The SPAB Building Performance Survey Interim Report 2015

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Acknowledgements

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1.1 Introduction

The SPAB Building Performance Survey looks at various aspects of building performance in older, traditionally constructed properties before and after energy efficiency refurbishment. The survey began in 2011 and measured in seven houses: fabric heat loss, air leakage, indoor air quality, wall moisture behaviour, room comfort and fabric risk conditions. In subsequent years, measurements were repeated in four of the properties that had undergone refurbishment and the findings published yearly as SPAB research reports.

In 2014 the Building Performance Survey was extended in order to focus on the performance of moisture in insulated solid walls. Measurements of temperature and relative humidity (RH) through and either side of an insulated wall section have been made continuously in three properties since 2012 as Interstitial Hygrothermal Gradient Monitoring (IHGM). These provide an indication of moisture performance via the measurement of water vapour. The extended Building Performance Survey II expands on this monitoring to include measurements of moisture content (MC) within the wall materials at the same locations (material moisture monitoring). Thus the Survey now looks at moisture within walls in two ways; measuring moisture as a vapour and moisture in its liquid state. It is hoped that these dual measurements will increase our understanding of moisture behaviour within these refurbished walls.

The properties in question are constructed of brick (Shrewsbury), granite (Drewsteignton) and cob (Riddlecombe). The walls at Shrewsbury and Drewsteignton have been internally insulated with woodfibre and polyisocyanurate (PIR) board respectively. The cob house has an external insulating render.

This report begins with a description of the methods used to undertake the study, including details of the monitoring installations and terms used in the analysis of monitoring data. Findings from the individual houses are then presented followed by a discussion of these results and conclusions. Further information about previous years can be found in earlier reports. All SPAB research reports can be downloaded from the SPAB website at https://www.spab.org.uk/advice/energy-efficiency/.

1.2 Methodology

Interstitial Hygrothermal Gradient Monitoring (IHGM)

Four sensor nodes containing precision temperature and RH sensors are embedded at varying depths through a wall section. Four separate 32 mm holes are dry core drilled from the interior side with the aim of distributing the sensors evenly through the wall thickness; with sensor 4 closest to external conditions, sensor 1 towards the internal side of the wall and sensors 2 and 3 bisecting the remaining material. If an air layer or material interface is present in the wall build-up, a sensor will be located here. Great care is taken, by use of sleeves, to isolate the sensors and ensure that they are only able to measure conditions within their immediate proximity, ‘in front’ of the node. Additional sensors are placed on the external wall face in parallel with the embedded wall sensors to measure air temperature, surface temperature, RH, and incident solar radiation. Measurements are also made internally of wall surface temperature, room air temperature and RH. Data from these sensors (15 values) are logged at five-minute intervals by a dedicated ArchiMetrics’ monitoring logger mounted in close proximity to the sensor array.

Material Moisture Monitoring

A single 32mm hole is dry core drilled from the interior side of the wall. This hole is of varying overall depth depending on the thickness of the wall under study and extends to within 100 – 150mm of the external face. Depending on wall thickness, a number of 100mm long gypsum sensor nodes measuring electrical resistance and temperature are evenly spaced through the core. These measure conditions towards the interior and exterior sides of the wall with, depending on available space, a number of other measurements made between these points. Importantly the nodes are carefully coupled to the wall material using a fine lime mortar to eliminate air pockets and ensure integrity between the proxy measurement material and the wall itself. Data from these sensors (8 values) are logged at ten-minute intervals by a dedicated ArchiMetrics' monitoring logger mounted in close proximity to the sensor array.

See Figures 3 - 4, 16 - 17 and 26 - 27 for photographs and schematic drawings of the individual installations in the three properties under study.

1.3 Definitions and Analyses

Absolute Humidity (AH) and Relative Humidity (RH)

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

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

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

Relative and absolute humidity behaviour is presented over time for the three walls within the study. Each property is provided with a graphical analysis based on daily aggregated data (an average of the values measured over a 24-hour period - 288 values). The daily aggregation analysis allows for greater differentiation between sensor plots and thus a clearer overview of conditions. However, as part of the reporting process we also make use of full resolution analyses (a plot of each data point collected every 5 minutes). These provide a more detailed picture where specific characteristics of particular walls, such as porosity and air tightness, can be discerned. Examples can be seen in previous versions of this report.

Dewpoint and Saturation Margins

Dewpoint is the temperature at which air reaches vapour saturation. The difference between the measured temperature and dewpoint temperature we term the ‘saturation margin’ and represents the temperature drop required for condensation to begin at the measured locations within the wall, Figure 1. In previous reports we have used the term ‘dewpoint margin’ as a means by which to quantify the risk of interstitial condensation. The term ‘saturation margin’ shifts the emphasis of this concept to point to the condition of wall material as well as the possibility of condensation. A narrow saturation margin is an indication that the air within the wall material is close to saturation, 100% RH. We may measure high RH values due to wetting from wind-driven rain, vaporisation from wet materials as a result of built-in construction moisture, the failure of rainwater goods and/or vapour control layers or just the inability, over time, for a wall to evaporate its moisture load. The term ‘saturation margin’ moves us away from the dewpoint/condensation risk paradigm which sees only internal water vapour moved by diffusion and condensed by cold temperatures as the sole moisture risk to buildings. ‘Saturation’ in this context refers to the state of air, but it also hints at the condition of surrounding fabric which may well be wet as a result of influences other than those of internally-driven vapour diffusion and condensation. Nevertheless, due to cycles of condensation and evaporation, this wet material can contribute to the wetting and drying of building fabric. Some moisture may be expected within building fabric, particularly towards the outside of the building envelope in proximity to cold external conditions during winter months. It is generally considered that this is acceptable if any interstitial moisture can dry out without accumulating over longer periods of time.

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

Dewpoint temperatures are presented in the form of hygrothermal sections, plots of averages of measured temperature and dewpoint temperatures for each of the walls on an annual basis. Saturation margins are shown over time as plots for each individual sensor and as monthly averages.

Moisture Content

Moisture content can be expressed as the difference between the dry and wet weight of a material over its dry weight and is given as a percentage. Moisture content is determined by measuring the electrical resistivity between two metal pins. These pins are best embedded in a ‘known’ material, that is to say a material where the relationship between the resistivity measured from that material at particular moisture contents has been predetermined under controlled conditions. As measurements of electrical resistivity in different materials will vary widely wood is often used as this ‘known’ material and acts as a proxy, in this instance, for the materials found within a wall. Although resistivity will still vary between timber species and other variations, plentiful tables of resistance values in relation to moisture content are available for a variety of wood types. Therefore, if the species is known, it is possible to deduce a reasonable idea of moisture content of the timber and by extension materials that are in contact with it assuming that they are in moisture equilibrium with the timber measurement medium. However, it is also possible to use other proxy materials as the basis for resistivity measurements, materials that may have characteristics more akin to the masonry materials under investigation. ArchiMetrics have developed a mineral-based resistivity sensor where the electrical probes are embedded in a gypsum medium and moisture content profiles have been produced for this specific material. The ArchiMetrics gypsum node also includes an accurate temperature sensor which allows further refinement of the resistance measurement and consequently the moisture content. It is hoped that these sensors together with careful installation that allows for good coupling between the sensor and the wall material can provide an accurate picture of moisture content within the wall over time.

Data Holes

The SPAB Building Performance Survey aims, through the use of monitoring, to provide a detailed investigation of the performance of older existing buildings occupied and operating within real-world conditions. There is little precedence for such work and much of the monitoring and analytical practices employed are experimental and developed specifically for this research to improve our understanding of building performance. The second phase Building Performance Survey II has seen the development of new, more sophisticated, monitoring equipment. Some of these new units, despite successful bench tests, have experienced periods of data loss when deployed in the field. Repeated attempts have been made throughout the past year to address the problem, which was related to power outages and ultimately resided in an error on the timekeeping chip on the microcontroller. This fault has, as of October 2015, been corrected on all affected units. However, data collected from the different locations has at times been limited by this fault. Where data is missing from an analysis values are shown as unchanging or as a gap and where this impinges on the written discussion the absence is noted within the text.

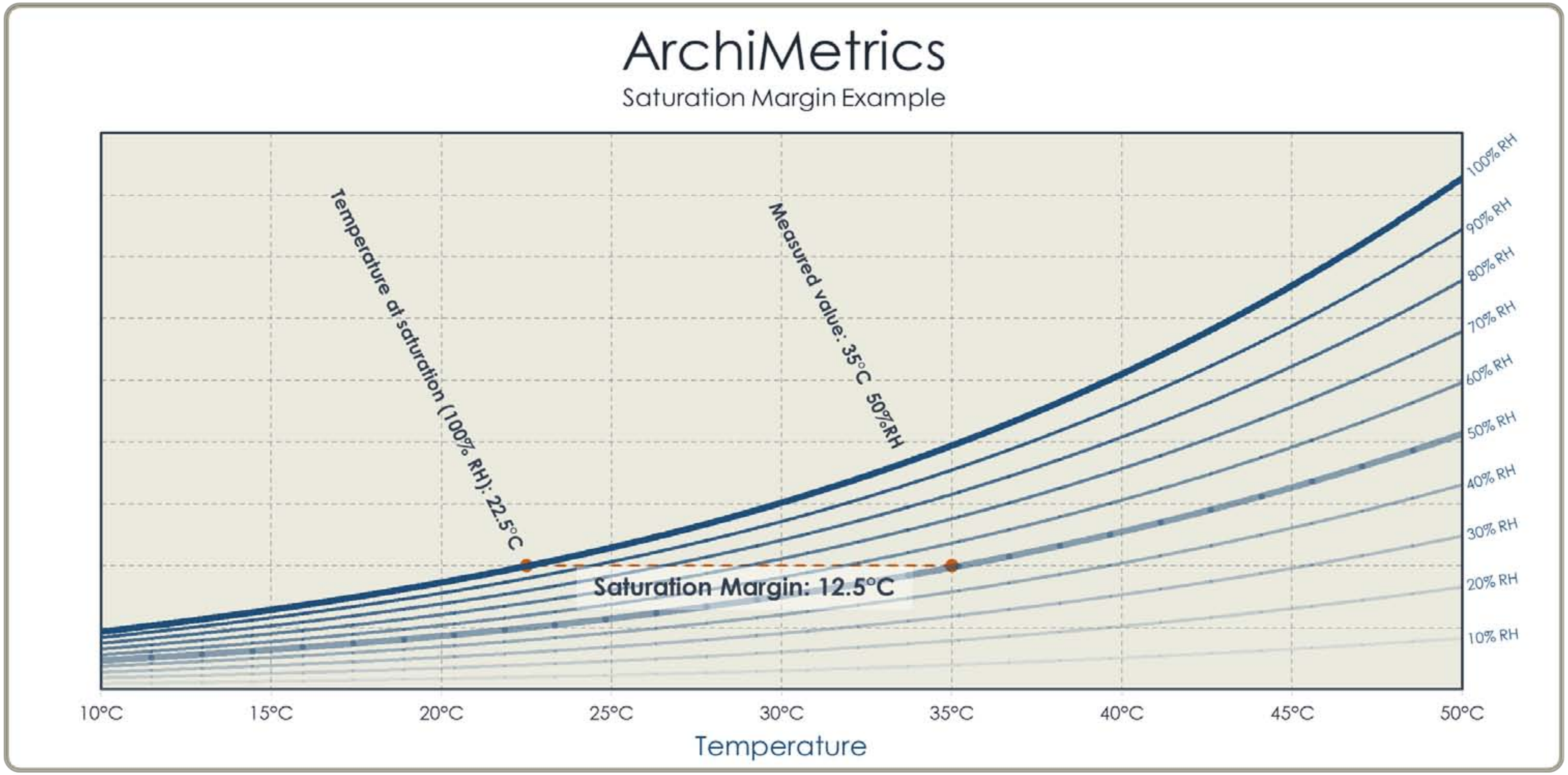


Figure 1. Illustration of Saturation Margin principle

2.1. 116 Abbeyforegate, Shrewsbury - 2014 - 15.

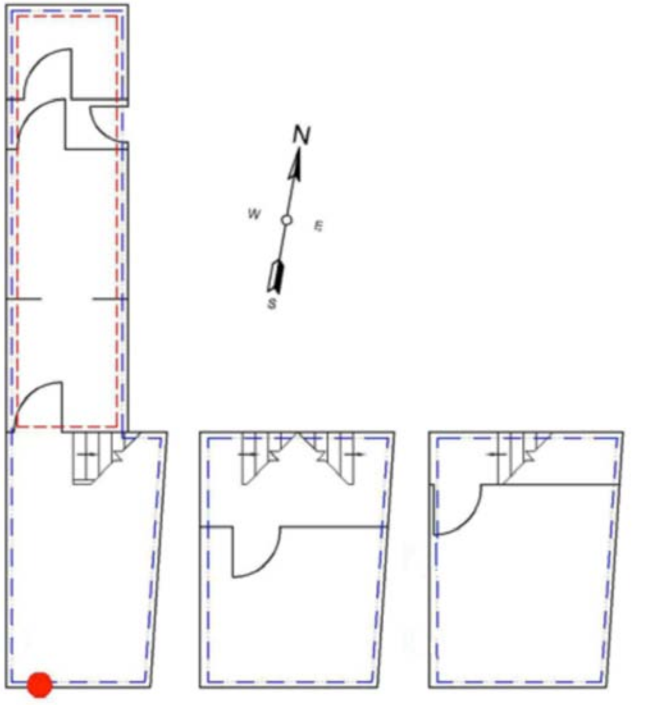


Figure 2. Plan of 116 Abbeyforegate, Shrewsbury, with ground floor on left hand side. The red dot indicates the location of the IHGM monitoring equipment.

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 floors with 40 mm woodfibre board finished with lime plaster (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: 60 m^2

Wall Condition Monitoring

Figure 3. Interstitial Hygrothermal Gradient and Material Moisture Monitoring, Shrewsbury.

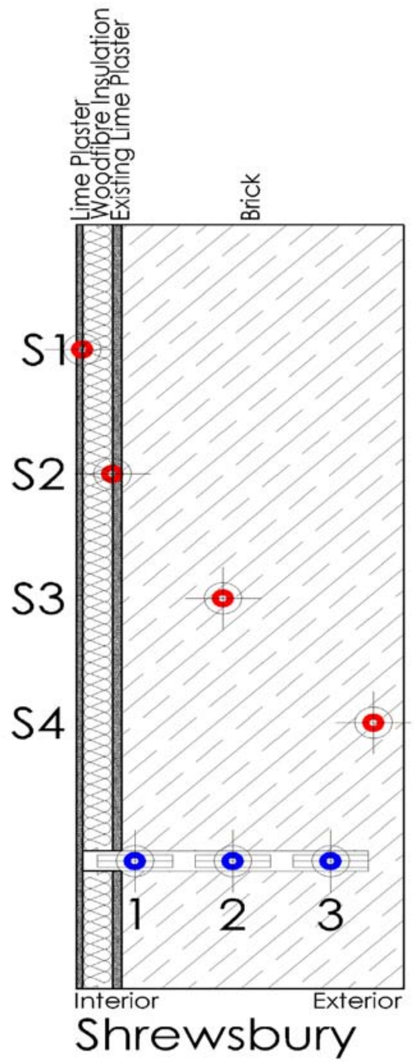


Figure 4. Position of wall sensors through section, Shrewsbury – red IHGM, blue Material Moisture

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 3 and 4). Combined temperature and relative humidity sensors are located at four points within the wall at the heights and depths given in Table 1. This table also gives details of the wall build up before and after insulation (in green).

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

Table 1. Interstitial Hygrothermal Gradient sensor positions for Abbeyforegate, Shrewsbury.

In addition to these measurements ambient conditions (temperature and %RH) are 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 1st September 2014 – 31st August 2015, has been used as the basis for the following analysis.

[1] In previous reports this depth was given as 385mm, this has now been revised.

Relative Humidity Over Time

Figure 5 shows the RH responses measured in and around the test wall at Shrewsbury over the past year. These show moisture vapour behaviour to be broadly consistent with those measured over previous years, post-refurbishment. The %RH responses are quite dynamic and we have ascribed this to the condition of the wall. The wall is quite thin and made of porous brick, it is south-facing so receives direct sunlight as well as the effects of the prevailing weather, with pointing in a poor state of repair. These elements combine to create a changeable picture with regards to heat and air exchange for the wall with a concomitant effect on temperature and moisture behaviour. Of continued note are the extremes of response at sensor 4 located in close proximity to external conditions, 50 mm back from the external wall surface. As with previous years there is a period of time over the winter months where %RH at this location is at, or exceeds, 100%. However, with the move into spring and warmer external temperatures, %RH at sensor 4 falls rapidly and is often the lowest recorded response over the summer months. This pattern, which repeats that of all previous years since measurements began in 2012, shows high %RH in the south-facing wall as a result of cold temperatures, rain and wind-driven rain over the winter months and lower %RH due to heat and direct sun in the spring and summer months.

Exceptions to this general pattern occur occasionally between April and September 2015 when the wall is subject to heavy rainfall causing %RH to peak at sensor 4 before drying out once again, most notably in the weeks beginning 1st June and 24th August. Rain, in combination with winds and decreasing temperatures are also most likely to be the cause of the start of the 100%+ RH peak measured over winter, see Figures 6 and 7. In October and November 2014 %RH fluctuates between 80 – 90%, the rise seen from 8th December onwards coincides with an increase in wind speeds from a south-westerly direction driving rain into the wall fabric which, coupled with falling temperatures, raises %RH measurements to dewpoint and beyond, a condition that persists towards the external side of the wall until spring 2015.

Elsewhere through the section, at sensors 1, 2 and 3 responses are less extreme as can be seen from the minimum and maximum values given in the table at the top of Figure 5. Annual average %RH values at these three locations are also under the threshold value (80%) for mould growth (Table 2). In the previous year, 2013-14, %RH at sensor 3, positioned approximately in the centre of the wall, rose to 100% in response to an exceptionally wet and windy weather. This year's account shows that the wall has recovered from this wetting and %RH levels within the centre of the wall have returned to those more usually found at this location and there is no repeat of this peak at sensor 3 over the 2014 – 15 winter. Overall the %RH picture for this wall is quite consistent with observations made in previous years and indicates a stable condition for the wall.

Annual Average RH	**Sensor 1**	**Sensor 2**	**Sensor 3**	**Sensor 4**
Shrewsbury				
2012 - 2013	66%	72%	75%	83%
2013 - 2014	66%	71%	77%	81%
2014 - 2015	64%	71%	77%	79%

Table 2. Comparison of annual averages of RH measured through wall section, Shrewsbury 2012 - 2015.

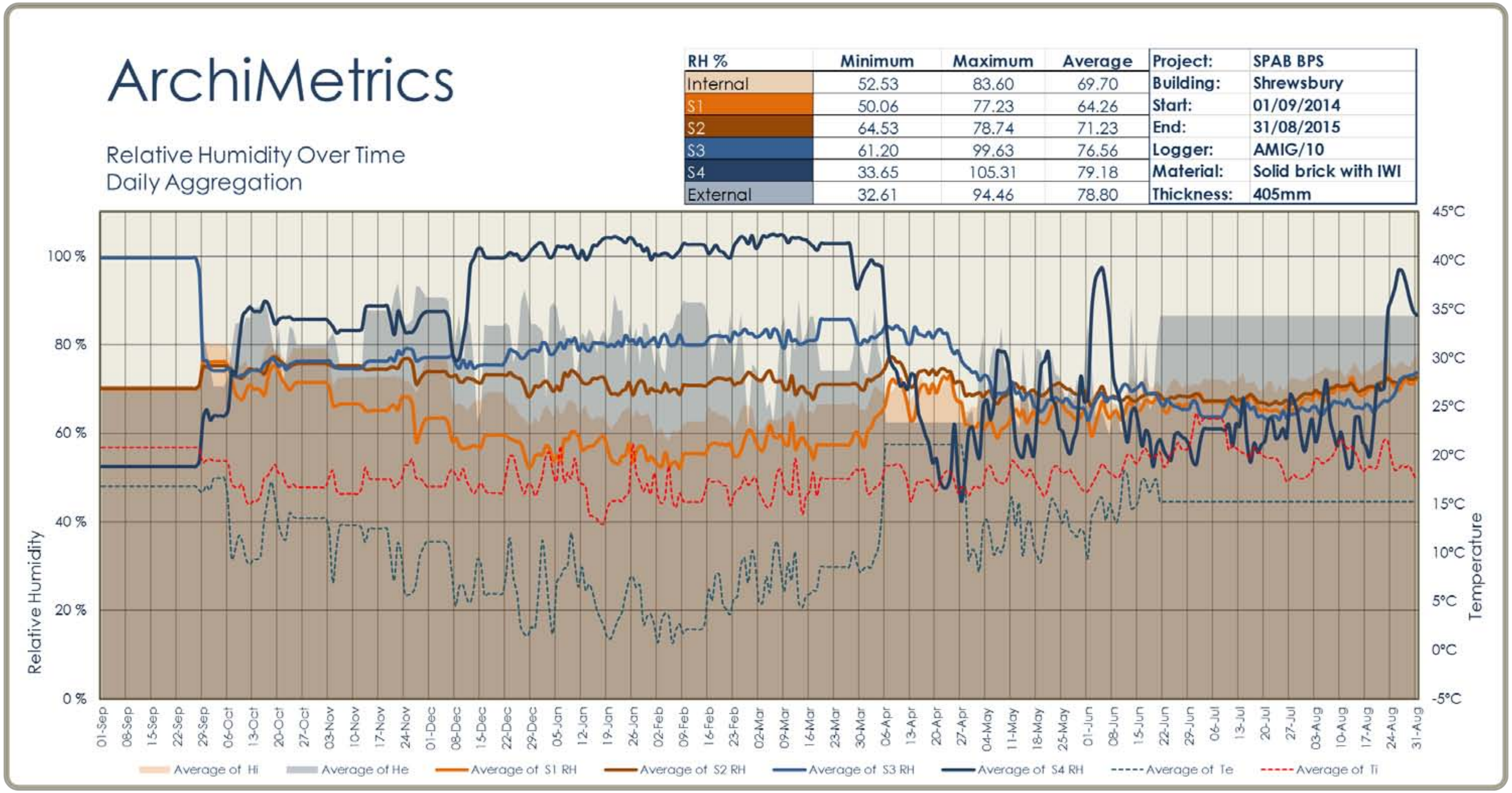


Figure 5: Relative Humidity over time, Abbeyforegate, Shrewsbury 2014 - 2015.

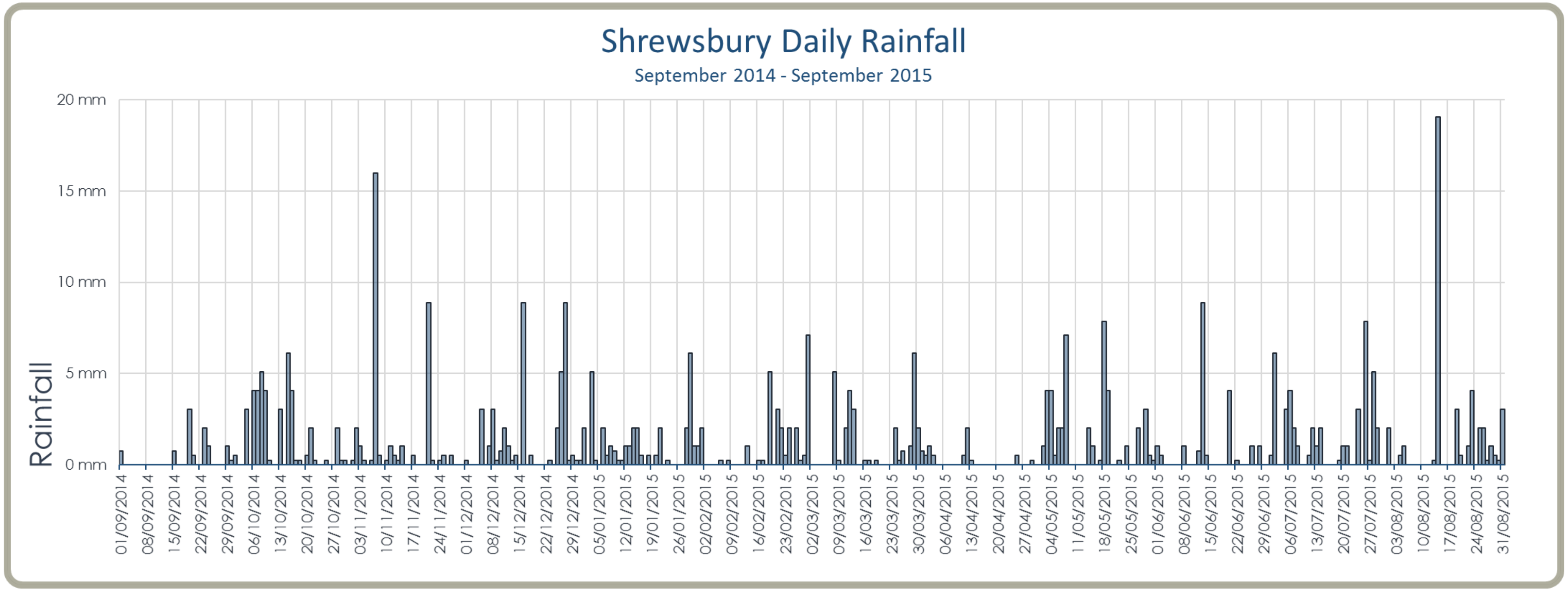


Figure 6: Daily Rainfall mm, Shrewsbury 2014 - 2015.

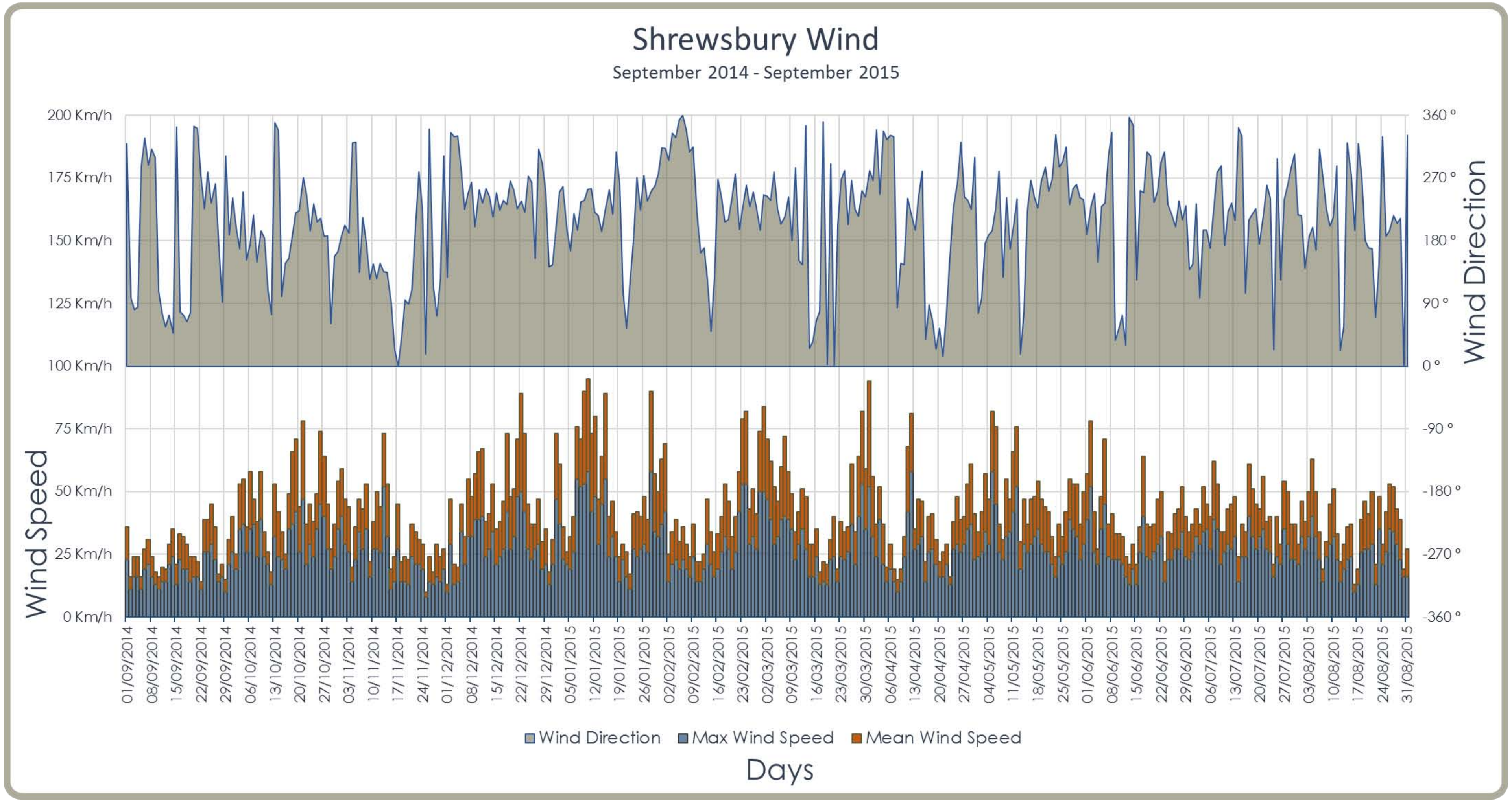


Figure 7: Annual Wind Speed (km/h) and Direction, Shrewsbury 2014 - 2015.

Shrewsbury Monthly RH Averages						
	Internal RH	**S1 RH**	**S2 RH**	**S3 RH**	**S4 RH**	**External RH**
2014						
Sep	70.26	70.48	70.52	97.97	53.39	70.53
Oct	77.86	72.04	75.01	74.99	81.24	80.53
Nov	73.15	66.04	74.83	76.32	85.36	84.18
Dec	68.43	58.58	72.39	76.70	94.45	83.65
2015						
Jan	64.52	56.44	71.11	80.11	102.11	82.24
Feb	62.74	55.83	71.13	81.31	101.74	81.98
Mar	64.87	58.04	70.95	82.77	102.32	76.57
Apr	69.28	67.66	73.09	81.18	68.02	65.38
May	68.65	63.47	69.37	68.39	65.04	72.05
Jun	69.74	65.47	68.20	67.84	66.72	74.96
Jul	71.45	66.55	67.52	64.63	60.34	86.57
Aug	74.84	70.10	70.70	67.53	70.21	86.57
Average	**69.70**	**64.26**	**71.23**	**76.56**	**79.18**	**78.80**

Table 3. Relative Humidity monthly averages, Abbeyforegate, Shrewsbury, 2014 -15.

Absolute Humidity Over Time

Figure 8 shows an analysis of absolute humidity through the insulated wall section at Shrewsbury between 1st September 2014 – 31st August 2015. This shows the same seasonal variation as observed in previous years; the weight of vapour within the wall increases with that of atmospheric humidity over the summer months. There is a similarity between this AH analysis and that of %RH where responses found at sensor 4 can be more extreme and are detached from those of the other sensors. Once again, this is due to the location of this sensor and the qualities of the wall fabric which mean it is measuring conditions closely influenced by changeable atmospheric conditions. Some peaks in the weights of vapour measured at sensor 4 can be seen, like those of %RH, to coincide with periods of wet and windy weather, in December 2014, June and August 2015. There is an interesting exception to this seen at the end of June 2015 where a peak in AH is not accompanied by a similar rise in RH. This takes place over a period of alternately hot and rainy days, where, on 30th June temperatures reach a peak for the year, 38˚C. (Unfortunately, external temperature data is missing for this part of the year from the analysis in Figure 8 but the influence of high external temperatures, which also reach an annual peak, can be seen in records of internal air temperature influenced by solar gain through glazing.) Rain on the days surrounding this temperature peak on 30th June accounts for the raised vapour within the wall structure at this location. However, the generally warm air temperatures and heating of the south-facing external fabric by the sun means that %RH remains low over this same period.

The drying that takes place within the brick section of the wall starting around the beginning of April is also visible in Figure 8. In the previous section this was seen as a rapid drop in %RH at sensor 4 due to the sharp increase in external temperatures beginning on 1st March. The effect on measurements of AH is exactly the opposite as weights of vapour within the wall at sensor 4 increase due to the heat encouraging evaporation from wet fabric, Figure 9. After this initial drying, from 6th April onwards, weights of AH decrease as material at this location loses its residual moisture (also reflected in the decrease of %RH over this time). At this time a similar if less pronounced trend, of AH increase followed by decrease, is seen further into the wall at sensor 3, albeit delayed by about half a day. At sensor 3 there is also a second bout of drying a week or so later, around 20th April, which is not preceded by similar activity at sensor 4. All four sensors within the wall stop their trend of decreasing AH on 12th April and begin to measure increasing weights of vapour again in response to an isolated rain event (apart from the start and end of the month this is the only rainfall seen in April). Following this rain, AH at sensor 4 falls rapidly once more to reach its lowest annual weigh, 3.34 g/m^3. But this response is not followed at sensor 3 as was seen previously but instead there is a further increase in AH prior to a drop in the weight of vapour at this location. This suggests that prior to 12th April the wall had not evaporated all the residual moisture accumulated in the fabric deeper within the wall at sensor 3 and the increase in weights following the rain event, above and beyond those measured at sensor 4, is due to the evaporation of this additional water facilitated by warmer temperatures.

The processes of solar-driven evaporation can also be observed in detail during the first week of June, Figure 10. There is little rainfall recorded for Shrewsbury this week and it is a week that shows a significant spike in the aggregated AH data at sensor 4, Figure 8. This spike can also be seen in the solar analysis of AH at sensors 3 and 4, Figure 10. The spike at sensor 4 coincides with a day of intense solar radiation measured from the south-facing wall. Interestingly the AH peak lags behind that of the solar radiation. This offset shows the time taken for the heat to pass through from the surface to warm the brick further back and cause the vaporisation measured at sensor 4. A similar offset and more muted response is then seen further back at sensor 3 where the effects of the heat are diminished. An examination of the peaks and the troughs of the sensor 3 and 4 gradients provides us with a sense of the AH trend over this week. In the first four days peaks and troughs rise up the scale in response to the increasing intensity of solar radiation on the wall. This ‘stair-stepping’ was first observed in the wall in Riddlecombe in 2013 and suggests over this time rates of vapour diffusion are unable to keep pace with that of the vaporisation of moisture from the wall material. In Figure 10, following on from the climatic radiation event 4th June we see these peaks and troughs begin to descend the scale. This suggests that surrounding fabric has lost much of its residual moisture and that the vaporisation response is subsequently diminished to the extent that diffusion is now able to move sufficient quantities of vapour to cause measurements of AH to begin to decrease as part of the drying process.

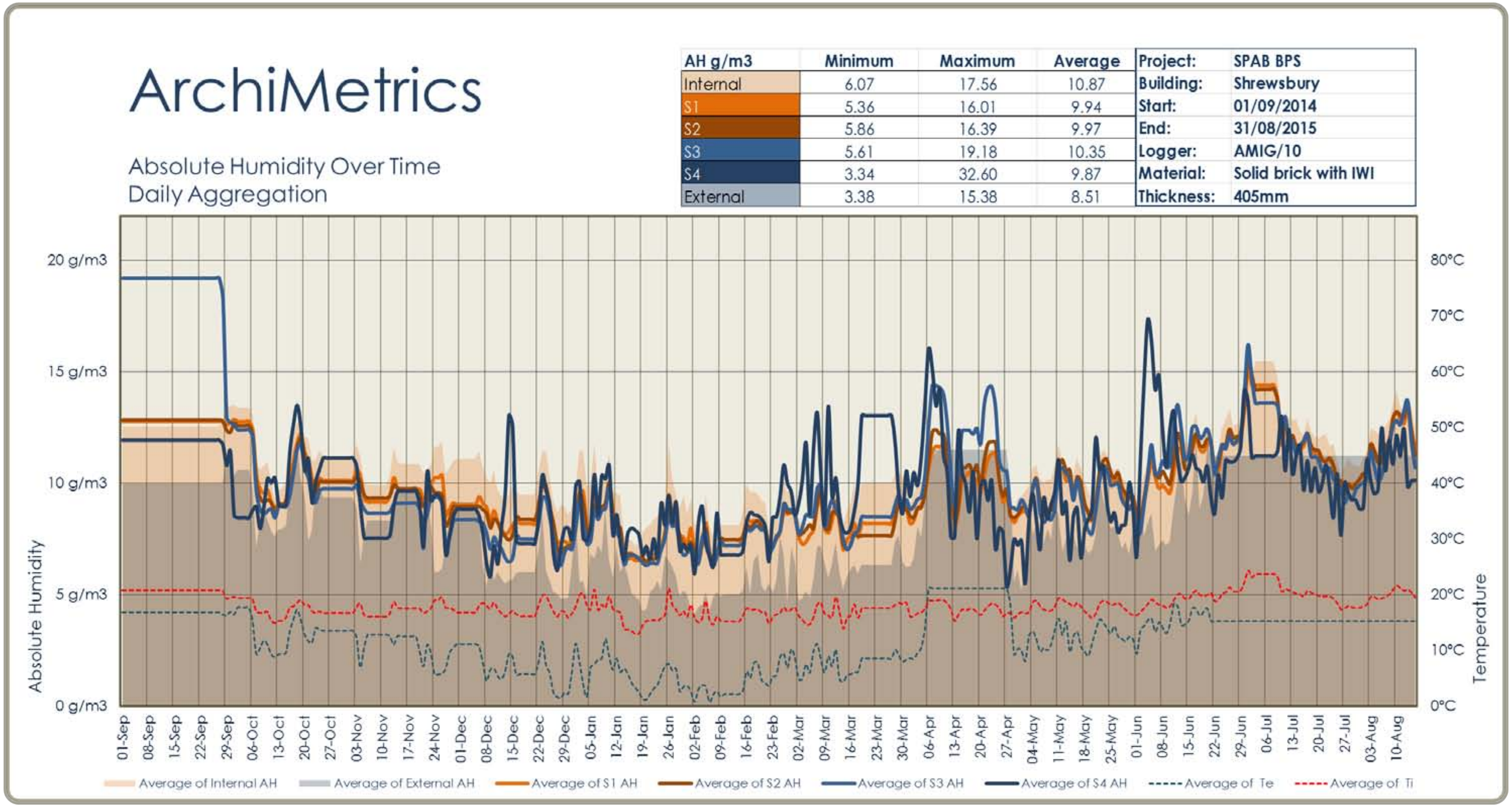


Figure 8: Absolute Humidity over time, Abbeyforegate, Shrewsbury 2014 - 2015.

Shrewsbury Monthly AH Averages (g/m3)						
	Internal Air	S1	S2	S3	S4	External Air
2014						
Sep	12.63	12.77	12.81	18.73	11.87	10.06
Oct	11.56	10.64	10.45	10.14	10.12	9.32
Nov	10.78	9.60	9.47	8.87	8.83	8.38
Dec	10.01	8.44	8.34	7.62	8.20	6.51
2015						
Jan	9.32	7.90	7.80	7.53	8.21	5.94
Feb	8.77	7.62	7.62	7.48	7.88	5.35
Mar	9.47	8.18	8.07	8.49	10.75	6.21
Apr	10.24	9.92	10.26	11.55	9.93	10.41
May	10.40	9.52	9.71	9.35	8.70	7.67
Jun	11.67	10.88	11.16	11.35	11.56	9.65
Jul	12.90	12.01	12.09	11.77	10.56	11.25
Aug	12.57	11.73	11.70	11.35	11.72	11.25
Average	**10.87**	**9.94**	**9.97**	**10.35**	**9.87**	**8.51**

Table 3. Absolute Humidity monthly averages, Abbeyforegate, Shrewsbury, 2014 -15.

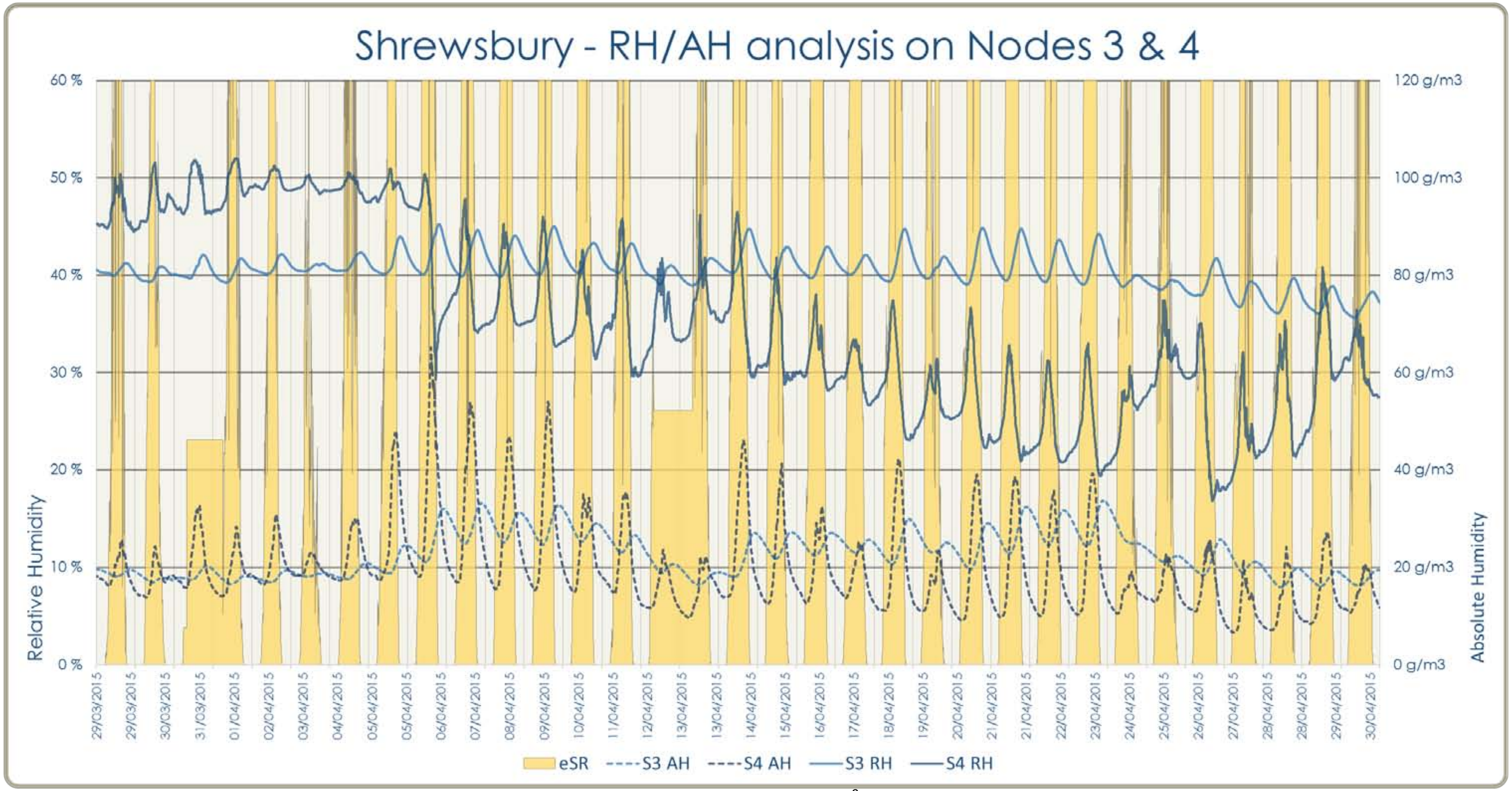


Figure 9: AH and RH Solar Analysis sensors 3 & 4 over time, Abbeyforegate, Shrewsbury 2014 - 2015.[2]

[2] In this and other Solar Analysis figures eSR refers to external surface radiation – the two thicker lines 31/03 - -01/04 and 12/04 – 13/04 are occasions where data has been lost and so the last recorded value persists until new data is received hence it appears that the sun is shining throughout the night!

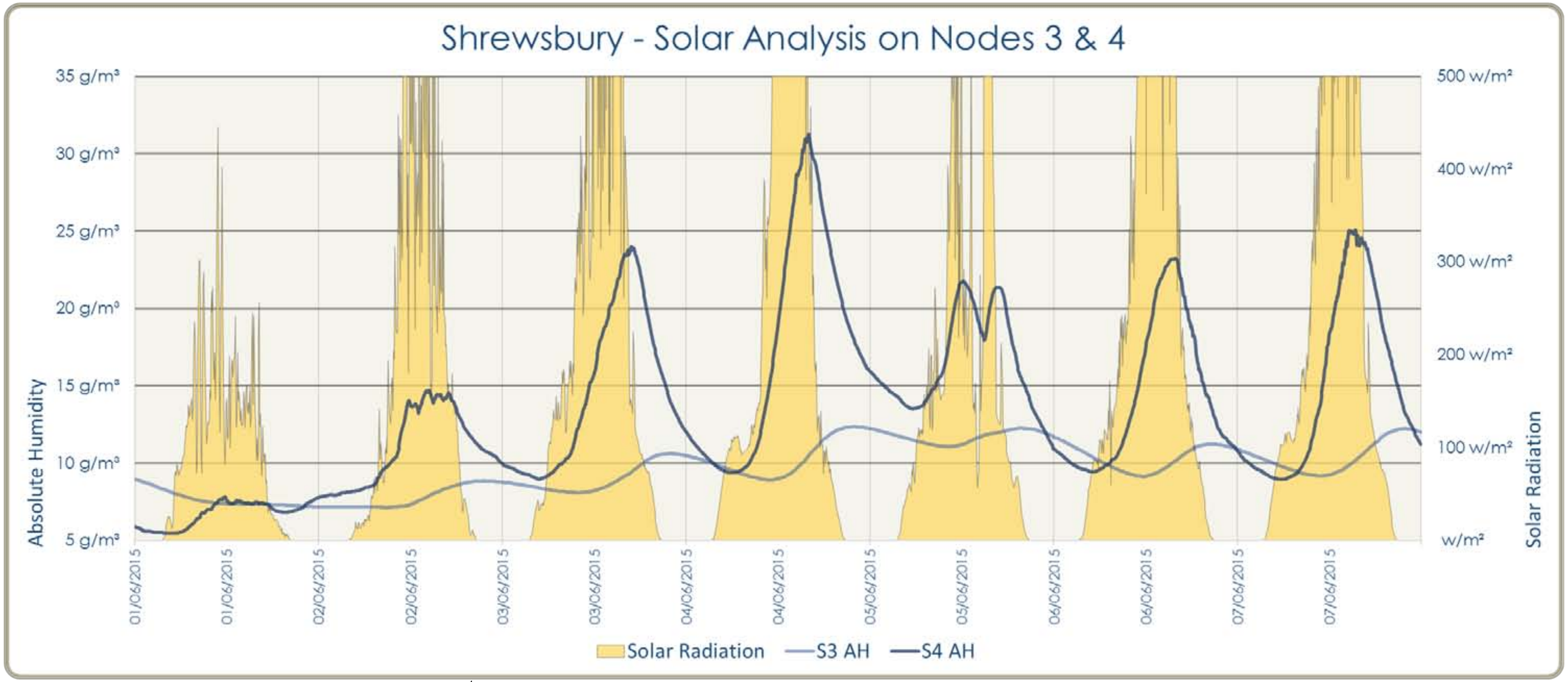


Figure 10: Solar Analysis on nodes 3 and 4 wk. bg. 1st June 2015, Abbeyforegate, Shrewsbury 2014 - 2015.

Saturation Margins and Hygrothermal Sections

Figure 11 presents plots of the saturation margins for the four sensors through the wall section over time. In a similar way to observations concerning %RH this analysis shows the period of time for which the air in proximity to sensor 4 was saturated. Indeed, just as %RH was recorded as beyond dewpoint, 100%, a negative saturation margin for much of this time suggests that the fabric at this location was likely to be wet. Figure 11 interestingly also shows how close the air in the wall at this location comes to saturation during the summer months, albeit briefly, on 6th June and 26th August. These isolated peaks are the result of vaporisation taking place within a damp substrate driven by strong solar radiation (see Figure 10 and AH commentary). The speed of the increase and decrease in %RH measured at sensor 4 is of note in relation to the more sustained peak measured here over the winter months. The difference is due to the effect of wetter conditions and the lower quantities of solar radiation contacting the wall over the winter period meaning that the air around sensor 4 remains saturated. In contrast, the summer peaks occur once the wall has lost its legacy of winter moisture, a drying process that starts 6th April. In June and August the vaporisation shown in both the RH and AH analysis begins from a lower moisture threshold and the wall is able to recover more quickly. Overall the analysis shows the safe operation of the wall as the long winter period of negative saturation margins recovers quickly after which the lowest margins are never much below 3˚C for the remaining part of the year with the exception of the two brief instances previously mentioned.

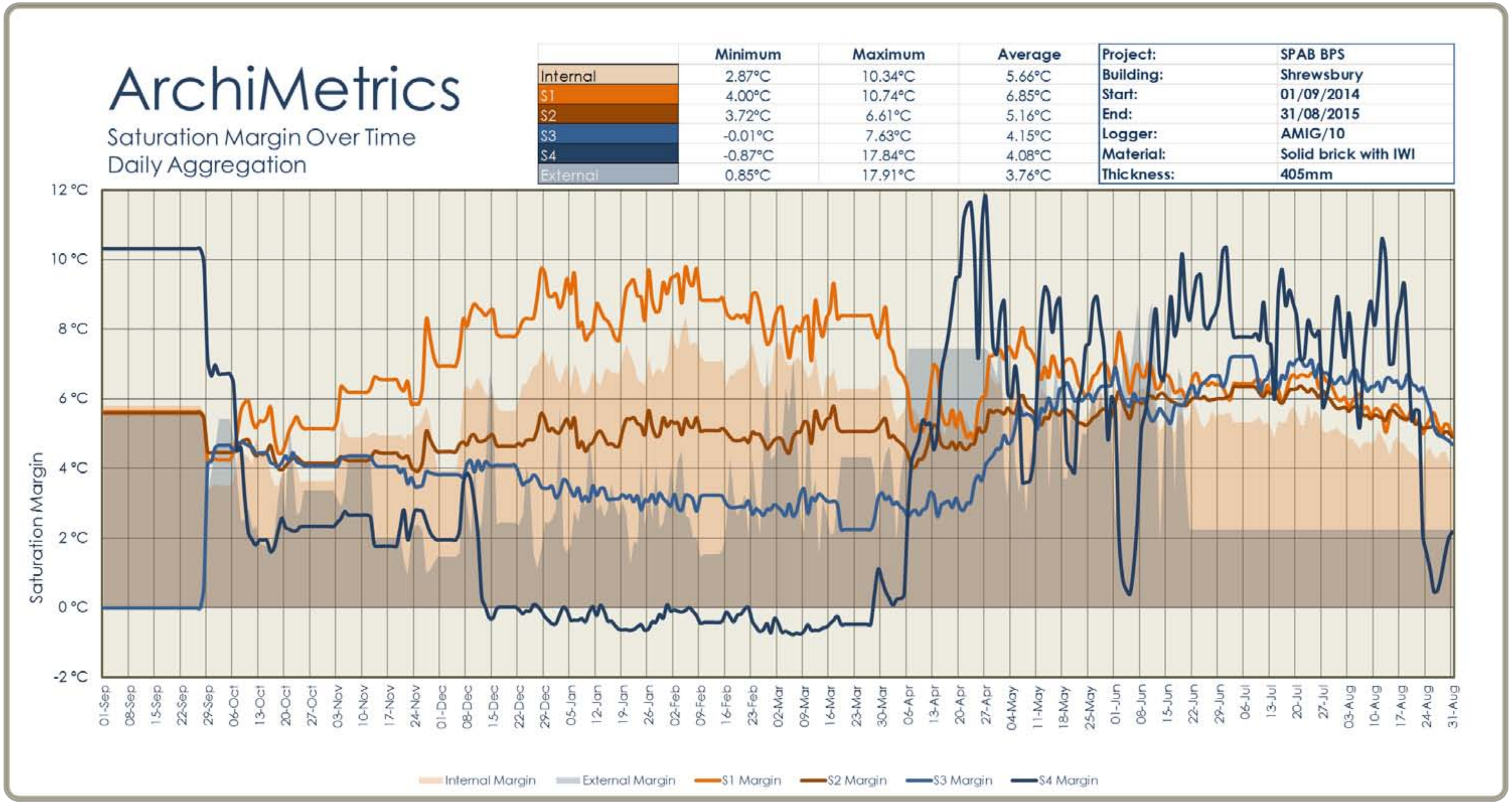
In Table 5, saturation margins are given as an average across all four measurement points within the section and also individually, showing the change in these average margins before and after the wall was insulated and over the following years. These figures have been calculated from measurements of %RH capped at 100% for the purposes of comparison with previous years. From Table 5 it can be seen that for the first two years, post-refurbishment, the saturation margins across all sensors had narrowed somewhat. This year, 2014-15, the margins at sensor 1 and sensor 4, towards the interior and exterior of the wall, have increased probably as a reflection of a drier 12 month period than the two previous years. This is also indicated by the annual average of all the sensor margins which has increased from previous averages to 5.11 ˚C, and is closer to the pre-insulation average, 5.49 ˚C.

Year	S1	S2	S3	S4	Ave
Pre-insulation					
2011 (28/1/11 - 28/2/11)	6.46˚C	6.41˚C	5.12˚C	3.96˚C	5.49˚C
Post-insulation					
2012 - 13 (9/5/12 - 11/4/13)	6.34˚C	5.08˚C	4.3˚C	3.08˚C	4.7˚C
Difference	**0.12˚C**	**1.33˚C**	**0.82˚C**	**0.88˚C**	**0.79˚C**
2013 - 2014 (1/5/13 - 30/4/14)	6.33˚C	5.00˚C	4.08˚C	3.45˚C	4.72˚C
Difference	**0.13˚C**	**1.41˚C**	**1.04˚C**	**0.51˚C**	**0.77˚C**

Table 5. Saturation Margins & Pre & Post-insulation Difference, Abbeyforegate, Shrewsbury 2011 - 2015.

The range of saturation margins across all sensors for the three years, post-insulation, is quite consistent and shows neither an increasing or decreasing trend. The difference between pre- and post-insulated margins, one indication of the degree of change that has taken place, is also smaller and where margins have increased since re-furbishment is shown as a negative number. In general, the margins found at Shrewsbury, in comparison with the other insulated walls in this study, suggest a lesser risk to the wall from moisture.

Measurements of temperature and RH are also used to plot annual averages of measured temperature and dewpoint temperature gradients through the wall section (Figures 12,13 and 14). These analyses show the similarity between the past three years and indeed the slight increase in temperature separation between the two margins found in 2013 – 14 and this year. Through the four measurement points, on average, we find no convergence of the two gradients, which in other walls coalesce towards the external wall face. Once again this suggests that over an annual cycle the wall is performing within safe margins with regard to risks from moisture



	Minimum	Maximum	Average
Internal	2.87°C	10.34°C	5.66°C
S1	4.00°C	10.74°C	6.85°C
S2	3.72°C	6.61°C	5.16°C
S3	-0.01°C	7.63°C	4.15°C
S4	-0.87°C	17.84°C	4.08°C
External	0.85°C	17.91°C	3.76°C

Project:	**SPAB BPS**
Building:	**Shrewsbury**
Start:	**01/09/2014**
End:	**31/08/2015**
Logger:	**AMIG/10**
Material:	**Solid brick with IWI**
Thickness:	**405mm**

Figure 11. Saturation Margin over time, Abbeyforegate, Shrewsbury 2014 - 2015.

Shrewsbury Monthly Saturation Margin Averages						
	Internal	**S1**	**S2**	**S3**	**S4**	**External**
2014						
Sep	5.63	5.53	5.50	0.29	10.07	5.41
Oct	3.91	5.05	4.34	4.37	3.22	3.37
Nov	4.87	6.37	4.32	4.03	2.32	2.63
Dec	5.91	8.15	4.79	3.87	0.84	2.67
2015						
Jan	6.74	8.65	5.04	3.22	-0.36	2.88
Feb	7.14	8.79	5.02	2.99	-0.31	2.94
Mar	6.68	8.24	5.10	2.78	-0.40	4.01
Apr	5.69	6.00	4.78	3.19	6.38	6.77
May	5.85	6.97	5.57	5.78	6.65	5.22
Jun	5.68	6.59	5.94	6.04	6.66	4.83
Jul	5.35	6.41	6.16	6.85	7.95	2.23
Aug	4.59	5.55	5.40	6.13	5.84	2.23
Average	**5.66**	**6.85**	**5.16**	**4.15**	**4.08**	**3.76**

Table 6. Saturation Margin monthly averages, Abbeyforegate, Shrewsbury, 2014 - 2015.

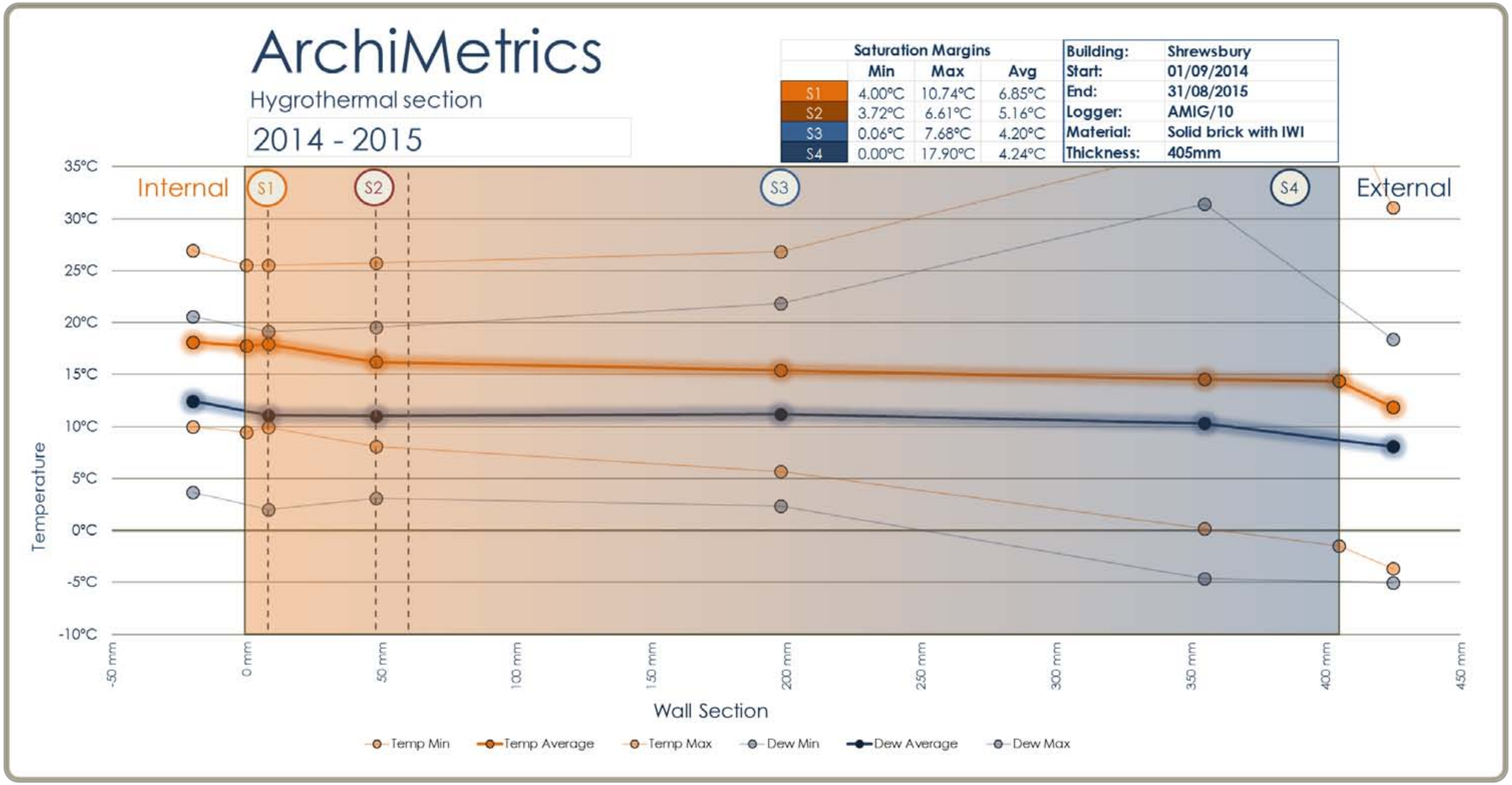


Figure 12. Hygrothermal Section, Abbeyforegate, Shrewsbury 2014 – 2015 (capped).

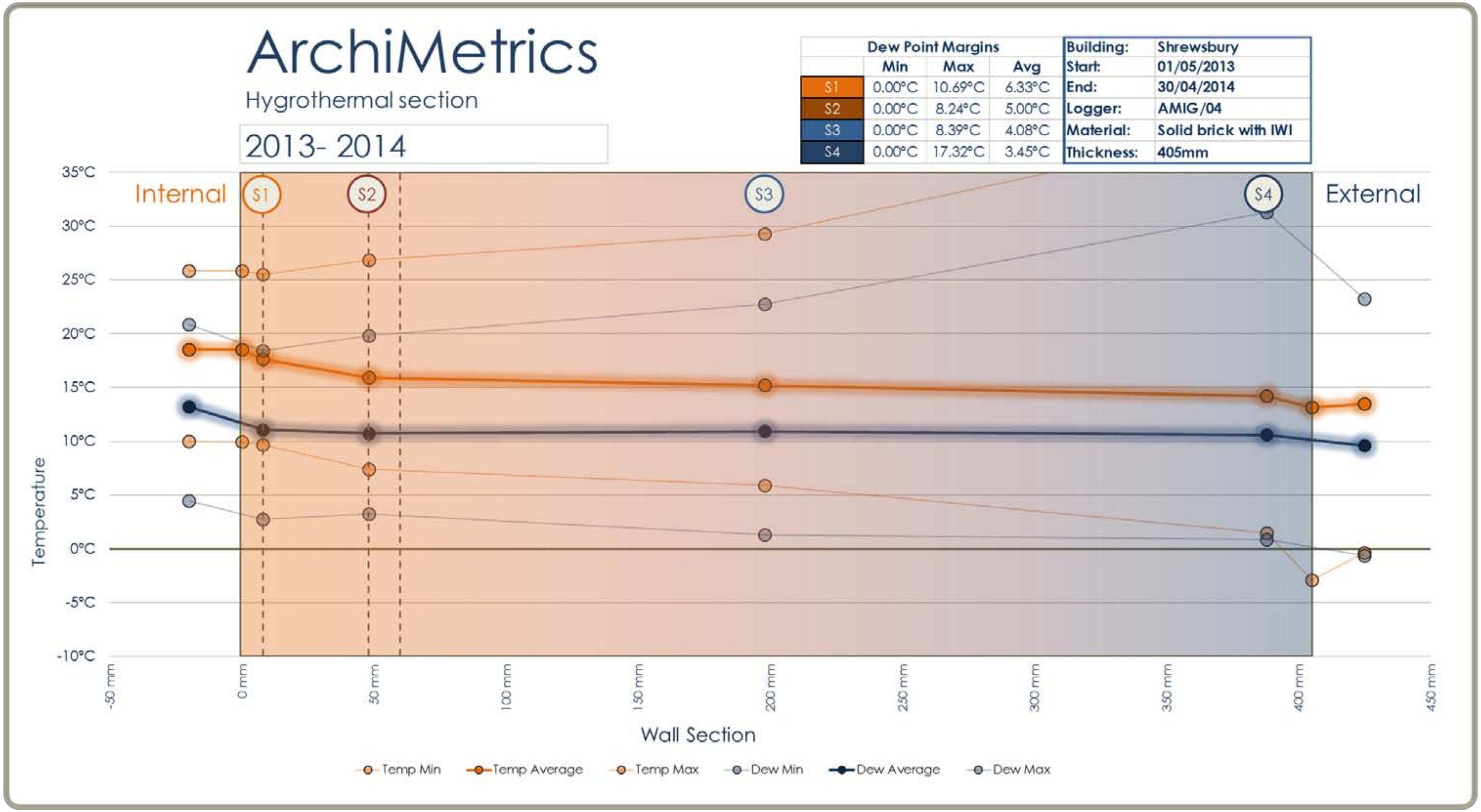


Figure 13. Hygrothermal Section, Abbeyforegate, Shrewsbury, 2013 - 2014.

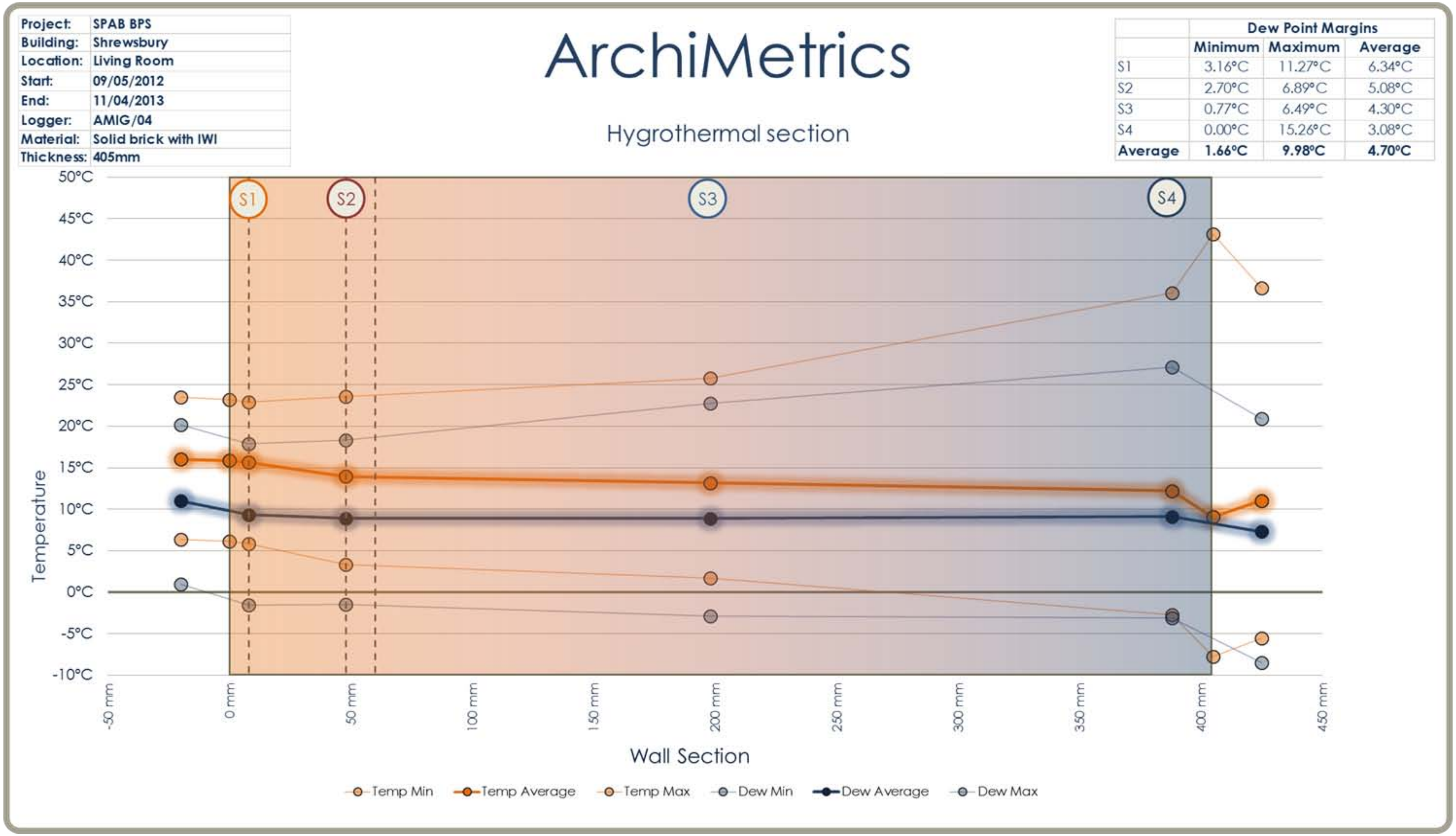


Figure 14. Hygrothermal Section, Abbeyforegate, Shrewsbury, 2012 - 2013.

2.2. Mill House, Drewsteignton, Devon - 2014 - 15.

Description: A barn built in granite dating from the nineteenth century or possibly earlier converted to a dwelling in 1970s incorporating a circa 1950's agricultural building at rear.

Refurbishment: The 1950'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 (the windows in the earlier 'barn' section of the house are in uPVC). In 2012, for experimental purposes, a short section of wall in a room in the older barn part of the dwelling, pictured above, was internally insulated using foil-faced polyisocyanurate (PIR) insulation with a plasterboard dry lining. It is this area, which corresponds with the pre-refurbishment monitoring location, which is the subject of long-term hygrothermal monitoring.

Occupancy: 2 persons.
Floor Area: 325 m^2

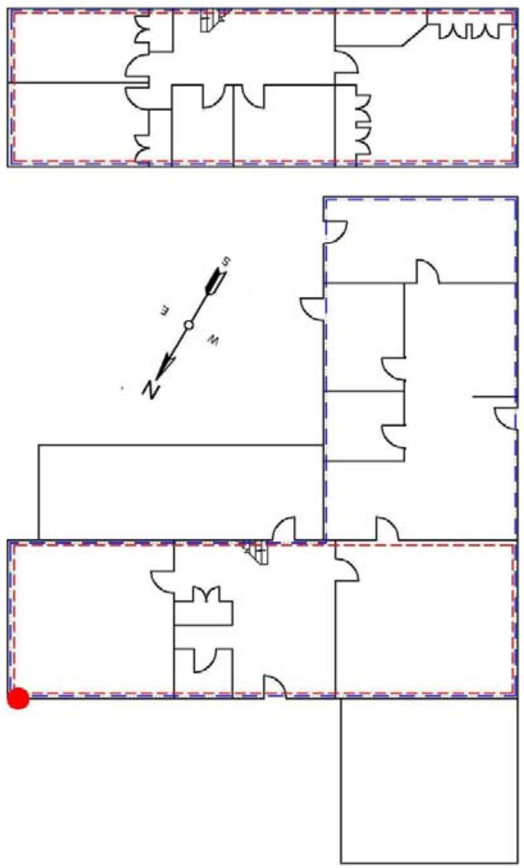


Figure 15. Plan of Mill House, Drewsteignton, the red dot indicates the location of the ground floor monitoring equipment.

Wall Condition Monitoring

Figure 16. Interstitial Hygrothermal Gradient and Material Moisture Monitoring, Drewsteignton.

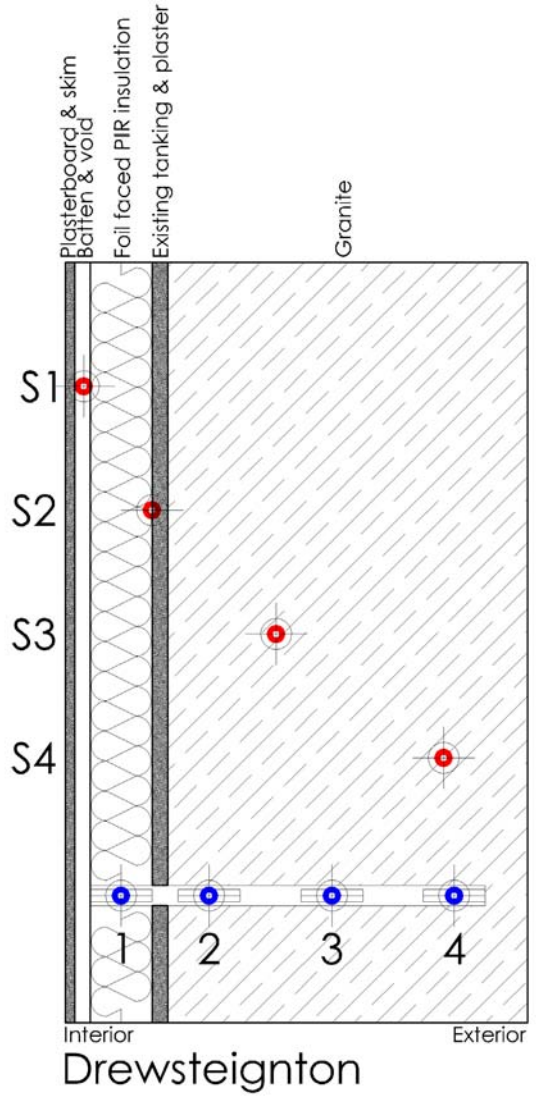


Figure 17. Position of wall sensors through section, Drewsteignton – red IHGM, blue Material Moisture

Interstitial Hygrothermal Conditions

Measurements of temperature and relative humidity (%RH) are being made through the test section of the north-west-facing wall of the study room at Mill House (Figures 16 and 17). Combined temperature and relative humidity sensors are located at four points within the wall at the heights and depths given in Table 7. This table also gives details of the wall build-up before and after insulation (in green).

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

Table 7. Interstitial hygrothermal gradient sensor positions for Mill House, Drewsteignton.

In addition to these measurements ambient conditions (temperature and %RH) are 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 1st September 2014 – 31st August 2015, has been used as the basis for the following analysis.

Relative Humidity Over Time

Figure 18 shows the %RH responses measured in and around the test wall at Drewsteignton 2014 -2015. The granite wall at Drewsteignton provides a contrasting picture compared with that of Shrewsbury, as here the %RH responses are more muted and do not have the volatility of those seen in Shrewsbury's brick wall. This suggests a different quality for the granite wall at Drewsteignton; it is thicker than that of Shrewsbury, constructed from more dense material, its pointing is in good condition and it has a north-west orientation. This construction is, therefore, less influenced by fluctuations in the weather and %RH responses are more muted as a consequence. (It should also be noted that at Drewsteignton, sensor 4, the sensor closest to external conditions within the interstitial array, is 135 mm back from the external face whereas at Shrewsbury this sensor is positioned only 20 mm back from the external wall face and is therefore more sensitive to changes in temperature and humidity caused by external conditions.) The measured responses from the wall at Drewsteignton post-insulation have, in the past, revealed a trend of rising RH over an annual cycle within the original masonry section of the insulated wall and we find, with the exception of sensor 4, this trend still in evidence over the past year. Table 8 provides the annual %RH averages for the wall. When these are compared with the previous year's averages, a year-on-year increase for sensors 2 and 3 is found.

Annual Average RH	**Sensor 1**	**Sensor 2**	**Sensor 3**	**Sensor 4**
2012 - 2013	68%	85%	90%	96%
2013 - 2014	64%	87%	92%	97%
2014 - 2015	63%	90%	95%	96%

Table 8. Comparison of annual averages of RH measured through wall section, Drewsteignton 2012 - 2015.

%RH responses at sensor 4 have been less extreme over the past twelve months. In 2013 – 14 measurements at this location peaked at 100% for five months between February and June whereas, for this same period this year, there is only a brief peak in April and shortly after this %RH begins to fall. By June 2015 measurements of %RH at sensor 4 become lower that those of sensor 3 something not seen since the wall was insulated in the winter of 2012. Indeed, this downward trend continues until data is lost week beginning 20th July with the possibility that %RH at this location may even have fallen below that of sensor 2 over the remaining summer months. Whilst it may appear, therefore, that there is an improving picture with regard to levels of %RH at sensor 4 this is not the case for the sensors deeper within the wall construction. An examination of Table 8 shows an increase in average %RH at these two locations and the difference, year-on-year, between the annual %RH averages shows that the rate of change may be increasing. Therefore, whilst the drop in %RH towards the external side of the wall may indicate some drying occurring in the summer months at this location, this effect would not appear to penetrate deeper into the wall fabric.

An examination of Figure 18 suggests that warmer summer temperatures may have some impact deep within the wall fabric as during these months, while %RH decreases at sensor 4, it increases at sensors 2 and 3. (Sensor 3 is positioned approximately half-way through the granite wall and sensor 2 is at the granite/foil-faced PIR insulation interface.) We have seen this behaviour elsewhere during the summer and have ascribed it to evaporation from damp materials increasing the vapour load of the air. It would seem that whilst a certain quantity of moisture may evaporate from materials this moisture, located further away from the external wall surface and unable to move towards the interior due to the presence of the foil vapour barrier, may not be able to leave the body of the wall during the warmer summer months. The vapour may then become stuck in cycles of evaporation and condensation and as the wall continues to receive moisture from the external environment its moisture load increases over time. This would account for the trend of rising %RH seen for this wall since it was insulated.

With regard to mould fungus, the wall at Drewsteignton is also at risk when examined against the 80% RH mould risk threshold. Only sensor 1, positioned in the air layer between the plasterboard dry-lining and insulation, records conditions below this threshold and levels here generally follow those of the interior. The three other sensors, however, now show averages of 90% or above and only sensor 2 records a minimum value over the year of below this (87%). Whilst %RH >80% may not represent a risk to masonry materials, high %RH may be an indication of material moisture content above 18% and in these circumstances organic materials embedded in the wall structure, such as timber lintels, joists etc. would be at risk of mould growth.

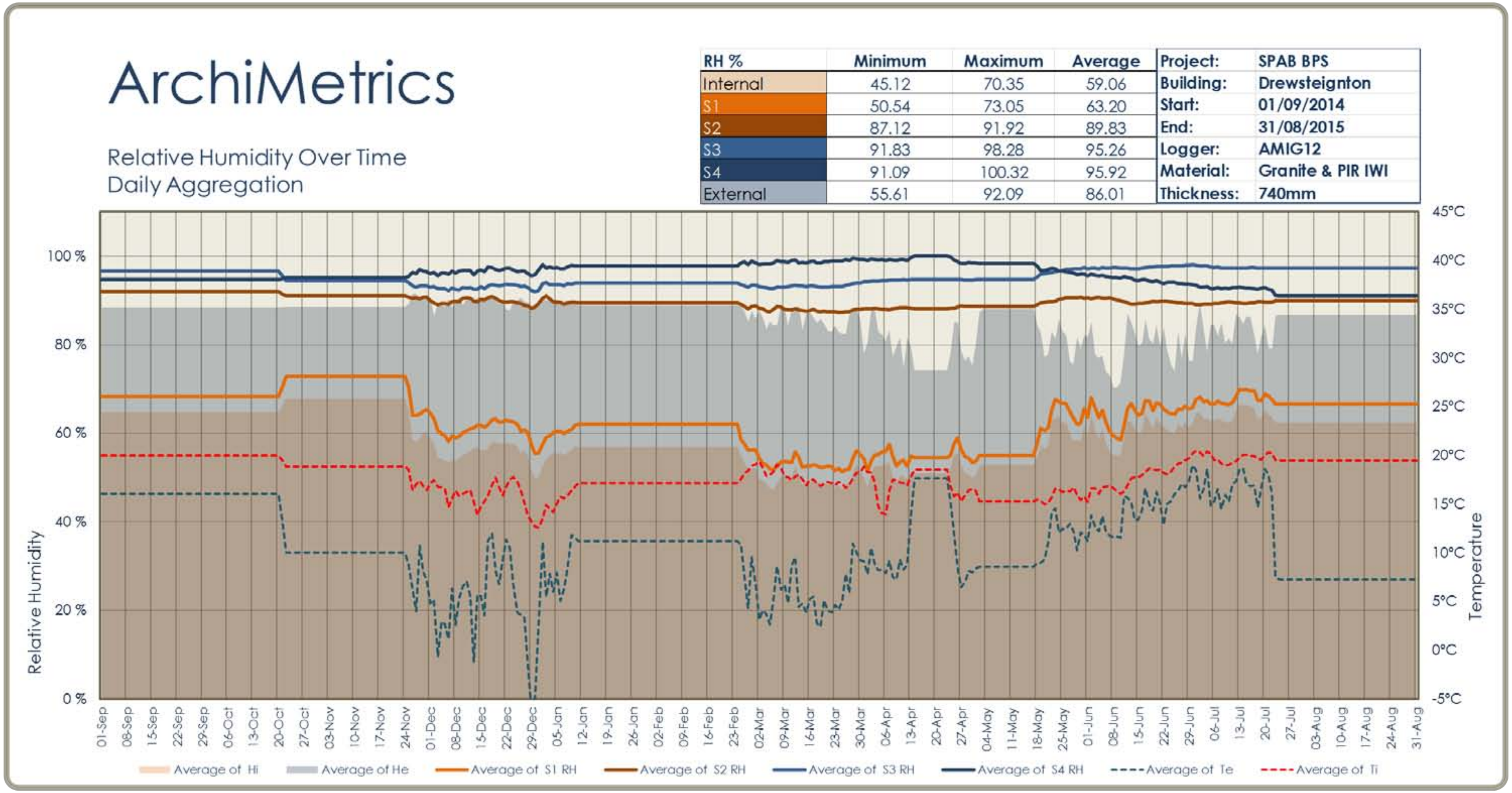


Figure 18: Relative Humidity over time, Mill House, Drewsteignton, 2014 2015.

Drewsteignton Monthly RH Averages						
	Internal RH	**S1 RH**	**S2 RH**	**S3 RH**	**S4 RH**	**External RH**
2014						
Sep	64.81	68.33	91.92	96.65	94.77	88.41
Oct	65.84	69.85	91.62	95.90	94.90	88.47
Nov	66.29	71.37	90.95	94.23	95.38	89.01
Dec	55.62	60.81	89.68	92.92	96.56	89.67
2015						
Jan	56.41	61.36	89.62	93.87	97.75	89.25
Feb	56.40	61.31	89.39	93.86	97.96	88.66
Mar	49.45	53.19	87.81	93.26	98.78	85.42
Apr	51.34	54.77	88.26	94.63	99.43	78.63
May	55.91	58.94	89.34	95.61	97.57	84.60
Jun	60.51	64.49	89.84	97.51	94.69	79.02
Jul	63.69	67.53	89.57	97.40	92.32	84.20
Aug	62.42	66.52	89.93	97.27	91.10	86.74
Average	**59.05**	**63.20**	**89.83**	**95.26**	**95.93**	**86.01**

Table 9. Relative Humidity Monthly Averages, Mill House, Drewsteignton, 2014 - 2015.

Absolute Humidity Over Time

Figure 19 shows an analysis of absolute humidity through the insulated wall section at Drewsteignton between 1st September 2014 – 31st August 2015. The same seasonal variation that was noted in previous reports is in evidence; generally quantities of vapour within the wall increase with that of atmospheric humidity during the spring and summer months when air is more humid. Also, as with previous years, the plot of AH from sensor 1 installed in the air layer behind the plasterboard is somewhat detached showing lower weights of vapour than those of the other sensors during this period. Here, as with the analysis of RH, sensor 1 reflects internal room conditions and the differentiation between this gradient and those from the sensors embedded in the masonry side of the wall (sensors 2 - 4) reveals the physical separation that has taken place via the construction of an air layer and installation of a vapour impermeable material (the foil-faced PIR board). Also of note over the spring and summer months are the raised gradients of the masonry sensors in relation to measurements of external AH. This suggests that there are additional sources of moisture other than solely that of the atmosphere, i.e. the wall fabric, that influence the vapour profile of the wall over this time. Although nowhere near as pronounced as in the south-facing walls at Shrewsbury or Riddlecombe, at Drewsteignton the effect of warmer temperatures and sunshine heating the wall fabric to promote the vaporisation of moisture can be seen in a solar analysis for week beginning 9th June, Figure 20.

The picture over winter is harder to discern due to data losses but seems similar to that of previous years where weights of vapour measured from all four sensor are lower and more closely grouped and lie between those of internal and external conditions. There is little differentiation between quantities found at sensor 1 and the other three sensors. For a time sensor 1 records the highest weights of vapour during December 2014, no doubt reflecting conditions within the room where higher quantities of vapour are supported by warmer indoor temperatures as a result of central heating.

Year-on-year there has been an increase in the average weights of vapour measured at Drewsteignton since the wall was insulated (Table 10). These increasing quantities may well correspond with the general trend of rising %RH also found for this wall. This trend has been less pronounced in the past year as annual averages of %RH were found to be lower at sensors 1 and 4 than those of previous years. However, this diminution of records of %RH in proximity to the interior and exterior side of the walls does not translate to a reduction in the annual average values for weights of vapour (AH) at these locations. The annual increase in average AH at sensor 1 is however small, 0.40 g/m^3, compared with the increases seen in the masonry section itself; sensor 2, 1.09 g/m^3, sensor 3, 1.25 g/m^3, and sensor 4, 0.84 g/m^3. This reflects a similar story to that of %RH where the greatest increases are seen deeper inside the wall away from evaporative surfaces.

Annual Average AH	**Sensor 1**	**Sensor 2**	**Sensor 3**	**Sensor 4**
2012 - 2013	8.53 g/m^3	8.76 g/m^3	8.96 g/m^3	9.13 g/m^3
2013 - 2014	9.24 g/m^3	10.04 g/m^3	10.24 g/m^3	10.17 g/m^3
2014 - 2015	9.64 g/m^3	11.13 g/m^3	11.49 g/m^3	11.04 g/m^3

Table 10. Average Absolute Humidity, Mill House, Drewsteignton, 2012 - 2014.

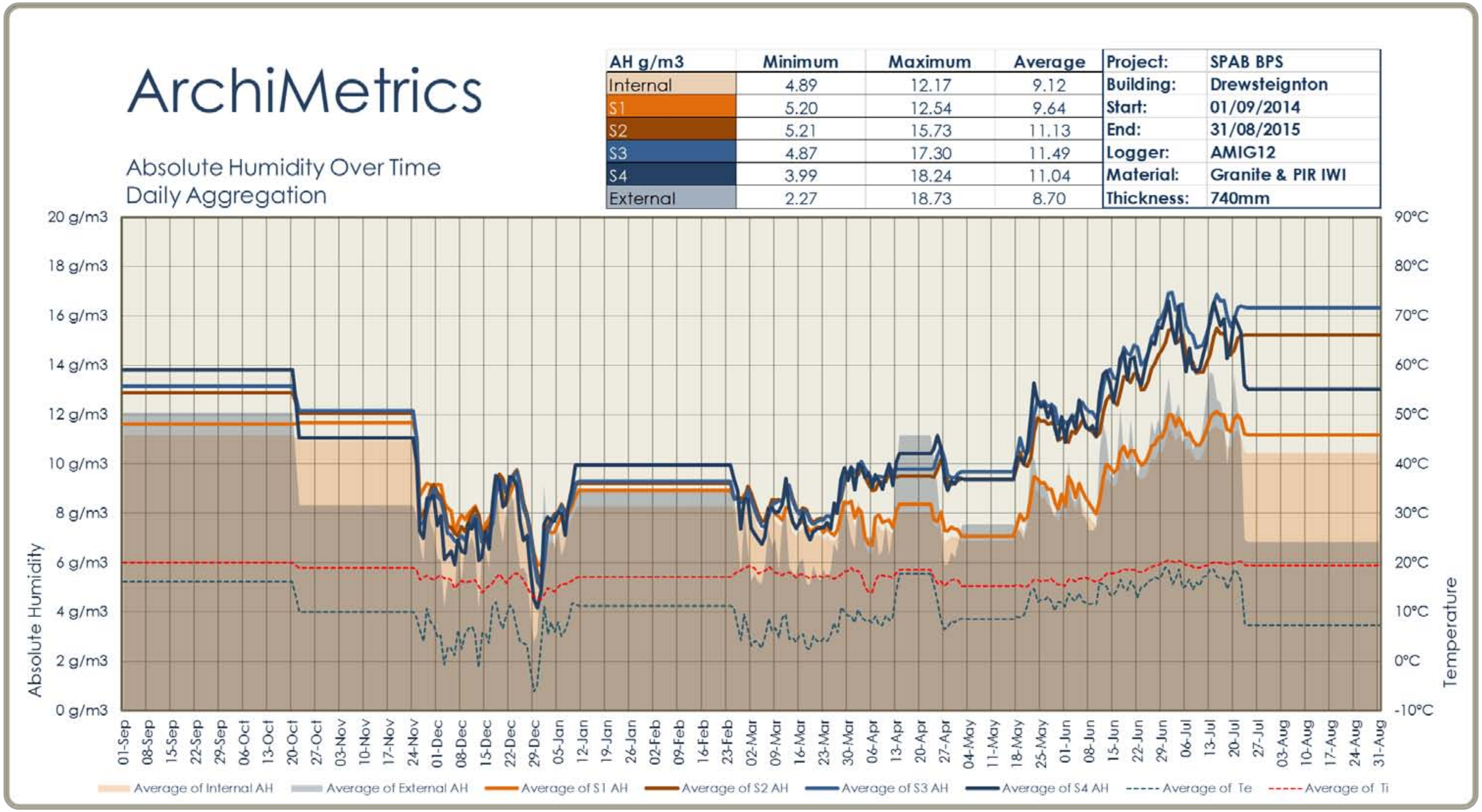


Figure 19: Absolute Humidity over time, Mill House, Drewsteignton 2014 - 2015.

Drewsteignton Monthly AH Averages						
	Int AH	**S1**	**S2**	**S3**	**S4**	**Ext AH**
2014						
Sep	11.17	11.62	12.87	13.14	13.82	12.08
Oct	11.10	11.63	12.59	12.80	12.88	10.81
Nov	10.52	11.19	11.41	11.45	10.51	8.15
Dec	7.54	8.03	7.95	7.72	7.15	6.19
2015						
Jan	7.95	8.52	8.81	8.83	9.36	8.55
Feb	8.29	8.89	9.13	9.17	9.75	8.75
Mar	7.50	7.81	8.35	8.29	7.95	6.25
Apr	7.51	7.85	9.47	9.76	9.90	8.59
May	7.44	7.77	10.11	10.57	10.37	7.98
Jun	9.18	9.74	12.61	13.61	13.27	9.93
Jul	10.81	11.46	14.86	16.06	14.54	10.46
Aug	10.43	11.18	15.23	16.31	13.02	6.83
Average	**9.12**	**9.64**	**11.12**	**11.48**	**11.04**	**8.71**

Table 11: Absolute Humidity monthly averages, Drewsteignton 2014 - 2015.

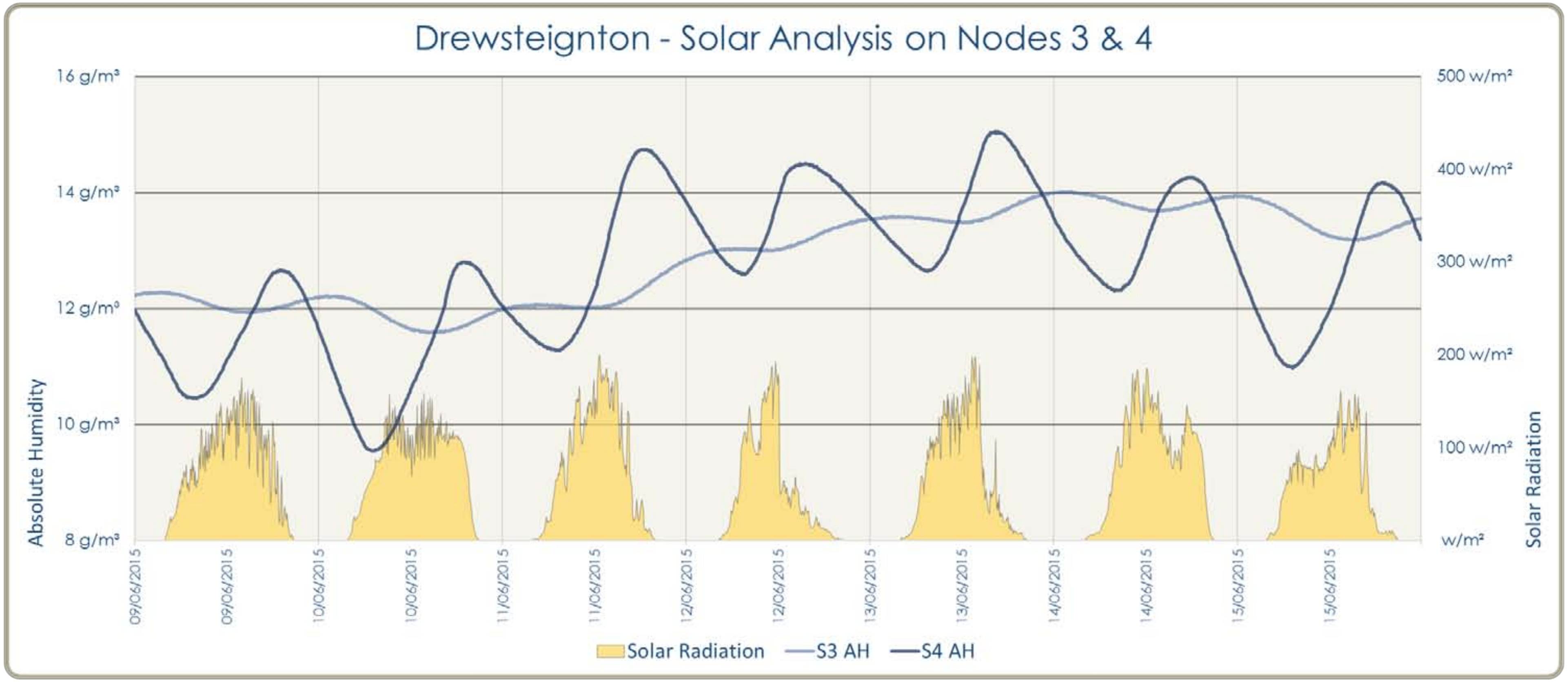


Figure 20: Solar Analysis sensors 3 and 4, Drewsteignton, June 2015.

Saturation Margins and Hygrothermal Sections.

Figure 21 presents plots of the saturation margins for the four sensors through the wall section over time. In a similar way to %RH this analysis clearly shows the period of time for which the air at the measured locations in the wall was close to or at dewpoint (saturation). Once again this analysis shows the distinction in measured conditions between those found at sensor 1 within the air layer behind the new dry-lining and the masonry of the original wall. On average the saturation margin at sensor 1 is 7.09˚C in contrast to those of sensors 2, 3 and 4 where margins remain below 2˚C, Table 12. Indeed the average margins found for sensors 2 and 3 are below 1˚C, being 0.67˚C and 0.59˚C respectively. Measurements from the wall show only a brief period of negative saturation margins at sensor 4 in mid-April, although overall the narrow margins measured in the masonry section show that the air here is close to saturation for much of the year.

In Table 12 saturation margins are written individually and as an average of all four sensors and shows the change in these margins before and after the wall was insulated. From this Table it can be seen that the saturation margins in the original masonry section of the wall have narrowed considerably following insulation and continue to narrow year-on-year. For the first time this year the margins at both sensor 4 and sensor 3 are both below 1˚C, although this year's margin at sensor 4 is a small improvement from that of the previous year, reflecting the slightly improved %RH picture from the sensor closest to external conditions. The diminution of saturation margins at sensors 2 and 3 continues at an increasing rate of change. The speed of this change is particularly marked at sensor 3 installed in the centre of the masonry; between 2013 and 2014 the difference between the average saturation margins increased by 0.39˚C, between 2014 – 2015 the increase was 0.47˚C. The continued narrowing of the saturation margins within the masonry section of the wall may well be a consequence of the year-on-year rise in humidity (AH) found for this wall which also leads to the continuing trend of rising RH.

Year	**S1**	**S2**	**S3**	**S4**	**Ave**
Pre-insulation					
2011 (4/3/11 - 18/3/11)	5.3˚C	4.82˚C	3.53˚C	2.38˚C	4.01˚C
Post-insulation					
2012 - 13 (8/2/12 - 28/2/13)	5.6˚C	2.23˚C	1.53˚C	0.57˚C	2.48˚C
Difference	**- 0.3**˚C	**2.59**˚C	**2**˚C	**1.81**˚C	**1.53**˚C
2013 - 2014 (1/4/13 - 31/3/14)	6.9˚C	1.97˚C	1.14˚C	0.49˚C	2.62˚C
Difference	**- 1.6**˚C	**2.85**˚C	**2.39**˚C	**1.89**˚C	**1.39**˚C
2014 - 2015 (1/9/14 - 31/8/15)	7.09˚C	1.58˚C	0.67˚C	0.59˚C	2.48˚C
Difference	**-1.79˚C**	**3.24˚C**	**2.86˚C**	**1.79˚C**	**1.53˚C**

Table 12. Saturation Margins & Pre & Post-insulation Difference, Mill House, Drewsteignton 2011 - 2015.

Measurements of temperature and %RH are also used to plot annual averages of measured temperature and dewpoint temperature through the wall section (Figures 22, 23 and 24). In these Figures the convergence of the measured temperature and dewpoint temperature gradients, shows, on average, just how close the air may be to saturation through the masonry part of the section. Comparison with previous years' analyses (Figures 23 and 24) shows how actual temperature and dewpoint temperature have continued to become more aligned over the past year, particularly in the centre of the wall around sensor 3. As with evidence from the saturation margins, %RH and AH analysis this shows how, with regard to indications of moisture performance, we find a worsening picture for the wall at Drewsteignton.

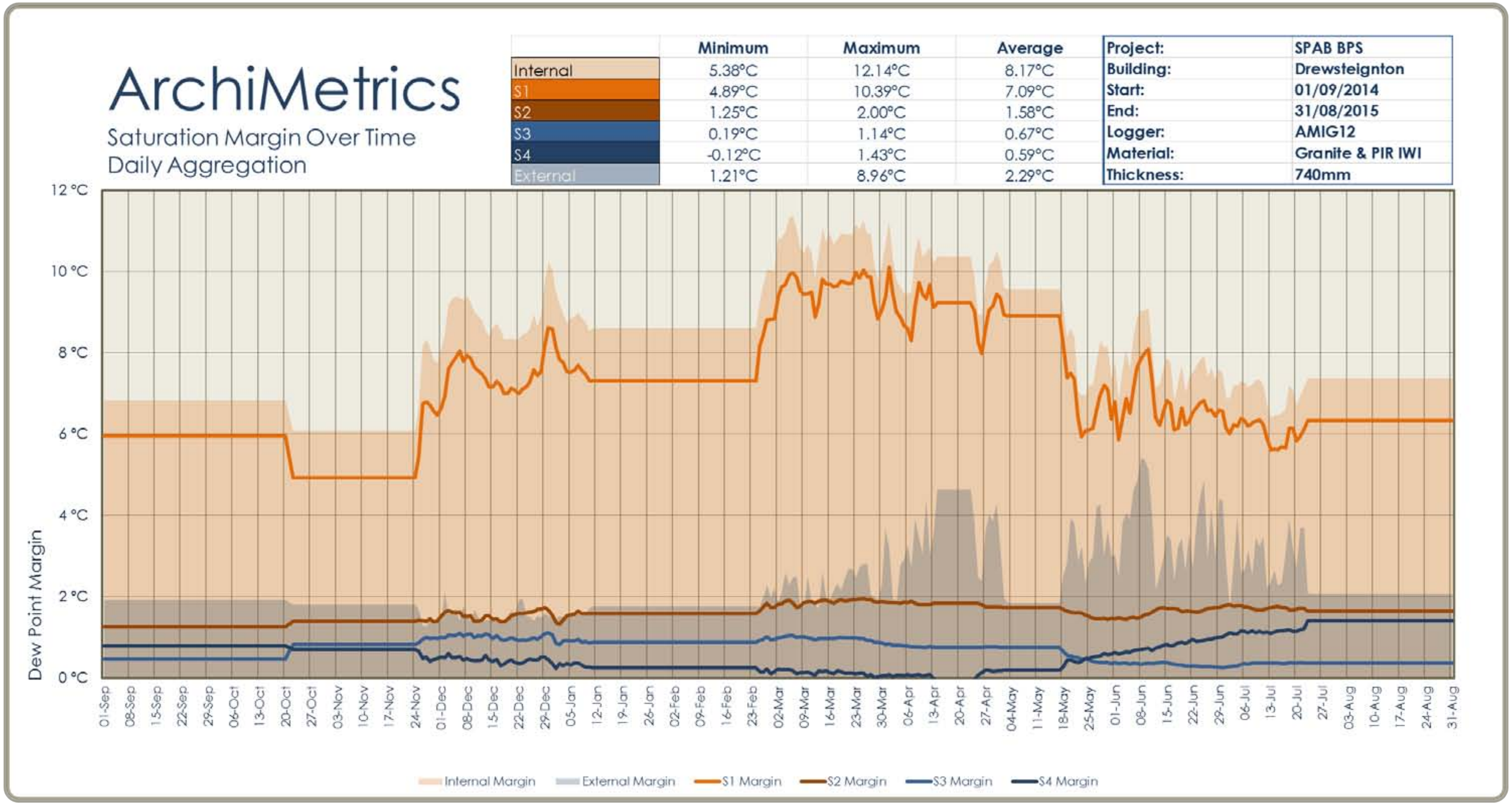


Figure 21. Saturation Margin Over Time, Mill House, Drewsteignton, 2014 - 2015.

Drewsteignton Monthly Saturation Margin Averages						
	Internal	S1	S2	S3	S4	External
2014						
Sep	6.83	5.95	1.26	0.47	0.79	1.92
Oct	6.57	5.60	1.30	0.59	0.76	1.88
Nov	6.42	5.23	1.39	0.85	0.66	1.72
Dec	8.88	7.48	1.54	1.01	0.44	1.55
2015						
Jan	8.71	7.41	1.57	0.88	0.27	1.69
Feb	8.77	7.48	1.61	0.88	0.24	1.80
Mar	10.74	9.57	1.87	0.96	0.12	2.29
Apr	10.14	9.11	1.82	0.76	0.02	3.70
May	8.80	7.98	1.64	0.62	0.31	2.53
Jun	7.75	6.74	1.62	0.32	0.80	3.70
Jul	7.08	6.13	1.70	0.35	1.21	2.68
Aug	7.37	6.34	1.64	0.36	1.41	2.06
Average	**8.17**	**7.09**	**1.58**	**0.67**	**0.59**	**2.29**

Table 13. Monthly Saturation Margin averages, Mill House, Drewsteignton, 2014 - 2015.

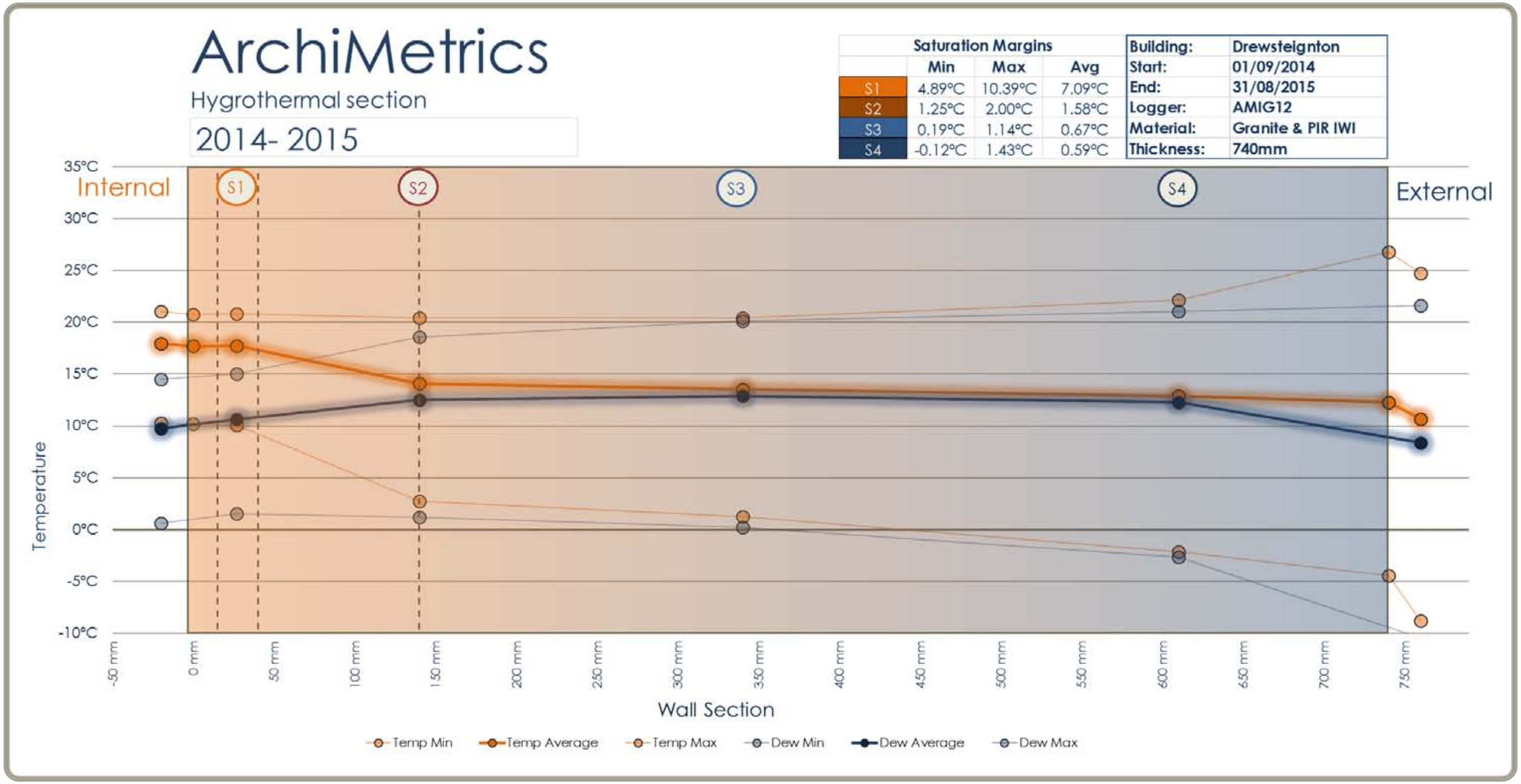


Figure 22. Hygrothermal Section, Mill House, Drewsteignton, 2014 – 2015 (capped).

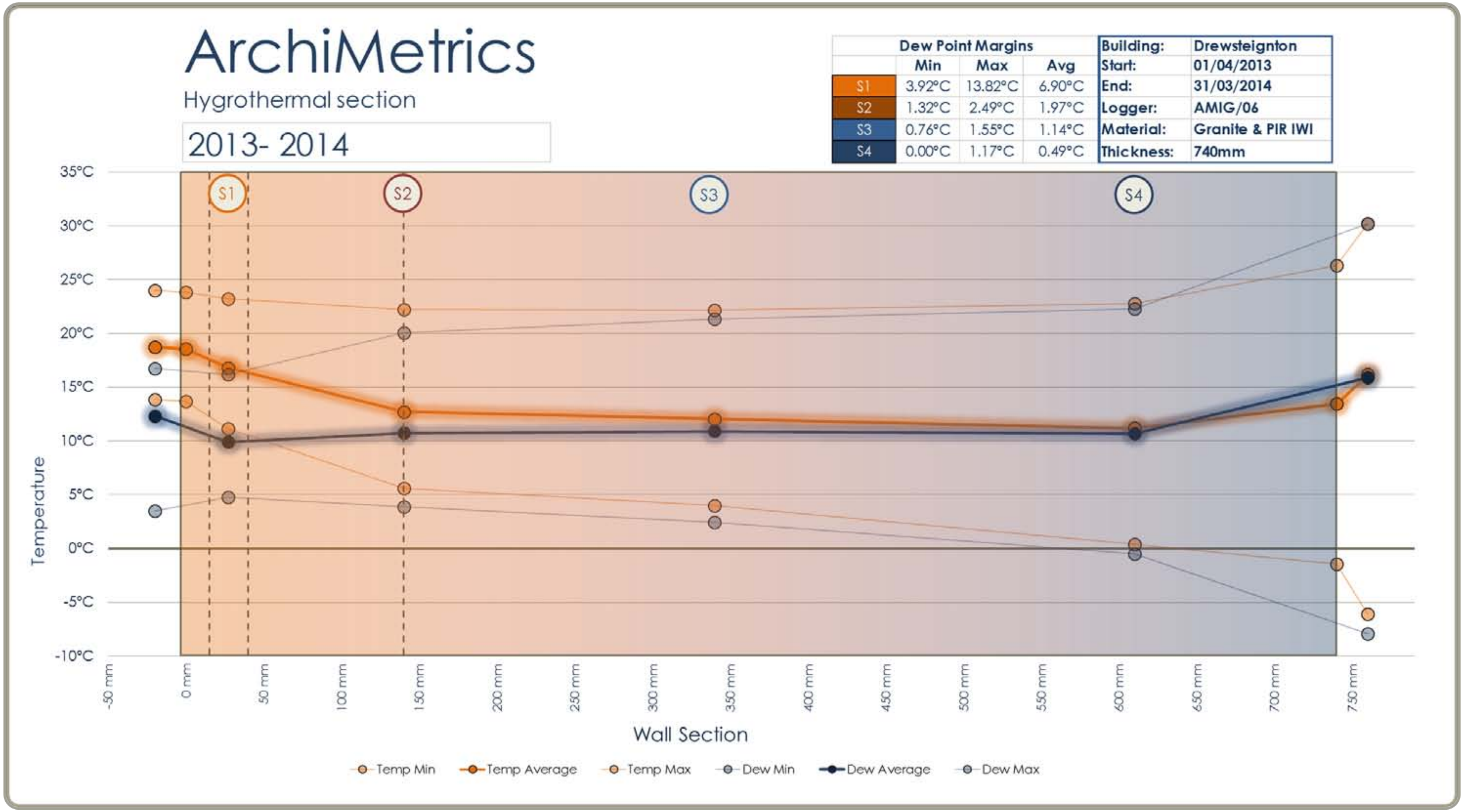


Figure 23. Hygrothermal Section, Mill House, Drewsteignton, 2013 - 2014.

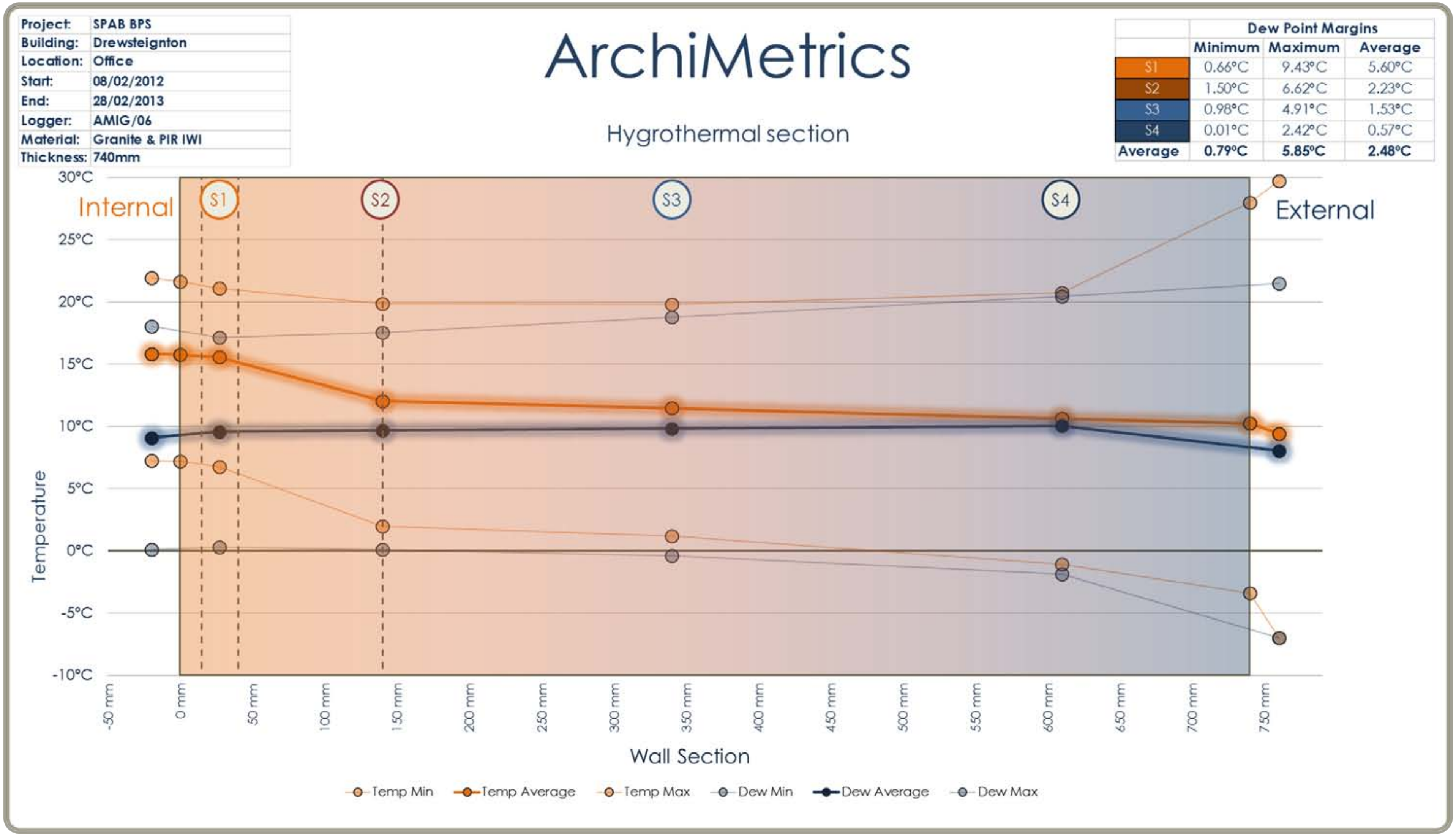


Figure 24. Hygrothermal Section, Mill House, Drewsteignton, 2012 - 2013.

2.3. The Firs, Riddlecombe, Devon - 2014 - 15.

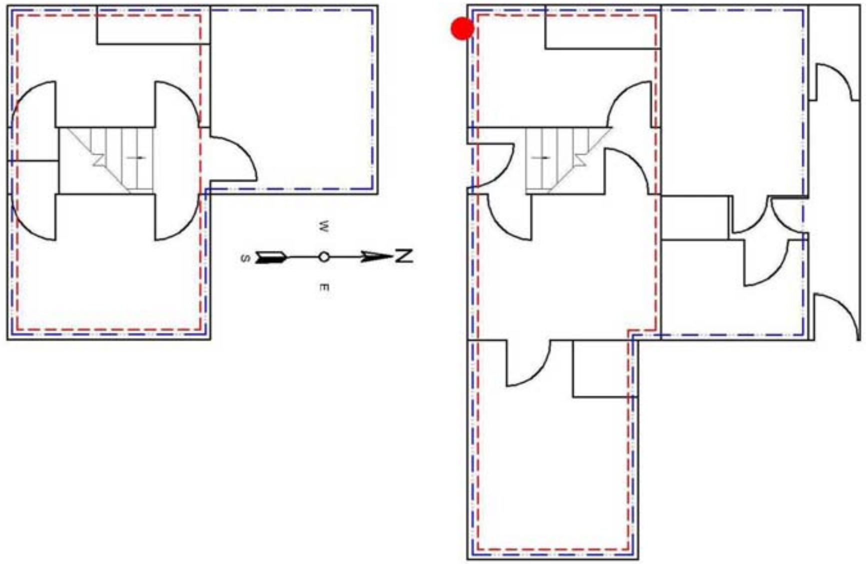


Figure 25. Plan of The Firs, Riddlecombe (ground floor on right hand side). Location of IHGM monitoring equipment shown by red dot.

Description: Two-storey, semi-detached, nineteenth-century cob cottage with early twentieth-century single storey addition in cob to east 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 a perlite-based insulating lime render. Internally gypsum plasters have largely 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: 86 m^2

Wall Condition Monitoring

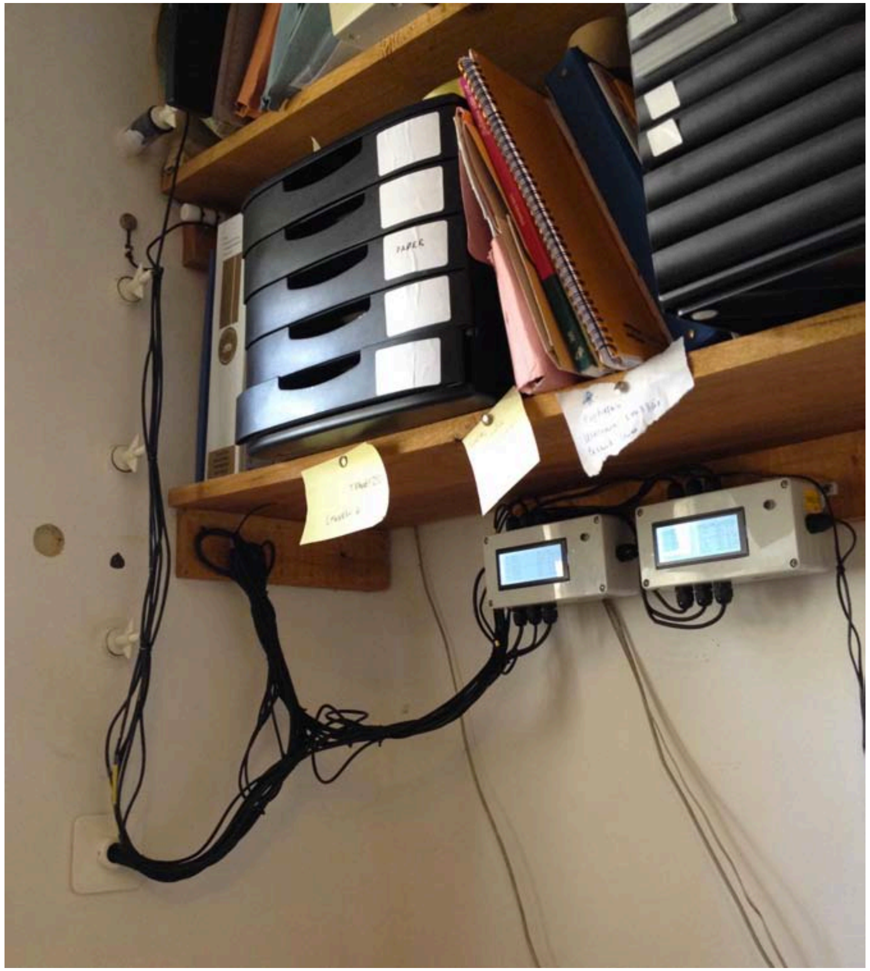


Figure 26. Interstitial Hygrothermal Gradient and Material Moisture Monitoring, Riddlecombe.

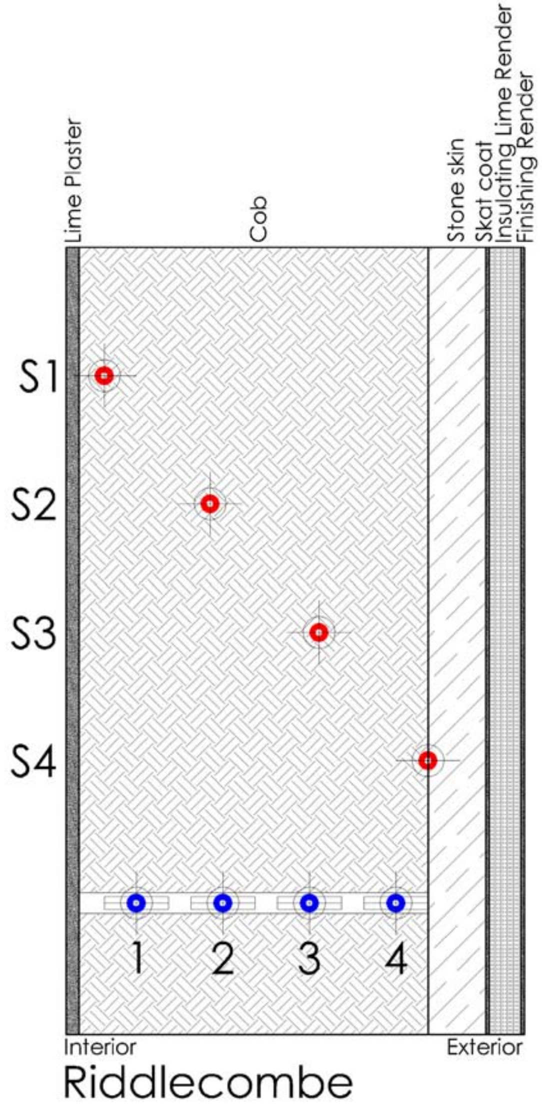


Figure 27. Position of sensors through wall section, Riddlecombe.

Interstitial Hygrothermal Conditions

Measurements of temperature and relative humidity (%RH) are being made through a section of the south-facing wall of the office room at The Firs, Riddlecombe (Figures 26 and 27). Combined temperature and relative humidity sensors are located at four points within the wall at heights and depths given in Table 14. This table also gives details of the wall build-up before and after insulation (in green).

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

Table 14. Interstitial hygrothermal gradient sensor positions and wall build up for The Firs, Riddlecombe.

In addition to these measurements, ambient conditions (temperature and %RH) are 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 1st September 2014 – 31st August 2015, has been used as the basis for the following analysis.

Relative Humidity Over Time

Figure 28 shows the %RH responses measured in and around the wall at Riddlecombe over the past year. In past years this wall has produced the highest %RH values of the three walls in the study and this is still the case for this year. The revised analysis, which now indicates %RH in excess of 100% (see page 4), shows the average level of %RH at sensor 4 to be 110% suggesting wet conditions and indeed wet material has been previously retrieved from the wall at this location. It is interesting to note just how consistent the high value of %RH measured at this location is. This characteristic has been a feature of previous reporting and in the past there has been the suggestion that this was due to sensor failure. Following the installation of new monitoring equipment in December 2014 sensor 4 was replaced and like its predecessor continued to report high RH values. (This event is visible in Figure 28 as %RH drops for a time due to the venting of the sensor sleeves that occurs when a sensor is removed – a phenomenon only seen in this cob wall due to its air-tight construction.) Figure 29, a detail from two weeks of monitoring in August 2015, demonstrates that sensor 4 is providing variable measurements of %RH overtime and that these measurements are very high, 111%. The consistency of the %RH value found at sensor 4 could, instead, be the result of conditions at this location being at the limits of this capacitance-based measurement technique.

An examination of average annual %RH values for this wall is shown in Table 15 (now re-adjusted to cap %RH at 100% for comparison with last year's figures) and may illustrate a slightly improving picture deeper inside the cob wall at sensor 3. However, there is no change elsewhere.

Annual Average RH	**Sensor 1**	**Sensor 2**	**Sensor 3**	**Sensor 4**
2013 - 2014	78%	91%	99%	100%
2014 - 2015	78%	91%	96%	100%

Table 15. Comparison of annual averages of RH measured through wall section, Riddlecombe 2013 - 2015.

It is also interesting to compare the minimum and maximum %RH values measured from the wall sensors over the past year with those of the previous year, Table 16. This may show a slightly improving picture with regards to %RH as, while minimum values have increased this year at sensors 1 and 2, towards the external half of the wall these measurements are lower than those of the previous year. At the opposite end of the range, this time at sensors 1 and 2, we also find that maximum values have reduced this year compared with 2013 -14. Once again the 2014 – 15 values are capped at 100% for the purposes of comparison and because in both years %RH peaks at the cut-off limit of 100% it is difficult to ascertain whether there has been a similar reduction in maximum values at sensor 3 and 4 for this year compared to 2013 -14.[3]

[3] Both the annual average and minimum/maximum tables compare this year's incomplete data set with that of the previous year's 12-month series. The annual average values for 2014-15 are made up from both summer and winter-time monitoring and therefore capture the temperature extremes of the year. However, the minimum/maximum analysis could be more circumscribed by this restricted data set as alternative values may be found with a longer time series.

Sensor Nos.	2013 - 14 Minimum %RH	2014 -15 Minimum %RH	2013 - 14 Maximum %RH	2014 - 15 Maximum %RH
Sensor 1	69.46	72.16	85.53	83.01
Sensor 2	87.03	88.79	94.08	94.01
Sensor 3	95.14	88.22	100	100
Sensor 4	100	94.47	100	100

Table 16. Comparison of minimum and maximum %RH measured through wall section, Riddlecombe 2013 - 2015.

In previous reports we have deemed the high levels of %RH found in the cob wall at Riddlecombe to mostly likely be the result of construction moisture bound within the earth fabric. Unusual %RH behaviour was observed as quantities rose during warmer summer months (when %RH is normally lower due to warmer temperatures). We ascribed this phenomena to the vaporisation of moisture from damp cob material which was particularly noticeable during periods of direct sun on the south-facing wall (see AH commentary). This moisture was introduced into the wall during the process of re-rendering when the wall, which had already measured high levels of %RH pre-insulation possibly due to a cracked cement render, was wetted down prior to the application of the new render. In 2013 – 14 it was also noticeable that rates of %RH diminished during and in spite of the colder winter months. This behaviour is less obvious in the 2014 -15 data although measurements of %RH at sensor 3 over the summer are raised in comparison with those between December 2014 and February 2015. However, they are on average not as great as those of the previous year. Overall the %RH picture for the wall at Riddlecombe seems to be one of stasis, or if one considers responses measured at sensor 3 taken with evidence of minimum and maximum records, this might suggest a possible improvement. From the point of view of the mould growth threshold the wall is still unsatisfactory with only sensor 1 towards the interior wall face recording an average of below 80% RH. The 3 others are all, like those of Drewsteignton, above 90%. However, unlike a granite stone, wall earth-based materials may be less tolerant of high humidity. They are also more likely to contain organic materials susceptible to rot and be less stable at high moisture content.

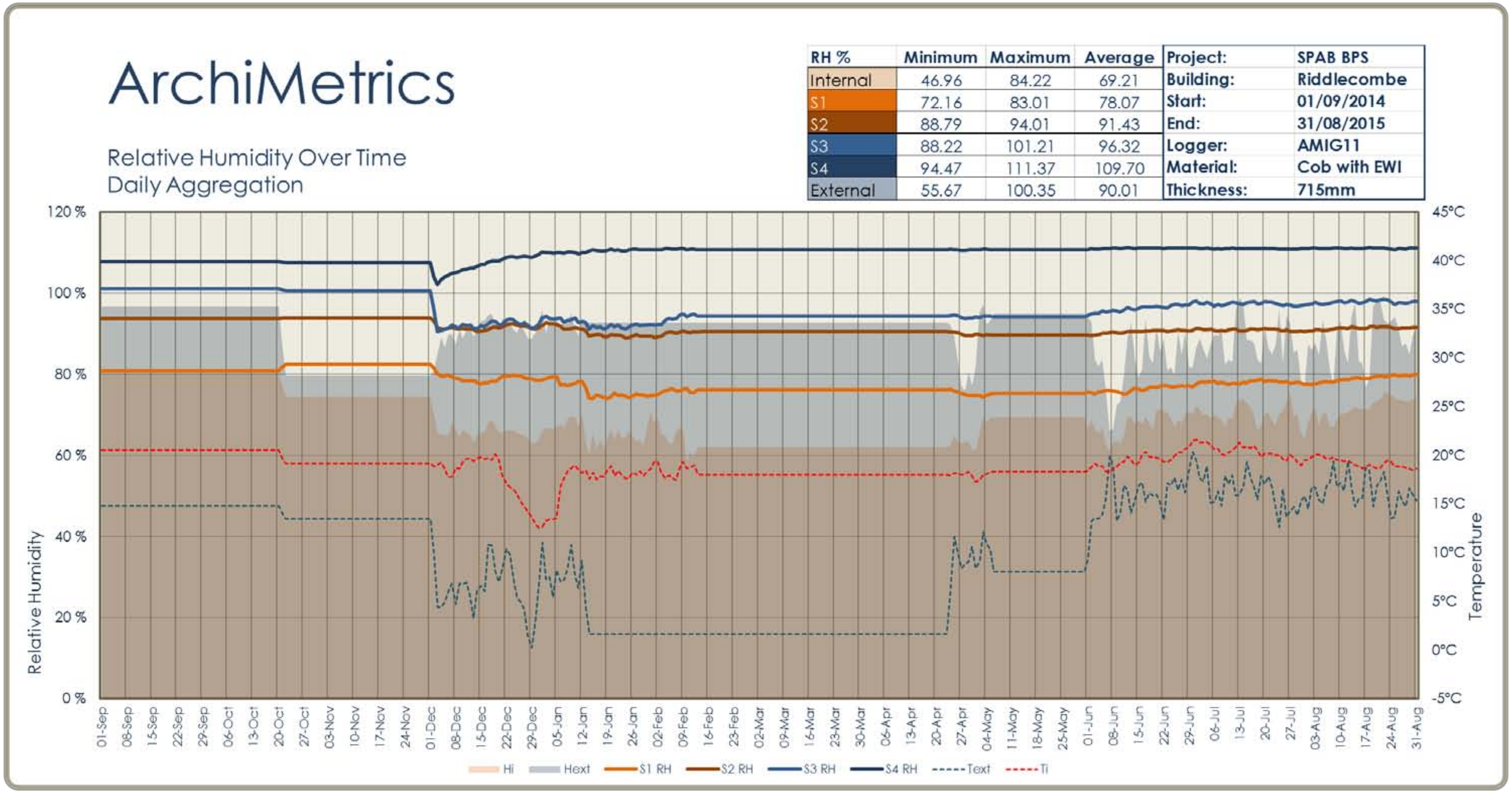


Figure 28: Relative Humidity over time, The Firs, Riddlecombe2014 - 2015.

Riddlecombe Monthly RH Averages						
	Internal RH	**S1 RH**	**S2 RH**	**S3 RH**	**S4 RH**	**External RH**
2014						
Sep	80.17	80.85	93.77	101.21	107.77	96.68
Oct	78.22	81.41	93.82	100.99	107.69	90.89
Nov	74.43	82.48	93.92	100.55	107.55	79.69
Dec	65.94	79.13	91.58	92.49	106.97	90.15
2015						
Jan	65.72	76.13	90.43	92.50	110.36	92.80
Feb	63.00	76.01	90.32	94.05	110.81	92.73
Mar	62.05	76.19	90.48	94.32	110.78	92.73
Apr	62.31	76.00	90.36	94.28	110.76	90.29
May	68.96	75.19	89.69	94.13	110.67	94.47
Jun	67.61	76.33	90.46	96.21	111.08	83.18
Jul	70.03	78.07	90.93	97.38	110.98	87.68
Aug	71.76	78.95	91.35	97.80	111.06	88.74
Average	**69.21**	**78.07**	**91.43**	**96.32**	**109.70**	**90.01**

Table 17: Relative Humidity monthly averages, Riddlecombe, 2014 - 2015.

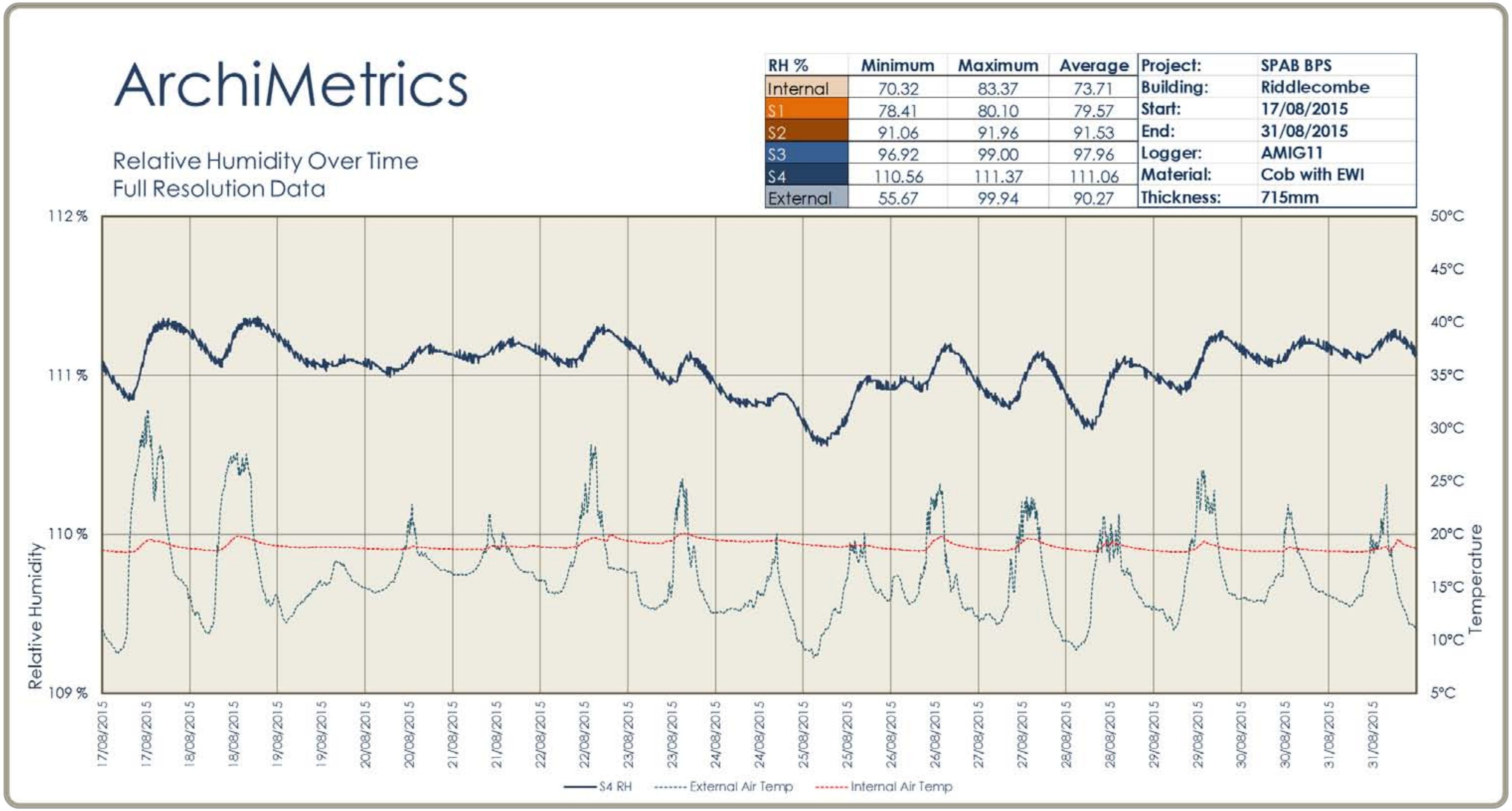


Figure 29: Relative Humidity over time, detail, The Firs, Riddlecombe August 2015.

Absolute Humidity Over Time

Figure 30 shows an analysis of absolute humidity through the insulated wall section at Riddlecombe September 2014 - August 2015. As with records of %RH, weights of vapour measured in the wall at Riddlecombe have in the past been higher than those of the other two walls in the study, something which we also feel is a reflection of the additional moisture load within this wall due to bound in construction moisture. This analysis shows a similar trend to that remarked on in previous reports for all walls in the study, i.e. that there is an increase in absolute humidity throughout the wall during the summer period due to increased atmospheric humidity. However, it is noticeable that sensor gradients over the summer months indicate weights of vapour higher than those of the external atmosphere, something that was also observed at Drewsteignton. This suggests an additional source of vapour (the vaporisation of built-in construction moisture) affecting conditions within the wall above and beyond that of internal and external air. The gradients of sensors 2, 3 and 4 are quite tightly grouped with the gradient from sensor 1, towards the interior side of the wall, somewhat lower but nevertheless apparently responding to the same influences as those deeper within the cob and further towards the exterior. Sensor 1 responses follow those of sensors 2 and 3 and these are all less conditioned by changes in the external environment than those of sensor 4 closest to the external wall face. In contrast to Drewsteignton, the broadly similar responses from all four wall sensors indicates the more homogenous nature of this cob wall, where all four measurements points sit within the same medium, which is not interrupted by a different material or air layer.

Measurements taken over the early part of December 2014 show the effect of heating on vapour levels within the cob where the interior side of the wall is warmed by heat from inside the house improving the vapour carrying capacity of the air at this location. Over this period highest weights of vapour are recorded towards the interior side of the wall due to the predominant source of heat (due to space heating) something seen in winter in other walls. However, towards the end of the week beginning 15th December this heat is removed as the house is unoccupied for a period (see internal temperature gradient Figure 30). This causes vapour levels to fall and become more similar through the section in response to lack of heat and associated colder entrained air and wall fabric. A differentiation in the gradients appears again week beginning 5th January 2015 with the resumption of space heating within the property.

Annual analysis of AH behaviour can enable an understanding of underlying vapour trends as unlike %RH it is a quantity not directly measured in relation to temperature and thus may be less impinged upon by variations in temperature. Of course the AH picture at Riddlecombe, as with elsewhere, is still affected by temperature, particularly in the spring and summer months when warmer weather encourages drying of materials, something that is likely to be particularly significant in the wet substrate found at Riddlecombe. Hence the higher weights of vapour recorded here. The annual average values compared year-on-year, Table 18, show that the greatest increases in vapour quantities since the wall was refurbished in the summer of 2012 have taken place towards the internal side of the wall at sensors 1 and 2. The picture at sensors 3 and 4 seems to be much more static with values being slightly higher this year than those of the previous year, possibly suggesting increased drying at these locations. This year the previously observed relationship between vapour production and warmer temperatures, particularly during periods of direct solar radiation falling upon the south-facing wall, is found, Figure 31. In this example, taken from a week in late July 2015, we can see drying taking place as a result of vaporisation due to solar radiation. Despite the high weights of vapour being measured over this time we can see the wall is drying as over the week quantities of vapour measured at sensors 3 and 4 fall (particularly noticeable in the more muted responses at sensor 3). The assumption is that vapour is dispersed from these locations by diffusion. In this context the increased weights of vapour at all points through the wall section seen this year may point to increased drying in this wall compared to the previous year. 2013 -14 was a particularly wet year with significant flooding in the south-west. In contrast conditions during the following year, being warmer and drier, have been more conducive to drying of the wall material at Riddlecombe. The increase in weights of vapour is particularly marked at sensor 2, which over the past two years has measured the highest weights of the four sensor. The measurements here are perhaps influenced by the movement of vapour from the exterior side travelling back through the wall towards the interior surface, Figure 32.

Annual Average AH	**Sensor 1**	**Sensor 2**	**Sensor 3**	**Sensor 4**
Feb - Aug 2012	9.47 g/m^3	12.66 g/m^3	12.74 g/m^3	12.27 g/m^3
Feb - Aug 2013	11.56 g/m^3	12.73 g/m^3	12.80 g/m^3	12.22 g/m^3
2013 - 2014	12.10 g/m^3	12.96 g/m^3	12.72 g/m^3	11.75 g/m^3
2014 - 2015	12.24 g/m^3	13.32 g/m^3	12.91 g/m^3	12.15 g/m^3

Table 18. Average Absolute Humidity, The Firs, Riddlecombe, 2012 - 2015.

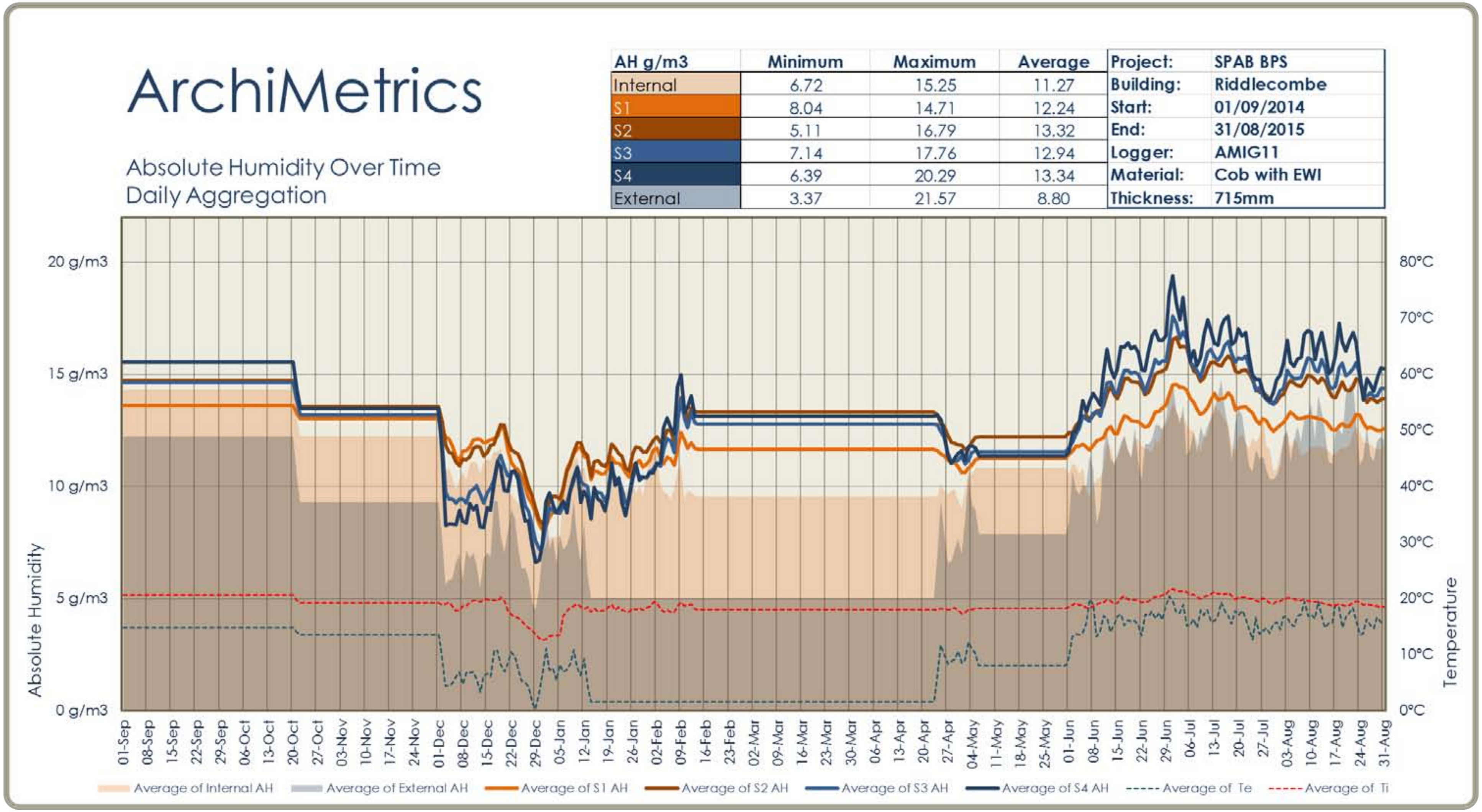


Figure 30: Absolute Humidity over time, The Firs, Riddlecombe, 2014 - 2015.

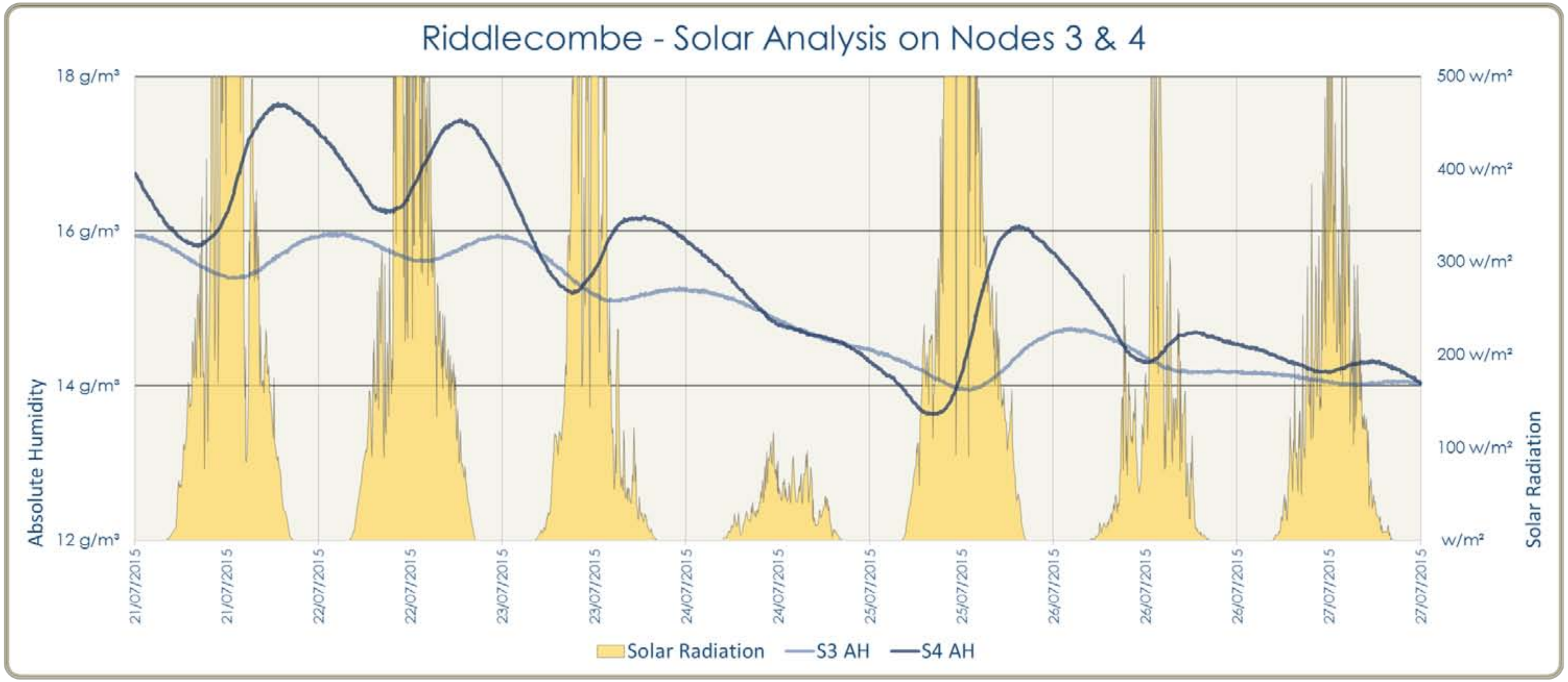


Figure 31: Solar Analysis - Absolute Humidity sensors 3 and 4 over time, Riddlecombe, July 2015.

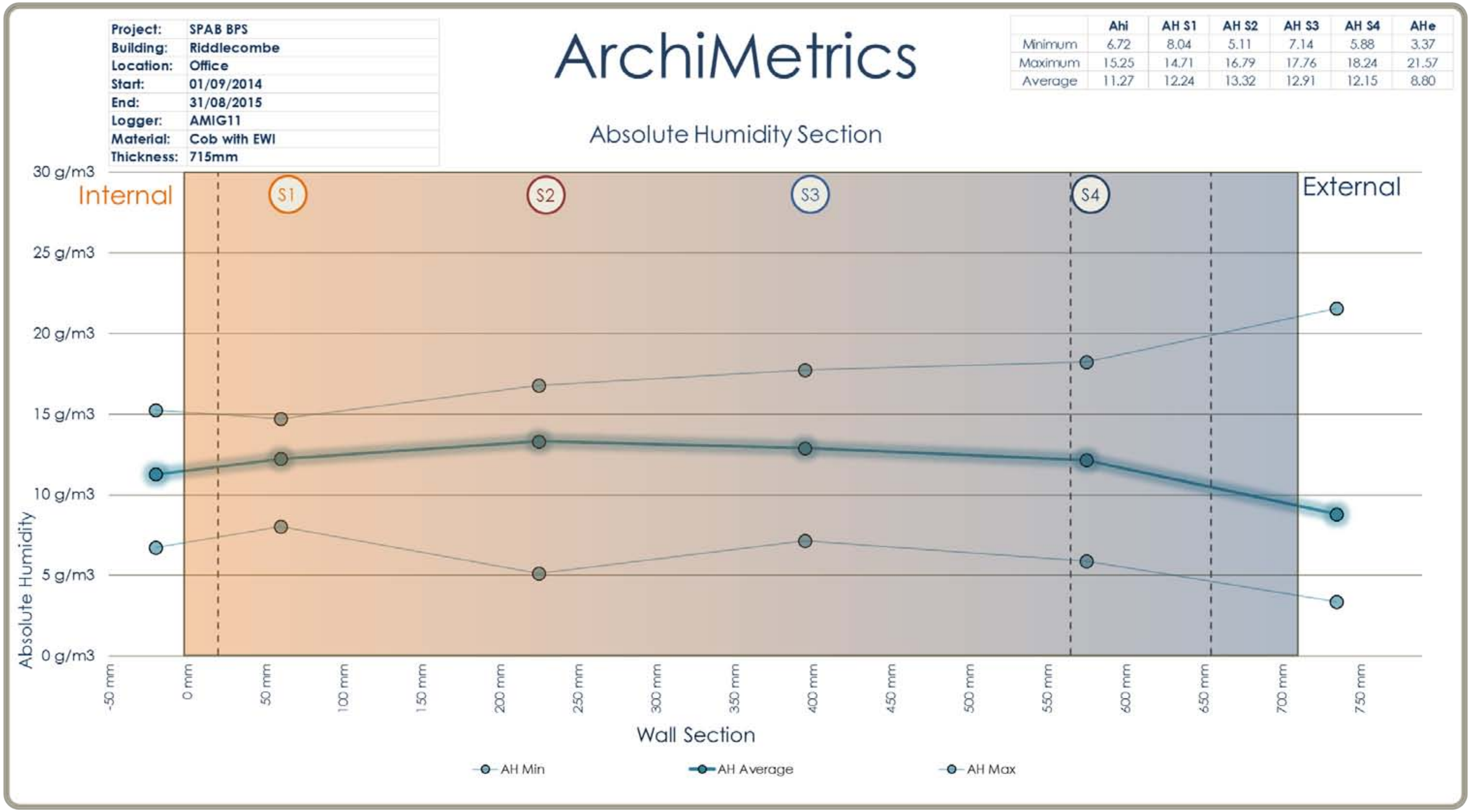


Figure 32: Absolute Humidity average section (capped). Riddlecombe, 2014 – 2015.

Riddlecombe Monthly AH Averages						
	Int AH	S1	S2	S3	S4	Ext AH
2014						
Sep	14.31	13.61	14.69	14.63	15.54	12.22
Oct	13.60	13.40	14.30	14.13	14.83	11.22
Nov	12.23	13.01	13.56	13.17	13.46	9.29
Dec	10.09	11.27	11.29	9.79	9.13	6.90
2015						
Jan	9.75	10.57	10.95	9.79	9.73	6.12
Feb	9.81	11.62	13.03	12.50	12.98	5.01
Mar	9.54	11.65	13.30	12.76	13.12	5.01
Apr	9.58	11.55	13.09	12.53	12.85	5.58
May	10.71	11.18	12.15	11.51	11.38	8.01
Jun	11.37	12.55	14.03	14.20	15.12	11.28
Jul	12.38	13.59	15.15	15.49	16.25	12.27
Aug	11.82	12.85	14.36	14.83	15.74	12.39
Average	**11.27**	**12.24**	**13.32**	**12.94**	**13.34**	**8.80**

Table 19: Absolute Humidity monthly averages, Riddlecombe 2014 - 2015.

Saturation Margins and Hygrothermal Section

Figure 33 presents plots of the saturation margins for the four sensors through the wall section over time. In a similar way to the observations concerning %RH, this analysis clearly shows the period of time for which the air in proximity to the wall sensors was close to saturation or saturated. Riddlecombe is the only wall of the three in the study to have, on average, a negative saturation margin, -1.49˚C at sensor 4, suggesting that conditions are wet at this location. The average margin at sensor 3 is also narrow, being less than 1˚C - 0.52˚C.

However, when adjusted to a 100% RH base for comparison purposes, the margin at sensor 3 defies the overall trend compared with the previous year in that it is the only location where the saturation margin has increased, Table 20. In relation to the previous commentary on AH this is interesting as this year, 2014 -15, seems to have seen higher weights of vapour measured in the wall (due perhaps to weather conditions encouraging greater evaporation). Saturation margins are calculated in relation to dewpoint temperature and the concept of dewpoint or 100%RH. As this relates to relative humidity warmer temperatures and increased direct sun on the south-facing wall improves the margin at sensor 3 in spite of, in this particular wall, the likelihood of increased vapour production. Towards the interior side of the wall, sensor 1 and 2 the margins have narrowed year-on-year, perhaps showing the influence of increased vapour production and possibly vapour migration but without the benefit of sufficient temperature transfer to raise margins at this location. The situation at sensor 4 seems to be one of stasis with no change and the average annual margin for all points through the wall is similarly consistent between the two years, 2013 -14 and 2014 – 15. If the saturation margin is taken as a risk indicator then despite the increased quantities of vapour the risk at the sensor 3 location would appear to have lessened slightly a change to the overall trend seen year-on-year for this wall.

Year	S1	S2	S3	S4	Ave
Pre-insulation					
2011 (25/2/11 - 11/3/11)	5.57˚C	3.22˚C	2.06˚C	0.6˚C	2.86˚C
Post-insulation					
2012 (07/2/12 - 11/09/12)	5.19˚C	1.4˚C	0.35˚C	0.03˚C	1.74˚C
Difference	**0.38˚C**	**1.82˚C**	**1.71˚C**	**0.57˚C**	**1.12˚C**
2013 - 2014 (1/6/13 - 31/5/14)	3.97˚C	1.55˚C	0.23˚C	0.00˚C	1.44˚C
Difference	**1.60˚C**	**1.67˚C**	**1.83˚C**	**0.60˚C**	**1.42˚C**
2014 – 2015 (1/9/14 - 31/8/15)	3.84˚C	1.35˚C	0.62˚C	0.00˚C	1.45˚C
Difference	**1.73˚C**	**1.87˚C**	**1.44˚C**	**0.60˚C**	**1.41˚C**

Table 20. Dewpoint Margins & Pre & Post-insulation Difference, The Firs, Riddlecombe, 2011 - 2015.

Measurements of temperature and RH are also used to plot annual temperature and dewpoint temperature gradients through the wall section (Figures 34 and 35). A comparison of the two monitored years shows the slight increase in the margin that occurs between the measured temperature and dewpoint in 2014 -15 at sensor 3. It also shows the increased convergence of the two gradients measured at sensor 1 and 2. This naturally corresponds with observations elsewhere of a slight reduction in %RH at sensor 3 and an increase in weights of vapour (AH) at sensor 2. That these changes have taken place over a year may indicate a very slight improvement in the vapour profile for the cob wall at Riddlecombe. However this will only be borne out by continued long-term measurements.

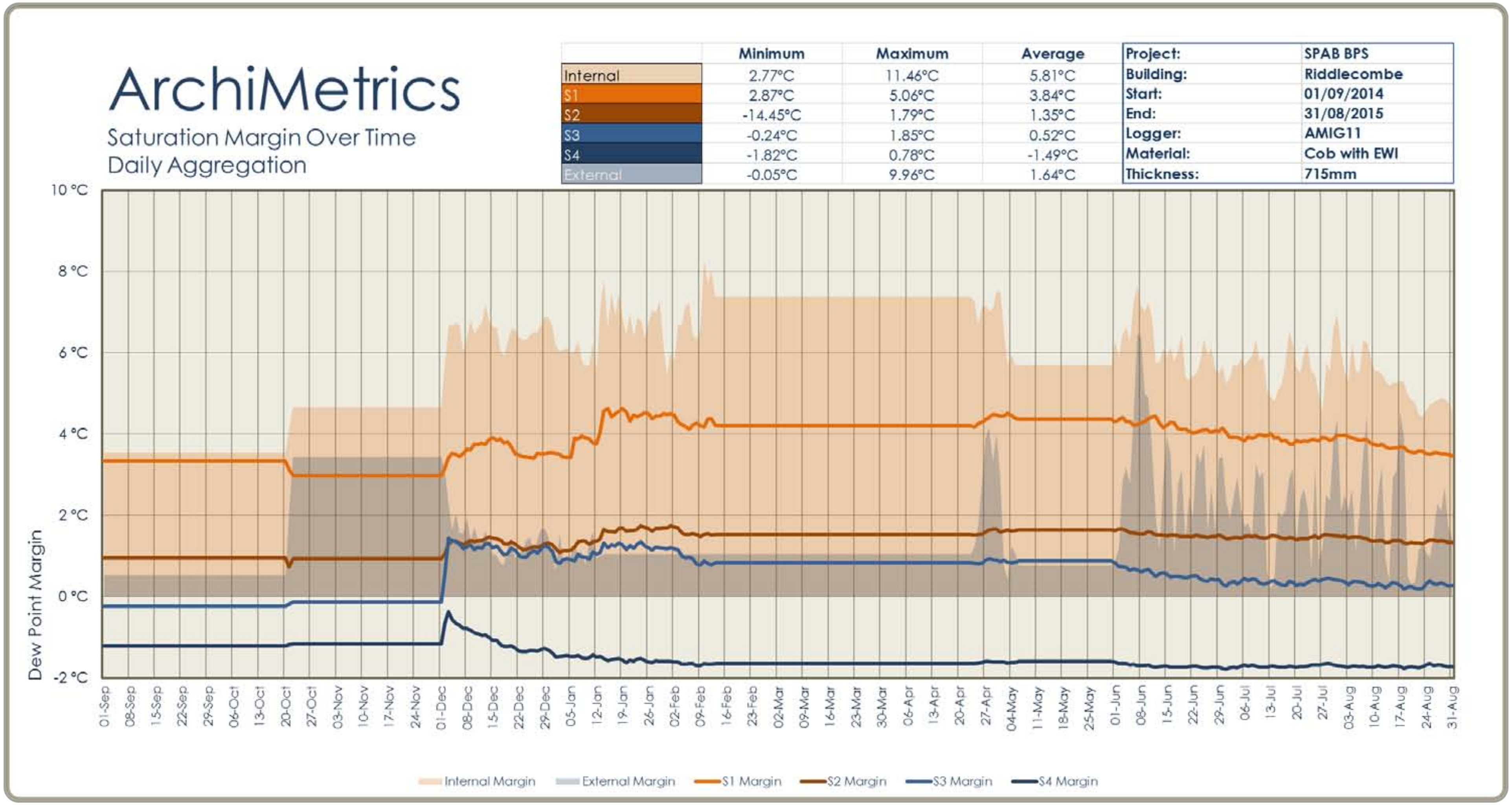


Figure 33. Saturation Margin over time, The Firs, Riddlecombe, 2014 - 2015.

Riddlecombe Monthly Saturation Margin Averages						
	Internal	**S1**	**S2**	**S3**	**S4**	**External**
2014						
Sep	3.54	3.33	0.95	-0.24	-1.21	0.52
Oct	3.92	3.21	0.94	-0.21	-1.20	1.52
Nov	4.66	2.98	0.93	-0.14	-1.17	3.44
Dec	6.46	3.58	1.29	1.12	-1.06	1.51
2015						
Jan	6.50	4.17	1.49	1.12	-1.53	1.06
Feb	7.18	4.24	1.54	0.88	-1.65	1.05
Mar	7.38	4.20	1.52	0.83	-1.65	1.05
Apr	7.32	4.23	1.54	0.84	-1.64	1.50
May	5.80	4.38	1.64	0.88	-1.60	0.84
Jun	6.17	4.21	1.53	0.55	-1.71	3.03
Jul	5.67	3.89	1.46	0.36	-1.71	2.17
Aug	5.24	3.68	1.38	0.29	-1.72	2.00
Average	**5.81**	**3.84**	**1.35**	**0.52**	**-1.49**	**1.64**

Table 21. Average monthly Saturation Margins, The Firs, Riddlecombe, 2014 - 2015.

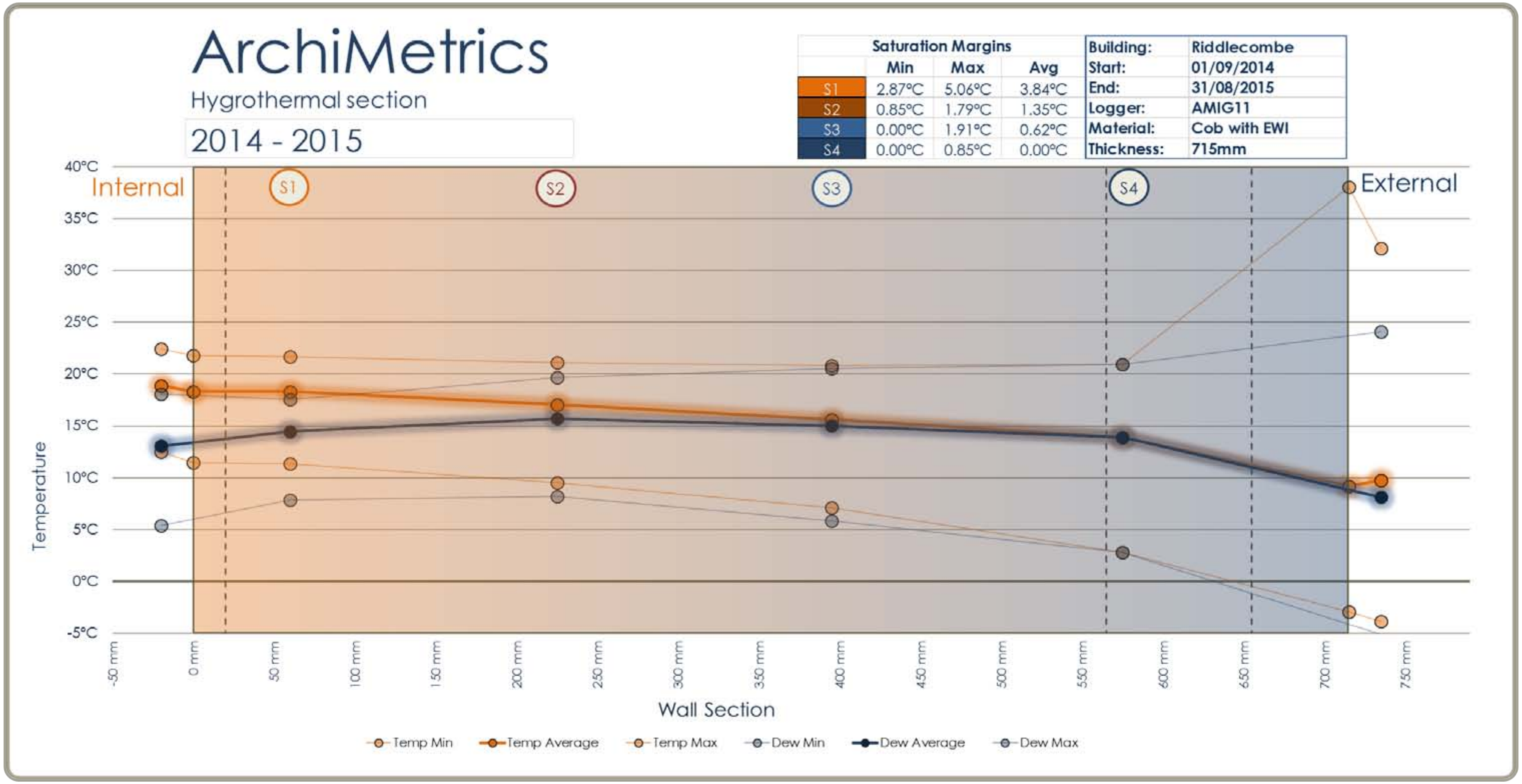


Figure 34. Hygrothermal Section, The Firs, Riddlecombe, 2014 - 2015.

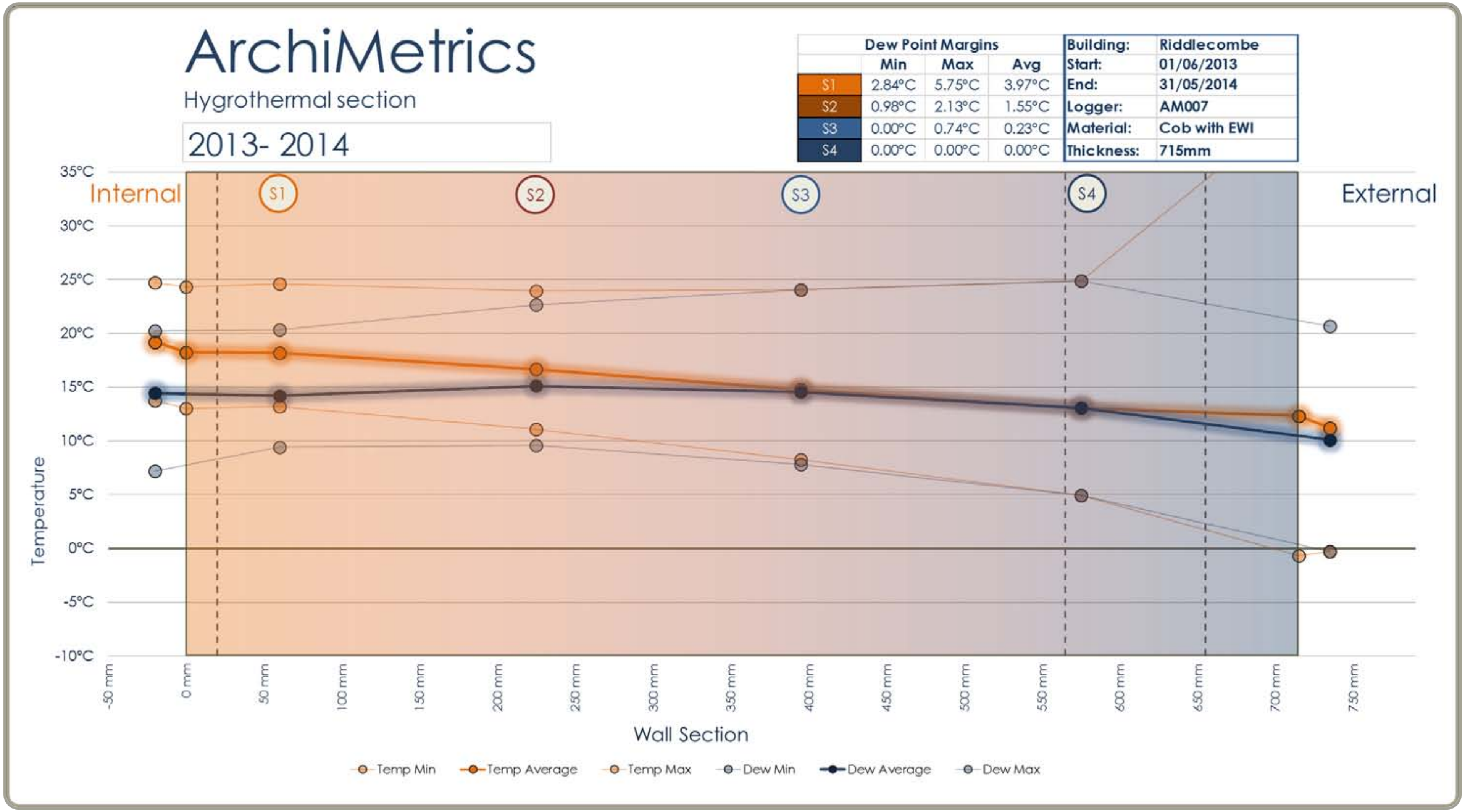


Figure 35. Hygrothermal Section, The Firs, Riddlecombe, 2013 - 2014.

3. DISCUSSION

Direct comparisons between moisture responses at the three properties in the survey are problematic given the differences between the buildings; their locations, wall orientations, materials, sensor positions and general condition. Nevertheless, bearing these differences in mind, it is interesting to look across the sample at the changes that are taking place in the walls over time for points of similarity and difference.

3.1 Relative Humidity (RH)

Table 22 provides details of the annual average %RH values for the four interstitial sensors situated in the monitored walls at Shrewsbury, Drewsteignton and Riddlecombe post-insulation. Blue shading indicates decreases in %RH and orange increases in %RH year-on-year.

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

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

Table 22. Annual Average %RH for all Interstitial Sensors 2012 - 2015.

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

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

Figures 36, 37 and 38 show the long-term trends of %RH responses in the three walls. (These are indicated by dashed trend lines, the dotted lines show this year's new analysis of RH beyond 100%). The Shrewsbury trend analysis, Figure 36, shows the lower %RH performance of the wall and the narrower range of the RH trends compared to Drewsteignton and Riddlecombe. This suggests, for the wall in Shrewsbury, a relatively stable and safe (with regards to mould growth) picture for the wall, despite the acute volatility of seasonal responses. At Shrewsbury the trends at sensors 1 and 2 are downward and sensor 4 is static, an upward trend at sensor 3 can be seen. We do not, however, expect this trend to persist as it is the result of the extreme wetting of the substrate that took place deep within the wall during the winter of 2013 -14. More recent data from this year shows that the air in the wall at this location has 'recovered' from this event and returned to lower %RH.

In Figure 37 for Drewsteignton the year on year rise in %RH in the centre of the wall can be seen as a long-term trend at sensors 2 and 3. The trends on sensors 1 and 4 at the periphery of the wall are downward. These are likely to be more strongly influenced by seasonal events and these decreases may reflect the warmer conditions experienced in 2014 – 15 compared with those of previous years. It is telling that, given the trends at sensors 1 and 4, those seen at sensors 2 and 3, more deeply embedded in the core of the wall, continue to climb. This suggests that currently drying influences within the environment are unable to penetrate conditions deeper within the wall to reduce %RH by drying the air and surrounding substrate, hence a rising trend.

Like Drewsteignton, the trends of %RH at Riddlecombe are high, well above the 80% threshold for mould growth, Figure 38. However, unlike Drewsteignton, the trend within the centre of the wall at Riddlecombe, at sensors 2 and 3, is one of falling RH. The trend for sensor 4, towards the external side of the wall, static at 100%, indicates perpetual saturation of the air and this persistence implies a wet substrate at this location. The high measurements of %RH at sensors 2 and 3 also suggest damp material but the decrease found over time here may imply that this material is drying out through solar driven vaporisation, albeit slowly. The upward trend at sensor 1 may also be a response to the drying taking place deeper within the wall as vapour travels back toward the internal wall surface, the area of lower vapour concentration.

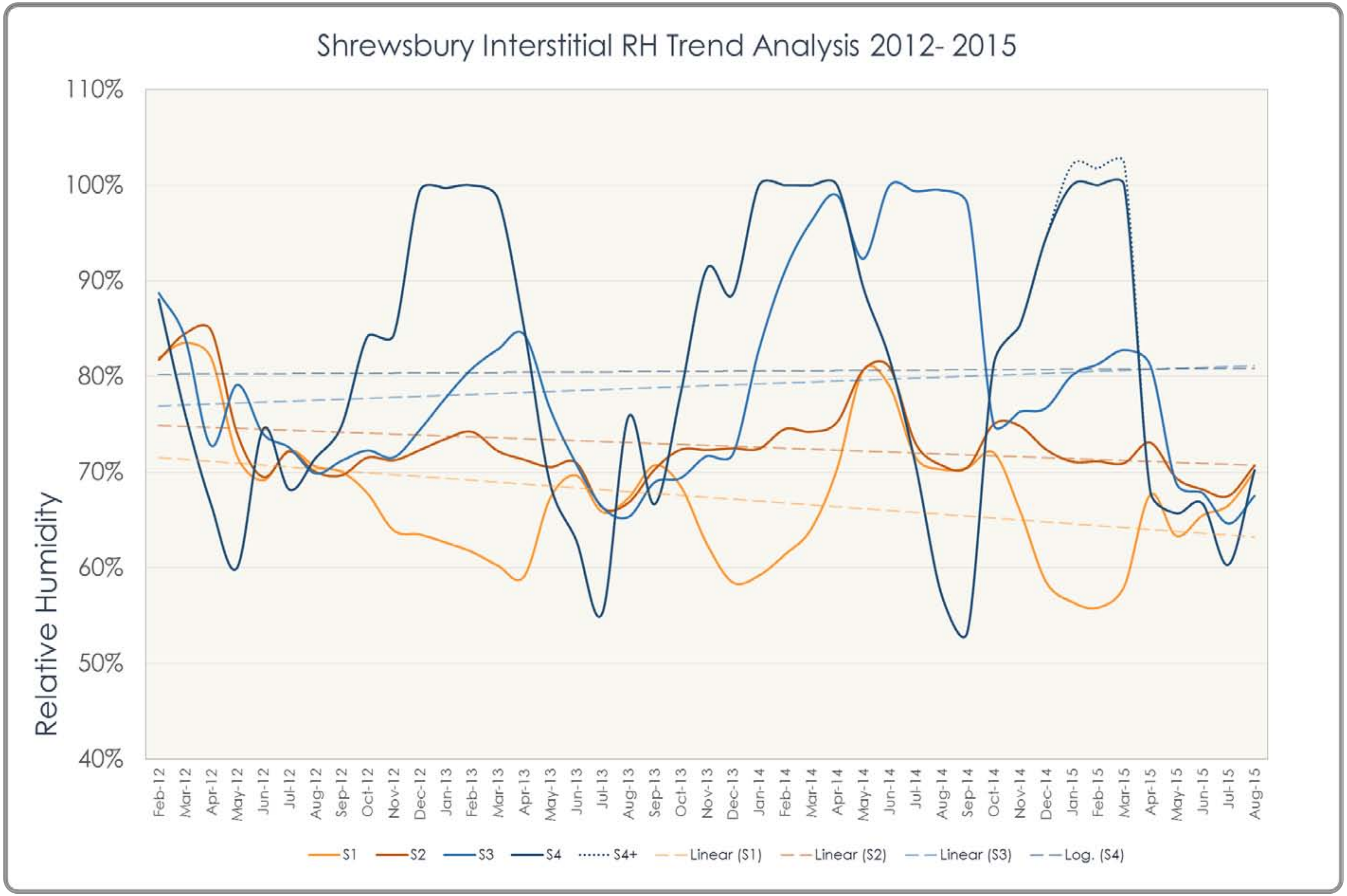


Figure 36: Relative Humidity Trends over time, Shrewsbury 2012 - 2015.

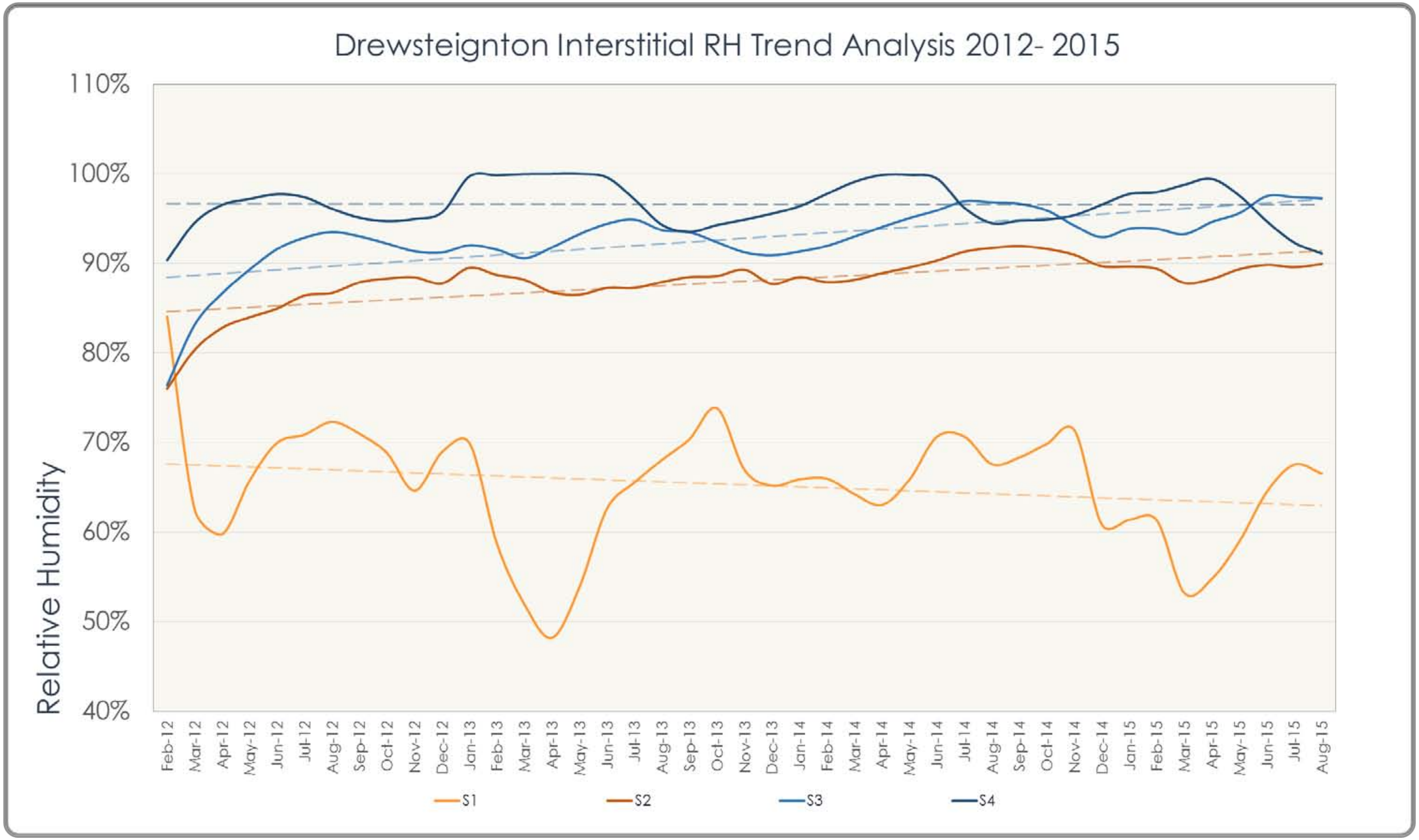


Figure 37: Relative Humidity Trends over time, Drewsteignton 2012 – 2015.

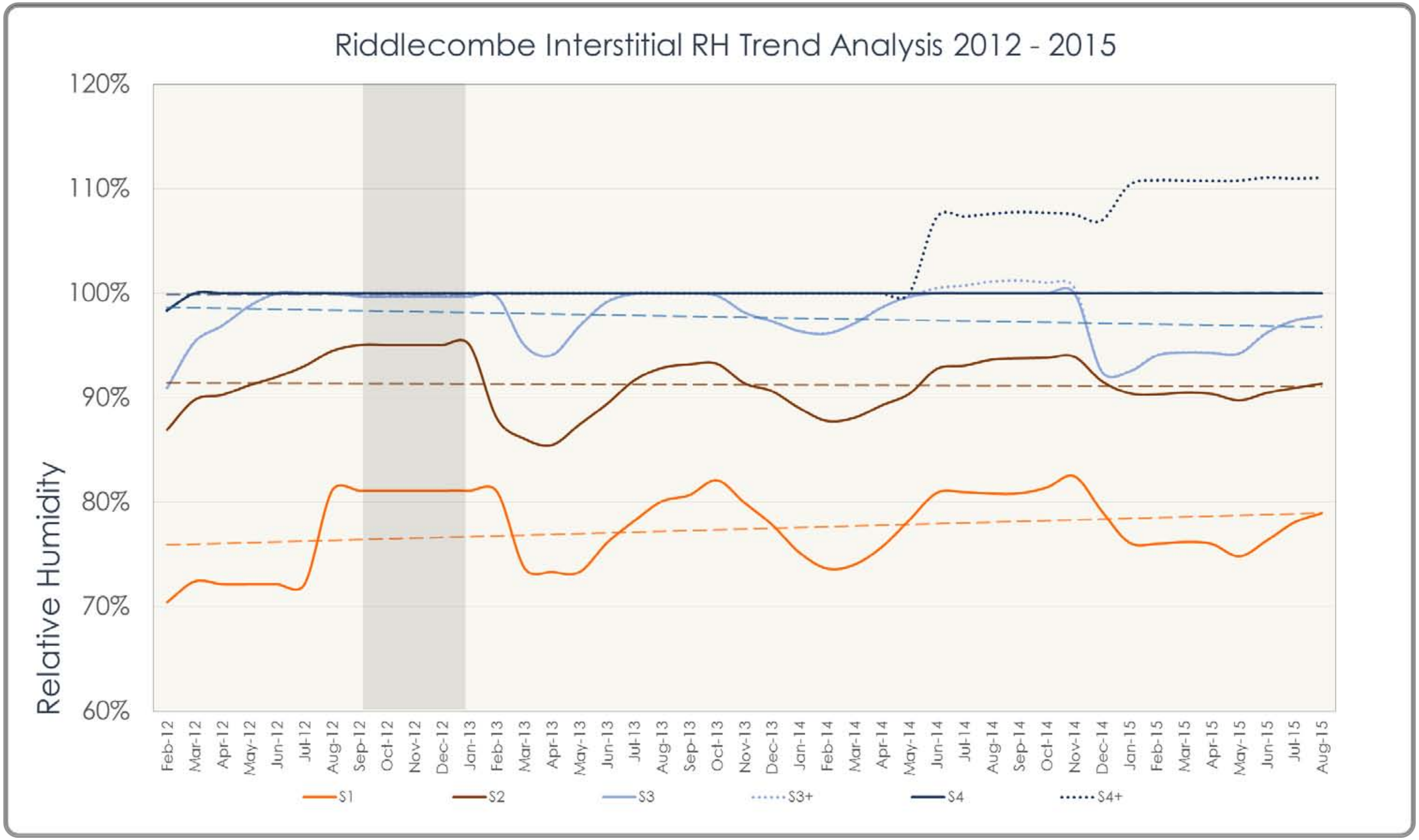


Figure 38. Relative Humidity Trends over time, Riddlecombe, 2012 - 2015.

3.2 Absolute Humidity (AH)

Table 23 provides details of the annual average AH values for the four interstitial sensors situated in the monitored walls at Shrewsbury, Drewsteignton and Riddlecombe post-insulation. Blue shading indicates decreases in AH and orange increases in AH year-on-year.

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

Table 23. Annual Average AH g/m^3 for all Interstitial Sensors 2012 - 2014.

All the three walls in the study show largely the same general trend of year-on-year increases in average weights of vapour. As has been demonstrated weights of vapour increase (to different degrees) through the individual wall sections in line with general increases in atmospheric vapour. The weather since post-refurbishment monitoring began in 2012 has been characterised by record-breaking rainfall and warm temperatures. 2012 saw a very wet spring and summer and had the second highest annual rainfall since 1910. 2013 had a cold and late spring followed by a very warm summer with a heat wave in July then severe storms with strong winds over the winter. 2014 was the warmest year on record (since 1659) and also much wetter than average, being the fourth wettest year since 1910. It seems probable therefore that the general increase in weights of vapour in the walls are a reflection of conditions that have caused exceptional wetting of substrates (including the effects of wind-driven rain and unseasonably high rainfall) combined with periods of higher than average warm, sunny weather which aid the vaporisation of moisture from materials.
However, a comparison of the difference between 2012 – 13 and 2014 -15 weights of vapour at each of the sensor locations shows different degrees of change and may reveal more individuated drivers for each wall. Weights of vapour measured through the section at Drewsteignton have increased more than those of Shrewsbury. Deep in the wall, at sensors 2 and 3, there is roughly a two-fold increase in the rise in AH measured on average compared with that of Shrewsbury. Both these increases are greater than those found for Riddlecombe, which has smaller gains of weights of vapour at sensors 2 and 3 and indeed a reduction in AH this year at sensor 4. The exception to this is the annual average AH measured at sensor 1 at Riddlecombe which shows the greatest increase of all the sensors in the three walls.

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

3.3 Saturation Margins

Table 24 shows the annual average saturation margins for the three walls in the survey. Blue shading indicates decreases in saturation margins and orange shading increases in margins year-on-year.

The saturation margin quantifies the temperature drop required for dewpoint conditions to be reached within the wall. It can be used as an indication of risk, that is the risk of air in the wall being at saturation (100% RH or dewpoint). This may also, at times, be an indication of wet fabric in proximity to the measurement sensor. Table 24 shows saturation margins as annual averages and so indicates the general condition of the wall in relation to proximity to dewpoint. From this it can be seen that, following both the RH and AH vapour trends, post-insulation margins at Shrewsbury are greater than those at Drewsteignton and Riddlecombe, indicating on average drier and ‘safer’ conditions as a greater temperature drop is required before dewpoint may be reached. Saturation margins at Drewsteignton and Riddlecombe are much narrower post-insulation, particularly at sensor positions 2, 3 and 4 away from the internal wall face and the benefit of interior heating during the colder winter months. In both these walls, at sensors 3 and 4, saturation margins are below that of 1˚C and given that these are average values we can speculate that temperature drops of this order occur frequently particularly over the winter time suggesting these walls are at greater risk from periods of saturated air. Indeed averages from sensor 4 at Riddlecombe over the past two monitoring years show dewpoint as the predominant condition suggesting that material here is likely to be wet.

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

Table 24. Annual Average Saturation Margins for all Interstitial Sensors 2011 - 2015.

The trend in these margins as indicated by the shading in the table also follows those indicated by an analysis of RH (this is to be expected as saturation margins are calculated from measurements of %RH). There has been a general increase in the margins for the wall at Shrewsbury reflecting warmer temperatures and fewer instances of driving rain leading to a reduction in wetting and also more effective drying over the past year. These factors, to a lesser extent can perhaps also be seen at play in the wall at Drewsteignton where margins at the periphery have slightly increased. In contrast those at the centre of the wall, sensors 2 and 3, continue to reduce in line with the trend of rising RH found for this part of the wall suggesting that the moisture risk is increasing in the middle of the wall and immediately behind the PIR insulation. Riddlecombe has the narrowest margins of all and no margin at all at sensor 4. In this sense there is nothing to quantify here in terms of how close the air is to saturation - it appears to be permanently saturated. Whilst margins at sensors 2 and 3 are quite small indicating a greater risk of saturation at these locations, there may also be a slight but encouraging trend if one accepts the premise that the vapour load is largely the result of the vaporisation of construction moisture. In these circumstances the increase in the margin measured at sensor 3 and the decrease in margins at sensors 1 and 2 as a result of vapour movement may indicate that moisture bound in to the centre of the walls is slowly beginning to dry out. Therefore, whilst the risk of saturation is still high in this wall we might be able to expect this to decrease over time.

4. SUMMARY AND CONCLUSIONS

Since 2011, the three walls in the SPAB Building Performance Survey have been subject to long-term interstitial hygrothermal gradient monitoring (IHGM) - measurements of temperature and relative humidity (RH) made through and either side of a wall section. Beginning in 2014 this series of measurements was joined by additional monitoring of material moisture using gypsum-bound resistivity sensors embedded in the substrate. As such this research attempts to identify aspects of moisture responses through the three insulated solid walls via different measurement proxies: air and/or gypsum plaster. As this research continues the value of long-term detailed measurements becomes increasingly apparent. Certain trends and tendencies are revealed as more or less significant depending on the different, and at times competing, influences on the moisture profiles of the walls.

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

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

The south-facing 655 mm cob wall at Riddlecombe is externally insulated with 60 mm of a lime-based external insulating render that incorporates perlite. Riddlecombe has the highest vapour profiles, %RH and AH g/m^3 of the three walls in the study. It also has the smallest or no saturation margins ˚C. Responses measured in this wall differ from those of the other two walls in the study largely we believe because the most significant factor with regard to vapour behaviour here is construction water. Findings of unseasonal persistent and rising %RH over summer months suggested substantial vaporisation of moisture within the earth wall material occurring as a result of the heating of the wall by solar radiation, something which this year's solar analysis, Figure 31, has confirmed. The question remains whether this wall is able to reduce its internal moisture load via vaporisation and evaporation? For the first time this year we see a reduced annual average measurement of %RH at the sensor 3 and a wider saturation margin implying that residual material moisture at this location may have fallen. This year measurements of vapour at sensors 1 and 2, towards the internal side of the wall, have increased and this may be due to the movement of vapour from the centre of the wall towards the internal wall surface. Over the three years it is now also possible to see a trend of %RH reduction at both sensors 2 and 3 over time, which also implies a possible gradual drying of the interior wall material. This drying is taking place very slowly, possibly inhibited by the thickness of the external render and the very air-tight cob wall construction. However, this also shows very high records of %RH and a static 0˚C saturation margin over the whole three years towards the external side of the wall at sensor 4, indicating that the wall continues to be wet at this location.

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

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

MATERIAL MOISTURE APPENDIX

Between May and June 2014 three ArchiMetrics material moisture sensing units were installed within the walls already under study in the SPAB Building Performance Survey. Further details concerning these units and the installation methodology are given in the introductory section of the report. Figure 39 provides details of the wall build-ups and sensor positions for each wall, blue indicating moisture sensors.

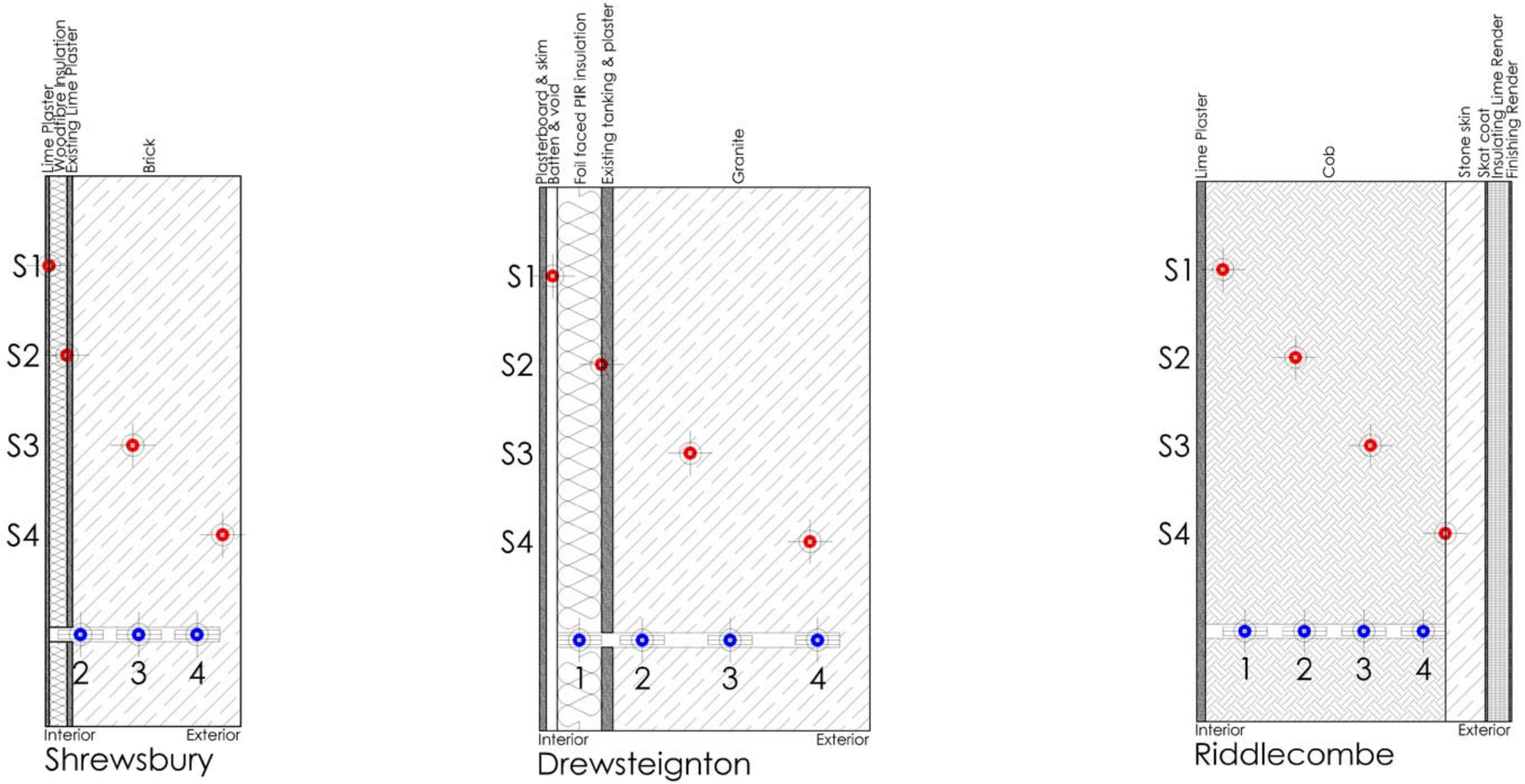


Figure 39. Wall build-ups and sensor positions; IHGM (red) and material moisture (blue).

Material Moisture Conditions

The three walls that are the focus of the SPAB BPS II study are quite different from one another in terms of materials, thickness, orientation and refurbishment treatments. The wall at Shrewsbury is a relatively thin (360 mm) south-facing brick wall insulated internally with 40 mm of woodfibre board. Drewsteignton is a much thicker, north-west facing stone wall made of granite, 600 mm thick, also insulated internal with 100 mm of PIR board. Riddlecombe is a south facing cob (earth) wall, 650 mm thick, insulated with a lime-based external insulating render approximately 50 mm in depth. Subsequently, each wall displays quite different characteristics with regard to temperature and moisture behaviour over an annual cycle.

Figures 40 – 42 show plots of moisture content measured by the individual interstitial wall sensors for each of the three walls for the year 2014 -15. The date range of each analysis graph is given in a table at the top right corner along with sensor depth information and minimum, maximum and average quantities for the reported period. The moisture content scale of the graphical analysis (vertical Y axis) is 0 – 5% for the walls at Shrewsbury and Drewsteignton and 0 – 6% for Riddlecombe. Flat lines indicate periods of time where no data is available.

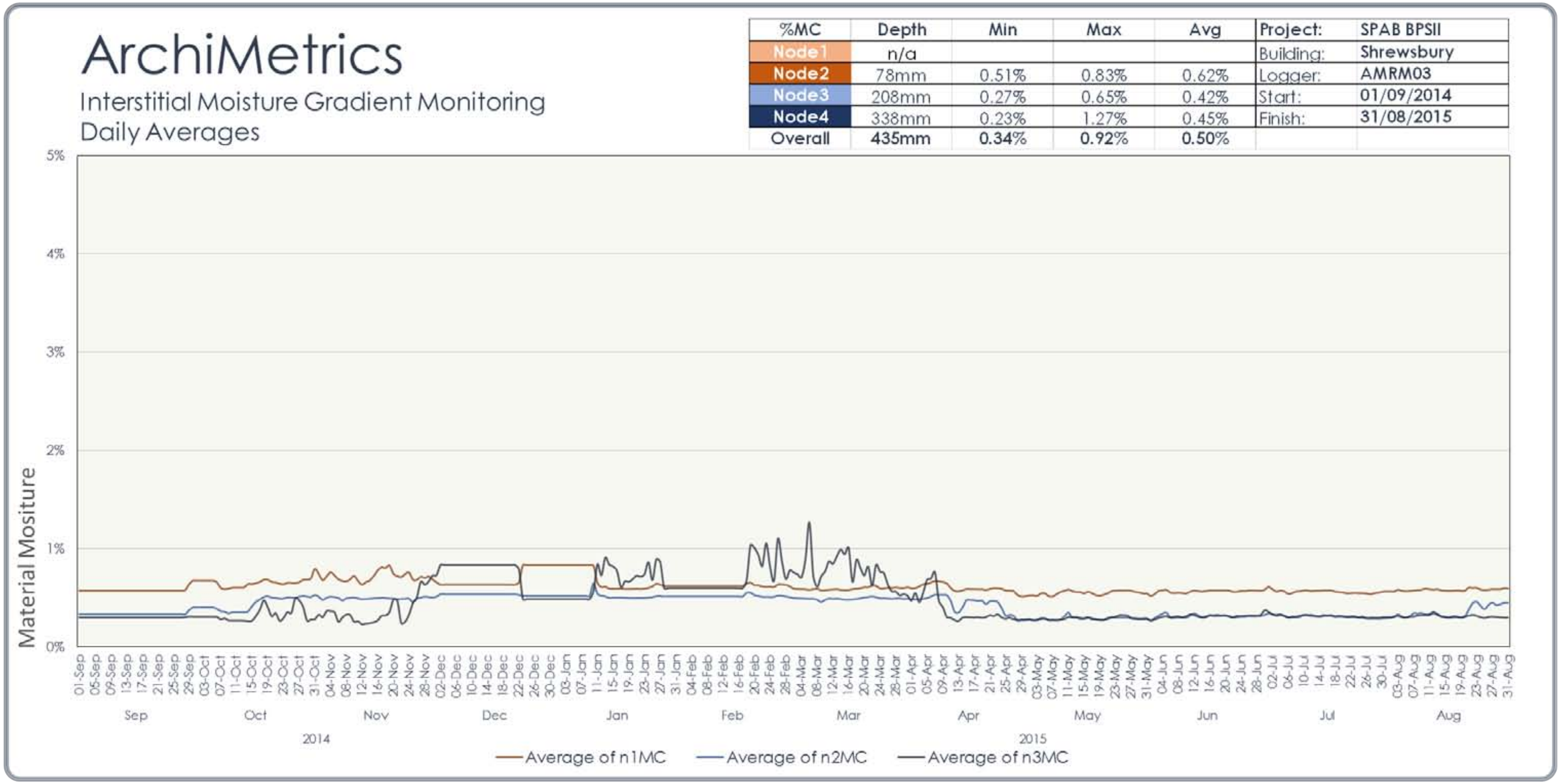


Figure 40: Material moisture content over time, Abbeyforegate, Shrewsbury 2014 - 2015.

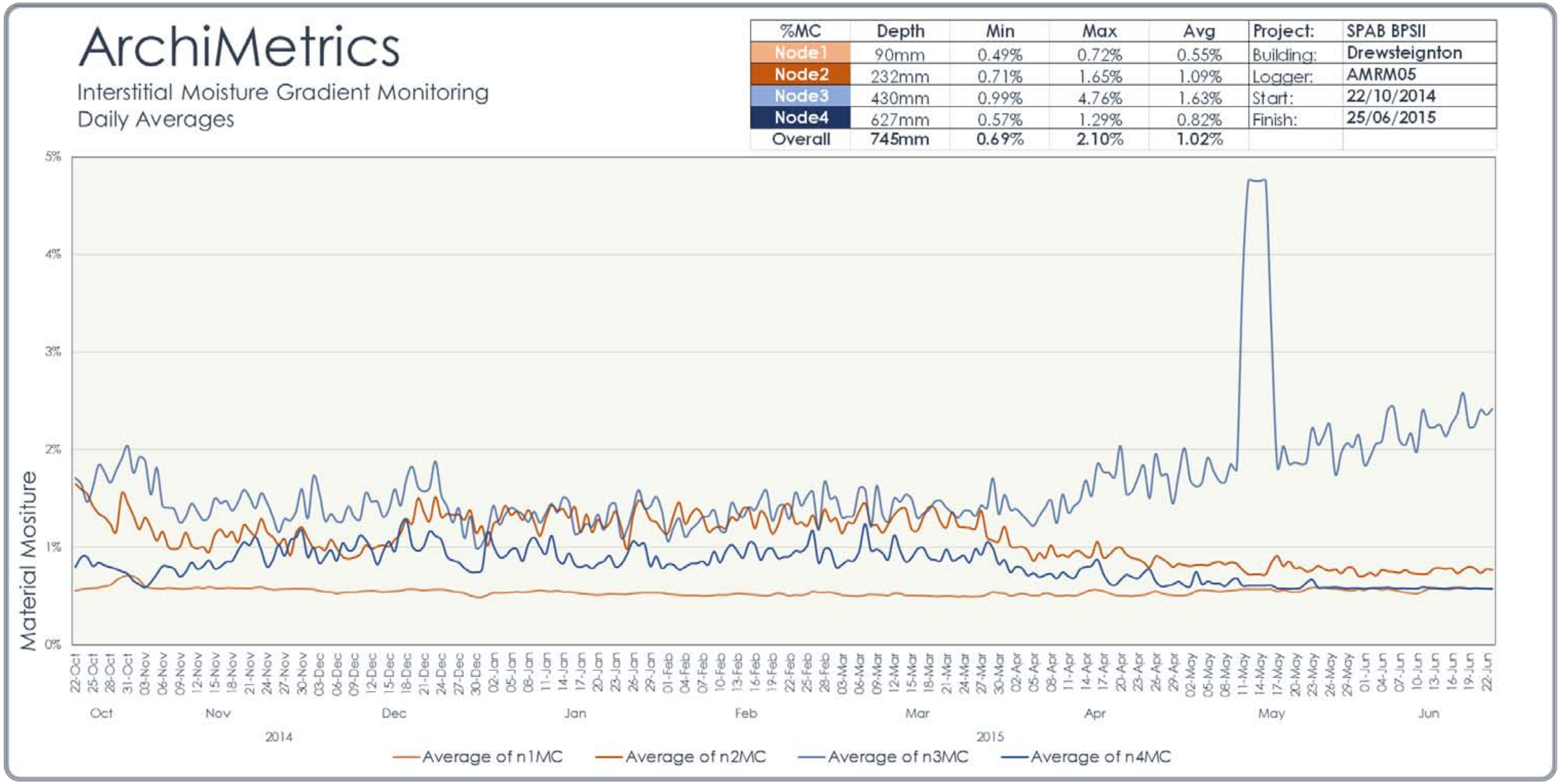


Figure 41: Material moisture content over time, Mill House, Drewsteignton, 2014 - 2015.

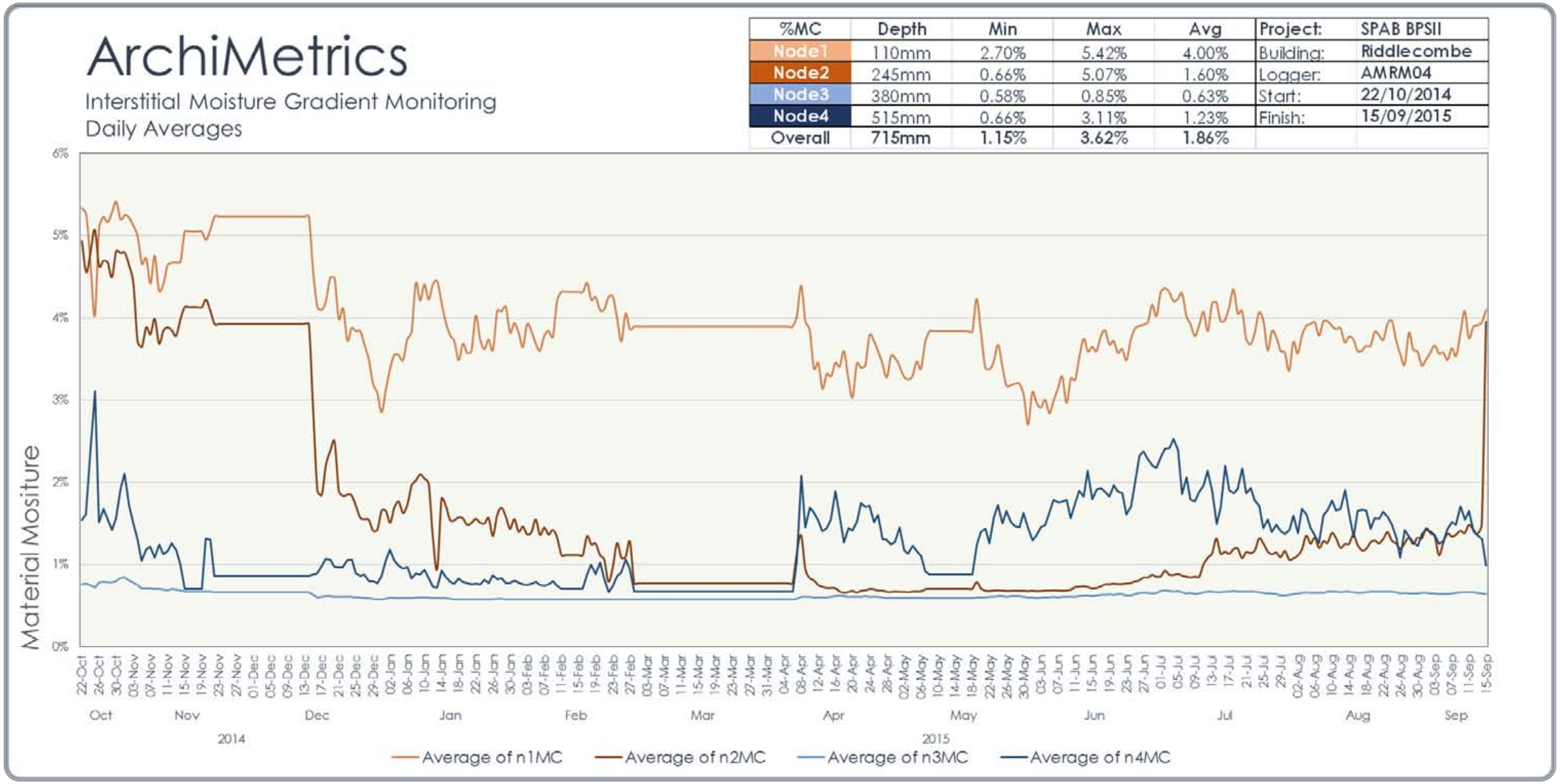


Figure 42: Material moisture content over time, The Firs, Riddlecombe, 2014 - 2015.

As can be seen from Figures 40 – 42 the brick wall at Shrewsbury provides the lowest moisture content measurements over the reporting period. At Shrewsbury %MC rarely peaks above 1% and only does so for a few brief periods at the end of the winter season at sensor 4, which is positioned towards the external face of the wall. Here moisture content peaks at 1.27% probably as a response to direct wetting from wind driven rain, behaviour that has been seen previously via the %RH measurements for this wall. Through autumn %MC at sensors 3 and 4, within the masonry section of the wall, are lower than that measured at sensor 2, the interface between the woodfibre insulation and the internal face of the brick wall. As we move into winter, measurements of %MC increase at sensors 3 and 4 and for a time are highest at sensor 4. However, measurements fall back to previous levels with the onset of spring and summer, first at sensor 4 and then, as drying takes place deeper within the wall, at sensor 3. Responses at sensors 3 and 4 are seasonally related whereas those at sensor 2, as with measurements of %RH, are roughly consistent throughout the year. For most of the year sensor 2, between the insulation and brickwork, has the highest levels of moisture content and %MC is always higher at this location than that recorded in the centre of the brick wall at sensor 3. For this reason the highest average %MC over the reporting period, 0.62%, is recorded from sensor 2 at the woodfibre/masonry interface, however, this value is well below any risk threshold for timber material. On average the %MC for this wall for all three sensors over the reporting period is 0.5%.

The walls at Drewsteignton and Riddlecombe both have higher % moisture measurements. The average %MC for the granite wall at Drewsteignton is roughly twice that of Shrewsbury, 1.02%. The sensor traces are also generally quite different for this wall compared to those of Shrewsbury with greater variation in %MC quantities measured through the masonry section throughout the year. The exception to this being measurements made at sensor 1 embedded within the PIR insulation material. Here moisture measurements are low with little variation throughout the year. This might be expected as this material is closed-cell and therefore not able to hold water and in addition is separated from the moisture influences of the solid masonry section of the wall and the room interior by the foil-facing membrane of the insulation board. Elsewhere, within the masonry section represented by sensors 2, 3 and 4, different seasonal variations can be observed. Measurements from the three sensors tend to coalesce over the winter months but with different directions of travel. %MC at sensors 2 and 4 rise over the winter period but decrease during the spring and summer months. In the centre of the granite wall, sensor 3 measures its lowest quantities of %MC over winter and sees %MC rise over spring and summer. This sensor position has the highest average measurement of all the four sensors for the year, 1.63%. This pattern may suggest that the falls seen in %MC over spring into summer at sensors 2 and 4 occurs, in part, due to moisture travelling towards the centre of the wall therefore raising %MC at the sensor 3 location. This might occur through surface diffusion, a process by which moisture condenses on pore surfaces and can form a liquid film by which the moisture then moves, or capillary transport, or a combination of both moisture movement mechanisms.

The cob wall at Riddlecombe has the highest records of %MC of the three walls in the study, the annual average recorded from all sensors in the wall being nearly double that of Drewsteignton, 1.87%. Overall, there is a greater range of quantities of moisture measured through the wall section. The unfired earth (cob) material of the wall at Riddlecombe has very different qualities in relation to moisture than those of the masonry (brick and stone) walls at Shrewsbury and Drewsteignton. The cob is highly hygroscopic and permeable and the dynamism of the moisture responses measured from sensors 1, 2 and 4 in this wall reflect these qualities to show a more moisture active wall. For this reason measurements from the individual sensors also cover a wider range than those from the walls at Shrewsbury or Drewsteignton, sensor 2 having the widest range from 0.66 – 5.07% MC. The exception to this is sensor 3 which shows quite different moisture content behaviour to that measured elsewhere in the wall. Here %MC is low and there is little variation throughout the year, similar to measurements taken from the 'dry' PIR layer at Drewsteignton. Sensor 3 at Riddlecombe should be embedded within the cob material within the wall, however the trace from this sensor may suggest that the sensor node is not fully bonded to the substrate. If the capsule sits within an accidental air pocket it may not be impacted by changes in moisture content within the cob and therefore will not exhibit the same dynamic responses shown by the other sensors. Another possibility is that the sensor has a broken wire which means it provides an incomplete or partial signal. As referenced previously, sensor 2 shows the greatest change over the reporting year, with a sustained decline in %MC from October 2015 to March 2016 and thereafter a slight rise to above 1% from July onwards. However, in the final week of the analysis, in September 2015, %MC rapidly increases up to levels seen during the previous autumn/winter. The reason for this sudden change is not known - it may be a seasonal/temperature related phenomenon - as the wall fabric cools with the change to autumn water that was held as a vapour condenses? The data series for next years report, which will follow on from September 2015, may shed more light.

In the second half of the year, from April onwards, the traces from sensor 1, towards the interior face of the wall and sensor 4, towards the exterior face, seem be following similar responses, albeit with a roughly 2% difference between the quantities measured, sensor 1 being the higher of the two. This is interesting given that these sensors are at the two opposite extremes of the wall section yet their moisture responses appear to be similar. The temperature difference either side of the wall section reduces in spring and summer (Fig. 28) therefore temperatures at these two locations may be similar and the changes in moisture content are perhaps temperature related? The analysis suggests that over the spring and summer the 'wettest' material in the wall can be found towards the internal and external surfaces of the wall, whilst conditions are drier towards the centre. This would correspond with behaviour previously commented on in relation to atypical %RH behaviour observed within this wall, where %RH rises during the summer months. It has been surmised that this is the result of evaporation occurring from a wet substrate saturated during the re-rendering process. The proposition is that this vapour will move towards the wall surfaces from whence it will evaporate. That we see high moisture content at the wall extremes during spring and summer may suggest that this process, which has been taking place for several years since the cottage was re-rendered, may result, for a time, in higher moisture content at the wall extremes.

The brick wall at Shrewsbury shows the lowest moisture contents over the reporting period, %MC quantities are roughly double those of Shrewsbury in the granite wall at Drewsteignton and almost double once again in the cob at Riddlecombe. This pattern follows the findings from this and previous years %RH measurements. Over an annual cycle Shrewsbury records lower amounts of water vapour than that of Drewsteignton and Riddlecombe. Quantities of %RH at Drewsteignton lie between those measured at Shrewsbury and Riddlecombe and the cob wall at Riddlecombe records the highest %RH values. Whilst it may not always be the case that measurements of high %RH indicate the presence of liquid moisture, for the three walls under study here there would seem to be a general relationship between quantities of liquid moisture recorded within the substrate and measurements of %RH. This relationship suggests that Shrewsbury is a relatively 'dry' wall in comparison with the walls at Drewsteignton and Riddlecombe, with Riddlecombe being the 'wettest'.

Material Moisture Content and %RH Comparison

Figures 43 – 45 show a comparison between the moisture content plots for the individual sensors for each of the three walls alongside measurements of %RH. %MC is mark as a solid line whereas %RH is a dashed line. The date range of each analysis graph is given in a table at the top right corner along with minimum, maximum and average %MC and %RH quantities for the reported period. The material moisture scale (%MC) is given on the left-hand side of the graph, %RH on the right-hand side.

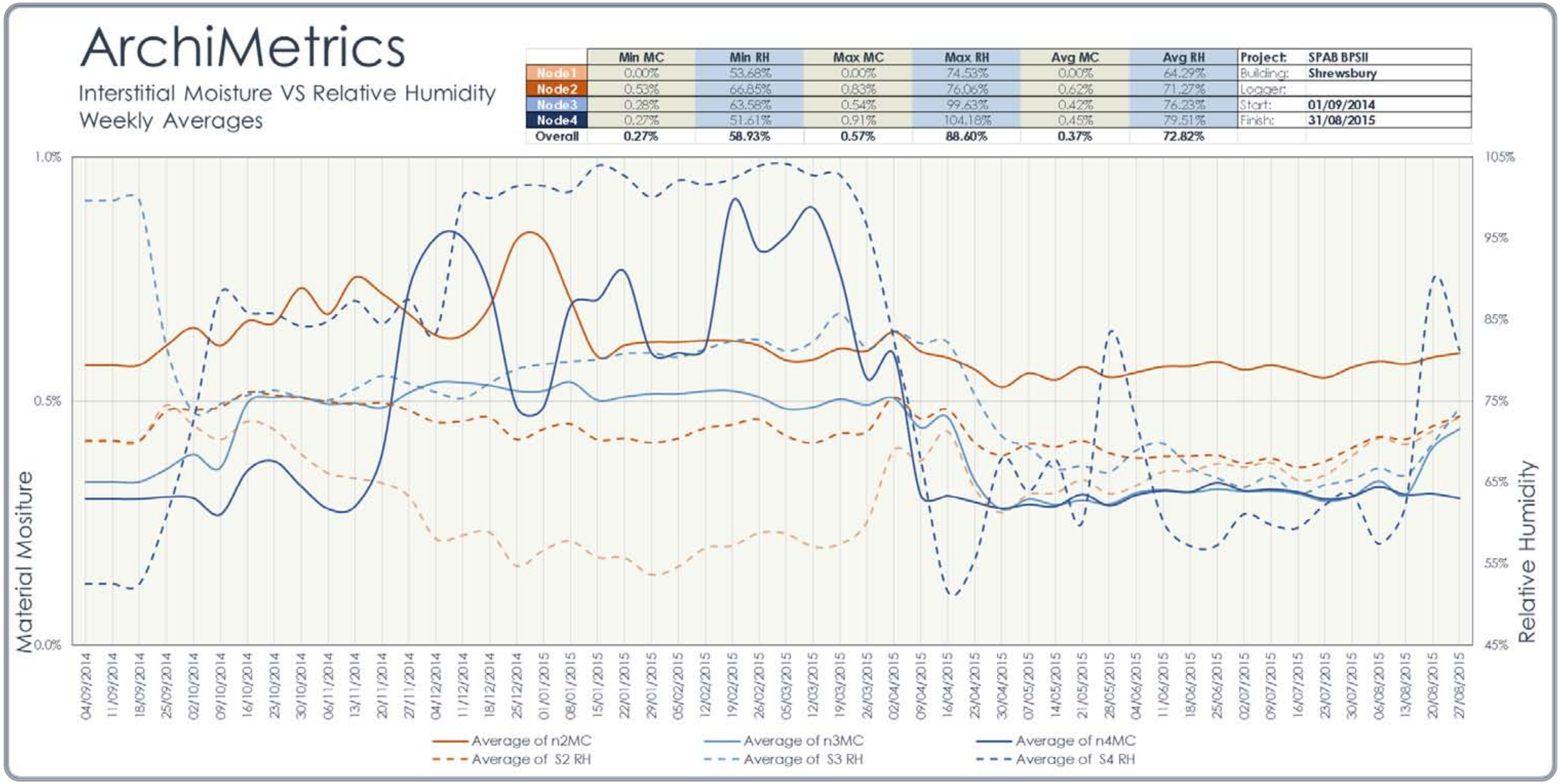


Figure 43: %MC and %RH comparison, Abbeyforegate, Shrewsbury 2014 - 2015.

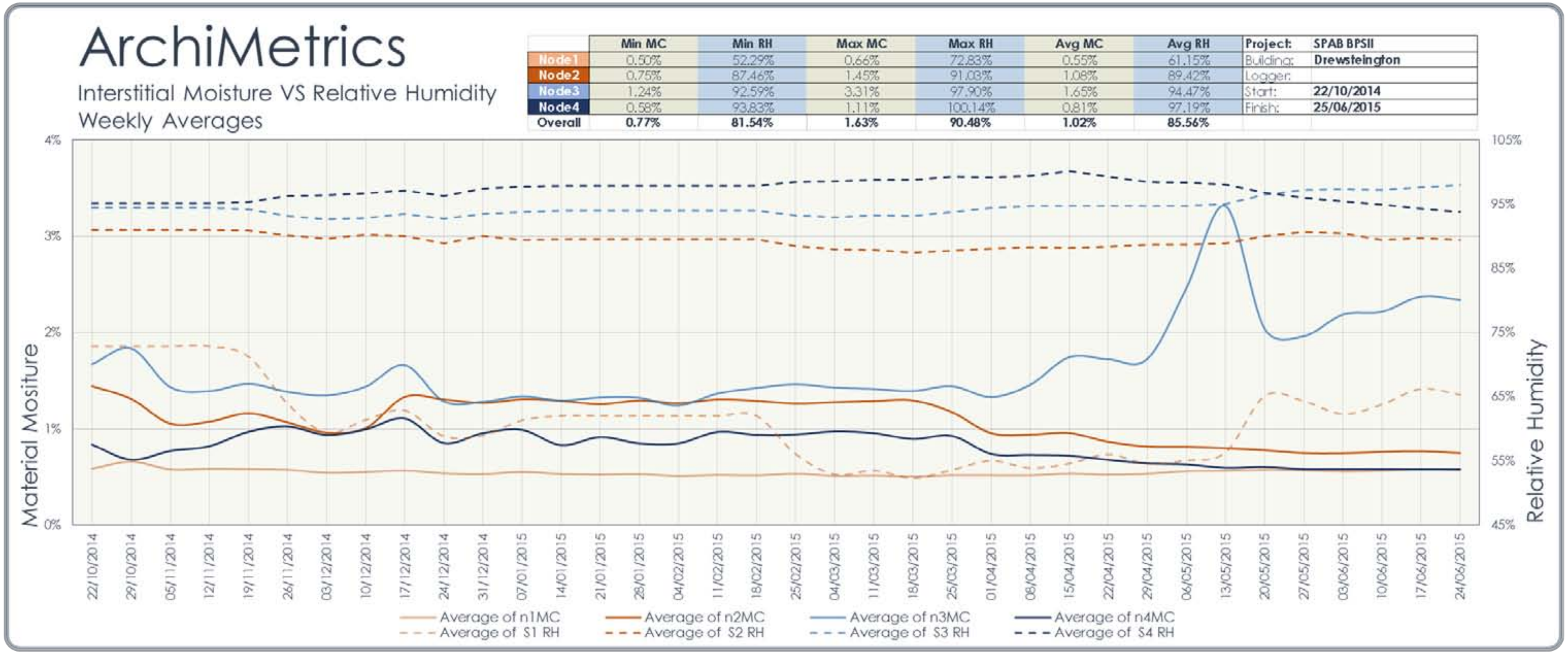


Figure 44. %MC and %RH comparison, Mill House, Drewsteignton, 2014 -15.

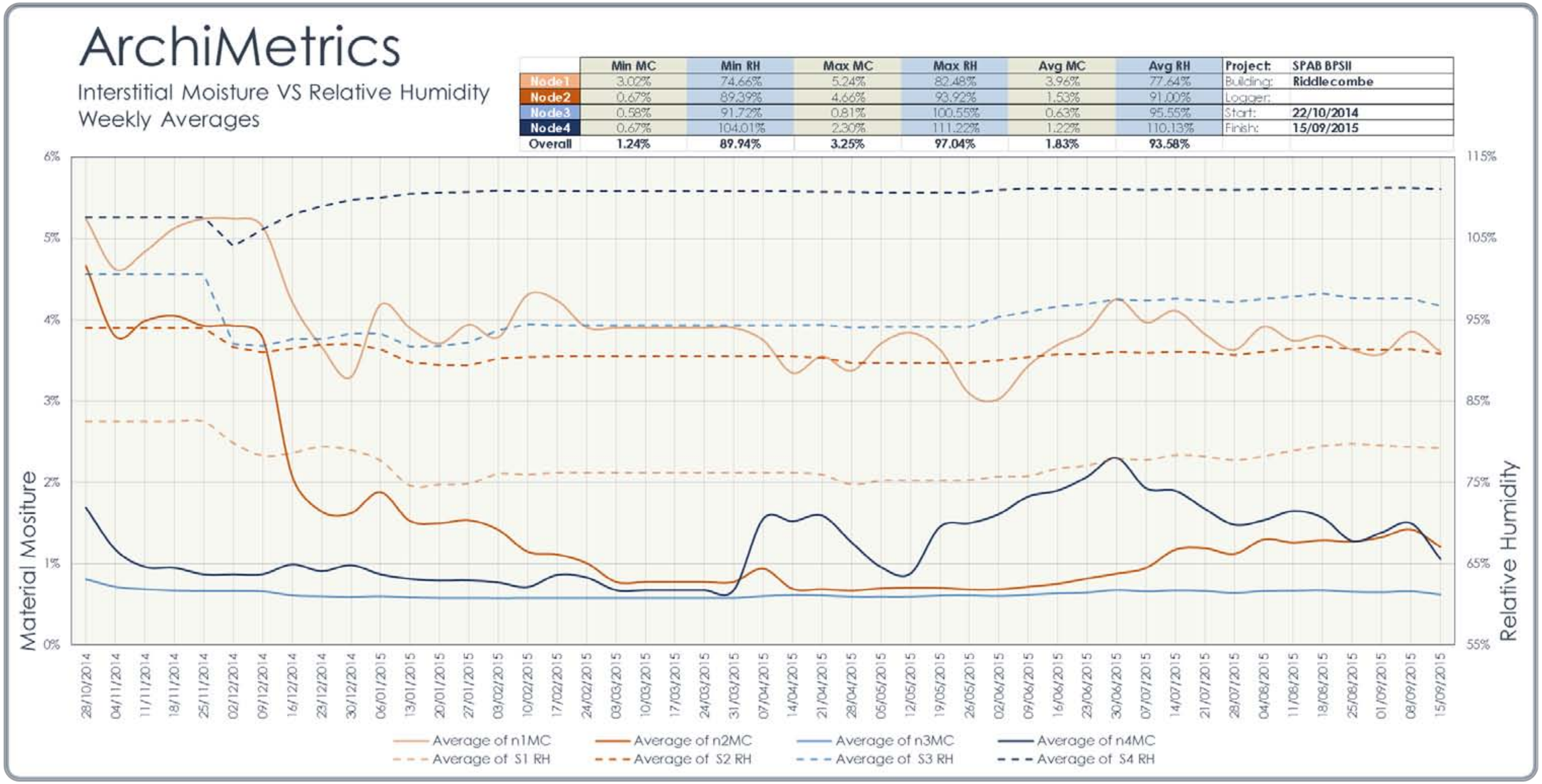


Figure 45: %MC and %RH comparison, The Firs, Riddlecombe, 2014 - 2015.

An examination of Figure 43 for the brick wall at Shrewsbury shows that, broadly speaking %MC and %RH measurements share similar responses. The sensors positioned towards the external wall face, sensors 3 and 4, see an increase in quantities over the winter period as the wall becomes colder and wet which diminish over the spring and summer months as wall material dries out. The RH and MC sensors in the 4th position, closest to external conditions, display the greatest range of responses over the reported year as this part of the wall is subject to the greatest degree of change with regards to moisture. The soft, hand-made bricks are quite porous and pointing is in poor repair so water is readily admitted into this part of the structure during times of rain and particularly rain driven by wind (see also Figs. 5 - 7 and pp. 9 – 10). With the onset of lower temperatures %RH begins to rise at sensor 4 from mid-September 2014, followed roughly two months later by a similar rise in %MC at this location as the moisture content of material increases. %RH remains persistently high throughout the winter months, at or around saturation, 100%, whilst %MC measured at sensor 4 is also at its highest over this period. Sensor 4 responses are the most volatile of all the sensor positions through the wall section due to their proximity not only to wet winter conditions but also warm summer drying where the open nature of the wall and south facing aspect encourage drying via heat and air movement. The steady decline in %RH, which starts in spring, week commencing 19/03/15, is preceded by a reduction in %MC which suggests that fabric at this location is drying via evaporation. The summer months see lower quantities and a narrower range of measurements for both %MC and %RH as moisture quantities are relatively low and there is less difference between amounts measured at each sensor position.

Responses from the moisture and humidity sensors located at the masonry/insulation interface, sensors 2, are of interest. As has been noted elsewhere (p. 69) the %RH response is particularly stable throughout the year operating within a narrow range of quantities 67 - 76%, possibly as a consequence of the moisture buffering (hygroscopic) qualities of the insulation material. The %MC response is somewhat different and shows more volatility over the wet winter period than through the following summer when %MC measurements are reduced. As has been previously noted this sensor position records the highest average %MC for the year, 0.62%, this again may related to the hygroscopic characteristic of the woodfibre material where due to the hydrophilic nature of the material water vapour is converted into liquid water by the process of adsorption (a phenomena possibly also observed in the cob wall at Riddlecombe see p. 19). This may also explain the more dynamic nature of %MC response at this sensor in comparison with the %RH response. However, the highest average %RH measurement, 80%, comes from sensor 4 as annual measurements are dominated by the peaks of vapour activity recorded towards the external wall face due to more intense cycles of wetting and drying.

Figure 44 presents the %MC and %RH comparison for the granite wall at Drewsteignton. The %RH gradients follow a standard pattern where %RH quantities increase in proximity to external conditions. This is true for the majority of the reporting period until the end of May 2015 where %RH at sensor 3 exceeds that of sensor 4 (see Fig. 18 and pp. 29 – 30 for further discussion). The %RH trace from sensor 1 is particularly detached from the remaining three sensors as it is located not within the masonry of the wall but in the air gap behind the plasterboard finish and this measures very different conditions, ostensibly those of the interior of the room. The material moisture gradient found for sensor 1 is quite distinct from the other gradients measured by %MC sensors 2, 3 and 4. This is also because this sensor is mounted in quite a different location, within the insulating PIR board, as opposed to the other three masonry sensors. The difference between the %MC and %RH traces for the two sensors situated in close proximity to the internal wall face can also be explained as each sensor measures quite different conditions. %RH is measured within an air gap and therefore shows a certain degree of moisture vapour volatility related to changes within the interior space whereas %MC is recorded within the very stable and dry foam insulation material, which is protected from any form of moisture incursion by the presence of a foil facing-membrane applied to the front and back of the insulating board.

The %MC traces from the three remaining material moisture sensors, sensors 2, 3 and 4, exhibit a different arrangement to that found for %RH. Highest quantities of moisture are not recorded towards the external wall face, as they are with vapour, but further back into the wall at the sensor 3 position. In fact, sensor 4 exhibits the lowest %MC records for the wall over the reporting year possibly because this part of the wall is closest to the drying influences of the external environment; solar radiation and air movement. Thus, as with Shrewsbury, the high vapour record for sensor 4 is a result of proximity to wetting and drying influences which in this case leads to relatively low %MC at this location in comparison with other parts of the wall deeper within the structure.

As has been noted elsewhere in this report (Figs. 36 – 38, pp. 62 – 63) the wall at Drewsteignton shows a year on year trend of increasing %RH following the insulation of the wall in 2012. It is not yet possible to determine long term %MC trends for any of the wall's as a more extended period of monitoring is required. What is visible from the comparison analysis for Drewsteignton, however, is an indication of how moisture behaviour might account for the rising %RH trend. From late April to mid May 2015 a spike is recorded in %MC quantities at the sensor 3 position (also seen in the previous Fig. 41) which is followed shortly afterwards by a rise in %RH at roughly the same depth within the wall. This occurs at the same time in the year when %RH at sensor 3 exceeds that of sensor 4. Preceding the spike in %MC at sensor 3, moisture content elsewhere within the masonry has started to drop (from mid- March onwards) as has %RH at sensor 4 (from mid April). Could the moisture spike at sensor 3 be the result of combined vapour and moisture movement from other parts of the masonry concentrating moisture within the central section of the masonry? In the %RH trend analysis for this wall (Fig. 37) the rising trend is most visible for conditions at the sensor 3 location. It is also the case (although this analysis does not comprise a full year's worth of data) that the %MC record at sensor 3 also has a rising trend for this period, in contrast to the gradients for sensors 2 and 4 which fall over the same period. Although the cause of the spike in material moisture measurements at sensor 3 is hard to determine it seems possible that the long term %RH trend for the wall maybe related to increases in moisture content quite deep within the body of the wall where, away from the external surface, it is harder for material to dry.

The cob wall at Riddlecombe (Fig. 45) also shows the conventional pattern of %RH distribution through the wall section, i.e. %RH increases towards the exterior conditions. Although, as has been previously noted, this wall has also demonstrates some atypical behaviour with increases in %RH measured over the spring and summer and %RH in this wall is high, largely above the 80% 'risk' threshold. The arrangement of the %MC traces are, however, largely the inverse of the %RH pattern. Leaving aside the plot for sensor 3 which may not be fully bonded to the substrate, for the first half of the reporting period the lowest rates of % moisture are recorded from a depth similar to that which measures the highest %RH, sensors 4. And visa versa, the sensor 1 position, which measures the lowest %RH of the four sensors in the wall, also shows the highest %MC. This changes in spring when %MC at sensor 4 begins to climb above that of sensor 2 and from around this time onwards the gradient traces from both sensor 1 and sensor 4 appear quite similar suggesting that they are responding to similar conditions. It has been suggested that these conditions are the saturation of the air causing condensation and wet material towards the interior and exterior surfaces of the wall due to high rates of evaporation from wet material within the centre of the wall.

In the cases of both Shrewsbury and Drewsteignton we have seen that the location of the sensor which records the peak average %RH does not correspond with that which measures peak average %MC. For these two walls in the study that can perhaps be explained by the degree of wetting and drying and hence vapour activity which takes places towards the external surface of the wall. Concomitantly, higher %MC is also measured deeper inside these walls away from drying opportunities. However, there is an almost completely inverse relationship between peaks of %RH and %MC at Riddlecombe. It is possible that this may relate to differences in materials and construction techniques between this wall and the other two walls in the study. Riddlecombe is the only wall of the three in the study that incorporates new materials on its external surface, in the form of an insulating lime render. It is possible that this formulated lime covering has increased the vapour resistance of this external surface to the extent that the conventional vapour diffusion path through the wall is reversed. Conventionally, the movement of vapour from the interior to the exterior of a building is encouraged via layers of material with diminishing vapour resistance, where interior coverings have the highest resistances. In this instance the wall is constructed from a highly vapour permeable material and the interior finish, lime plaster, is also relatively permeably. Under these circumstances vapour generated within the interior spaces may freely enter and move through the wall structure but its ultimate release via the external wall surface may be hindered or retarded by the higher vapour resistance of the insulating render causing vapour to accumulate within the structure, particularly towards the external surface.

In addition, another difference between this wall and those of Shrewsbury and Drewsteignton is the material it is principally made of. The unbaked earth material (cob) has far greater hygroscopic capacity than the baked earth (brick) of Shrewsbury and the granite stone of Drewsteignton. Records show that the %RH within the wall at Riddlecombe is generally high, for reasons previously discussed. It is possible that the higher moisture contents measured in the cob wall are also a result of this due to the process of condensation by adsorption. A description of this process is given in Historic Scotland Technical Paper 15; “Vapour diffusion describes the movement of gaseous water molecules in air. If these molecules come into contact with the surface of a hygroscopic material, e.g. within the material’s pore structure, the water can condense through adsorption, changing from vapour into a liquid. This condensation by adsorption is slightly different……..because it is not strictly tied to saturation and dewpoint temperature. It is rather that the molecular forces close to the surface are strong enough to pull nearby water molecules out of the vapour into a liquid state on the surface……The higher the relative humidity, the more easily the water molecules condense in this fashion. This only occurs on material surfaces to which water molecules can adhere, namely hydrophilic surfaces.” (p. 50). Therefore, the wall at Riddlecombe displays both high %RH and high %MC possibly due to inhibited vapour diffusion from its external surface as well as the saturation that has occurred to materials as part of the re-rendering process which vaporises during the warm summer months in the south facing wall. Some of this vapour then re-condenses back into liquid as it moves towards the wall surfaces due to the hygroscopic nature of the cob resulting in higher %MC at the wall extremes.

Summary

The comparison of the %RH and %MC findings from the three walls in the SPAB study shows that there is no simple relationship between %RH and %MC. Depending upon external conditions and the construction differences of the individual walls there are occasions when high %RH corresponds to higher measurements of %MC and times, as at Riddlecombe, when this relationship is inverted. What can be said with some certainty is that the general moisture profile of the walls is shared whether that profile be determined by measurements of water in a gaseous state or as a liquid. Relative to the other two walls the wall at Shrewsbury measures lower rates of %RH and %MC, Drewsteignton sits in the middle of the scale and Riddlecombe records the highest rates of both %RH and %MC.

The risk that these different levels of moisture pose to the individual wall structures is, however, harder to determine. Knowing the %MC of a material cannot tell you whether that material is wet or not as the percentage given is a measure of the difference between the dry and wet weight of the materials divided by the dry weight. Thus, smaller percentages in heavy-weight materials indicate similar amounts of moisture to those of lighter materials with higher percentages. An added complication is that although we know the main constituent materials of the individual walls we do not know these in detail and at the specific sites of measurement. The moisture sensor nodes are made of the same material and therefore measurements made between the walls can be compared. Beyond this, what these measurements indicate in relation to moisture and the risk of degradation as a result of high moisture content in the exact materials found within the walls is less certain.

From the point of view of determining risk %RH is a more satisfactory unit of measurement and the risk scale of most moisture probes is determined by relating measurements of the %MC of a material back to a generic timber species, as a known material, and relating this to an %RH scale where it is assumed that the timber is in moisture equilibrium with the air. As the %RH of air increases as does the %MC of the timber. This scale assumes that measurements of RH at 70 - 75% are equivalent to the MC of a generic timber material of about 15 – 16% and that these conditions do not represent a risk to fabric from moisture. 80% RH is the threshold commonly given for the commencement of mould growth on certain building substrates which can be related to a timber %MC of around 17 - 18%, the percentage at which timber is judged to begin to be at risk. With regards to %MC risk scales can be found for other generic materials; for example plaster at +1%, brick at + 2%, cement mortar at +5% and lime mortar at +6% might all be judged to be 'at risk' but as these materials are non specific and the percentages are determined by weights how translatable these figures are to the specific materials within the walls in the SPAB study is difficult to know.

The %RH measurements for the walls suggest that Riddlecombe is at greatest risk, where average %RH measurements for sensors, 2, 3 and 4 are above 80%, as are those for the wall at Drewsteignton. These measurements suggest %MCs of wood (or wood moisture equivalents - WME) of 23% and above. As timber is more susceptible to rotting than other building materials this is, therefore, also a useful indicator of risk. Regardless of the specific make up of particular walls there is often the possibility that timber maybe embedded within the structure (as lintels, joists or bearers etc.) and that in the event of damp conditions this may be the first element to fail. It is not know whether the walls under investigation contain embedded timbers or whether the higher %MC measured for the walls at Drewsteignton and Riddlecombe indicate an increased risk for these walls, particularly given the different nature of the cob material how this may influence it's moisture profile. As has been noted in the main body of this report,

%RH measurements made within the walls at Drewsteignton and Riddlecombe do indicate some risk which may in turn suggest that the +1% average %MCs measured for the granite and cob walls may equate to ‘dangerous’ moisture conditions? It is likely that the best use of this data, as with that of %RH, is as a means by which to determine longer term trends, for example such as the trend of rising %RH found for the wall at Drewsteignton. The moisture measurements made at this location, which perhaps show moisture movement towards the centre of the wall away from evaporative opportunities, may begin to shed some light as to the reasons for this trend. These measurements can therefore not only show us what is happening within the walls over the long term but also why it may be occurring.