Historic England

SPAB Building Performance Survey 2016

Interim Report
February 2017

Research conducted on behalf of the SPAB by ArchiMetrics Ltd
Supported by Historic England

February 2017

The SPAB RESEARCH REPORT 2.

The SPAB Building Performance Survey 2016

Interim Report

FEBRUARY 2017

ArchiMetrics Ltd.

www.spab.org.uk

The SPAB Building Performance Survey Interim Report 2016

Table of Contents

1. Introduction 2

1.1 Introduction 2
1.2 Methodology 2
1.3 Definitions and Analyses 3

2. Individual Property Reports 7

2.1 116 Abbeyforegate, Shrewsbury 7
2.2 Mill House, Drewsteignton 34
2.3 The Firs, Riddlecombe 56

3. Discussion 79

3.1 Relative Humidity 79
3.2 Absolute Humidity 85
3.3 Saturation Margins 90
3.4 Material Moisture 91

4. Summary and Conclusions 92

Acknowledgements

The SPAB would like to thank the owners of the properties used in the SPAB Building Performance Survey: James Ayres, Jason & Doe Fitzsimmons and Sebastian & Rosemary Payne. We are also grateful to Paul Bedford and Stephen Bull of the SPAB Technical Panel. We would particularly like to thank Historic England for its support of the monitoring and reporting work via its Heritage Protection Commissions grant.

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

Supported by:

Historic England

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, Devon) and cob (Riddlecombe, Devon). 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. Sensor specifications are as follows:

RH	Accuracy ±3%
	Repeatability ±0.1%
	Resolution (typical) 0.05%
	Long-term drift < 0.5% per year
T	Accuracy ±0.4˚C
	Repeatability ±0.1˚C
	Resolution (typical) 0.01˚C
	Long-term drift < 0.04˚C per year

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) is logged at five-minute intervals by a dedicated ArchiMetrics' monitoring logger mounted in close proximity to the sensor array.

Material Moisture Monitoring

A single 32 mm 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 – 150 mm of the external face. Depending on wall thickness, a number of 100 mm 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) is logged at ten-minute intervals by a dedicated ArchiMetrics' monitoring logger mounted in close proximity to the sensor array.

See Figures 3 - 4, 19 - 20 and 32 - 33 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 2015 – 16 data series will use +100% RH where as hygrothermal sectional averages use a capped value as do some comparative tables. Where capped values have been used this is noted in the Figure or Table caption.

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.

Dewpoint and Saturation Margins

Dewpoint (100% RH) 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. An illustration of the relationship between %RH, temperature and the ‘saturation margin’ is provided in 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 could be deemed to be of substance.

Dewpoint temperatures are presented in the form of hygrothermal sections, plots of the 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 the 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 and use 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 for 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 and Date Series

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. Occasionally, during the course of this work there are periods of time when data is lost. This can be for a number of reasons including power outages and equipment malfunction. 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. For operational reasons this year's, 2015 -16, Shrewsbury analysis begins and ends a week earlier than those of Drewsteignton and Riddlecombe.

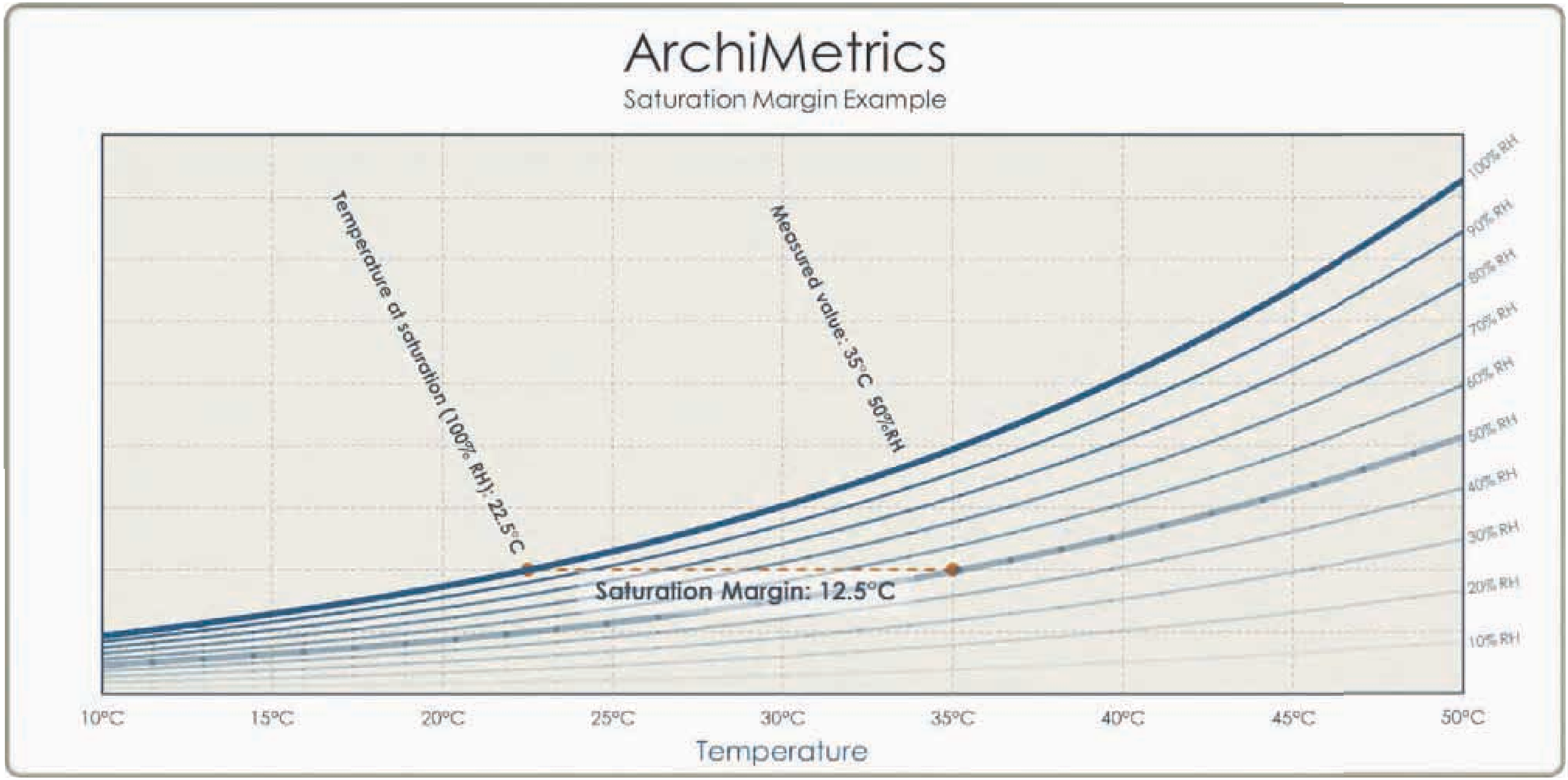


Figure 1. Illustration of Saturation Margin principle

2.1. 116 Abbeyforegate, Shrewsbury - 2015 - 16.

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.

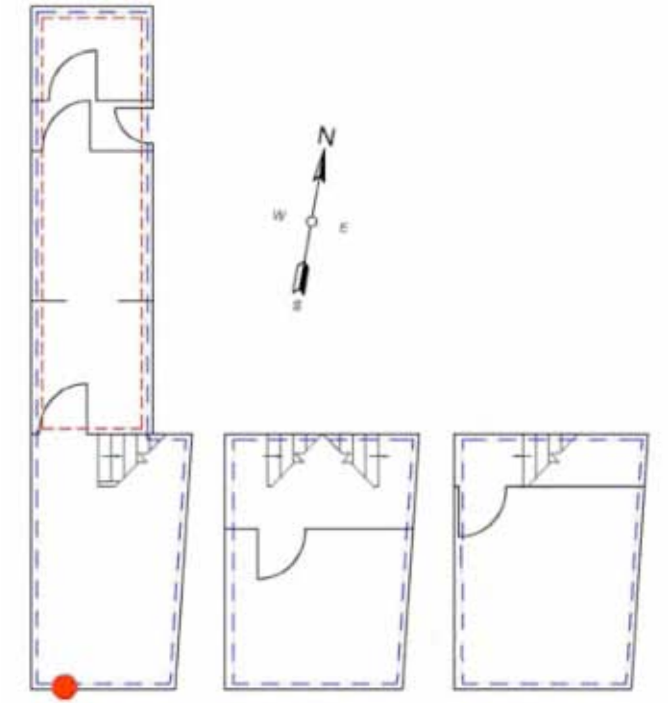


Figure 2. Plan of 116 Abbeyforegate, Shrewsbury, with ground floor on left hand side. The red dot indicates the location of the IHGM monitoring equipment.

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.

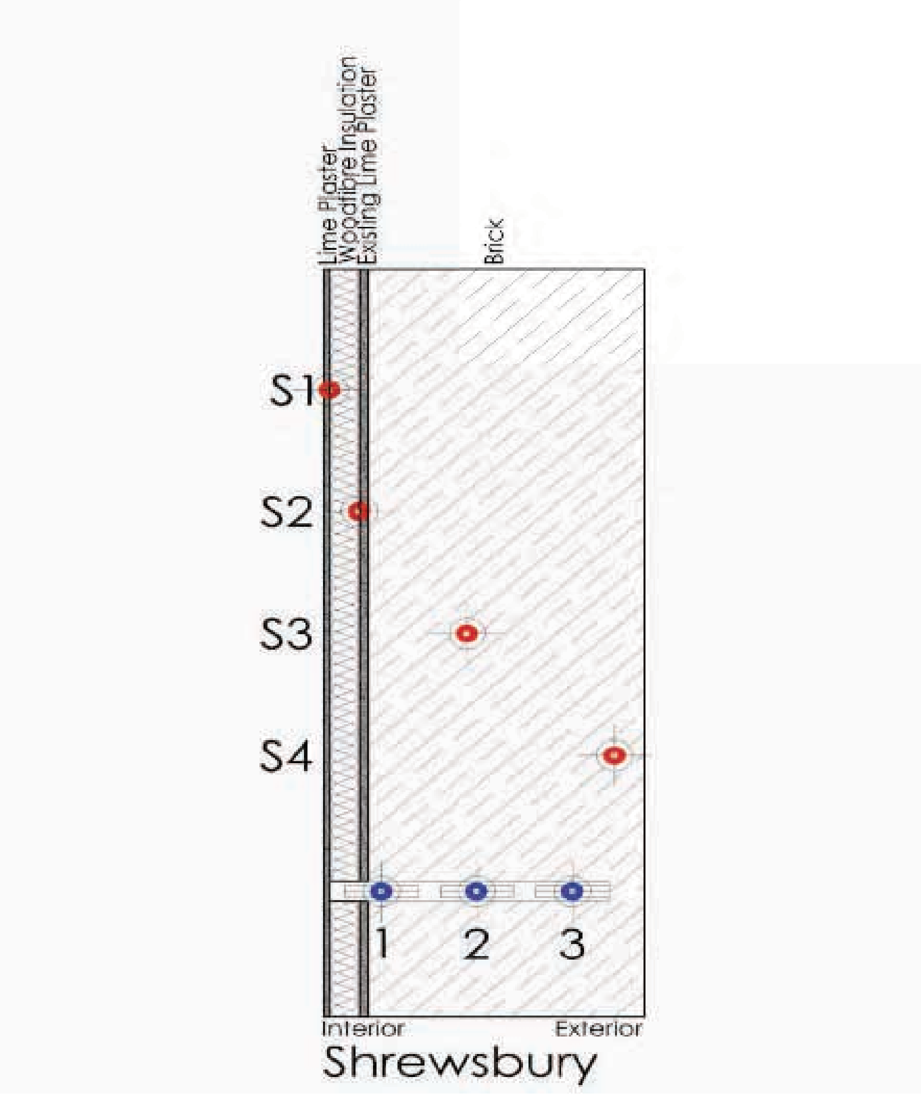


Figure 4. Position of wall sensors through section, Shrewsbury – red IHGM, blue Material Moisture

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
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 24th August 2015 – 23rd August 2016, has been used as the basis for the following analysis.

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. There is a period of time over the winter months where %RH at this location exceeds, 100%. For 2015 -16 this period is longer than that of the previous year, starting a month earlier in November 2015 and only falling below 100% towards the end of April 2016. %RH values are also slightly higher at S4 than those recorded over the 2014 – 15 winter. 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. These patterns, which repeat those of all previous years since measurements began in 2012, shows high %RH 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 on the south-facing wall.

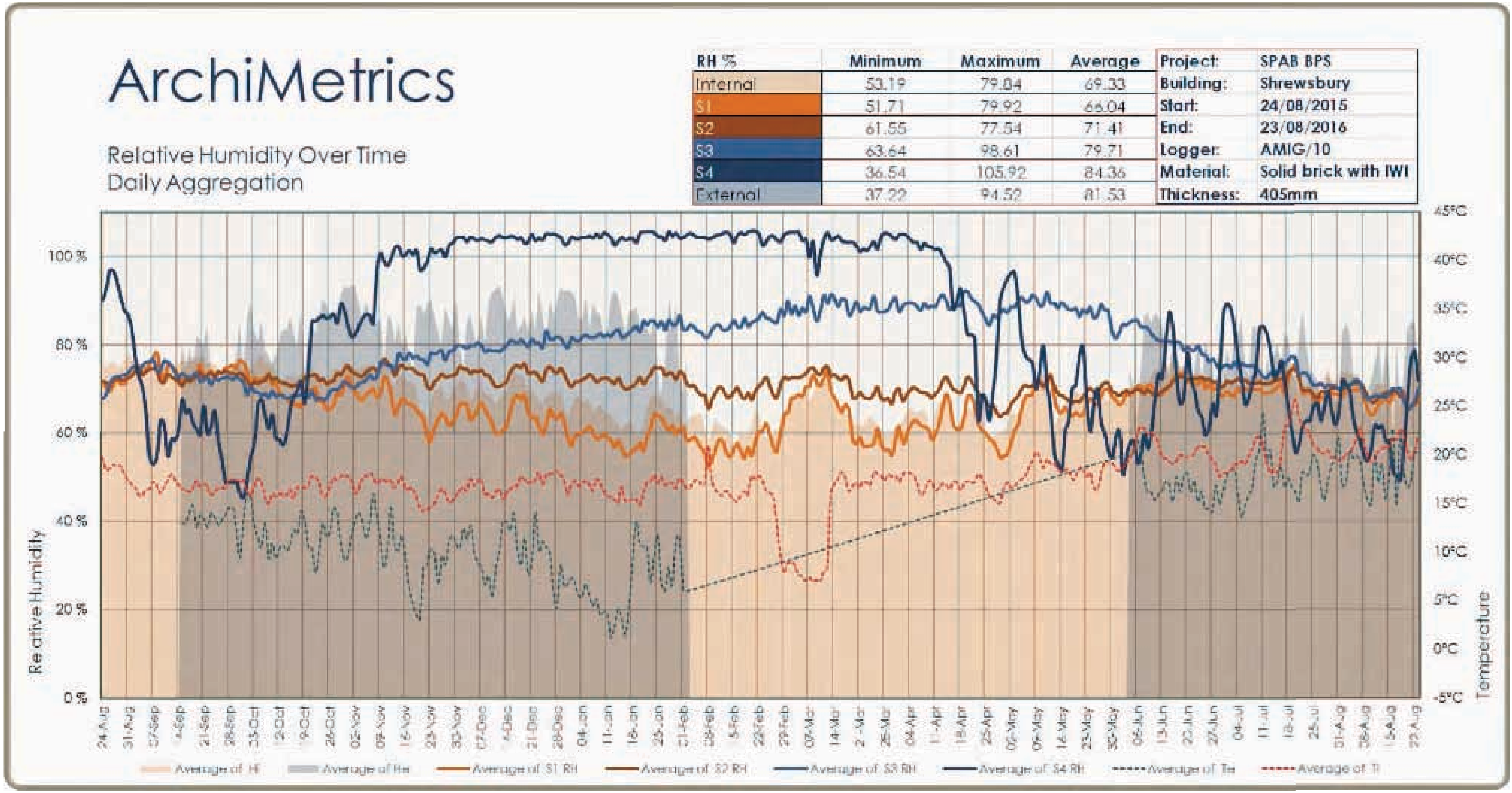
As before, exceptions to this general pattern occur occasionally between April and August 2016 when the wall is subject to heavy rainfall causing %RH to peak at sensor 4 before drying out once again (Figure 6). A different effect can be seen in conditions measured further back into the body of the wall at sensor 3. During the 2015 – 16 winter %RH at S3 increases gradually throughout the winter months and reduces more slowly following the drop in %RH at S4 at the end of April. Responses deeper within the wall at S3 are more muted and show a general trend of reducing %RH over the warmer summer months without the more volatile responses recorded at S4 towards the external surface of the wall.

In general, the higher %RH values which persist within the wall fabric for a longer period in 2015 -16 are a reflection of the wetter year. The total rainfall for Shrewsbury 2015 -16 was 489 mm as compared with 352 mm the previous year (Figs. 6 and 7). The effect of the wetter winter can be seen in Tables 2 and 3 as sensors 3 and 4 record their highest averages for these two locations since post-refurbishment measurements began. The picture at sensors 1 and 2 is more consistent where internal conditions are more controlled and stable year-on-year, but also reflect the buffering effect of the woodfibre insulation on conditions measured in proximity to this insulating layer.

At sensors 1 and 2 responses are less extreme. Once again, despite the periods of high %RH recorded at sensor 3 and 4, values at sensors 1 and 2 remain quite stable and below the 80% mould growth threshold. In the week beginning 23rd Feb until 15th March heating was switched off in the house resulting in colder internal temperatures. It is interesting to note the effect of this on measurements of %RH during this period. An increase in %RH is measured in response to these lower temperatures at sensor 1, the sensor closest to the internal wall surface as the room cools. Whilst there is also a %RH increase measured at sensor 2, 48 mm further into the wall at the woodfibre insulation, the increase is minimal. This suggests a moderating of both temperature and %RH responses in proximity to the insulation material. The very consistent annual average %RH measured at sensor 2 also demonstrates that this point of the wall is to some extent protected from changes caused by shifts in both internal and external conditions which can alter %RH values (Table 2). This creates a stable %RH profile below the mould risk threshold in a part of the wall often considered to be the most vulnerable with regard to internal wall insulation (IWI) applications.

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%
2015 - 2016	66%	71%	80%	84%

Table 2. Comparison of annual averages of RH measured through wall section, Shrewsbury 2012 - 2016.



RH %	Minimum	Maximum	Average
Internal	53.19	79.84	69.33
S1	51.71	79.92	66.04
S2	61.55	77.54	71.41
S3	63.64	98.61	79.71
S4	36.54	105.92	84.36
External	37.22	94.52	81.53

Project:	**SPAB BPS**
Building:	**Shrewsbury**
Start:	**24/08/2015**
End:	**23/08/2016**
Logger:	**AMIG/10**
Material:	**Solid brick with IWI**
Thickness:	**405mm**

Figure 5: Relative Humidity over time, Abbeyforegate, Shrewsbury 2015 - 2016.

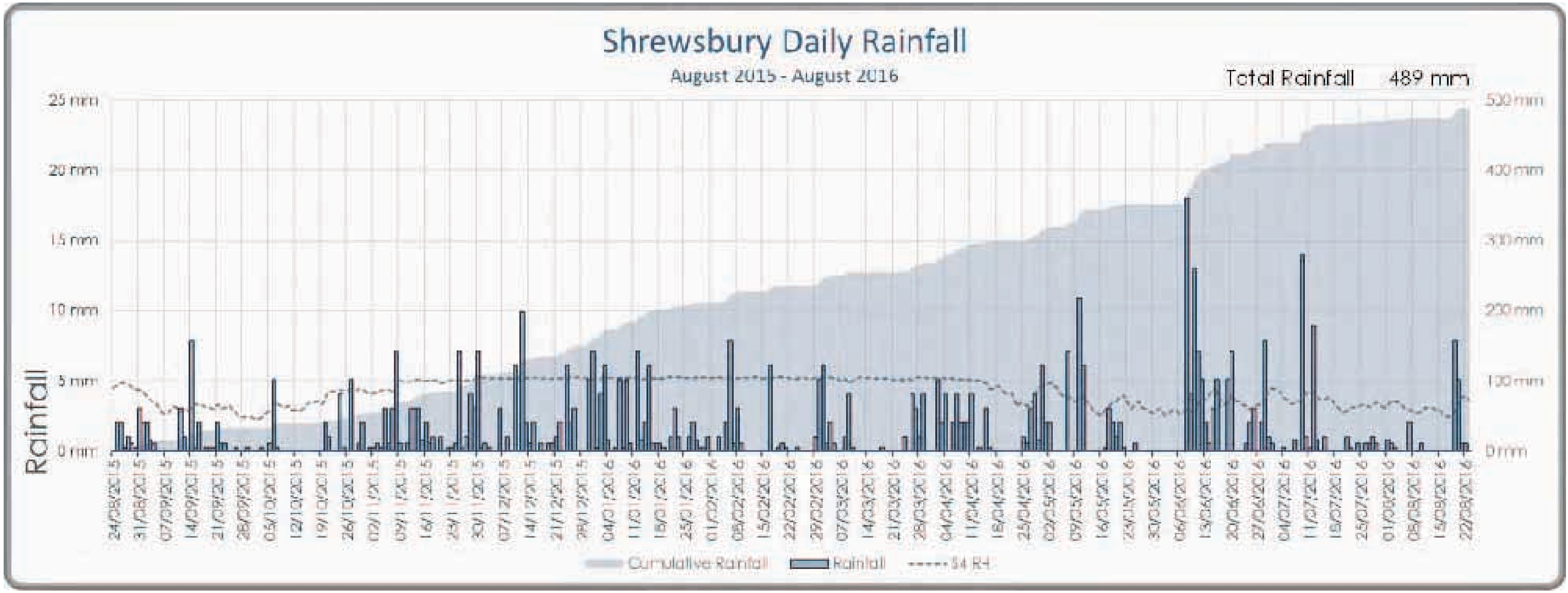


Figure 6: Daily & Annual Rainfall mm, including S4 RH trace, Shrewsbury 2015 - 2016.

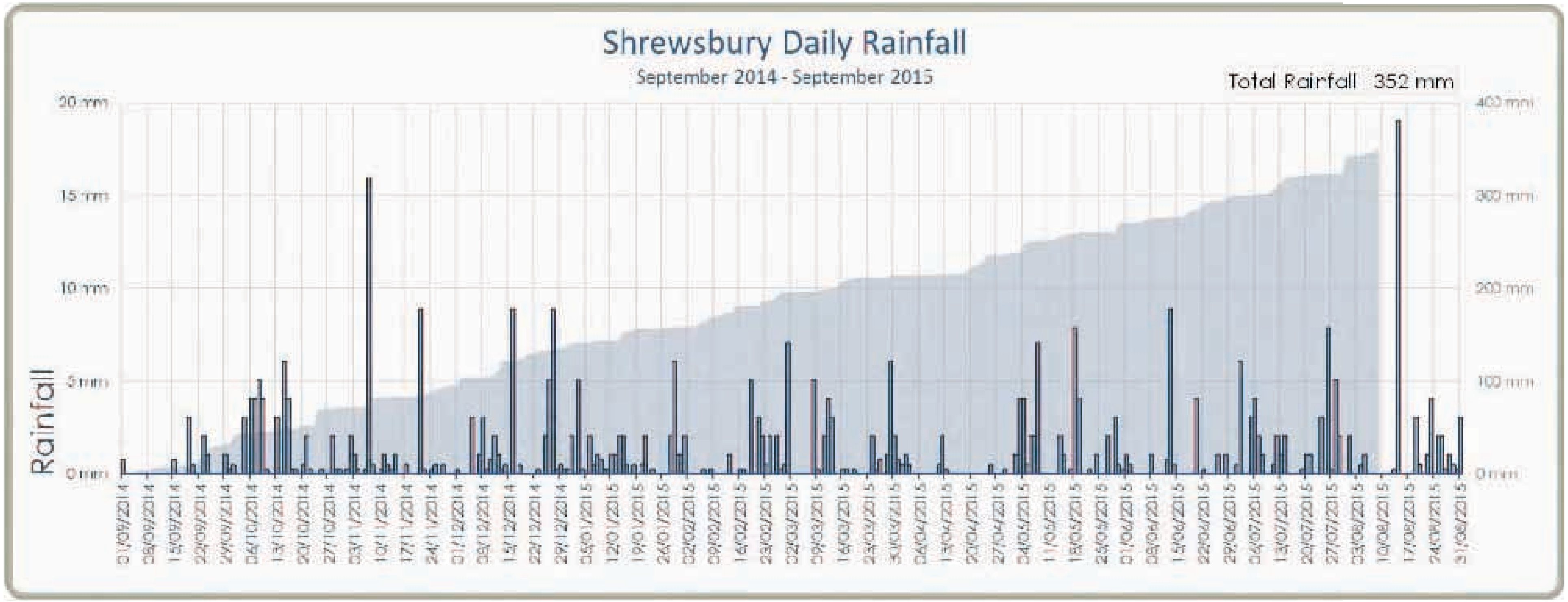
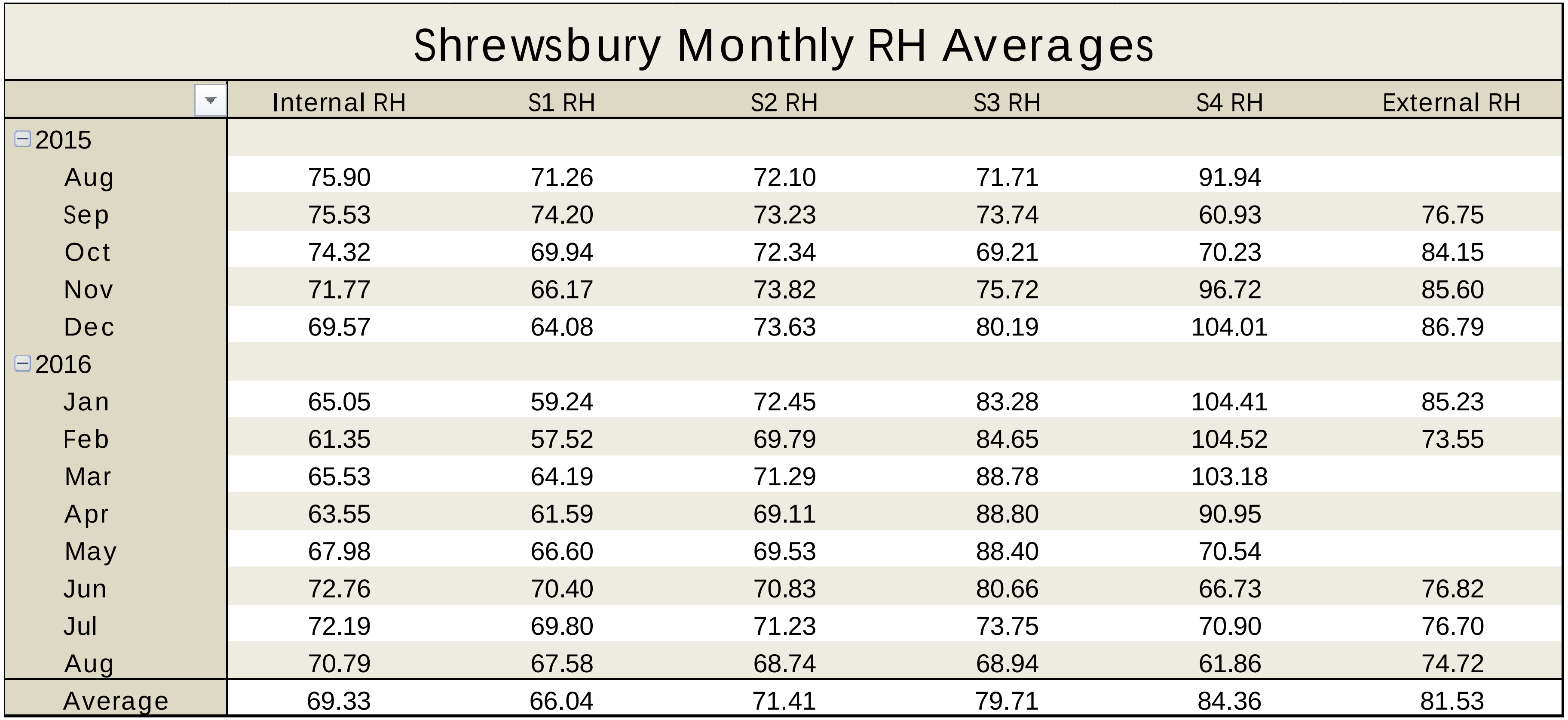


Figure 7: Daily Rainfall mm, Shrewsbury 2014 - 2015.



Shrewsbury Monthly RH Averages

	Internal RH	S1 RH	S2 RH	S3 RH	S4 RH	External RH
⊟2015						
Aug	75.90	71.26	72.10	71.71	91.94	
Sep	75.53	74.20	73.23	73.74	60.93	76.75
Oct	74.32	69.94	72.34	69.21	70.23	84.15
Nov	71.77	66.17	73.82	75.72	96.72	85.60
Dec	69.57	64.08	73.63	80.19	104.01	86.79
⊟2016						
Jan	65.05	59.24	72.45	83.28	104.41	85.23
Feb	61.35	57.52	69.79	84.65	104.52	73.55
Mar	65.53	64.19	71.29	88.78	103.18	
Apr	63.55	61.59	69.11	88.80	90.95	
May	67.98	66.60	69.53	88.40	70.54	
Jun	72.76	70.40	70.83	80.66	66.73	76.82
Jul	72.19	69.80	71.23	73.75	70.90	76.70
Aug	70.79	67.58	68.74	68.94	61.86	74.72
Average	69.33	66.04	71.41	79.71	84.36	81.53

Table 3. Relative Humidity monthly averages, Abbeyforegate, Shrewsbury, 2015 -16.

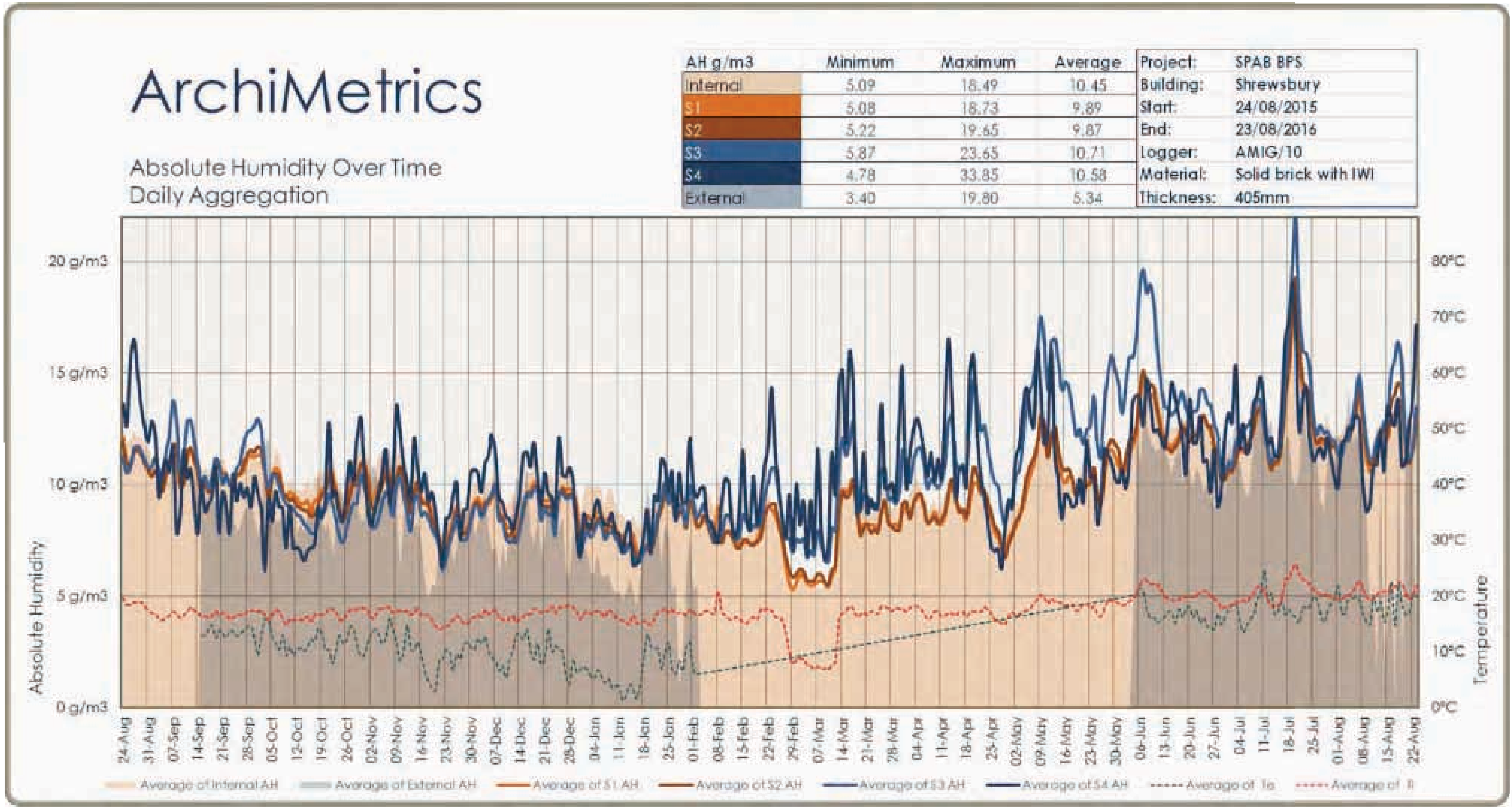
Absolute Humidity Over Time

Figure 8 shows an analysis of absolute humidity through the insulated wall section at Shrewsbury 24th August 2015 – 23rd August 2016. 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. However, it is the distinct peaks of AH measured over the summer months at sensor 3 that are of interest in this year's analysis. During a dry period around the end of May – beginning of June evaporative drying can be see to be taking place around sensor 3 signalled by the increasing weights of vapour measured over this time. As a daily aggregated average these quantities are greater than those measured concurrently at sensor 4, where most of the residual moisture accumulated within the fabric over winter has already been evaporated as can be seen from AH peaks from sensor 4 in March and April. Figure 6 shows a week of heavy rainfall starting around 7th June and as atmospheric conditions no longer support evaporation from the building fabric the AH record for this week shows a decline in weights of vapour at sensors 3 and 4. (The sensor 4 RH record moves in a contrary direction peaking at the end of this week as the wall becomes increasingly wet.) June is a very wet month, wetter than average and 8th June sees the highest daily rainfall total of the year for Shrewsbury, with little vapour activity on this day as well as the 10th (Figure 9). Weights of vapour measured at sensors 3 and 4 continue to decline throughout the month of June. There are two other rainfall peaks in the first two weeks of July (the influence of which is once again visible in the sensor 4 RH response) but thereafter conditions become more settled. This allows the process of evaporative drying to become the predominant influence once again and weights of vapour peak across all four sensor nodes on 19th July (Figures 10 and 11). Whilst the detail analysis, Figure 11, shows the highest weight of vapour at sensor 4, aggregated on a daily basis we can see that it is sensor 3 that has the more sustained and highest of these peaks (Figures 8 and 12). Due to the wetter winter this part of the wall, deeper within its structure, still bears a residual legacy of winter moisture and it is only now, towards the end of July, that the wall receives sufficient solar energy for vaporisation from materials at this location to occur.

A comparison of the year-on-year AH averages for the four sensors in the wall is given in Table 4. This shows a change in the AH trend hitherto for the wall where weights of vapour have increased year-on-year. This year, 2015 – 16, vapour quantities have decreased at the two sensor locations towards the internal side of the wall and increased at sensors 3 and 4. This is most likely, once again, the result of the wet winter which has increased the moisture load in the original masonry half of the wall on the cold side of the insulation. The additional input of water in the form of winter rain has also lead to increased production of vapour when this moisture evaporated during the spring and summer months.

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
2015 - 2016	9.89 g/m^3	9.87 g/m^3	10.71 g/m^3	10.58 g/m^3

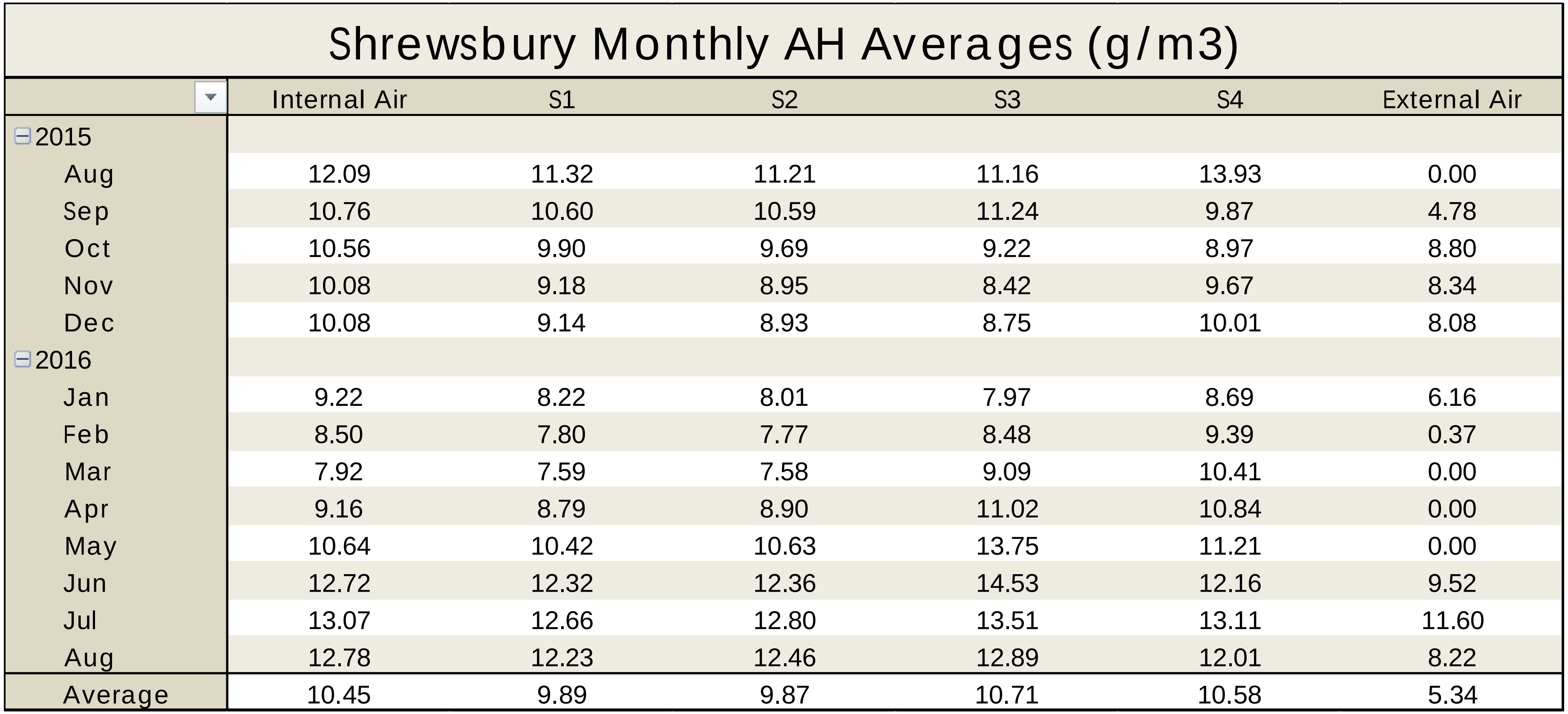
Table 4. Comparison of annual averages of AH measured through wall section, Shrewsbury 2012 - 2016



AH g/m3	Minimum	Maximum	Average
Internal	5.09	18.49	10.45
S1	5.08	18.73	9.89
S2	5.22	19.65	9.87
S3	5.87	23.65	10.71
S4	4.78	33.85	10.58
External	3.40	19.80	5.34

Project:	SPAB BPS
Building:	Shrewsbury
Start:	24/08/2015
End:	23/08/2016
Logger:	AMIG/10
Material:	Solid brick with IWI
Thickness:	405mm

Figure 8: Absolute Humidity over time, Abbeyforegate, Shrewsbury 2015 - 2016.



Shrewsbury Monthly AH Averages (g/m3)

▾	Internal Air	S1	S2	S3	S4	External Air
⊟2015						
Aug	12.09	11.32	11.21	11.16	13.93	0.00
Sep	10.76	10.60	10.59	11.24	9.87	4.78
Oct	10.56	9.90	9.69	9.22	8.97	8.80
Nov	10.08	9.18	8.95	8.42	9.67	8.34
Dec	10.08	9.14	8.93	8.75	10.01	8.08
⊟2016						
Jan	9.22	8.22	8.01	7.97	8.69	6.16
Feb	8.50	7.80	7.77	8.48	9.39	0.37
Mar	7.92	7.59	7.58	9.09	10.41	0.00
Apr	9.16	8.79	8.90	11.02	10.84	0.00
May	10.64	10.42	10.63	13.75	11.21	0.00
Jun	12.72	12.32	12.36	14.53	12.16	9.52
Jul	13.07	12.66	12.80	13.51	13.11	11.60
Aug	12.78	12.23	12.46	12.89	12.01	8.22
Average	10.45	9.89	9.87	10.71	10.58	5.34

Table 5. Absolute Humidity monthly averages, Abbeyforegate, Shrewsbury, 2015 -16.

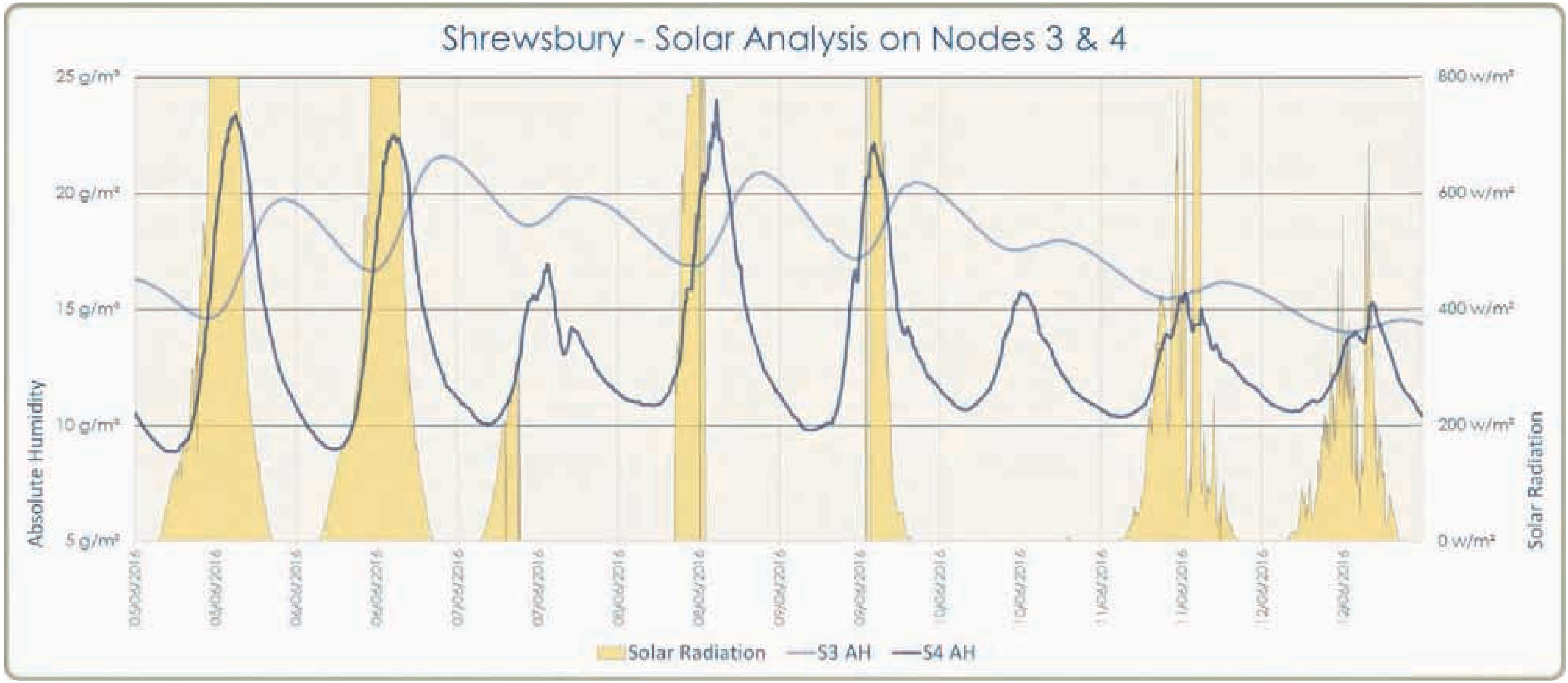


Figure 9: AH and Solar Analysis sensors 3 & 4 over time, Abbeyforegate, Shrewsbury June 2015 - 2016. Note: some solar radiation data is missing between 7 – 10 June.

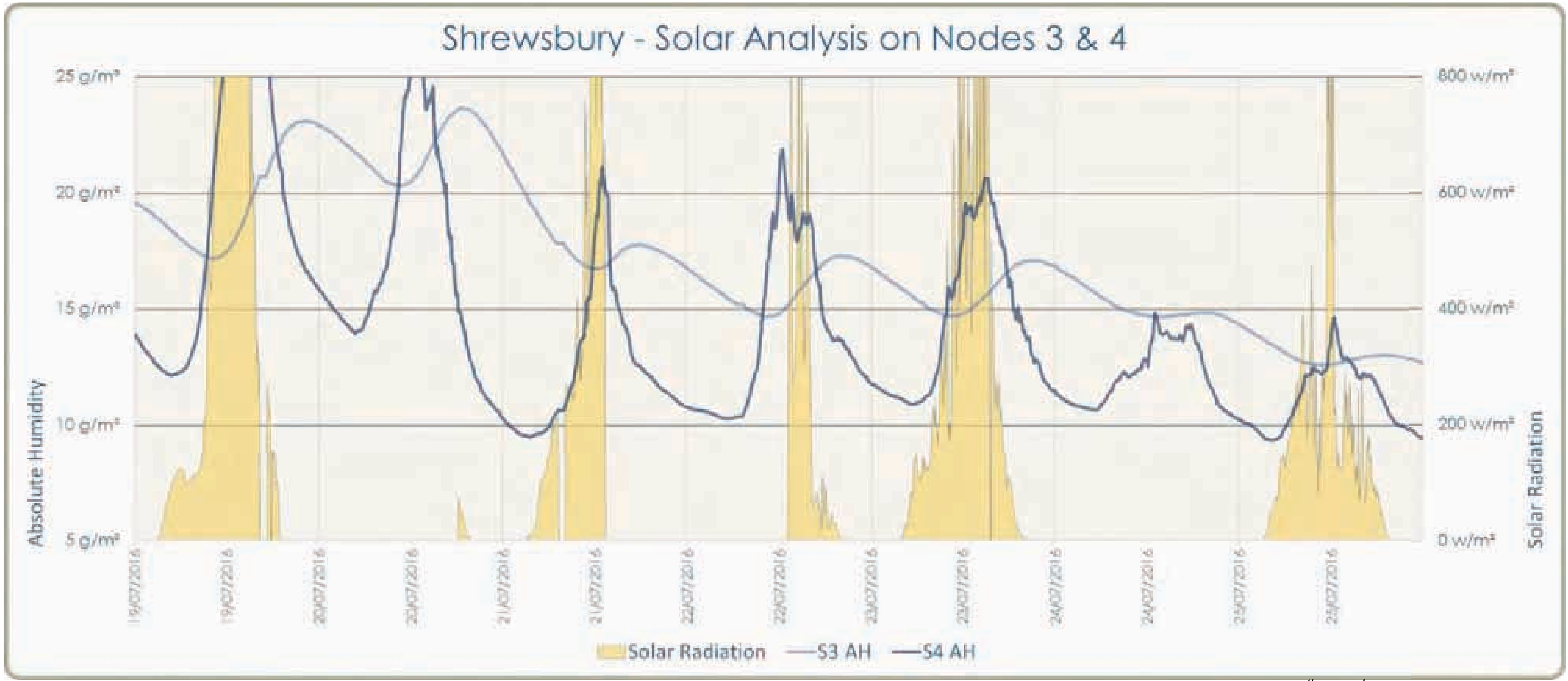


Figure 10: AH and Solar Analysis sensors 3 & 4 over time, Abbeyforegate, Shrewsbury July 2015 - 2016. Note: some solar radiation data is missing 20th, 22nd and 24th June.

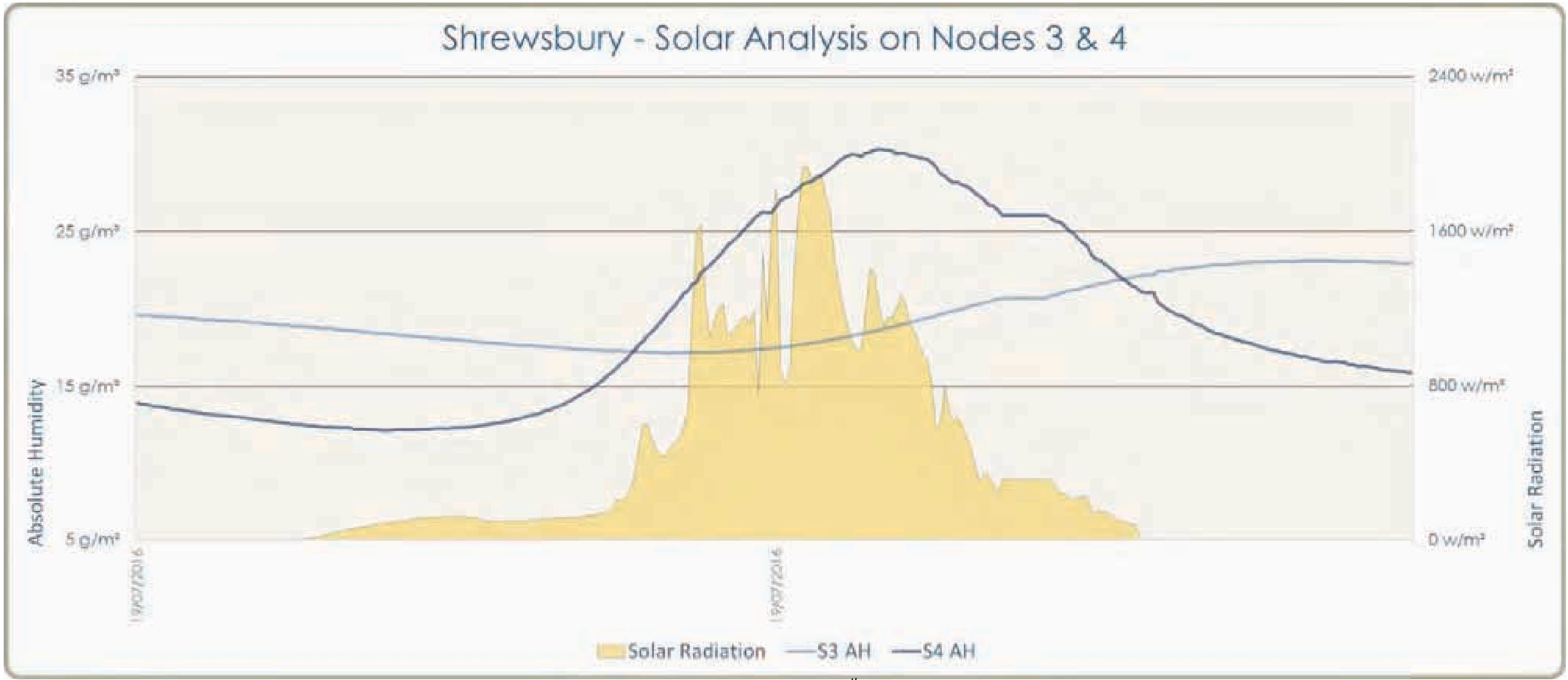
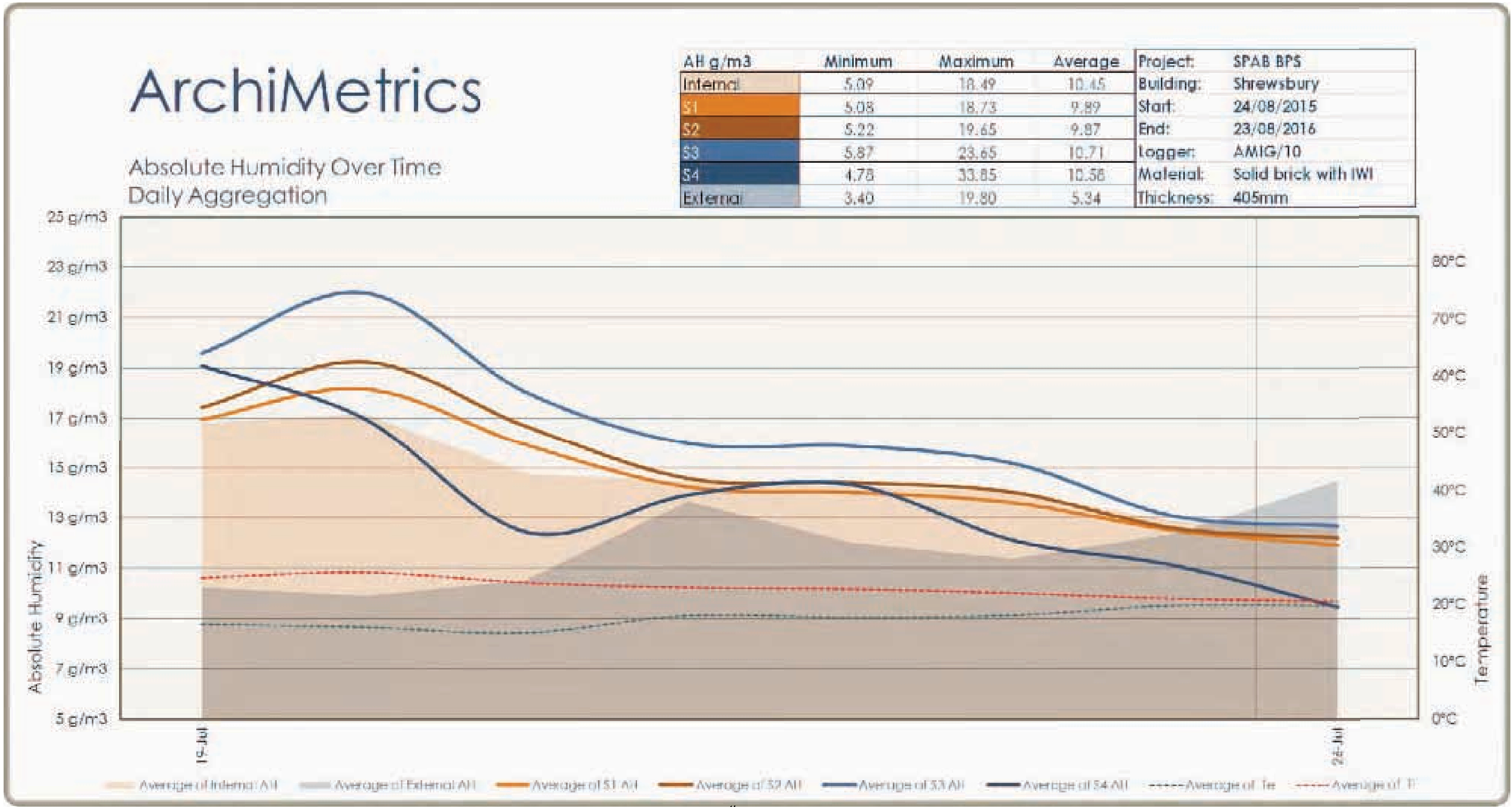


Figure 11: AH and Solar Analysis sensors 3 & 4 over time - Detail, Abbeyforegate, Shrewsbury 19th July 2016.



AH g/m3	Minimum	Maximum	Average
Internal	5.09	18.49	10.45
S1	5.08	18.73	9.89
S2	5.22	19.65	9.87
S3	5.87	23.65	10.71
S4	4.78	33.85	10.58
External	3.40	19.80	5.34

Project:	SPAB BPS
Building:	Shrewsbury
Start:	24/08/2015
End:	23/08/2016
Logger:	AMIG/10
Material:	Solid brick with IWI
Thickness:	405mm

Figure 12: Absolute Humidity over time - Detail, Abbeyforegate, Shrewsbury 19th – 26th July 2016.

Saturation Margins

Figure 13 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. Records of %RH beyond dewpoint, 100%, create a negative saturation margin which suggests that during these periods of time wall fabric is likely to be accumulating liquid water. Figure 13 also shows how close the air in the wall at sensor 4 comes to saturation during warmer spring months.

Once again the plot of sensor 4 is closely related to external conditions. Following the wet winter the ‘drying’ of material at this location can be seen to take effect week beginning 12th April as the saturation margin at sensor 4 rapidly increases. This and the following week see a period of fine weather with very little rain which evaporates moisture from the wall (AH increases, RH decreases, see Figures 5, 6 and 8). The next week, beginning 26th, the weather changes and there is rain everyday and in response RH increases and the saturation margin decreases as the wall becomes wet. This week of wet weather brings the air in the wall near the external surface close to saturation once again causing the narrow margin measurement for 3rd May. This low point is not sustained however as week beginning 3rd May is once again mostly dry and the wall repeats its evaporative cycle as part of the trend through the fabric of lower RH and larger saturation margins that dominates in the warmer drier summer months. This trend is more clearly read from the sensor 3 saturation margin trace, which, being further back in the wall, begins its recovery a week after 12th April. This is interrupted by the wetter weather in the following week but then resumes and continues to steadily increase throughout the remaining summer months.

At the end of the analysis year the plots of saturation margins for sensors 2, 3 and 4 are at similar levels to those found at the beginning of the year. This suggests that despite the wetter 2015 -16 winter over the spring and summer the wall has evaporated its increased moisture load and returned to a condition similar to that of the previous year.

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.

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**
2014 - 2015 (1/9/14- 31/8/15)	6.85°C	5.16°C	4.20°C	4.24°C	5.11°C
Difference	**-0.39°C**	**1.25°C**	**0.92°C**	**-0.28°C**	**0.38°C**
2015 - 2016 (28/08/15 – 27/08/16)	6.41°C	5.12°C	3.57°C	3.37°C	4.62°C
Difference	**0.05°C**	**1.29°C**	**1.55°C**	**0.59°C**	**0.87°C**

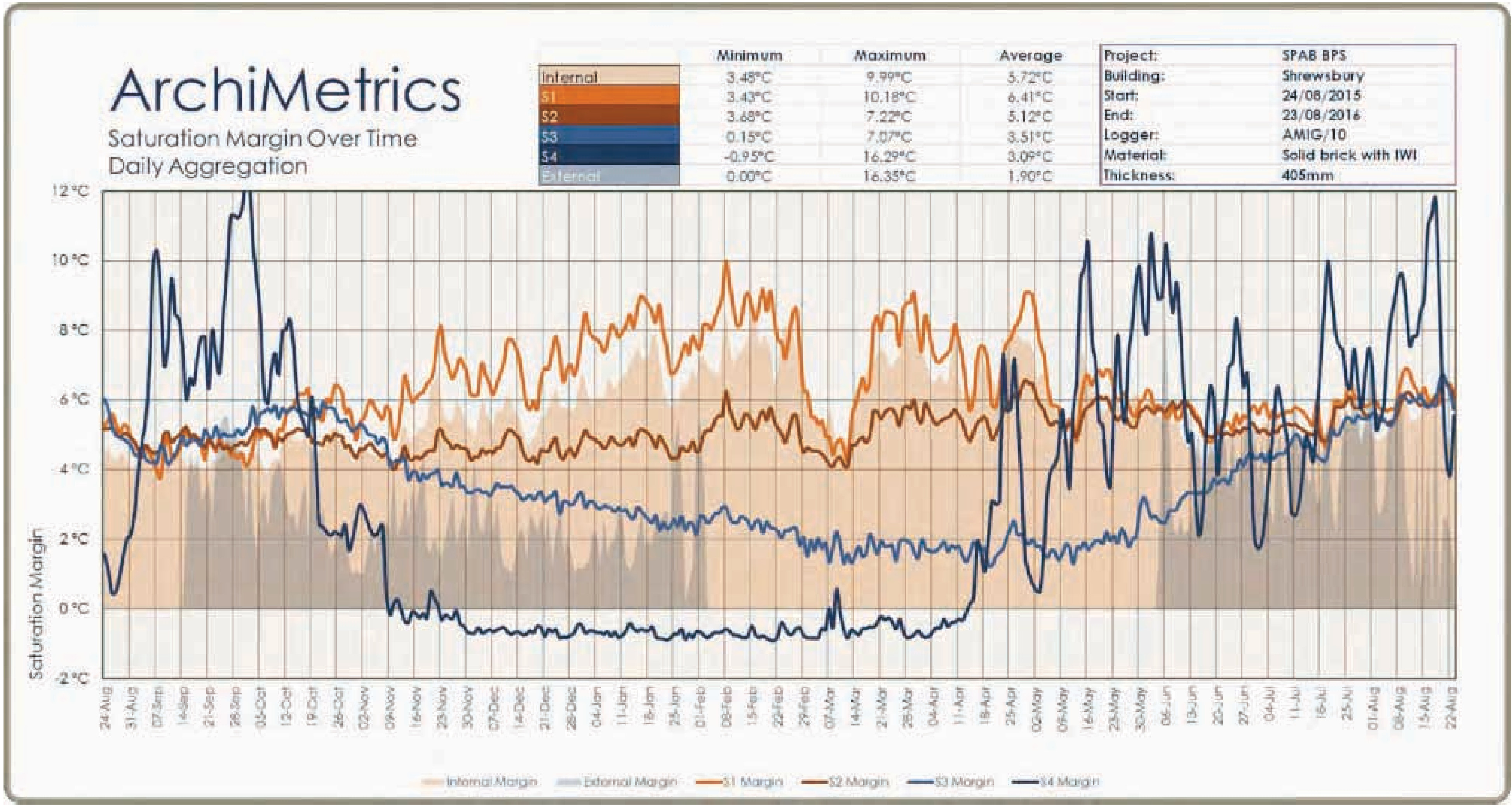
Table 5. Saturation Margins & Pre & Post-insulation Difference, Abbeyforegate, Shrewsbury 2011 – 2015 (capped).

From Table 5 it can be seen that for the first two years, post-refurbishment, the saturation margins across all sensors had narrowed in comparison with pre-refurbishment margins. In 2014-15, the margins at sensor 1 and sensor 4, towards the interior and exterior of the wall, were greater than the pre-refurbishment margins probably as a reflection of a drier 12-month period. However in this wetter year, 2015 – 16, they are more similar to the margins found in the first two post-refurbishment years. Sensor 3 records the lowest annual average margin since post-refurbishment whereas the margin at sensor 1 is to all intents and purposes the same as that of found for the wall before it was insulated.

The range of saturation margins across all sensors for the three years, post-insulation, is quite consistent and shows neither an increasing or decreasing year-on-year trend. Another indication of the change that has taken place in the wall is the difference calculated in ˚C between pre- and post-refurbishment margins. This shows that although margins have general narrowed slightly since refurbishment this difference is under 2˚C (when margins have increased this is shown as a negative number). The difference between these pre- and post-refurbishment margins at Shrewsbury is small in comparison with those of the other insulated walls in this study, suggesting the wall has undergone a smaller change in relation to its moisture profile.

Hygrothermal Sections

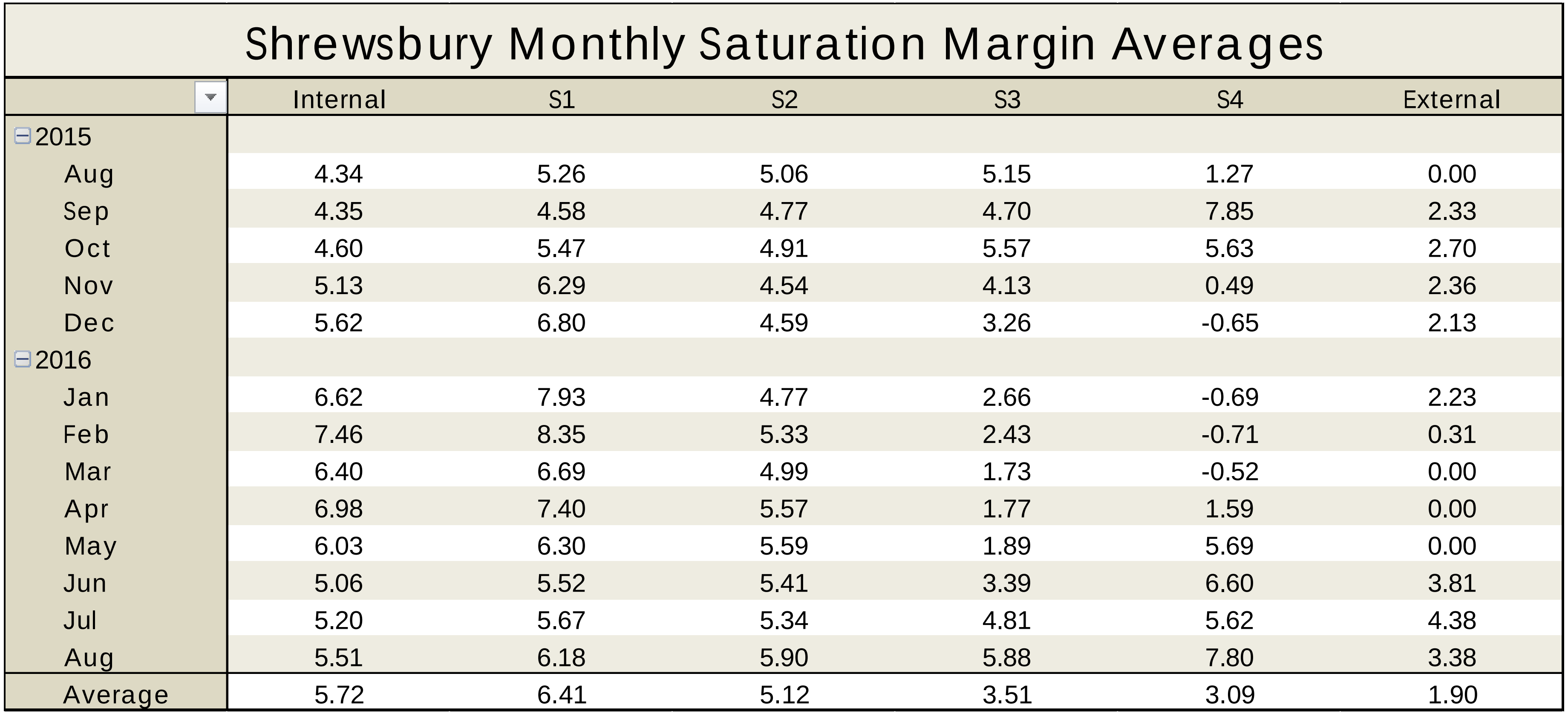
Measurements of temperature and RH are also used to plot annual averages of measured temperature and dewpoint temperature gradients through the wall section (Figures 13 - 16). These analyses show the similarity between the past four years. Through the four measurement points, on average, we find no convergence 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	3.48°C	9.99°C	5.72°C
S1	3.43°C	10.18°C	6.41°C
S2	3.68°C	7.22°C	5.12°C
S3	0.15°C	7.07°C	3.51°C
S4	-0.95°C	16.29°C	3.09°C
External	0.00°C	16.35°C	1.90°C

Project:	SPAB BPS
Building:	Shrewsbury
Start:	24/08/2015
End:	23/08/2016
Logger:	AMIG/10
Material:	Solid brick with IWI
Thickness:	405mm

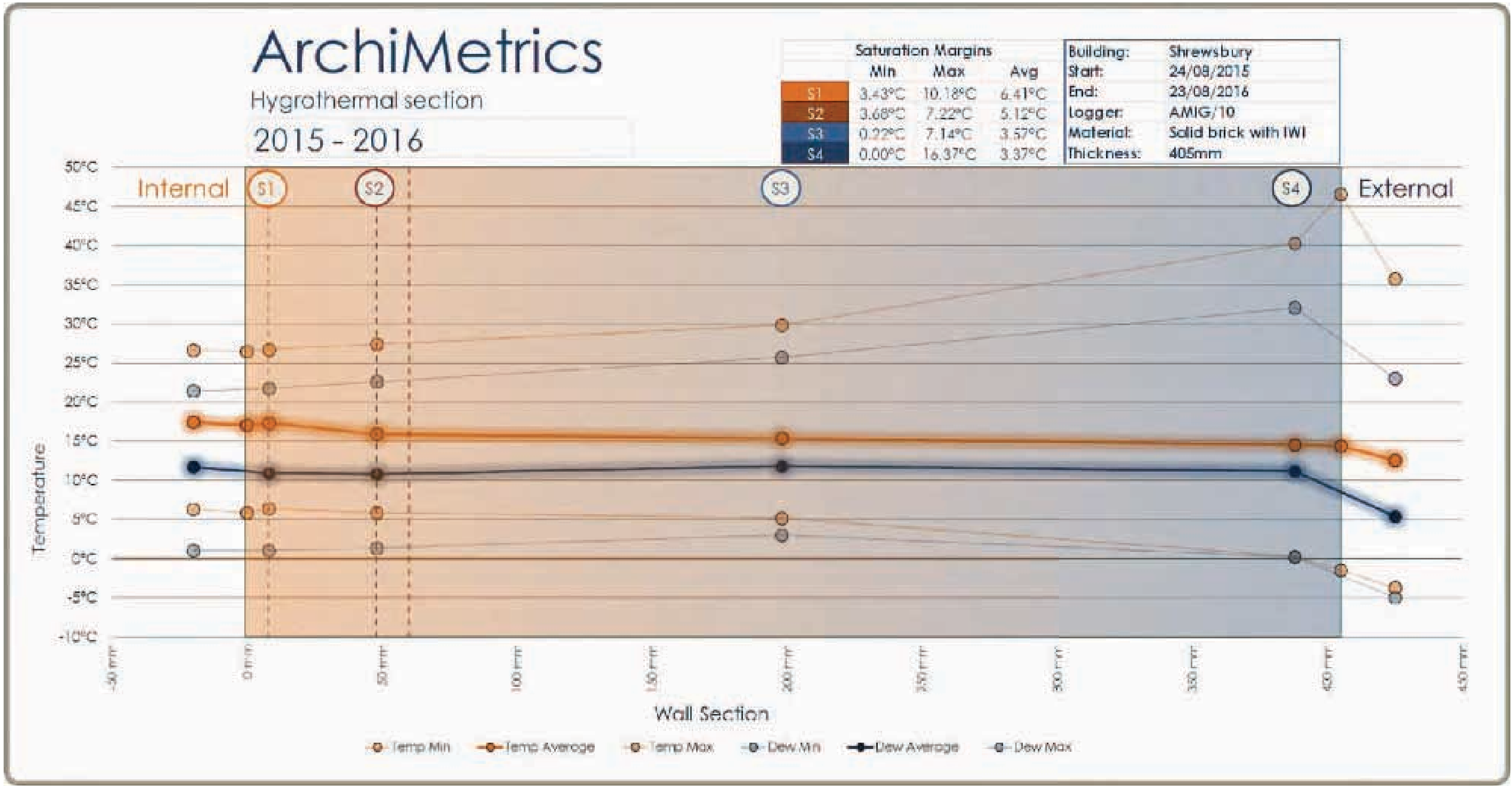
Figure 12. Saturation Margin over time, Abbeyforegate, Shrewsbury 2015 - 2016.



Shrewsbury Monthly Saturation Margin Averages

	Internal	S1	S2	S3	S4	External
⊟2015						
Aug	4.34	5.26	5.06	5.15	1.27	0.00
Sep	4.35	4.58	4.77	4.70	7.85	2.33
Oct	4.60	5.47	4.91	5.57	5.63	2.70
Nov	5.13	6.29	4.54	4.13	0.49	2.36
Dec	5.62	6.80	4.59	3.26	-0.65	2.13
⊟2016						
Jan	6.62	7.93	4.77	2.66	-0.69	2.23
Feb	7.46	8.35	5.33	2.43	-0.71	0.31
Mar	6.40	6.69	4.99	1.73	-0.52	0.00
Apr	6.98	7.40	5.57	1.77	1.59	0.00
May	6.03	6.30	5.59	1.89	5.69	0.00
Jun	5.06	5.52	5.41	3.39	6.60	3.81
Jul	5.20	5.67	5.34	4.81	5.62	4.38
Aug	5.51	6.18	5.90	5.88	7.80	3.38
Average	5.72	6.41	5.12	3.51	3.09	1.90

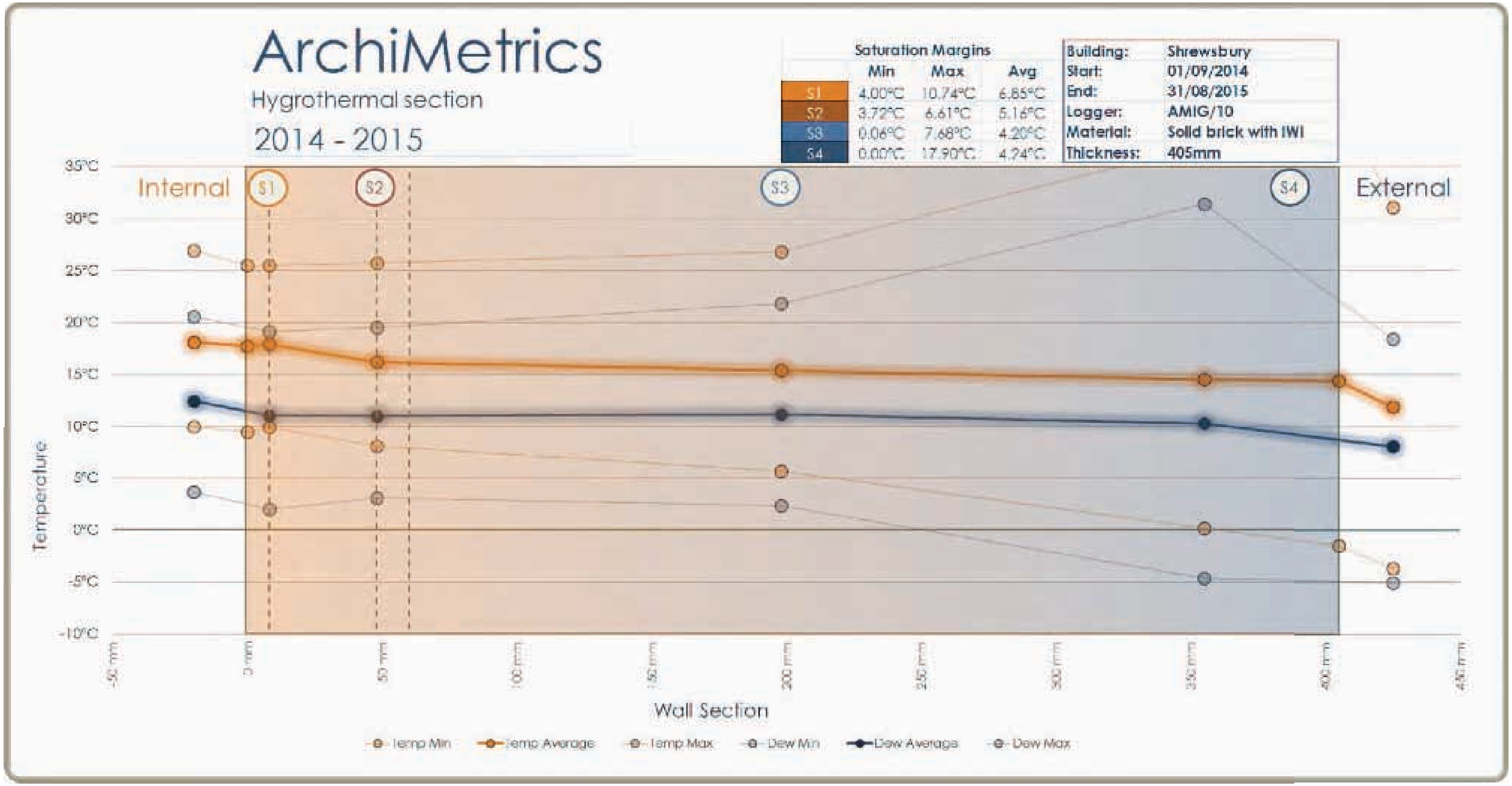
Table 6. Saturation Margin monthly averages, Abbeyforegate, Shrewsbury, 2015 - 2016.



	Saturation Margins		
	Min	Max	Avg
S1	3.43°C	10.18°C	6.41°C
S2	3.68°C	7.22°C	5.12°C
S3	0.22°C	7.14°C	3.57°C
S4	0.00°C	16.37°C	3.37°C

Building:	Shrewsbury
Start:	24/08/2015
End:	23/08/2016
Logger:	AMIG/10
Material:	Solid brick with IWI
Thickness:	405mm

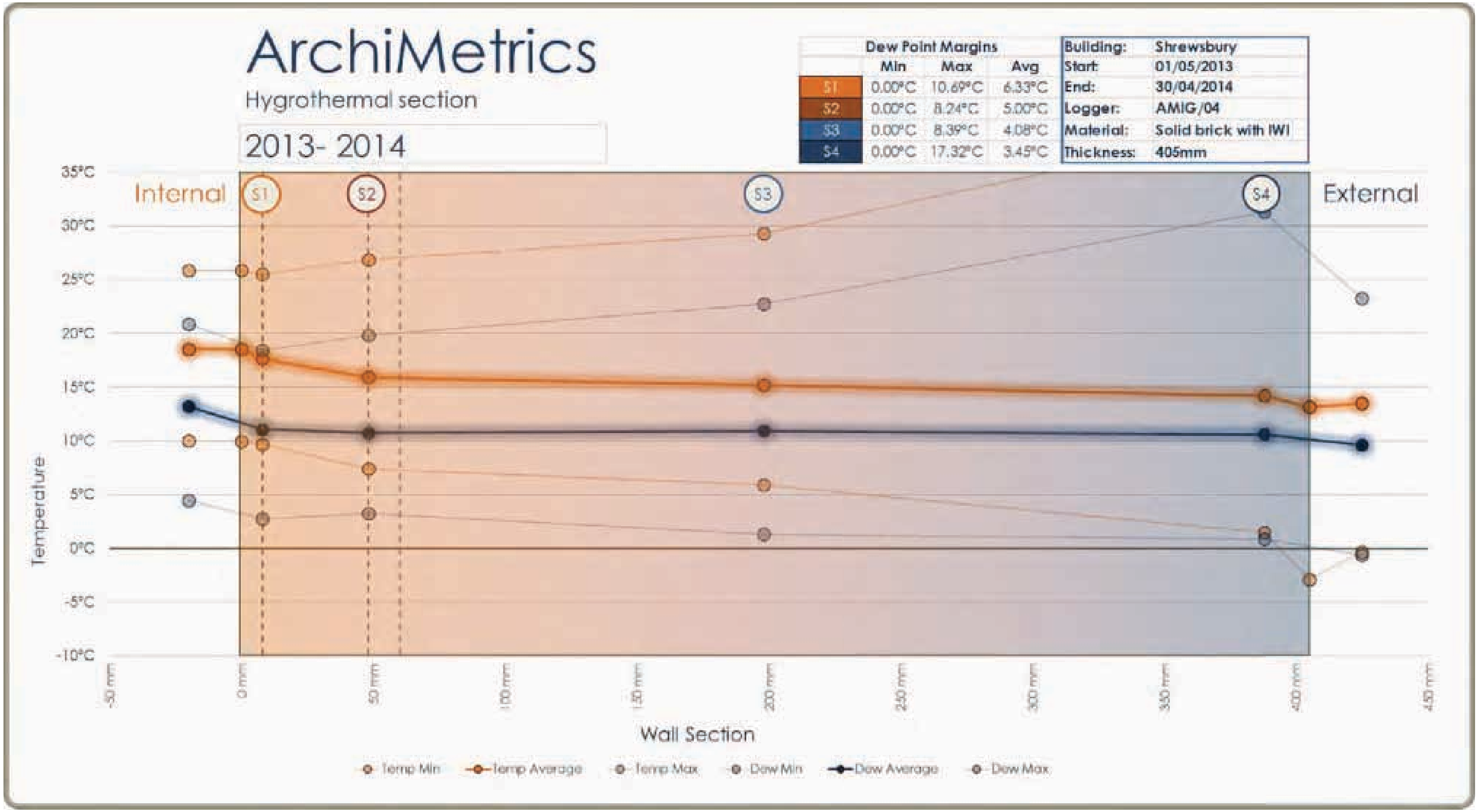
Figure 13. Hygrothermal Section, Abbeyforegate, Shrewsbury 2015 – 2016 (capped).



	Saturation Margins		
	Min	Max	Avg
S1	4.00°C	10.74°C	6.85°C
S2	3.72°C	6.61°C	5.16°C
S3	0.06°C	7.68°C	4.20°C
S4	0.00°C	17.90°C	4.24°C

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

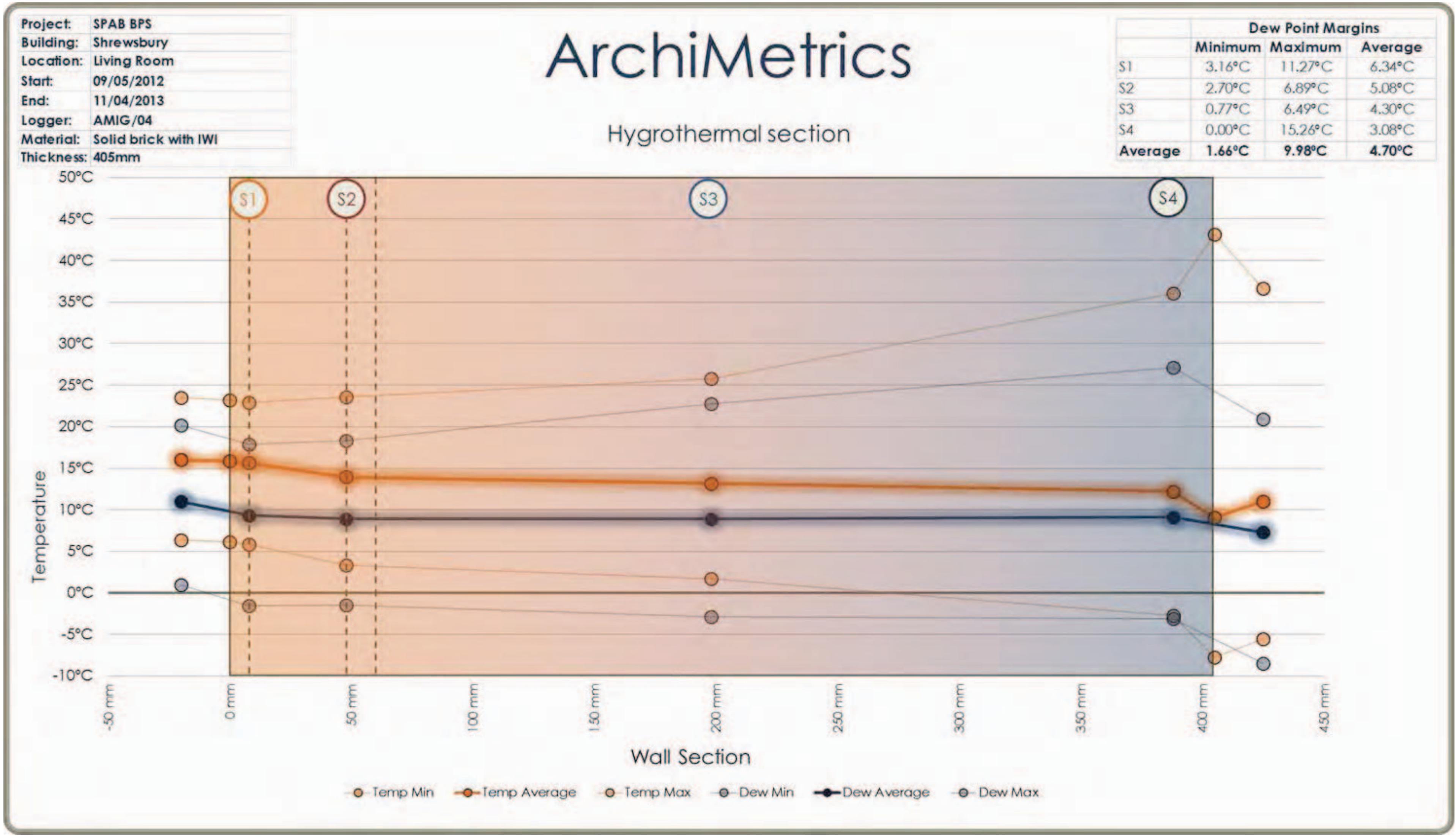
Figure 14. Hygrothermal Section, Abbeyforegate, Shrewsbury 2014 – 2015 (capped).



	Dew Point Margins		
	Min	Max	Avg
S1	0.00°C	10.69°C	6.33°C
S2	0.00°C	8.24°C	5.00°C
S3	0.00°C	8.39°C	4.08°C
S4	0.00°C	17.32°C	3.45°C

Building:	Shrewsbury
Start:	01/05/2013
End:	30/04/2014
Logger:	AMIG/04
Material:	Solid brick with IWI
Thickness:	405mm

Figure 15. Hygrothermal Section, Abbeyforegate, Shrewsbury, 2013 - 2014.



Project:	**SPAB BPS**
Building:	**Shrewsbury**
Location:	**Living Room**
Start:	**09/05/2012**
End:	**11/04/2013**
Logger:	**AMIG/04**
Material:	**Solid brick with IWI**
Thickness:	**405mm**

	Dew Point Margins		
	Minimum	**Maximum**	**Average**
S1	3.16°C	11.27°C	6.34°C
S2	2.70°C	6.89°C	5.08°C
S3	0.77°C	6.49°C	4.30°C
S4	0.00°C	15.26°C	3.08°C
Average	**1.66°C**	**9.98°C**	**4.70°C**

Figure 16. Hygrothermal Section, Abbeyforegate, Shrewsbury, 2012 - 2013.

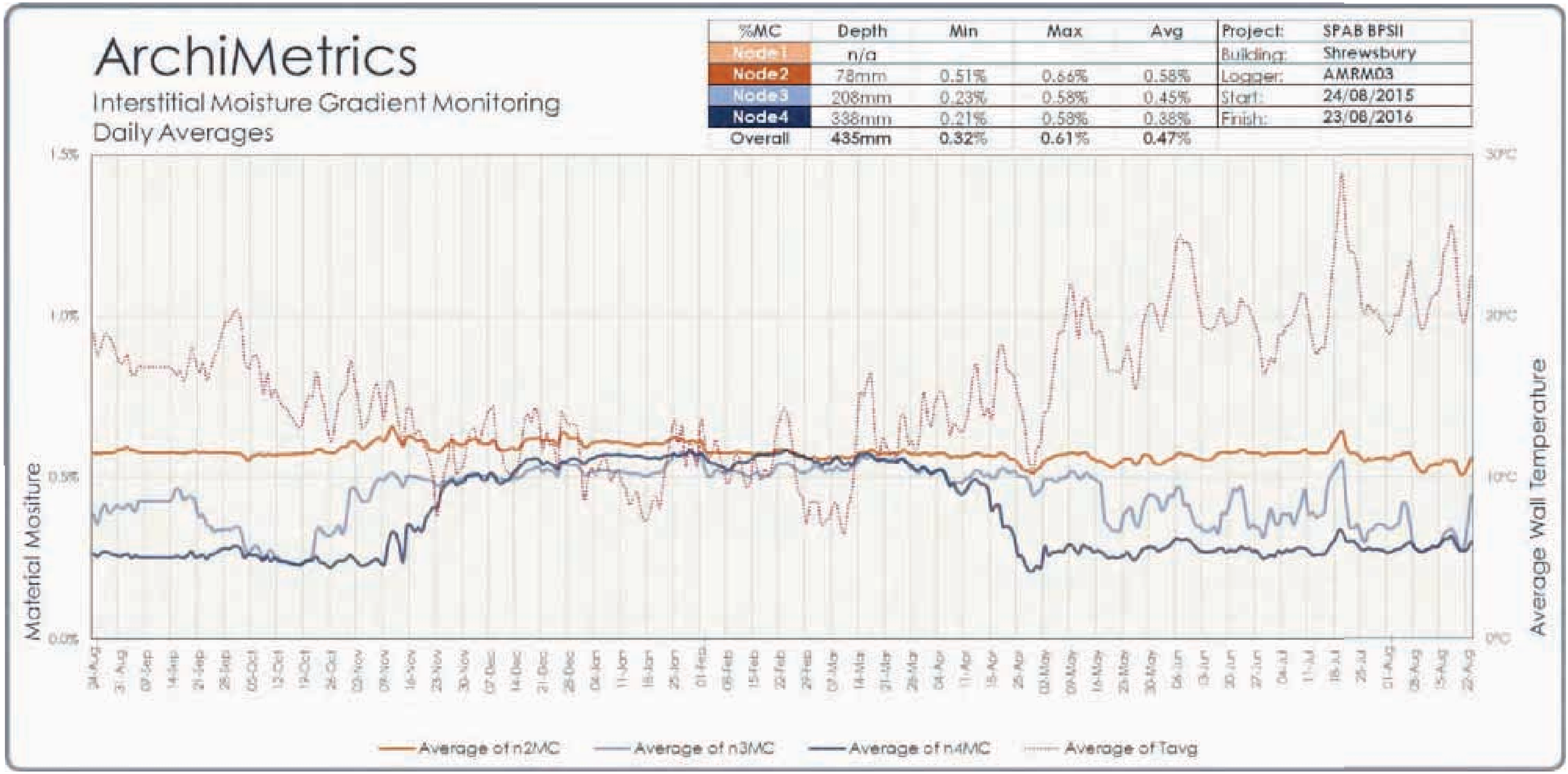
Material Moisture

The brick wall at Shrewsbury provides the lowest moisture content measurements of the three walls under study. The annual average %MC is roughly half that of Drewsteignton and a third of that found for the wall at Riddlecombe. There are similarities between the findings for Shrewsbury in 2015 – 16 compared with those of the previous year (Figures 17 & 18). Due to increased and more frequent rainfall sensors 3 and 4, towards the external side of the wall, measure an increase in moisture content during the winter period. Something that is also seen in the %RH record previously commented on (Figure 5.). Measurements from sensor 2 remain more consistent throughout the year which is also a pattern similar to that found in the vapour record for the wall. Specifically, for 2015 – 16, a decline in %MC at sensors 3 and 4 is measured starting with the onset of warmer drier weather in April and thereafter we see occasional peaks which coincide with wet weather, mostly notably the event around 19th July. Once again this behaviour is also consistent with the 2015 -16 %RH and AH records for the wall; as is the response which sees a slower decline in %MC measured at sensor 3, deeper within the wall, compared to that of sensor 4.

One noticeable difference between sensor traces from the two years of material moisture records is the quality of responses from sensor 4. In the year 2014 – 15 there are a number of detached peaks during February and March (maximum peak 1.27%) suggesting a volatility of response not dissimilar to those seen in humidity measurements. 2015 - 16 is quite different, despite being a wetter winter. Sensor 4 peaks at 0.58 %MC, roughly half that of the previous year and in general the plot is more muted without any detached peaks throughout the year. Other observations concerning the material moisture within the wall are how these deviate from those found for humidity and show how measurements of the two different states of water, as a gas and as a liquid, at times, present contrary behaviour as might be expected at certain times of year. Following an almost dry two weeks at the start of October 2015 rain begins to fall week beginning 20th. %RH at sensor 4 immediately increases in response but there is not a similar reaction from sensor 4 measuring %MC. Instead it is sensor 3 deeper within the wall that shows an increase in %MC at this location. Whilst we can surmise that both locations become wetter due to the rain, the area in proximity to the external wall surface is more readily able to evaporate moisture, hence a high vapour record and little change to material %MC at this location. Rain also penetrates deeper into the wall towards sensor 3 where the chances of evaporation are greatly reduced, hence material absorbs and retains the water leading to higher %MC than those measured at sensor 4. Then, as temperatures decrease (the average temperature inside the wall section is shown in Figure 17) and rain falls on most days of the week (until mid February!) the opportunities for evaporation from wall materials become negligible. From mid November %MC at sensor 4 increases and then exceeds that measured by sensor 3 as the external surface of the wall is wet. %RH is also highest at sensor 4 for the majority of the winter period but this is now due to the proximity of liquid water within the materials at this location.

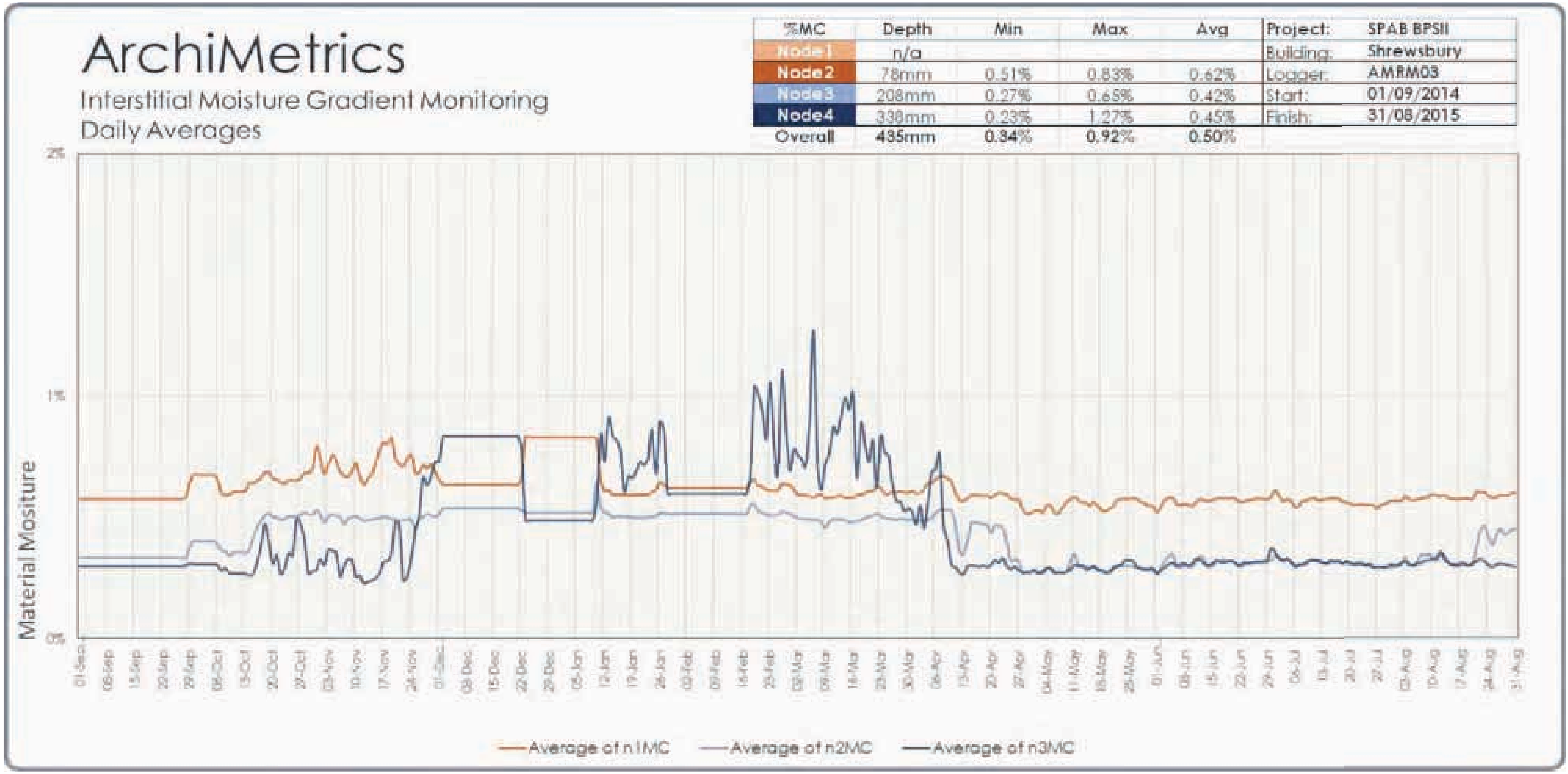
The start of drying out is also visible from the %MC analysis although this could be said to begin earlier than the time suggested by plots of %RH. A gradual decline in %MC is measured across both sensors 3 and 4 from a peak starting week beginning 14th March. This coincides with the resumption of internal heating in the property as well as a largely dry period of weather. %RH and AH records for this period remain high however as this moisture is being released in the form of vapour. The reduction in %MC becomes more rapid at sensor 4 week beginning 11th April, the week that also sees a sharp decrease in RH measured by the %RH sensor in close proximity to the external wall surface. This perhaps marks a tipping point where sufficient moisture has been expelled by evaporation that vapour quantities measured at this location now also begin to decline. This can be seen in the AH peak on 12th April followed by a decline and the decreasing %RH plot over this period. The role that heat plays in relation to liquid moisture behaviour within the wall is perhaps most clearly seen in relation to the plot of sensor 3 where peaks in temperature see similar spikes in %MC (and visa versa). Although it is also possible to see smaller temperature related responses in the MC plots of the other two sensors. In a porous material such as the brick found in the wall at Shrewsbury higher temperatures will lead to more vaporisation from wall materials as well as movement of liquid water through interconnected pores. As the temperature trace marked in Figure 17 is an average of those measured by the three wall sensors perhaps it is not surprising that the greatest correlation of this temperature is with the responses of sensor 3 which sits roughly in the centre of the wall. Sensors 2 and 4 are placed on either side of the wall and therefore MC responses here are also likely to be impinged upon by influences from the internal and external environments.

Other anomalies between the %MC and %RH records for Shrewsbury lie in the total annual average quantities found for the wall. The 2015 - 16 %RH and AH averages have increased from those calculated for the previous year whereas the opposite is true for %MC where, despite a wetter winter, overall the average %MC is lower than that of 2014 – 15. This finding might be impacted by the effect of the moisture added to the walls around the MC sensors in the form of lime mortar which takes sometime to dry over the first year of measurements. We could also conclude from this that despite higher annual rainfall in 2015 -16 conditions have also been conducive to evaporation, the evaporation of higher quantities of winter moisture creating higher vapour records and thus less moisture in materials over the annual cycle.



%MC	Depth	Min	Max	Avg	Project:	SPAB BFSII
Node1	n/a				Building:	Shrewsbury
Node2	78mm	0.51%	0.66%	0.58%	Logger:	AMRM03
Node3	208mm	0.23%	0.58%	0.45%	Start:	24/08/2015
Node4	338mm	0.21%	0.58%	0.38%	Finish:	23/08/2016
Overall	435mm	0.32%	0.61%	0.47%		

Figure 17: Material moisture content over time, Abbeyforegate, Shrewsbury 2015 - 2016.



%MC	Depth	Min	Max	Avg	Project:	SPAB BPSII
Node1	n/a				Building:	Shrewsbury
Node2	78mm	0.51%	0.83%	0.62%	Logger:	AMRM03
Node3	208mm	0.27%	0.65%	0.42%	Start:	01/09/2014
Node4	338mm	0.23%	1.27%	0.45%	Finish:	31/08/2015
Overall	435mm	0.34%	0.92%	0.50%		

Figure 18: Material moisture content over time, Abbeyforegate, Shrewsbury 2014 - 2015.

2.2. Mill House, Drewsteignton, Devon - 2015 - 16.

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 PVCu). 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

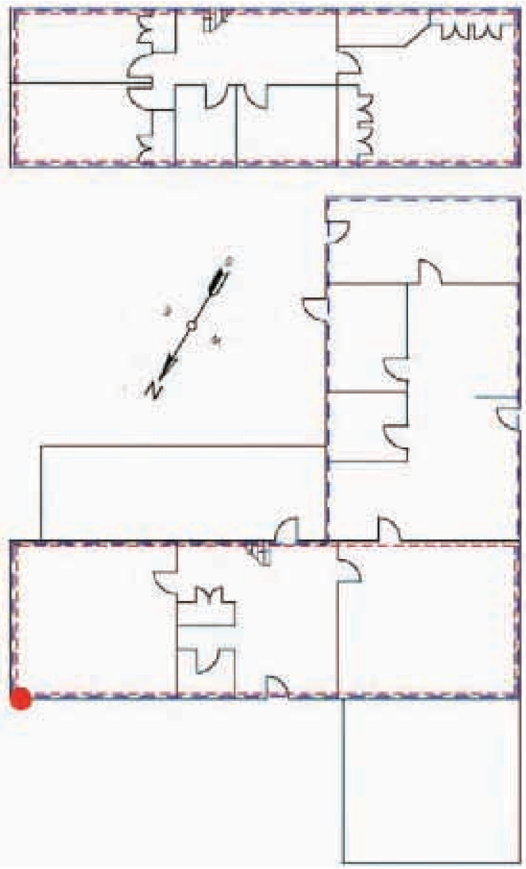


Figure 15. Plan of Mill House, Drewsteignton, the red dot indicates the location of the ground floor monitoring equipment.

Wall Condition Monitoring

Figure 19. Interstitial Hygrothermal Gradient and Material Moisture Monitoring, Drewsteignton.

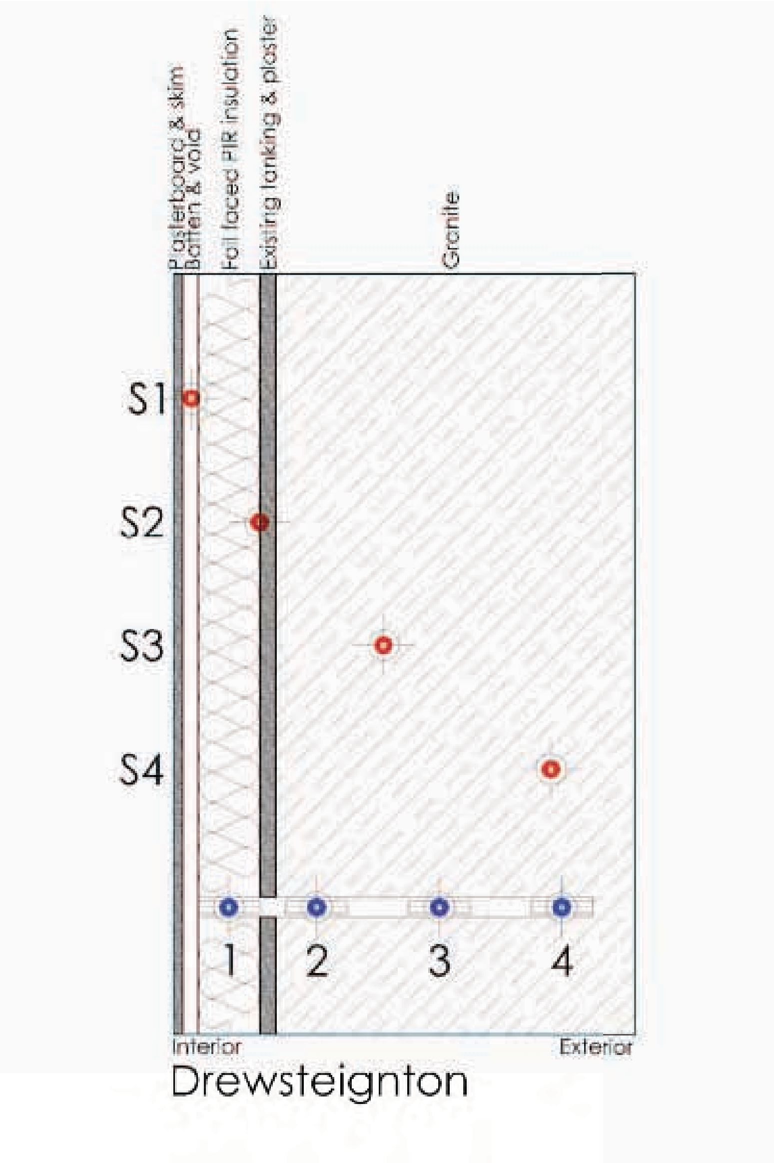


Figure 20. Position of wall sensors through section, Drewsteignton – red IHGM, blue Material Moisture

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	1 mm			
Lime Plaster	20 mm			
Granite	580 mm	Sensor 3	1430 mm	340 mm
		Sensor 4	1280 mm	610 mm
Total	**742 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 2015 – 31st August 2016, has been used as the basis for the following analysis.

Relative Humidity Over Time

Figure 21 shows the %RH responses measured in and around the test wall at Drewsteignton 2015 -2016. 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.

The measured responses from the wall at Drewsteignton post-insulation have revealed a trend of rising RH over an annual cycle within the original masonry section of the insulated wall and we find 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, this year, a year-on-year increase for sensors 1, 3 and 4 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%
2015 - 2016	64%	90%	96%	98%

Table 8. Comparison of annual averages of RH measured through wall section, Drewsteignton 2012 - 2016.

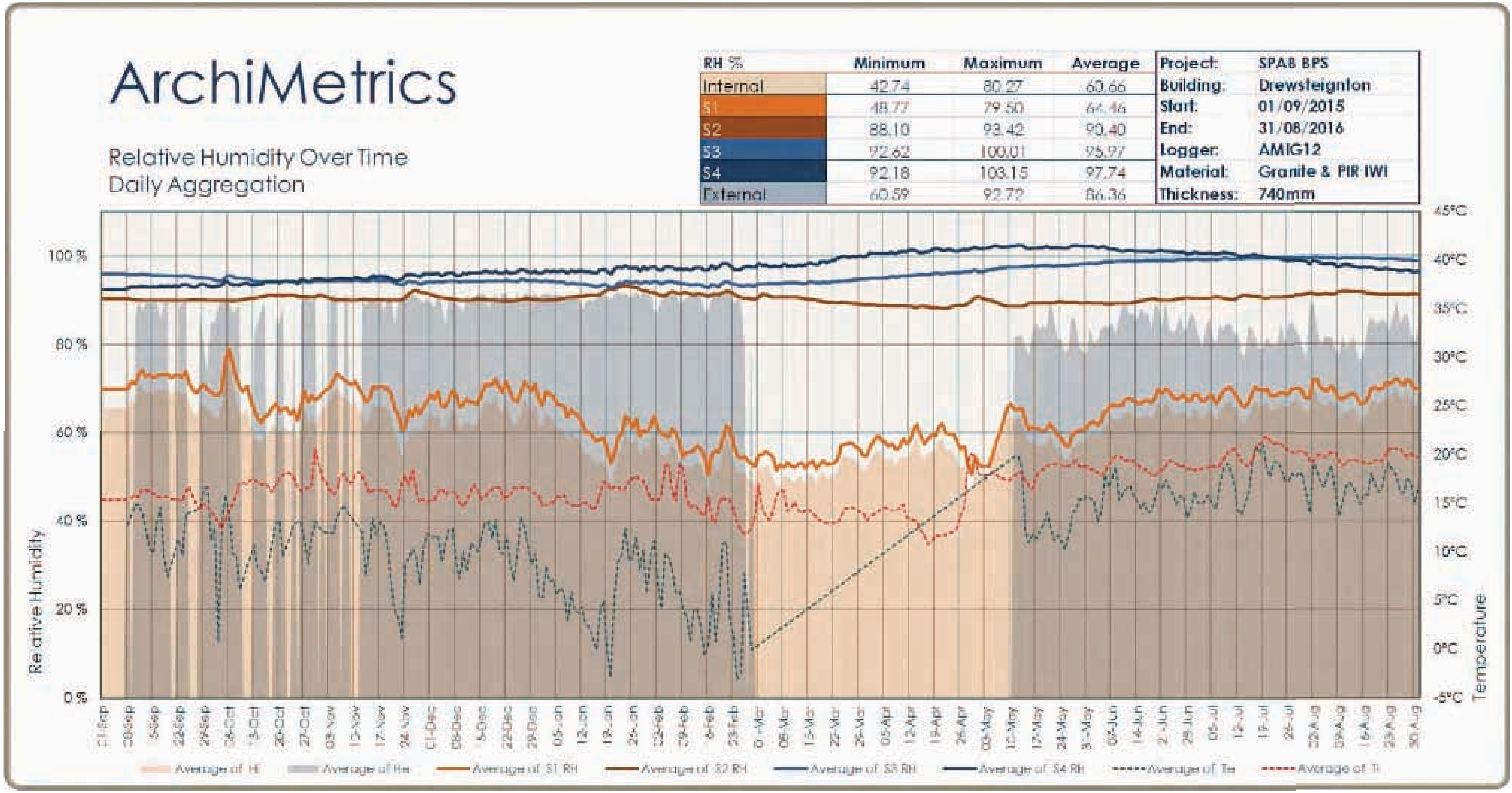
%RH responses peak at sensor 4 around the end of May and approximately two months later at the end of July/August for sensor 3. These peaks occur roughly a month later than those of the previous year, perhaps a reflection of the wetter winter and the increased length of time required for evaporation to take place from materials.

Last year there were no occurrences of a monthly average at or above 100% RH at any sensor (Table 9). This year, 2015 -16, is more like other years where average %RH at sensor 4 exceeds 100% in the months April, May and June. (In 2013 – 14 measurements peaked at 100% for five months between February and June.) There are similarities however in responses with those of 2014 – 15, other than the obvious general one of high %RH through the masonry section. This year, once again, we see %RH plots from sensors 3 and 4 crossing as %RH decreases at sensor 4 whilst still increasing at sensor 3. In 2014 - 15 this event took place week beginning 25th May but this year, as with previous observations, certain 'drying' behaviours occur later within the year and the divergent plots are seen week beginning 19th July during a peak in internal and external temperatures. (This week also sees the peak of AH values for the wall, see Figure 22.)

The annual average %RH calculated for sensor 2 is the same between the years 2014 -15 and 2015 – 16 (Table 8). And whilst from this there appears to have been little change between the two years the longer-term trend of %RH at sensor 2 is still increasing as is that of sensor 3 and 4 (Fig. 43). The greatest increases since the first post-refurbishment averages were calculated, of 5 and 6%, take place at sensors 2 and 3 respectively, deeper within the wall and further away from any significant evaporative surface.

An examination of Figure 21 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 continues to be 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 throughout the year and only sensor 2 records two average monthly values fractionally below this (89% in April and May). Whilst %RH above 80% may not represent a risk to masonry materials, persistently high %RH of 80% or above is one of the conditions required to initiate and support the growth of mould fungus formations in organic materials. In these circumstances organic materials embedded within the wall structure, such as timber lintels, joists etc. are at risk of mould growth.



RH %	Minimum	Maximum	Average
Internal	42.74	80.27	60.66
S1	48.77	79.50	64.46
S2	88.10	93.42	90.40
S3	92.62	100.01	95.97
S4	92.18	103.15	97.74
External	60.59	92.72	86.36

Project:	**SPAB BPS**
Building:	**Drewsteignton**
Start:	**01/09/2015**
End:	**31/08/2016**
Logger:	**AMIG12**
Material:	**Granite & PIR IWI**
Thickness:	**740mm**

Figure 21: Relative Humidity over time, Mill House, Drewsteignton, 2015 2016.

Drewsteignton Monthly RH Averages

	Internal RH	S1 RH	S2 RH	S3 RH	S4 RH	External RH
⊟2015						
Sep	67.55	71.60	90.13	95.68	93.03	88.28
Oct	63.42	67.95	90.61	94.53	93.97	89.01
Nov	64.05	68.46	90.54	94.29	95.15	90.19
Dec	64.25	68.84	90.24	94.35	96.23	90.20
⊟2016						
Jan	57.25	61.99	91.58	93.82	96.81	90.87
Feb	52.97	56.82	91.30	93.68	97.35	90.32
Mar	50.92	54.05	90.11	94.12	98.61	
Apr	54.45	57.99	88.81	95.81	101.14	
May	57.13	60.00	89.44	97.56	102.05	82.16
Jun	63.61	66.88	89.83	98.89	101.29	85.38
Jul	65.37	68.72	90.75	99.46	99.95	81.85
Aug	66.47	69.72	91.49	99.34	97.44	82.99
Average	60.66	64.46	90.40	95.97	97.74	86.36

Table 9. Relative Humidity Monthly Averages, Mill House, Drewsteignton, 2015 - 2016.

Absolute Humidity Over Time

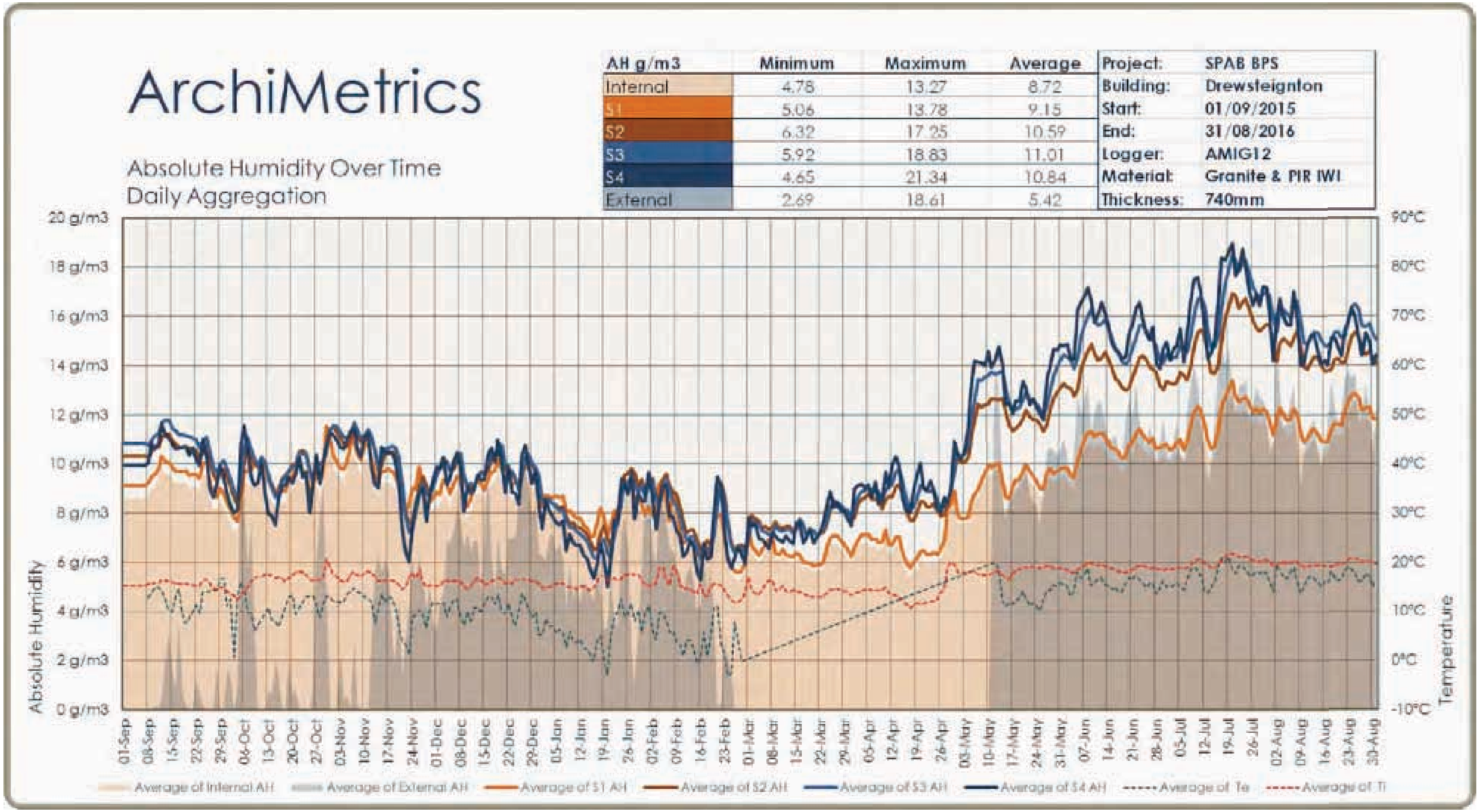
Figure 22 shows an analysis of absolute humidity through the insulated wall section at Drewsteignton 1st September 2015 – 31st August 2016. The same seasonal variation that was noted in previous reports across all walls in the study is in evidence; generally quantities of vapour within the wall increase 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 plots 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 from wall fabric can be seen in a solar analysis for week beginning 12th July, Figure 23.

The picture over winter is similar to that of previous years where weights of vapour measured from all four sensors are lower and more closely grouped. This grouping sits mostly slightly above the weight of vapour measured from the room interior and as with summer records, continues to be higher than ambient external vapour quantities. 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 January 2016 during a period of low external temperatures where AH humidity declines but, higher quantities of vapour are supported by warmer indoor temperatures as a result of central heating.

For the first three years following insulation there has been a year-on-year increase in the annual average weights of vapour measured at Drewsteignton (Table 10). This year the annual average weights of vapour measured by all four sensors in the wall section have reduced. %RH levels in the wall have continued to increase year-on-year since 2012 and are well above the mould growth risk threshold which suggest high levels of vapour within the wall fabric. It could be that despite a wetter year evaporative opportunities were not so great as in previous years for this north-west facing wall, it received less solar radiation and temperatures were generally cooler. This would result in a decrease in measured weights of vapour whilst a high %RH would still persist within the fabric.

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
2015 - 2016	9.15 g/m^3	10.59 g/m^3	11.01 g/m^3	10.84 g/m^3

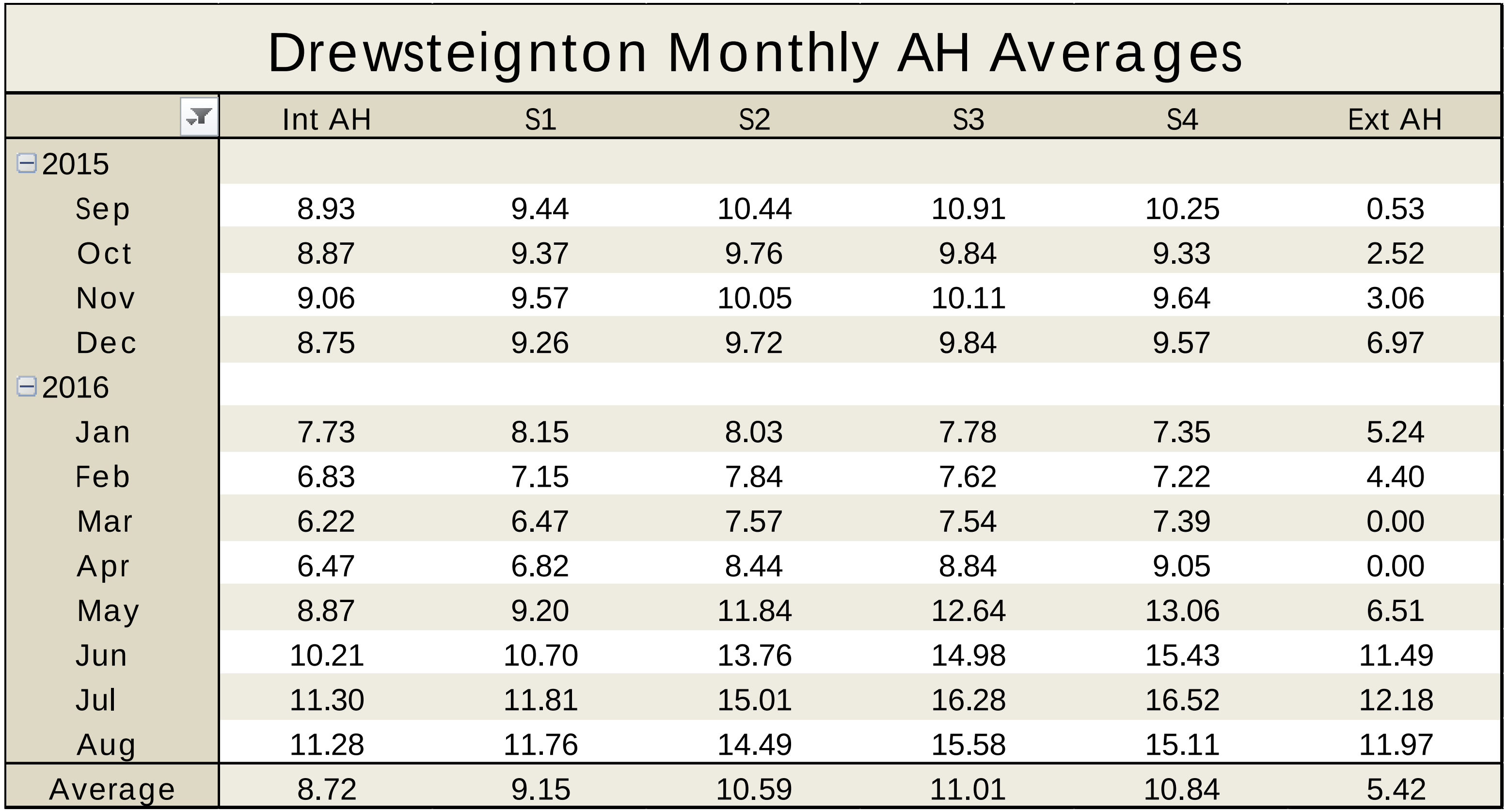
Table 10. Average Absolute Humidity, Mill House, Drewsteignton, 2012 - 2016.



AH g/m3	Minimum	Maximum	Average
Internal	4.78	13.27	8.72
S1	5.06	13.78	9.15
S2	6.32	17.25	10.59
S3	5.92	18.83	11.01
S4	4.65	21.34	10.84
External	2.69	18.61	5.42

Project:	SPAB BPS
Building:	Drewsteignton
Start:	01/09/2015
End:	31/08/2016
Logger:	AMIG12
Material:	Granite & PIR IWI
Thickness:	740mm

Figure 22: Absolute Humidity over time, Mill House, Drewsteignton 2015 - 2016.



Drewsteignton Monthly AH Averages

	Int AH	S1	S2	S3	S4	Ext AH
⊟2015						
Sep	8.93	9.44	10.44	10.91	10.25	0.53
Oct	8.87	9.37	9.76	9.84	9.33	2.52
Nov	9.06	9.57	10.05	10.11	9.64	3.06
Dec	8.75	9.26	9.72	9.84	9.57	6.97
⊟2016						
Jan	7.73	8.15	8.03	7.78	7.35	5.24
Feb	6.83	7.15	7.84	7.62	7.22	4.40
Mar	6.22	6.47	7.57	7.54	7.39	0.00
Apr	6.47	6.82	8.44	8.84	9.05	0.00
May	8.87	9.20	11.84	12.64	13.06	6.51
Jun	10.21	10.70	13.76	14.98	15.43	11.49
Jul	11.30	11.81	15.01	16.28	16.52	12.18
Aug	11.28	11.76	14.49	15.58	15.11	11.97
Average	8.72	9.15	10.59	11.01	10.84	5.42

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

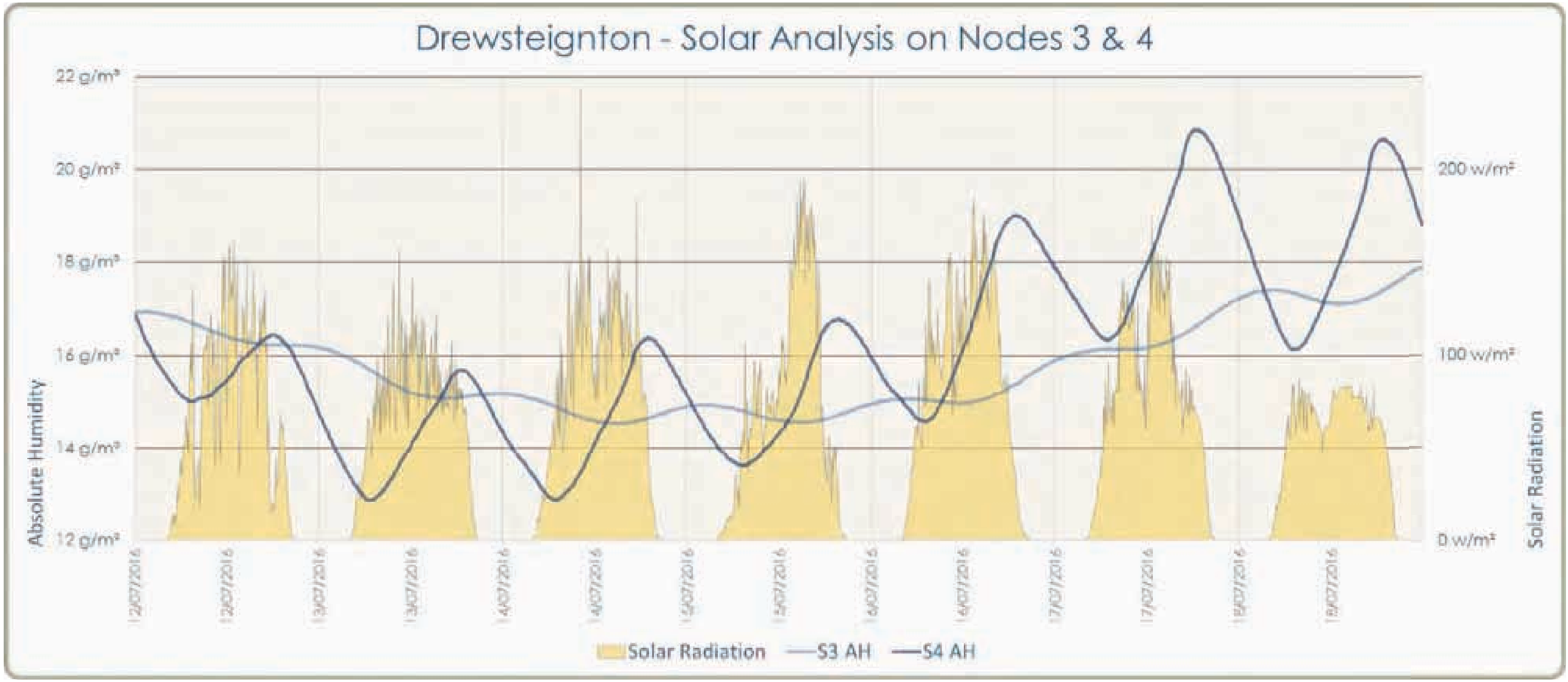


Figure 23: Solar Analysis sensors 3 and 4, Drewsteignton, July 2016.

Saturation Margins

Figure 24 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 6.73˚C in contrast to those of sensors 2, 3 and 4 where margins remain below 1.5˚C, Table 12. Indeed the average margins found for sensors 3 and 4 are below 1˚C, being 0.55˚C and 0.29˚C respectively. The annual average saturation margins for all three masonry sensors are at their narrowest since the wall was insulated in 2012.

Figure 24 shows that within the masonry part of the wall air was close to saturation for much of the year. At sensor 4 negative margins are calculated for the months April – July (Table 12) suggesting conditions ‘exceed’ dewpoint and the possible accumulation of liquid water at this location during these months. Conditions may not be dissimilar deeper within the wall at sensor 3 where margins are close to 0˚C June – August. That the wall reaches dewpoint during warmer summer months is due to a combination of factors. As has been previously noted air in general becomes more humid over summer and this effect is compound by evaporation from moisture bound within the wall materials. There is some recovery in the moisture picture towards the end of the summer presumably because sufficient moisture has now been evaporated from the wall to reduce vapour levels bringing saturation margins above 0˚C once again. However, as with the trend for %RH, the long-term trend for the wall shows a year-on-year reduction in these margins suggesting that over the long term the wall is unable to evaporate sufficient quantities of moisture to maintain an equilibrium below the vapour risk threshold.

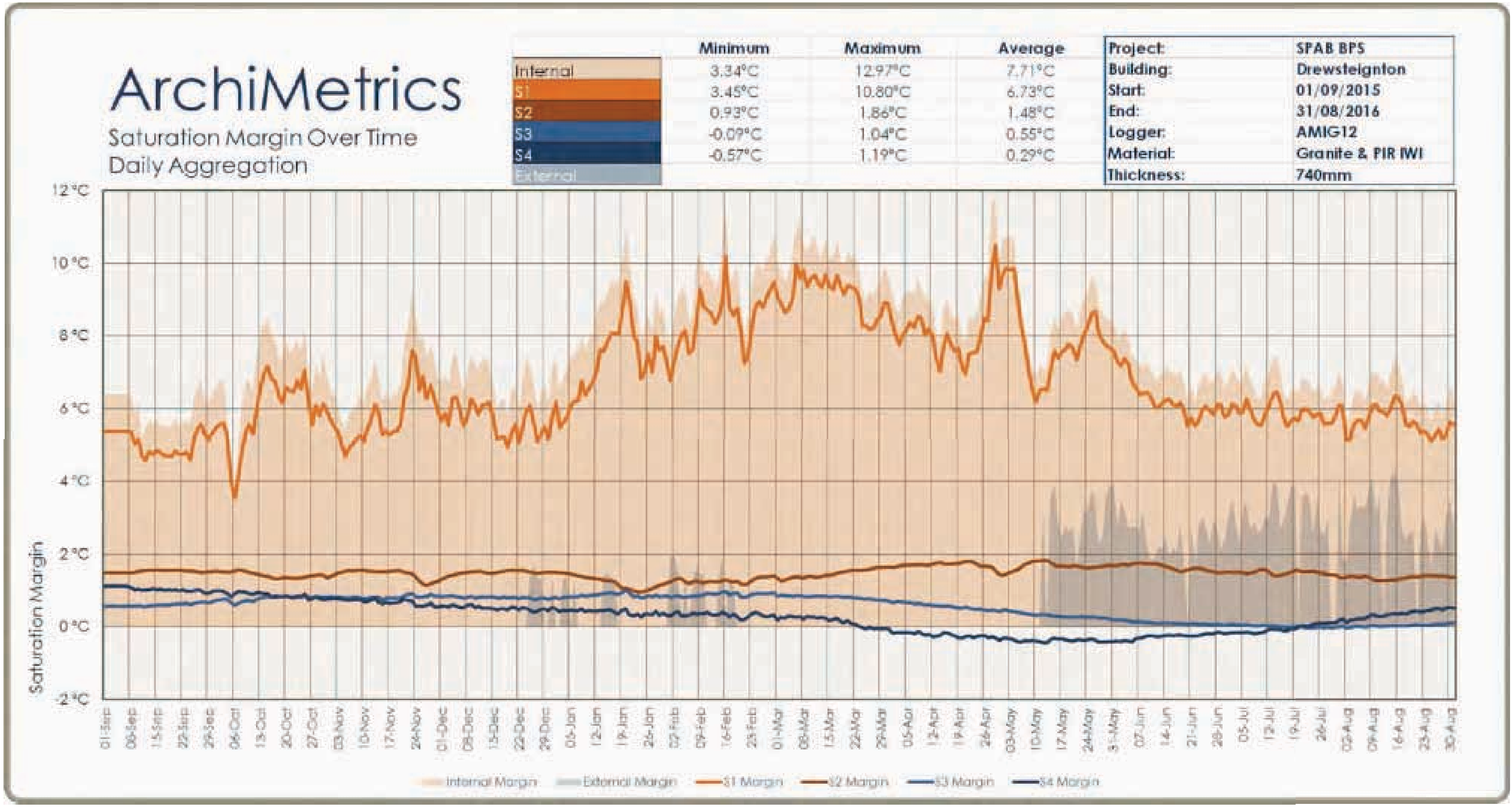
In Table 12 saturation margins are written individually and as an average of all four sensors and shows the change in these margins before and after the wall was insulated. From this table it can be seen that the saturation margins in the original masonry section of the wall (sensors 2, 3 and 4) have narrowed considerably following insulation and continue to narrow year-on-year. Margins at both sensor 4 and sensor 3 are below 1˚C for a second year. The rate of change (shown by a calculation of the difference between pre-refurbishment and post-refurbishment margins) has slowed at sensors 2 and 3 but increased at sensor 4. The margins found for this year are the narrowest recorded since insulation was added to the wall and the difference between these and pre-refurbishment margins is at its greatest. This conforms with the general trend of increasing %RH found for this wall. As an indication of risk the continued narrowing of the saturation margins within the masonry section of the wall shows that air within the wall structure continues to move closer to dewpoint suggesting an ever increasing moisture presence within the wall.

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**
2015 – 2016 (1/9/15 - 31/8/16)	6.73˚C	1.48˚C	0.62˚C	0.41˚C	2.31˚C
Difference	**-1.43˚C**	**3.34˚C**	**2.91˚C**	**1.97˚C**	**1.70˚C**

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

Hygrothermal Section

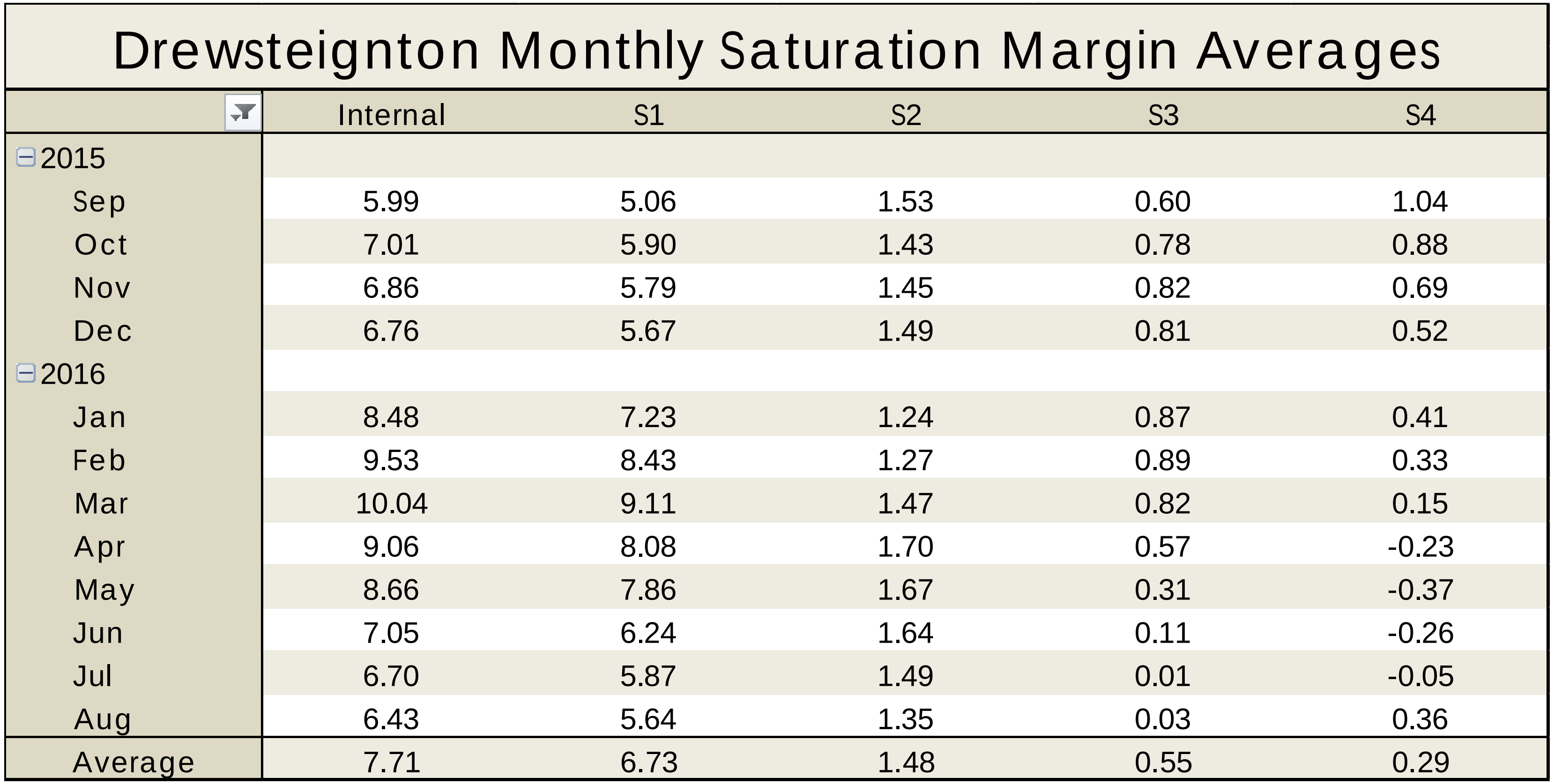
Measurements of temperature and %RH are also used to plot annual averages of measured temperature and dewpoint temperature through the wall section (Figure 25). In these Figures the convergence of the measured temperature and dewpoint temperature gradients, shows, on average, just how close the air may be to saturation through the masonry part of the section. Comparison with previous years' analyses (Figures 26, 27 and 28) shows how actual temperature and dewpoint temperature have continued to move closer together over the past four years. This is particularly the case towards the external side of the wall around sensor 4, where, with an annual average (capped) saturation margin of 0.41˚C the two temperatures are very similar. As with evidence from the saturation margins and %RH this shows how, with regard to indications of moisture performance, we continue to find a worsening picture for the wall at Drewsteignton.



	Minimum	Maximum	Average
Internal	3.34°C	12.97°C	7.71°C
S1	3.45°C	10.80°C	6.73°C
S2	0.93°C	1.86°C	1.48°C
S3	-0.09°C	1.04°C	0.55°C
S4	-0.57°C	1.19°C	0.29°C
External			

Project:	SPAB BPS
Building:	Drewsteignton
Start:	01/09/2015
End:	31/08/2016
Logger:	AMIG12
Material:	Granite & PIR IWI
Thickness:	740mm

Figure 24. Saturation Margin Over Time, Mill House, Drewsteignton, 2015 - 2016.



Drewsteignton Monthly Saturation Margin Averages

	Internal	S1	S2	S3	S4
⊟2015					
Sep	5.99	5.06	1.53	0.60	1.04
Oct	7.01	5.90	1.43	0.78	0.88
Nov	6.86	5.79	1.45	0.82	0.69
Dec	6.76	5.67	1.49	0.81	0.52
⊟2016					
Jan	8.48	7.23	1.24	0.87	0.41
Feb	9.53	8.43	1.27	0.89	0.33
Mar	10.04	9.11	1.47	0.82	0.15
Apr	9.06	8.08	1.70	0.57	-0.23
May	8.66	7.86	1.67	0.31	-0.37
Jun	7.05	6.24	1.64	0.11	-0.26
Jul	6.70	5.87	1.49	0.01	-0.05
Aug	6.43	5.64	1.35	0.03	0.36
Average	7.71	6.73	1.48	0.55	0.29

Table 13. Monthly Saturation Margin averages, Mill House, Drewsteignton, 2015 – 2016.

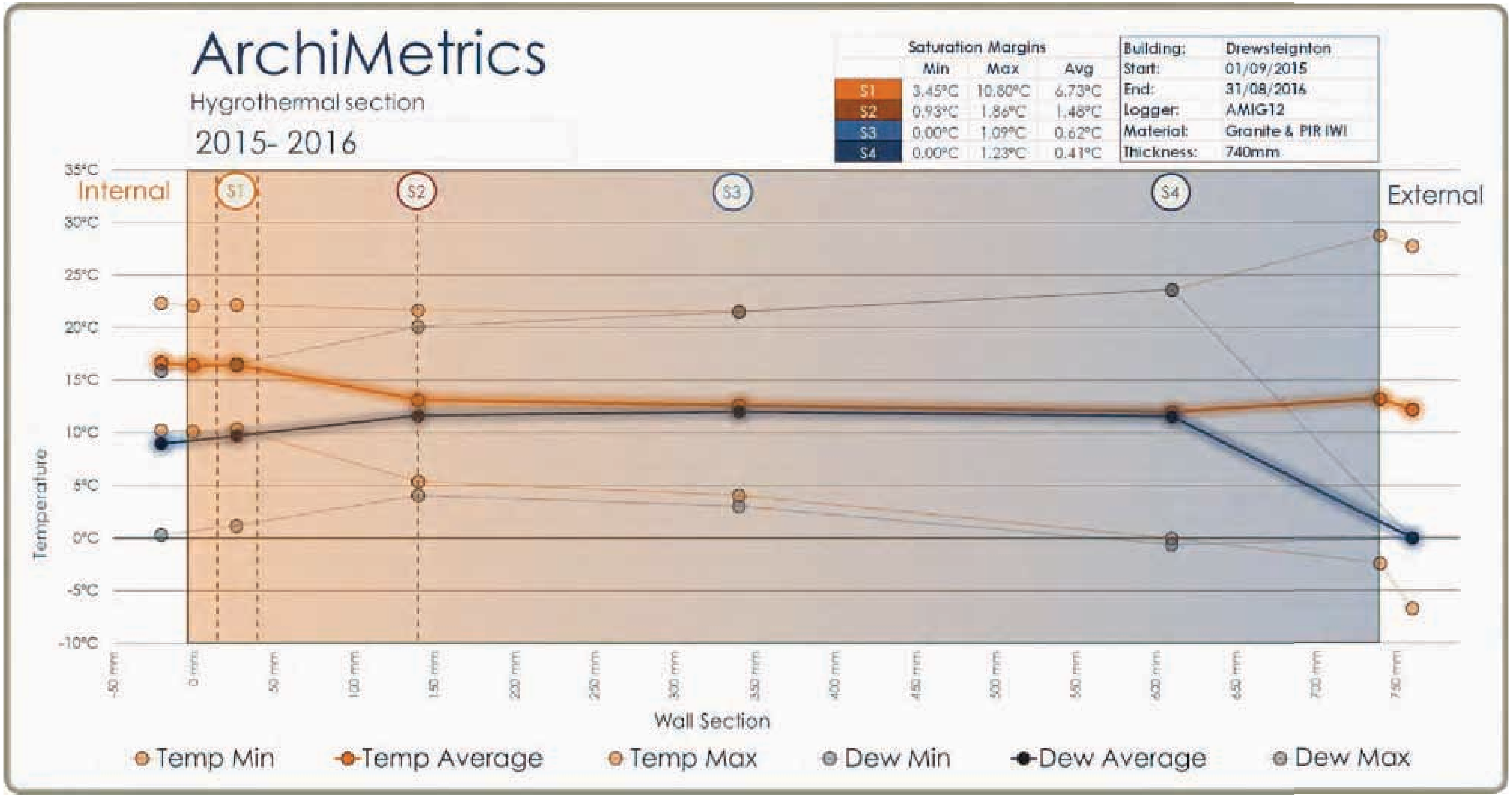
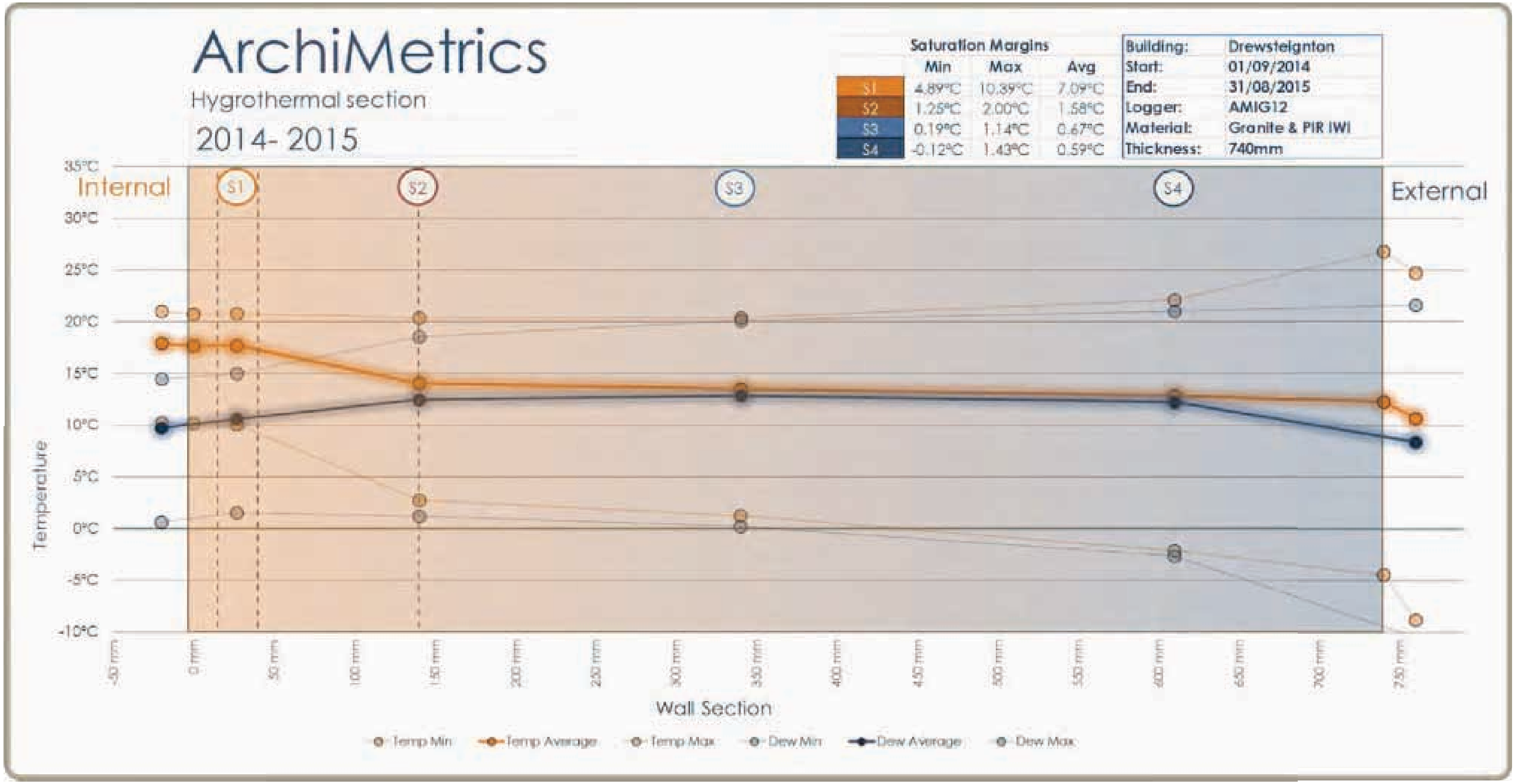


Figure 25. Hygrothermal Section, Mill House, Drewsteignton, 2015 – 2016 (capped).

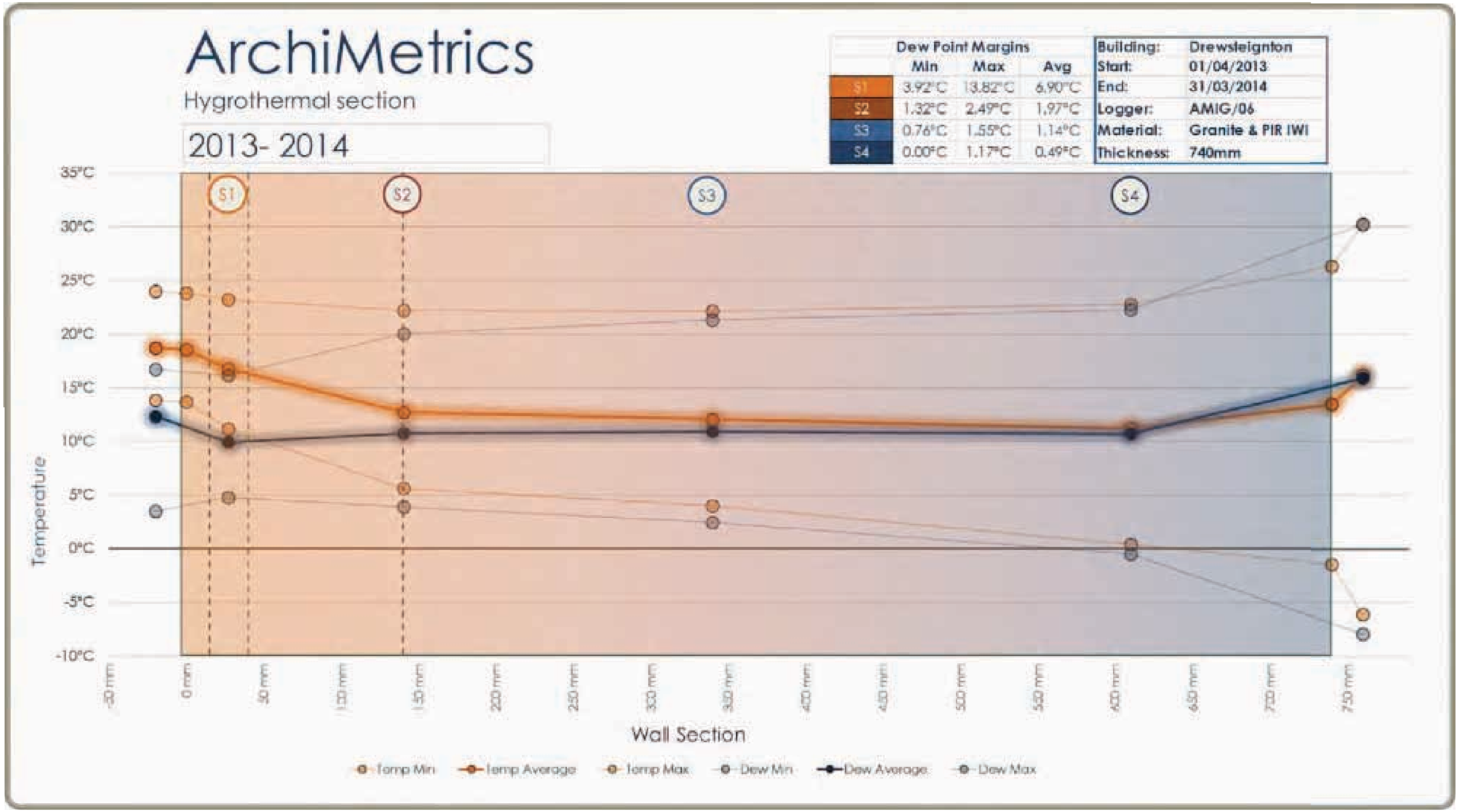
.



Saturation Margins	Min	Max	Avg
S1	4.89°C	10.39°C	7.09°C
S2	1.25°C	2.00°C	1.58°C
S3	0.19°C	1.14°C	0.67°C
S4	-0.12°C	1.43°C	0.59°C

Building:	Drewsteignton
Start:	01/09/2014
End:	31/08/2015
Logger:	AMIG12
Material:	Granite & PIR IWI
Thickness:	740mm

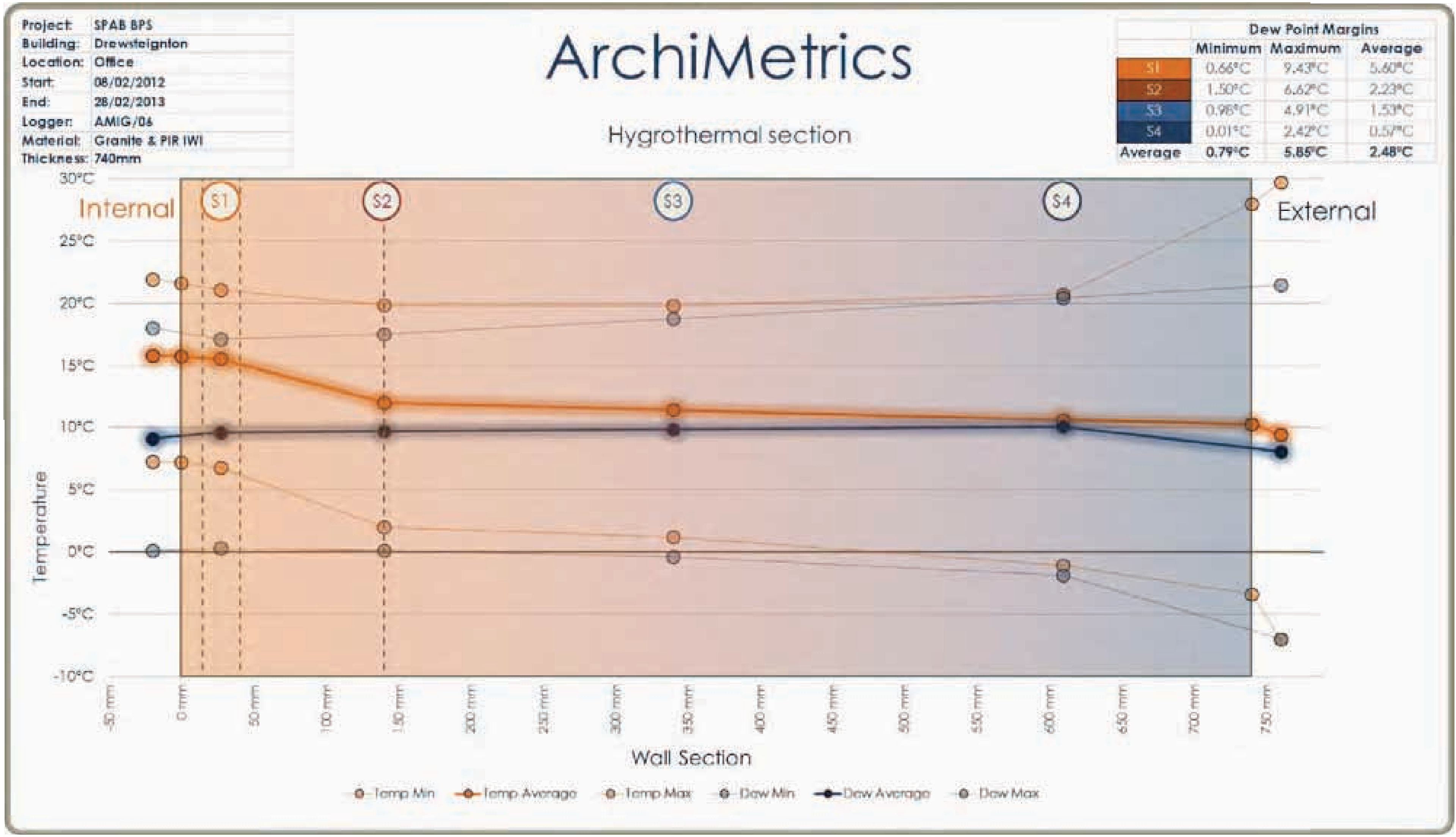
Figure 26. Hygrothermal Section, Mill House, Drewsteignton, 2014 – 2015 .



	Dew Point Margins		
	Min	Max	Avg
S1	3.92°C	13.82°C	6.90°C
S2	1.32°C	2.49°C	1.97°C
S3	0.76°C	1.55°C	1.14°C
S4	0.00°C	1.17°C	0.49°C

Building:	Drewsteignton
Start:	01/04/2013
End:	31/03/2014
Logger:	AMIG/06
Material:	Granite & PIR IWI
Thickness:	740mm

Figure 27. Hygrothermal Section, Mill House, Drewsteignton, 2013 - 2014.



Project:	SPAB BPS
Building:	Drewsteignton
Location:	Office
Start:	08/02/2012
End:	28/02/2013
Logger:	AMIG/06
Material:	Granite & PIR IWI
Thickness:	740mm

	Dew Point Margins		
	Minimum	Maximum	Average
S1	0.66°C	9.43°C	5.60°C
S2	1.50°C	6.62°C	2.23°C
S3	0.98°C	4.91°C	1.53°C
S4	0.01°C	2.42°C	0.57°C
Average	0.79°C	5.85°C	2.48°C

Figure 27. Hygrothermal Section, Mill House, Drewsteignton, 2012 - 2013.

Material Moisture

The wall at Drewsteignton has higher % moisture measurements than that of Shrewsbury. The annual average %MC for the granite wall, 0.79%, is close to double that of Shrewsbury, 0.47%.

There are some differences in the plots made during the first year's measurements and those made during 2015 – 16 (Figures 29 and 30). The most striking being the lack of variation in %MC measured from sensors 2 and 4 this year in comparison with those of the previous year. In contrast, plots from sensors 1 and 3 bear a resemblance to those recorded in the previous year. Sensor 1 is embedded within the PIR insulation material and here moisture measurements are low with little variation throughout both years as might be expected from a hydrophobic closed cell material. %MC measured at sensor 3 is also similar to the previous year, the annual average value, 1.52%, being slightly lower than the 2014 – 15 average 1.63%. However, %MC is lower at sensors 2 and 4 year and remains consistently so throughout the year.

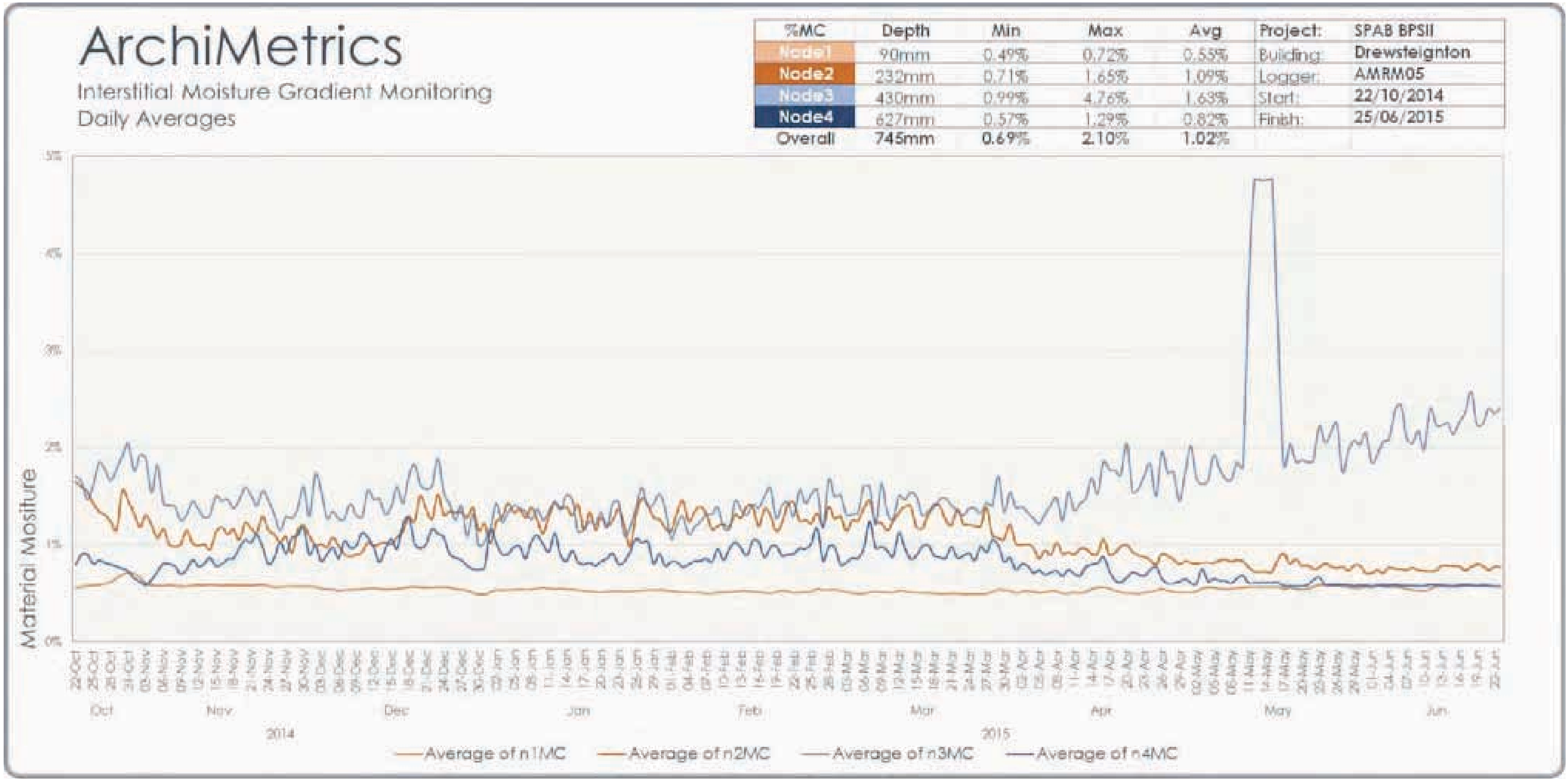
An explanation as to the difference between the two years lies in the particular qualities of the granite wall and may also explain the difference between the vapour records for the wall, which are generally high and the relatively low %MC measured in some parts of the wall section. Granite is a dense igneous rock formed by the crystallisation of magma as such it lacks an interconnected pore structure, has limited permeability and low water carrying capacity. Sensors 2 and 4 are embedded within blocks of granite and thus, in a way not dissimilar to sensor 1, isolated within a material. The nature of this stone means that it is hard to add moisture to it and similarly difficult to reduce its moisture content as the movement of moisture, either as a liquid or a vapour, will be limited within the granite stone itself. However, measurements both of material moisture and vapour show that these quantities vary throughout the year, perhaps principally via the influence of other aspects of the wall's construction; cracks and fissures and the lime mortar bedding joints between the stone blocks. The majority of moisture reduction (drying) in these materials is likely to take place through the slower process of vaporisation and diffusion, which in certain materials and at certain times of the year lead to higher RH and AH readings.

The process of embedding the sensors introduces moisture into the wall in the form of lime mortar. This is the reason, we believe, we record higher %MC readings in the first year of monitoring at sensor locations 2 and 4. The material moisture sensors were installed in May 2014 and we can see from the previous year's analysis (Figure 28) that %MC quantities at sensors 2 and 4 reduce at the end of March 2015, ten months later. A continuation of the drying process is visible at the beginning of this year's analysis where MC quantities at sensor 2 are still reducing through September and October before reaching what appears to be some form of equilibrium with percentages between 0.5 – 0.6% measured at sensors 1, 2 and 4. If drying takes place via the evaporation and diffusion of water this can explain why, although the wall, in parts, records low %MC similar locations can measure high weights and proportions of vapour. To the extent that, at certain times of the year, despite warmer temperatures which should lead to a reduction in %RH, RH is close to or above 100% and saturation margins suggest that vapour may be condensing back to a liquid.

Sensor 3 obviously presents quite a different %MC picture from those of the other three material moisture sensors in the wall. Here %MC is higher and reaches a peak week beginning 19th July of 2.14% which coincides with a peak in AH and high external temperatures. We believe that this sensor is not embedded within a granite block (as might be expected for sensor positions 2 and 4 positioned towards the external and internal side of the masonry wall) but is in contact with and influenced by the moisture within a mortar bed as might be expected in the centre of a stone wall. The lime mortar is more porous and permeable than the surrounding granite and thus shows a higher moisture content and peaks in vapour, as it is able to hold and move more moisture, both as a liquid and a vapour. The fundamentally different qualities of lime mortar in relation to the granite become visible in the %MC record from the previous 2014 – 15 year. Just as sensor positions 2 and 4 begin to dry around the end of March 2015, %MC at sensor 3 increases as part of this drying process. The mortar beds through the wall create a network by which moisture is moved and can be evaporated and over time the %MC slowly reduces in less porous materials and increases in the more porous and permeable lime mortar, a relationship which has been established by the time of the follow year's, 2015 -16 analysis.

%MC	Depth	Min	Max	Avg	Project:	SPAB BPSII
Node1	90mm	0.48%	0.68%	0.57%	Building:	Drewsteignton
Node2	232mm	0.50%	1.10%	0.57%	Logger:	AMRM05
Node3	430mm	0.76%	4.22%	1.81%	Start:	01/09/2015
Node4	627mm	0.40%	0.57%	0.51%	Finish:	31/08/2016
Overall	745mm	0.55%	1.64%	0.86%		

Figure 29: Material moisture content over time, Mill House, Drewsteignton, 2015 - 2016.



%MC	Depth	Min	Max	Avg	Project:	SPAB BPSII
Node1	90mm	0.49%	0.72%	0.55%	Building:	Drewsteignton
Node2	232mm	0.71%	1.65%	1.09%	Logger:	AMRM05
Node3	430mm	0.99%	4.76%	1.63%	Start:	22/10/2014
Node4	627mm	0.57%	1.29%	0.82%	Finish:	25/06/2015
Overall	745mm	0.69%	2.10%	1.02%		

Figure 30: Material moisture content over time, Mill House, Drewsteignton, 2014 - 2015.

2.3. The Firs, Riddlecombe, Devon - 2015 - 16.

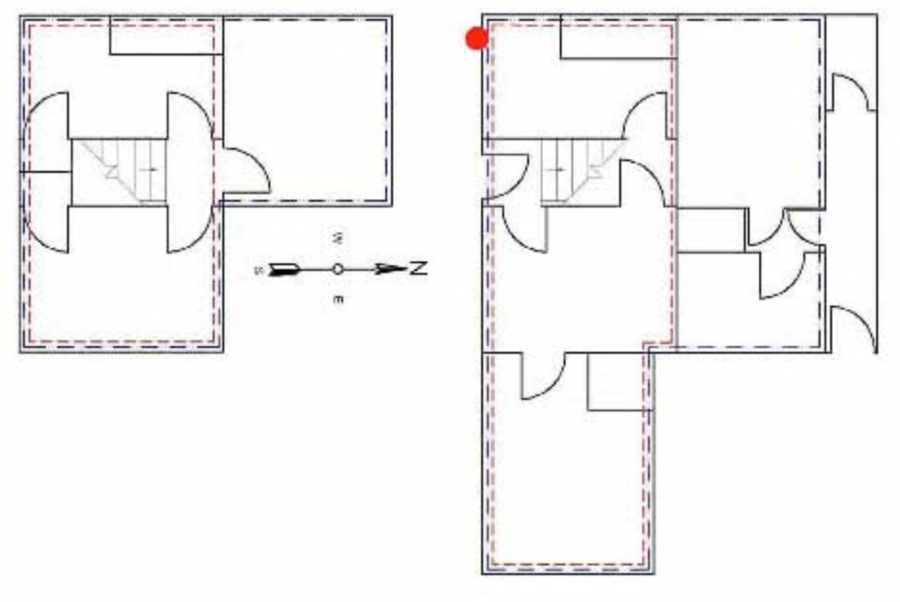


Figure 31. Plan of The Firs, Riddlecombe (ground floor on right hand side). Location of IHGM monitoring equipment shown by red dot.

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 32. Interstitial Hygrothermal Gradient and Material Moisture Monitoring, Riddlecombe.

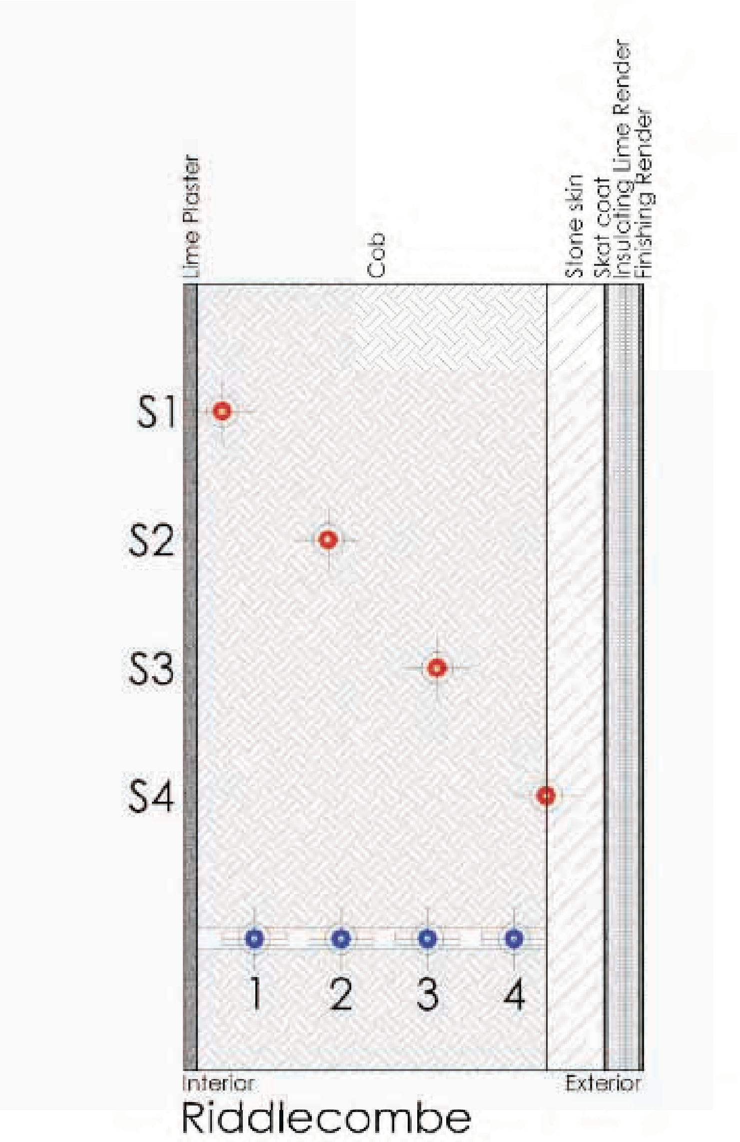


Figure 33. Position of sensors through wall section, Riddlecombe.

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 32 and 33). 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 2015 – 31st August 2016, has been used as the basis for the following analysis.

Relative Humidity Over Time

Figure 34 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 indicates %RH in excess of 100%, shows the average level of %RH at sensor 4 to be 112% suggesting wet conditions and indeed wet material has been previously retrieved from the wall at this location. Annual average %RH values are also higher than those found for the wall at Drewsteignton at the other three sensors albeit by only 1% for sensors 2 and 3.

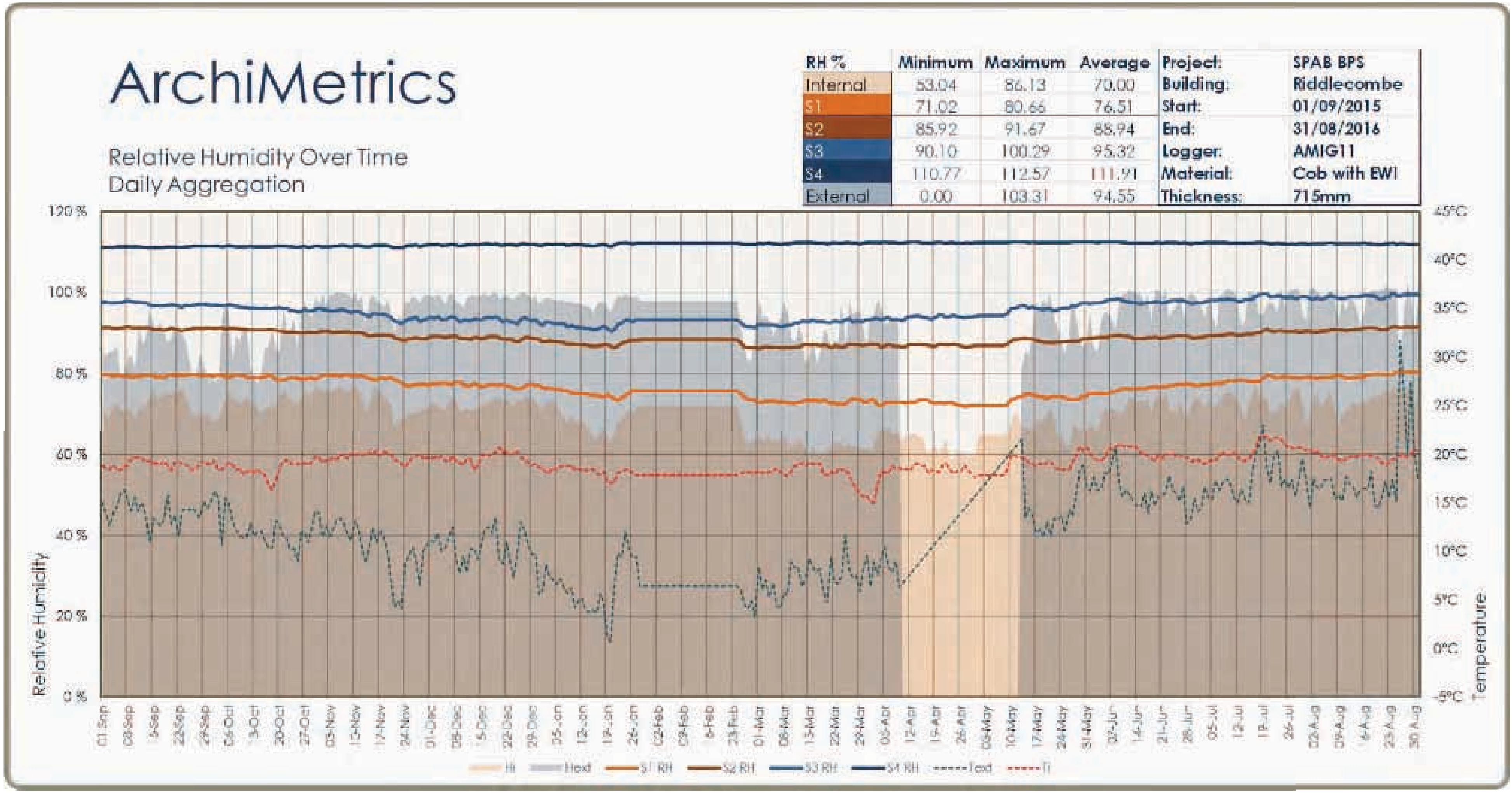
In previous reports we have deemed the high levels of %RH found in the cob wall at Riddlecombe to mostly likely be the result of evaporation of construction moisture bound within the earth fabric. An inversion of the ‘normal’ pattern of %RH behaviour was seen in the cob wall where %RH was at its lowest during the wintertime (when normally colder temperatures would lead to higher %RH) and higher %RH over summer. This pattern is still in evidence in this 2015 -16 analysis. This can be explained by the vaporisation of moisture bound within the materials caused by warmer summer temperatures and in particular direct solar radiation on the south-facing wall (see previous reports for more detail). (A similar effect is becoming visible within the Drewsteignton analysis although the peaks and troughs of %RH measurements do not occur so absolutely with the lowest and highest external temperatures but slightly earlier in both the winter and summer seasons.) Due to the permeable nature of the wall materials at Riddlecombe, cob and lime finishes, we have hoped that over time we would see vapour quantities diminish within the wall as this moisture vaporised and evaporated. Last year an examination of average annual %RH values for this wall showed a possible slight reduction in %RH at the sensor 3 location. This year 2015 – 16 the annual average values shown in Table 15 illustrate a slightly improving picture deeper inside the cob wall as average %RH measured at sensors 1, 2 and 3 has reduced.

Annual Average RH	**Sensor 1**	**Sensor 2**	**Sensor 3**	**Sensor 4**
2013 - 2014	78%	91%	99%	100%*
2014 - 2015	78%	91%	96%	110%
2015 - 2016	77%	89%	95%	112%

*Table 15. Comparison of annual averages of RH measured through wall section, Riddlecombe 2013 - 2015. *Capped at 100%.*

The 2015 -16 data shows a decrease in %RH at three of the four wall sensors which builds on a trend hinted at in the previous year's report. The exception to this being responses at sensor 4 which suggest conditions at this location continue to be at dewpoint. We believe sensor 4 is located in proximity to a stone buttress built to reinforce the external face of the cob wall. As part of the refurbishment work the external face of the wall has been covered with a new insulating lime render incorporating a natural hydraulic lime, aggregates and perlite. It maybe that conditions at this location are different from those in other parts of the wall due to the drying that is taking place moving vapour from the centre of the wall towards the external wall surface. The materials which constitute the render coupled with its thickness may be retarding this migration of vapour in proximity to the external surface around sensor 4 causing moisture to accumulate.

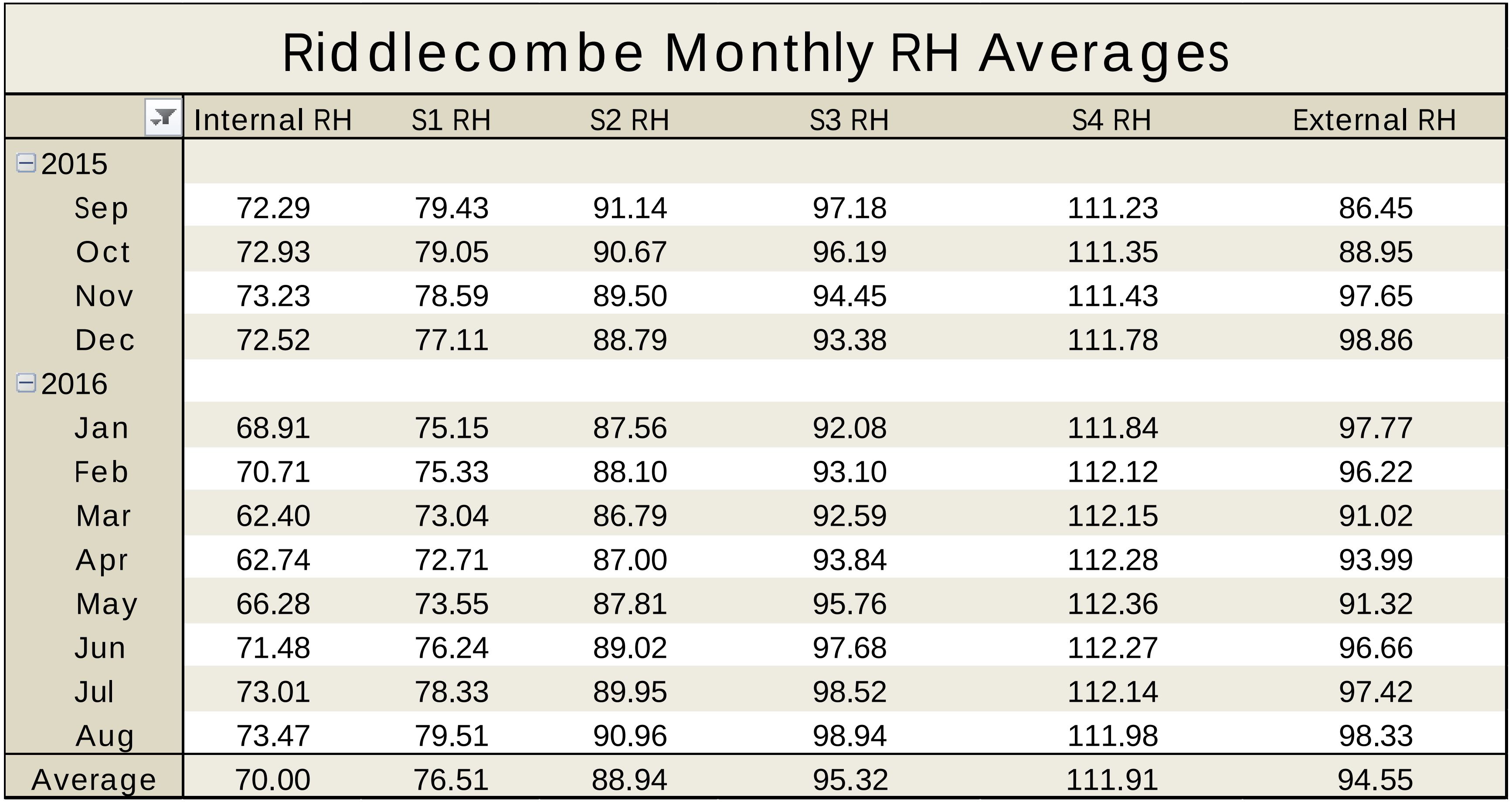
From the point of view of the mould growth threshold the wall is still unsatisfactory with only sensor 1 towards the interior wall face recording an average of below 80% RH. Annual average measurements at sensors 2, 3 and 4 are above this threshold although for the first time since post-refurbishment measurements began the annual average value for sensor 2 is below 90%. Sensor 4 is above 100%. Due to the nature of its materials an earth-based wall may have the capacity to contain higher quantities of moisture. However, they are also more likely to contain organic materials susceptible to rot at humidity above 80% for prolonged periods of time and be less stable when moisture content is too high.



RH %	Minimum	Maximum	Average
Internal	53.04	86.13	70.00
S1	71.02	80.66	76.51
S2	85.92	91.67	88.94
S3	90.10	100.29	95.32
S4	110.77	112.57	111.91
External	0.00	103.31	94.55

Project:	**SPAB BPS**
Building:	**Riddlecombe**
Start:	**01/09/2015**
End:	**31/08/2016**
Logger:	**AMIG11**
Material:	**Cob with EWI**
Thickness:	**715mm**

Figure 34: Relative Humidity over time, The Firs, Riddlecombe 2015 - 2016.



Riddlecombe Monthly RH Averages

	Internal RH	S1 RH	S2 RH	S3 RH	S4 RH	External RH
⊟2015						
Sep	72.29	79.43	91.14	97.18	111.23	86.45
Oct	72.93	79.05	90.67	96.19	111.35	88.95
Nov	73.23	78.59	89.50	94.45	111.43	97.65
Dec	72.52	77.11	88.79	93.38	111.78	98.86
⊟2016						
Jan	68.91	75.15	87.56	92.08	111.84	97.77
Feb	70.71	75.33	88.10	93.10	112.12	96.22
Mar	62.40	73.04	86.79	92.59	112.15	91.02
Apr	62.74	72.71	87.00	93.84	112.28	93.99
May	66.28	73.55	87.81	95.76	112.36	91.32
Jun	71.48	76.24	89.02	97.68	112.27	96.66
Jul	73.01	78.33	89.95	98.52	112.14	97.42
Aug	73.47	79.51	90.96	98.94	111.98	98.33
Average	70.00	76.51	88.94	95.32	111.91	94.55

Table 16: Relative Humidity monthly averages, Riddlecombe, 2015 - 2016.

Absolute Humidity Over Time

Figure 35 shows an analysis of absolute humidity through the insulated wall section at Riddlecombe September 2015 - August 2016. As with records of %RH, weights of vapour measured in the wall at Riddlecombe are higher than those of the other two walls in the study, something that we believe is a reflection of the additional moisture load within this wall due to bound in construction moisture added during the refurbishment re-rendering process. 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 material moisture) affecting conditions within the wall above and beyond that of internal and external air.

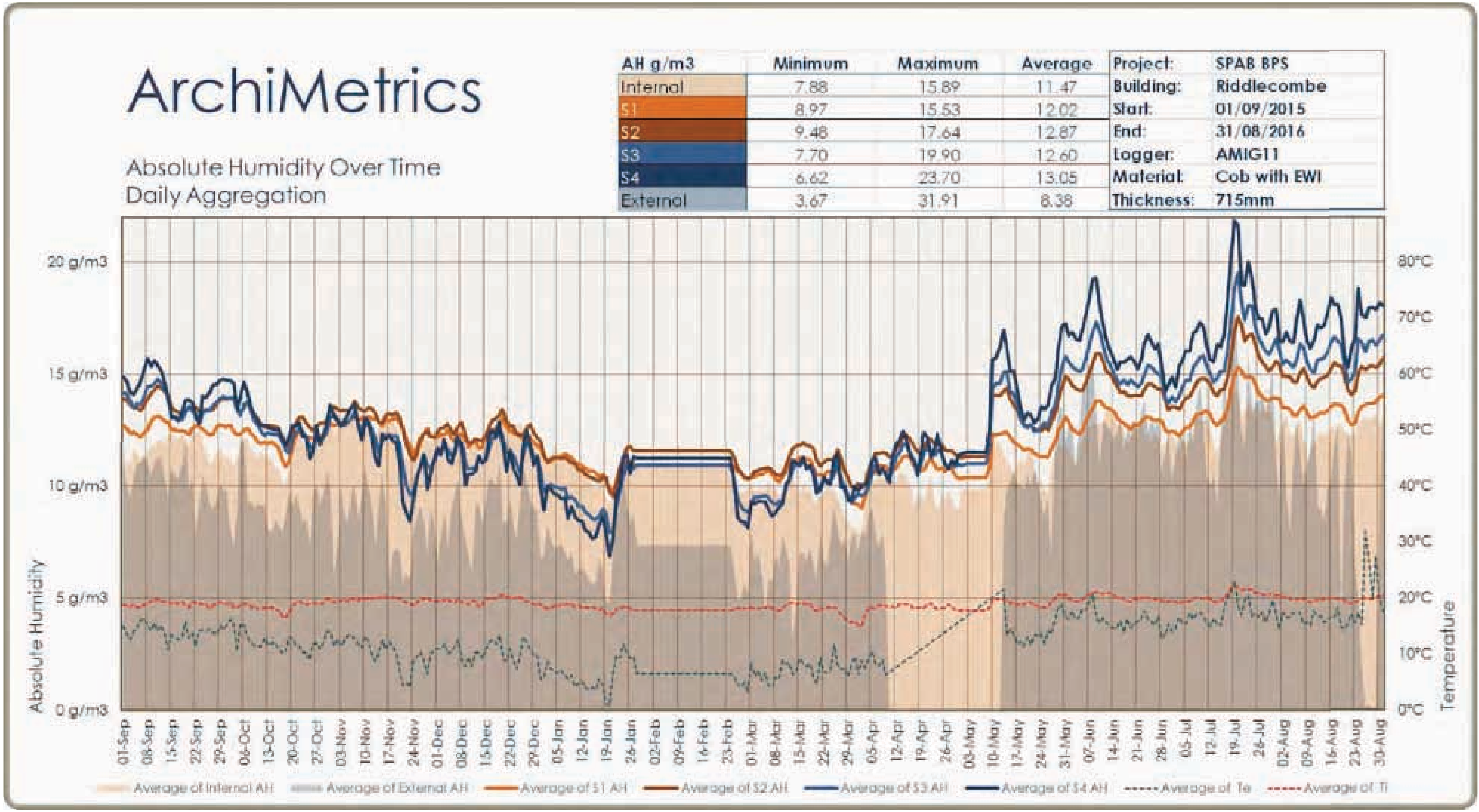
For an extended period of time in the Riddlecombe analysis, weights of vapour towards the internal side of the wall at sensors 1 and 2 exceed those measured at sensors 3 and 4. This reflects the ambient conditions surrounding the wall during the winter where the warmer internal space contains more vapour. (A similar phenomenon is seen at Drewsteignton but for a much shorter duration.) There then follows a brief period, end of March beginning of April, when quantities of vapour are similar throughout the measured section before a summertime pattern emerges. Now measurements towards the external side of the wall show the highest weights of vapour once again reflecting ambient conditions. The homogeneity of the wall can be seen in the similarity of the plots between the four sensors (unlike Drewsteignton where the wall has been added with internal insulation).

As is the case with Shrewsbury (although less dramatically), responses are more extreme towards the external side of the wall which, being south-facing, receives direct solar radiation over the summer provoking a strong vapour response. Weights of vapour reach a peak through the measured section week beginning 19th July coinciding with a peak in external temperatures (as do external AH conditions). It is interesting to note the vapour response within the wall during another peak in external temperatures later in the year. Week beginning 23rd August sees a spike in external temperatures which exceeds 30°C (Figure 36). Whilst an increase in AH can be seen to coincide with this temperature spike the peak is not as great as that seen previously despite the high external temperature. This suggests that by this time in the year the wall may have passed ‘peak drying’ i.e. excess residual moisture bound within materials has largely been vaporised during earlier periods of warm weather meaning responses during this later week are less pronounced.

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. Compared year-on-year, the annual average AH values for 2015 -16 suggest a change is occurring within the cob wall at Riddlecombe which corresponds with that also indicated by the %RH data (Table 17). This is the first year, since refurbishment measurements began, where a decrease in average weights of vapour is recorded from three of the four sensor positions. As previously noted AH (and %RH) at sensor 4 persistently records the highest quantities found throughout the study. At this location sensor 4 continues a trend which had earlier been found across the whole wall section - vapour weights increase year-on-year. However, at the other three sensors we see a reversal of this trend and average annual weights of vapour fall. Could this mean that the 'peak drying' observed for the week beginning 19th July and discussed above indicates that the wall has dispersed sufficient quantities of the moisture that was added to it's fabric to now be moving into a new phase where we will see diminishing quantities of vapour, year-on-year, until the cob arrives as some form of moisture equilibrium?

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
2015 - 2014	12.02 g/m^3	12.87 g/m^3	12.60 g/m^3	13.05 g/m^3

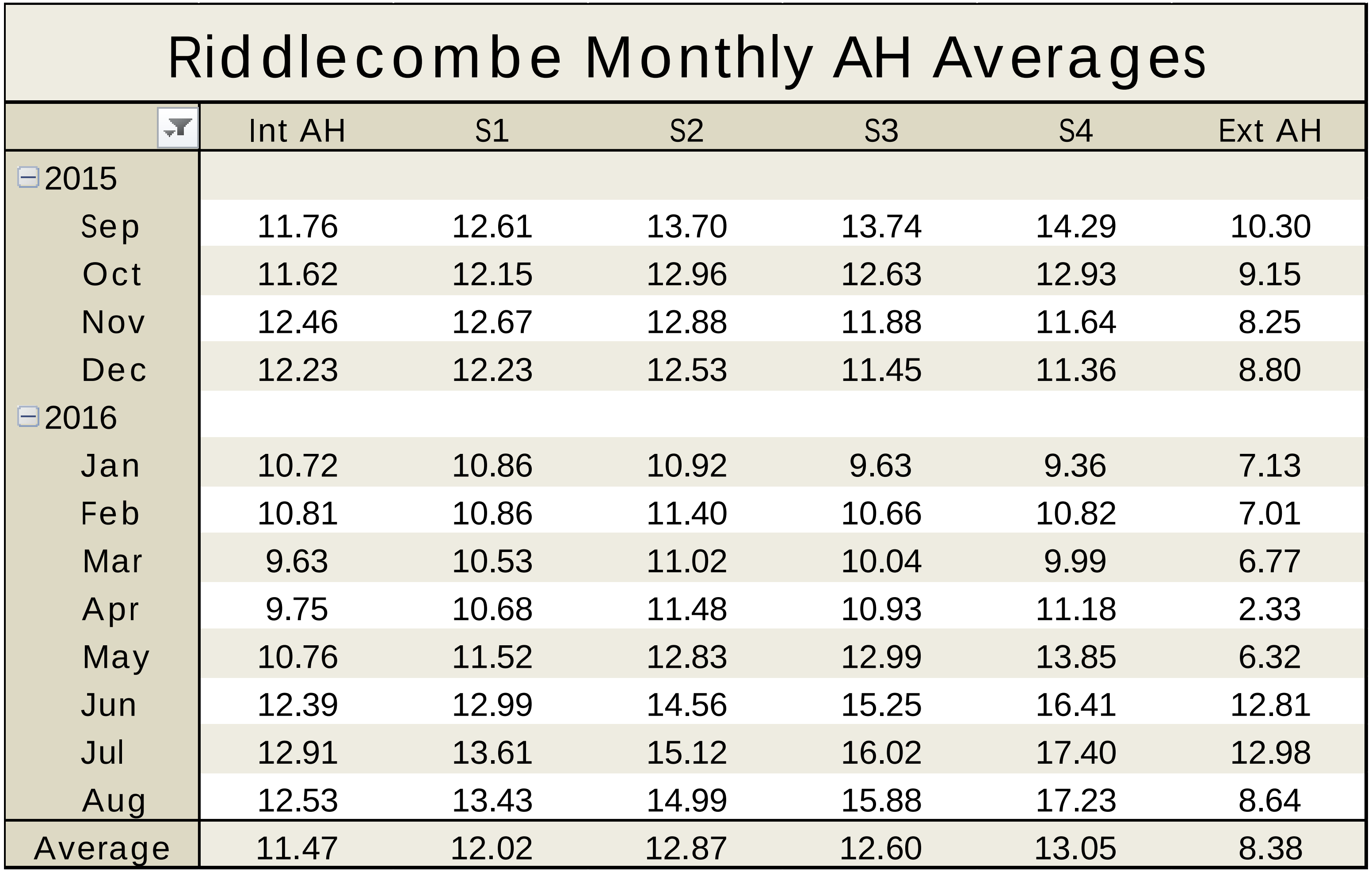
Table 17. Average Absolute Humidity, The Firs, Riddlecombe, 2012 - 2016.



AH g/m3	Minimum	Maximum	Average
Internal	7.88	15.89	11.47
S1	8.97	15.53	12.02
S2	9.48	17.64	12.87
S3	7.70	19.90	12.60
S4	6.62	23.70	13.05
External	3.67	31.91	8.38

Project:	SPAB BPS
Building:	Riddlecombe
Start:	01/09/2015
End:	31/08/2016
Logger:	AMIG11
Material:	Cob with EWI
Thickness:	715mm

Figure 35: Absolute Humidity over time, The Firs, Riddlecombe, 2015 - 2016.



Riddlecombe Monthly AH Averages

	Int AH	S1	S2	S3	S4	Ext AH
⊟2015						
Sep	11.76	12.61	13.70	13.74	14.29	10.30
Oct	11.62	12.15	12.96	12.63	12.93	9.15
Nov	12.46	12.67	12.88	11.88	11.64	8.25
Dec	12.23	12.23	12.53	11.45	11.36	8.80
⊟2016						
Jan	10.72	10.86	10.92	9.63	9.36	7.13
Feb	10.81	10.86	11.40	10.66	10.82	7.01
Mar	9.63	10.53	11.02	10.04	9.99	6.77
Apr	9.75	10.68	11.48	10.93	11.18	2.33
May	10.76	11.52	12.83	12.99	13.85	6.32
Jun	12.39	12.99	14.56	15.25	16.41	12.81
Jul	12.91	13.61	15.12	16.02	17.40	12.98
Aug	12.53	13.43	14.99	15.88	17.23	8.64
Average	11.47	12.02	12.87	12.60	13.05	8.38

Table 18: Absolute Humidity monthly averages, Riddlecombe 2015 - 2016.

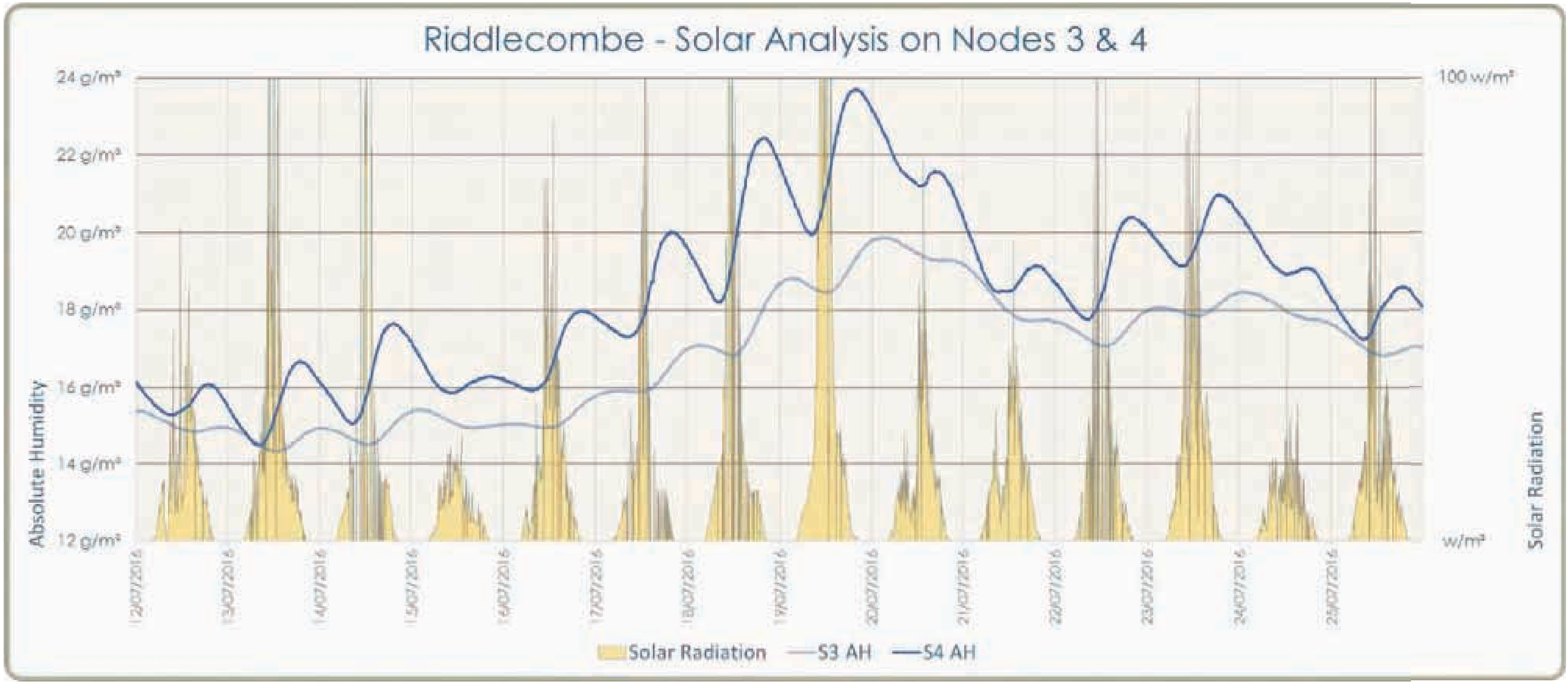


Figure 36: Solar Analysis - Absolute Humidity sensors 3 and 4 over time, Riddlecombe, July 2016.

Saturation Margins

Figure 37 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 consistently records %RH in excess of 100% throughout the year and hence is the only wall of the three in the study to have, on average, a negative saturation margin, -1.79˚C at sensor 4. The average margin at sensor 3 is narrow, being less than 1˚C, but due to the diminishing vapour trend found at Riddlecombe this year this margin has now increased to 0.68˚C from that of last year's 0.52˚C. Thus the granite wall at Drewsteignton now displays conditions closer to dewpoint around its sensor 3 location than those found at Riddlecombe, the wall hitherto considered to be the wettest and most humid of the three walls in the study.

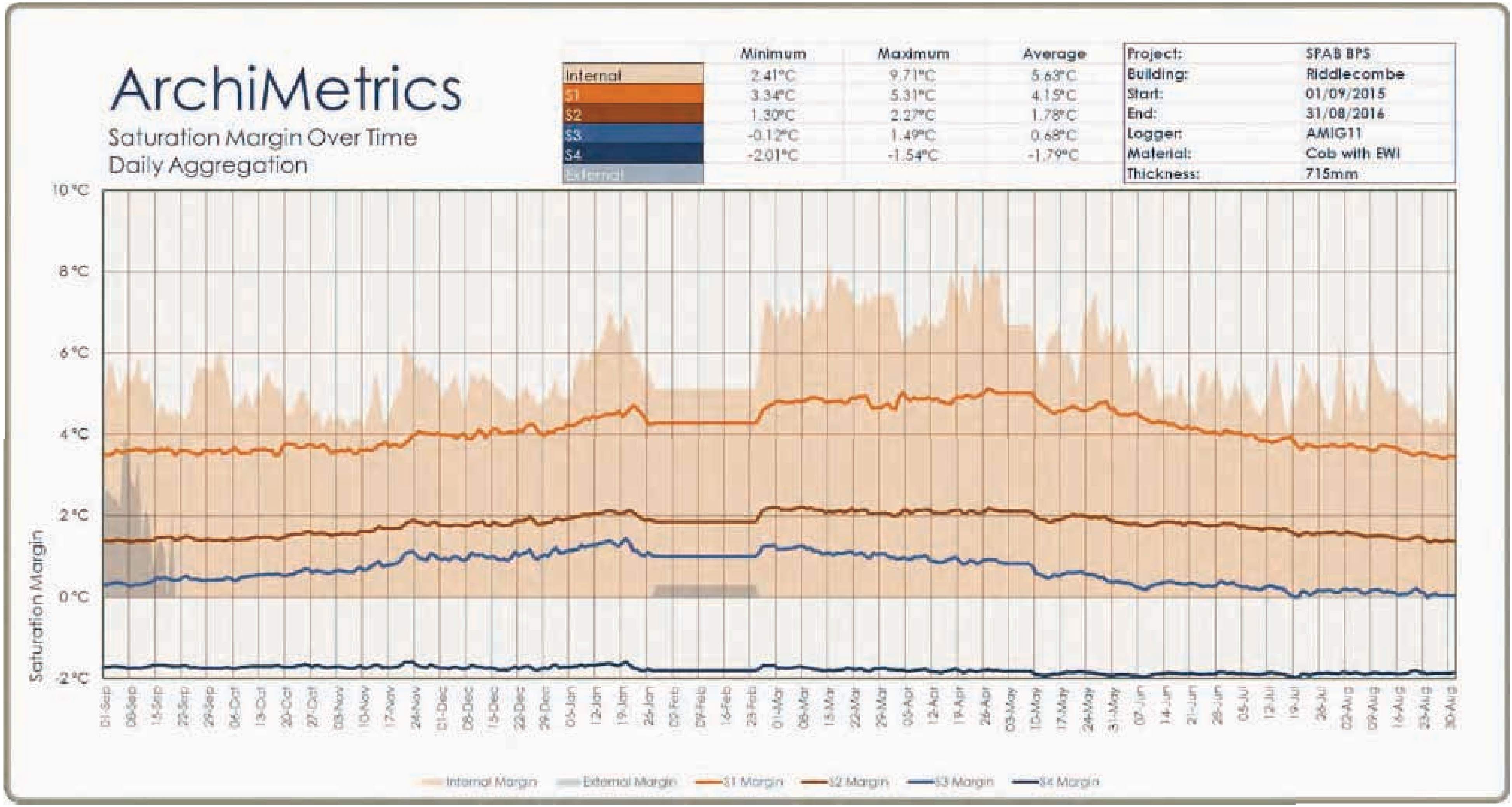
A comparison of previous year's saturation margins, including a calculation of the difference between post-refurbishment margins and those calculated pre-refurbishment, is presented in Table 19. Like the RH and AH vapour analyses this table shows an improving picture for the wall at Riddlecombe suggesting that moisture levels within the wall maybe decreasing. The saturation margin could be used as an indicator of risk, that is it quantifies how close the air at a particular location is to dewpoint and thus by extension the possibility of condensation or liquid water. This year sees increases in the saturation margins at sensors 1, 2 and 3, moving conditions at these locations within the cob wall further away from the possibility of dewpoint, condensation and the deposition of liquid water. Just as conditions measured from the majority of the wall sensors show increased margins for this year this inevitably has an impact upon the average saturation margin calculated for all four sensors through the section, which also increases. As before however the same cannot be said for the margin at sensor 4. As %RH has been capped at 100%, the threshold limit of dewpoint, in this table margins are shown as 0˚C where they have remained for the past three years, suggesting conditions at this location may be permanently wet.

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**
2015 – 2016 (1/9/15 - 31/8/16	4.15˚C	1.78˚C	0.74˚C	0.00˚C	1.67˚C
Difference	**1.42˚C**	**1.44˚C**	**1.32˚C**	**0.06˚C**	**1.19˚C**

Table 19. Dewpoint Margins & Pre & Post-insulation Difference, The Firs, Riddlecombe, 2011 – 2016 (2015 & 2016 margins capped).

Hygrothermal Section

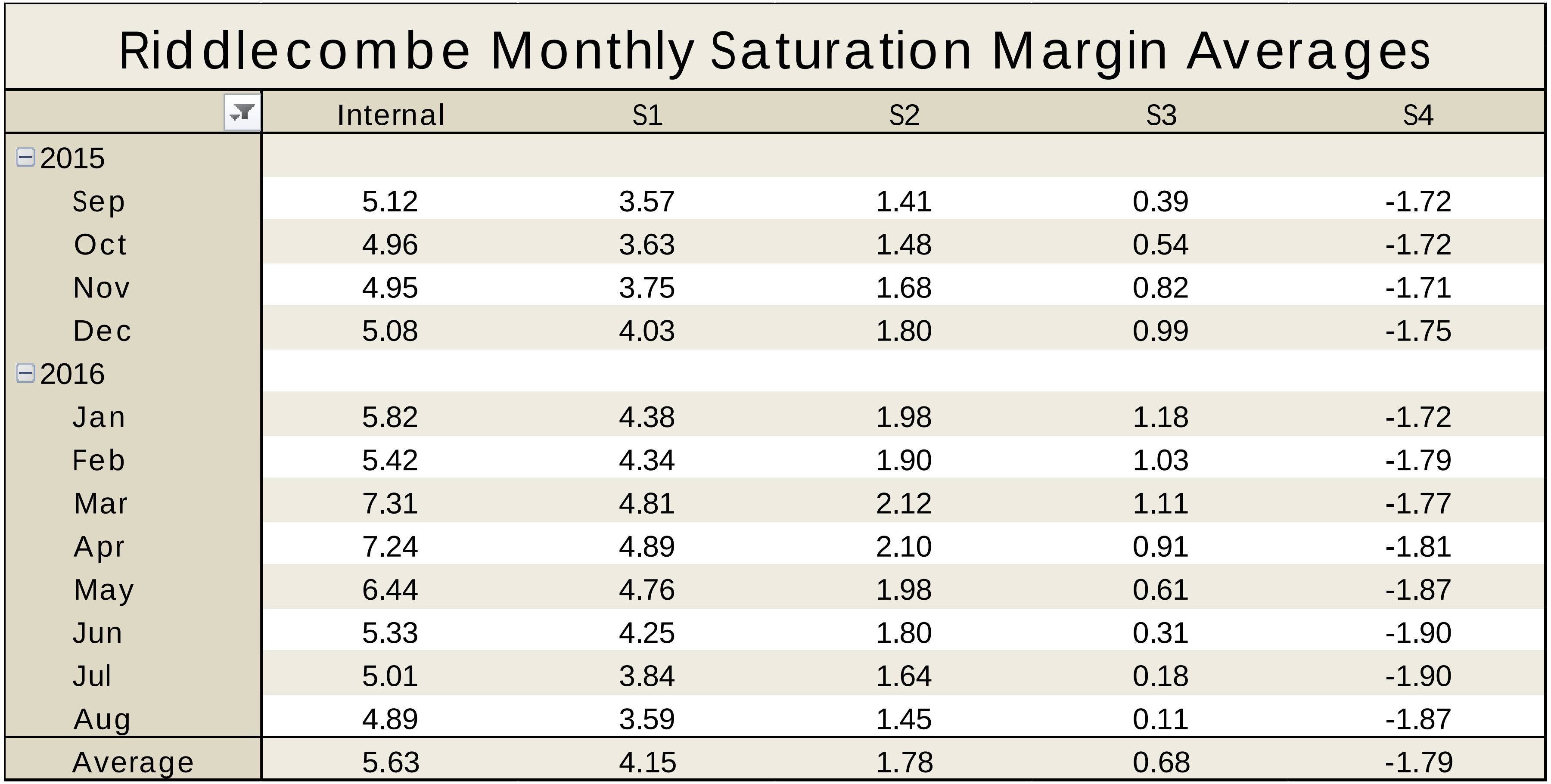
Measurements of temperature and RH are also used to plot annual temperature and dewpoint temperature gradients through the wall section (Figures 38 - 40). A comparison of the three monitored years shows a gradual change taking place within the wall as the narrow margin between the measured temperatures and dewpoint temperatures gradually widens. Plots of the two averaged temperatures though remain converged at sensor 4. These hygrothermal sections describe 'average' conditions and these continue to show that the air within the cob is close to saturation particularly around the sensors further back in the wall; 2, 3 and 4. However it would seem that over the past three years, as with observations elsewhere of a reductions in %RH and AH measured within the wall, that these changes indicate an improvement in the vapour profile for the cob wall at Riddlecombe.



	Minimum	Maximum	Average
Internal	2.41°C	9.71°C	5.63°C
S1	3.34°C	5.31°C	4.15°C
S2	1.30°C	2.27°C	1.78°C
S3	-0.12°C	1.49°C	0.68°C
S4	-2.01°C	-1.54°C	-1.79°C
External			

Project:	SPAB BPS
Building:	Riddlecombe
Start:	01/09/2015
End:	31/08/2016
Logger:	AMIG11
Material:	Cob with EWI
Thickness:	715mm

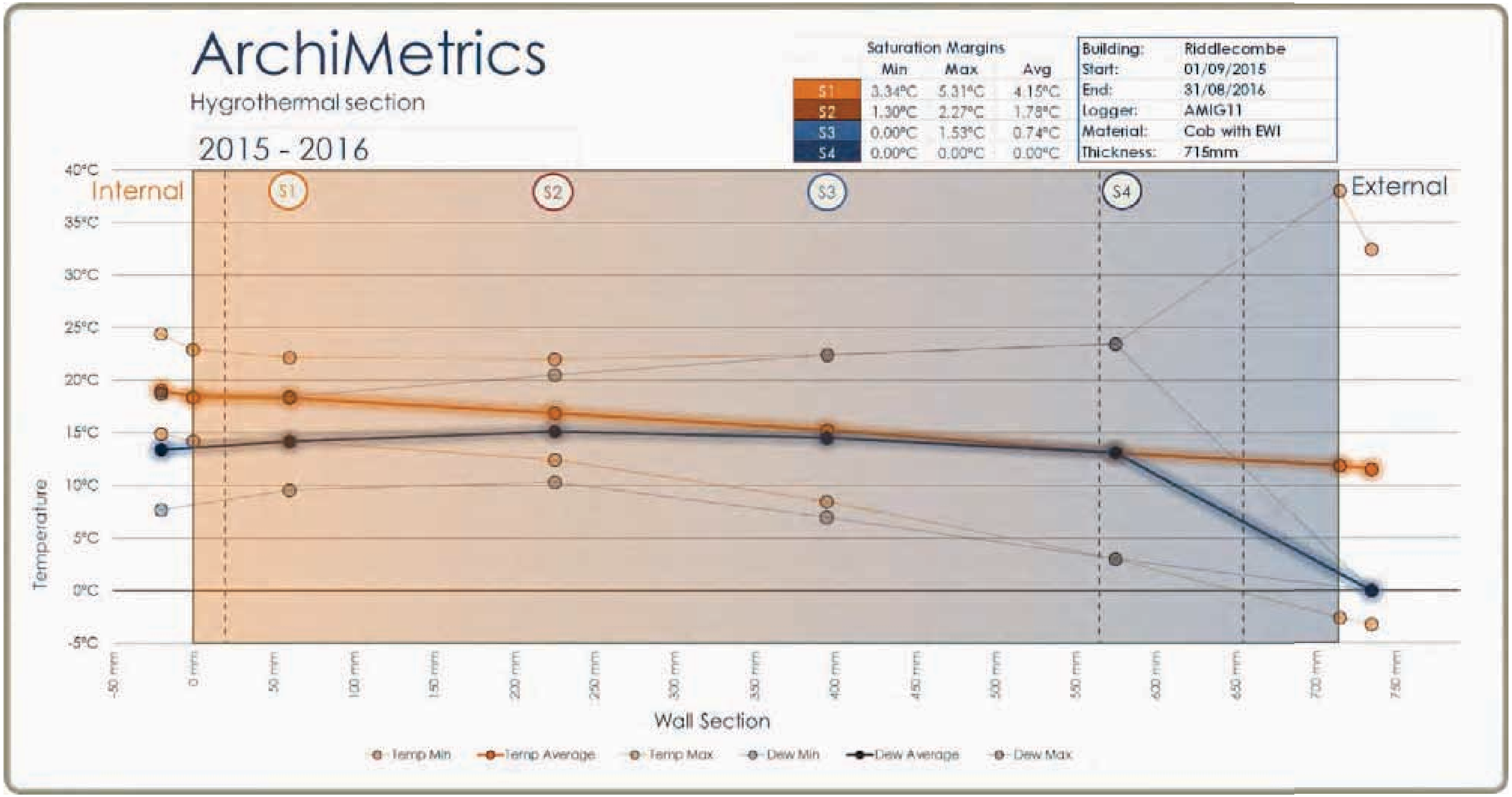
Figure 37. Saturation Margin over time, The Firs, Riddlecombe, 2015 - 2016.



Riddlecombe Monthly Saturation Margin Averages

	Internal	S1	S2	S3	S4
⊟2015					
Sep	5.12	3.57	1.41	0.39	-1.72
Oct	4.96	3.63	1.48	0.54	-1.72
Nov	4.95	3.75	1.68	0.82	-1.71
Dec	5.08	4.03	1.80	0.99	-1.75
⊟2016					
Jan	5.82	4.38	1.98	1.18	-1.72
Feb	5.42	4.34	1.90	1.03	-1.79
Mar	7.31	4.81	2.12	1.11	-1.77
Apr	7.24	4.89	2.10	0.91	-1.81
May	6.44	4.76	1.98	0.61	-1.87
Jun	5.33	4.25	1.80	0.31	-1.90
Jul	5.01	3.84	1.64	0.18	-1.90
Aug	4.89	3.59	1.45	0.11	-1.87
Average	5.63	4.15	1.78	0.68	-1.79

Table 20. Average monthly Saturation Margins, The Firs, Riddlecombe, 2015 - 2016.

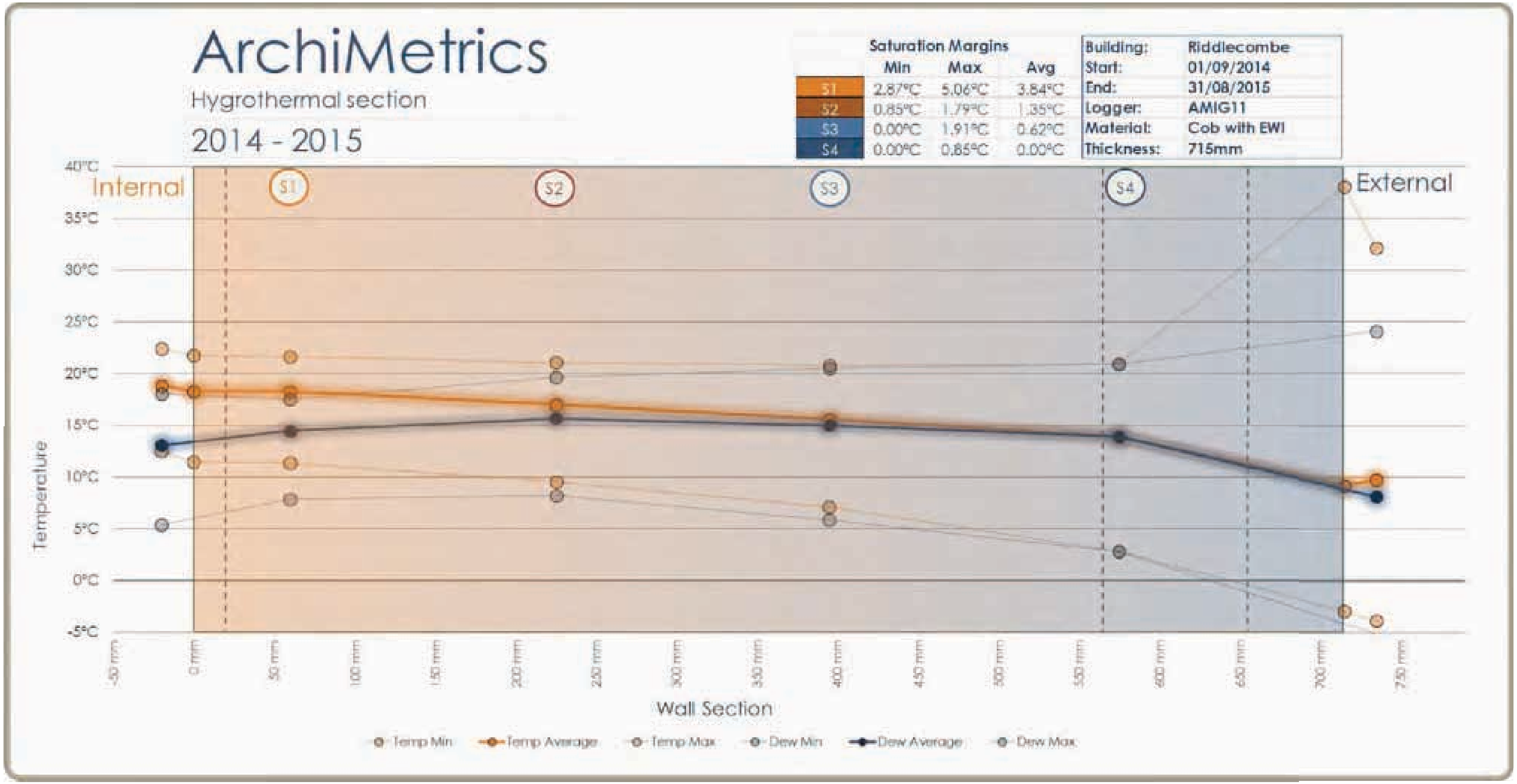


Saturation Margins

	Min	Max	Avg
S1	3.34°C	5.31°C	4.15°C
S2	1.30°C	2.27°C	1.78°C
S3	0.00°C	1.53°C	0.74°C
S4	0.00°C	0.00°C	0.00°C

Building:	Riddlecombe
Start:	01/09/2015
End:	31/08/2016
Logger:	AMIG11
Material:	Cob with EWI
Thickness:	715mm

Figure 38. Hygrothermal Section, The Firs, Riddlecombe, 2015 - 2016.

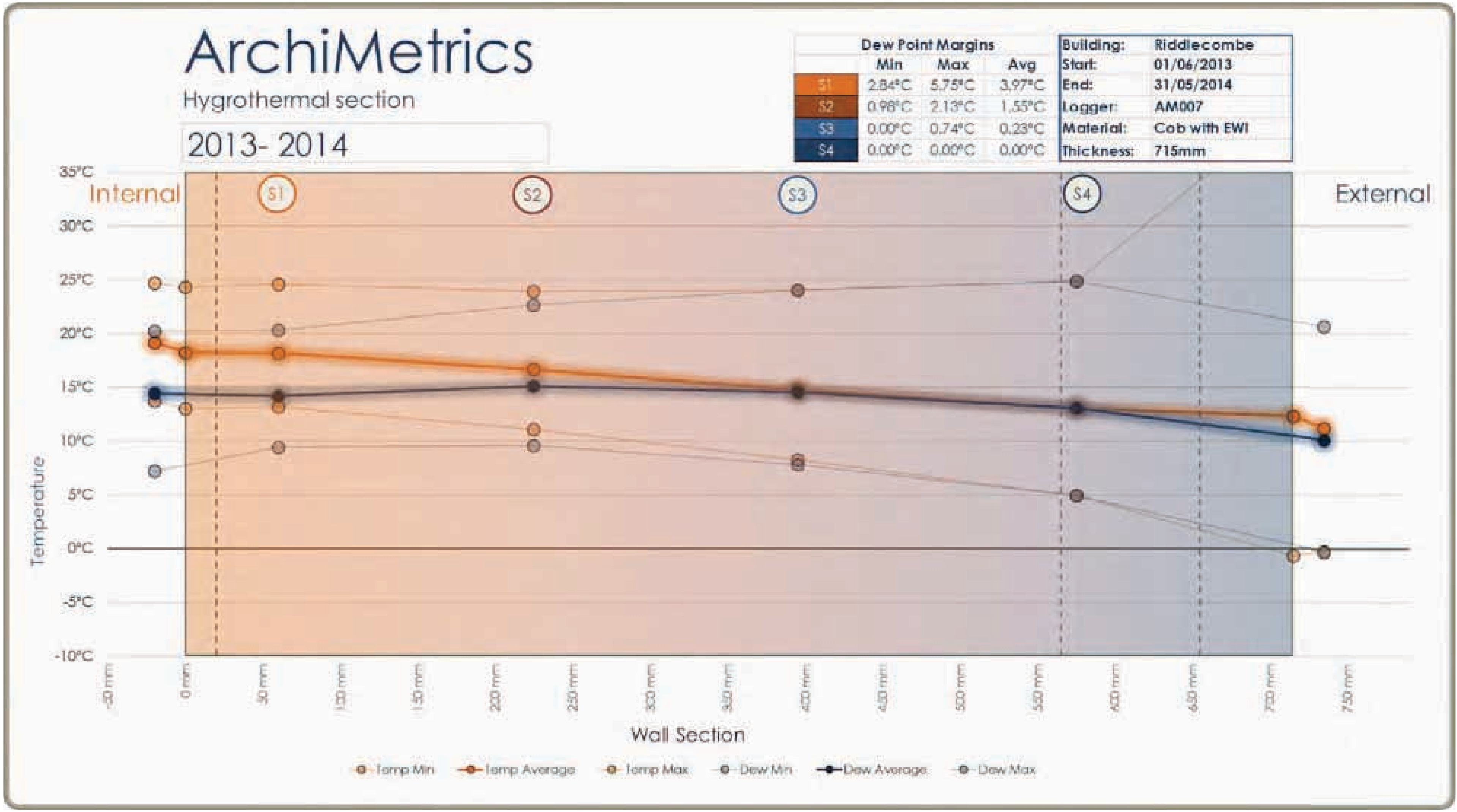


Saturation Margins

	Min	Max	Avg
S1	2.87°C	5.06°C	3.84°C
S2	0.85°C	1.79°C	1.35°C
S3	0.00°C	1.91°C	0.62°C
S4	0.00°C	0.85°C	0.00°C

Building:	Riddlecombe
Start:	01/09/2014
End:	31/08/2015
Logger:	AMIG11
Material:	Cob with EWI
Thickness:	715mm

Figure 39. Hygrothermal Section, The Firs, Riddlecombe, 2014 - 2015.



Dew Point Margins	Min	Max	Avg
S1	2.84°C	5.75°C	3.97°C
S2	0.98°C	2.13°C	1.55°C
S3	0.00°C	0.74°C	0.23°C
S4	0.00°C	0.00°C	0.00°C

Building:	Riddlecombe
Start:	01/06/2013
End:	31/05/2014
Logger:	AM007
Material:	Cob with EWI
Thickness:	715mm

Figure 40.. Hygrothermal Section, The Firs, Riddlecombe, 2013 - 2014.

Material Moisture

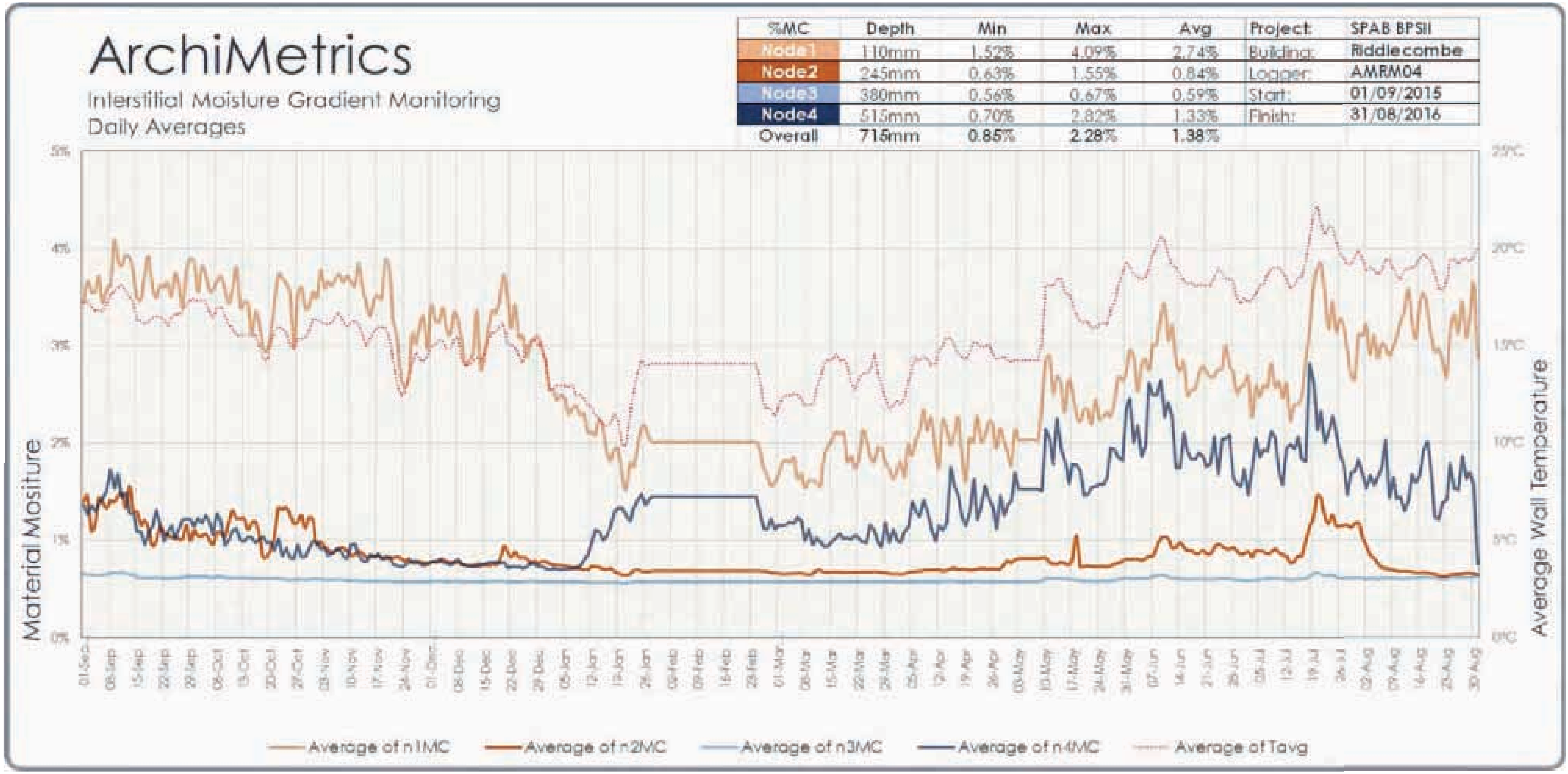
Figures 41 and 42 present an analysis of %MC in the wall at Riddlecombe over the past two years. The cob wall at Riddlecombe has the highest records of %MC of the three walls in the study. The annual average recorded from all sensors in the wall at Riddlecombe, 1.34 %MC is nearly double that of Drewsteignton, 0.79 %MC, and roughly three times greater than Shrewsbury, 0.47 %MC. However, this year's average 1.34 %MC has reduced from that found for the previous year where the annual average at Riddlecombe was 1.87%. This is possibly a reflection of the 'improving' moisture picture over the past year described in the earlier section where we think we see a general reduction in moisture within the wall material.

In last year's report it was noted that there was a greater range of quantities of moisture measured through this wall section in comparison with ranges measured in the other two properties. We thought this was due to the behaviour of moisture in unfired earth (cob) compared to that of masonry (Shrewsbury and Drewsteignton have brick and stone walls respectively). The cob is 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 at Riddlecombe cover a wider range than those from the walls at Shrewsbury or Drewsteignton. Last year sensor 2 had the widest range from 0.66 – 5.07% MC, this year, perhaps once again as part of the improving picture, this range is smaller, 1.52 – 3.90% and is now located at sensor 1 closer towards the internal surface of the wall. The exceptions to this dynamic behaviour are the moisture content measurements made at sensor 3. Here %MC is low and there is little variation throughout the year. We had previously thought that the trace from sensor 3 indicated an incomplete or partial signal caused by a broken wire but it is possible to see small responses at this location which echo those seen at other sensors coinciding with peak events, most obviously in the week beginning 19th July. Therefore we think that the sensor is functioning correctly. Sensor 3 at Riddlecombe should be embedded within the cob material within the wall, however the low %MC measured by this sensor may suggest that the sensor node is not fully bonded to the substrate. If the capsule sits within a void 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. Or, alternatively, this location could have a low moisture content and in a similar way to the sensor 3 responses measured at Drewsteignton, there is something particular about the materials surrounding this sensor that create a moisture response that is in opposition to the general trend within the wall.

The analysis for this year, Figure 41, presents quite a different picture to that of the previous year. From September to December 2015 %MC at sensor 1 is much higher than that measured by the other three sensors in the wall. In January 2016 this reduces whilst at the same time %MC at sensor 4 increases. Unfortunately data for February is lost as the homeowner inadvertently switched off logging equipment. When the logger comes back on stream in March we see similar activity across both sensors 1 and 4 with sensor 4 recording higher %MC. %MC at these two sensors steadily increases to a peak in mid-July and thereafter decreases at sensor 4 but continues to climb at sensor 1. Throughout this time there are a few peaks on sensor 2 which coincide with more significant peaks on sensors 1 and 4 but %MC remains relatively low, mostly below 1%. In the previous year, Figure 42, %MC performance at sensor 2 was quite different. In October 2014 %MC was around 5% and falls throughout the winter period to around 1% by March 2015. Thereafter %MC remains at lower levels similar to these measured in 2015 – 16. Looking across the two years it would seem that materials at sensor 2 were maybe going through a drying phase in the first half of the 2014 -15 analysis and thereafter have reached an equilibrium with little variation in moisture content. In the previous year, February/March 2015, also sees a change in the relationship between sensors 1 and 4 which until this time have been at opposite ends of the %MC range measured in the wall. In the latter half of the year %MC quantities at sensor 4 increase moving closer towards those of sensor 1 and sharing similar responses. This pattern for sensors 1 and 4, divergent plots over winter which become more closely associated over summertime repeats the following year 2015 - 16. In winter the internal surface, in close proximity to sensor 1, is heated by room heating whereas sensor 4 is closest to cold external temperatures. In summertime the temperature gradient through the wall is less extreme as external temperatures increase. It is possible that this pattern therefore is a response to these seasonal differences, with increased quantities of moisture and more dynamic responses measured at sensor 4 as a result of warmer external conditions.

As previously mentioned a peak in liquid moisture is measured across all four wall sensors in the middle of the week beginning 19th July. This is also the peak vapour week previously noted in the AH commentary explained by drying taking place within the fabric as a result of high solar radiation on the external face of the south-facing wall, Figures 35 and 36. It is likely that warm temperatures passing through the cob promoting evaporative activity stimulates liquid moisture movement as moisture moves through the substrate and is vaporised. That this moisture behaviour is related to external temperature seems to be confirmed by the fact that a close examination of the individual MC peaks from the sensors in the wall show that they are staggered overtime in relation to proximity to external conditions. In this warm week with high external solar radiation on the south facing wall the MC peak is first seen at sensor 4, then sensor 2 and finally sensor 1 as the effect of the heat gradually transfers through the wall. Temperature measurements made by each of the four wall sensors is averaged and included as an average wall temperature plot in Figure 41. Week beginning 19th July this temperature peak occurs inside the wall sometime after that seen on the wall's external surface (Figures 34 and 35). The wall temperature peaks after that of the %MC peak at sensor 4, the sensor closest to external conditions and before that of sensors 1 and 2 suggesting this moisture activity is indeed a temperature related phenomenon. These peaks coincide with temperature peaks as heat is transferred into and through the wall from solar radiation on the external surface.

The %MC recorded in the wall at Riddlecombe seems high in comparison with other sites. Cob is a low density material with a high water carrying capacity and thus will inevitably produce higher %MC values. We believe these values are also influenced by water which was added to the substrate as part of the re-rendering process. Findings from this years %MC analysis, as with those of moisture vapour, suggest that the excess moisture that has been retained with the cob material, has over the past few years been slowly diminishing in quantity within the wall via a process of evaporation and diffusion. Following the peak drying event which was noted in July 2016 for both vapour and liquid moisture quantities it will be interesting to see whether these quantities continue to decrease year-on-year, something that has been seen across the two previous years for moisture factored both as a vapour and as a liquid.



%MC	Depth	Min	Max	Avg	Project:	SPAB BPSII
Node1	110mm	1.52%	4.09%	2.74%	Building:	Riddlecombe
Node2	245mm	0.63%	1.55%	0.84%	Logger:	AMRM04
Node3	380mm	0.56%	0.67%	0.59%	Start:	01/09/2015
Node4	515mm	0.70%	2.82%	1.33%	Finish:	31/08/2016
Overall	715mm	0.85%	2.28%	1.38%		

Figure 41: Material moisture content over time, The Firs, Riddlecombe 2015 - 2016.

%MC	Depth	Min	Max	Avg	Project:	SPAB BPSII
Node1	110mm	2.70%	5.42%	3.98%	Building:	Riddlecombe
Node2	245mm	0.66%	5.07%	1.59%	Logger:	AMRM04
Node3	380mm	0.58%	0.85%	0.63%	Start:	22/10/2014
Node4	515mm	0.66%	3.11%	1.24%	Finish:	18/09/2015
Overall	715mm	1.15%	3.62%	1.86%		

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

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 21 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 between monitored years.

The table shows the relative differences in %RH found between the three walls. Over the four years of monitoring Shrewsbury has had the lowest rates of annual average %RH ranging between 64% - 84%. Drewsteignton sits higher up the scale with a range between 63% - 98%. The externally insulated cob wall at Riddlecombe, which had high %RH prior to refurbishment, sits at the top end of the range 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%
2015 - 2016	66%	71%	80%	84%
Difference 2012 - 2016	0.00%	-1.00%	5.00%	1.00%
Drewsteignton				
2012 - 2013	68%	85%	90%	96%
2013 - 2014	64%	87%	92%	97%
2014 - 2015	63%	90%	95%	96%
2015 - 2016	64%	90%	96%	98%
Difference 2012 - 2016	-4.00%	5.00%	6.00%	2.00%
Riddlecombe				
2012	72%	91%	98%	100%
2013 - 2014	78%	91%	99%	100%
2014 - 2015	78%	91%	96%	100%
2015 - 2016	77%	89%	95%	100%
Difference 2012 - 2016	5.00%	-2.00%	-3.00%	0.00%

Table 21. Annual Average %RH for all Interstitial Sensors 2012 - 2016.

There are some similarities between %RH behaviour for the internally insulated walls at Shrewsbury and Drewsteignton. Figures 43 and 44 show that both these walls have a trend of rising %RH (indicated by a dashed line) post-refurbishment on the cold side of the wall insulation. This year both these walls have seen increases in annual averages of RH at sensors 1, 3 and 4. Average conditions at the insulation interfaces, sensor 2, continue to be the same as the previous year..

The highest annual average measurements since refurbishment in 2012, 84% for Shrewsbury and 98% for Drewsteignton, were both recorded during the past year. This year for the first time two sensors at Shrewsbury, sensors 3 and 4, measured annual averages at or above the mould growth risk threshold of 80%. At Drewsteignton sensors 2, 3 and 4 are above this threshold and have been since post refurbishment measurements began.

Whilst there may be some similarity between the RH pictures for the two walls, there are also important differences. Measurements of RH from the granite wall at Drewsteignton are much higher than those of Shrewsbury, the averages ranging between 66 – 84% at Shrewsbury and 64 – 98% at Drewsteignton this year. At Drewsteignton RH is 90% or above at sensors 2, 3 and 4 and sensor 4's average, 98% is close to dewpoint. By comparison, at Shrewsbury, sensors 2, 3 and 4 average 71, 80 and 84% respectively. The difference between this year's averages and those of the first year post-refurbishment, 2012 – 13, are also greatest at Drewsteignton, particularly at sensor 2. These high RH averages have been a persistent feature of the wall since it was refurbished. Therefore, in terms of risk, whilst parts of the wall at Shrewsbury have moved above the mould growth threshold 80% this year for the first time, humidity measured in the wall at Drewsteignton has been higher for longer and this trend looks set to continue. Thus the chances of mould growth on a suitable substrate such as timber embedded in the wall are greater at Drewsteignton.

The high 80%+ averages recorded for the first time at Shrewsbury may be a result of a particularly wet year. In November and December 2015 the UK was subject to a series of Atlantic storms which particularly affected the west side of the country causing severe flooding in places. Overall 2015 was the seventh wettest year since 1981 and December 2015 was the wettest month in this date series. Storms continued in January 2016 and the summer months of June and July were wetter than average. We have seen from the rainfall totals (Figures 6 and 7) that Shrewsbury received 130 mm more rain in 2015 -16 than the previous year. Given the porous nature of the brickwork in this wall it is likely then that the wall materials absorbed more water over the year. We have also seen, however, from the RH over time analysis (Figure 5) that the wall was able to evaporate sufficient moisture over a twelve-month cycle so that %RH conditions at the end of the year were very similar to those at the start. The higher annual averages, calculated this year for sensors 3 and 4 around the 80% threshold, may be an aberration caused by a wetter than average year. Or we may see that, as is indicated by the plots of long term trends in Figure 43, that %RH at sensors 3 and 4 continue to rise above this threshold in following years. Interestingly, the trend for the other two sensors within the wall at Shrewsbury is in the opposite direction and we are seeing RH decrease year-on-year. This is particularly important at sensor 2 in proximity to the woodfibre insulation which, as with other organic materials, may be vulnerable to mould growth if exposed to RH higher than 80% for prolonged periods of time. The average annual RH value at sensor 2 is 71% and that value has been stable for some years. This indicates that, unlike parts of the wall in closer proximity to external conditions, at this potential vulnerable location, RH in the wall behaves somewhat independently of the extremes of seasonal differences. As in previous reports, we once again suggest that this maybe due to the hygroscopic, humidity buffering, qualities of the woodfibre insulation material.

Despite the wetter than average year the picture at Riddlecombe, the externally insulated cob wall, is different from that of Shrewsbury and Drewsteignton. This wall, which has the highest %RH of the three walls in the study, continues a trend hinted at by behaviour measured at sensor 3 the previous year. This year annual average quantities of %RH have declined at sensors 1, 2 and 3 in opposition to the trend at Shrewsbury and Drewsteignton (sensor 4 values are capped at 100% and thus appear static). Annual average quantities at sensors 2 and 3, although still high, are for the first time lower than those calculated for the same sensor positions at Drewsteignton. The negative difference values found for these averages compared with those for the first year, post-refurbishment, also show a decrease in %RH conforming to the idea that over time the wall is losing excess moisture present in the cob material. As with previous reports here we find that the moisture metrics for the wall at Riddlecombe behave in contrary ways to trends seen elsewhere. These more 'normal' trends are those which are largely determined by the weather, the south-facing wall at Shrewsbury being the clearest example of this in this study. Previously we have suggested that Riddlecombe's contrary behaviour therefore indicates the influence of moisture sources which are independent of external conditions, namely moisture bound within the cob as a result of the failure of the previous cement render as well as water added to the wall as part of the re-rendering process. The vaporisation of this excess internal moisture dominates the moisture behaviour trends found in this wall and is the reason that %RH might decline this year in this wall whilst increasing in other walls elsewhere.

A long-term declining trend of %RH at Riddlecombe's sensors 2 and 3, in the centre of the wall, can now be clearly seen in the long-term analysis (trend marked by dashed line) in Figure 45. However, it is important to remember that %RH is still high, on average, well above the mould growth risk threshold of 80% and conditions around sensor 4 are permanently at dewpoint (100%). The %RH profiles suggests there is a continued risk of mould growth particularly on biological organic substrates and that the wall may still have excess moisture present within its materials. Over the coming year it will be interesting to see whether %RH continues to decline in this wall as materials dry and/or whether the wall stabilises at a new equilibrium, perhaps more directly related to external conditions. It may be that cob, as a highly porous and permeable material, displays higher humidity than that found in masonry materials and therefore that relatively high %RH is 'normal' for such walls.

Whilst RH levels at Riddlecombe may be decreasing slowly Drewsteignton now has an RH profile not dissimilar to that of the cob wall, particularly if one ignores behaviour at the sensor 1 location. (At Drewsteignton sensor 1 is located in the air gap between the dry-lining and the PIR insulation, unlike the sensor 1 position at Riddlecombe it is therefore de-coupled from the mass of the wall and reflects room conditions.) Annual averaged measurements of RH are similar between the sensor 2, 3 and 4 positions in each of the walls, with only 1-2% difference between them. If an average wall RH is taken from all four sensors the average for Drewsteignton, 87%, is only slightly lower than that of the wall at Riddlecombe, 90%. However, if sensor 1 values are excluded from the calculation we find that Drewsteignton and Riddlecombe have the same annual average wall RH of 95%. Given that we find a trend of declining RH for the wall at Riddlecombe it is possible that in the coming year we will see RH values in the granite wall at Drewsteignton exceeding those of the cob wall. RH is still high in both walls, Riddlecombe's is decreasing whilst at Drewsteignton RH continues on an upward trajectory.

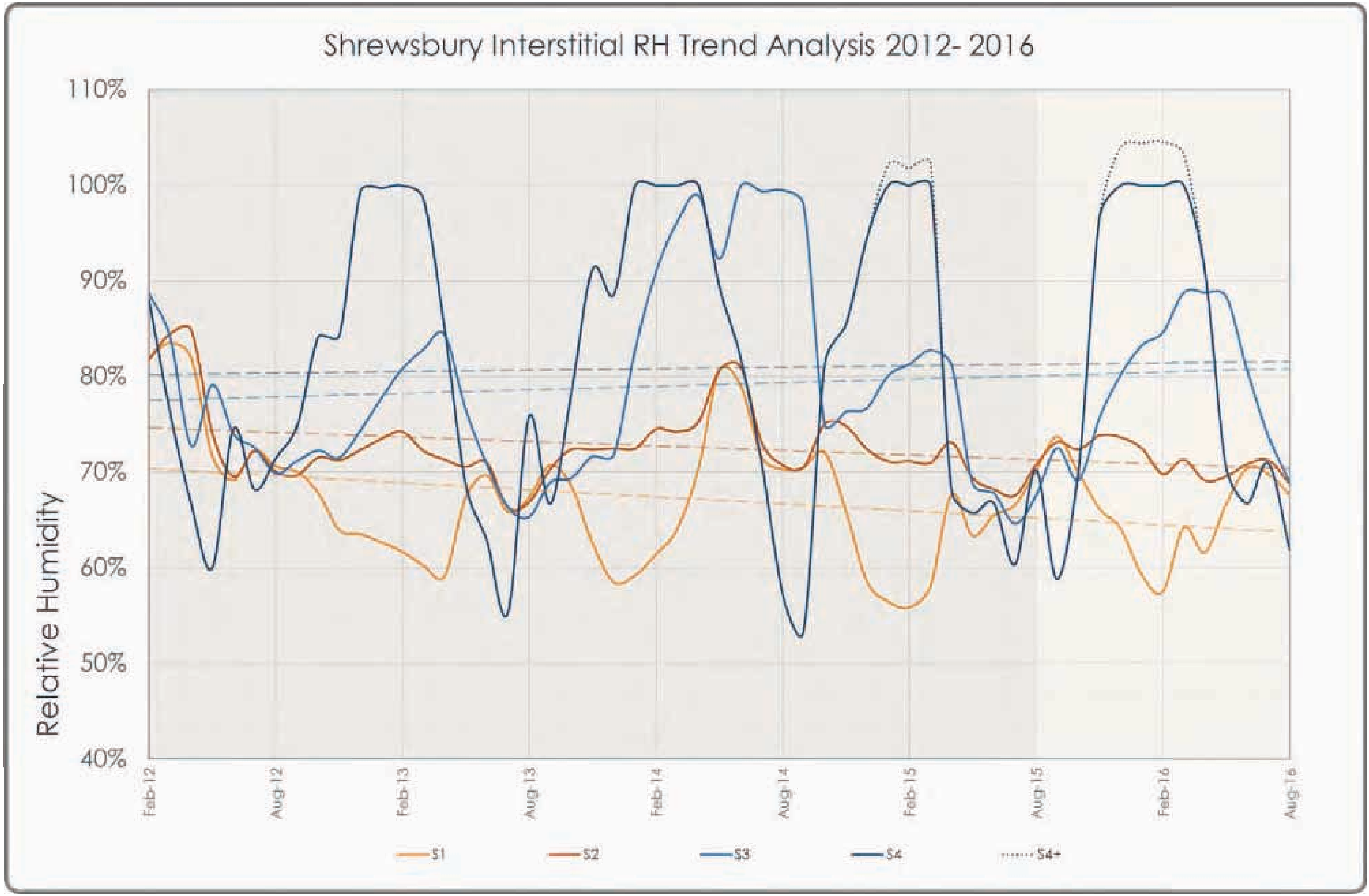


Figure 43: Relative Humidity Trends over time, Shrewsbury 2012 - 2016.

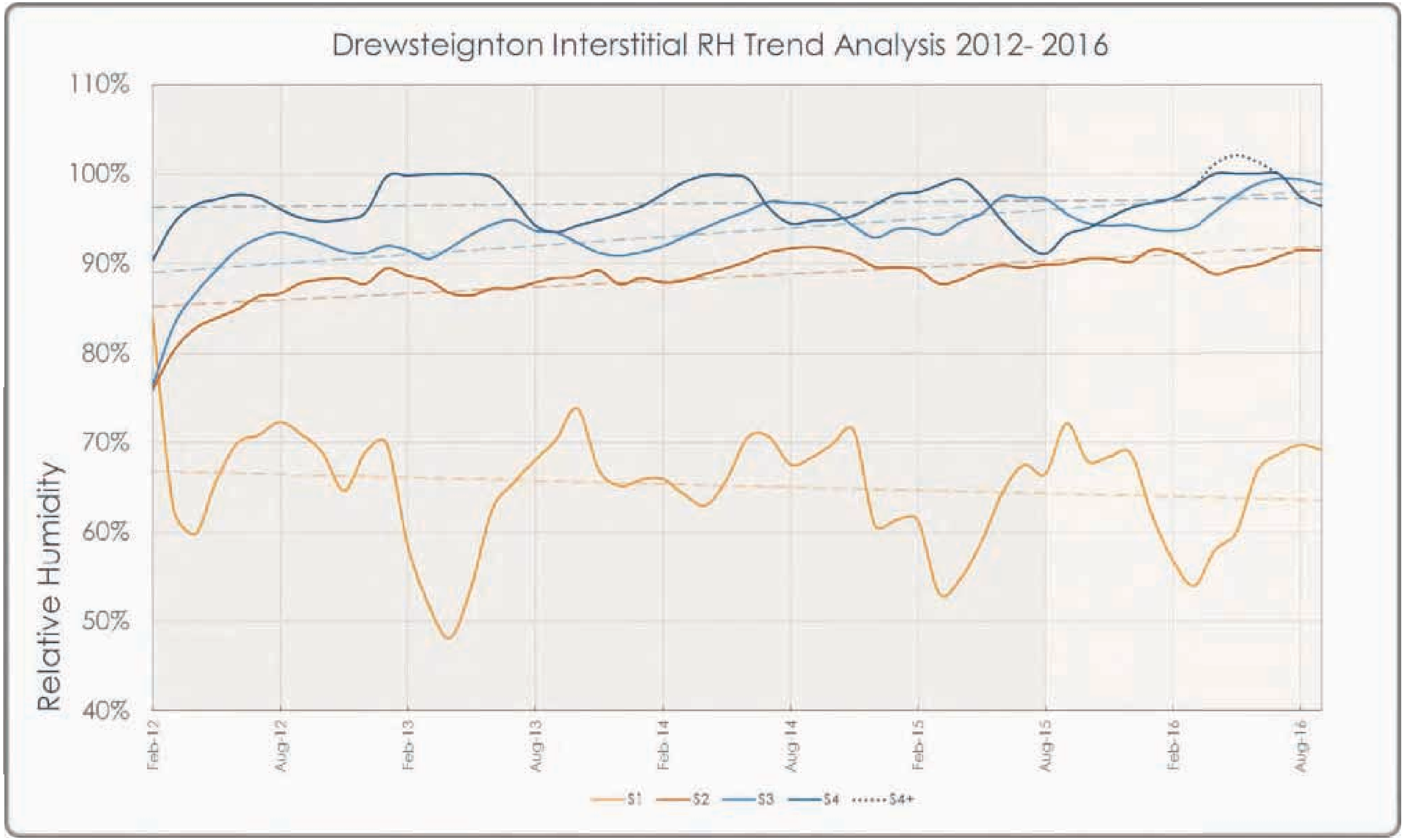


Figure 44: Relative Humidity Trends over time, Drewsteignton 2012 – 2016.

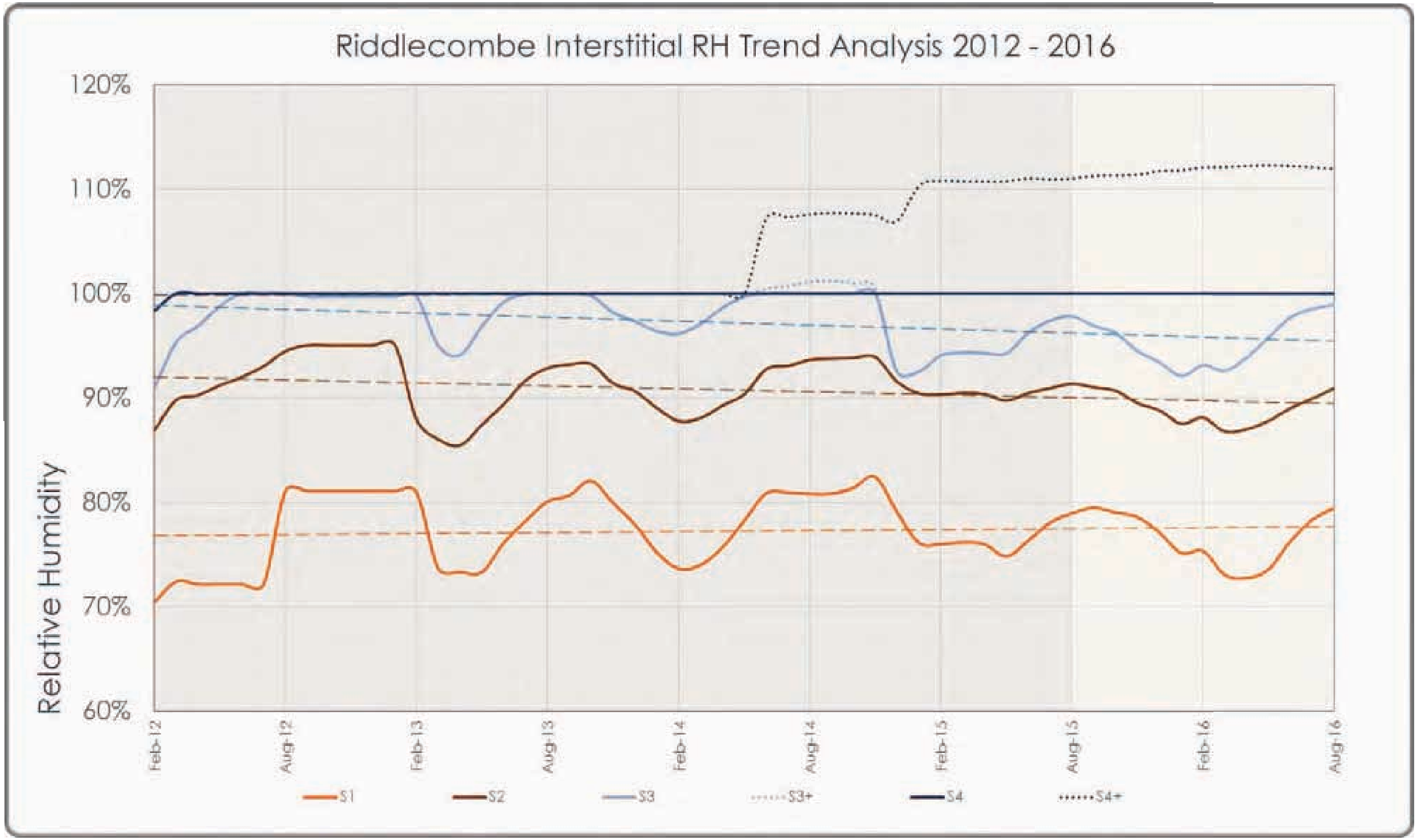


Figure 45. Relative Humidity Trends over time, Riddlecombe, 2012 - 2016.

3.2 Absolute Humidity (AH)

Table 22 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 between years.

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
2015 - 2016	9.89 g/m^3	9.87 g/m^3	10.71 g/m^3	10.43 g/m^3
Difference 2012 - 2016	0.88 g/m^3	1.07 g/m^3	1.76 g/m^3	1.25 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
2015 - 2016	9.15 g/m^3	10.59 g/m^3	11.01 g/m^3	10.79 g/m^3
Difference 2012 - 2016	0.62 g/m^3	1.83 g/m^3	2.05 g/m^3	1.66 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
2015 - 2014	12.02 g/m^3	12.87 g/m^3	12.60 g/m^3	11.66 g/m^3
Difference 2012 - 2016	2.55 g/m^3	0.21 g/m^3	-0.14 g/m^3	-0.61 g/m^3

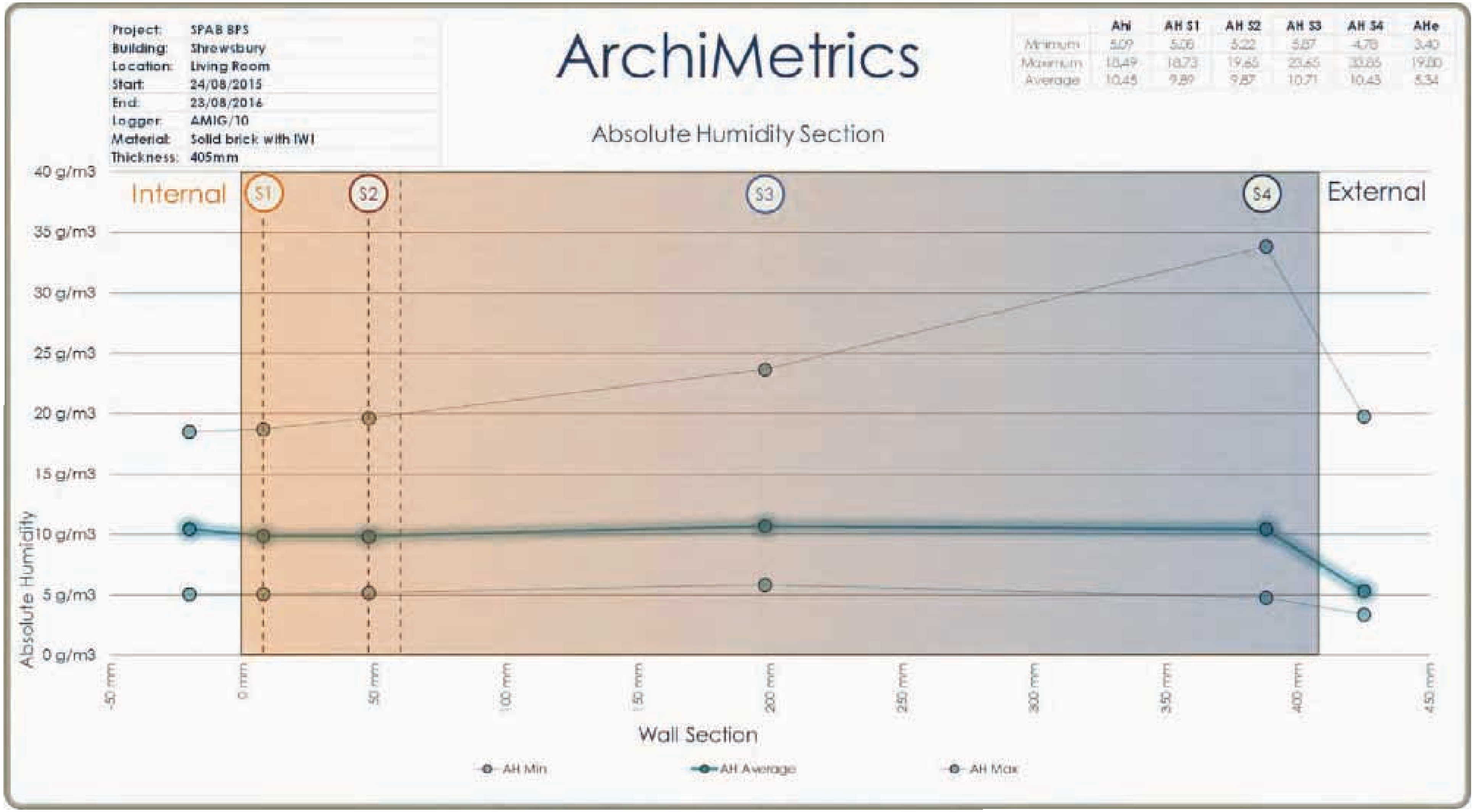
Table 22. Annual Average AH g/m^3 for all Interstitial Sensors 2012 - 2016 (capped).

This year, across all three walls the predominant trend sees a decrease in vapour quantities from those of the previous year. The exceptions being increases in AH at sensors 3 and 4 at Shrewsbury. Prior to this year all the three walls in the study showed largely the same general trend of year-on-year increases in average weights of vapour. However, examination of the AH over time analyses (Figures 8, 22 and 35) shows a difference between AH as measured in the wall at Shrewsbury and those of Drewsteignton and Riddlecombe. For the majority of the year weights of vapour measured in the wall at Shrewsbury sit between or close to quantities measured from the internal and external environments. Just as the wall physically bisects these two environments vapour quantities measured within the wall straddle the difference between internal and external vapour quantities. The exception to this being the period of time between February and June when weights increase towards the external side of the wall, sensors 3 and 4, as vapour is produced as part of a seasonal drying process and the wall evaporates moisture that has built up in its materials over winter. The AH analysis for Drewsteignton and Riddlecombe look different, as plots of vapour weights made within the walls sit mostly above the quantities measured from the internal and external environments of these two walls, more so at Drewsteignton than Riddlecombe.

Average AH section analyses have been produced for the walls, Figures 46 – 48, these include in their top right corner a table showing the annual average weights of vapour for each wall sensor as well as the average for both internal (AHi) and external (AHe) environments. At Shrewsbury the annual average internal AH is 10.45 g/m^3 and 5.34 g/m^3 externally. As can be seen annual average weights of vapour from the four sensors in the wall sit between the two extremes of this range, towards its top end. The annual internal and external AH averages at Drewsteignton are 8.72 g/m^3 and 5.42 g/m^3 respectively. All four averages from the wall sensors show higher weights of vapour. The same is true for Riddlecombe, the internal and external averages being 11.47 g/m^3 and 8.38 g/m^3 respectively with average weights of vapour from the wall sensors well above these values.

Weights of vapour measured from the wall increase during the summer in line with ambient conditions and exceed these while evaporation from damp wall materials is taking place - as is seen at Shrewsbury. However, that weights of vapour are greater than ambient conditions throughout most of the year, as is the case at Drewsteignton and roughly nine months of the year at Riddlecombe might suggest that additional quantities of moisture are present in these walls (something also indicated by material moisture measurements for the three walls). This could be the result of weather trends, as this part of the country sees higher annual rainfall than that of Shrewsbury and thus the Drewsteignton and Riddlecombe walls are subject to a higher moisture load. Vapour quantities might also be higher in the Devon walls as both these more monolithic wall structures may lose moisture via diffusion of water vapour whereas the thinner south facing wall Shrewsbury may benefit from the movement of liquid water as a drying mechanism.

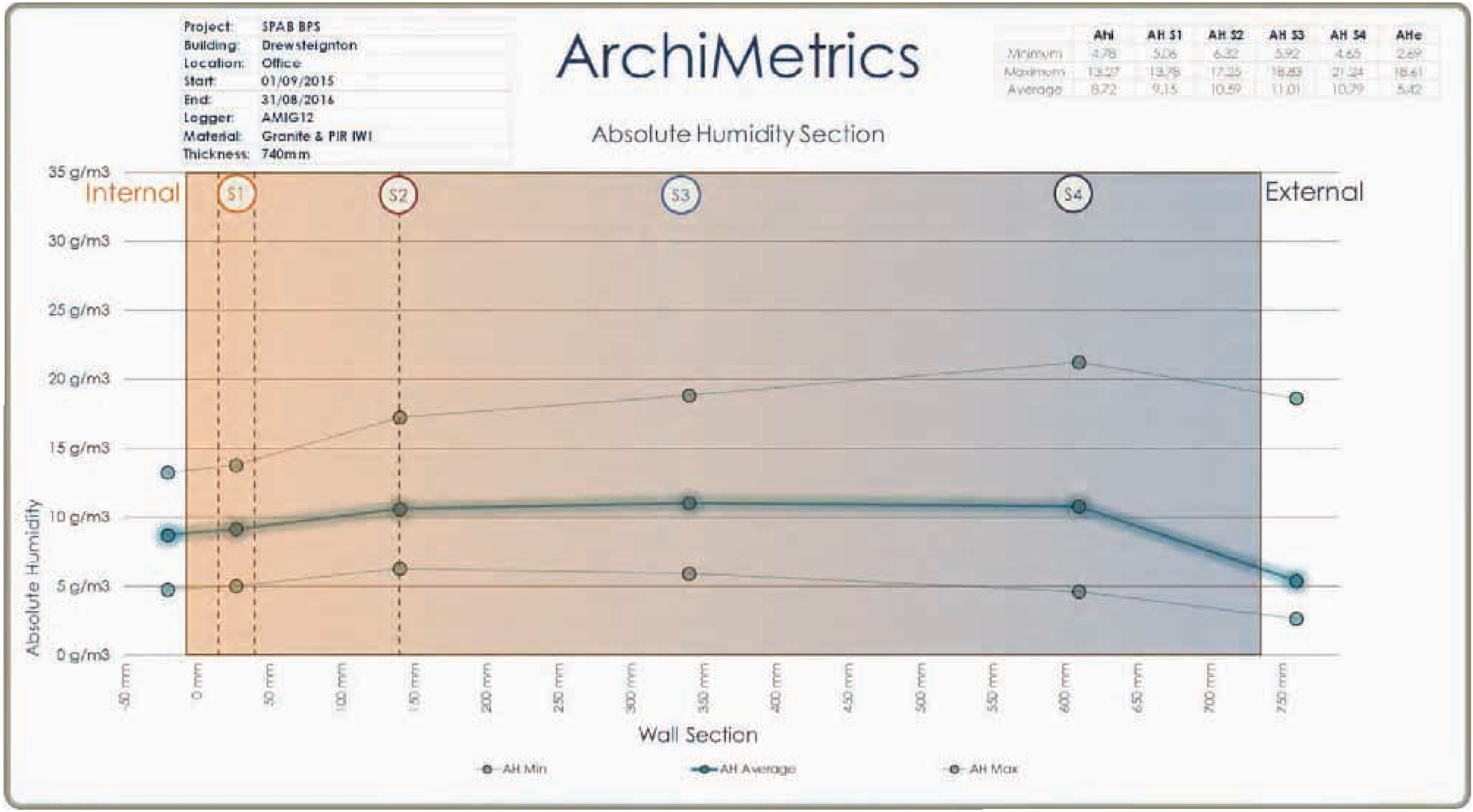
If we assume increases in AH suggest the vaporisation of moisture from materials, this year we can see this has taken place to a greater extent than last year in the external side of the wall at Shrewsbury. As with the RH analysis, we might speculate that this additional vaporisation is due to a wetter twelve months than that of the previous year but also sufficient drying opportunities for the thin south-facing wall to heat up enough for additional evaporation to have occurred. This could explain the rise in AH at sensors 3 and 4 seen in this year. Drewsteignton and Riddlecombe both see decreases in AH across all four sensor positions this year suggesting that less vaporisation of moisture has taken place in the past twelve months than that of the previous year. We suspect from the %RH trend at Drewsteignton that moisture is accumulating year-on-year in this wall so a fall in AH this year could be due to lack of evaporative drying opportunities. This wall is very thick, 600+ mm and north-west facing, so does not occupy an optimum position to benefit from solar radiation heating of its fabric. The wall at Riddlecombe is similarly thick but is south-facing. If we accept the premise that the moisture bound into the cob materials as a result of the re-rendering process is now slowly drying out a decrease in vapour could be measured in this wall for the first time this year. As moisture quantities diminish vaporisation also occurs less often perhaps. If this supposition is correct we could expect AH to decrease once again in the following year or until the wall reaches a moisture equilibrium.



Project: SPAB BPS
Building: Shrewsbury
Location: Living Room
Start: 24/08/2015
End: 23/08/2016
Logger: AMIG/10
Material: Solid brick with IWI
Thickness: 405mm

	AHi	AH S1	AH S2	AH S3	AH S4	AHe
Minimum	5.09	5.06	5.22	5.87	4.78	3.40
Maximum	18.49	18.73	19.65	23.65	33.85	19.80
Average	10.45	9.89	9.87	10.71	10.43	5.34

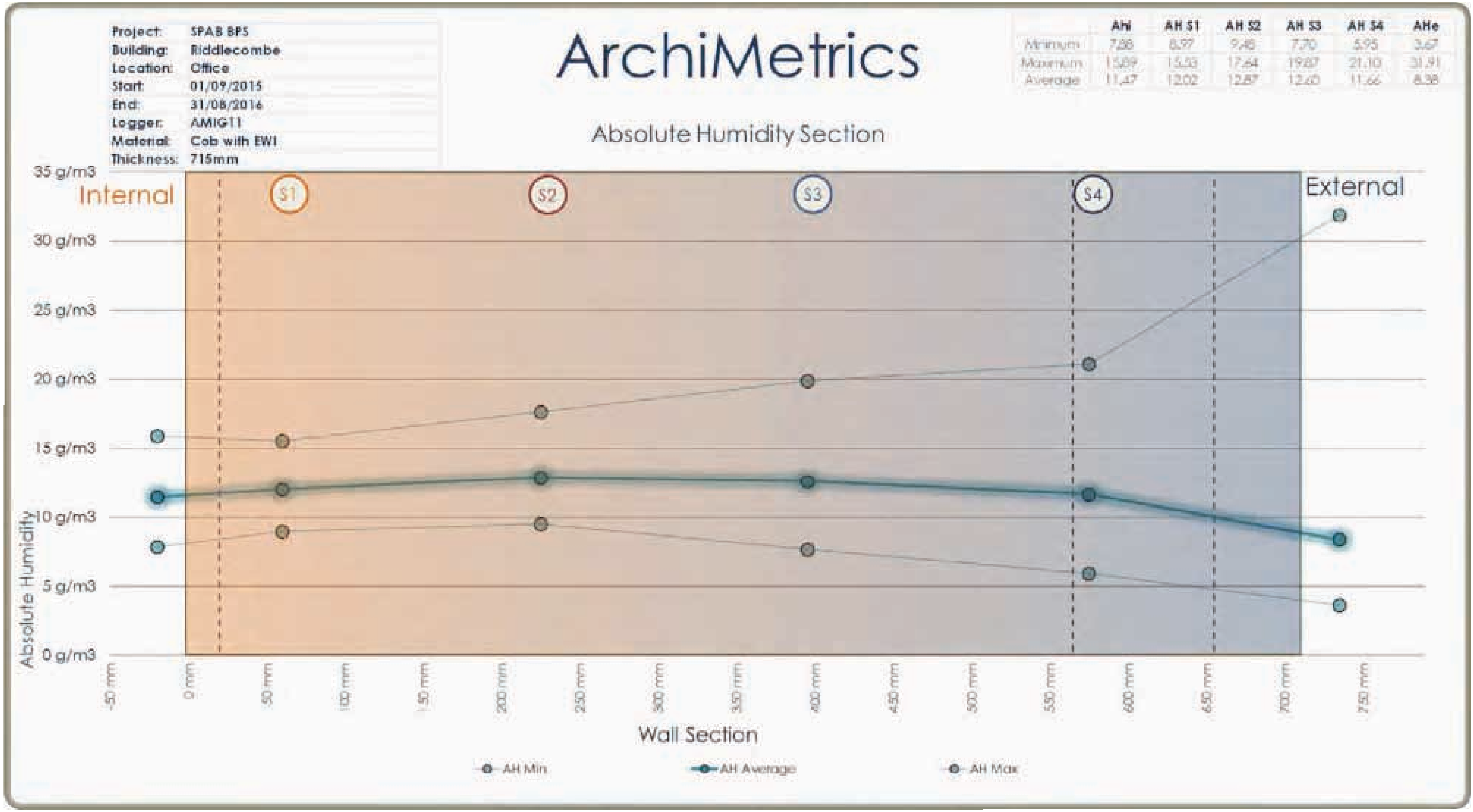
Figure 46. Absolute Humidity Average Section, Shrewsbury, 2015 - 2016.



Project: SPAB BPS
Building: Drewsteignton
Location: Office
Start: 01/09/2015
End: 31/08/2016
Logger: AMIG12
Material: Granite & PIR IWI
Thickness: 740mm

	AHi	AH S1	AH S2	AH S3	AH S4	AHe
Minimum	4.78	5.06	6.32	5.92	4.65	2.89
Maximum	13.27	13.78	17.25	18.83	21.24	18.61
Average	8.72	9.15	10.59	11.01	10.79	5.42

Figure 47. Absolute Humidity Average Section, Drewsteignton, 2015 - 2016.



Project: SPAB BPS
Building: Riddlecombe
Location: Office
Start: 01/09/2015
End: 31/08/2016
Logger: AMIG11
Material: Cob with EWI
Thickness: 715mm

	AHi	AH S1	AH S2	AH S3	AH S4	AHe
Minimum	7.88	8.97	9.46	7.70	5.95	3.67
Maximum	15.89	15.53	17.64	19.87	21.10	31.91
Average	11.47	12.02	12.87	12.60	11.66	8.38

Figure 48. Absolute Humidity Average Section, Riddlecombe, 2015 - 2016.

3.3 Saturation Margins

Table 23 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 between years. The table also provides a value for 2011, the year prior to wall refurbishment.

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
2015 - 2016	6.41˚C	5.12˚C	3.57˚C	3.37˚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
2015 – 2016	6.73˚C	1.48˚C	0.62˚C	0.41˚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
2015 – 2016	4.15˚C	1.78˚C	0.74˚C	0.00˚C

Table 23. Annual Average Saturation Margins for all Interstitial Sensors 2011 - 2016.

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 the accumulation of water in fabric in proximity to the measurement sensor. Table 23 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 ‘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 accumulating moisture.

The trend in these margins as indicated by the shading in the table also follows those indicated by the analysis of RH (although colours are reversed in relation to concepts of risk as increases in margins move the wall away from the risk of dewpoint whereas increases in RH move it towards dewpoint). Both Shrewsbury and Drewsteignton have seen saturation margins decrease i.e. narrow from those found in the previous year. Once again this may be due to wet weather, particular for the wall at Shrewsbury where responses are found to have a close relationship with external conditions. The narrowing of margins at sensors towards the external side of the wall is also in line with the long term RH trends found for these walls which sees %RH increasing year-on-year (Figures 43 – 45). However, the persistent difference between the narrow margins found for Drewsteignton (0.41 – 1.48˚C) compared with those at Shrewsbury (3.37 – 5.12˚C for 2015

-16) shows that the risk of dewpoint is much greater at Drewsteignton and has been the case for a number of years.

Whilst the saturation margins found for Riddlecombe this year are not that dissimilar to those of Drewsteignton, the margins for the cob wall have increased as opposed to those of the other two walls. This perhaps accords with the general picture we have found throughout the vapour record this year at Riddlecombe which sees quantities decreasing as a result of the drying of excess construction moisture from the fabric. Indeed, a shift in the relative relationship between Drewsteignton and Riddlecombe can be seen to have taken place this year as saturation margins at sensors 2 and 3 are now wider (further away from dewpoint) at Riddlecombe than they are at Drewsteignton for the first time since the walls were insulated. Weights of vapour are still greatest at Riddlecombe but in relation to RH over the long term this wall has a declining trajectory as opposed to that of Drewsteignton. If this trend is seen to continue at Riddlecombe the associated risks to fabric from high quantities of vapour will decrease whilst those at Drewsteignton increase.

3.3 Material Moisture

For the past two years material moisture content measurements have been made as part of the SPAB Building Performance Survey in each of the three walls. These show that, when quantities are averaged through each of the walls the same relationship exists between them as that of vapour records. That is, Shrewsbury records the lowest MC%, Riddlecombe the highest, with quantities measured at Drewsteignton lying between those of the other two walls (Table 24).

Annual Average %MC	**Shrewsbury**	**Drewsteignton**	**Riddlecombe**
2014 - 2015	0.50%	1.02%	1.86%
2015 - 2016	0.47%	0.86%	1.38%

Table 24. Annual Average Moisture Content for BPS Properties 2014 - 2016.

These findings are comparable with other observations we have made concerning the three walls in the study. Whilst the wall at Shrewsbury becomes quite wet at certain times due to rain and in particular wind driven rain, it is able to evaporate this water when conditions improve being a relatively thin, porous, south-facing wall. Hence we might expect MC measured in this wall to be relatively low. The wall at Drewsteignton is much thicker, made of granite and north-west facing. It is also, like that of Riddlecombe, situated in a wetter part of the UK, annual average rainfall being 1053 mm as opposed to 660 mm for Shrewsbury (based on 1981 – 2010 series). Therefore, we might expect this wall to have a higher moisture content. As has been discussed elsewhere in this and previous reports we believe that the cob wall at Riddlecombe, also situated in the soggy south west and relatively thick, is likely to have a higher MC due to the nature of its construction materials. We believe it also has excess moisture present within it due to water sprayed onto its external surface as part of the refurbishment rendering process. There may also have been be a legacy of additional moisture within this wall prior to refurbishment due to cracks in the previous cement render admitting water. Under these circumstances we might expect that the cob wall would exhibit higher %MC than both that of Shrewsbury and Drewsteignton.

As can be seen in Table 24 blue shading indicates decreases in MC quantities for this year in comparison with the average of those measured in the previous year. This generally accords with records of Absolute Humidity for the three walls where, with the exception of sensors 3 and 4 at Shrewsbury, weights of vapour also decreased.

Weights of vapour are to some extent conditioned by vaporisation from wet wall materials at certain times of the year so perhaps there is some correlation between decreases in vapour and decreases in moisture content as there is less moisture present within the wall materials.

There is a general similarity between moisture content and vapour records for the three walls. However, water, both as a liquid and as a vapour, will behave quite differently in different walls depending on their constituent materials, orientation, thickness, general condition and the time of year. As has been seen in the analyses of findings from the individual properties, the walls measured in the Building Performance Survey at times exhibit MC behaviour in opposition to that of vapour trends, for example, during periods of evaporative drying. This is particularly the case for the wall at Drewsteignton where the MC measured by some sensors is quite low while %RH is high. Here we believe MC findings are conditioned by the location of specific sensors within either granite blocks or lime mortar and thus individual sensors display very different MC quantities within the wall and MC maybe low in some parts of the wall whilst vapour could be high (see pages 52 - 3). Therefore, whilst moisture content and AH measured in the walls over the past year has decreased this may not imply that risks from moisture have also decreased. Indeed, risk as determined by %RH measurements has increased in the walls at Shrewsbury and Drewsteignton over the past year. (Annual average quantities of RH have actually fallen at Riddlecombe in 2015 – 16 but remain the highest of all three walls and therefore represent a continued risk.) Percentage moisture content is a weight dependent quantity smaller percentages in heavyweight materials indicate similar amounts of moisture to those of lighter materials with higher percentages. Therefore recognising what %MC represents a risk relies on knowledge of the exact constituents of the wall and their weights. MC risk scales can be found for 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. Hence %RH is a more straightforward quantity in judgements of risk and these suggest that there is some risk in all three walls which may mean in turn that the %MC measured in parts of these same walls, for example, seemingly low %MC from heavy weight granite materials, may indicate higher than desirable quantities of liquid moisture.

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. In 2014 this series of measurements was joined by additional monitoring of material moisture content (MC) using gypsum-bound resistivity sensors embedded in the substrate. As such this research uses two different measurement proxies: air and gypsum plaster to identify aspects of moisture responses through the three insulated solid walls. As 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.

At Shrewsbury the thinner, south-facing porous brick wall is insulated internally with 40 mm of woodfibre board with a lime plaster finish. Of the three walls under study, it has the lowest rates of relative and absolute humidity (%RH, AH g/m^3) the widest saturation margins and lowest MC. 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. To this extent moisture behaviour in the wall is closely coupled to the weather and external environment. It is noticeable that despite the volatility of response parts of this wall, in particular the interface between the woodfibre insulation and masonry, maintain a relatively stable RH profile below that of the 80% risk threshold. Indeed the long-term trend of RH at this potentially vulnerable location continues to decline (sensor 2, Figure 43). It is possible that the hygroscopic qualities of the woodfibre insulation added to the wall make a positive contribution to this vapour profile by 'buffering' humidity and flattening out RH responses at this location. However, further towards the outside face of the wall, for the first time since refurbishment, we see average quantities of %RH which are at or exceed the 80% threshold. In the past we have judged this wall, or more specifically organic materials within the wall, such as embedded timbers, not to be at risk. It is likely that this shift in risk profile for the wall is derived from recent weather patterns, in particular a wetter than average year. A continuation of long-term measurements will show whether these diverging trends - increasing RH towards the outside face of the wall and decreasing towards the interior side - persist within the wall in contrast to the influence of an individual year's weather..

The wall at Drewsteignton in Devon is quite different being a north-west-facing, 600 mm-thick granite construction internally insulated with 100 mm of PIR board finished with a plasterboard dry lining. In this wall we find higher measurements of %RH, AH g/m^3, narrower saturation margins and higher MC. Within the original masonry element of the wall on the cold side of the insulation there continues to be average measurements of %RH above 90%, well above the 80% threshold for mould growth. We also find, over the past four 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. For the first time since post-insulation measurements began this year RH measured in the wall at Drewsteignton at sensors 2 and 3 now exceeds that found for the cob wall at Riddlecombe. The wall at Riddlecombe has a trend of decreasing RH. If the increasing RH trend for the wall at Drewsteignton continues with a similar trajectory it seems likely that within the next few years this wall will see the highest quantities of %RH of the three walls in the study, perhaps indicative of the accumulation of moisture over the long term. 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, however, vapour profiles have climbed since the wall was insulated and have not returned to pre-insulation levels, suggesting that the insulation itself maybe having some impact on the wall's performance. The greater quantity of more thermally resistive insulation (which reduced the U-value measured from this construction from 1.20 W/m^{2}K to 0.16 W/m^{2}K) 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 as well as the highest %MC. 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 moisture behaviour here is construction water. The question has been whether this wall is able to reduce its internal moisture load via vaporisation and evaporation over time? For the first time this year we see reduced %RH and AH measured across all wall sensors (except that of RH at sensor 4 which is at capped at 100%). Saturation margins have also widened suggesting an improved moisture profile for this wall. The long-term analysis shows a trend of declining RH for sensors 2 and 3 and a slight increase at sensor 1 (sensor 4 is static once again due to the 100% cap). It is possible that the slight trend of increasing RH at sensor 1 reflects the process of diffusion whereby moisture is moving through the centre of the wall to a surface from where it may evaporate. The persistent dewpoint conditions measured at sensor 4 may be for similar reasons, i.e. the migration of vapour from the centre of the wall towards an evaporative surface. However, in this instance, perhaps the relative permeability and thickness of the external render slow down this passage of vapour to the extent that %RH is continually high at this location. Although there seems to be an improving moisture trajectory for the wall at Riddlecombe it should however be bourn in mind that the RH is still high and well above the 80% risk threshold.

In an attempt to map long-term RH behavior trends across all three walls in the study, Figure 49 presents an average of measurements from sensors 2 – 4 for all three walls. (Sensor 1 has been excluded as, in the IWI walls, this sensor is placed on the warm side of the insulation and thus may confuse the picture with regard to RH behaviour within the original masonry part of the wall. In the interests of balance sensor 1 data is also excluded from the Riddlecombe average.) Figure 49 confirms that Drewsteignton has a high, 90%+, and increasing RH trend, whilst the other wall which exhibits high RH, Riddlecombe, has a long term trend which shows that RH is gradually declining. The long-term trends plotted in this analysis (dashed lines) shows that between February and August 2016 the trend of rising RH at Drewsteignton exceeded that of Riddlecombe. These divergent trajectories are perhaps something we could expect to see continue in the following year, 2016 -17, as RH continues to rise at Drewsteignton as a result of the accumulation of moisture within the fabric whilst the cob at Riddlecombe continues to dry excess moisture.

The long-term trend for Shrewsbury is different. Unlike Drewsteignton and Riddlecombe it is under the 80% mould growth threshold and shows only a slightly increasing RH trend since 2012. As can be seen from the average plot for Shrewsbury, average values from the three sensors (solid line) are much more variable than those of the other two walls. These more dynamic extremes of RH illustrate that the wall is more directly impinged upon by external conditions – the extremes of ‘drying’ and ‘wetting’ in relation to annual weather patterns. To this extent this wall is more ‘in touch’ with its immediate surroundings and it is likely that this wall trend reflects a broader trend found for external conditions in proximity to the building in Shrewsbury. How this trend progresses is likely to be more closely linked with annual weather patterns and thus is not necessarily symptomatic of underlying conditions within the wall itself.

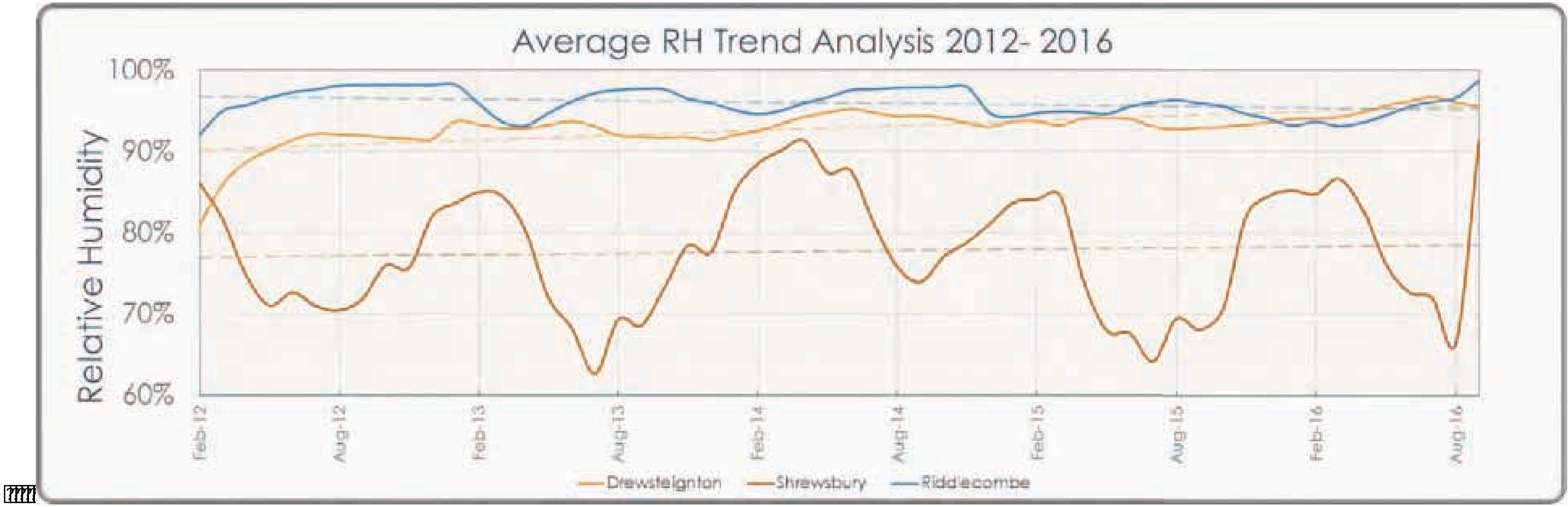


Figure 49. Average RH Trend Analysis, Shrewsbury, Drewsteignton & Riddlecombe, 2012 - 2016.

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. Across the three walls there is a broadly proportionate relationship between vapour quantities and those of material moisture content, with Riddlecombe exhibiting the highest, Shrewsbury the lowest and Drewsteignton between these two. As with measurements of AH, material moisture shows a decrease in quantities from those measured in the previous year possibly as a result of drying occurring around sensor positions following installation in 2014 -15. Measurements of %RH over the past four years show high (90%+) RH in the walls at Drewsteignton and Riddlecombe. The long-term trend for the cob wall at Riddlecombe shows that RH, whilst still high, is declining as the walling materials dry. The RH trend at Drewsteignton continues to increase as materials accumulate moisture. At Shrewsbury there is also a trend of slightly rising RH in the masonry side of the wall which is below the 80% mould growth threshold and likely to be more directly related to weather patterns than the trends found for the other two walls.

Over the coming year it will be interesting to see what happens to the RH trends and MC measurements within the walls. We expect to see RH at Drewsteignton increase whilst Shrewsbury continues to show rapid and extreme responses to local weather events. Riddlecombe may finally evaporate enough excess moisture to reach a form of equilibrium whilst still maintaining high RH. If and how these conditions are reflected in MC measurements may also allow us to better understand what represents ‘high’ moisture content for particular materials. The long-term measurement of these walls allows not only a more confident assertion of risk thresholds but also allows us to begin to see what we might consider to be ‘normal’ vapour or material moisture quantities for certain types of wall.