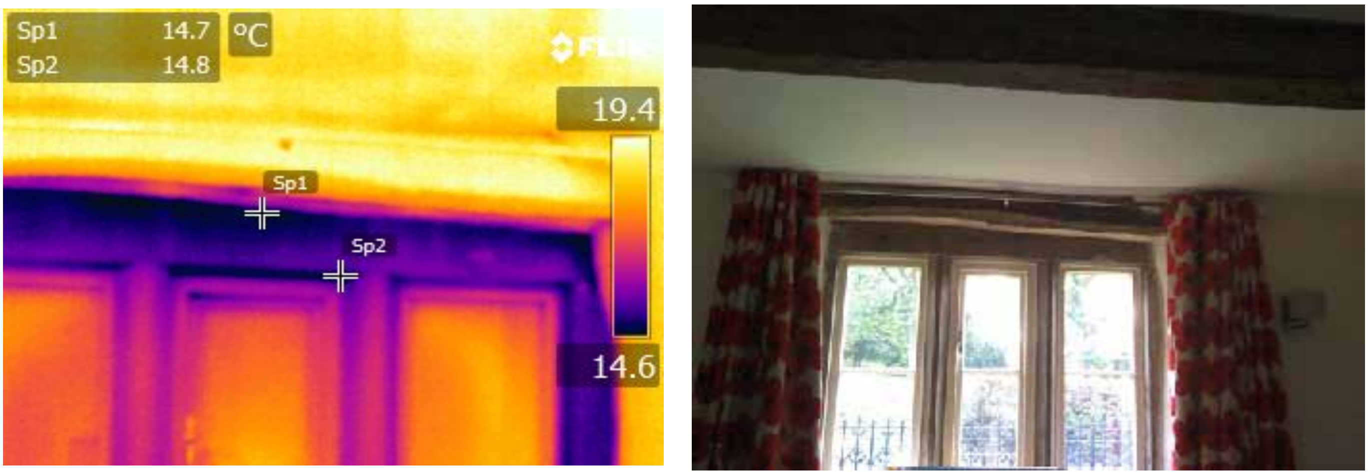


Figure 47. White House Farm, Stirton, Skipton – Thermal bridging on mullion and air ingress around lintel (NB. lower portion of window mullions are subject to solar gain).

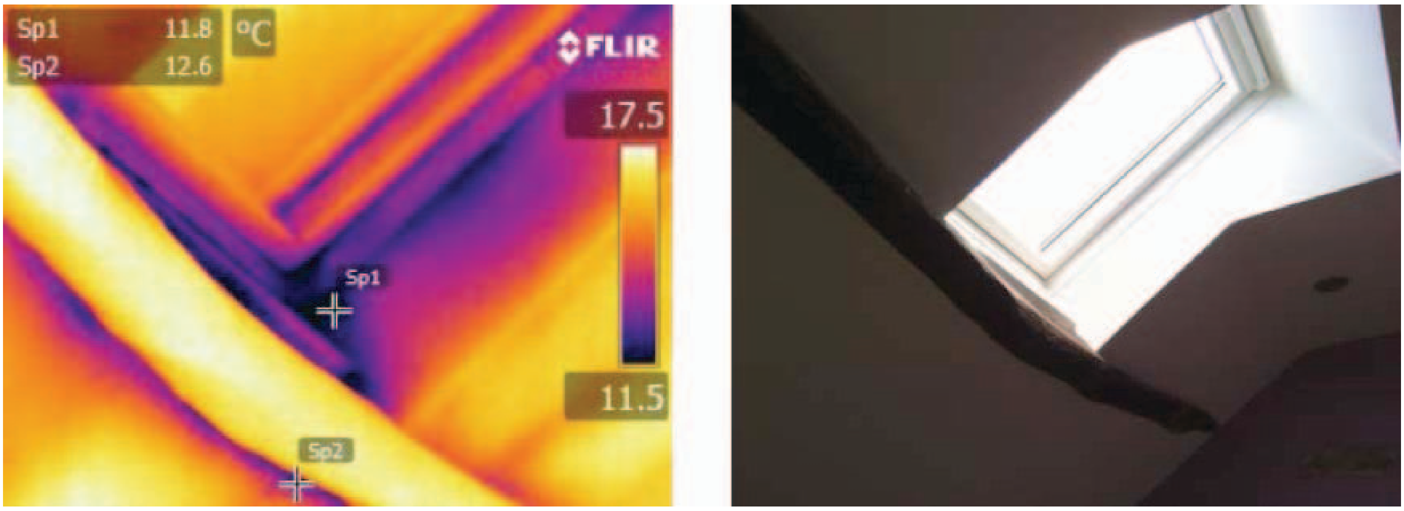


Figure 48. White House Farm, Stirton, Skipton □ north facing ceiling in bathroom air ingress around roof light and beam.

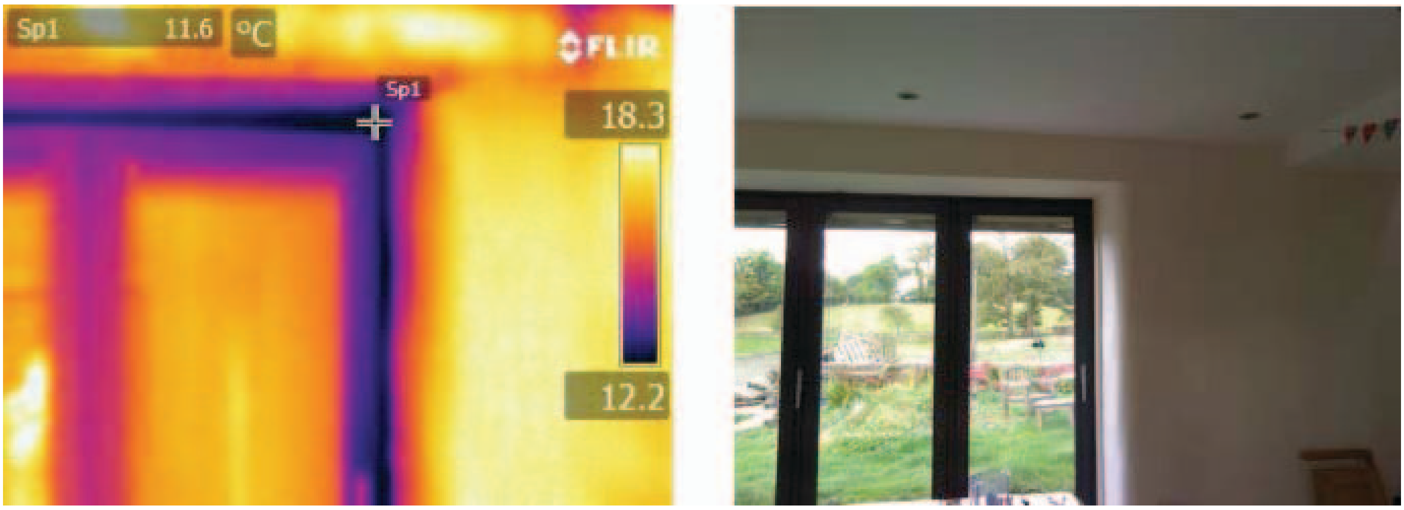


Figure 49. White House Farm, Stirton, Skipton □ north wall in kitchen showing ingress around new door casement

Unlike the older part of the building, the new addition displays a great range of temperatures under the air permeability test conditions (Figure 50). The pattern displayed is likely to relate to the location of plaster dabs. The images also show some ingress around the door frames and light fittings.

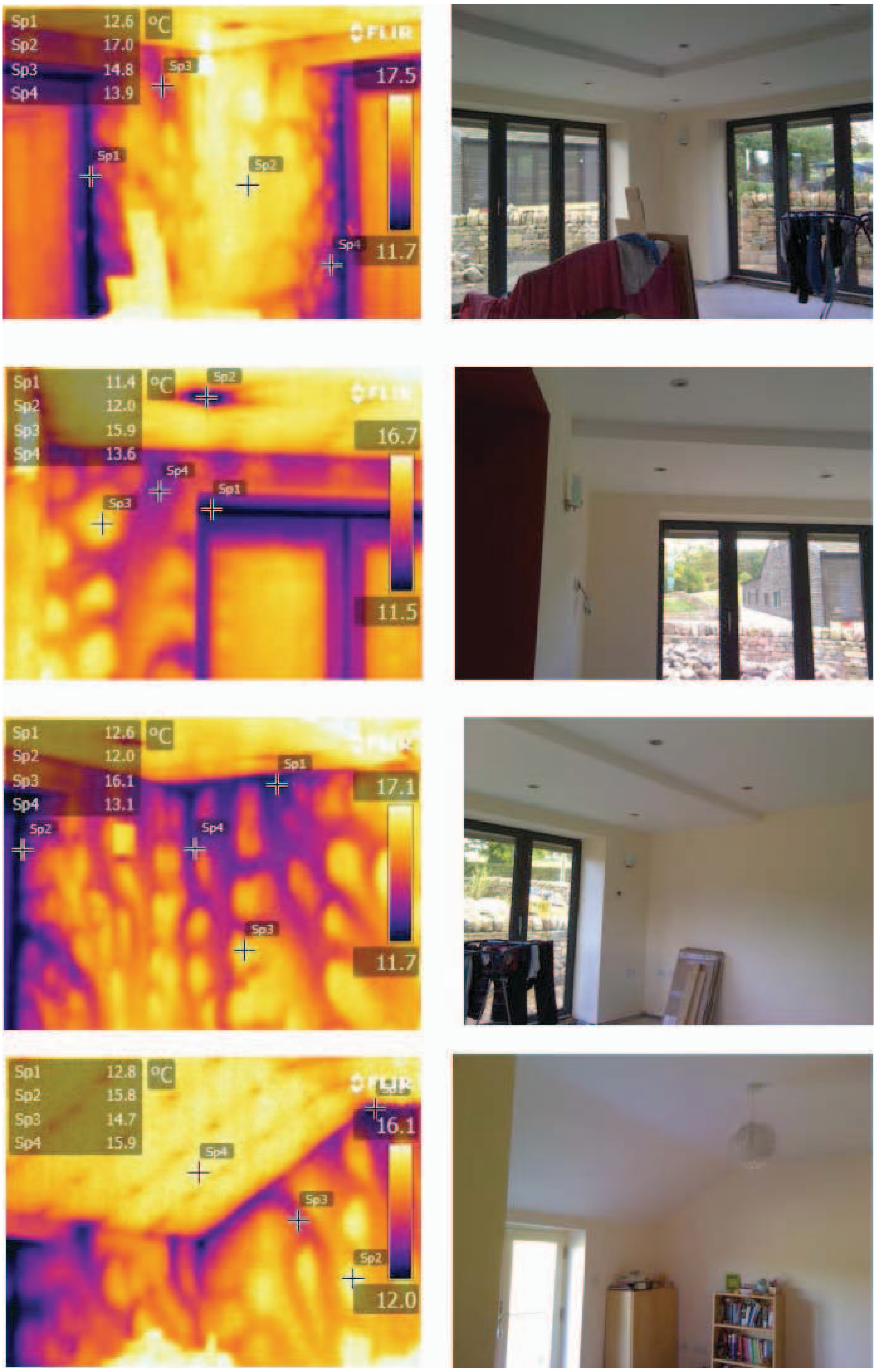


Figure 50. White House Farm, Stirton, Skipton - Addition to dwelling. Top – North east corner of addition, middle – north wall and east wall, including section which protrudes, bottom – north east corner on bedroom on first floor of addition.

Ingress around beams and window frames is evident in the extension (Figure 51) with the window in the first floor bedroom showing ingress through its opening sections (Figure 52).

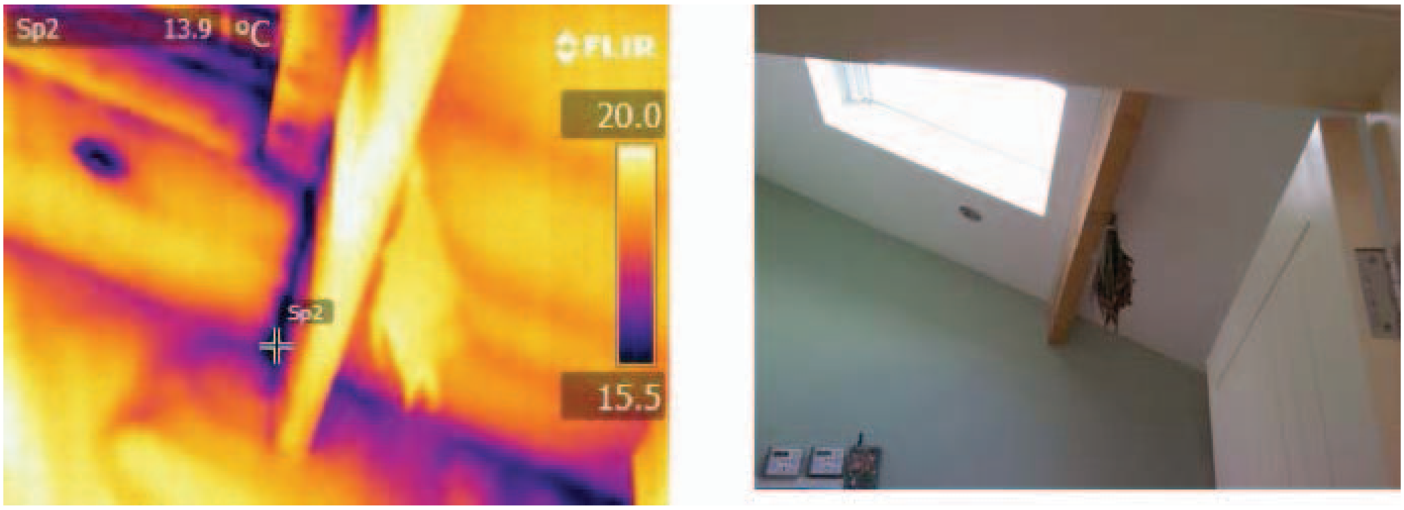


Figure 51. White House Farm, Stirton, Skipton □ ingress around roof light casement, beam, wall joint and light fitting in Utility Room.

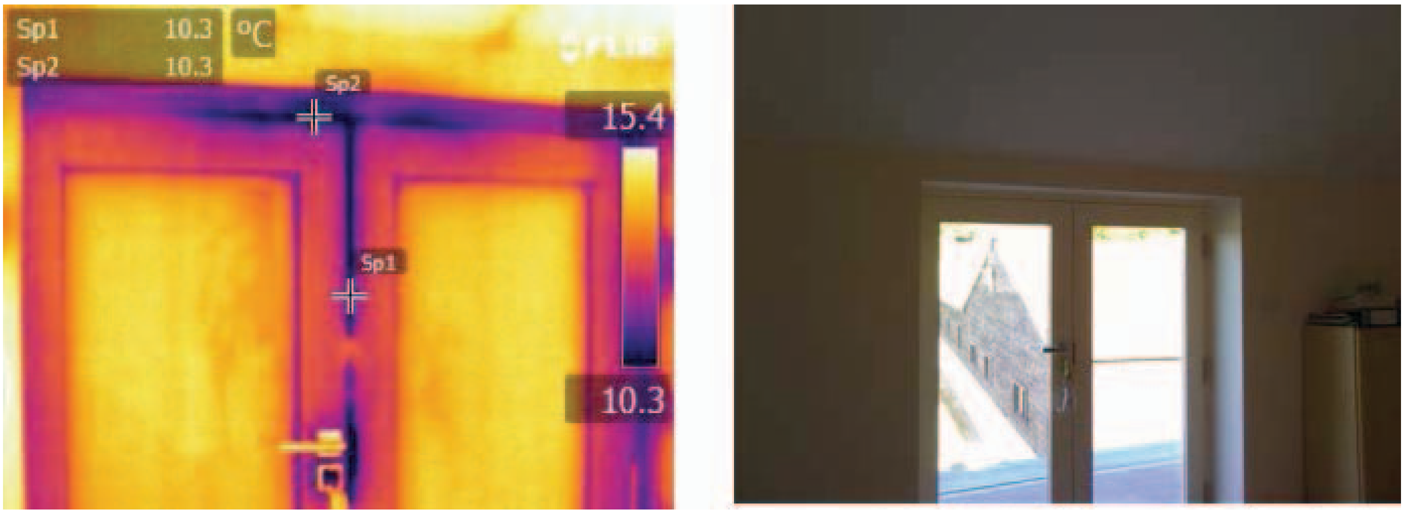


Figure 52. White House Farm, Stirton, Skipton □ ingress through opening section of north facing window in first floor bedroom in addition.

The sills in the extension are yet to be fitted and so ingress is displayed in this area (Figure 53).

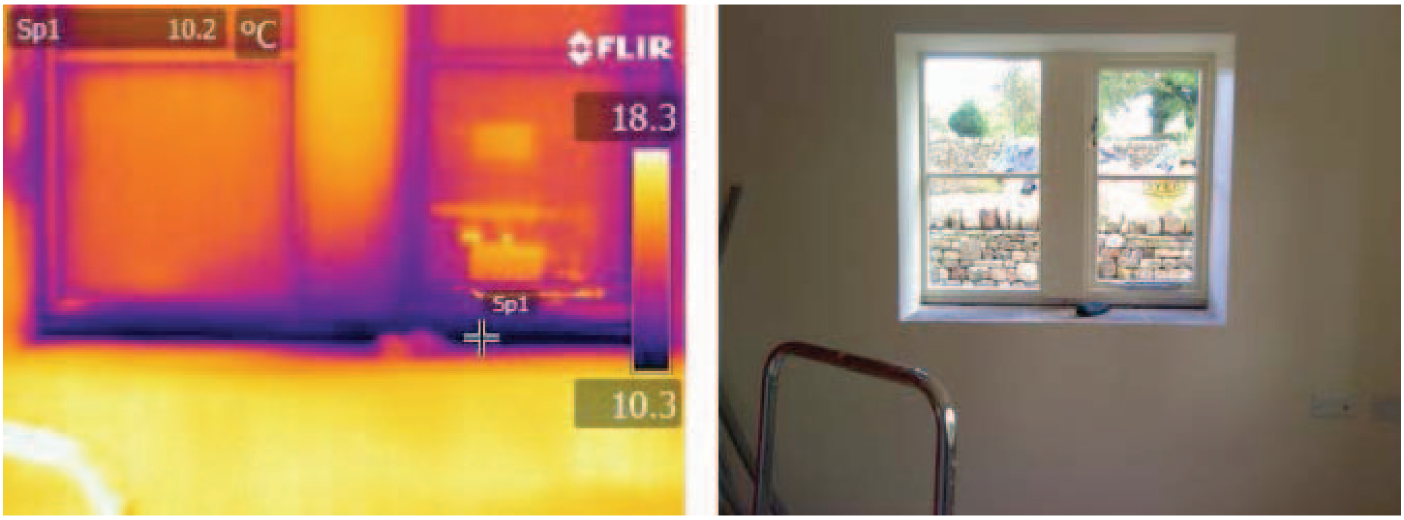


Figure 53. White House Farm, Stirton, Skipton □ingress at base of window on east wall (no sill fitted).

There is also evidence of missing or reduced insulation in the first floor en-suite shower room (Figure 54).

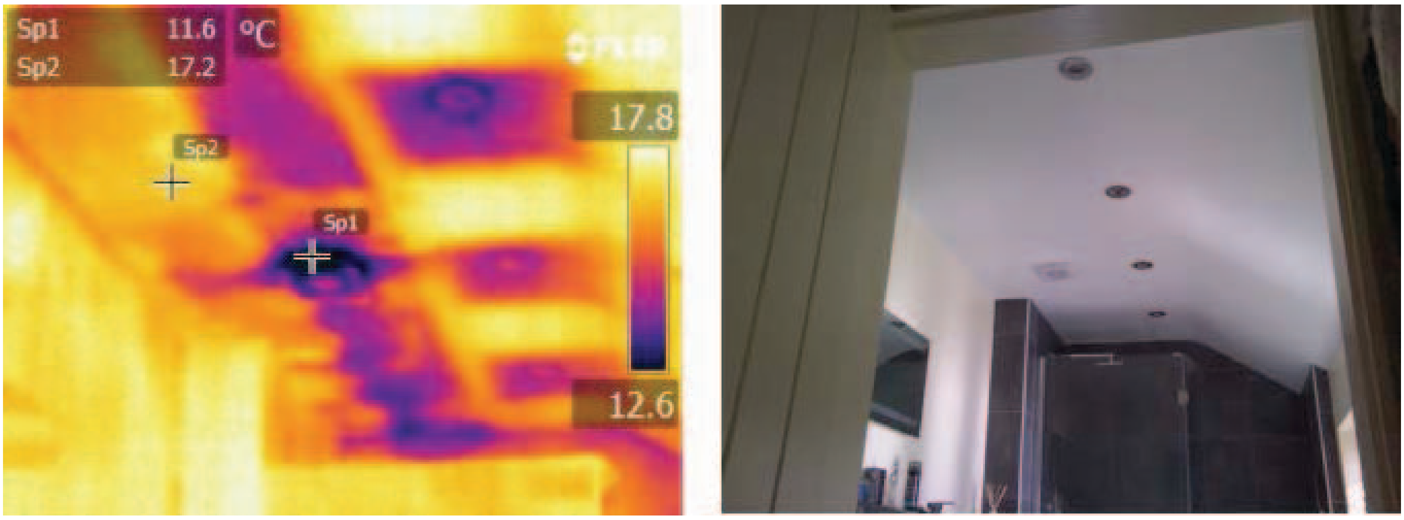


Figure 54. White House Farm, Stirton, Skipton. Reduced insulation in the ceiling of the first floor en-suite shower room.

The main area of ingress in the property is around the top, sides and base of the unfinished doorway between the main bedroom and bathroom, Figure 45. However the following general points can also be observed:

- Though extract fans are taped over during the test, every installed fan showed a poor connection between the base of the cover plate and wall, Figure 55. There are 5 extract fans fitted in the property.

- There was significant ingress around the two loft hatches in the older part of the building (Figure 56).
- Ingress is present around most of the recessed light fittings, together with the fuse box.

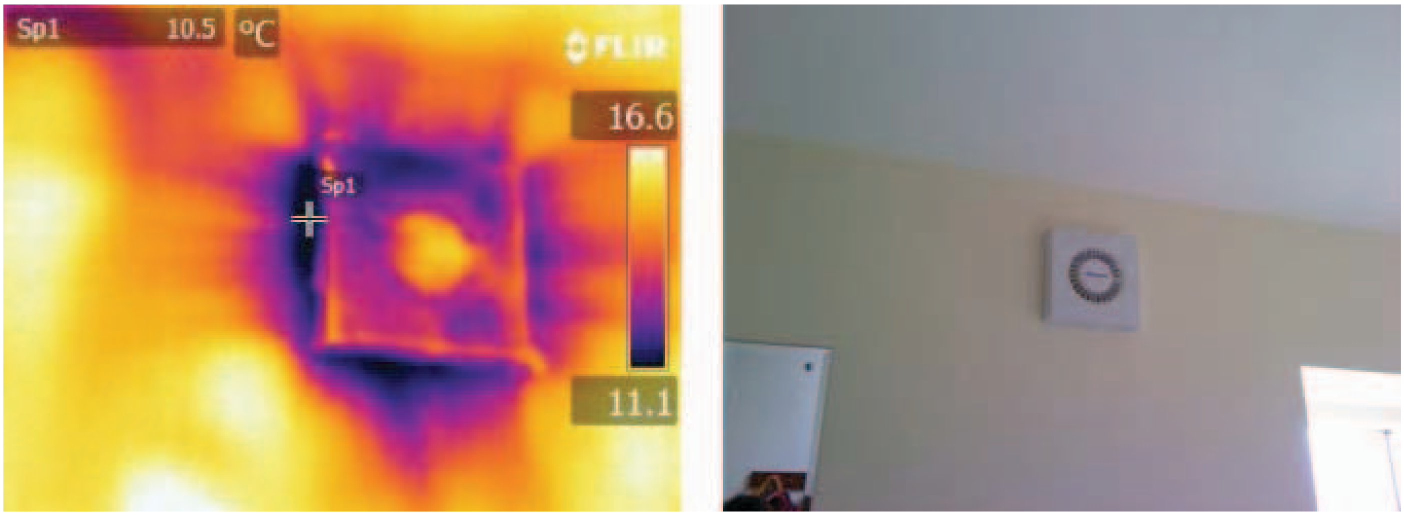


Figure 55. White House Farm, Stirton, Skipton. Ground floor cloakroom extractor fan showing poor connection between the base of the cover plate and wall.

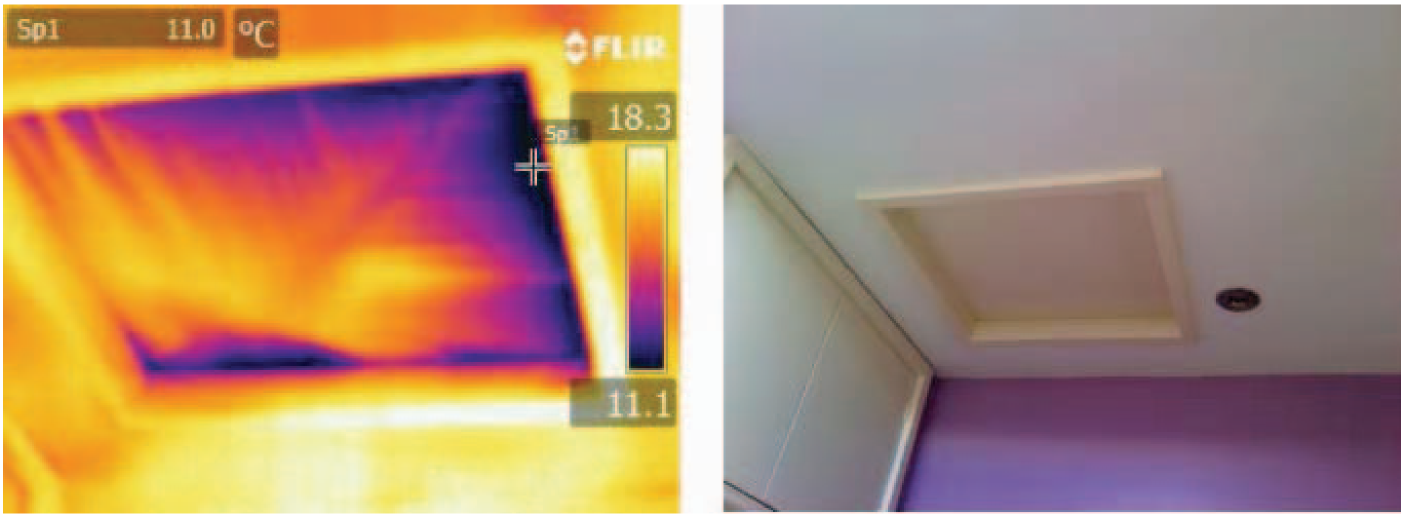


Figure 56. White House Farm, Stirton, Skipton. Ingress around loft hatch in main bathroom.

MOISTURE

Surface and Sub-Surface Moisture

On 1st April 2013 two measurements were taken to record the moisture conditions of the refurbished interior wall surface of the south-facing kitchen wall at White Hill Farm. A measurement of the surface, approximately 2mm deep, was taken using a twin-pinned resistivity probe and an additional capacitance reading was taken of conditions at approximately 40mm deep behind the interior wall face. Figure 4 plots these measurements alongside those previously taken in 2011 for the same wall pre-refurbishment, these values are plotted against a nominal moisture scale to a height of 2000mm above finished floor level.

The 2011 moisture profiles show fluctuating levels of moisture both at the surface and sub-surface of the wall below the height of 1000mm - 1200mm. There is a particularly sever deformation of the surface moisture gradient recorded at 600mm above finished floor level which coincides with the bottom of the window cill leading to speculation that moisture may be tracking from the exterior to the interior wall face, beneath the stone window cill leading to a concentration of moisture at this location. Or this may be the affect of the cill creating a thermal bridge and therefore cooling the interior wall face at this point leading to increased surface and sub-surface humidity. It is interesting to note that this affect seems to have completely disappeared in the 2013 set of measurements. In 2013 both the surface and sub-surface measurements have moved towards the 'drier' end of the moisture scale and whilst, quite low down, the surface of the wall shows a slightly erratic profile in general both gradients are more stable. This apparent reduction and stabilisation in the surface and sub-surface moisture profile for the wall may be due to the addition of 40mm of lime and hemp/lime plaster to the interior wall face. Measurements only penetrate approximately 40mm into the wall therefore this new layer moves the zone of measurement away from the stone wall itself and so the presence of moisture within the masonry of the wall is no longer being directly measured. It may also be that the hemp and lime as relatively vapour permeable and hygroscopic materials have a beneficial affect with regard to humidity levels and that the surface and sub-surface of the wall appears drier in 2013 as these materials, given appropriate internal conditions, promote evaporation from the internal wall surface. This may also help to explain the disappearance of the 'cill affect' in the measurements from the refurbished wall in that the internal finish encourages the evaporation of any penetrating moisture or this may simply be because the zone of measurement zone no longer penetrates as far as the masonry.

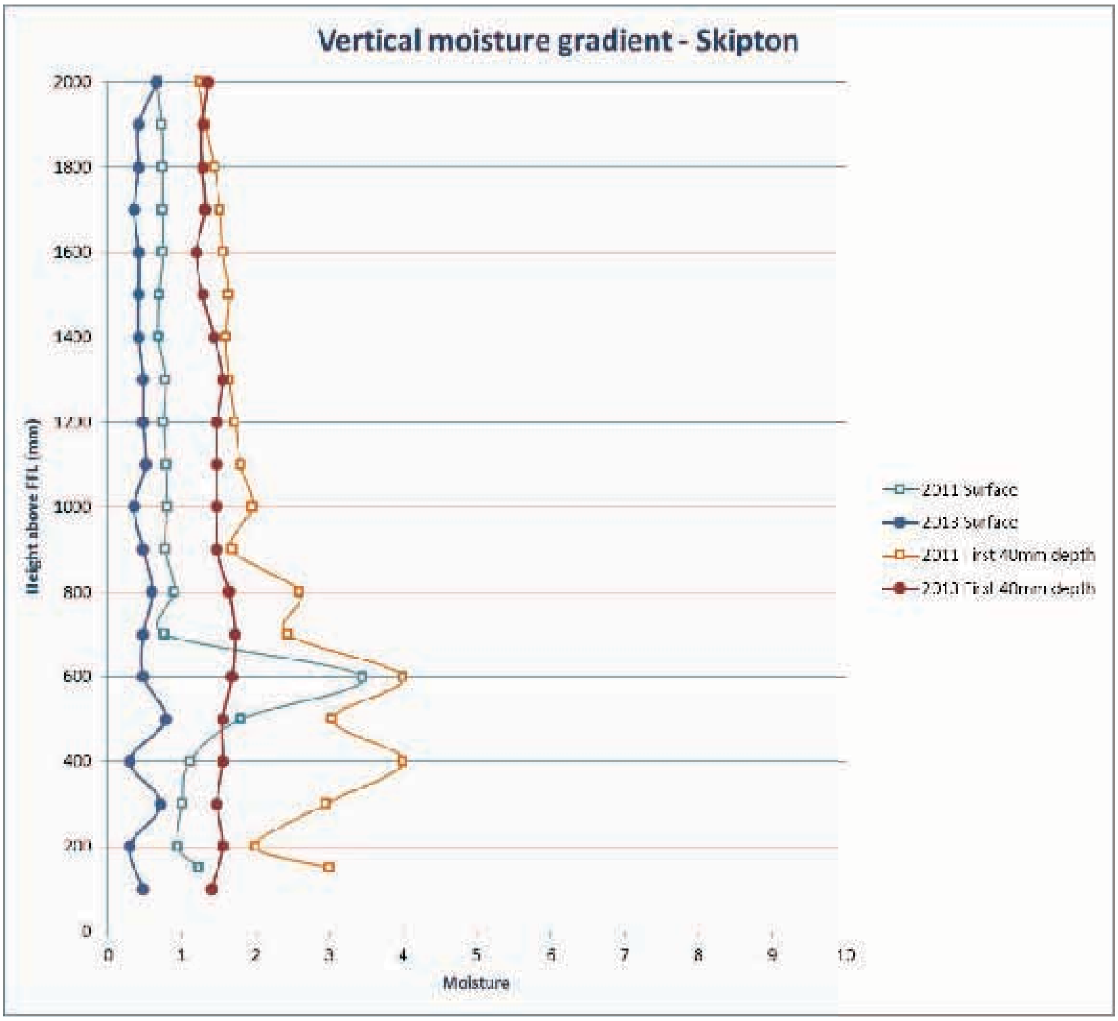


Figure 4. Pre and post refurbishment measurements of surface & sub-surface moisture at White House Farm, Skipton 2011 & 2013.

Interstitial Hygrothermal Conditions

Figure 57. Interstitial monitoring set up at White House Farm, Skipton, 2013.

Material moisture measurements were made on the south facing ground floor wall of the kitchen (Figure 57). Interstitial temperature and relative humidity sensors were located at the heights and depths given in Table 12 and recorded temperature and relative humidity changes at four points within the wall between the period 1st July 2012 and 31st August 2013.

The position of the four in-wall sensors accords with those of the pre-refurbishment interstitial monitoring at Skipton except for that of sensor 4 positioned closest to the external face which, due to an obstruction in the wall core is located 40mm further back in to the body of the wall, Figure 58. Records of interstitial temperatures and relative humidities are combined with the same measurements for internal and external conditions in proximity to the monitored section to provide the following analysis.

Build-up - internal - external	Depth of material	Sensor no.	Height from finished floor level	Depth of sensor from internal surface
Lime plaster	5mm			
Hemp Lime Plaster	35mm	Sensor 1	17300mm	40mm
Sandstone	540mm	Sensor 2	1600mm	200mm
		Sensor 3	1400mm	300mm
		Sensor 4	1200mm	460mm
Overall	**580mm**			

Table 12. Interstitial gradient sensor record for White House Farm, Skipton, 2012 -13.

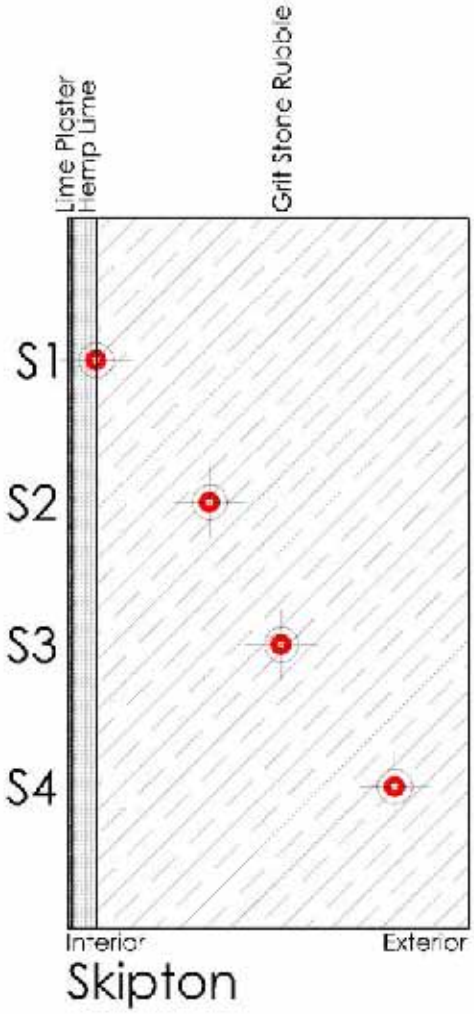


Figure 58: Wall Section showing position of sensors, White House Farm, Skipton, 2012 - 2013.

Relative Humidity Over Time

Figure 7 shows plots of %RH from the four sensors located within the wall at Skipton along with internal and external temperature and relative humidity conditions over time. In general, the graph follows a pattern seen elsewhere (Shrewsbury) of two distinct summer and winter arrangements of %RH distribution through the wall. %RH indicates the proportion of vapour held within air at a certain temperature in relation to saturation or dewpoint and is a temperature dependent quantity. During the warmer spring and summer months levels of %RH at all four wall sensors are more aligned as the temperature difference across the wall is less acute due to similar internal and external temperatures. Moving into winter however, internal and external temperature difference becomes more polarised leading to an increase in temperature difference through the wall and hence greater differentiation in the %RH measured by the four sensors through the wall section. By and large, lower %RH is found towards the warmer internal side of the wall and %RH increases in proximity to colder external conditions. The average %RH values calculated for each of the sensors in the wall at Skipton, is shown in the Table at the top right-hand side of Figure 7.

There are a number of other features of the %RH over time graph for Skipton which are of interest. There is a decreasing trend in %RH over the reporting period July 2012 - August 2013. This may reflect a general improvement in weather conditions between the two years, where 2012 was noted to be a particularly wet and cold year compared with that of 2013. In Figure 7 plots of external temperature and %RH show warmer and drier conditions from spring 2013 onward which in turn most likely lead to reduce %RH within the majority of the wall fabric. However, the %RH profiles of sensor 1 and sensor 2, positioned towards the internal side of the wall, may be less driven by external conditions. Here we also see a decline in %RH through the monitoring period which may be more related to the drying of the hemp and lime plaster internal finishes. The drying of these finishes, from haptic observation, has taken place over an extremely long period of time. It was not possible to carry out certain tests at the property in the winter of 2012 because finishes were still wet and the degree of drying has been noticed during regular visits to the property. The relationship between %RH measured at sensor 1 and sensor 2 also undergoes a change during the week beginning 13th January 2013. Until this date conditions at both sensors seem closely matched, if more volatile at sensor 2, and roughly track internal conditions. However after this date a margin of difference appears between the %RH measurements at sensors 1 and 2. This coincides with a period of extremely low external temperatures where the internal/external temperature difference is at its greatest. This may cause a more differentiated temperature gradient through the wall section and an alteration of the predominant influences on %RH behaviour at sensor 2 which is now more driven by external conditions than internal ones.

A further feature of Figure 7 are the sudden rapid drops of %RH recorded at sensor 4, 120mm back from the external wall face. These occur during periods of low external %RH and indicate that this part of the wall is well coupled with external conditions

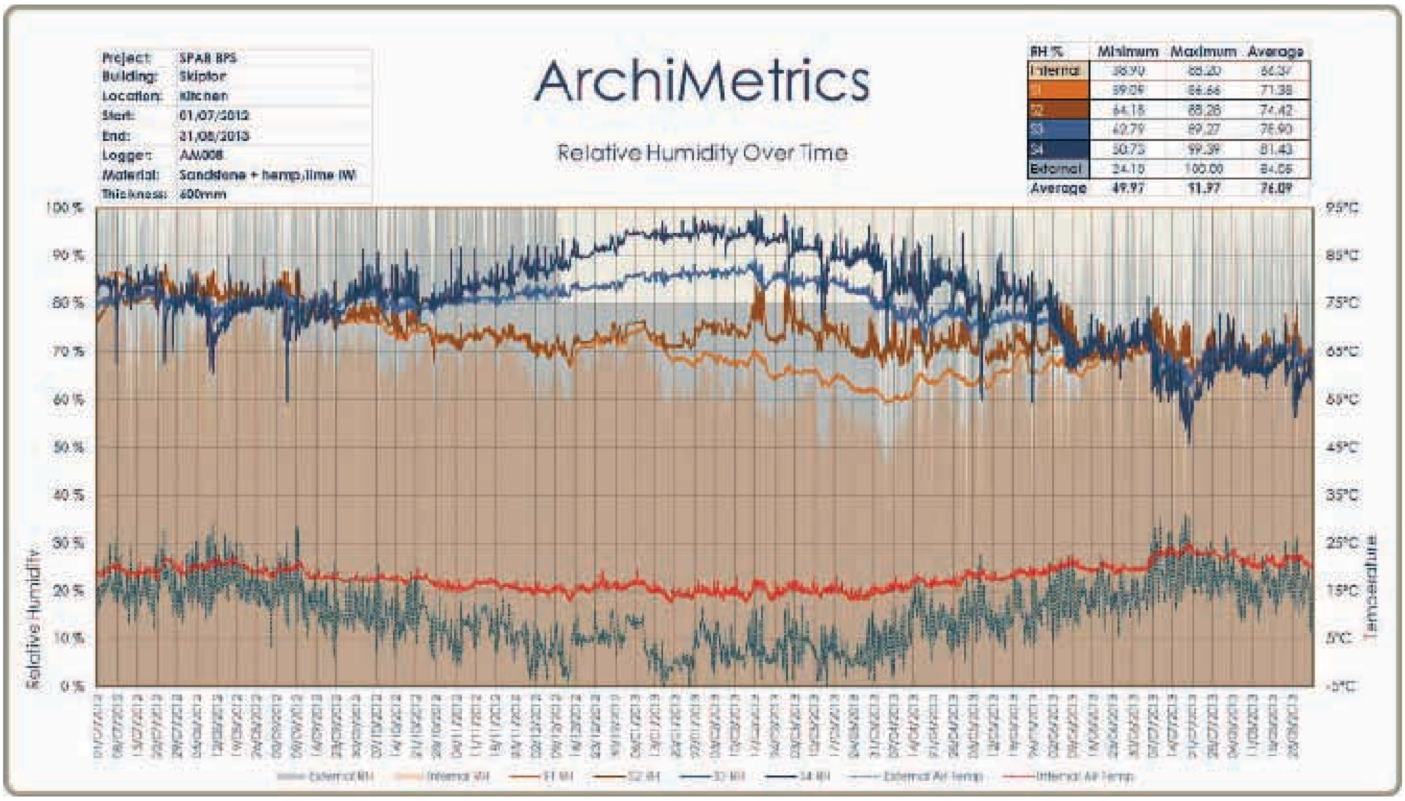


Figure 7. Relative Humidity over time, White House Farm, Skipton, 2012 -13.

A detailed examination of one of these rapid drops in %RH is provided in Figure 59. As temperature increases through the day the external relative humidity falls and this decline is echoed, albeit with a slight time lag of about two hours, by the %RH conditions measured at sensor 4. Interestingly the same dramatic response is not seen at sensor 3 which sees a gradual rise and decline in %RH replicated in miniature at sensor 2 which then rises quickly to meet the gradient of sensor 3, a trajectory that runs in parallel with sensor 4 at the end of the day. This detailed section may show the competing influence on %RH behaviour within the wall under different conditions. Rises in %RH at sensors 2 and 3 may be in response to increased external temperatures and therefore indicate sweating or vaporisation, similar to that seen at Riddlecombe, taking place at these locations. At the end of the day sensors 4 and 2 seem to share a driving influence which causes %RH to rise, perhaps increasing external %RH and declining external temperatures. Reponses at sensors 4 and 2 share a volatile characteristic which is interesting as they are some distance apart from one another within the wall and normally volatility of response declines in proximity to internal conditions whereas here responses at sensor 3, closer to the external wall face, are generally more muted than those at sensor 2. The wall at Skipton is a rubble core construction with many internal voids and fractures, during installation the core of sensor 3 become blocked by dust and rubble as a result of this relatively unstable internal construction, it is proposed that responses at sensor 3 are dampened by this debris whereas the cores of sensor 4 and 2 are more open to the influences of the external environment. What is also clear in Figure 59, however, is that whilst, by and large behaviour in the wall is affected by external conditions, 40mm back from the internal wall face %RH conditions are extremely static and in this way more in line with internal temperature conditions and perhaps reflect a buffering of internal %RH by the presence of hemp within the lime plaster finish.

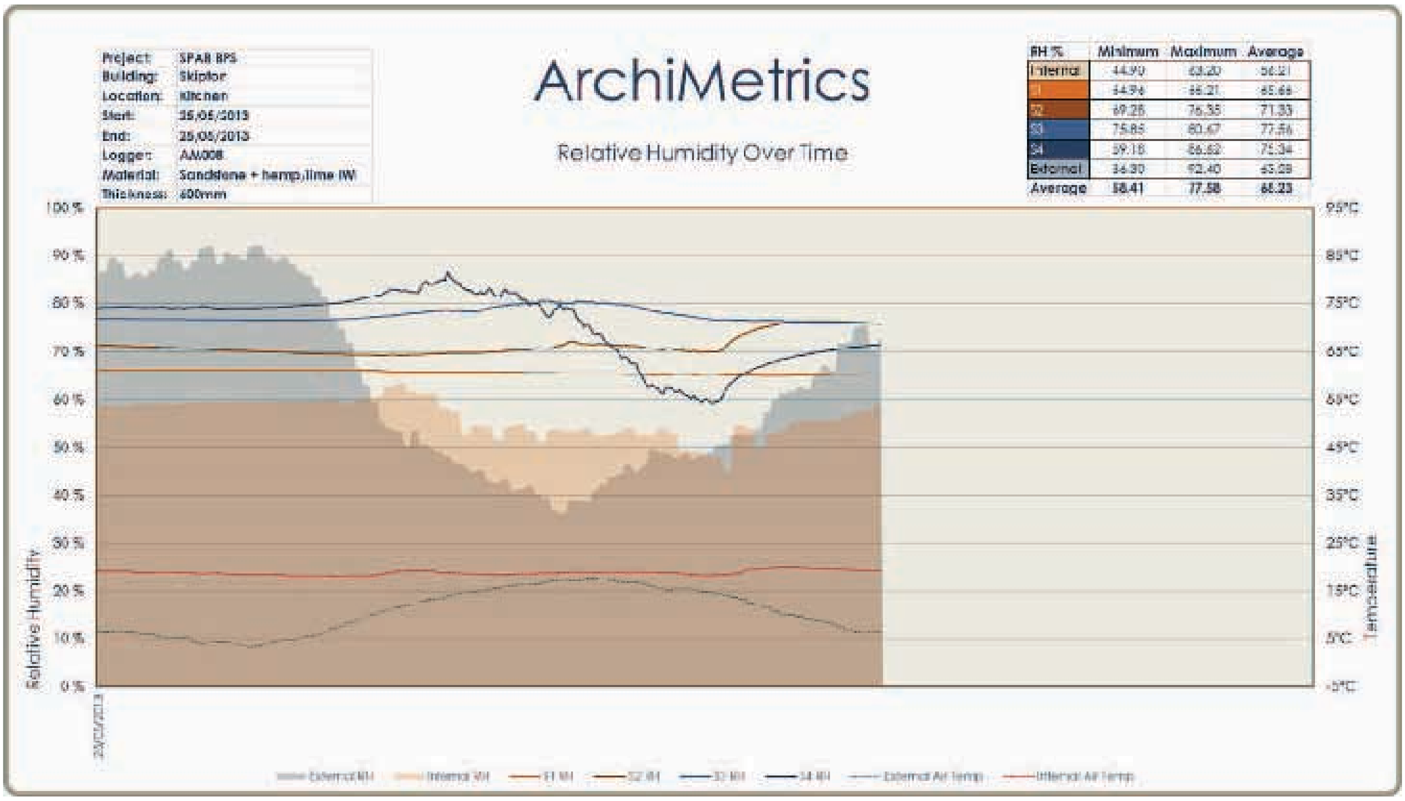


Figure 59. Relative Humidity over time, 25th May 2013, White House Farm, Skipton.

Another detail, this time for December 2012 Figure 60, shows a different relationship between the %RH responses of the interstitial sensors at Skipton. In this month responses at sensors 4 - 2 are similar and can be mapped over the external temperature profile, where peaks in temperature provoke peaks in %RH albeit of decreasing quantity in relation to the thermal profile through the wall section (driven by the wintertime internal high/external low temperature difference). These peaks in %RH once again indicate vaporisation of wet material due to this increased heat. Levels of %RH at sensors 3 and 4 are quite closely grouped, however, the volatility of responses does not decline through the wall section, as might be expected, as responses become more muted as measurements are taken further away from the driving external conditions. Instead, sensor 2 occasionally exhibits more significant changes in %RH than that of sensor 3 and in this way is more aligned with that of sensor 4. As was noted in the 2011 edition of this report, the wall at Skipton is a rubble core construction and as such contains plenty of voids. In this way it differs to another stone wall in this study, that at Drewsteignton, where the form of construction is very homogenous and compact with little voiding. As was noted in the previous paragraph, the loose rubble construction at Skipton allows for a great deal of air transfer through the wall therefore conditions at a particular sensor position will be highly dependent on these air pathways and may alter depending on weather conditions including wind speed and direction. It is possible therefore, that while %RH at sensor 2 is lower as it is warmer here, due to its position towards internal heated conditions, there is more air exchange taking place with the outside so we see more extreme changes in %RH conditions overall. Whereas, perhaps sensor 3 is more isolated from direct contact with external air and so responses are similar to that of sensors 4 and 2 but more muted.

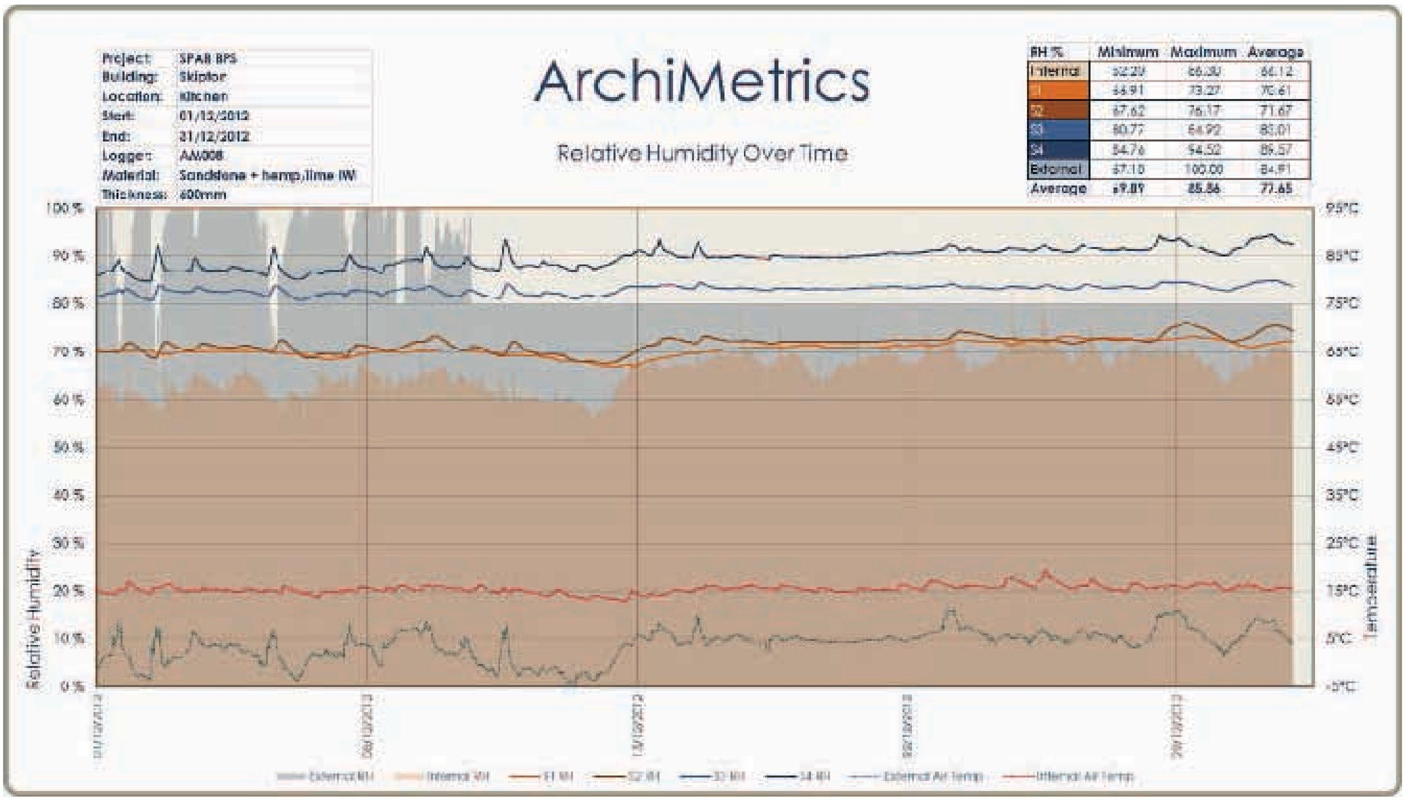


Figure 60. Relative Humidity over time, December 2012, White House Farm, Skipton.

Absolute Humidity Over Time

Figures 11 and 61 show plots of absolute humidity over time for the refurbished wall at Skipton (Figure 61 is given for clarity to show plots from sensors 1 - 3 which may be obscured by the plot from sensor 4 in Figure 11). Graphs of absolute humidity over time for all four buildings in the Building Performance Survey (and elsewhere) show the same basic trend; that interstitial absolute humidity increases in the summer along with atmospheric humidity. Unlike the plots of %RH in Figure 7, which are temperature dependent, the plots of absolute humidity, which is a measure of the weight of vapour by volume (g/m$^{3)}$ do show a volatility of response at each sensor position which is in proportion to that sensor's proximity to external conditions. Thus, sensor 4 shows the greatest fluctuations of vapour quantities driven by changing external conditions e.g. increased temperatures result in higher absolute humidity and similar but less pronounced and increasingly diminished responses are seen at sensors 3 and 2. Indeed, responses from all the three sensors placed in the masonry element of the wall are closely coupled and this is particularly clearly seen in the graph over the winter months, October 2012 - February 2013, in Figure 11. Over the winter it can also be seen that measurements of absolute humidity become more dispersed between the sensors and that in terms of weight of vapour the interface between the hemp/lime plaster and the masonry is the 'wettest' part of the wall presumably as a result of the internal, centrally heated air driving moisture arising due to occupancy into the wall surface combined with the vapour buffering capabilities of this internal finish. The same pattern is found over the same months in the monitored wall at Shrewsbury, which also has a hygroscopic surface finish, but not Drewsteignton. The other occasion where levels of absolute humidity at sensor 1 are slightly greater and seem somewhat distinct from those measured within the masonry section is early on in July 2012, Figure 61. Is it that here we can see the drying of the hemp lime plaster layer, in a similar but much less distinct way to that of the gypsum skim on plasterboard at Drewsteignton (Figure 8) causing relatively high levels of vapour over this time?

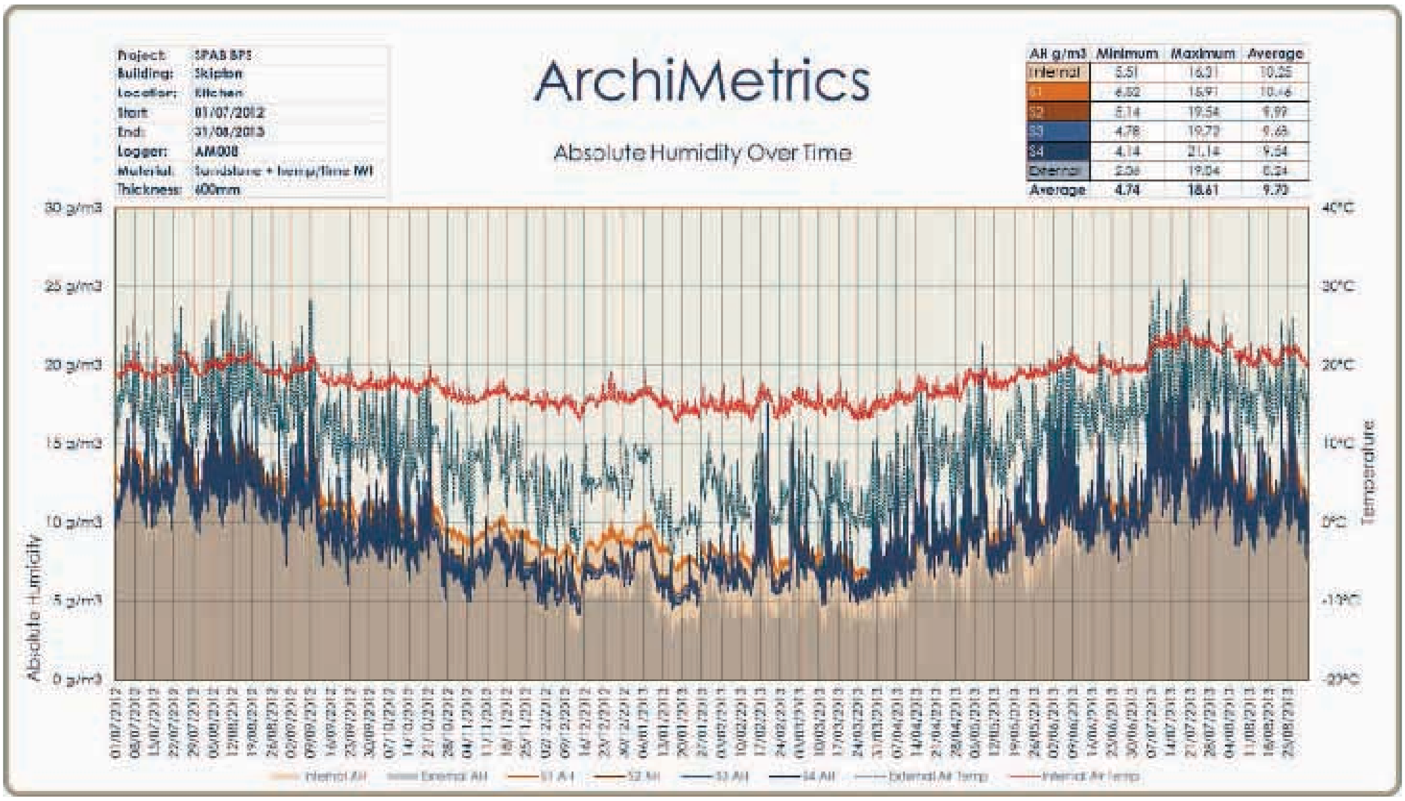


Figure 11: Absolute Humidity over time, Sensors 1 - 4, White House Farm, Skipton, 2012 -13.

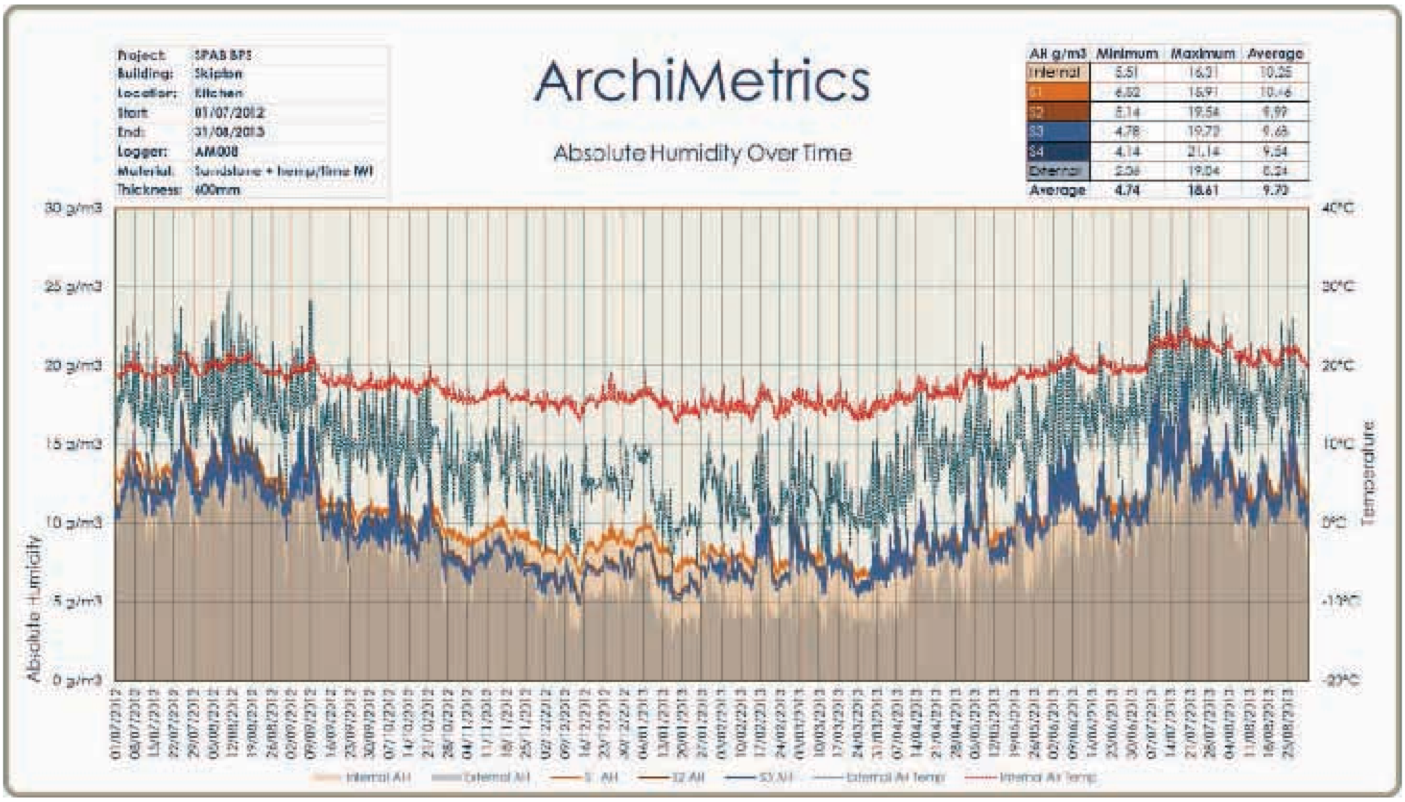


Figure 61: Absolute Humidity over time, Sensors 1 - 4, White House Farm, Skipton, 2012 -13.

Average Absolute Humidity

The absolute humidity profile of the wall at Skipton is also provided in the form of a section graph, Figure 15, which plots the average g/m^3 of water vapour either side of and through the wall. This graph shows a steady fall in the measured averages of absolute humidity at each of the four sensors in the wall, from sensor 1 at the internal leaf to sensor 4 and the external atmosphere. This decline from the interior side of the wall to the exterior contrasts with other walls in this survey, Shrewsbury and Drewsteignton (Figures 14 and 16) where average absolute humidity values peak at sensor 4 at the exterior of the wall and decline towards the interior wall face and may reflect the influence of the wet internal hemp/lime finishes drying over the reported monitoring period.

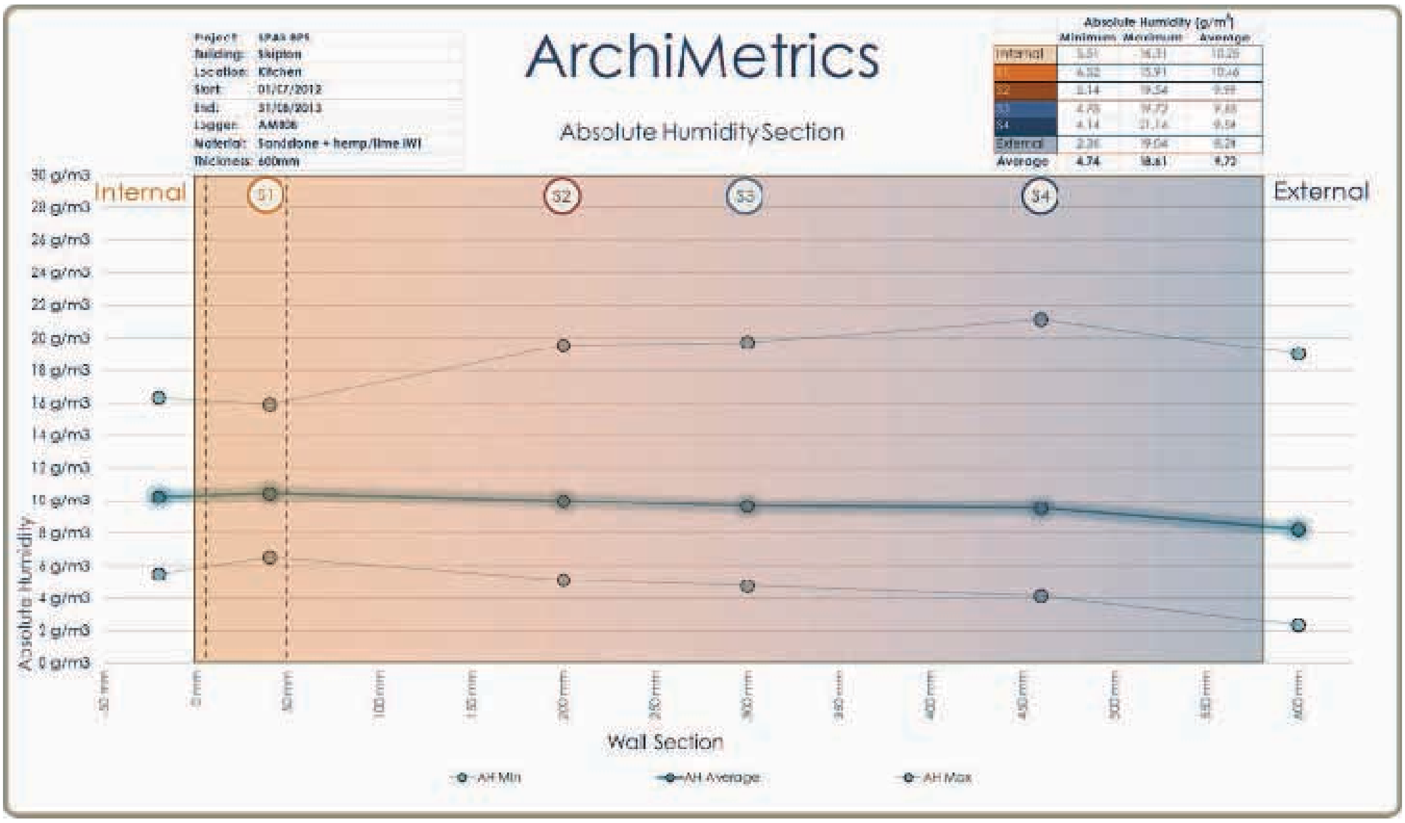


Figure 15: Absolute Humidity Section, White House Farm, Skipton, 2012 -13.

Hygrothermal Section

Figures 62, 63 and 19 show the average values of each sensor graphed as separate temperature and dewpoint gradients from both the pre and post-refurbishment monitoring periods. Data from the extended post-refurbishment monitoring has been graphed in two ways, Figure 63 shows a short time period (10th - 24th February) for comparison purposes with the pre-refurbishment interstitial hygrothermal monitoring shown in Figure 62. Figure 19 provides a section for the longer 13 month monitoring duration at White House Farm. The values derived from the relative humidity sensors have been converted to dewpoints in order to indicate the likelihood of condensation forming within the wall. (The temperature gradient is that much flatter in the long term post-refurbishment graph, Figure 19, because this covers a far greater period of time and includes both summer and winter time temperatures in contrast to the data in Figures 62 and 63 which was gathered over the winter only, between 10th - 24th February 2011/13, and so naturally shows a greater internal/external temperature difference). The 2011 analysis, pre-refurbishment, Figure 62, showed a variety of gradients between the sensor measurement locations indicating a non-homogenous wall with varying degrees of thermal resistivity/conductivity. The character and construction of this wall was ascertained during core drilling to install the interstitial sensors which revealed a variety of stone material types, a rubble core and plenty of voiding all of which would contribute to altering heat flow through the element. In Figure 19, the 2012 - 13 post-refurbishment section this same character is seen, the affect of the rubble core, bracketed between sensors 2 and 3, is still visible although differences in gradient between the sensor points is less pronounced due to the flattened temperature gradient in general. This centre part of the wall contains plenty of air which perhaps acts as a thermal break hence a slightly steeper temperature drop is seen across this part of the construction. The other steeper part of the temperature gradient in Figures 63 and 19 is seen between the measurements of internal surface temperature and sensor 1, either side of the lime and hemp/lime insulating plaster finishes. This indicates, once again, the insulation affect of this layer in the construction, something that is confirmed by the in situ U-values measured, post-refurbishment for this wall (Figures 43 and 44) which showed a 38% reduction in heat loss most likely due to the addition of the insulating hemp/lime plaster.

These Figures, 62, 63 and 19, also allow an examination of the average dewpoint margins for the wall at Skipton, that is the nominal temperature drop required at certain locations for condensation to possibly occur. As can been seen in both Figures 62 and 19 there is no instance in which the temperature gradient intersects with the dewpoint suggesting that, on average, there are no significant periods of interstitial condensation risk within the walls either prior to, or post, refurbishment. However, from measurements taken in Feb 2013 alone, Figure 63, does show a narrowing for the dewpoint margin particularly at sensor 4 where the ˚C margin becomes less than 1˚C, 0.87˚C. There is also, in Figure 19, a less pronounced narrowing of the dewpoint margin following refurbishment, particularly towards the inner side of the wall. However, this is, once again, mostly a result of the flattened temperature gradient over this extended 13 month time period. In 2011, pre-refurbishment, a dewpoint margin was averaged across all four interstitial sensors of 4.34˚C. For the re-furbished wall in 2012 - 2013 this margin in February 2013 has dropped to 3.29˚C but when calculated over 13 months has risen to 4.19˚C to just below the pre-refurbishment value. However, considering each sensor position individually, there is of course an increased vulnerability with regard to condensation towards the colder, exterior side of the wall where temperatures are lower. And indeed Figure 63, for February 2013, shows a reduced dewpoint margin of 0.87˚C at sensor 4, where as in 2011, pre-refurbishment, the margin here was found to be greater, 2.49˚C. Figure 63 does not show dewpoint occurring which would of course be indicated by a margin of 0˚C however it does suggest that the likelihood of condensation occurring at this point may have now increased. The slightly reduced dewpoint margins found for the wall following refurbishment, Figures 63 and 19, suggest that whilst it seems that there maybe an increased risk of interstitial condensation in the wall at Skipton during the winter months, particularly towards the external leaf the average dewpoint margins over an annual cycle including those for sensor 4 of 3.27˚C suggests that significant quantities of condensation are unlikely to be deposited.

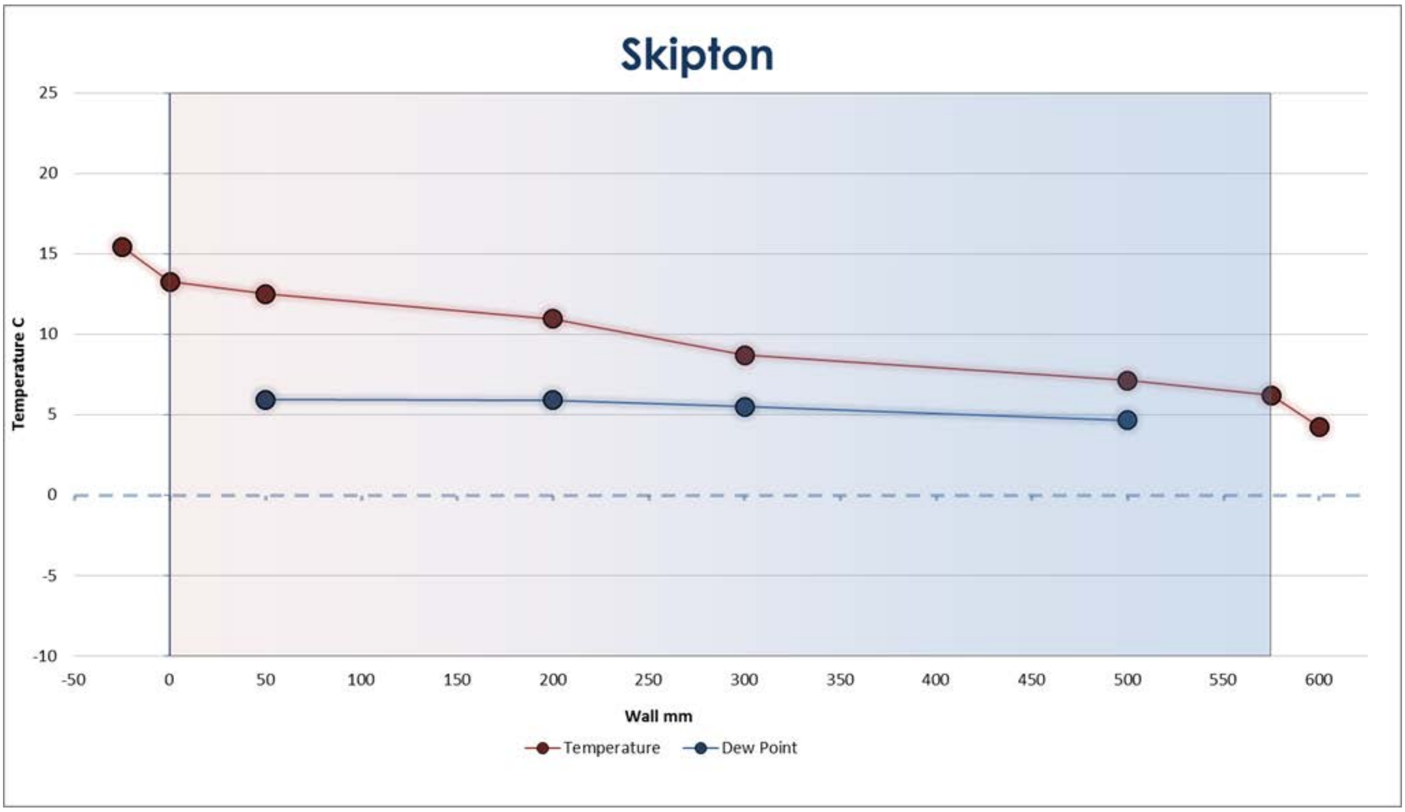


Figure 62: Hygrothermal Section, White House Farm, Skipton, 10th - 24th February 2011.

Sensor Position	Min	Max	Average
S1	6.39	6.91	6.57
S2	5.29	4.49	5.05
S3	3.30	3.30	3.23
S4	0.10	2.40	2.49
Average	**3.77**	**4.28**	**4.34**

Table 13. Minimum, Maximum and Average Dewpoint Margins, White House Farm, Skipton, 10th - 24th February 2011.

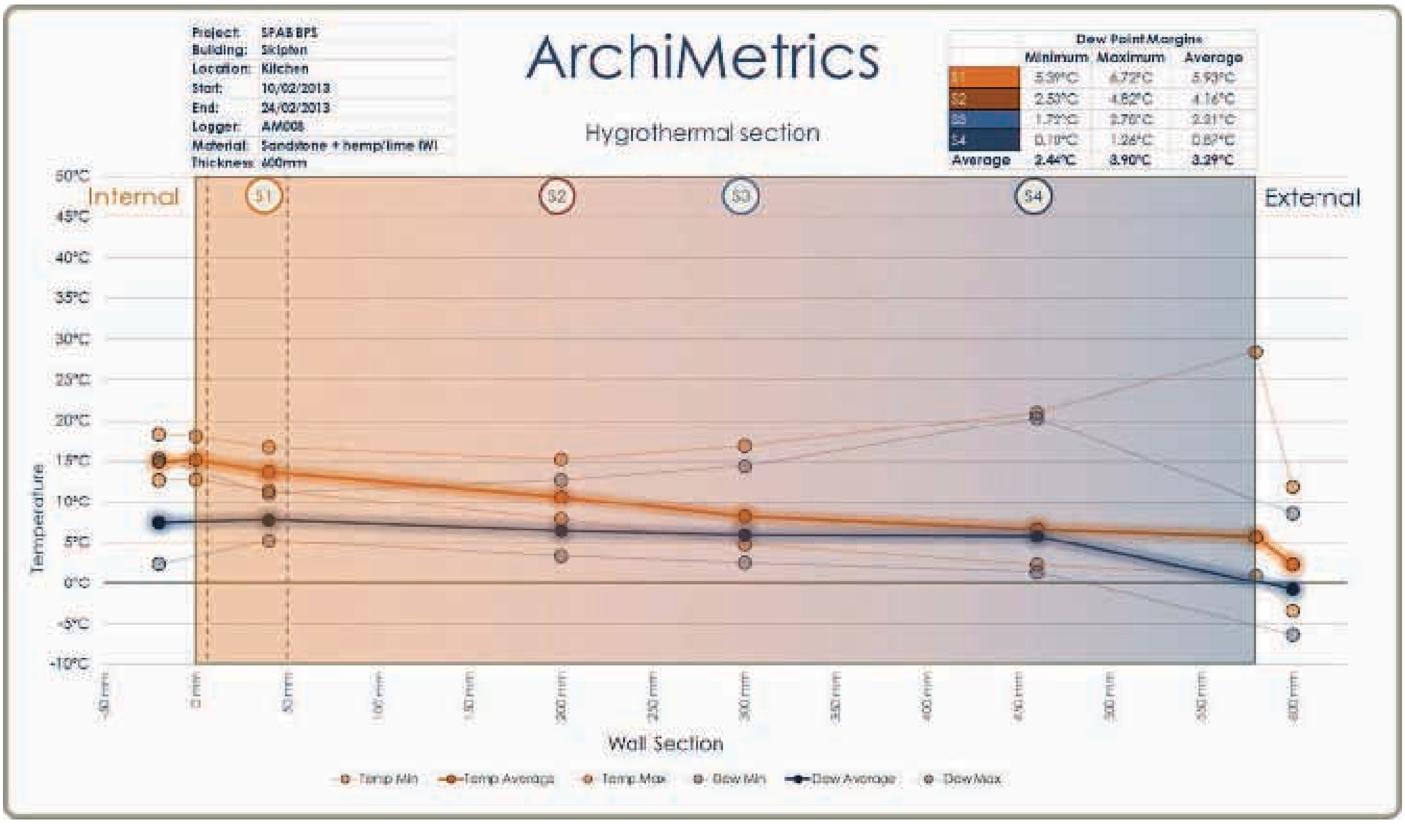


Figure 63: Hygrothermal Section, White House Farm, Skipton, 10th - 24th February 2013.

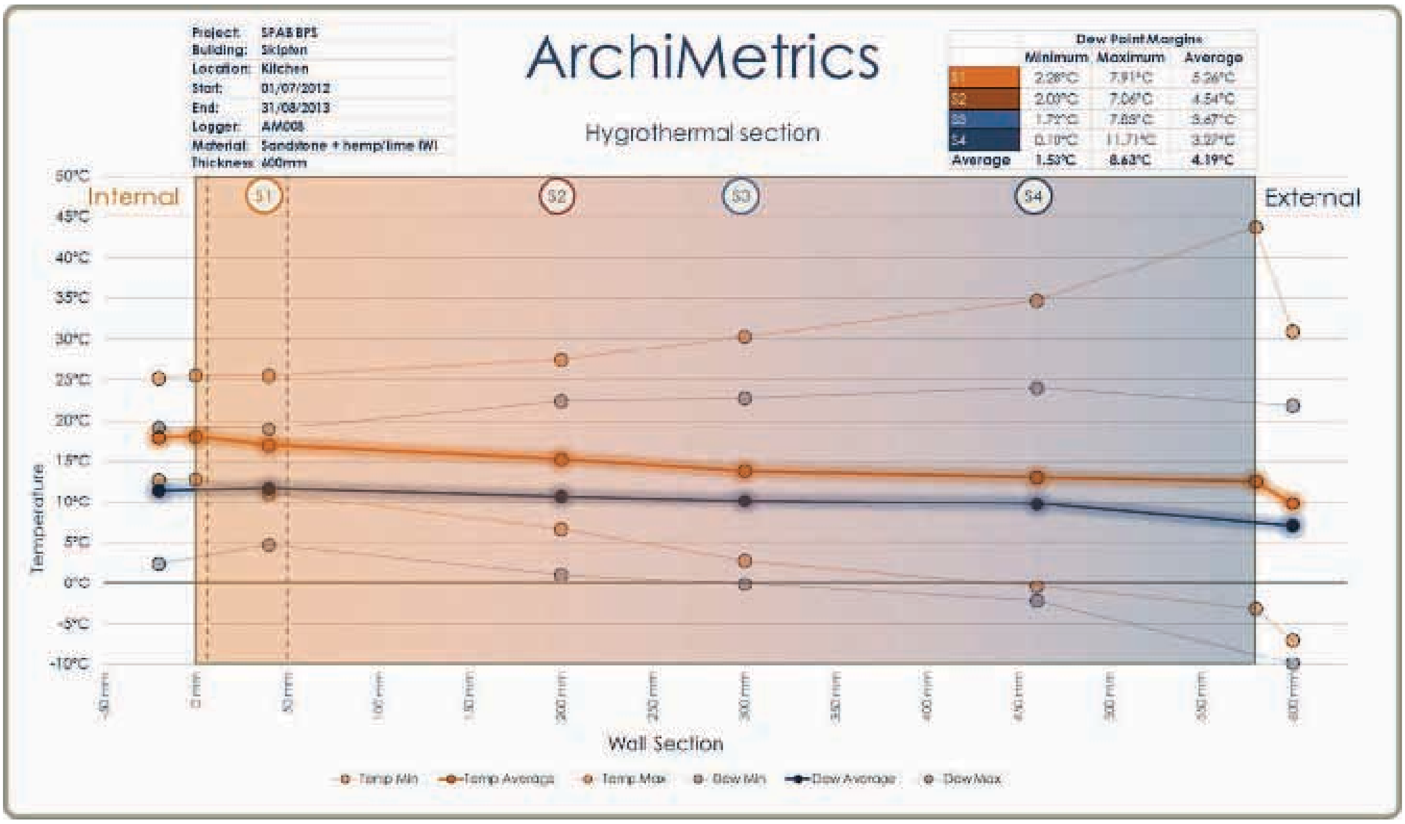


Figure 19: Hygrothermal Section, White House Farm, Skipton, July 2012 - August 2013.

Dewpoint Margin Over Time

In Figure 23 the dewpoint margins calculated for the four interstitial sensors in the wall at Skipton are plotted over time. From this it can be seen that the most vulnerable period of time with regard to the potential for condensation occurs not surprisingly during the coldest months of the year around the sensor positioned closest to external conditions, sensor 4. From December 2012 through to March 2013 the dewpoint margin calculated for sensor 4 remains below 2˚C and records a minimum value of 0.1˚C on or around 17th February 2013. Unlike all the other locations in this study this graph does not find a margin of 0˚C, indicating dewpoint and therefore the likely formation of condensation, at any point over the monitoring period for the wall at Skipton. However, it should be noted that the position of sensor 4 is someway back into the body of the wall at Skipton, 255 mm away from external conditions, and low external temperatures

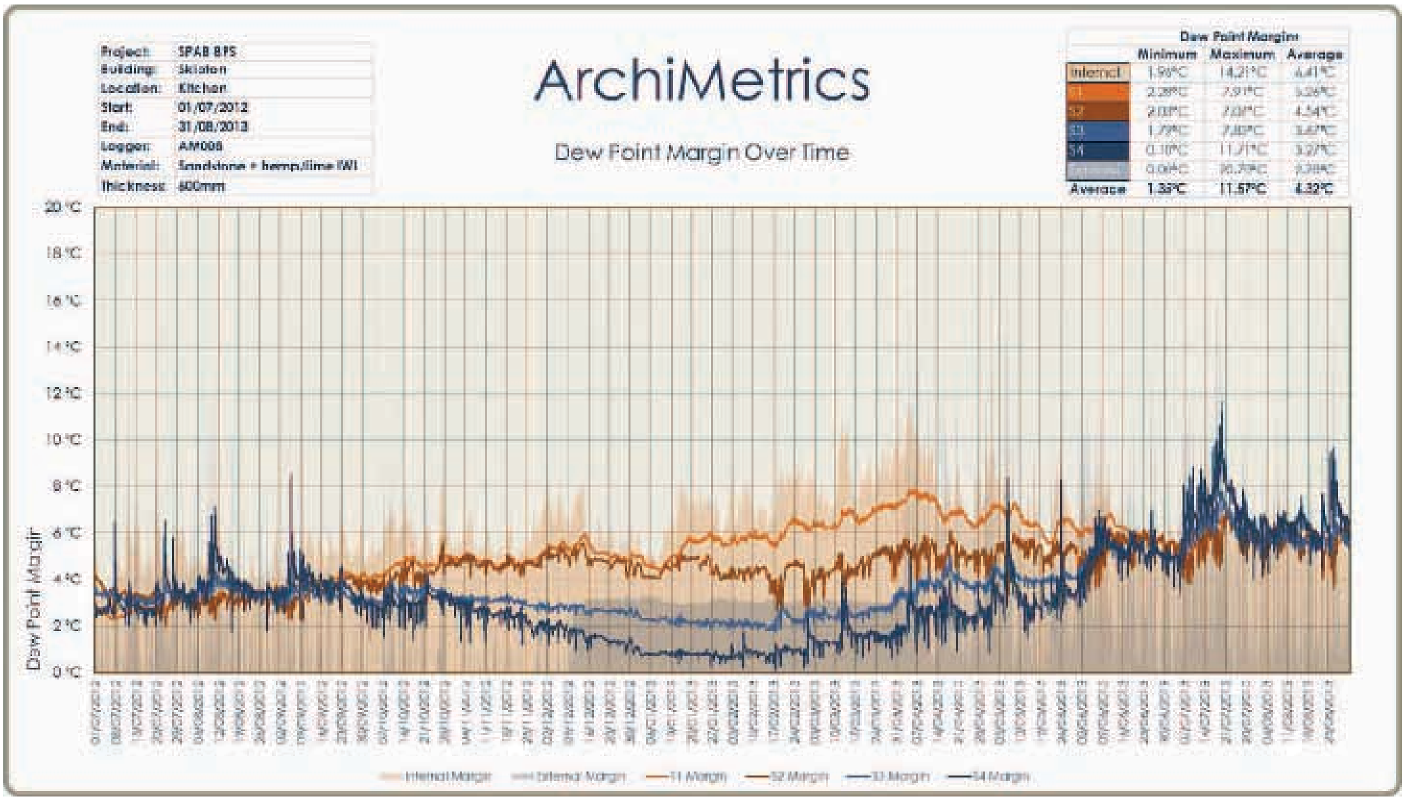


Figure 23: Dewpoint Margin over time, White House Farm, Skipton, 2012 -13.

INDOOR AIR QUALITY & COMFORT/FABRIC RISK

Figure 64. Interstitial and Air Quality loggers at White House Farm, Skipton, 2013.

Indoor Air Quality

Figure 27 plots temperature, %RH and CO_2 levels for the kitchen at White House Farm, Skipton, between the period 24th January - 16th February 2013. Table 14 provides a summary of the indoor conditions surveyed within the kitchen on the ground floor at White House Farm pre and post refurbishment, the figures represent average values recorded over the monitoring period 10 - 24th February 2011 and 24th January - 16th February 2013. There seems to be very little change in the conditions within the kitchen pre and post refurbishment, average levels of CO_2 and %RH are very slightly lower, whilst the temperature is slightly warmer. The removal of cement-based wall finishes and the addition of more hygroscopic finishes in the form of lime and hemp/lime insulating plaster may account for a lowering of %RH between 2011 and 2013 where these materials may absorb and thereby buffer water vapour. Underfloor central heating was installed throughout the ground floor at White House Farm but the air temperature within the kitchen does not appear to have altered significantly between the pre and post-refurbishment phases, 16.2˚C in 2011 and 16.56˚C in 2013. This is interesting as the perception of comfort in the building has altered and the dwelling is now reported to be appreciable warmer. This is a noted affect of heat delivered via, in this case, the stone floor of a dwelling where the occupant feels warm despite a lower than 'ideal' internal air temperature. During the monitoring period in 2013, peak CO_2 is recorded as 854 ppm which is below the 1000 ppm quantity of CO_2 often used to indicate inadequate ventilation. The average value, 549ppm, is below 600 ppm which is commonly used to indicate 'good' or 'acceptable' levels of CO_2 and is not that much greater than concentrations of CO_2 measured in external air, reckoned to be 350 - 450 ppm.

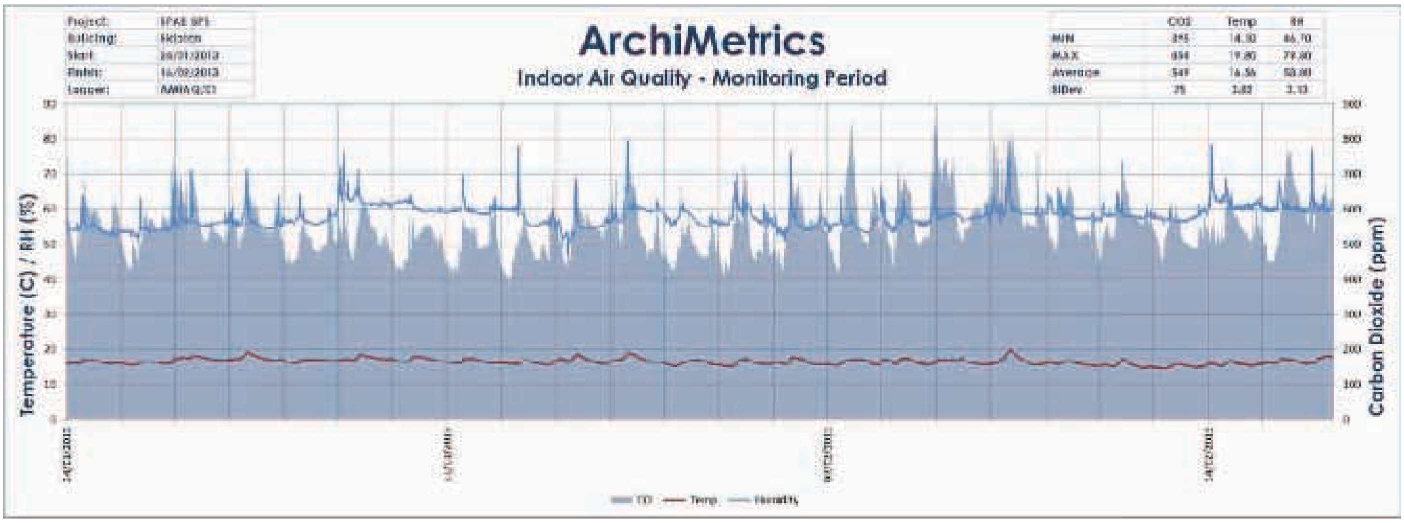


Figure 27. Indoor Air Quality (CO_2, temperature and RH) White House Farm, Skipton 2013.

PROPERTY	CO_2 (ppm)	Temp (˚C)	RH (%)
Skipton 2011	554.5	16.2	63.3
Skipton 2013	540	16.56	58

Table 14. Indoor Conditions at White House Farm, Skipton 2011 & 2013.

Figure 65 provides a detail from a week of internal conditions monitoring at Skipton in 2013. This shows that whereas by and large peaks in %RH also coincide with peaks in CO_2 indicating occupancy and activity within the kitchen environment, this is not always the case. Peaks of %RH independent of CO_2 can perhaps be explained by cooking activities taking place during the day accompanied by intermittent or low room occupancy.

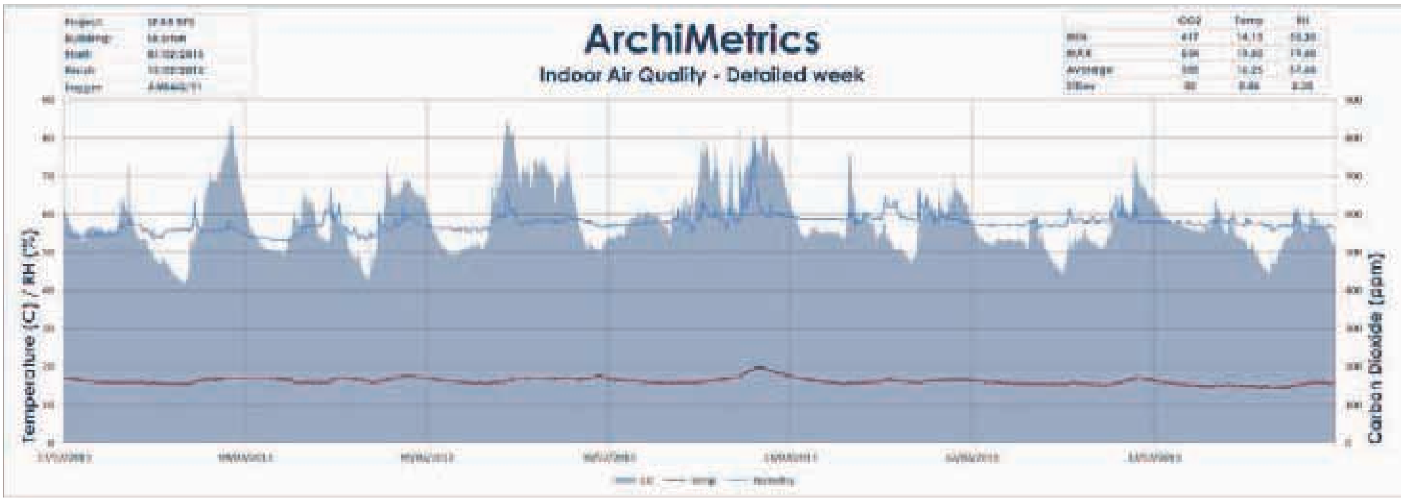


Figure 65. Indoor Air Quality (CO_2, temperature and RH) detail, White House Farm, Skipton 7th - 13th February 2013.

Comfort and Fabric Risk

Individual indoor temperature and relative humidity readings have also been plotted against an index of human comfort and fabric risk for the full monitoring period, 1st July 2012 - 31st August 2013, Figure 31. This shows that over the 13 month monitoring period the average air temperature in the kitchen was 17.85˚C and %RH was 66.37% (figures that are slightly higher than those gathered over the much shorter time period of the IAQ monitoring, Figure 66). Over the extended year it can be seen that whilst the majority of the temperature measurements sit within the acceptable range of temperature with regard to comfort, a certain proportion of these lie outside this polygon at the lower end of the temperature scale. However, as was noted in the commentary on Indoor Air Quality above, the house is said to be significantly more comfortable and these low air temperatures may be a reflection of the way heat is delivered to the building, via underfloor heating, resulting in relatively lower air temperatures but conditions that are still perceived by occupants as comfortable. Figure 31 also shows a proportion of %RH samples that sit above the gradients which indicate the limiting isopleths for mould growth (LIM) on various, more or less, biologically active substrates; LIM0 being an optimal substrate, LIM1 being biodegradable materials and LIM2 representing porous materials [9]. A small proportion of these %RH points sit above LIMs 1 and 2 suggesting that there is a slight possibility of mould growth formation on the wall surfaces of the kitchen at Skipton although no growth has been noted through observation and may be retarded by the presence of lime-based internal wall finishes.

[9] Sedlbauer, K. (2001). Prediction of mould fungus formation on the surface of and inside building components. Fraunhofer Institute for Building Physics.

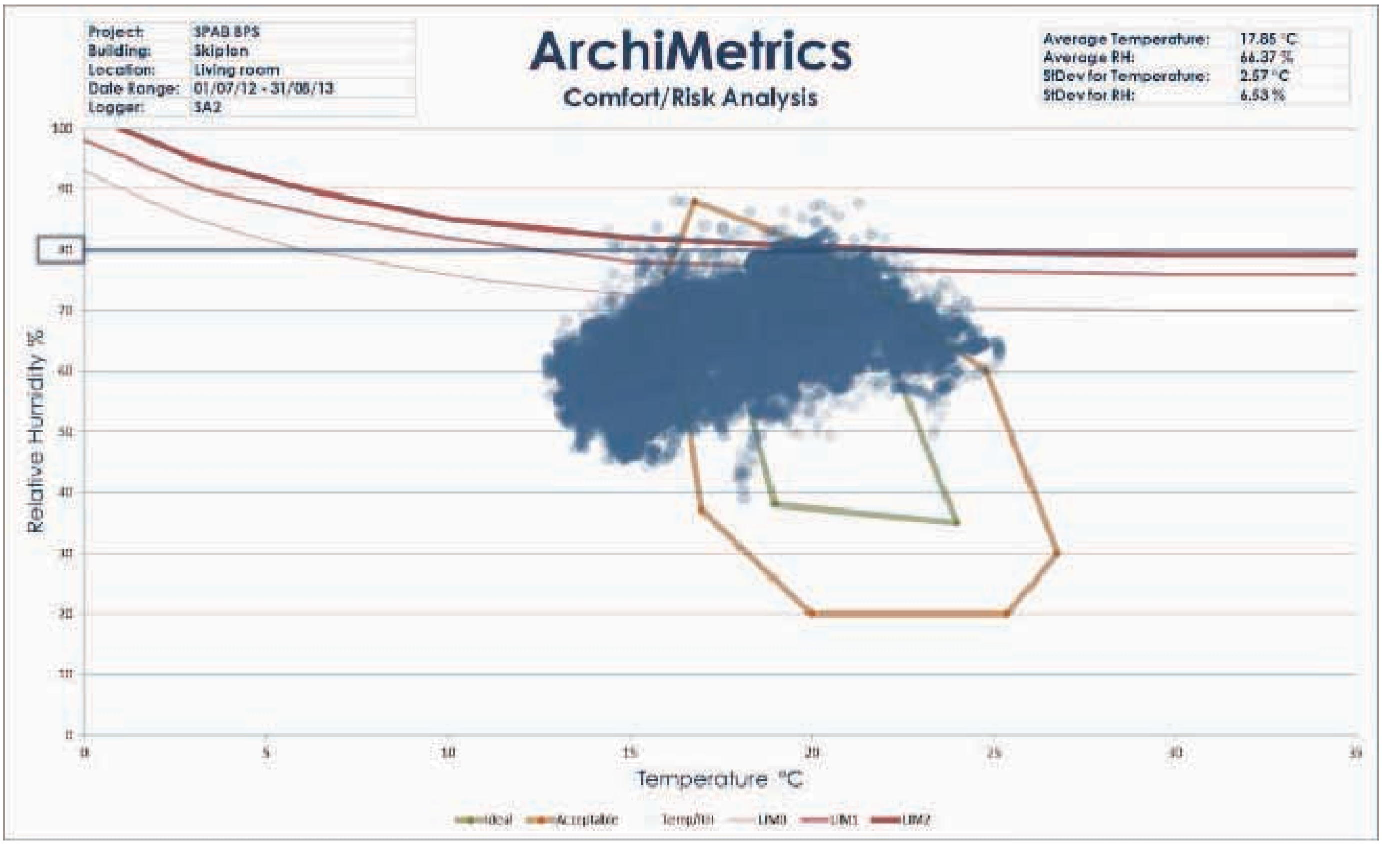


Figure 31. Comfort/Risk Analysis for White House Farm, Skipton, 2012 - 13.

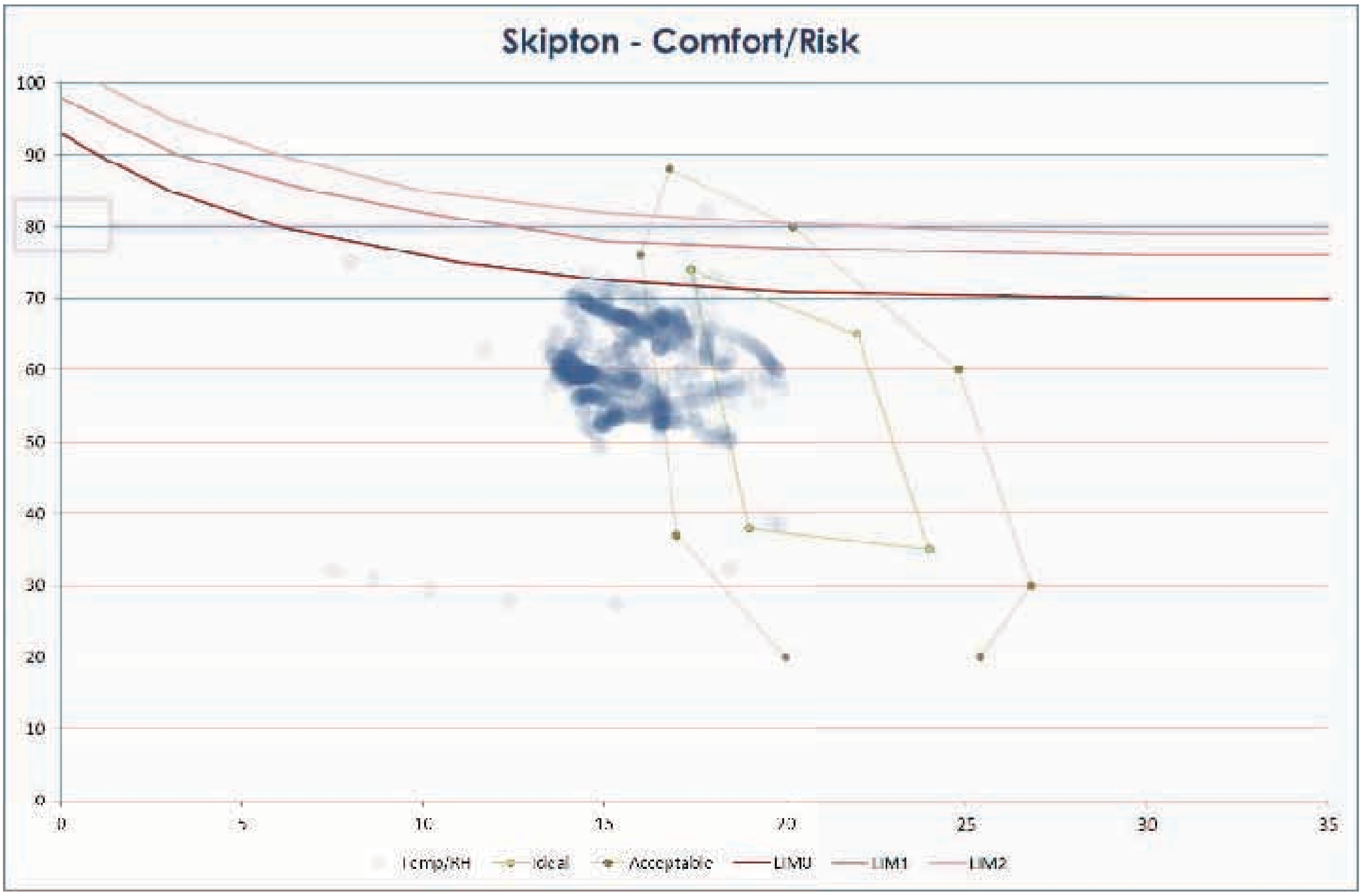


Figure 66. Comfort/Risk Analysis for White House Farm, 19th - 25th February, Skipton, 2011.

To allow some form of comparison with the pre-refurbishment data a comparative graph has been provided, Figure 67, which looks at the same date range as that of 2011 19th - 25th February (Figure 66). The average temperature during this period in 2011 was 15.70˚C and the average %RH 60.54%. The post-refurbishment data shows that over the same period in 2013 the average indoor air temperature in the kitchen was 14.87 ˚C and %RH also slightly lower at 57.58%. The reasons for these reductions are probably similar to those commented on in relation to Figures 27 and Figures 65 concerning the method of heat delivery and volume of the room. The underfloor heating has reportedly improved comfort but lowered air temperatures whilst the lower %RH is may be a reflection of the greater volume now given over the to the kitchen/dining as well as the addition of extract ventilation immediately over the cooking area. The distribution of the individual plots of temperature and %RH in Figures 66 and 67 are interesting to compare, measurements from 2011 are much more dispersed perhaps indicating greater air movement within the room compared with a much tighter cluster of data from the 2013 record due to new windows and an effective new air tight layer in the form of the hemp/lime finish.

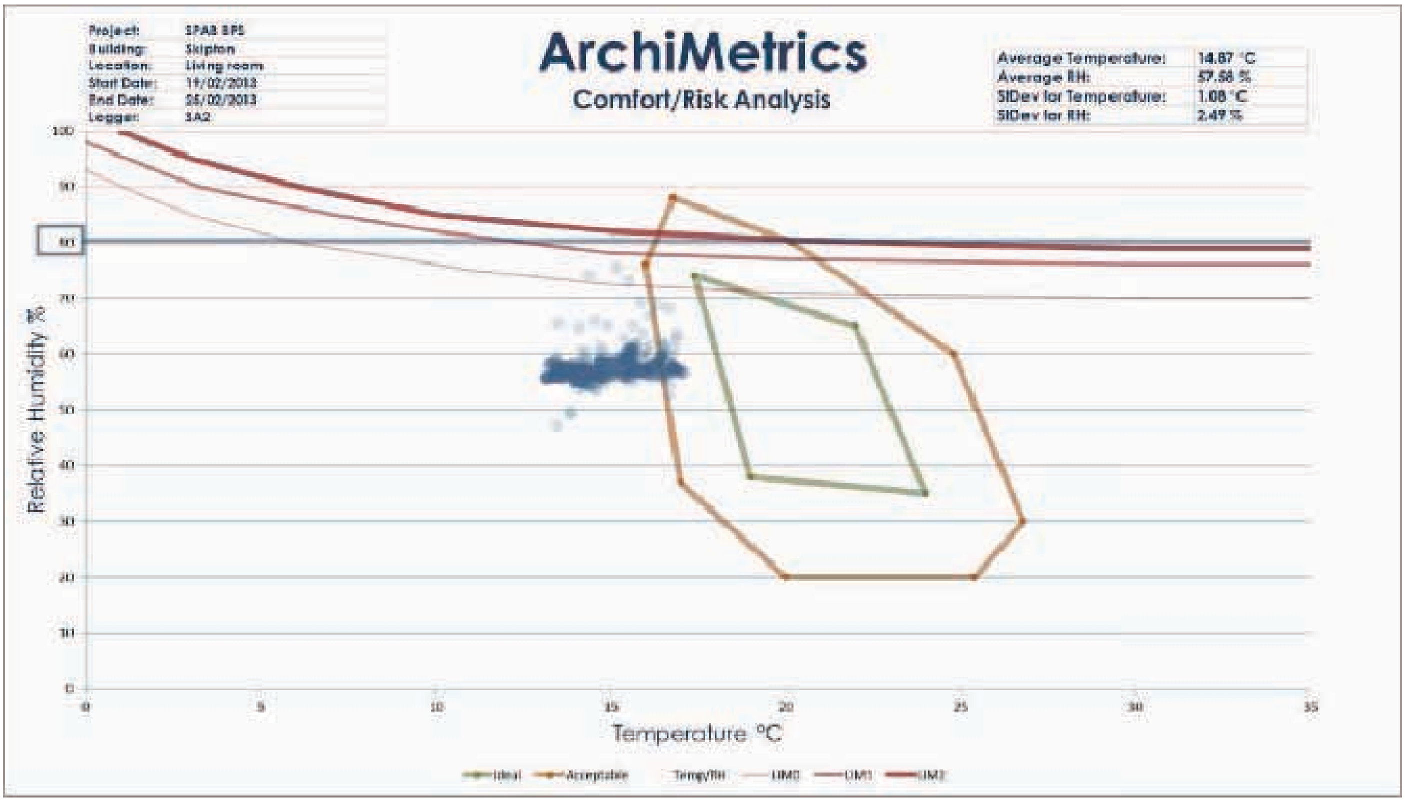


Figure 67. Comfort/Risk Analysis for White House Farm, Skipton, 19th - 25th February 2013

Mill House, Drewsteignton, Devon.
2013

Description: A barn built in granite dating from the nineteenth century or possibly earlier converted to a dwelling in 1970s with a modern extension added to the south east. UPVC double glazed windows throughout.

Refurbishment: The 1970's extension to the rear of the building has been extensively rebuilt as a timber-frame construction, insulated with woodfibre insulation and has new double-glazed timber windows, work on this is ongoing. In 2012, for experimental purposes, a short section of wall in a room in the older barn part of the dwelling was internally insulated using PIR insulation and it is this area, which corresponds with the pre-refurbishment monitoring location, that is the subject of long-term IHGM monitoring.

Occupancy: 2 persons.

Floor Area: 325m^2

Figure 68. Plan of Mill House, Drewsteignton, with ground floor on left hand side.

The red dot indicates the location of the monitoring equipment. The air permeability perimeter of the 2011 test is shown in blue, with the secondary test zone shown in red.

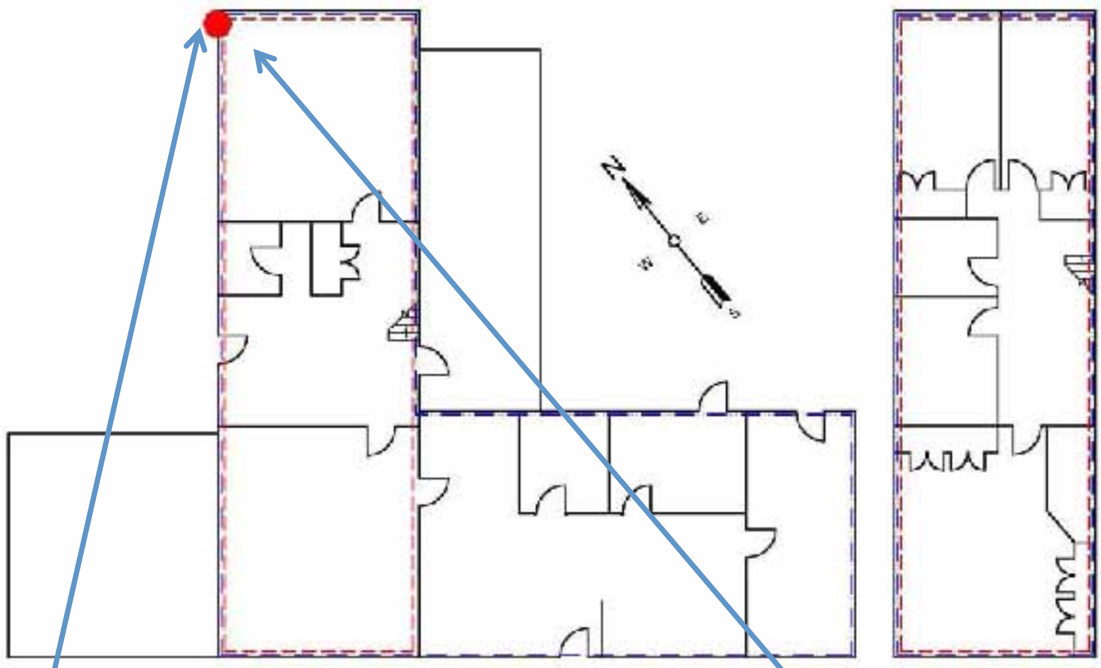


Figure 69. Positions of in situ monitoring equipment at Mill House, Drewsteignton, 2012.

MOISTURE

Interstitial Hygrothermal Conditions

Figure 70. Interstitial, U-value and IAQ monitoring set up at Mill House, Drewsteignton, 2012.

Temperature and moisture measurements are being made through the test section of west-facing wall of the study room at Mill House (Figure 70). Combined temperature and relative humidity sensors are located at four points within the wall at the heights and depths given in Table 15 coupled with sensors to record internal and external conditions. Data from all these sensors, for the period 8th February 2012 - 4th March 2013, has been collected and used as the basis for the following analysis. The positions of sensors 3 and 4 in the 2012 -13 monitoring correspond with those of the pre-refurbishment monitoring carried out in 2011 (albeit sensor 3 now occupies the 2011 sensor 2 core). However, sensors 1 and 2 have now been positioned to provide readings from the air gap behind the plasterboard finish and at the insulation/masonry interface, see Figure 71.

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

Table 15. Interstitial gradient sensor record for Mill House, Drewsteignton, 2012.

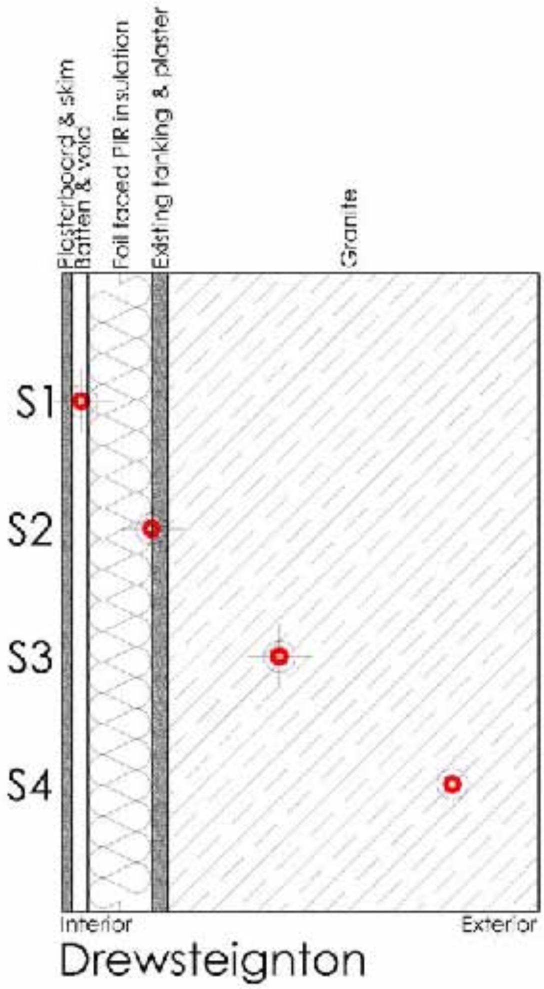


Figure 71: Wall Section showing position of sensors, Mill House, Drewsteignton.

Relative Humidity Over Time

Figure 8 plots levels of %RH recorded by the interstitial and internal and external sensors over time, along with internal and external temperature data. The trend of rising %RH at sensors 2, 3 and 4 that was noted in the previous report (*The SPAB Building Performance Survey 2012, Interim Report*) is confirmed by this graph which looks at %RH responses over a full annual cycle. Whilst it is possible to see a small reduction in %RH measured at sensor positions 3 and 4 over the months of July, August and September, once the cold weather recommences %RH begins to rise at these two locations once again. Indeed, at the beginning of February 2013 %RH reaches 100% at the outer sensor (sensor 4, 134mm back from the external wall face) and remains there throughout this month suggesting an increased risk of condensation at this point. Unlike sensors 3 and 4, there is no period in the year where %RH diminishes at sensor 2 which is located immediately behind the PIR insulation at the insulation/masonry interface. Here a steady rise in %RH is measured over the full 13 month reporting period, however, unlike sensor 4 neither sensor 2 or 3 reaches saturation (100% RH) over this time. The average %RH values of the three sensors position on the cold side of the insulation are all above 80%, a threshold commonly used to indicate the possibility of mould growth, and are; sensor 2 = 85%, sensor 3 = 80% and sensor 4 = 96% (see table at top right of Figure 8). Following the installation of insulation at Drewsteignton and the drying of the plasterboard's gypsum plaster skim coat behaviour of %RH at sensor 1 is, as was previously noted, closely coupled to that of the internal room %RH. This suggests that there is a high degree of vapour exchange from the room through the plasterboard to the air gap between the plasterboard and PIR insulation.

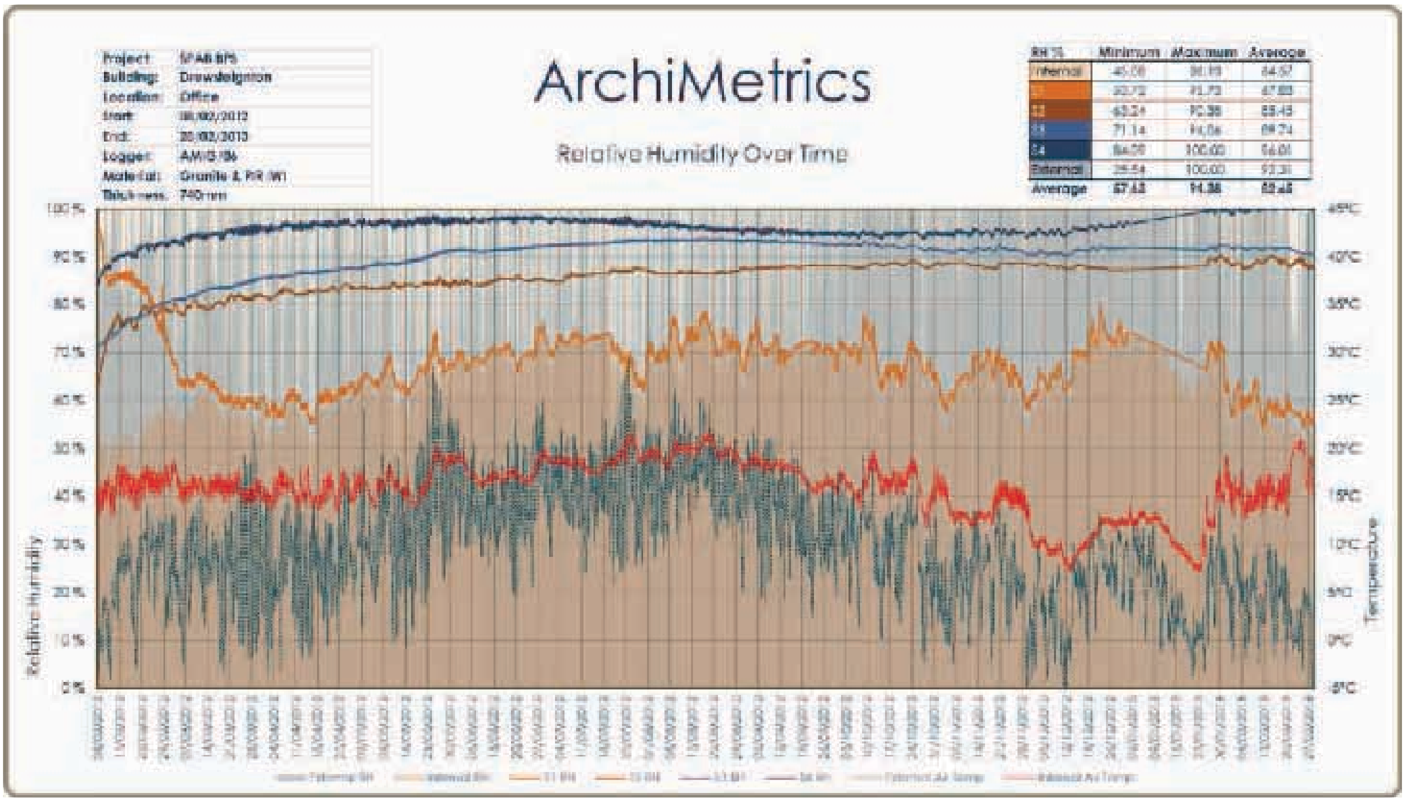


Figure 8: Relative Humidity over time, Mill House, Drewsteignton 2012 - 2013.

Absolute Humidity Over Time

Figures 12 and 72 show plots of absolute humidity over time for the insulated granite wall at Drewsteignton (Figure 72 is given for clarity to show plots from sensors 1 - 3 which are obscured by the plot from sensor 4 in Figure 12). These show that humidity rises within the wall over the warmer summer months as warmer temperatures and enable more vapour to be held in the air. The pattern for the summer months is also more dispersed, that is to say there is greater variation in the weight of water vapour measured at the four locations through the wall and, in general, this increases in relation to proximity to more humid external conditions. This relationship is clearly seen in Figure 72 for measurements from sensors 1 - 3 but is less defined in Figure 12 where plots from sensor 4, the outer most sensor, are more volatile reflecting more dynamic influences on quantities of water vapour in the immediate atmosphere. The drying of the gypsum plaster skim previously noted in relation to %RH can also be seen in plots of absolute humidity for sensor 1 installed in the air gap behind the plasterboard. Following this drying sensor 1 once again follows internal room conditions and shows the lowest weight of vapour by volume for this part of the wall during the summer. This changes in winter when, in general, quantities of water vapour are lower through the wall section as the colder temperatures are less able to promote evaporation and/or carry water vapour within the air. The quantities of vapour measured at each sensing point are also similar or more closely aligned during the winter period and now there are periods of time when the quantity of vapour is at its highest in proximity to warm, centrally heated, internal conditions. This is most marked in the week beginning 21/02/13 at the end of the reporting period where it would seem in response to extreme internal and external temperature difference measurements of absolute humidity are unusually dispersed through the wall section and increase in quantity in proximity to internal conditions (the inverse of the summertime pattern). It has been speculated that this behaviour is in response to a very cold but sunny period where the internal room temperature is increased above its usual 18˚C to a winter peak of 20˚C by solar radiation (entering the building through it's glazing) heating the internal environment and increasing absolute humidity within the room and immediately behind the drylining. This, coupled with cold and dry conditions externally, provides an unusually sharp delineation of quantities of absolute humidity through the wall section.

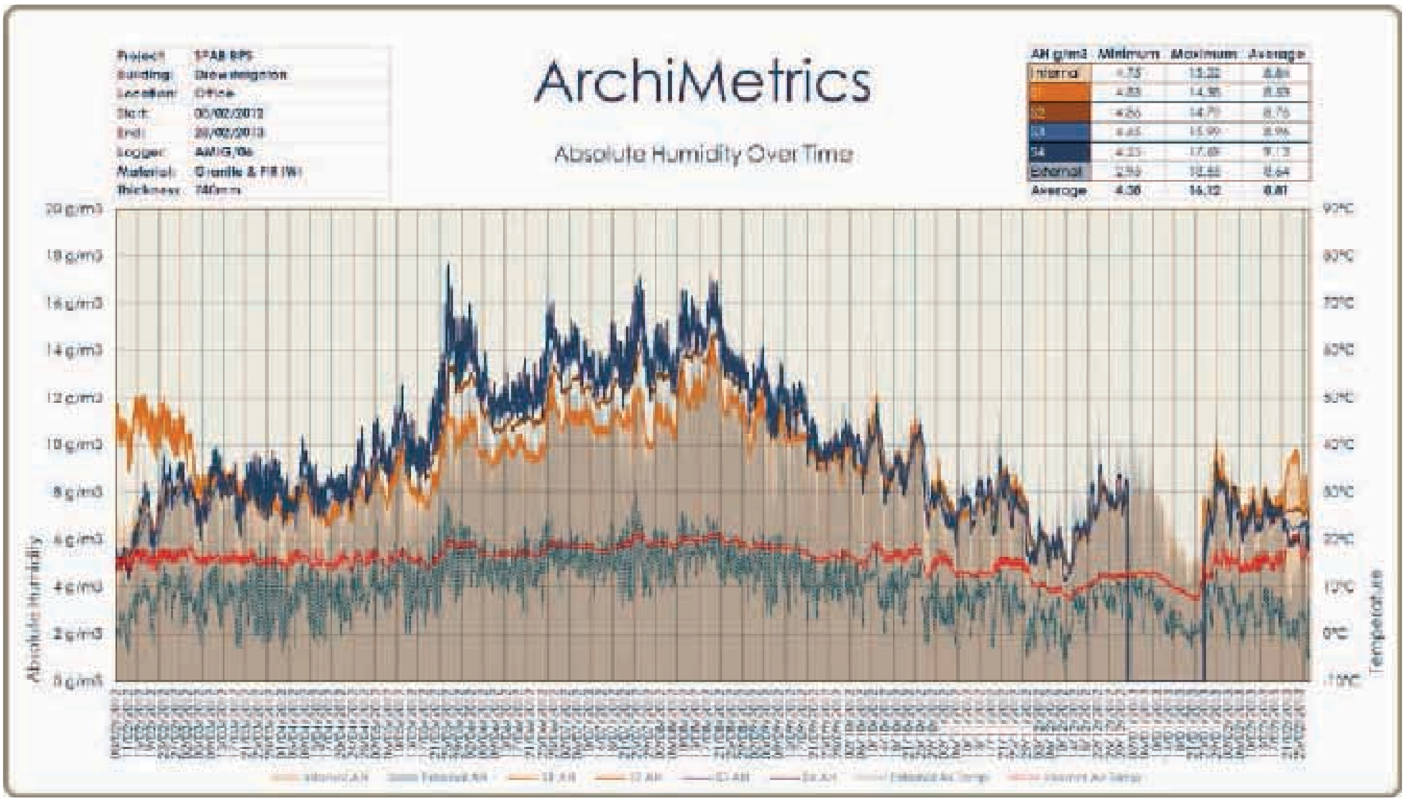


Figure 12: Absolute Humidity over time, Sensors 1 - 4, Mill House, Drewsteignton 2012 - 2013.

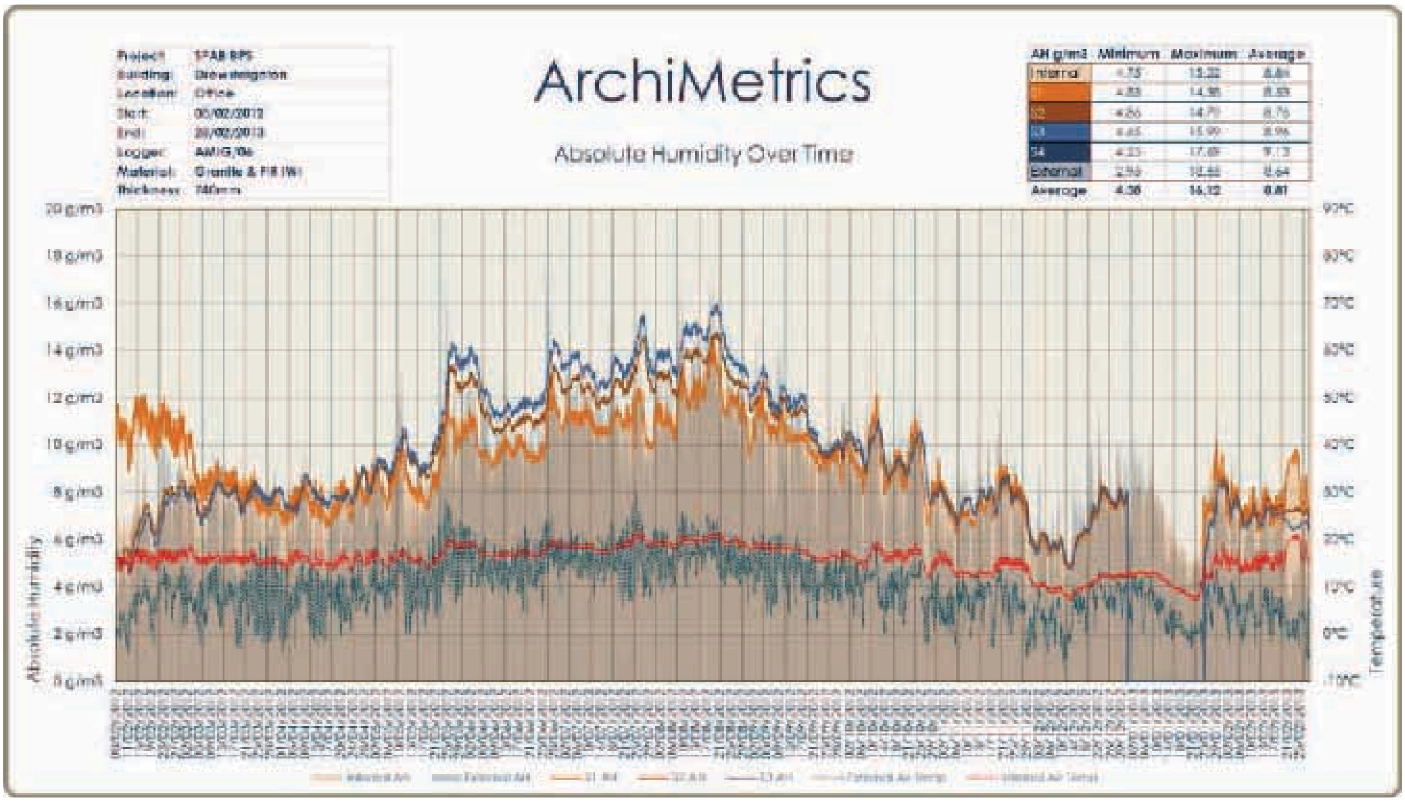


Figure 72: Absolute Humidity over time, Sensors 1 - 3, Mill House, Drewsteignton 2012 - 2013.

Average Absolute Humidity

The absolute humidity section for Drewsteignton, Figure 16, provides an indication of the average g/m^3 of water vapour either side of and through the wall section over the period 8th February 2012 - 4th March 2013. From this graph it can be seen that at this location quantities of internal and external water vapour are very similar, 8.84 g/m^3 internally and 8.64 g/m^3 externally, suggesting that by and large conditions with regard to quantities of water vapour are similar both inside and outside the property. The highest average weight of water vapour over the reporting period is recorded within the wall at the sensor 4 position towards the exterior wall face and diminishes in quantity travelling back through the wall section to the interior side. This gradient may be significant with regard to other observations of humidity conditions within the wall as it suggests that vapour movement through the wall may be static or indeed in a reverse direction, that is to say travelling towards the interior side of the wall. As is standard, the PIR insulation is sandwiched between aluminium foil and the joints of these boards are taped with adhesive foil tape upon installation. This foil creates a mostly impermeable layer and resists the passage of water both in a liquid and vapour form. In situations of reverse vapour flow this layer may prevent the progress of vapour through the wall section thus causing humidity to increase within the structure. Therefore perhaps it is possible that the incorporation of this insulation may account for the trend of rising %RH previously noted for this wall (Figure 8).

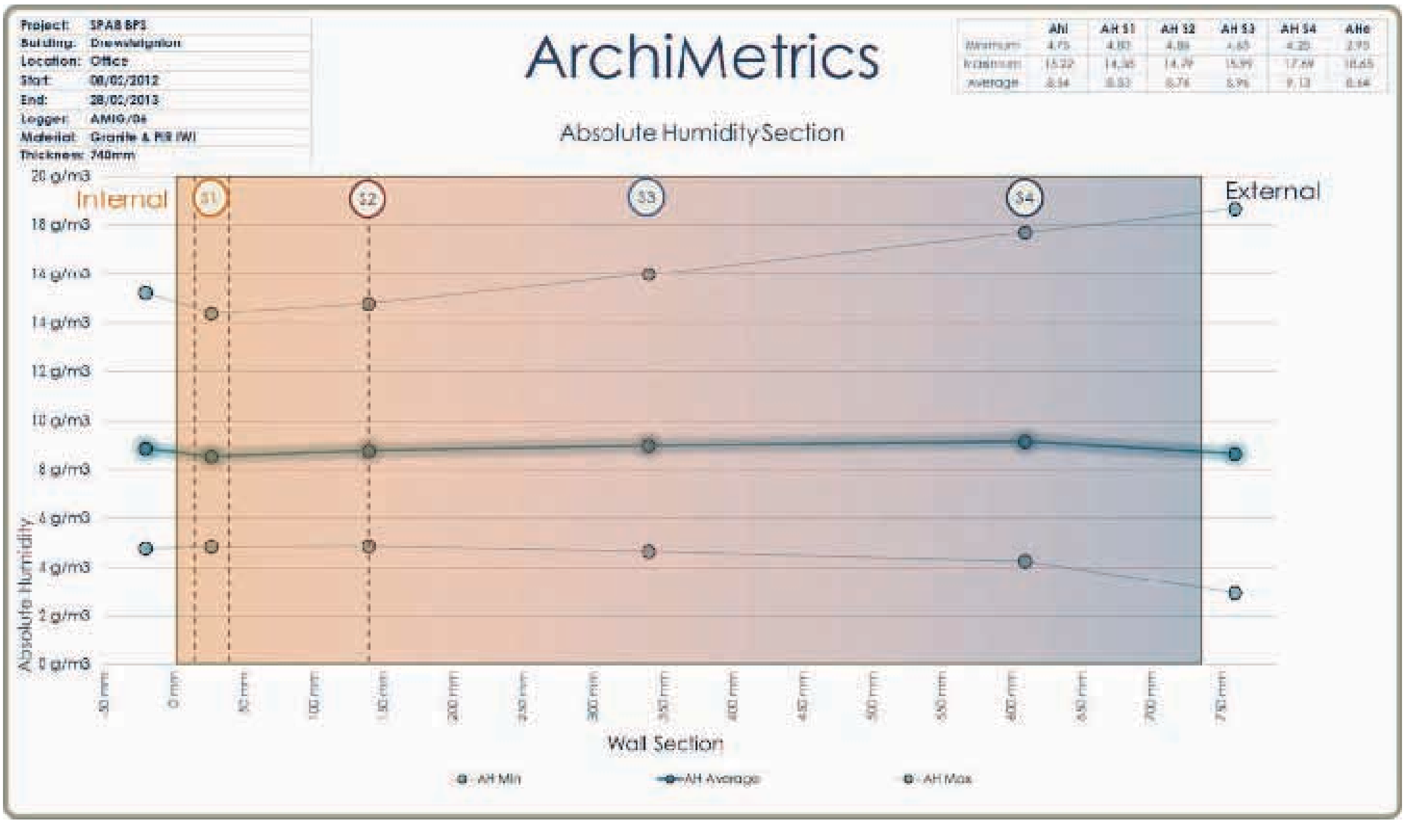


Figure 16: Absolute Humidity Section, Mill House, Drewsteignton 2012 - 2013.

Hygrothermal Section

Figure 20 allows an examination of temperature and dewpoint gradients through the wall section at Drewsteignton recorded over 13 months, between 8th February 2012 - 4th March 2013. Figure 73 reproduces the graph from the 2012 Interim report which shows plots of these same gradients over a shorter period, spring and summer 2102. The temperature profile through the section remains very similar over the two reporting periods and shows the different thermal resistances of the wall materials. The gradient is steep through the PIR insulating layer section (the addition of 100mm of PIR reduced the wall's measured U-value from 1.20 W/m2K to 0.16 W/m2K) and much more shallow, 1 - 2˚C difference, through the original granite masonry of the wall reflecting the reduction of heat travelling through this part of the wall as a result of the internal wall insulation. As is to be expected the dewpoint margin (the temperature drop required for dewpoint to occur at a certain point) is at its narrowest towards the coldest part of the wall. Prior to insulation, in 2011, the dewpoint margin averaged across all four measurement sensors for the wall was 4.01˚C, and the average at the most vulnerable outer 4th sensor in isolation was 2.38˚C. From the spring/summer 2012 data (Figure 73) the average dewpoint margin across all four sensors was reduced to 2.77˚C and 0.64˚C for the fourth sensor alone. Now, with a complete annual cycle of data (Figure 20) the margins are found to have reduced slightly once more and are 2.65˚C averaged across all four sensors and 0.61˚C at sensor 4. This further reduction reflects the addition of colder autumn and winter temperatures into the data set, cold temperatures inevitably increase %RH and thus moves conditions within the fabric closer towards dewpoint.

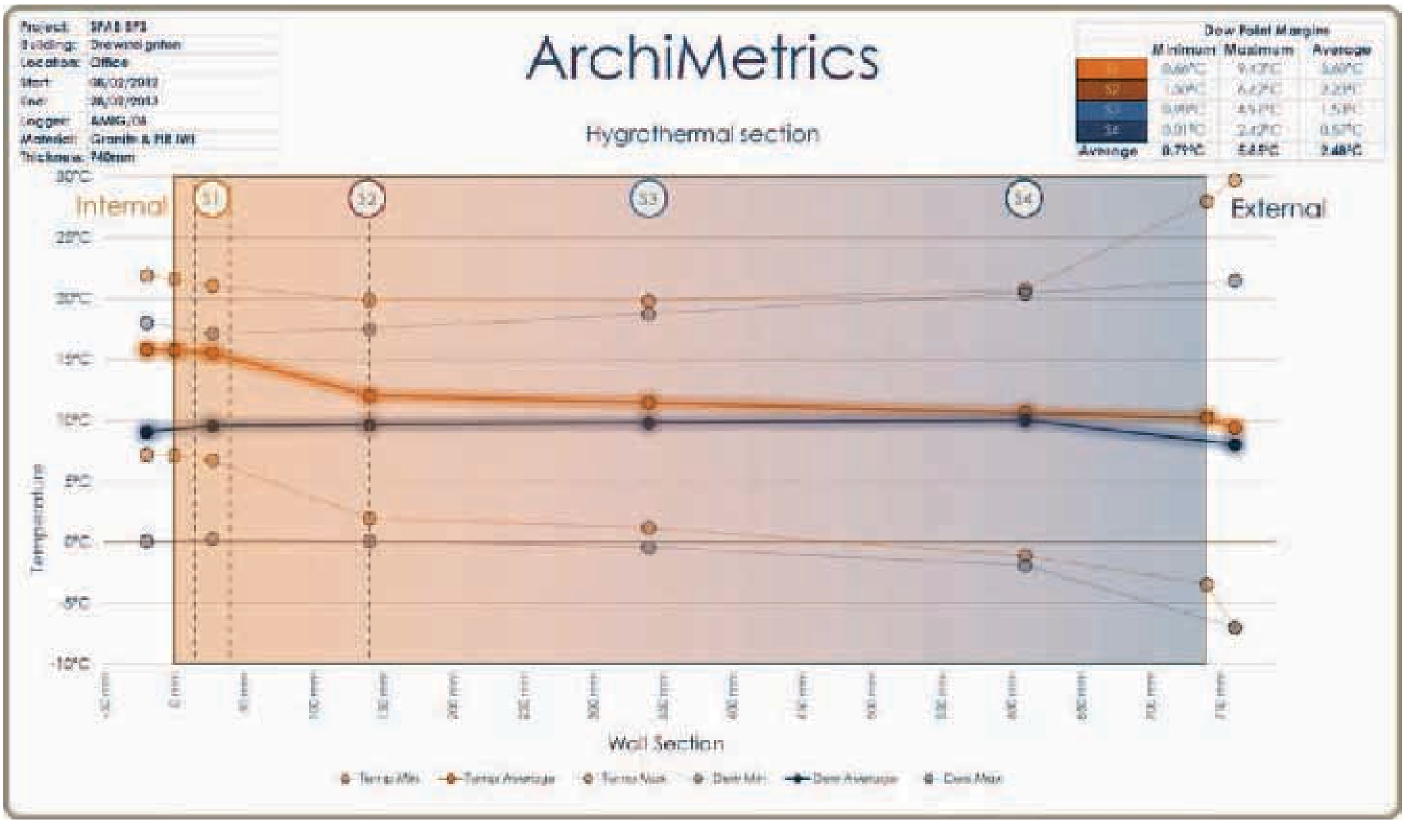


Figure 20: Hygrothermal Section, Mill House, Drewsteignton 2012 - 2013.

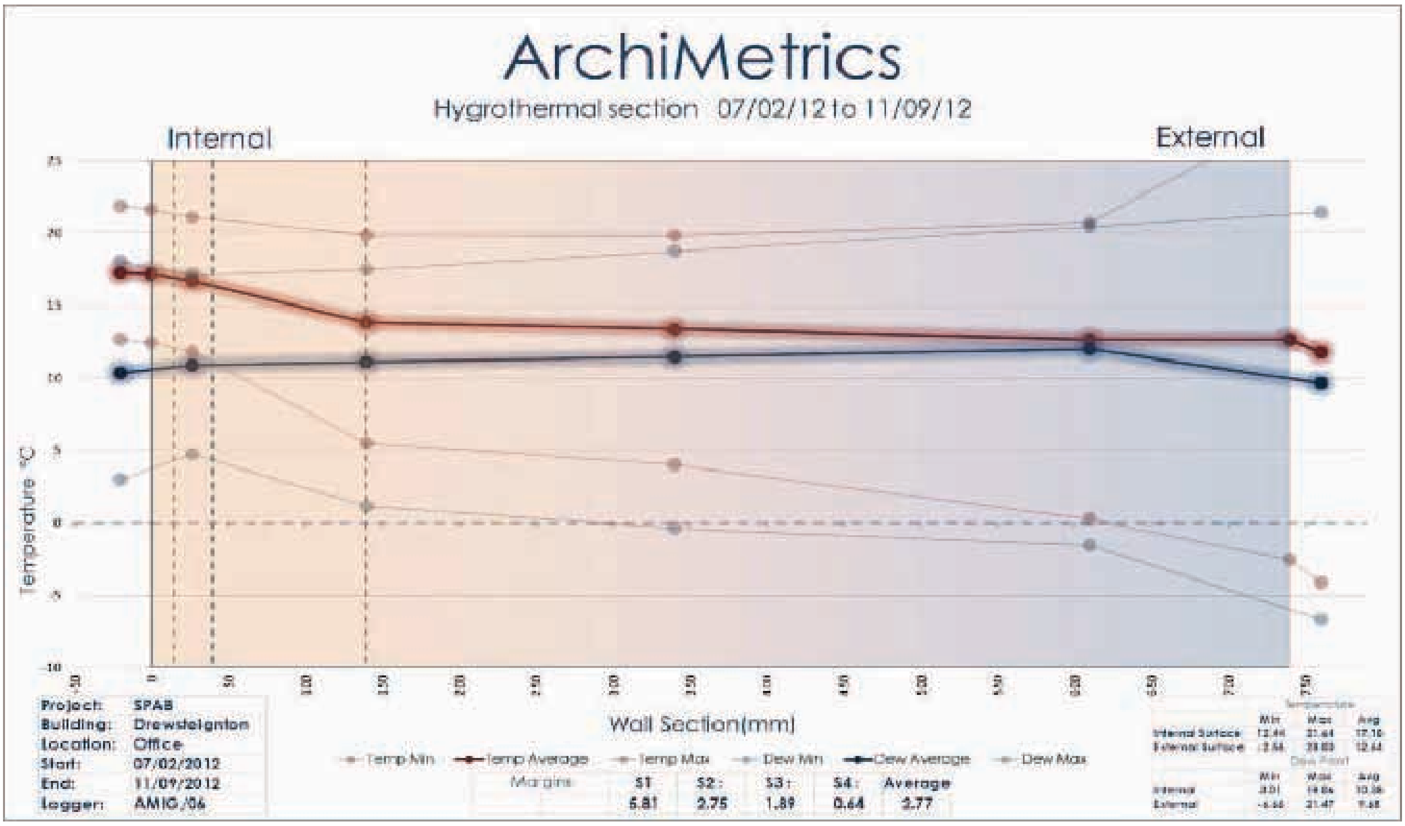


Figure 73. Hygrothermal Section, Mill House, Drewsteignton, Feb - Sept 2012.

Dewpoint Margin Over Time

Figure 24 presents a plot of dewpoint margins over time for the wall at Drewsteignton. Dewpoint is a function of %RH thus, as with the trend of increasing %RH for this wall (Figure 8) an inverse trend of decreasing dewpoint margins is found over the reporting period. Likewise, as with the plots of %RH there is an interruption in this trend at sensors 3 and 4 for a period of time (although not at sensor 2 at the insulation/masonry interface) but following this, entering the coldest months of the year, margins at all three sensors continue to narrow. Indeed, from the end of January 2013 the margin at sensor 4 has reached 0˚C, i.e. there is no margin and this location is at 100%RH or saturation. The reduction of dewpoint margins found for the wall at Drewsteignton is similar to that found for other internally insulated walls and is probably at least in part a response to the reduction of heat passing into the original fabric of the wall as the colder temperatures increase %RH. However, the reduction in dewpoint margins at Drewsteignton, particularly at the 4th node (average 0.61˚C) are quite extreme and in this sense may be a response to the extreme heat loss reduction that has occurred as a result of the application of 100mm of PIR insulation and also the introduction of a vapour barrier, in the form of the aluminium foil facing either side of the PIR insulation, which prevents the migration of vapour. The addition of insulation reduced the U-value measured for the wall from 1.20 W/m2k to 0.16 W/m2K a reduction in heat loss of 87%. The highly reduced dewpoint margins at Drewsteignton may also be a reflection of the increased presence of vapour within the wall over time as indicated by the overall trend of rising %RH, as vapour accumulates dewpoint is more likely to be reached. In this context however it should be noted that as condensation is a function of both humidity and temperature it is highly dependent upon ambient conditions, particularly external weather conditions and this reporting period covers a year which has been noted for high rainfall and cold winter temperatures. The degree to which the temperature and moisture behaviour of the wall at Drewsteignton is a response to these extremes of weather, rather than the addition of internal wall insulation, is difficult to determine. However, by monitoring the wall over the longer term the drivers of hygrothermal behaviour should become clearer. For example, we may find after a warm and dry summer %RH starts to reduce and falls below 80% once more or that the wall reaches some form of thermal and moisture equilibrium which reflects the affect of significant heat loss reduction over the longer term.

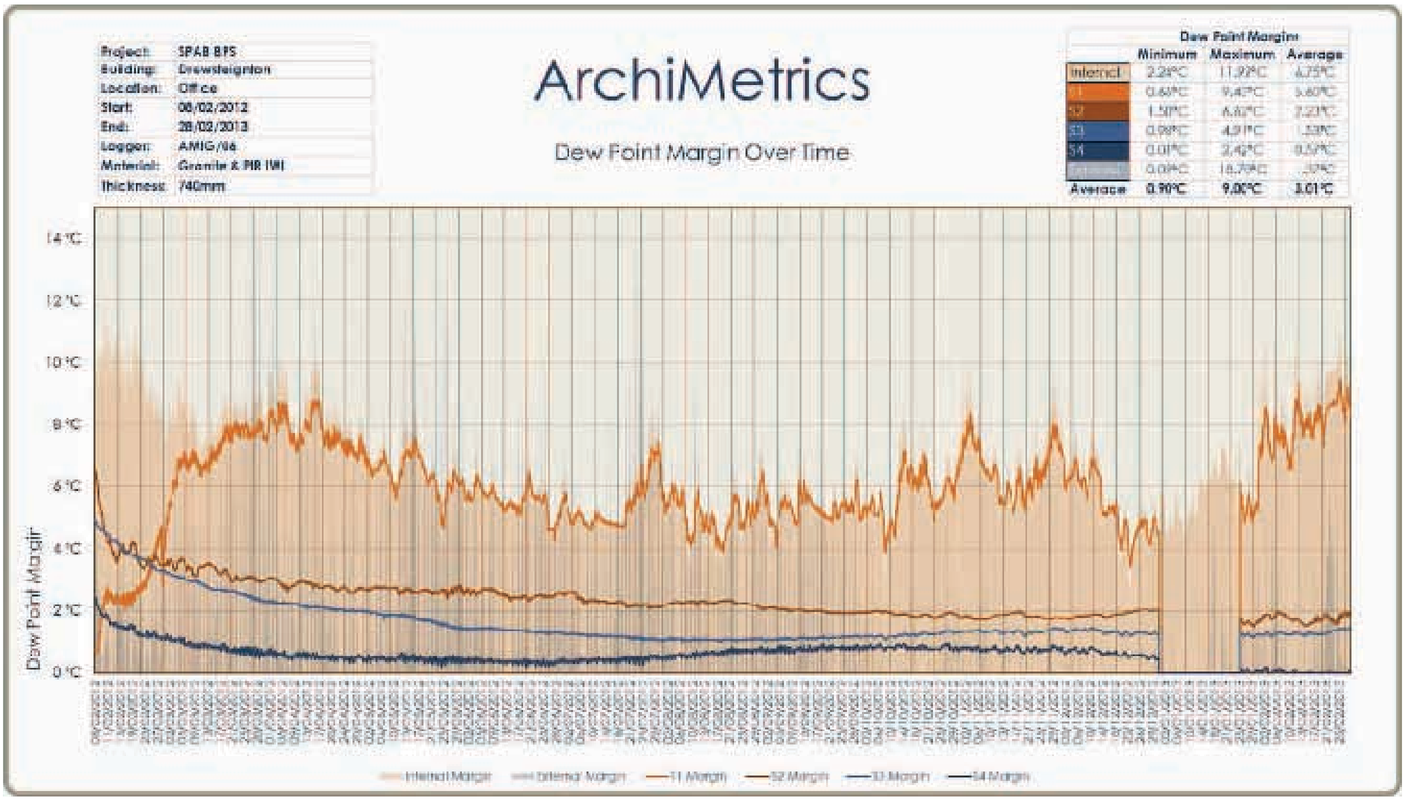


Figure 24: Dewpoint Margin over time, Mill House, Drewsteignton 2012 - 2013.

The Firs, Riddlecombe, Devon.
2013

Description: Two storey, semi-detached, nineteenth-century cob cottage with early twentieth-century single storey addition in cob to right side and more recent extensions to rear. Mainly new timber double-glazed units.

Refurbishment: Work at The Firs, Riddlecombe included the removal of external cement render, walls were repaired and re-rendered with an insulating lime render. Internally gypsum plasters have been replaced with lime and limewash finishes. Floors in the older part of the house have been insulated. Particular attention has been paid to air tightness detailing through the house.

Occupancy: Family of 5.

Floor Area: 86m^2

Preface

The previous edition of this report, dated 2012, found high and rising levels of %RH at Riddlecombe and dewpoint was measured for several months within the cob wall of the office under survey. As with any building the presence of high quantities of moisture within building fabric over a prolonged period of time is undesirable, but is particularly critical for materials such as unbaked earth (cob) which can fail causing structural collapse. Due to these conditions and the nature of the building materials at Riddlecombe a separate investigation as to the cause of the high %RH at Riddlecombe was initiated by the SPAB in collaboration with English Heritage in January 2013. Partners including representatives from Dartmoor National Park, the Devon Earth Building Association (DEBA), Archimetrics Ltd, SPAB and English Heritage met on site to discuss the case and instigate additional monitoring and laboratory-based measurements of the moisture content of the cob. As a multi-partner investigation the findings from this work will be the subject of a separate case study report.

Figure 74. Plan of The Firs, Riddlecombe (ground floor on right hand side).

Location of monitoring equipment shown by red dot. Air permeability test perimeter shown in blue, with secondary test zone indicated with red dotted line.

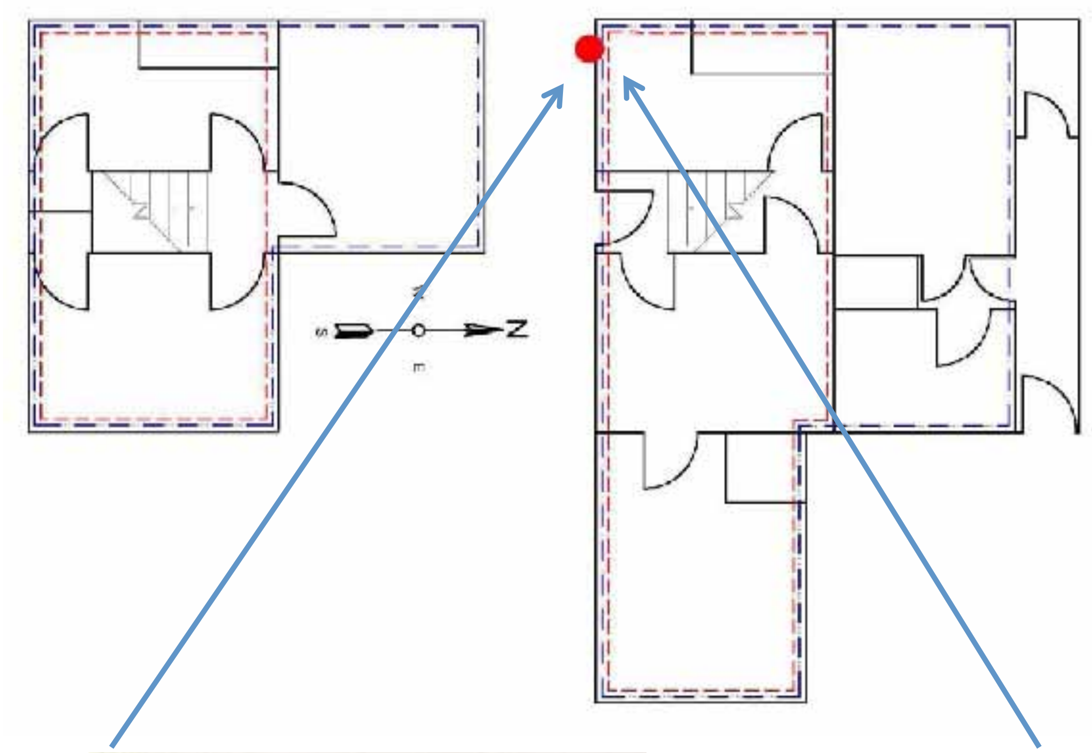


Figure 75. Positions of in situ monitoring equipment at The Firs Riddlecombe 2012.

U-VALUES

Figure 76. The Firs, Riddlecombe front elevation showing masonry buttress bottom left of frame.

In the summer of 2011, during the re-rendering of the south facing front facade at The Firs, Riddlecombe, it became apparent that the area of the wall under examination in this survey included an external stone buttress that had previously been hidden under the cement render (Figure 76). The addition of this component altered the build up of the wall used for U-value calculation purposes and new U-value calculations were undertaken for both the uninsulated and insulated walls to take account of these differences. These were reported in Table 10 of the 2012 version of the Building Performance Survey report (naturally the measured in situ U-values were unaffected by these changes). Subsequently, during the monitoring that has taken place in 2013, further details of the wall build ups at Riddlecombe have emerged resulting in minor alterations to the dimensions of the individual components that comprise the measured wall section. To reflect these changes new U-values have been calculated once again and details of these calculations and updated wall build ups are given in Table 16 below. The pre and post insulation calculated U-values have altered slightly increasing from 0.93 to 0.95 W/m^{2}K for the uninsulated wall at Riddlecombe, reflecting the greater quantity of more conductive stone within the overall build up and decreasing from 0.6 to 0.56 W/m^{2}K for the same wall post insulation, as a result of an increase in the quantity of insulating render ascribed to this wall.

Un-insulated 2011				**Insulated 2012**			
Materials & Build Up internal - external	**mm**	***In situ* U value W/m²K**	**Calculated U-value W/m²K**	**Materials & Build Up** internal - external	**mm**	***In situ* U value W/m²K**	**Calculated U-value W/m²K**
				Lime Plaster	20		
Gypsum skim	5			Cob	545		
Lime Plaster	20			Stone	90		
Cob	545			Lime Render Skat Coat	5		
Stone	90			Insulating Lime Render	50		
Cement render	40			Lime Render Finish Skim	5		
Total	**700**	**0.76**	**0.95**	**Total**	**715**	**0.72**	**0.56**

Table 16. In situ and calculated U-value results for The Firs, Riddlecombe 2011 & 2012 (2013).

The changes to these calculated U-values do not alter the commentary on U-value findings given in the previous 2012 report. The changes to calculated U-values are in the same direction as previous calculations; this shows a discrepancy between measured and calculated U-values for the wall before insulation where the calculation indicates greater heat loss than the measured U-value (as is common with many solid walls) and then, as before, post insulation, this relationship is reversed and the measured U-value shows greater heat loss than the calculation. The reduction in heat loss following the addition of insulating render at Riddlecombe was quantified in terms of percentages for both the calculated and measured U-values, and whilst the direction of change is consistent in both sets of U-values before and after insulation the percentage reduction for the calculated U-value has altered slightly from those previously published. The calculated U-values for the wall now show a theoretical reduction in heat loss from 0.95 W/m^2K to 0.56 W/m^2K following insulation which represents a 41% reduction in heat loss for this wall. The percentage reduction of 4% derived from the measured U-values (0.76 W/m^2K to 0.72 W/m^2K) remains unchanged as these alterations only affect the calculated U-value.

MOISTURE

Interstitial Hygrothermal Conditions

Temperature and moisture measurements are being made through a section of south-facing wall of the office room at Riddlecombe (Figure 77). Combined temperature and relative humidity sensors are located at four points within the wall at the heights and depths given in Table 17 coupled with sensors to record internal and external conditions. The position of these sensors through the wall section is shown in Figure 78. These sensors where first installed, pre-refurbishment in February 2011 and monitored conditions between 25th February - 11th March 2011. The following winter, 2011 -12, after the cottage had been re-rendering, the sensors were re-installed in identical positions and measured conditions between February - September 2012, (findings from this period were written up in the 2012 edition of this Interim Report). Unfortunately, due to interruptions to power supplies some data from the winter period 2012 - 2013 is not available for Riddlecombe. Consistent records recommence in February 2013 and data from the period 27th February - 13th August 2013 has been used as the basis for the following analysis and compared with the measurements made during the previous year.

Figure 77. Interstitial, U-value and IAQ monitoring set up at The Firs, Riddlecombe, 2012.

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

Table 17. Interstitial hygrothermal gradient sensor positions for The Firs, Riddlecombe, 2012.

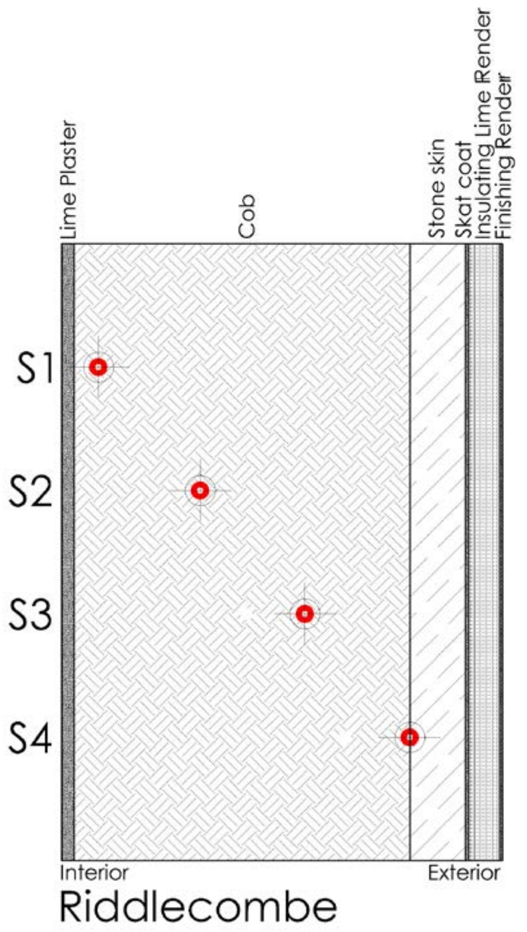


Figure 78: Wall Section showing position of sensors, The Firs, Riddlecombe.

Relative Humidity Over Time

Over the same period the previous year, February - August 2012, a very similar plot of %RH behaviour over time was produced for the insulated wall at Riddlecombe (Figures 79 & 9). Both graphs show %RH rising within the wall at all four sensor positions over time and levels of %RH reaching 100% indicating saturation and the possibility of condensation, first at sensor four and then later into the summer, further back within the wall at sensor 3. However, there are some slight variations in the plots of %RH recorded during 2013 which may give some cause for optimism given the alarming trend of raised %RH within the wall. At sensor 3, 395mm into the body of the wall, in 2012 %RH rose from 84.37% to 100% over a period of 15 weeks and the average %RH over the whole reporting period, February - August 2012, was 97.65%. In 2013, at the same sensor, %RH rises from 85.6% to 100% over a longer period of time, 18 weeks and the average %RH at sensor 3 over the reporting period Feb - Aug 2013 is slightly lower, 96.57%. Furthermore, unlike the graph for 2012 (Figure 79) in 2013 there is also a hint that levels of %RH at sensor 3 may begin to reduce towards the end of the reporting period, around the week beginning 7th August 2013.

That %RH appears to increase through the wall over the summer months is curious and is a pattern that is repeated over two years following the application of external insulating render. It is also contrary to findings at other locations where, in general, %RH tends to decrease in the summer as the warmer external temperatures lower %RH throughout a wall section. Over the first two weeks of the 2013 reporting period %RH rises on all four sensors, reaching 100% at sensor 4 before diminishing towards the end of the second week. Given conventional %RH behaviour this could be ascribed to the loss of heat experienced by the wall while the occupants were away on holiday (the rise in %RH is mirrored by a decline in internal temperature over the same period). However, looking at the graph over a longer time period, shows that the trend of rising %RH is matched not by declining internal temperatures but by rising external ones and indeed weeks 27th February and 6th March 2013 also saw steep rises in external temperature. It was noted in the previous edition of this report that the rise in relative humidity measured within the wall at Riddlecombe may be driven by raised external temperatures and was illustrated by a detailed graph for the period 15th - 29th May 2012 (Figure 80).

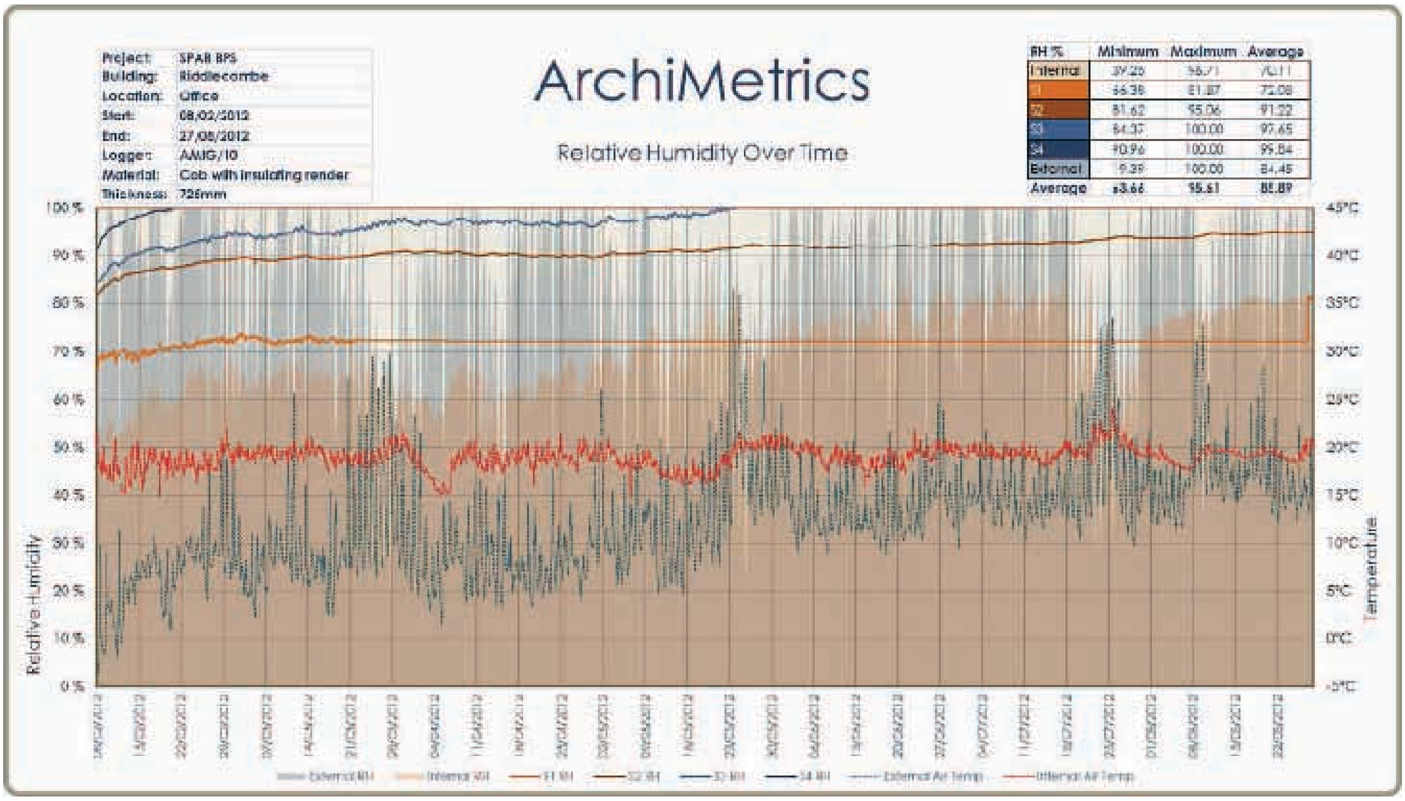


Figure 79. Relative Humidity over time, The Firs, Riddlecombe Feb - Aug 2012.

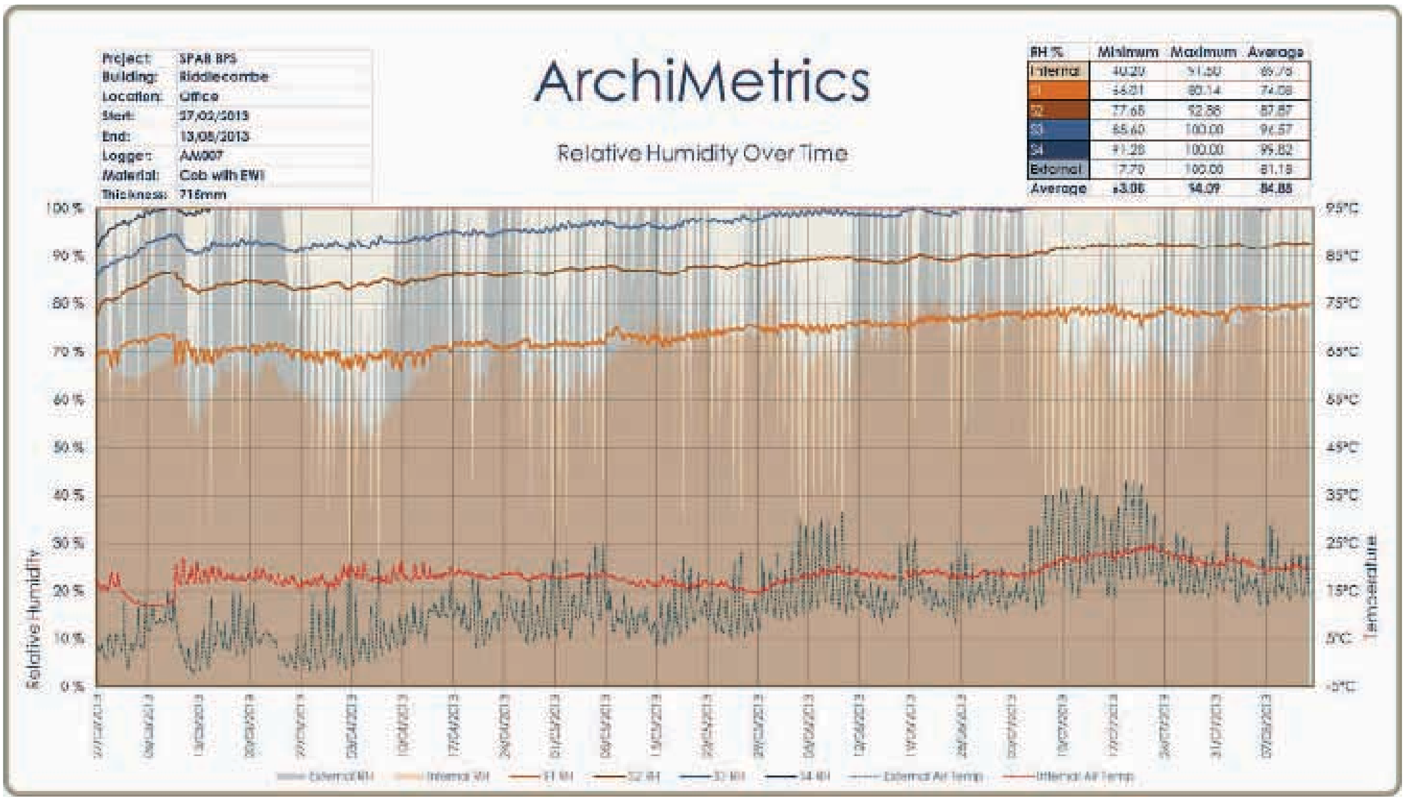


Figure 9: Relative Humidity over time, The Firs, Riddlecombe Feb - Aug 2013.

The discussion in the 2012 report stated "Figure 80 shows a detailed plot of the RH values for the wall at Riddlecombe between 15th - 29th May. It is during these two weeks that the level of RH measured at sensor 3 exceeds 100%. It appears that this occurs in parallel with rising external temperatures and a similar although somewhat delayed and less pronounced increase can be seen in sensor 2....In contrast to the wall at Shrewsbury where interstitial RH more or less maps that of external temperature and RH i.e. when temperatures rise interstitial RH falls the opposite appears to be happening in the wall at Riddlecombe. RH increases with external temperature increase and continues to accumulate over time. This leads us to speculate that the raised temperatures are perhaps causing bound construction water to develop into vapour which is in turn slow to migrate out of the wall due to the now in tact and much thicker external render system."

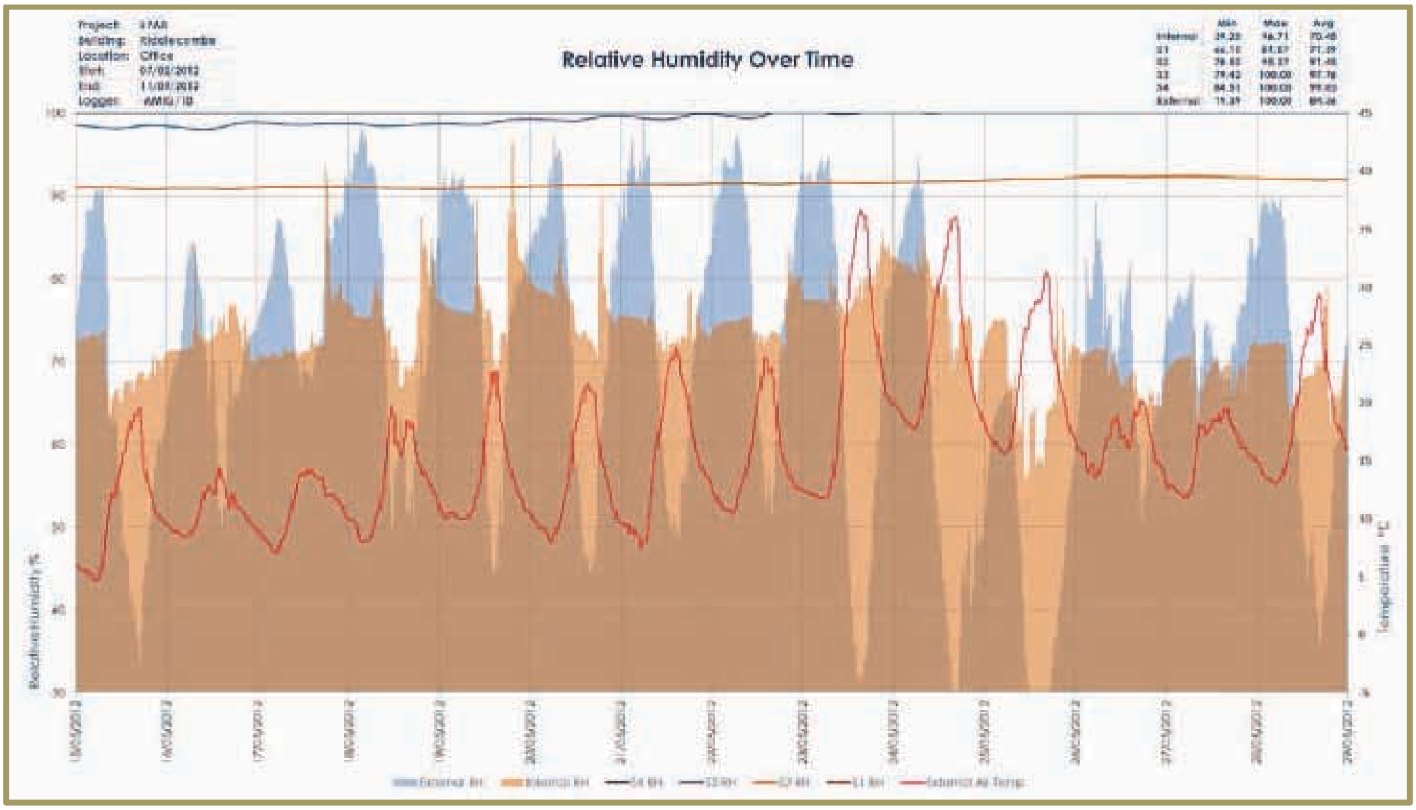


Figure 80. Detail - plots of interstitial RH, internal room RH and external RH and temperature, The Firs, Riddlecombe, 15th - 29th May 2012.

Figure 81 provides a detailed description of %RH behaviour during the two weeks that sensor 3 exceeds 100% this time over the summer of 2013. As with the previous year, this shows that the peak at 100% is achieved just shortly after a peak in external temperature on the 25th June and that, following this, humidity then hovers just below 100% during a period of slightly lower external temperatures but returns to saturation on the 4th July and remains there over the very warm days that follow.

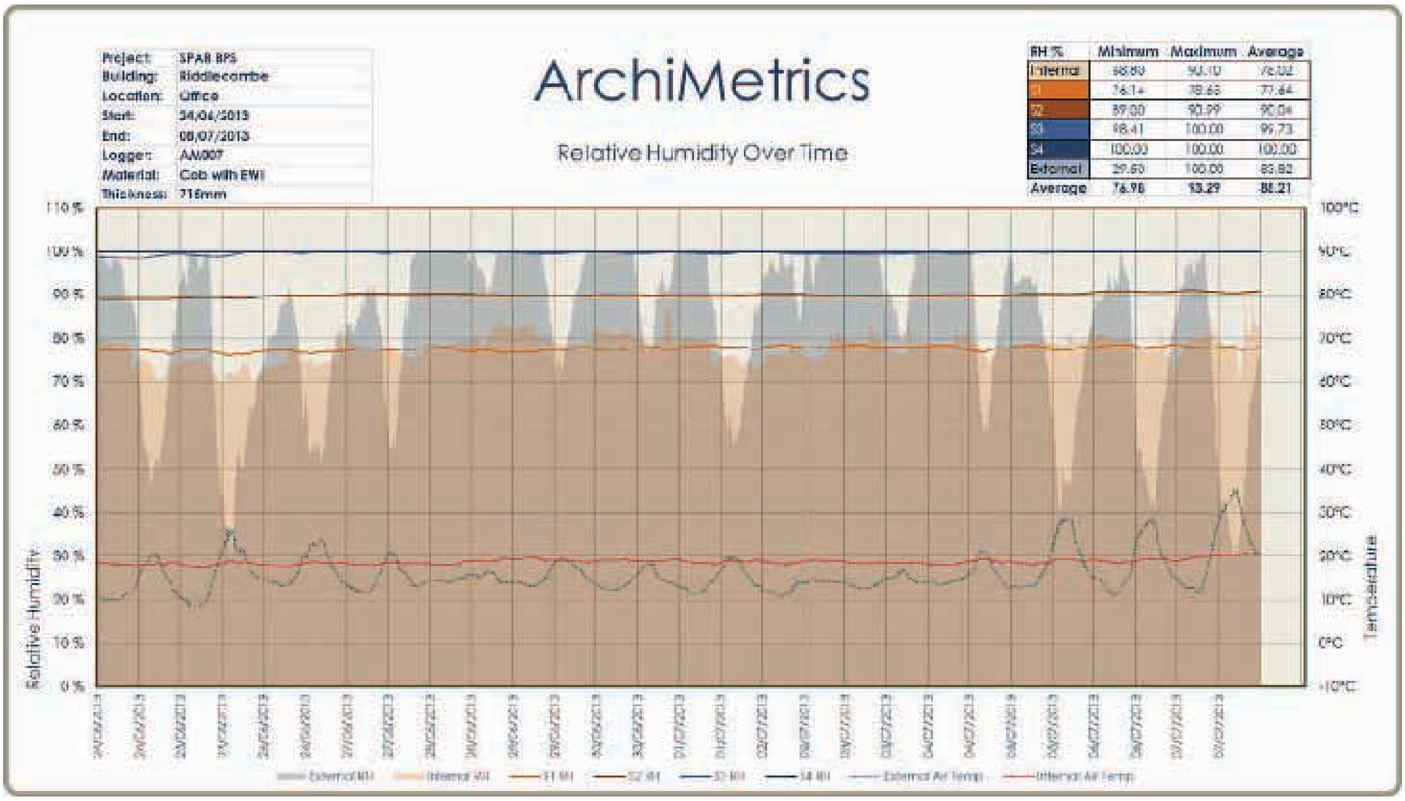


Figure 81. Relative Humidity over time, Sensors 1 - 3, The Firs, Riddlecombe, 24th June - 8th July 2013.

A detailed graph for a week earlier in the year also shows some interesting trends regarding %RH behaviour in the cob wall, Figure 82. Week beginning 6th March 2013 coincides with the end of the holiday period previously mentioned and therefore sees quite low internal room temperatures over the early part of this week. After the family has returned heat is once more input into the building and patterns of %RH measured at sensor 1, 60mm back from the internal wall face, immediately respond following the conventional pattern of decreasing %RH during periods of raised internal temperature. However, measurements from the other three sensors seem to be less determined by internal conditions and may be affected, contrary to orthodoxy, by a decline in %RH which follows the decline in external temperatures. Sensor 4, closest to the external wall face, in particular, seems to be responding to external conditions in this contrarian way where %RH peaks close to 100% during periods of slightly warmer temperatures during the days of the 11th and 12th of March.

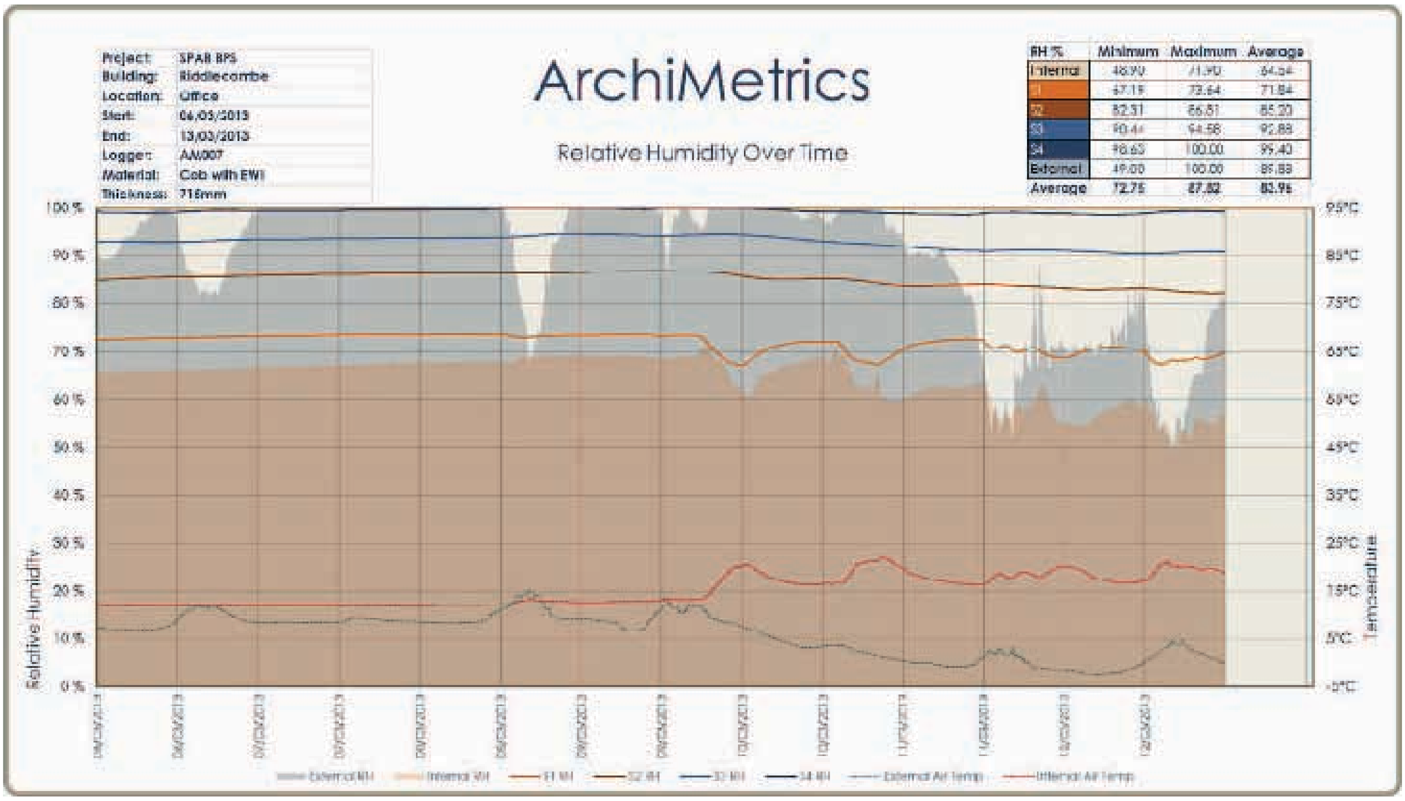


Figure 82: Relative Humidity over time, Sensors 1 - 4, The Firs, Riddlecombe 6th March - 12th March 2013.

Absolute Humidity Over Time

Following on from observations made concerning rising levels of %RH coinciding with warmer temperatures in the wall in Riddlecombe, plots of absolute humidity over time show an increase in vapour in the wall during higher external temperatures. This behaviour can be seen in the plots for both the 2012 spring and summer data (Figure 83) as well as this year's records, Figure 13. In both years the weight of vapour measured within the wall increases and peaks alongside peaks in external air temperature. Furthermore, over both years, these peaks are cumulative, that is quantities of vapour increase over time. In the discussion concerning %RH in the wall at Riddlecombe it was suggested that the increase in %RH measured in the wall over summer could be explained by vaporisation occurring from the wet cob material as a result of the higher temperatures within the wall. The plots of absolute humidity would seem to reinforce this notion as we can see vapour levels increasing during periods of high external air temperature. Once external temperatures diminish however neither absolute nor relative humidity levels return to those found prior to the warm spell. The fact that these levels of vapour appear to be cumulative suggests that once a certain quantity of moisture has vaporised from the cob material it then remains in a vapour form due to the warm temperatures and struggles to migrate out of the wall until such vapour has accumulated for parts of the wall to reach 100% RH despite summer time conditions.

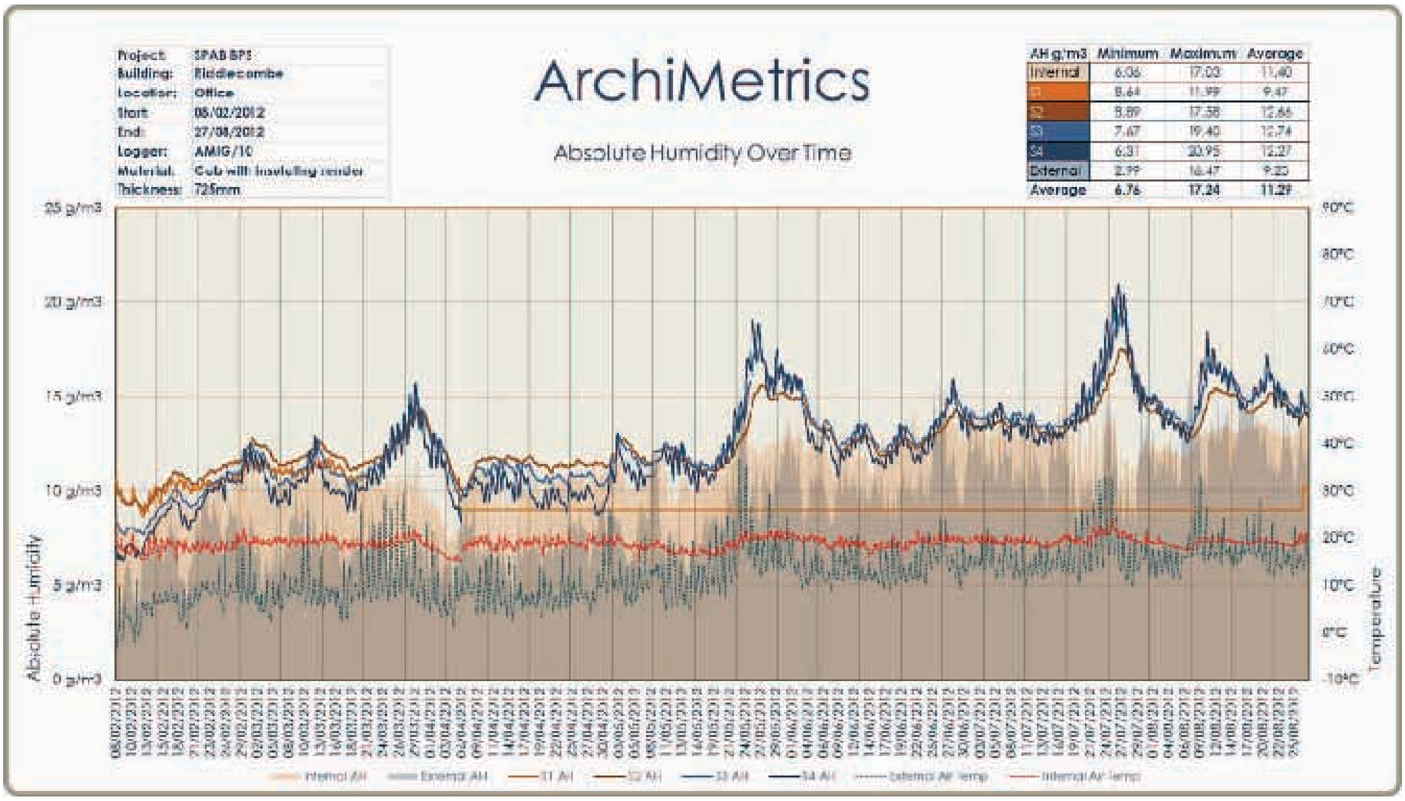


Figure 83: Absolute Humidity over time, Sensors 1 - 4, The Firs, Riddlecombe February - September 2012.

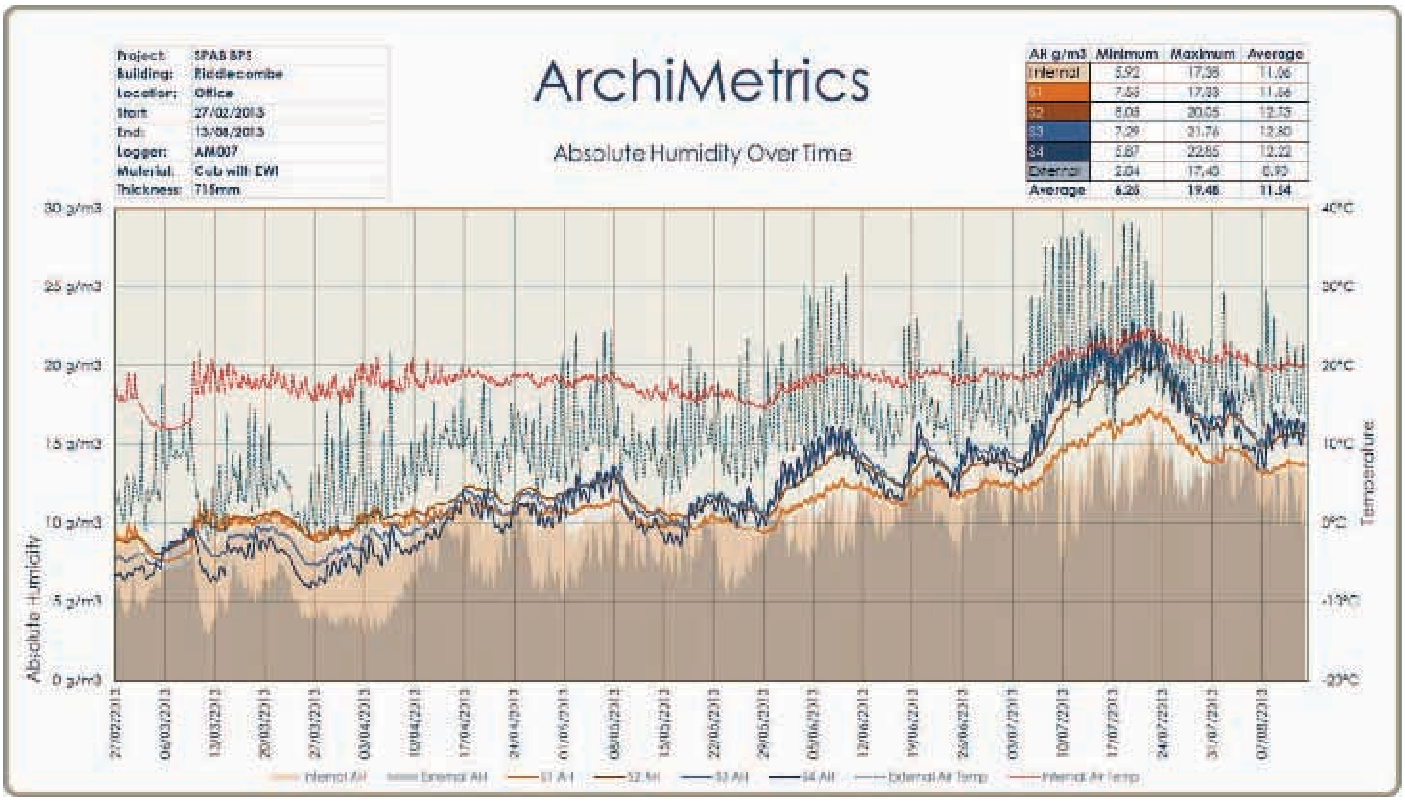


Figure 13: Absolute Humidity over time, Sensors 1 - 4, The Firs, Riddlecombe February - August 2013.

The same detailed weeks discussed in the commentary on %RH above have been graphed to provide a picture of the behaviour within the wall with regard to absolute humidity, Figure 84. Vapour responses at sensor 4 can be clearly seen to map increases in temperature in Figure 84, with similar, if slightly delayed and increasingly muted responses seen for the other three sensors in the wall. The period of time when external temperatures peak above 20˚C and then 30˚C beginning on the 4th July see an increase vapour throughout the wall section over this time.

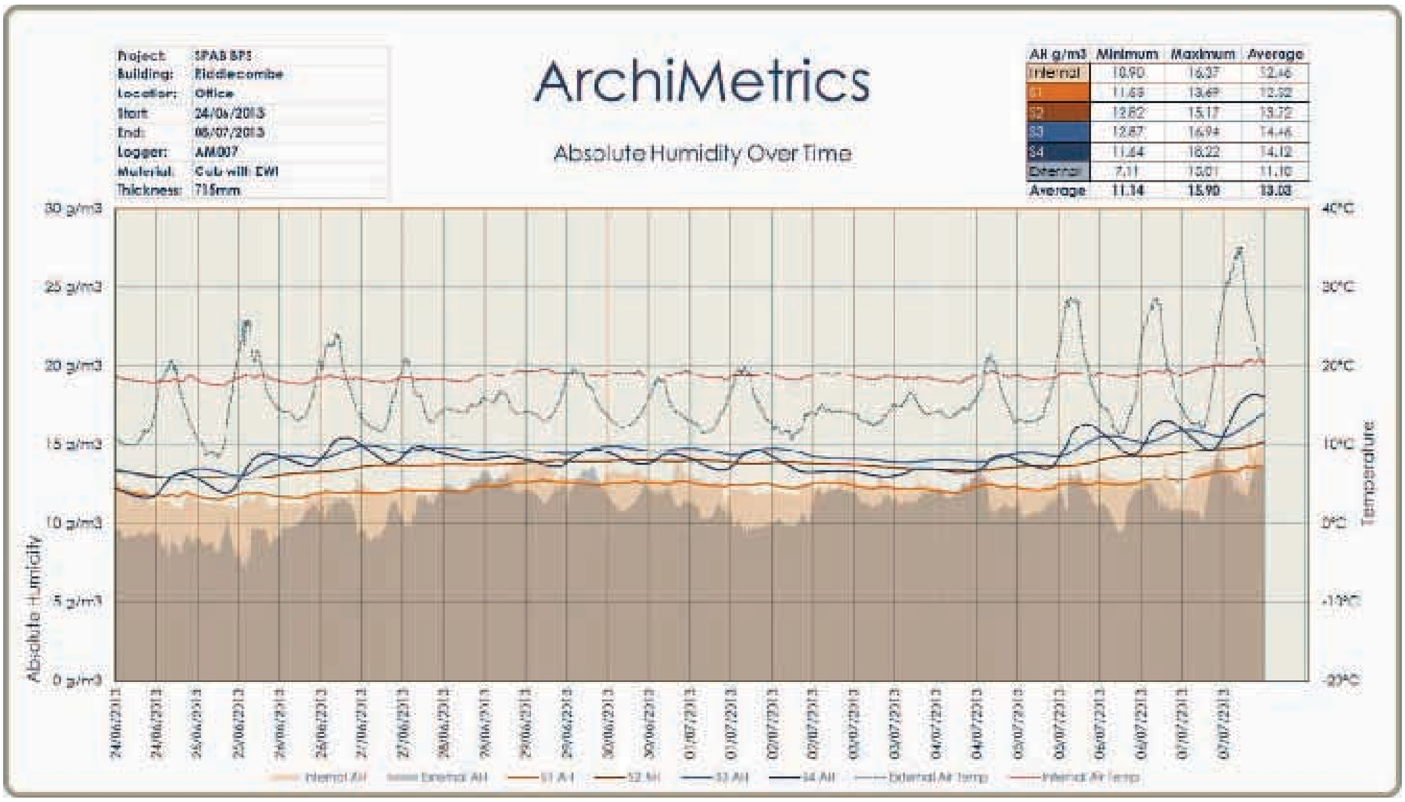


Figure 84: Absolute Humidity over time, Sensors 1 - 4, The Firs, Riddlecombe 24th June - 8th July 2013.

The detailed graph for the earlier week in the 2013 reporting period, Figure 85, shows increases in the g/m^3 of vapour at sensor 1 starting on 9th March which are a response to increases in internal room heat (despite the increase in vapour %RH declines at this location during these periods due to the ability of warm air to hold greater quantities of water as a vapour, Figure 85). Quantities of vapour measured at sensor 2 may, in this early colder period of the year, also be mostly determined by heat originating from inside the building, as, at least initially, following 9th March g/m^3 of vapour increase at this location like that of sensor 1. However, this increase in vapour quantities following the input of interior heat to the wall is not seen further out towards the exterior at sensors 3 and 4, where, contrary to sensors 1 and 2, g/m^3 of vapour decline over this time and show only slight increases (at sensor 4 only) during slightly raised daytime temperatures on 11th and 12th March 2013.

Although the graph for Riddlecombe, Figure 13, covers a shorter time period the increase in absolute humidity here also follows the seasonal pattern and increases with increasing external temperatures/external absolute humidity. There is, however, a significant difference in the plots of absolute humidity for the wall at Riddlecombe compared with those at the other locations. By and large, plots of absolute humidity in the other walls broadly match, sit between or fractional surmount, those of internal and external levels of absolute humidity showing a close correlation between internal/external and interstitial conditions. At Riddlecombe plots of interstitial absolute humidity are detached from and significantly higher than those of external humidity and also internal absolute humidity from May 2013 onwards. This suggests that there is an additional or additional factors driving quantities of vapour in this cob wall independent of ambient internal and external vapour conditions. In the previous discussion on %RH and in the individual report on Riddlecombe it is suggested that excess moisture is contained within the cob as a result of a past failing external render as well as water added to the wall during the re-rendering process and this is vaporising during periods of warm temperatures as sun falls on the south facing wall. This might explain the detachment seen between internal and external vapour conditions and those within the wall, as the moisture within the cob material provides an additional and independent source of vapour.

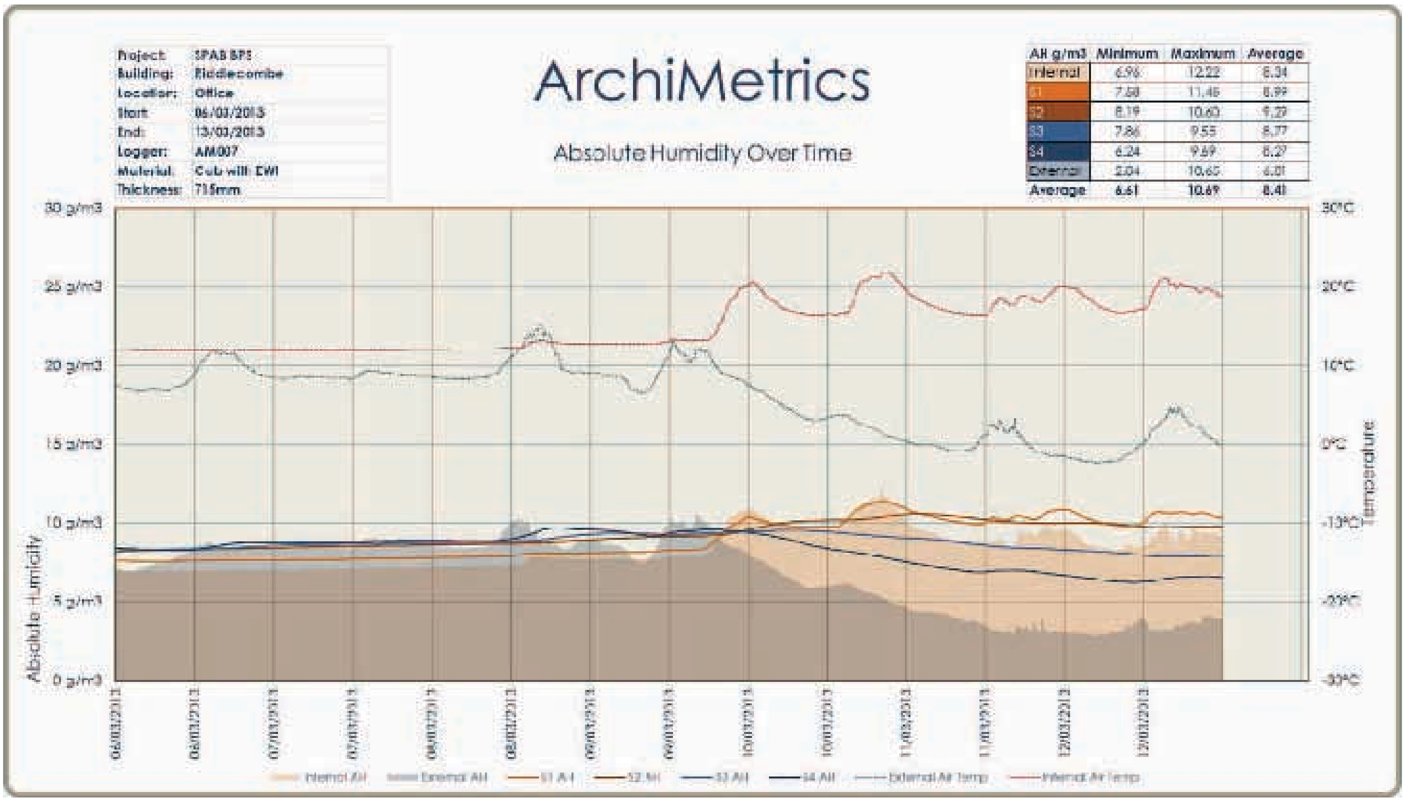


Figure 85: Absolute Humidity over time, Sensors 1 - 4, The Firs, Riddlecombe 6th March - 12th March 2013.

Average Absolute Humidity

The absolute humidity profile of the wall at Riddlecombe is also provided in the form of a section graph which plots the average g/m^3 of water vapour either side of and through the wall. Figure 86 shows the section for the 2012 data and Figure 17 the section for 2013. Both the 2012 and 2013 sections finds that of the four sensors in the wall sensor 3 records the highest weight of vapour by volume; 12.74 g/m^3 in 2012 and the slightly higher value of 12.80 g/m^3 in 2013. On average the total weight of vapour in the wall has increased from 47.07 g/m^3 in 2012 to 49.31 g/m^3 in 2013 but comparison of the two years shows that vapour is also distributed slightly more evenly throughout the section in the 2013 readings. This may suggest that whilst vapour still seems to be accumulating in the wall at Riddlecombe that there is also some movement in this vapour outwards from the centre of the wall towards the wall surfaces where, given suitably vapour permeable finishes, there may be some chance of vapour migration to the inside/outside occurring.

The relative and absolute humidity data from Riddlecombe leads us to speculate that we may be watching the damp cob wall at Riddlecombe drying out, or at least beginning to dry out, albeit very slowly. The cob was found to be wet prior to refurbishment, mostly likely as a result of the cracked external cement render. Whilst the replacement of this render took place over 4 weeks in the summer, which provided a short opportunity for drying of the cob, the application of the new insulating external render also involved the significant wetting of the substrate with a water hose. In these circumstances, it may be that the cob at Riddlecombe has a high moisture content; additional measurements, as well as damp insulating material removed from the monitoring wall cores prior to the commencement of refurbishment monitoring, suggest this is the case. Therefore, rather than seeing vapour accumulating within the cob material due to low rates of ventilation and air permeability, high rates of internal humidity and the inhibition of internal to external vapour flows, instead, during periods of high external temperatures, the south-facing wall heats up enough to cause the moisture that is bound within the cob material to vaporise. If, as is may be suggested by the 2103 absolute humidity section (Figure 17), this vapour then migrates towards internal or external wall surfaces then there is a possibility that it can be dispelled into the atmosphere. Whilst the quantity of vapour appears to have increased over time between 2012 and 2013 this may be a factor of the quantity of moisture held within the cob and the warmer temperatures of the 2013 summer encouraging more vaporisation. However whether this actually leads to lower quantities of moisture overall within the wall relies on the ability of this vapour to travel through the materials to exit the wall. In Figure 9, the %RH over time graph for summer 2013 for this wall, it is possible to see a very slight recovery in %RH measurements at sensor 3, which dip below 100% RH occurring around the week beginning 7th August. This may suggest that vapour is able to successfully migrate through the wall structure and therefore we may see %RH values measured in this wall begin to reduce however, at present, overall vapour quantities appear to still be increasing. Monitoring over the longer term will determine whether, during different conditions and over a longer time span vapour, is able to escape from the cob thus reducing moisture levels within the material to more acceptable limits.

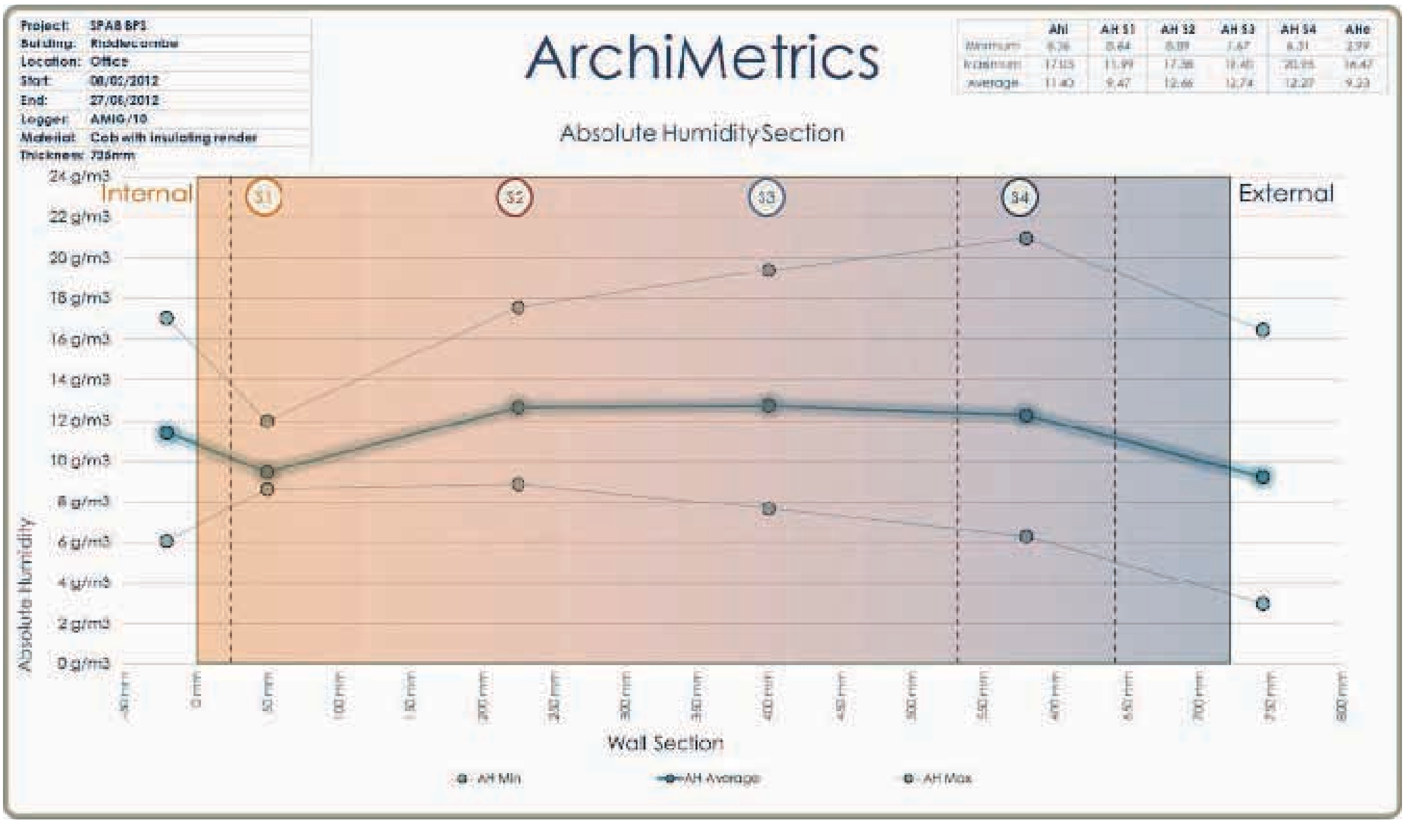


Figure 86: Absolute Humidity Section, The Firs, Riddlecombe February - September 2012.

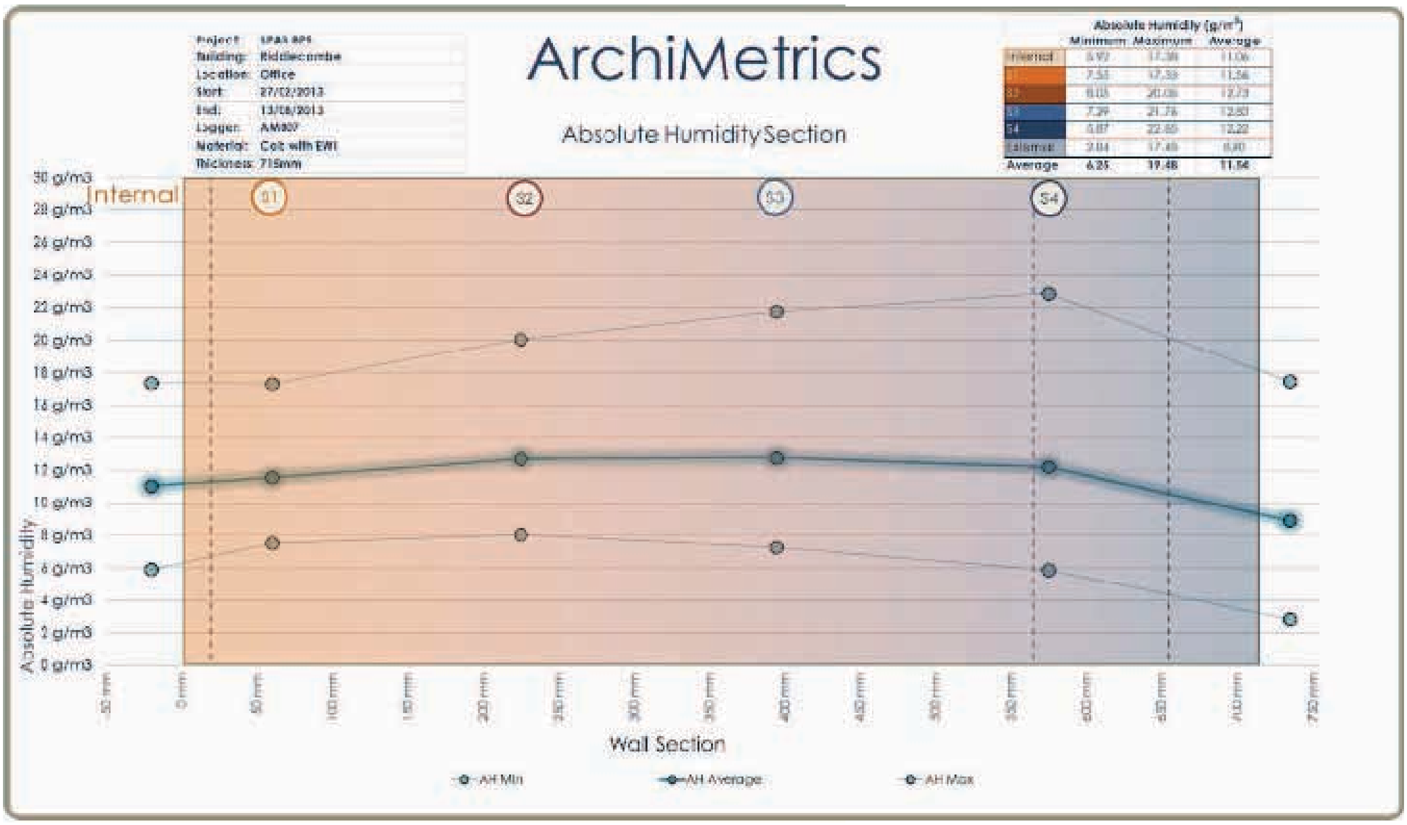


Figure 17: Absolute Humidity Section, The Firs, Riddlecombe February - August 2013.

Hygrothermal Section

Figures 87 & 21 allow an examination of the temperature and dewpoint gradients through the wall section at Riddlecombe recorded over the periods February - August 2012 and 2013. Ostensibly these look very similar for both years where the temperature and dewpoint margins narrow towards the external side of the wall and are coincidental between sensors 3 and 4. There is a slight difference for the plots of temperature gradient towards the internal side of the wall; in 2012 there is a dip in the temperature/gradient at sensor 1 between the internal surface and sensor 2, whereas in 2013 the temperature recorded at sensor 1 has increased and the gradient begins to decline through the wall from this point. Whilst the temperature at sensor 1 seems to have improved at this location the dewpoint margin (the hypothetical temperature drop required for dewpoint to occur) has, however, decreased from 5.02˚C in 2012 to 4.70˚C. This narrowing is unexpected as %RH should decrease with increased temperatures and was occasionally found to do so during the early part of the year, see Figure 9. Therefore, this is perhaps a reflection of the increased quantities of vapour found in general over the longer term at this point in the wall in 2013 as compared with 2012, something that is confirmed by records of absolute humidity for 2012 and 2013 at this location (Figures 86 & 17).

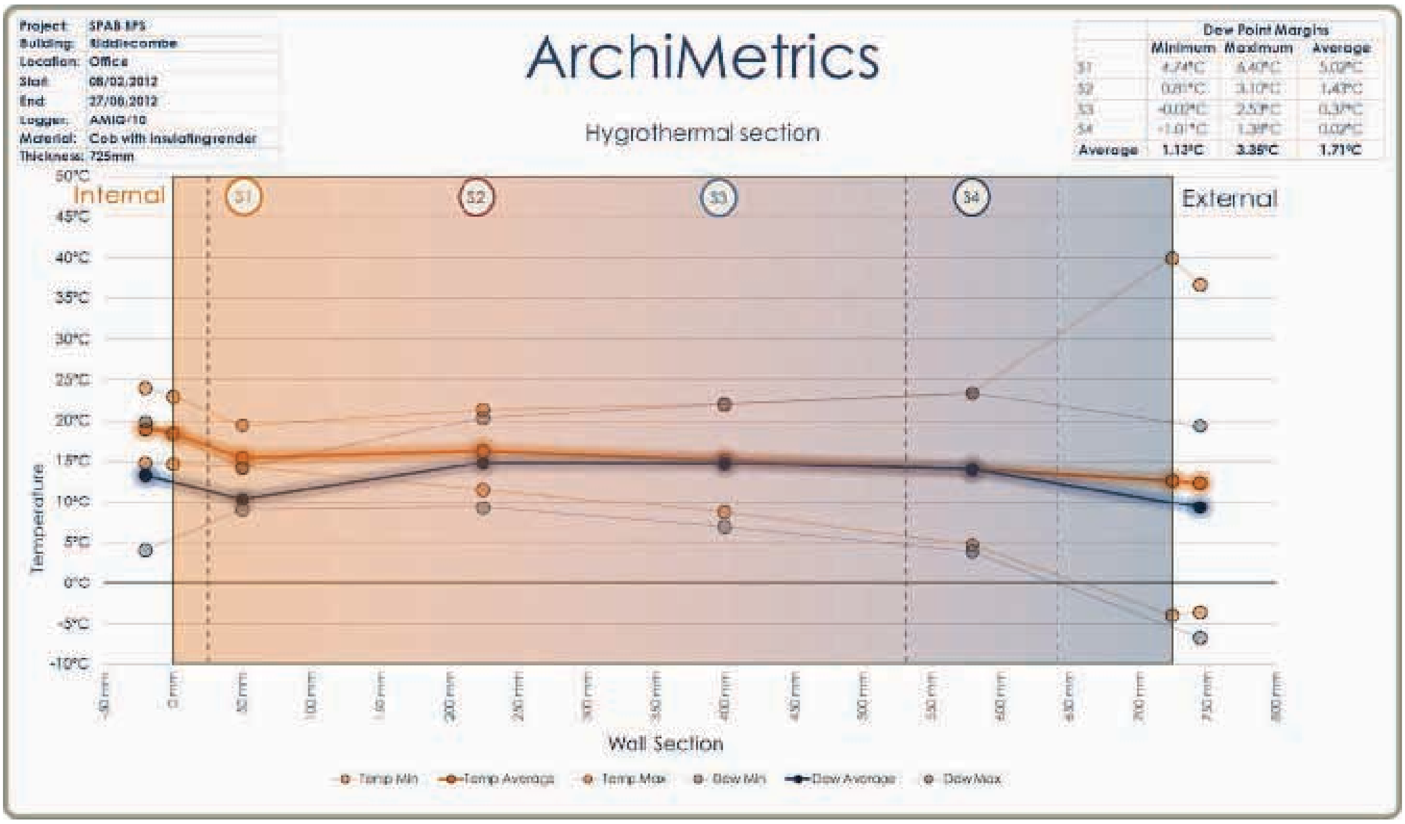


Figure 87: Hygrothermal Section, The Firs, Riddlecombe February - August 2012.

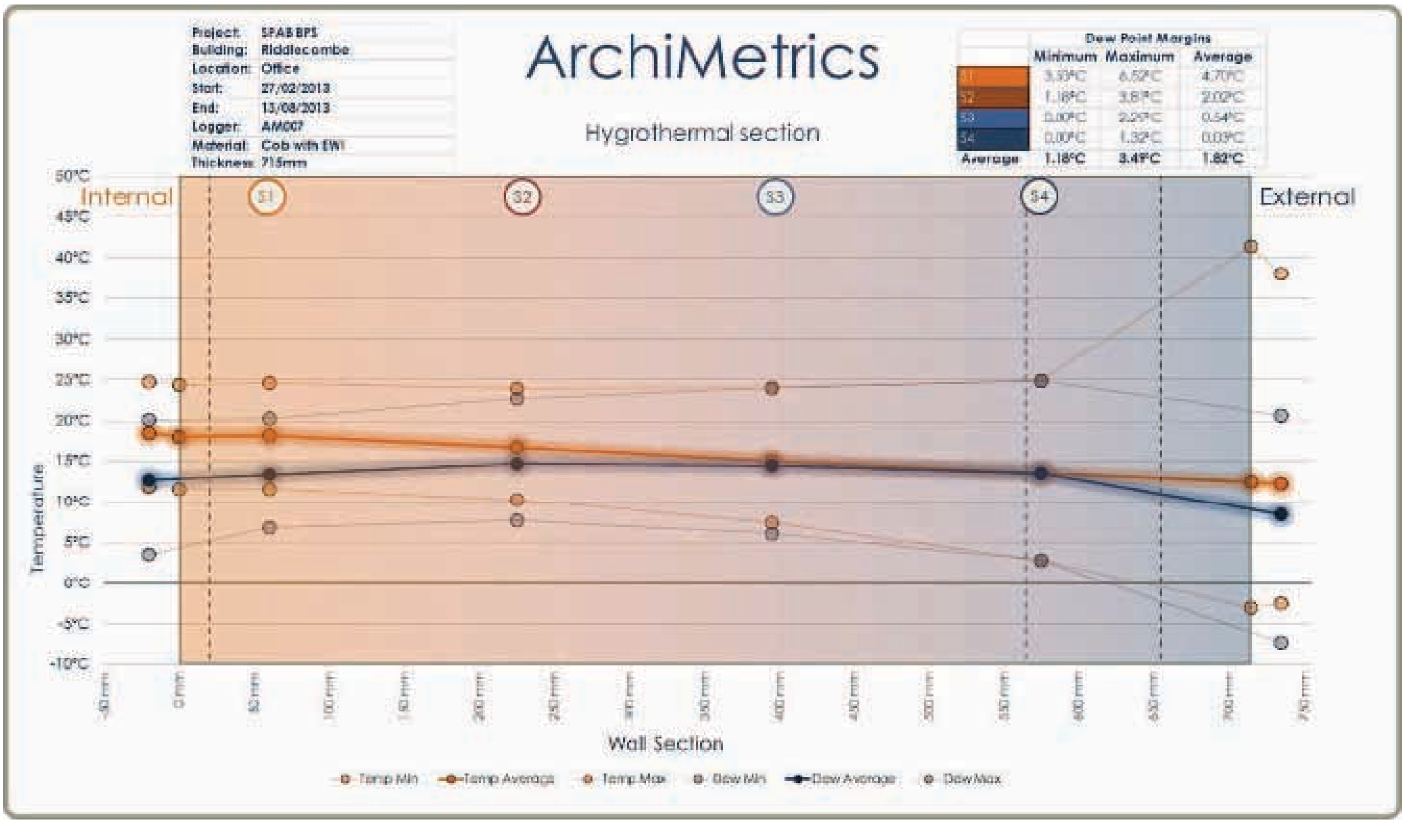


Figure 21: Hygrothermal Section, The Firs, Riddlecombe February - August 2013.

Dewpoint Margin Over Time

The dewpoint margins for the wall at Riddlecombe are also expressed for each sensor plotted over time, Figures 88 and 25. Once again, the graphs for 2012 and 2013 do not appear to be significantly different to one another and both show the same pattern of decreasing dewpoint margins over time. Over the two reporting periods first the margin at sensor 4 reaches a margin of 0˚C followed later by sensor 3. However, there are slight differences between the two years and whilst it would appear that saturation is occurring within some parts of the wall, as with the %RH findings (Figure 9) it takes a longer period of time for this to occur at sensor 3 in 2013. But perhaps most significantly, despite a slight increase in quantities of vapour in the wall in 2013 (Figure 17) the overall dewpoint margin for all four sensor positions has also increased very slightly from 1.71˚C in 2012 to 1.82˚C in 2013. This may reflect the slightly higher temperatures recorded at 3 of the 4 sensor positions for the 2013 period, which, despite high and increasing quantities of vapour, are able to lower the %RH sufficiently to cause this small increase in the overall dewpoint margin for 2013. Indeed records of %RH for the wall overall show a fractional improvement in overall %RH between 2012 and 2013, from 90.20% in 2012 to 89.59% in 2013. Furthermore, as with the 2013 plots of %RH over time (Figure 9) a slight recovery can be seen towards the end of the reporting period in the dewpoint margin at sensor 3. This may indicate the start of an improving situation for the wall where excess material moisture is slowly reducing via cycles of vaporisation and migration. Continued monitoring and monitoring over the colder winter months may be able to shed more light on the behaviour of moisture within the wall at Riddlecombe.

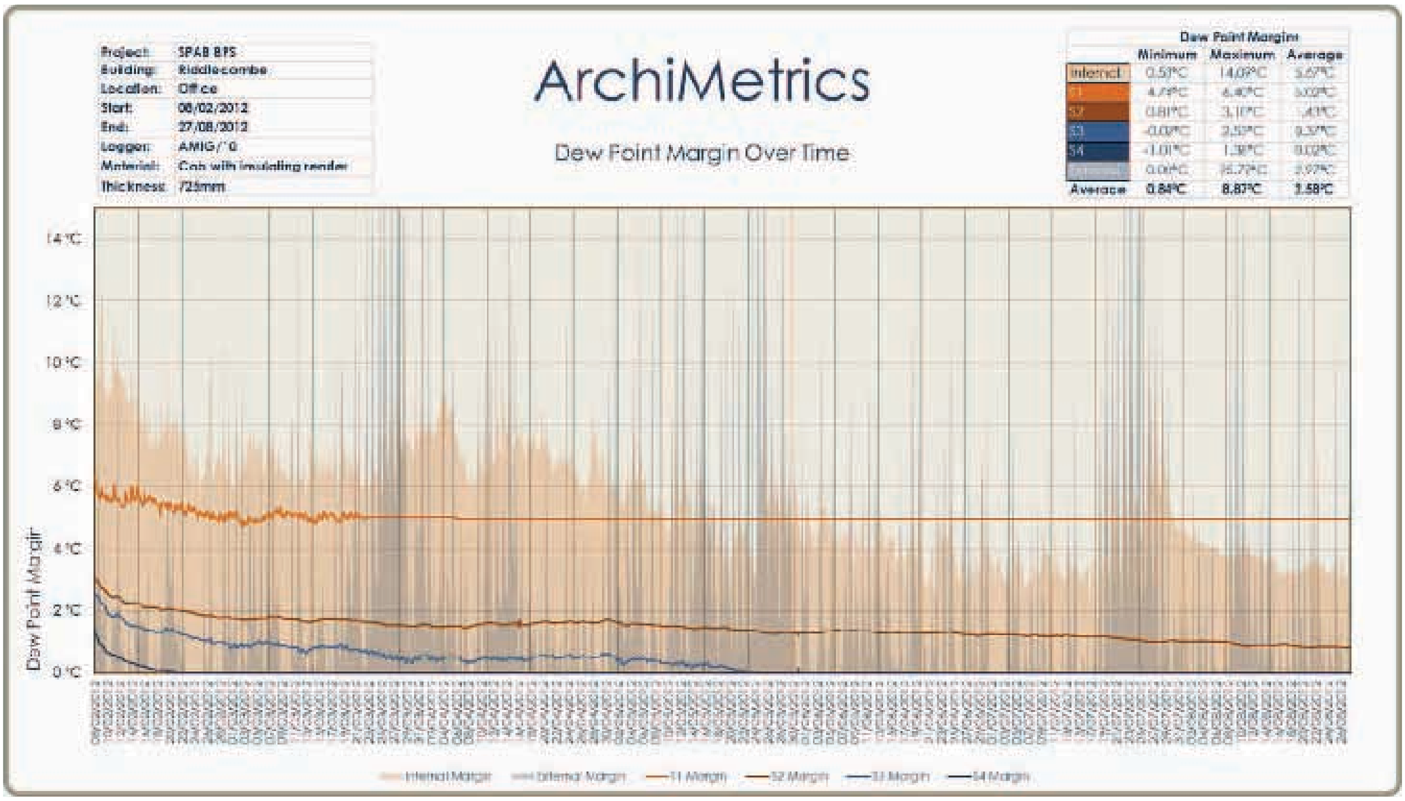


Figure 88: Dewpoint Margin over time, The Firs, Riddlecombe February - August 2012.

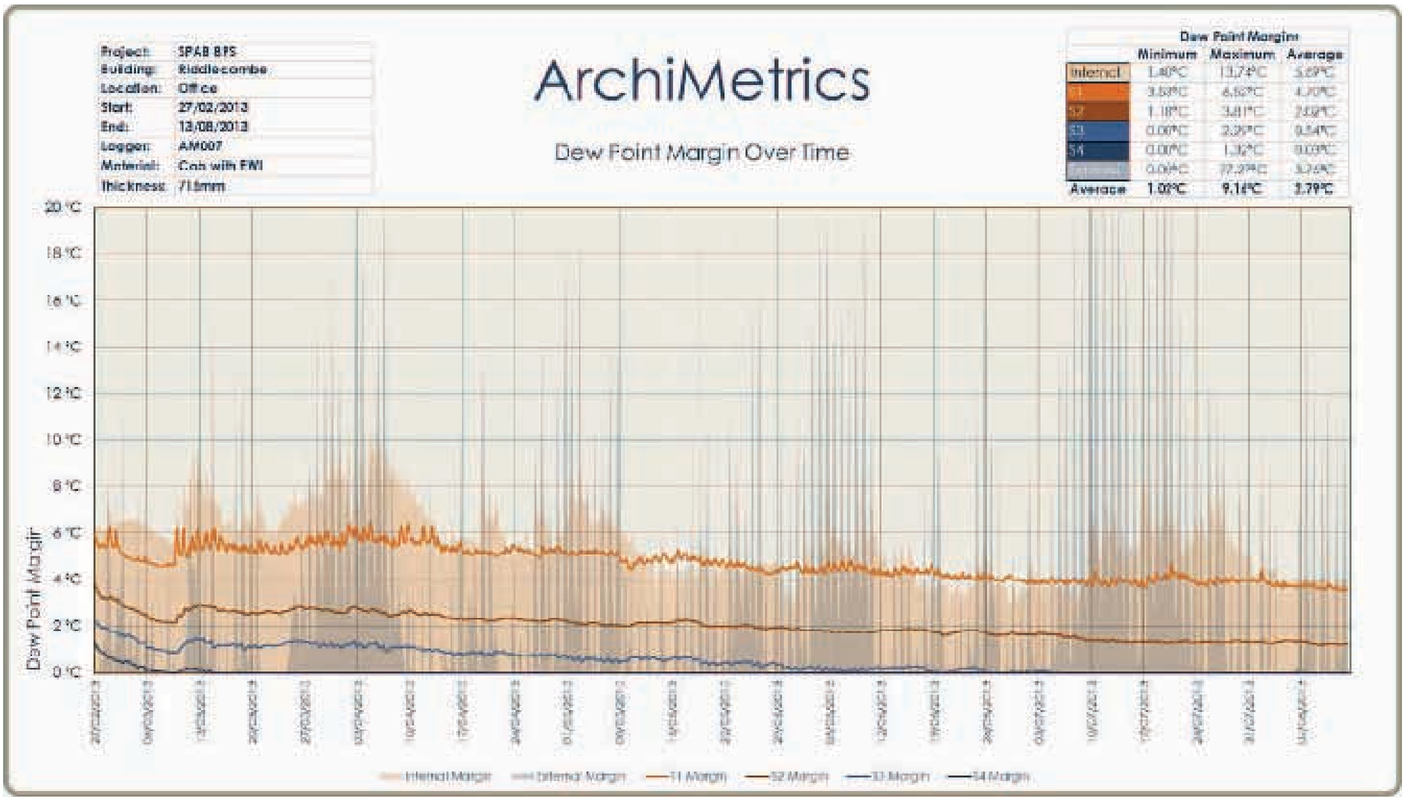


Figure 25: Dewpoint Margin over time, The Firs, Riddlecombe February - August 2013.

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