Historic England

SPAB Building Performance Survey 2017

Interim Report
December 2017

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

December 2017

The SPAB RESEARCH REPORT 2.

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1.1 Introduction

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

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

The properties in question are constructed of brick (Shrewsbury), granite (Drewsteignton, 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. This report is the final interim report for the three properties involved in the SPAB Building Performance Survey. A Final report presenting a summary of the findings of the research project over the past six years will be produced in 2018. 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/research/findings/.

1.2 Methodology

<u>Interstitial Hygrothermal Gradient Monitoring (IHGM)</u>

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 (eight 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, 21-22 and 37-38 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 is a relational concept used to describe the water vapour content of air expressed as percentage of total capacity. Capacity varies with temperature. In previous analyses, RH reporting has been capped at 100% as this is the upper limit of the concept of 'dewpoint' when the air becomes saturated and moisture vapour begins to condense. 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 whereas 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.

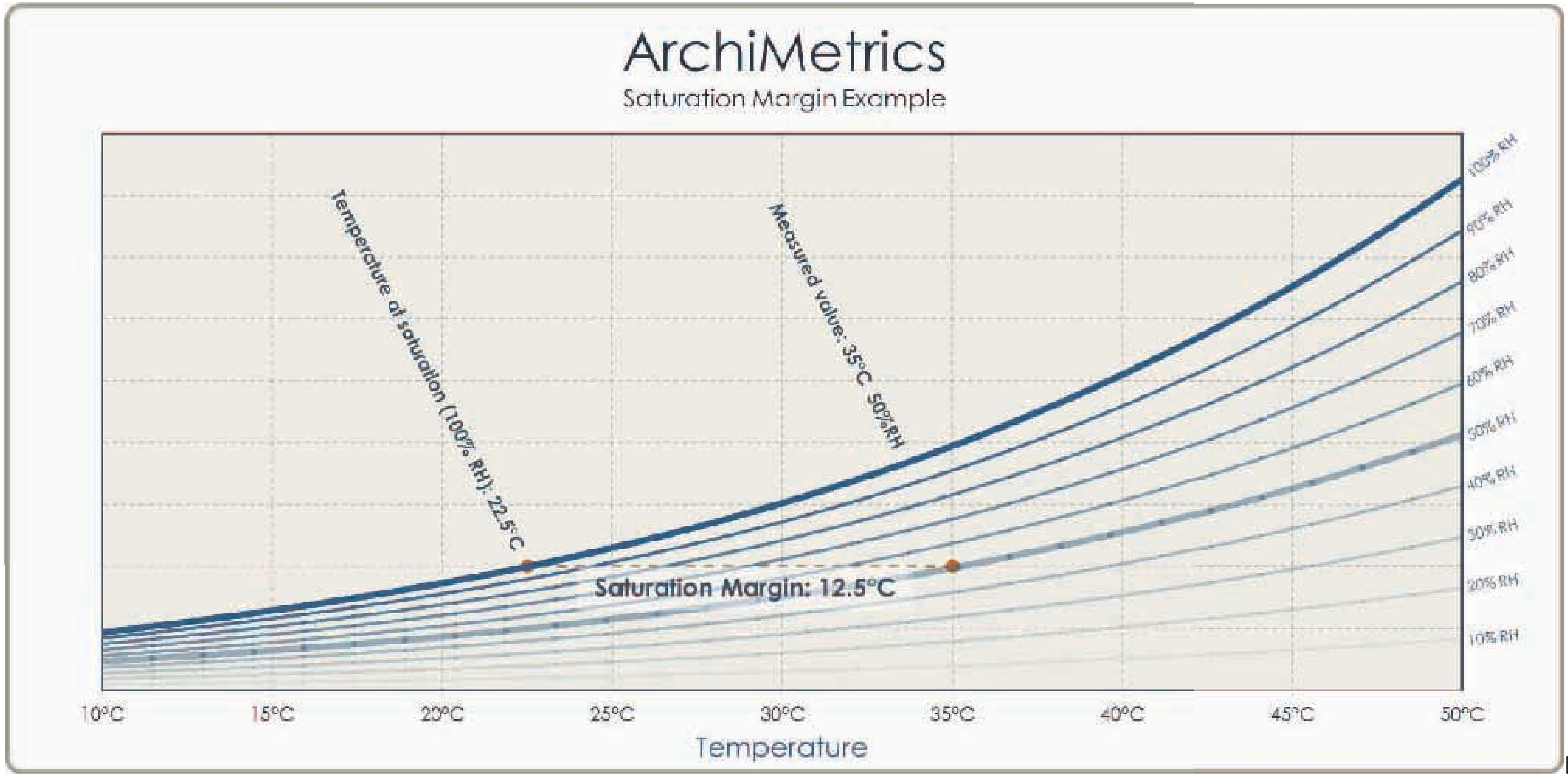

Figure 1. Illustration of saturation margin principle

2.1. 116 Abbeyforegate, Shrewsbury - 2016-17.

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.

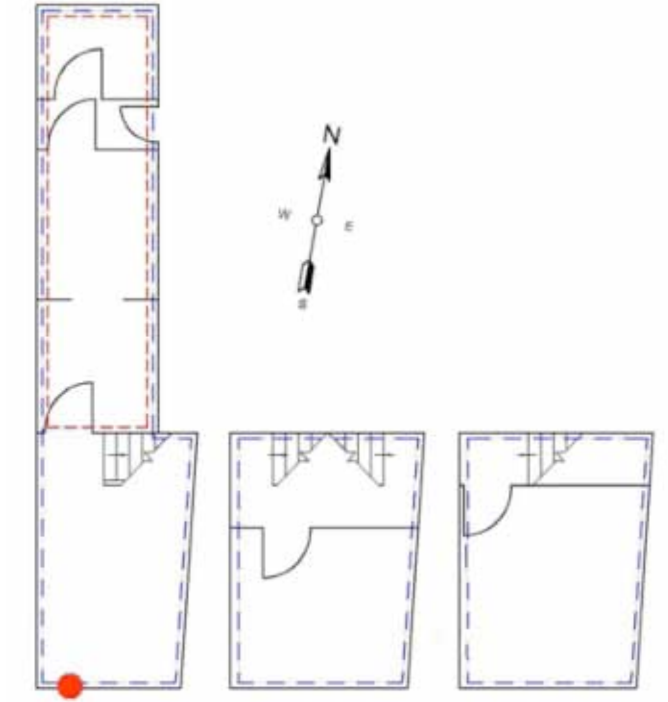

Figure 2. Plan of 116 Abbeyforegate, Shrewsbury, with ground floor on left hand side. The red dot indicates the location of monitoring equipment.

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.

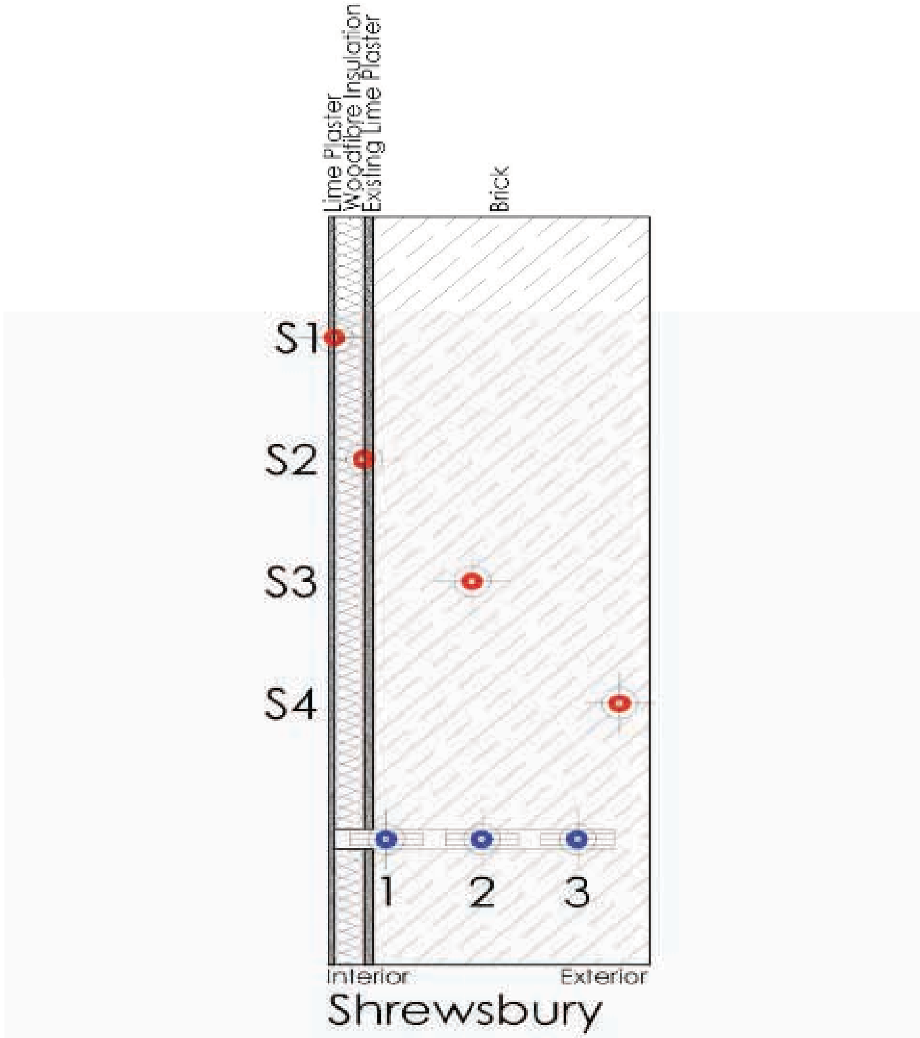

Figure 4. Position of wall sensors through section, Shrewsbury – red IHGM, blue material moisture.

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 1st September 2016–31st August 2017, 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 and permeable brick, it is south-facing so receives direct sunlight as well as the affects 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.

Moisture behaviour in the wall at Shrewsbury is closely linked with external weather conditions. This year (2016-17) %RH is generally lower throughout the section (Table 2) and the annual averages of %RH at sensors 3 and 4 are, in particular, much lower than those of the previous year. As can be seen in the aggregated data, Figure 5, there is a week at the start of March when %RH exceeds 100% at sensor 4. This is in contrast to previous years when records of %RH from this location, towards the external side of the wall, have exceeded 100% persistently for a number of months over winter.

Sensor 3 shows a similar response to that found for sensor 4 in that quantities of %RH measured in the past year are generally lower than those of previous years. In the past, following external surface winter wetting, RH at sensor 3, deeper within the wall fabric, would increase in a delayed response to the initial specific weather event. It would then exceed 80% (the mould growth threshold) for a number of months before recovering (following a similar decrease measured at sensor 4) sometime during the spring or summer. However, this year, in the aggregated data, %RH only briefly peaks above 80%, week commencing 9th March, a week after the peak found for sensor 4.

This behaviour suggests that the year 2016–17 has seen much drier conditions, particularly over the winter time, than those of previous years. Figure 7 shows that overall, this year in Shrewsbury has been a dry one, with a total rainfall of 334 mm in contrast with previous total; 489 mm (2015–16) and 352 mm (2014–15). In particular, following a single day of very high rainfall (31 mm, 21st November) there are only a handful of days until the start of March when its rains more than 1 mm in a day. The record for winter 2015–16, Figure 8, is very different and shows many more rainy days with a number of daily rainfall totals in excess of 5 mm.

The 'high' peaks of RH found for this year at sensors 3 and 4 are caused by a spell of wetter weather at the end of February/start of March. The wettest day of this period occurred on February 28th leading two days later, 2nd March, to the peak in sensor 4 and a week later, 9th March, to the peak at sensor 3. These peaks are best identified from the non-aggregated full resolution analysis in Figure 6. Following this, there is period of rapid decrease in %RH measured at sensor 4, as has been observed in previous years over a similar time period, as material closest to the external environment dries by evaporation. Likewise, sensor 3 follows a similar but less extreme trajectory shortly afterwards for the same reason. Thereafter, occasional peaks in RH towards the external side of the wall can be accounted for by clusters of rainy days which occur sporadically through the remaining spring and summer months, Figure 7.

Sensor 2, the 'critical interface', also has an 80% RH peak which coincides with that of sensor 3, triggered by the same wetting that took place a week earlier. However, the average RH value found for this location, 70%, once again shows that the interface between the woodfibre insulation and masonry wall is below the risk threshold with regard to the mould (80%). As is usual, the responses from both sensors 2 and 3 are more muted than those of sensor 4, which is in much closer proximity to external conditions. Over the year the RH range measured by sensor 4 is 31–103% which demonstrates the extreme responses to wetting a drying taking place in this part of the wall. In contrast, the annual range for sensor 3 is of RH between 61-86%, no doubt benefitting from the drier winter, which keeps winter peaks lower than normal. Even narrower is the range recorded for sensor 2, 62–80% providing an indication of the stability of the RH response deep within the wall. As before, we believe that this narrow range of RH may be an indication of the hygroscopic characteristics of the woodfibre material which is able to hold and release vapour in response to changes within its immediate environment. This buffering effect may account for the even and less extreme responses measured in proximity to this material. 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.

Table 2, RH annual averages, also provides an illustration of the stability of response at sensor 2 since the wall was refurbished. The range of averages measured over the years since the wall was insulated in 2012 has varied very little, 70–72%. This year has recorded the lowest average at sensor 2 since post-refurbishment measurements began, 70%. This is also the case for the other three wall sensors where this year's averages are also the lowest yet. The difference between the previous year's wet conditions (2015–16) and this year's very dry twelve months is illustrated by the difference between the averages found for sensors 3 and 4 across the two monitored years. The year 2015-16 saw the highest RH averages recorded at sensors 3 and 4 since the wall was insulated, 80 and 84% respectively. Whereas this year these sensors record their lowest averages yet, 70 and 73%, indicative of the extreme difference between the two years.

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%
2016-2017	63%	70%	70%	73%

Table 2. Comparison of annual averages of RH measured through wall section, Shrewsbury 2012-2017.

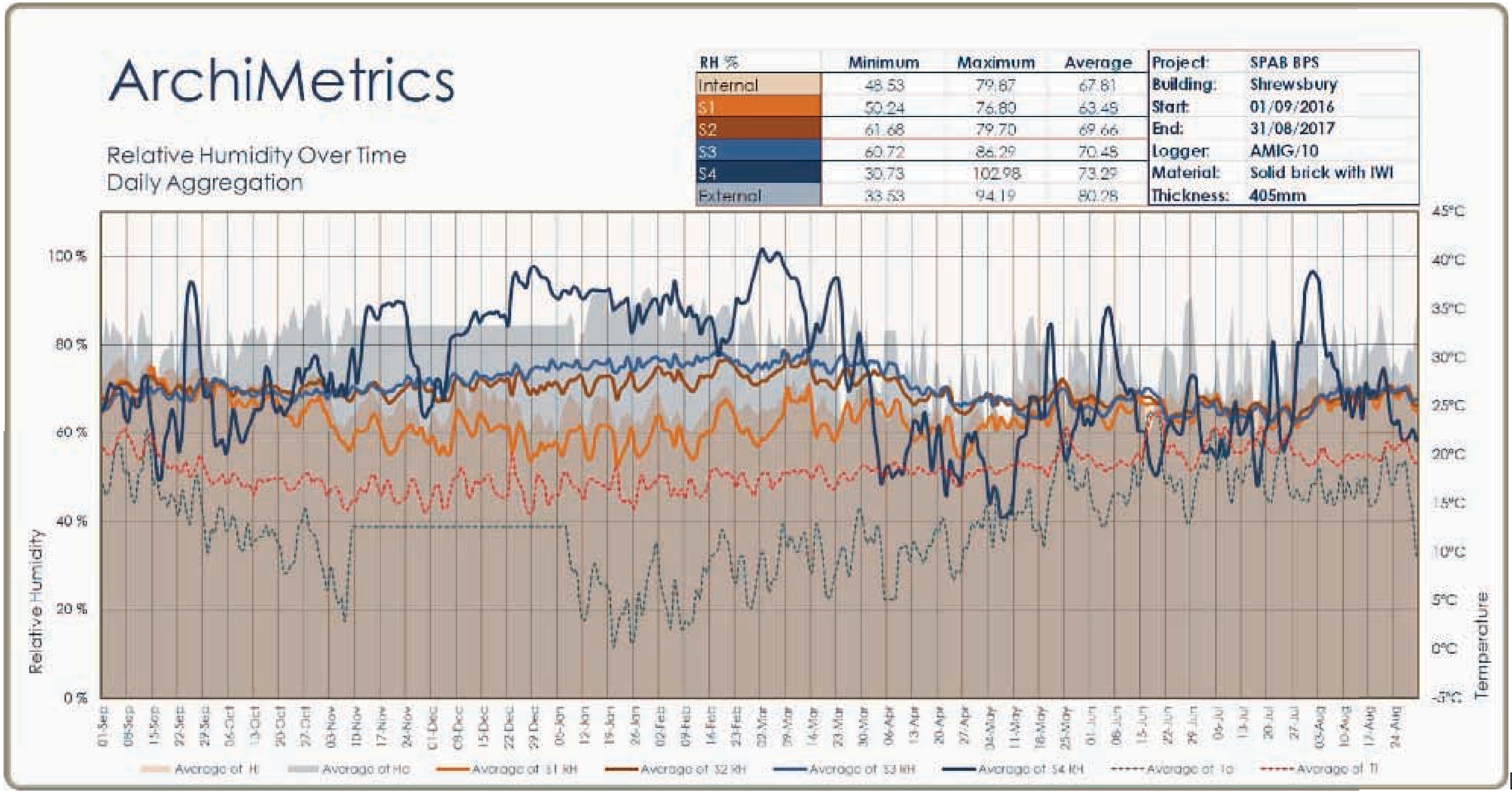

Figure 5. Relative humidity over time, daily aggregation, Abbeyforegate, Shrewsbury 2016-2017. (Ti = Internal temperature, Te = External temperature, Hi = Internal RH, He = External RH.)

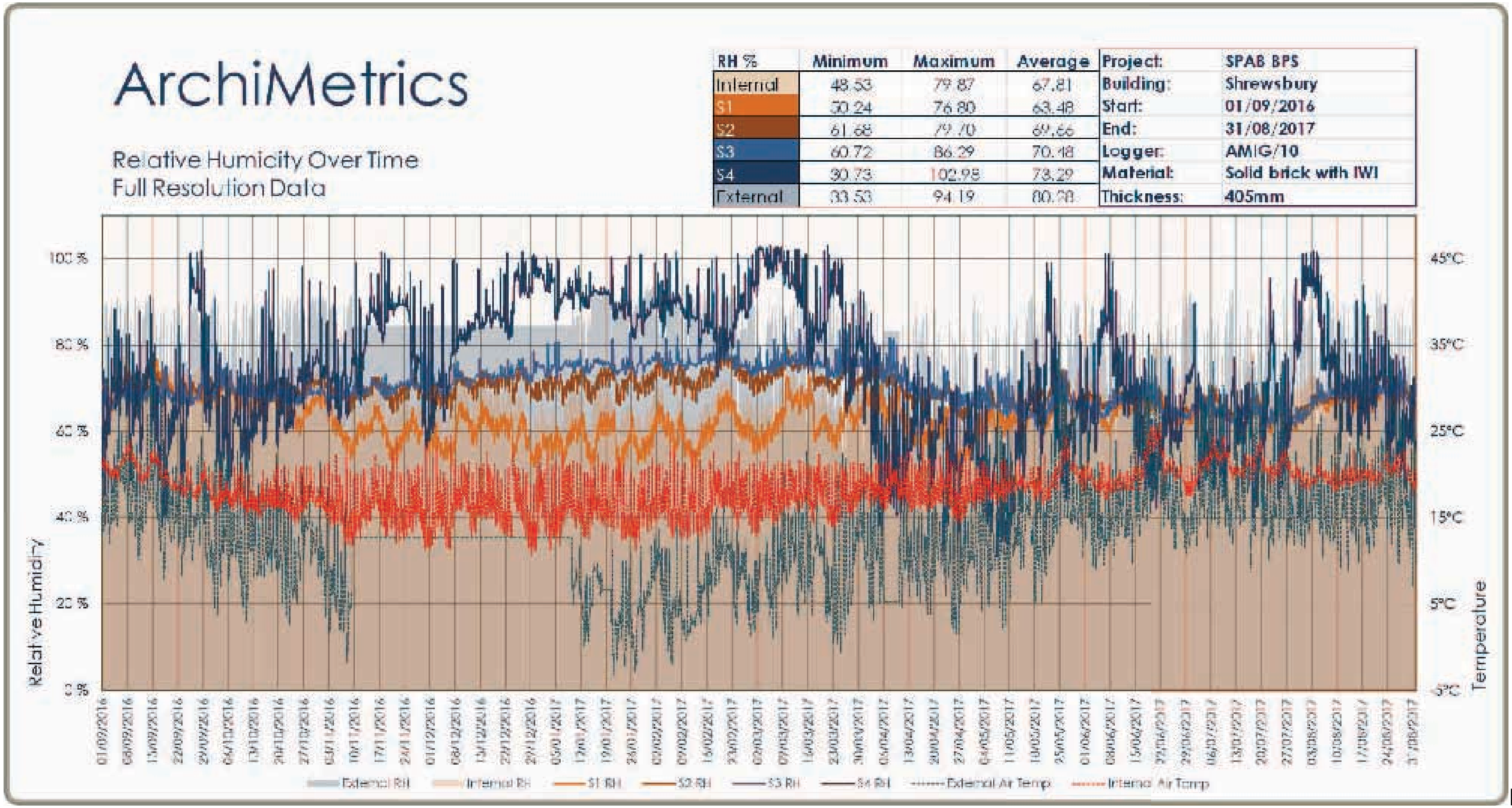

Figure 6. Relative humidity over time, full resolution, Abbeyforegate, Shrewsbury 2016-2017

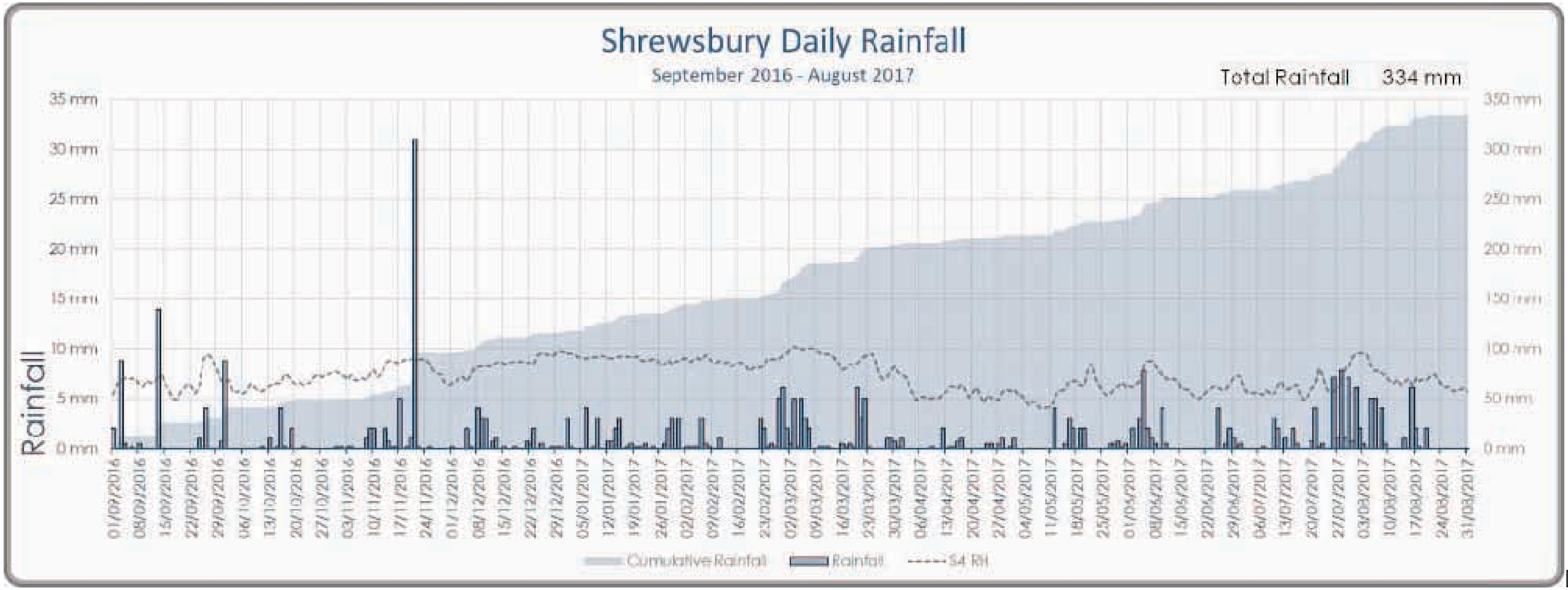

Figure 7. Daily and annual rainfall mm, including S4 RH trace, Shrewsbury 2016-2017.

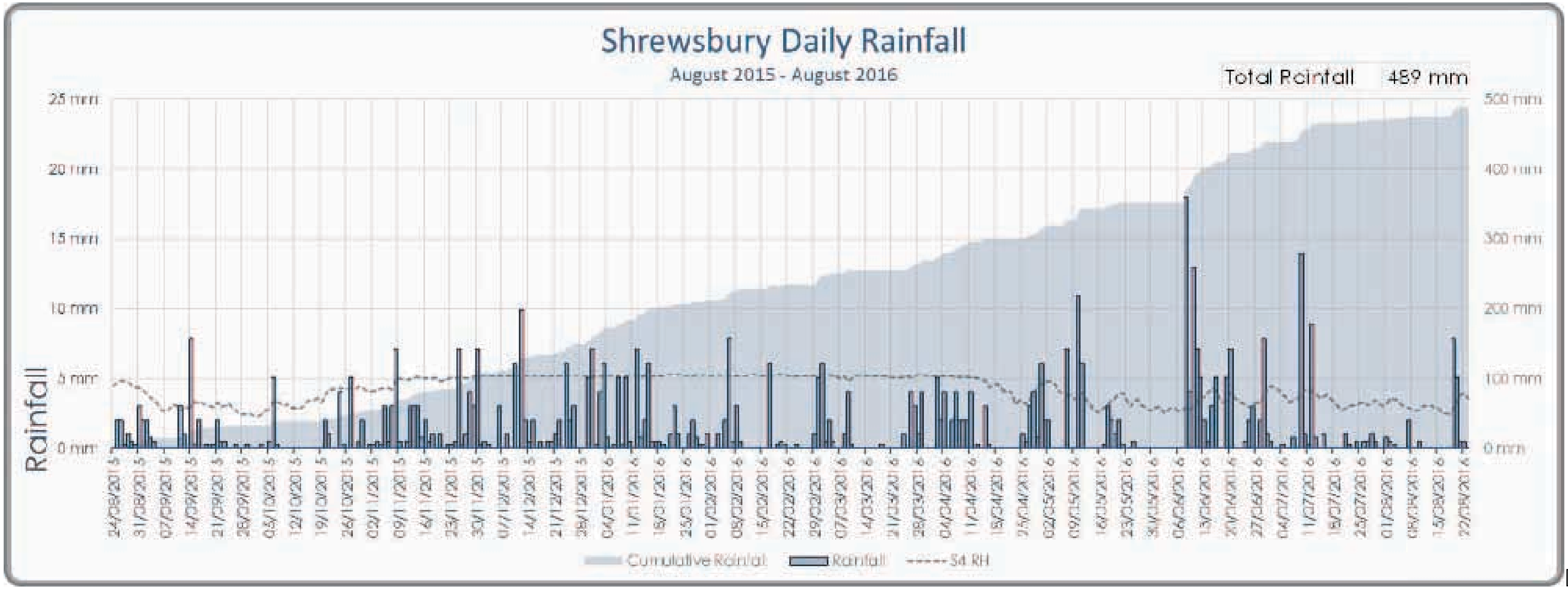

Figure 8. Daily and annual rainfall mm, including S4 RH trace, Shrewsbury 2015-2016.

Shrewsbury Monthly RH Averages						
	Internal RH	**S1 RH**	**S2 RH**	**S3 RH**	**S4 RH**	**External RH**
2016						
Sep	73.71	70.00	70.22	68.68	67.86	80.45
Oct	70.94	66.90	70.18	69.39	66.18	82.28
Nov	65.65	60.24	69.61	70.18	78.92	84.45
Dec	66.32	59.55	70.59	72.68	84.66	84.50
2017						
Jan	64.53	57.85	71.13	75.39	90.62	87.43
Feb	65.77	60.86	73.38	76.43	87.10	86.68
Mar	66.80	63.17	73.25	76.11	89.67	80.55
Apr	63.81	61.57	69.24	71.01	56.24	73.78
May	67.72	64.19	67.88	66.47	58.23	73.73
Jun	68.78	64.97	66.74	66.33	66.31	76.42
Jul	68.59	64.71	65.63	64.60	62.75	74.66
Aug	71.03	67.68	68.43	68.98	71.79	78.77
Average	**67.81**	**63.48**	**69.67**	**70.49**	**73.32**	**80.28**

Table 3. Relative humidity monthly averages, Abbeyforegate, Shrewsbury, 2016-17.

Absolute Humidity Over Time

Figure 9 shows an analysis of absolute humidity through the insulated wall section at Shrewsbury 1st September 2016–31st August 2017. Peaks in AH, measured as the weight of vapour, g/m^3, can be indicative of materials drying through evaporation during periods of warm weather. This response is particularly marked in the wall at Shrewsbury as it is south-facing and receives plenty of direct solar radiation.

As can be seen in Figure 9, external temperatures start to rise at the end of February/beginning of March. In the second week of March, external temperatures reach a peak at around 25˚C causing an 'evaporative' spike at sensor 4 (these peaks are more obvious in the full resolution analysis, Figure 10). This peak is followed by further diminishing temperature/AH spikes throughout the rest of March as drying takes place towards the external face of the wall. In April, as materials closest to the external wall face have now evaporated winter-accumulated moisture, this pattern of temperature/AH spikes can now be seen at sensor 3, as a similar drying process takes place deeper within the wall fabric. Throughout March and April evaporation has been taking place, as can be seen from the reduction over time in weights of vapour measured through the section over these two months. From May onwards, vapour begins to increase within the wall again, in line with that of external vapour as the atmosphere warms into the summer months. Henceforth, peaks in AH occur after periods of rain followed by warm sunny spells and these peaks are now measured throughout the wall section, sensors 1–4. Previously, lesser peaks have been seen from sensors 1 and 2, towards the internal side of the wall, particularly during the second month of 'drying' in April. Two events standout in May and June, when AH quantities peak, once again, within the wall. As can be seen in the rainfall analysis, Figure 7, the weeks 18th and 25th May and 15th June are both preceded by periods of rain often falling persistently over a number of days. This re-introduces moisture into the wall. The following weeks then see peaks in external temperatures (the June week being referred to, at the time, as a 'mini-heat wave'), where the wall in Shrewsbury records an external temperature peak of over 35˚C. High external temperatures are accompanied by similarly high internal temperatures (the room, which is relatively small, has a large area of south-facing glazing creating solar gain within the space). These high temperatures provoke the evaporation of recently added moisture from the substrate as well as more latent moisture held towards the interior side of the wall at sensors 1 and 2. This produces a temporary increase in the weights of vapour recorded from all four sensors throughout the wall sections over these weeks.

The final peak visible in Figure 9 occurs predominantly at sensor 4 around the 3rd August. It has rained every day in the preceding week (week commencing 27th July) and every other day of this week has seen daily rainfall totals of over 50 mm. It continues to rain into the week of the 3rd August, creating the longest period of persistent rain seen for this dry year. The RH over time analysis, Figure 5, not surprisingly shows an increase in humidity at sensor 4 during the week of rain and a peak of RH occurring at the end of this week. The AH analysis for sensor 4 shows a more 'stair-stepped' profile over the same period of time as some evaporative drying takes place between bouts of rain. The AH peak follows after that of the RH peak, during a day of no rain where external temperatures peak at over 25˚C. The evaporative drying over this day is sufficient to return vapour weights to those not dissimilar to that measured at the start of the wet spell. Thereafter, the wall records weights of vapour between 10–15 g/m^3 across all four sensors for the remainder of the month until another steep drop at sensor 4 at the end of the analysis period. This, again, coincides with a number of days of external temperatures peaking above 25˚C in the last week of August.

A comparison of the year-on-year AH averages for the four sensors in the wall is given in Table 4. In 2015–16 vapour quantities decreased at the two sensor locations towards the internal side of the wall and increased at sensors 3 and 4. This was as a result of the wet winter which increased the moisture load in the original masonry half of the wall, which in turn lead to an increased production of vapour when this moisture evaporated during the spring and summer months. As has already been noted, this past year, 2016 – 17, has been much drier in Shrewsbury. Consequently, we see a reduction in average weights of vapour at sensors 3 and 4 as a reflection of the reduced amounts of moisture available for evaporation. Also, for the first time, this year we see average AH quantities that are higher towards the internal side of the wall, at sensors 1 and 2, partly as a result of these lower exterior side values. Sensor 1 and 2 average weights are the highest annual weights of vapour recorded since refurbishment in 2012. Weights of vapour through the section as a whole occupy a narrower range than that seen in the two previous years being more akin to those measured earlier on in the study between 2012-14.

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
2016-2017	9.95 g/m^3	9.93 g/m^3	9.74 g/m^3	9.55 g/m^3

Table 4. Comparison of annual averages of AH measured through wall section, Shrewsbury 2012-2017.

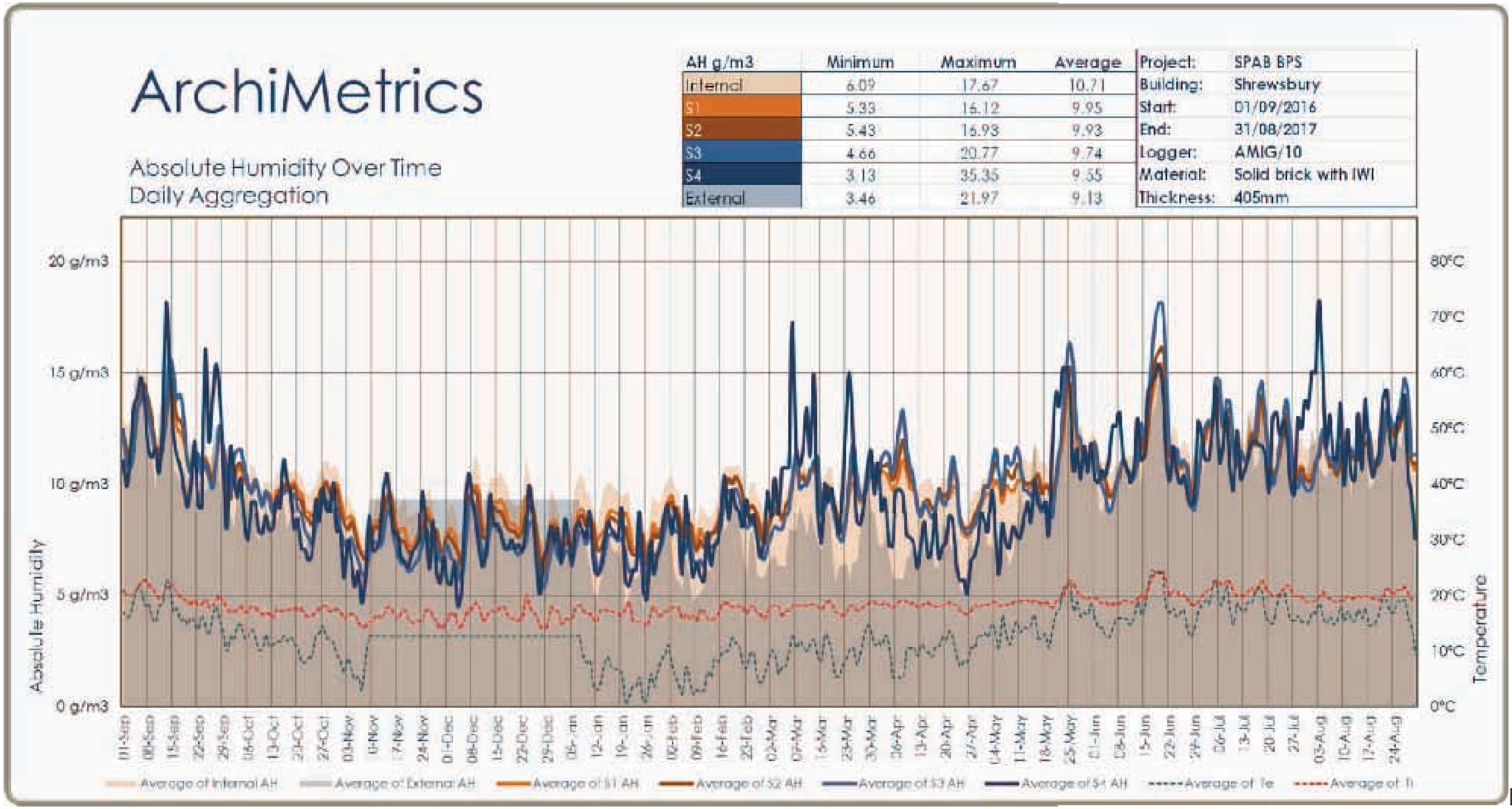

Figure 9. Absolute humidity over time, daily aggregation, Abbeyforegate, Shrewsbury 2016-2017.

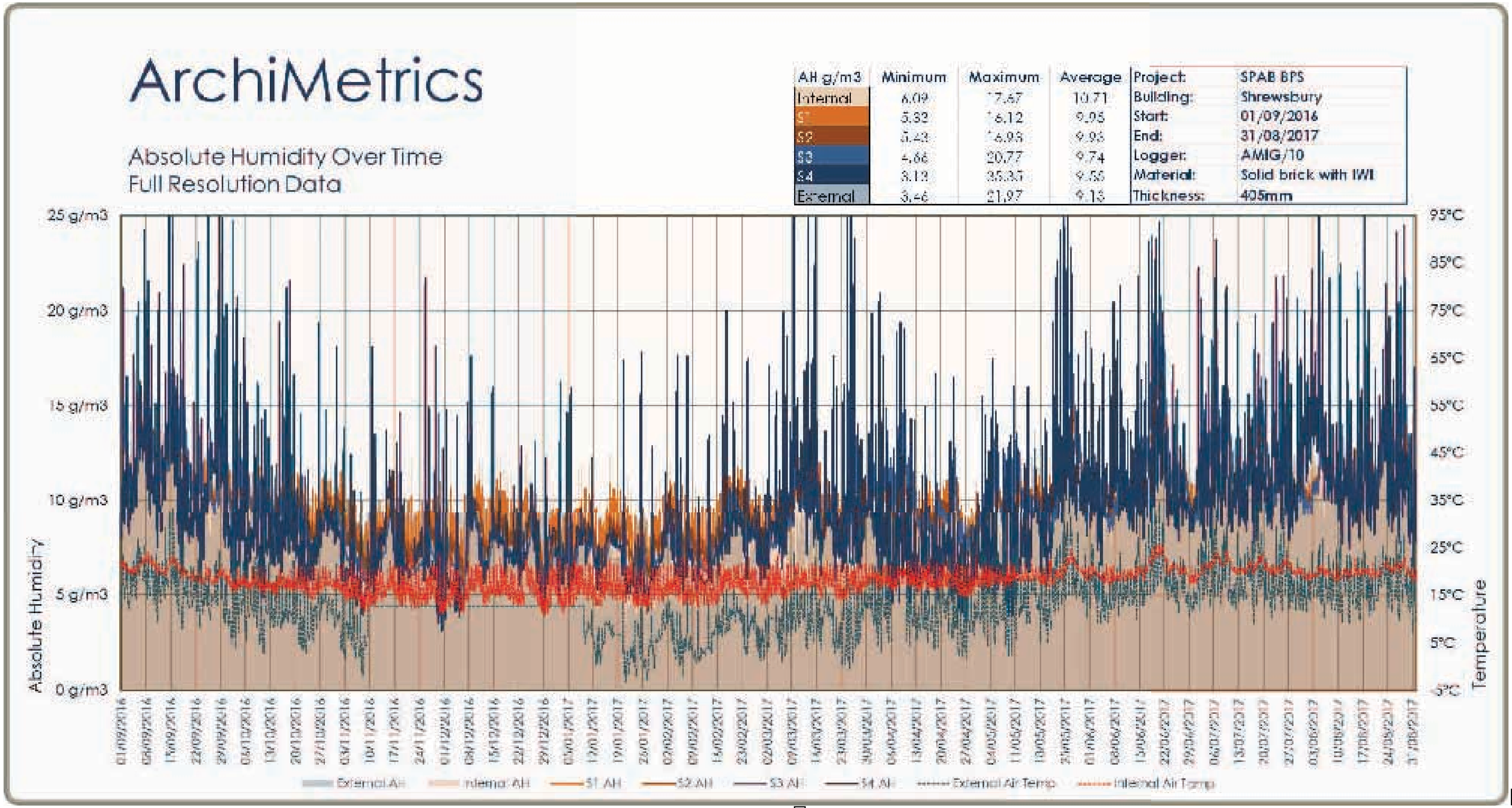

Figure 10. Absolute humidity over time, full resolution, Abbeyforegate, Shrewsbury 2016–2017.

Shrewsbury Monthly AH Averages (g/m3)						
	Internal Air	S1	S2	S3	S4	External Air
2016						
Sep	12.80	12.16	12.18	12.25	12.23	11.68
Oct	10.42	9.77	9.64	9.41	8.80	8.59
Nov	9.04	8.14	7.89	7.16	7.24	8.49
Dec	9.39	8.25	7.95	7.21	7.36	9.34
2017						
Jan	9.15	7.98	7.64	6.93	7.12	7.00
Feb	9.63	8.71	8.54	7.86	7.89	6.83
Mar	10.13	9.45	9.51	9.30	10.57	7.45
Apr	9.92	9.47	9.78	9.90	7.69	6.84
May	11.19	10.58	10.91	10.94	9.84	9.48
Jun	12.06	11.41	11.57	11.82	11.58	11.12
Jul	12.56	11.84	11.94	12.08	11.80	11.49
Aug	12.22	11.63	11.57	11.89	12.47	11.19
Average	**10.71**	**9.95**	**9.93**	**9.73**	**9.55**	**9.13**

Table 5. Absolute humidity monthly averages, Abbeyforegate, Shrewsbury, 2016-17.

Saturation Margins

Figure 11 presents plots of the saturation margins for the four sensors through the wall section over time. Records of %RH at or higher than dewpoint, 100%, indicate the saturation of air within the wall and create a negative saturation margin. This, in turn, suggests that during these periods of time wall fabric is likely to be accumulating liquid water. Figure 11 also shows how close the air in the wall comes to saturation during warmer months of the year.

Unusually, in comparison with previous years there is only a brief period of time over the 2016–17 winter when the wall at sensor 4 measures negative saturation margins, week commencing 3rd March 2017. The minimum margin recorded is less than that of one degree Celsius, -0.57˚C. Once again, the plot of sensor 4 is closely related to external conditions, which have been particularly dry over the past twelve months of this year's analysis. Thus, this year we do not find an extended period of time over the winter months when the wall experiences saturation conditions towards the external wall leaf. The negative margins at sensor 4 are a function of a period of wet weather and cold temperatures towards the end of February, already noted in the RH over-time analysis, Figure 5, as the only time RH exceeds 100% during the analysis year. This nadir for sensor 4 is followed by a two-month period where margins at sensor 4 increase due to an extended period of 'drying' during the spring previously referenced in the AH analysis. As with the RH analysis, sensor 4 experiences the greatest variation in values over the year covering the widest range of RH and saturation margins of the four sensors in the wall as it experiences both the wettest and driest (hottest) conditions.

Less extreme are responses at sensors 2 and 3, which show steadily narrowing margins as the winter progresses and temperatures fall. This trajectory alters come spring. With the advent of warmer temperatures, saturation margins begin to widen again. Margins at sensor 1, closest to internal heated conditions, are quite wide over winter benefitting from warmer internal conditions. By mid-May margins at sensors 1–3 are all quite similar at it is only sensor 4 which continues its erratic fluctuations, heavily depending upon the weather conditions of individual days as to whether the substrate its wet or warm. It is interesting to see briefly how close conditions get to saturation at the beginning of August due to the week or more of wet weather, despite warmer summer temperatures.

In Table 6, saturation margins are given as an average across all four measurement points within the section and also individually and show the change in these average margins before and after the wall was insulated over the following years since 2012. 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**
2016 - 2017 (1/9/16-31/8/17)	7.02˚C	5.53˚C	5.35˚C	5.16˚C	5.77˚C
Difference	**-0.56˚C**	**0.88˚C**	**-0.23˚C**	**-1.20˚C**	**-0.28˚C**

Table 6. Saturation margins and pre- and post-insulation difference, Abbeyforegate, Shrewsbury 2011–2017 (capped).

From Table 6, it can be seen that for the first two years, post-refurbishment, the saturation margins across all sensors 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 the wetter year, 2015–16, they are narrower once again and more similar to the margins found in the first two post-refurbishment years. This year, 2016 -17, for the first time since the wall was insulated, the majority of the averaged saturation margins are wider than those recorded from the wall prior to insulation. These show in the difference row of the table as negative numbers. The only exception is the difference from the 2011 margin calculated for sensor 2, in proximity to the woodfibre insulation, the part of the wall which has most immediately been impacted by the addition of a new material. Following the addition of internal wall insulation, a narrowing of saturation margins through the wall section may be expected, particularly in the masonry of wall on the 'cold' side of the insulation. However, the dry weather of the year 2016-17 has caused a widening in the most of the saturation margins, even in comparison with measurements made prior to the addition of the woodfibre IWI. If narrower margins, indicating proximity to saturation of the air within the wall assembly, are taken as indicator of risk, in this instance this year the insulated wall is less at risk than it was prior to refurbishment in 2011. It should be emphasised, once again, that this is a function of an exceptionally dry year rather than any inherently protective qualities pertaining to the insulation itself!

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 12-16). These analyses show the similarity and differences between the past five years. This year's analysis, Figure 12, shows (like Table 6), the widest average margins (with the exception of sensor 2) found through the wall section for the wall both pre- and post-insulation. Through the four measurement points, on average, we find no convergence of the two gradients which, in other thicker walls with a less sunny aspect, coalesce towards the external wall face as behaviour during the colder winter months dominates the analysis. This suggests that over an annual cycle the wall is performing within safe margins with regard to risks from moisture.

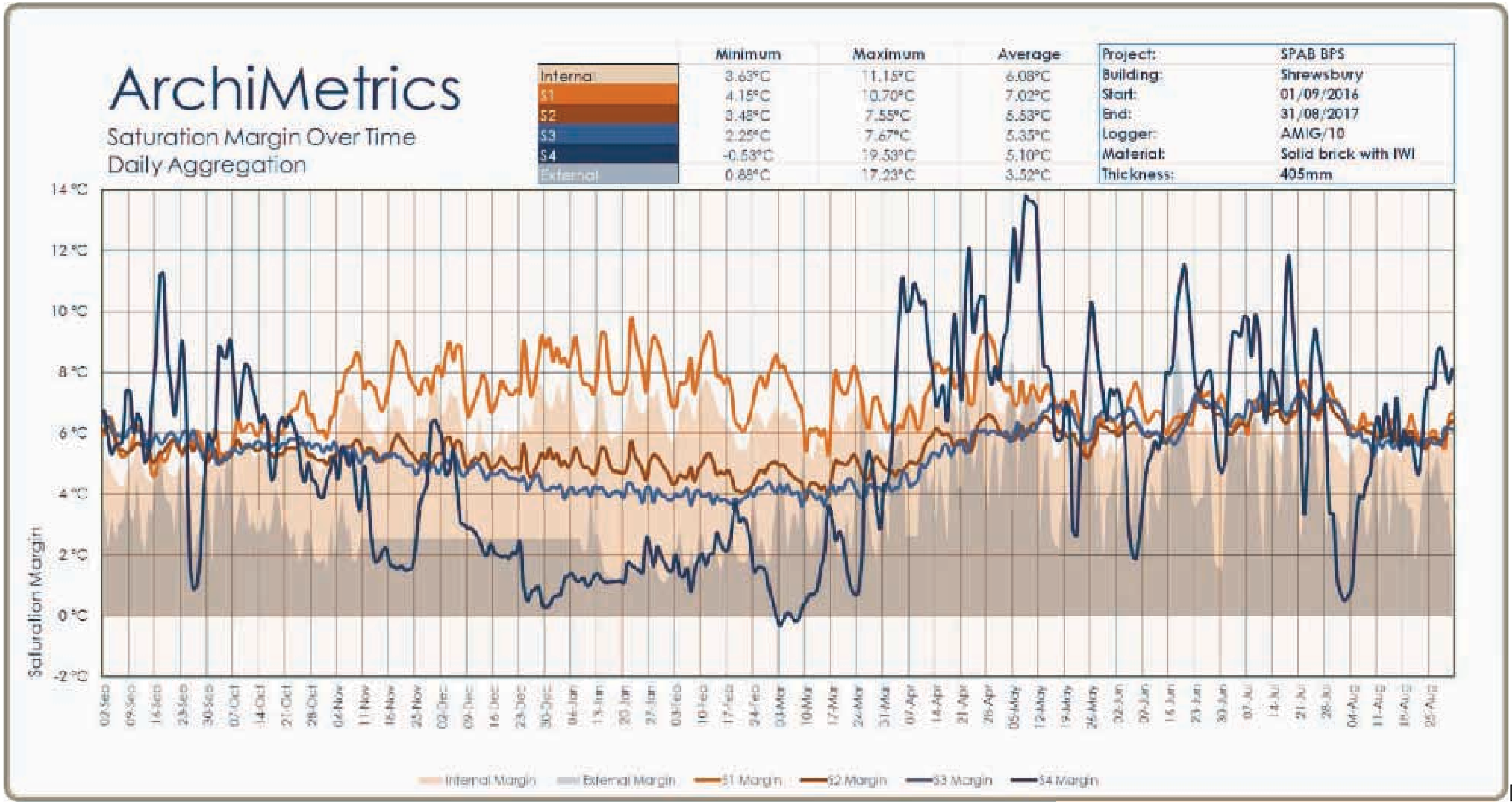

Figure 11. Saturation margin over time, Abbeyforegate, Shrewsbury 2016-2017.

Shrewsbury Monthly Saturation Margin Averages						
	Internal	**S1**	**S2**	**S3**	**S4**	**External**
2016						
Sep	4.85	5.60	5.54	5.90	6.35	3.54
Oct	5.33	6.16	5.38	5.54	6.33	3.06
Nov	6.45	7.66	5.37	5.19	3.51	2.54
Dec	6.33	7.86	5.16	4.66	2.46	2.54
2017						
Jan	6.74	8.28	5.02	4.09	1.37	1.98
Feb	6.48	7.57	4.61	3.94	2.00	2.10
Mar	6.27	7.06	4.70	4.09	1.70	3.36
Apr	6.99	7.48	5.61	5.22	8.86	4.71
May	6.13	6.89	6.00	6.34	8.69	5.06
Jun	5.93	6.76	6.32	6.43	6.67	4.44
Jul	6.01	6.86	6.62	6.89	7.61	4.90
Aug	5.42	6.11	5.92	5.81	5.40	3.90
Average	**6.08**	**7.03**	**5.53**	**5.35**	**5.09**	**3.52**

Table 7. Saturation margin monthly averages, Abbeyforegate, Shrewsbury, 2016-2017.

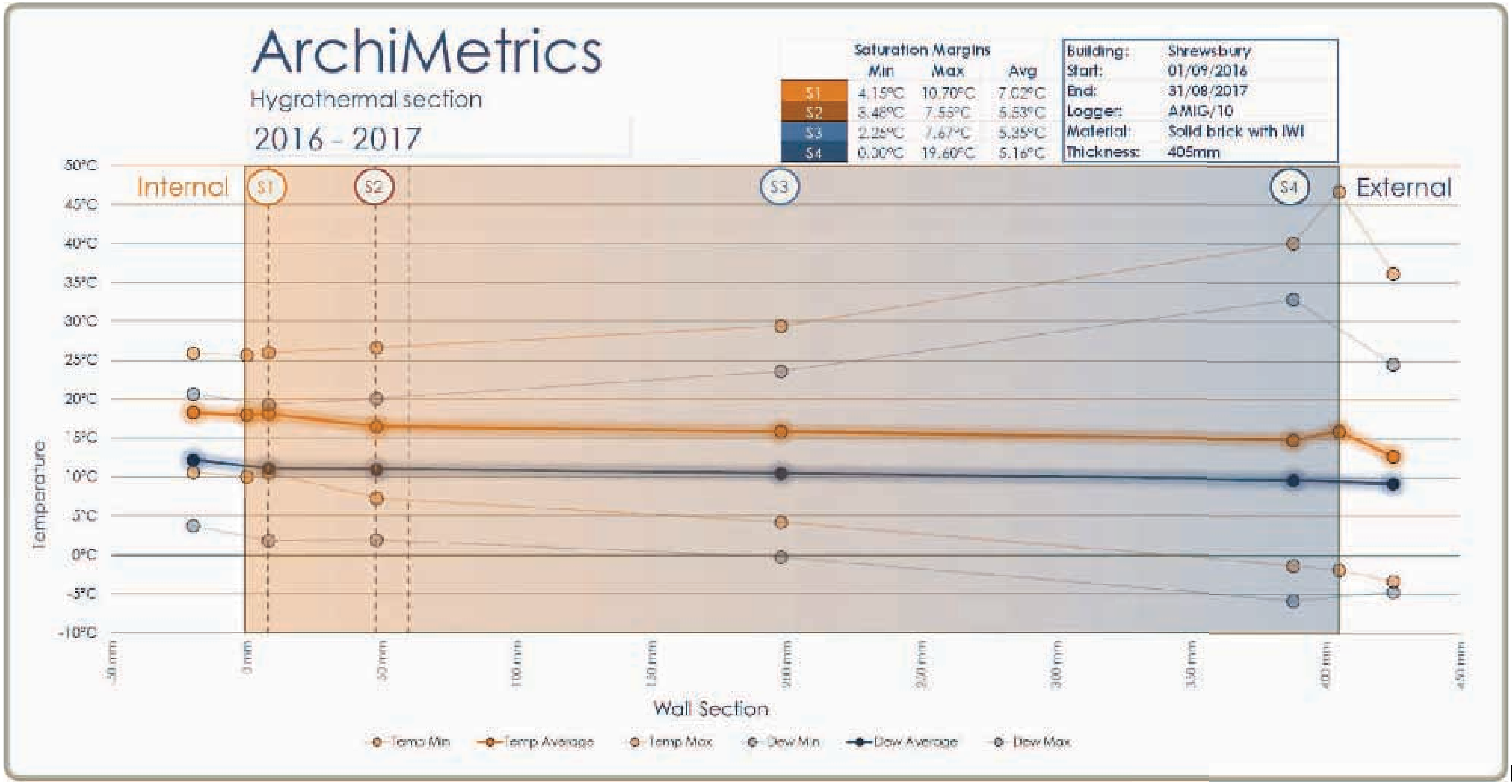

Figure 12. Hygrothermal section, Abbeyforegate, Shrewsbury 2016–2017 (capped).

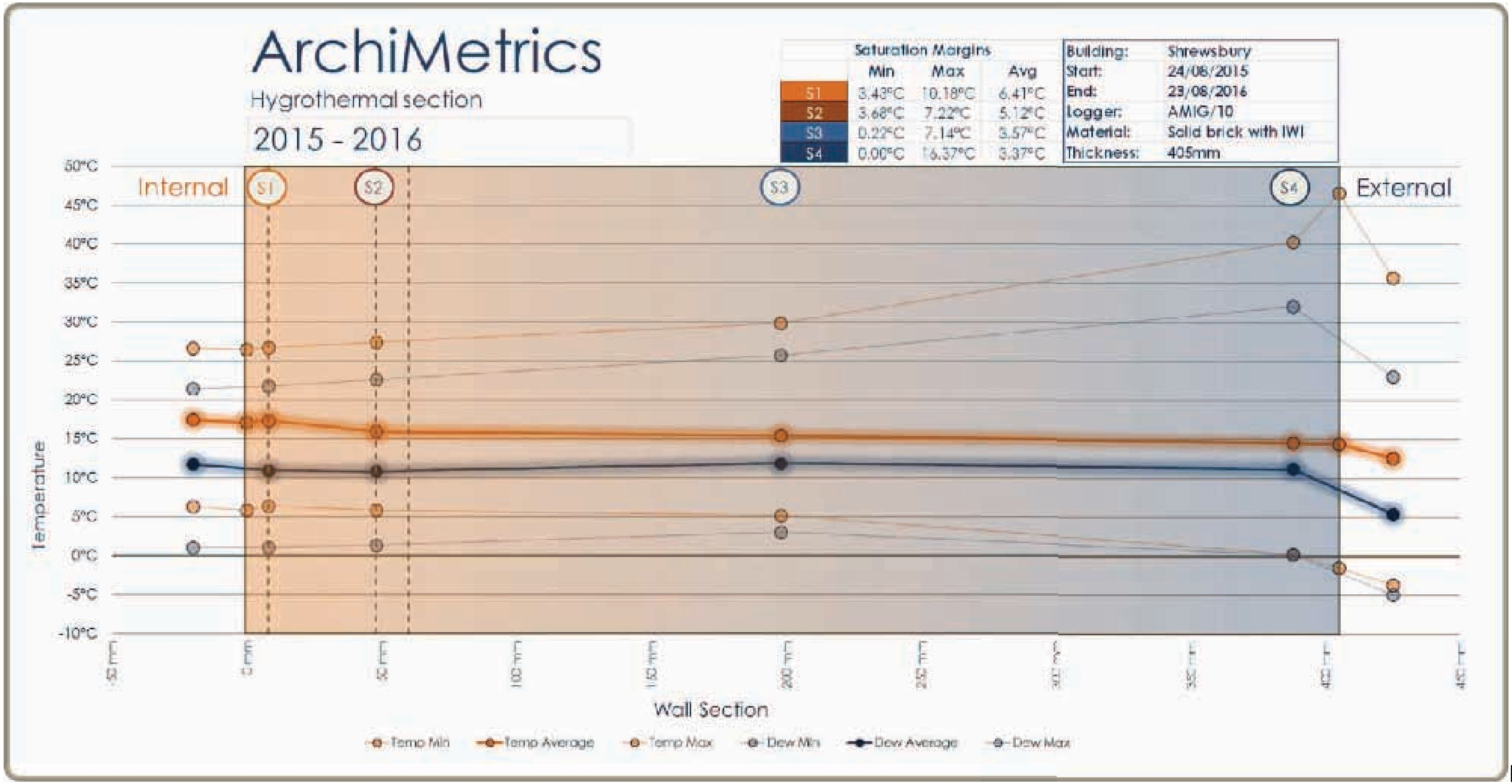

Figure 13. Hygrothermal section, Abbeyforegate, Shrewsbury 2015–2016 (capped).

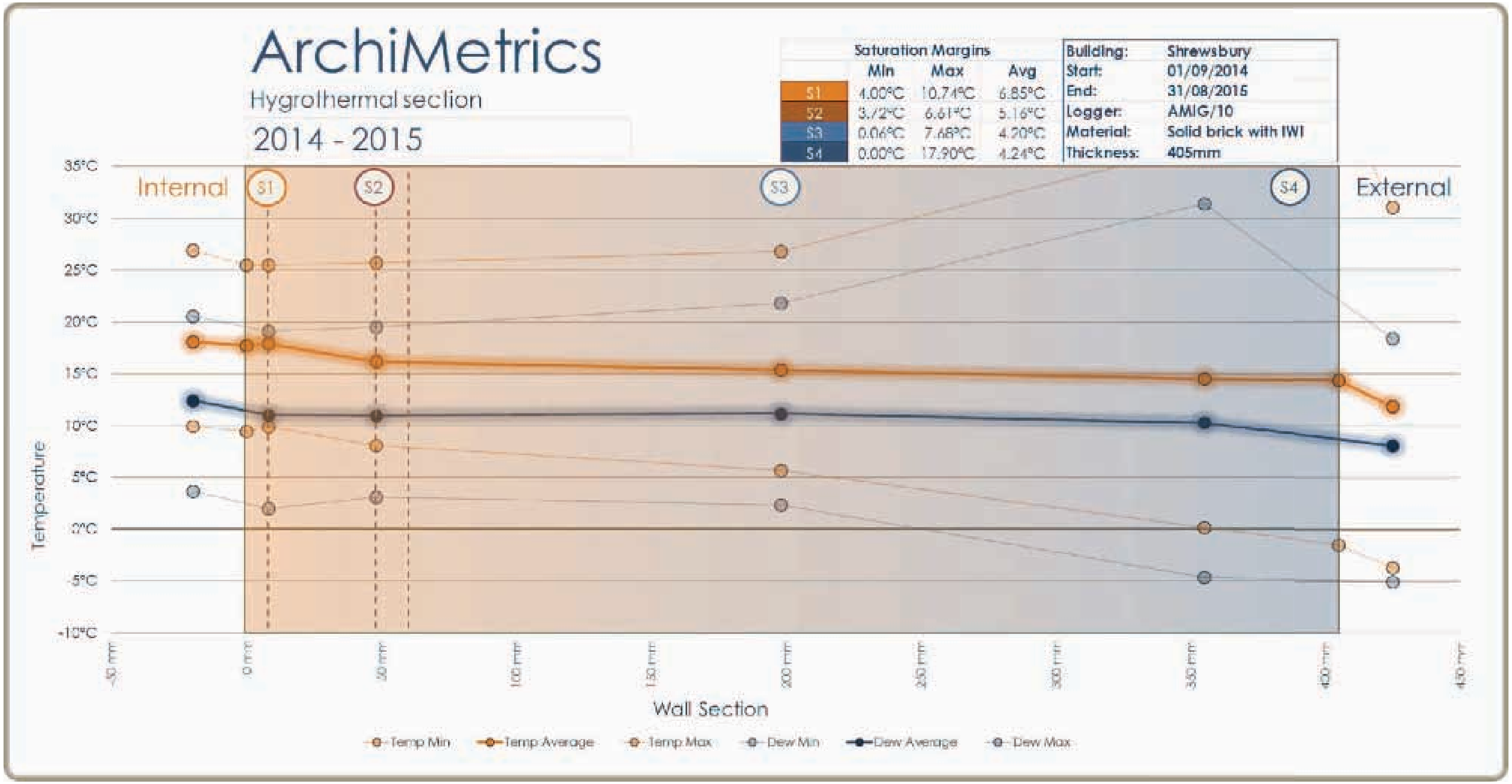

Figure 14. Hygrothermal section, Abbeyforegate, Shrewsbury 2014–2015 (capped).

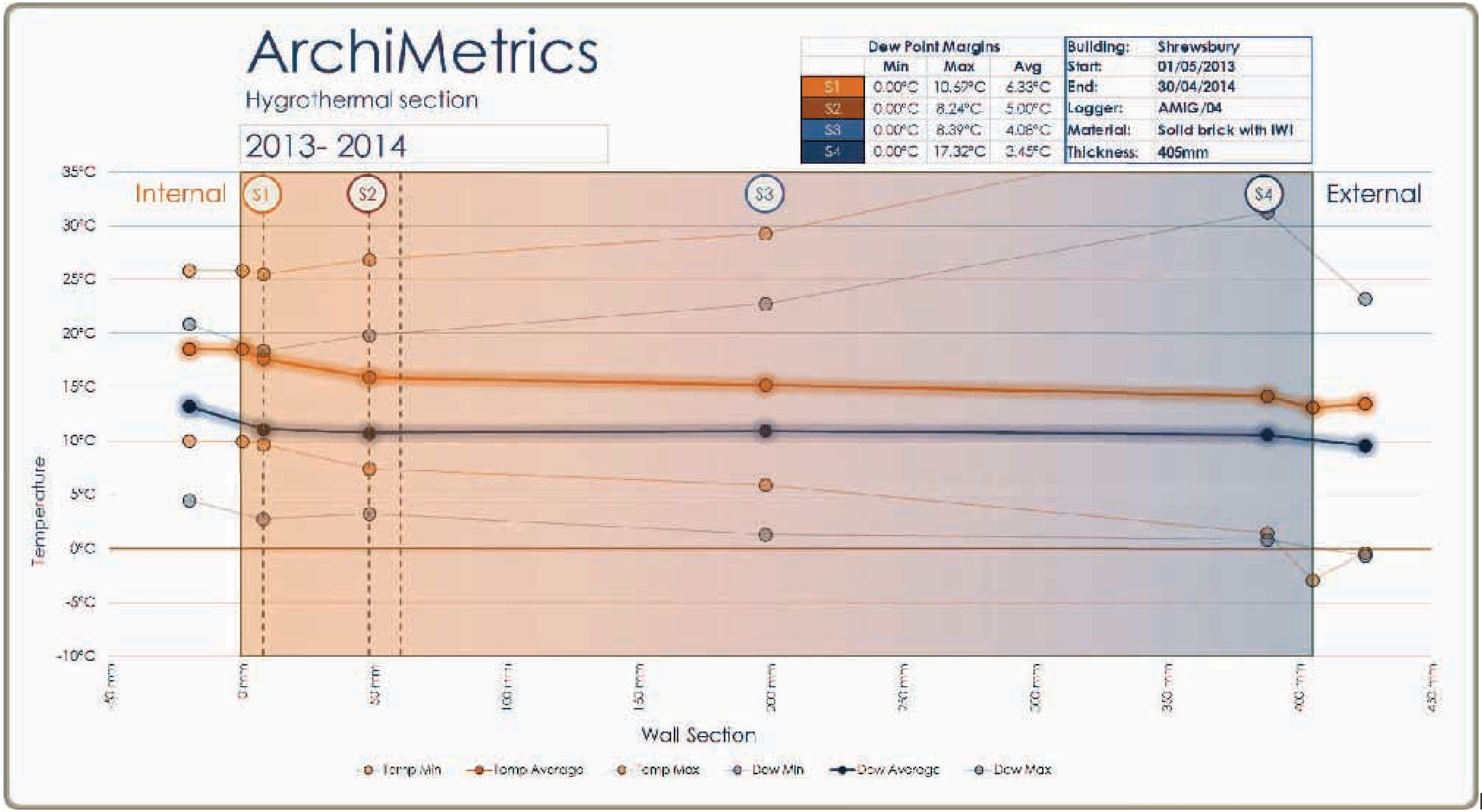

Figure 15. Hygrothermal section, Abbeyforegate, Shrewsbury, 2013-2014.

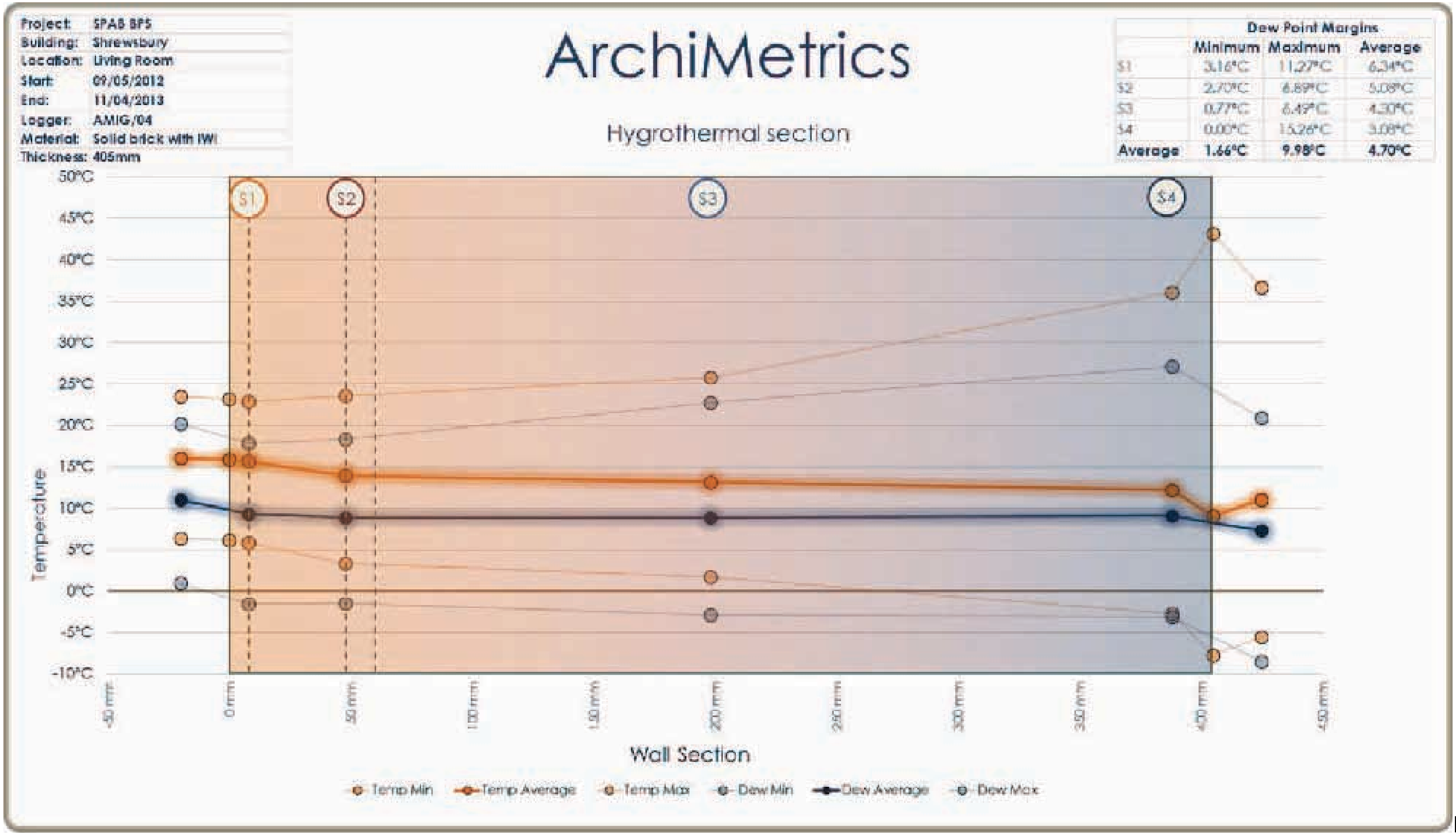

Figure 16. Hygrothermal section, Abbeyforegate, Shrewsbury, 2012-2013.

Material Moisture

The difference between the weather patterns of the previous two years monitored is immediately visible in a comparison between this year's %MC analysis, Figure 17, and that of last year's, Figure 18. As was seen in the account of vapour responses, RH and AH, the drier weather of 2016-17 also has an impact on %MC values through the wall.

%MC quantities measured at sensor 4 between summer and winter over this past year are the same, being the minimum value possible for the measurement equipment and this location measures the lowest %MC values of the three sensors in the wall. A seasonal difference is, however, discernable in the trace from sensor 3 where %MC is raised between November/December to mid-April, although it never exceeds 0.5%. There is also a slight rise in the %MC profile from sensor 2 over this time. In contrast, over 2015-16, %MC values were seen to increase at both sensors 3 and 4 over the winter period, peaking at 0.58%. An examination of Figures 7 and 8, *Daily and Annual Rainfall for Shrewsbury*, shows just how different the two previous winters have been. There are only a few days over the 2015-16 when it did not rain and often daily rainfall was close to or in excess of 10 mm. Conversely, in 2016-17, there are weeks over winter when barely any rain falls and (apart from a trend-defying day towards the end of November) daily rainfall totals do not approach 5 mm, half those of the previous year. Consequently, in 2016–17, materials close to the exterior face of the wall, around sensor 4, never retain enough moisture to register an increase in %MC. The sporadic and moderate nature of the rainfall means that, even when it does rain, moisture is able to quickly evaporate from these materials as soon as the rain ceases. At sensor 3, deeper within the wall fabric, the opportunities for evaporation are not so immediate so that here even moderate rainfall causes an increase in the %MC over time. A similar phenomenon was noted for the period October/November last year, when the winter wetting of 2015-16 first registered at sensor 3 before being joined later by an increase in %MC at sensor 4.

Individual peaks in %MC recorded by sensor 3, like that of peaks from sensor 4 in the RH record, can often be tagged against specific weather events. For example, peaks in November, 25th May and at the start of August, are all preceded by a week, or so, of wet weather. Just as RH peaks at sensor 4 following these events - as materials near the exterior wall surface begin to evaporate excess moisture - similarly %MC peaks further back within the wall as vapour pressure gradients reverse due to the rapid evaporation at the wall surface and moisture tracks back into the wall. Much as the RH trace from sensor 4 acts like a weather record for the year, the same could be said for the %MC trace from sensor 3. The fact that these two different sensors measure different quantities in different positions within the wall tells us something about the qualities of the wall as well as the difference between the two metrics. Table 8 shows us that, as might be expected, average %MC is lower this year through the wall section than that of the previous two years. It also shows an inverse relationship to that given in the table of annual averages of RH for Shrewsbury, Table 2. Annual average RH measured through the wall is highest at sensor 4 and diminishes in relation to an individual sensor's proximity to the interior side of the wall. The opposite is true for the averages of %MC, where these increase in value the further away the sensor is from the exterior side of the wall.

Bearing in mind that neither the RH or %MC measurements indicate that the wall is at risk from moisture, higher RH records seem to equate with lower %MC in specific parts of the wall at Shrewsbury. This is a result of the materials, condition and aspect of the wall; the bricks, being Georgian, are handmade, low-fired and thus quite porous and permeable. The pointing is in poor condition and the wall, being south-facing, receives the prevailing weather and plentiful solar radiation. These qualities combine to create a very dynamic vapour picture with materials in proximity to these conditions becoming rapidly wet but also readily evaporating moisture. As RH is dependent upon temperature, the highest records of RH will occur towards the coldest side of the wall – the outside. Over cold winters, materials may record high RH even in the absence of an immediate source of liquid moisture such as rain.

At Shrewsbury, %MC is higher towards the inside of the wall precisely because vapour is lower, less dynamic here, as this side of the wall does not receive extremes of moisture or temperature input. The interior space is heated over winter and internal temperatures throughout the year occupy a narrower range than those of external conditions, between 15–25 ˚C. There are, of course, moisture inputs on the interior side of the wall from the activities of living taking place inside the house but these are minuscule in comparison with the wetting that takes place during a routine rainy day to the exterior of the building. In addition, the application of woodfibre insulation and lime plaster to the interior side of the wall has created a barrier to reduce air movement. Whilst these materials still allow for the movement of moisture both as a liquid and a vapour, the evaporative opportunities are not so great towards the internal wall face. The RH is lower as temperatures tend to be higher inside over winter and the central heating 'dries' the air but the %MC is higher as there is more moisture embedded within the materials here (albeit at a low percentage, the overall average for this year being 0.43%) and less opportunities for these quantities to either increase or decrease. This also accounts for the lack of volatility in the sensor 2 moisture response throughout the years, which has very little variation.

Annual Average %MC	**Sensor 2**	**Sensor 3**	**Sensor 4**	**Average**
Shrewsbury				
2014-2015	0.62 %MC	0.42 %MC	0.45 %MC	0.50 %MC
2015-2016	0.58 %MC	0.45 %MC	0.38 %MC	0.47 %MC
2016-2017	0.56 %MC	0.39 %MC	0.34 %MC	0.43 %MC

Table 8. Comparison of annual averages of %MC measured through wall section, Shrewsbury 2014-2017

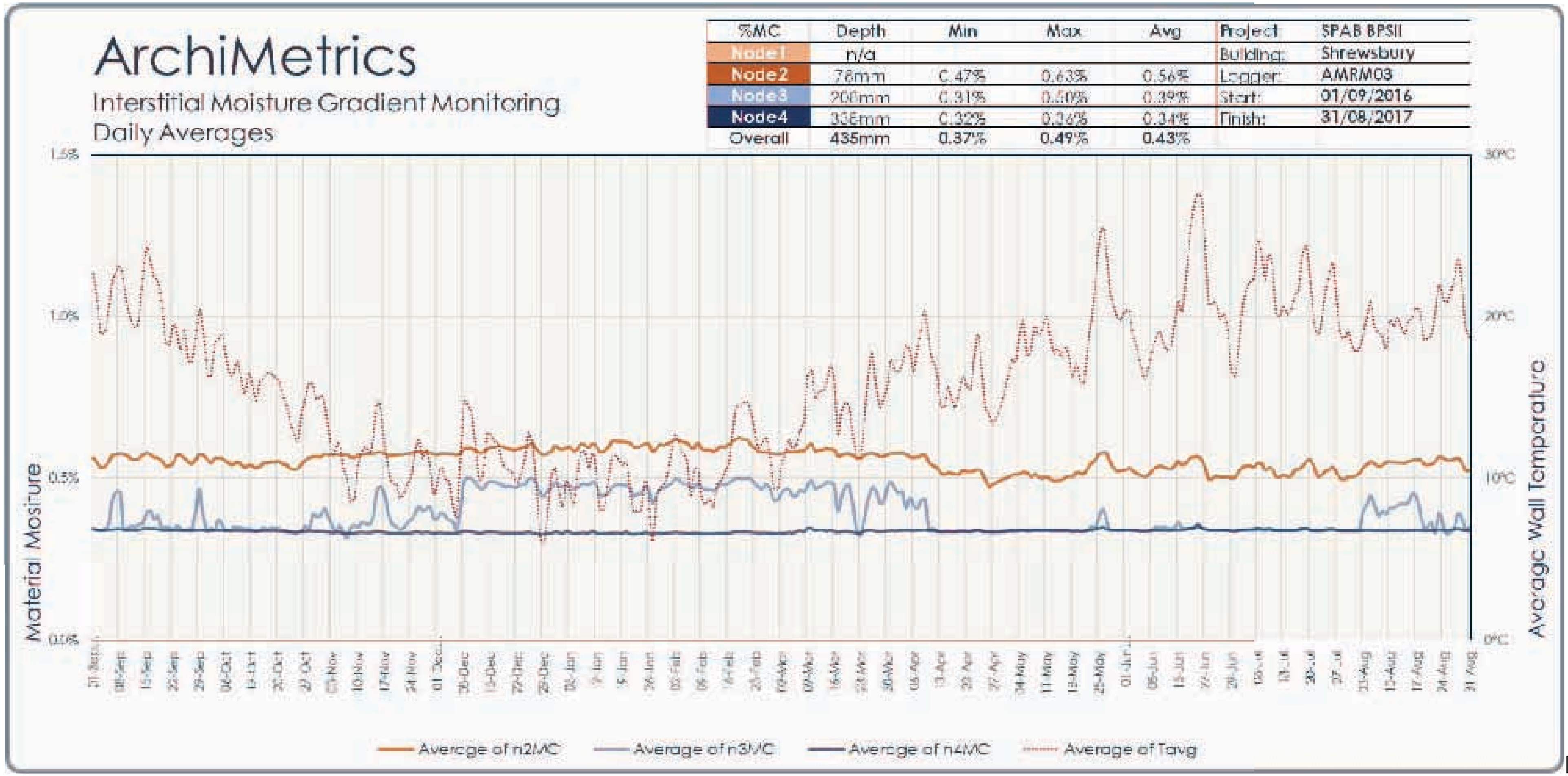

Figure 17. Material moisture content over time, Abbeyforegate, Shrewsbury 2016-2017.

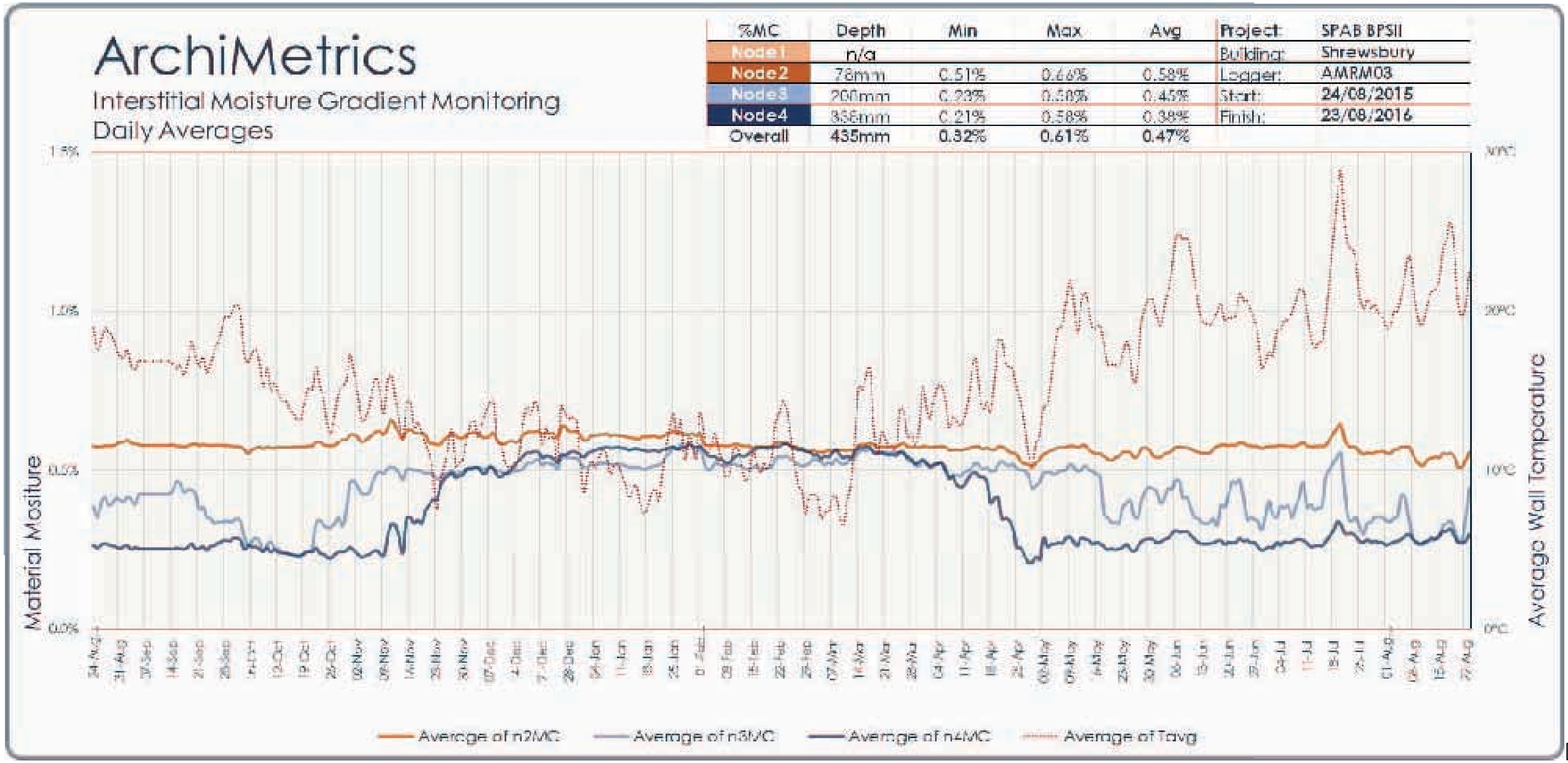

Figure 18. Material moisture content over time, Abbeyforegate, Shrewsbury 2015-2016.

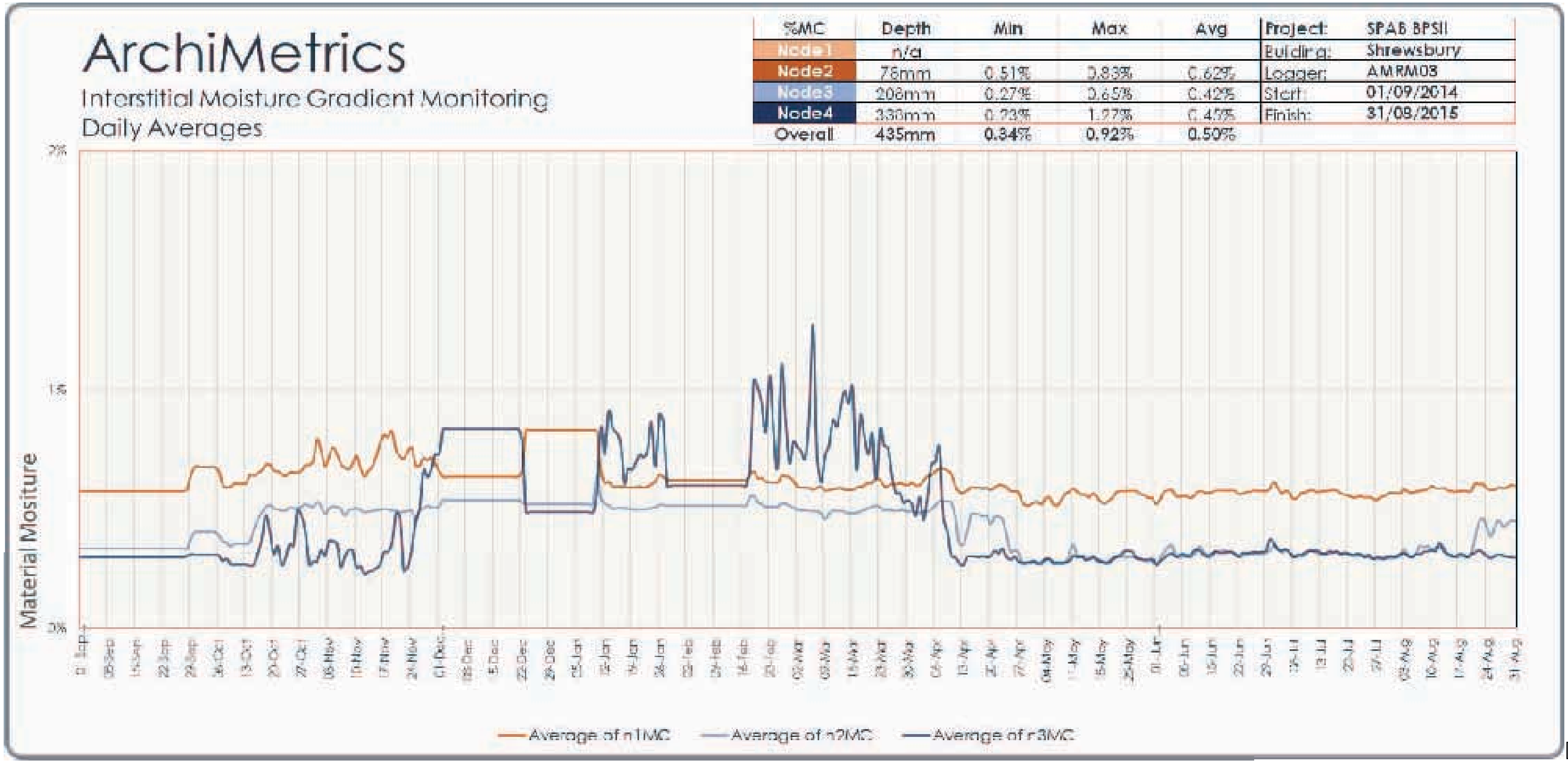

Figure 19. Material moisture content over time, Abbeyforegate, Shrewsbury 2014-2015.

2.2. Mill House, Drewsteignton, Devon - 2016-17.

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

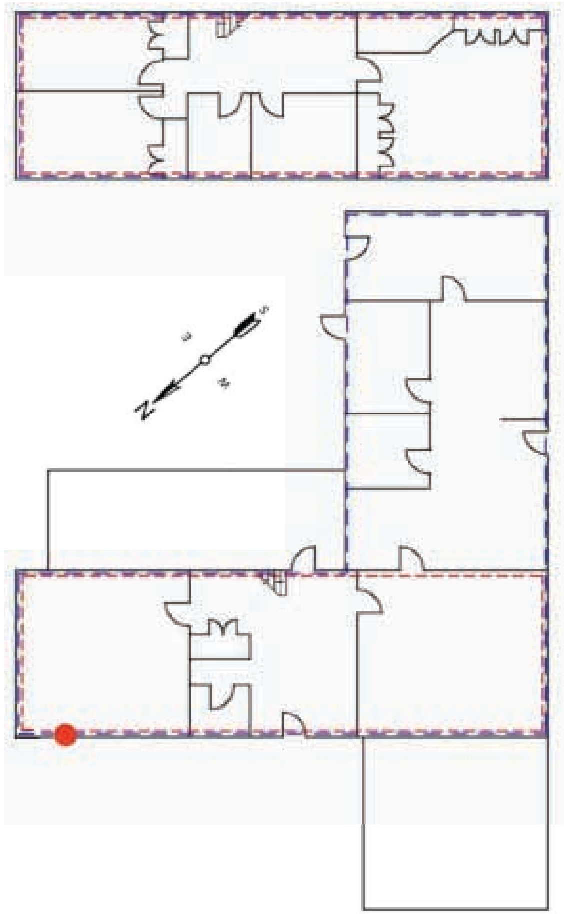

Figure 20. Plan of Mill House, Drewsteignton,. the red dot indicates the location of the ground floor monitoring equipment.

Wall Condition Monitoring

Figure 21. Interstitial hygrothermal gradient and material moisture monitoring, Drewsteignton.

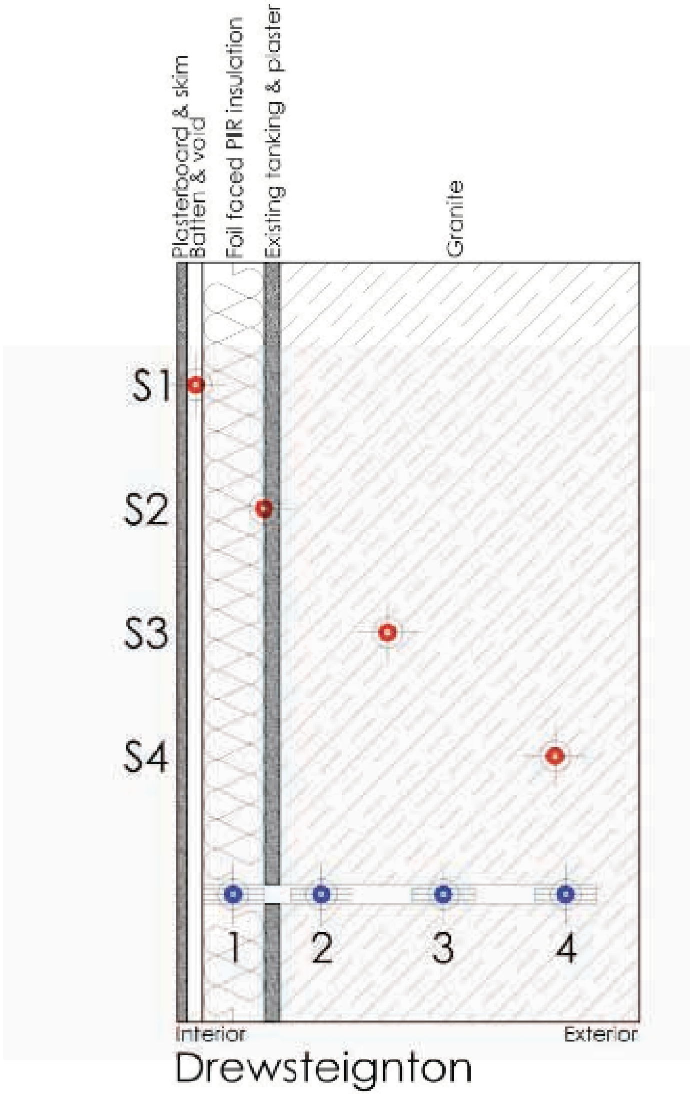

Figure 22. Position of wall sensors through section, Drewsteignton – red IHGM, blue material moisture

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 21 and 22). Combined temperature and relative humidity sensors are located at four points within the wall at the heights and depths given in Table 9. 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 9. 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 2016–31st August 2017, has been used as the basis for the following analysis.

Relative Humidity Over Time

Figure 23 shows the %RH responses measured in and around the test wall at Drewsteignton 2016-2017. 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 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.

Measurements of RH in this wall continue to show a picture of high humidity. Sensors 2–4 all have an annual average RH of above 90% and only sensor 2 records a few monthly averages and a minimum value below this, 89%, over the year (Table 11). This is still higher than the 80% threshold often quoted for the commencement of mould growth. However, the drier year is perhaps to some extent reflected in measurements from sensor 4 which peak around 100% in March, but in contrast with the previous year, do not result in any monthly averages of greater than 100%. In this respect, records for this year, 2016-17, are more akin to those of 2014–15, another noted dry year, with no sustained peaks of RH above 100%. RH measured by sensor 1, in the air gap between the PIR insulation material and the plasterboard finish, is, in effect, de-coupled from the rest of the wall assembly and as a result shows very different responses to those of the other sensors. Here, RH can be seen to be largely a function of internal room conditions as it mirrors these responses albeit at a slightly raised level. This indicates plentiful vapour exchange between the two spaces and possibly air exchange as well if the air gap is not isolated from the room at skirting and/or ceiling level.

It has been a pattern for a number of years now that the plots from sensors 3 and 4 cross and re-cross one another over the twelve month analysis period. This year quantities of RH measured at sensor 4 exceed those of sensor 3 in October 2016 and return below those of sensor 3 in May 2017. This is the 'normal' wintertime response driven no doubt by colder external temperatures increasing the RH of the air at sensor 4 in proximity to external conditions. Conversely, RH at sensor 3 falls through the autumn and winter to reach its lowest monthly average in January 2017, 94%, before increasing again through spring and summer, to end the year at a slightly lower level than that of the previous year, again perhaps a reflection of the generally drier conditions?

As RH at sensor 3 increases from February 2017 onwards, RH at sensor 2 reaches its lowest level and a sort of stasis over March and April. It is over this period that RH within the wall, although high at all three sensors, has its widest range of the year, with sensor 4 around 100% and sensor 2 at about 90%. Winter wetting, colder temperatures and diurnal cycles of evaporation (visible in the full resolution analysis, Figure 24) are driving the vapour quantities measured at sensor 4, in proximity to external conditions. Here, diurnal peaks in %RH become more defined as the wall moves from winter into spring and summer, during which evaporation of winter moisture is likely to be taking place and as a consequence %RH begins to fall around the end of April. The greatest extent of these diurnal %RH fluctuations is seen in the week beginning 15th June, a week which also sees the highest external temperature peak of the year for this location (29˚C, 22nd June). This coincides, too, with a peak in AH measured for the wall (see Figure 25) and marks the point where the drying of residual winter moisture is more or less concluded around the sensor 4 location. As a consequence, thereafter, %RH diurnal peaks are more subdued and %RH quantities are quite static.

Deeper within the wall the picture is perhaps a little more complicated. Sensor 3 records its lowest %RH values over the wintertime and these then begin to rise from February onwards, coinciding with some warm external temperatures and peak in July. Once again, the full resolution analysis shows diurnal %RH peaks on sensor 3 as external temperatures start to rise (although these are much smaller than those plotted for sensor 4), suggestive of vaporisation taking place at this location. The AH peak for sensor 3 occurs on the same day as that of sensor 4. However, unlike sensor 4, %RH is still rising over this time, perhaps indicating that vapour is less able to exit the wall structure, being located deeper within the wall. Indeed, the beginning of the year's analysis (and past years') suggests that once again %RH will be at its lowest point in this location over late autumn/winter when the wall has lost whatever vapour it can from this location and conditions are less directly affected by cold external temperatures or winter wetting and the wall perhaps also benefits slightly from interior heat lowering the %RH at this time.

Responses at sensor 2 are generally quite static with only a slight variation (there is only a 5% RH difference in the range of values recorded for the past year). The monthly %RH average is highest for the month of November (Table 11) which would suggest that %RH in this part of the wall, closer to the interior side, is not being lowered by heat transferring through the wall from the internal space heating at this time (the spike in the internal air temperature suggests that the heating was switched on in the week commencing 22nd September). However, perhaps the effect of this is cumulative as from November onwards %RH does decline to reach its lowest point around March followed by stasis. It is in March when responses at sensors 2 and 3 begin to diverge, responses at sensor 2 are virtually flat whilst quantities at sensor 3 increase. Whilst sensor 3 is influenced by increases in external temperatures it is hard to discern all but a few very small diurnal peaks in the %RH trace from sensor 2 and here the influence of the external environment is very muted. If vaporisation is taking place over the summer months, it also seems unlikely that vapour produced this deep is able to move towards the external side of the wall to escape (the interior surface is sealed with an impermeable foil membrane).

It is interesting that this wall provides its narrowest ranges of %RH over the autumn/winter and widest range in the late spring/summer. To this extent, it is more like patterns we have observed from the cob wall in Riddlecombe, where %RH is dominated by vaporisation, than those of Shrewsbury, where %RH is dominated by wet weather and temperature difference through the section. By the late autumn any lowering of %RH that can occur as a result of warmer conditions is complete at sensor 4 and to a lesser extent sensor 3 – prior to winter wetting. The shift to wetter and colder weather increases %RH measurements at sensor 4 but has little discernible influence on conditions further within the wall, where %RH at sensor 2 may be slightly lowered by internal heat gains. Come February/March and warmer temperatures, %RH at sensor 3 also begins to increase so that by April the wall has its widest range of %RH due to a combination of wetting towards the external surface, vaporisation here and to a lesser extent at sensor 3 and the lower winter heating stasis at sensor 2.

The only location within the three wall sensors which seems to benefited from this evaporative process in terms of long-term averages of RH is that of sensor 4, closest to external conditions. Here, this year's drier conditions have resulted in an annual average slightly lower than that of the previous year, 97%, Table 10. However, despite a less wet winter, the annual average RH deeper within the wall, at sensor 3, remains unchanged, 96%, and has even slightly increased at sensor 2, 91%. This suggests that the wall, as it is currently configured, is unable to take advantage of favourable conditions (ie a dry year) to reduce its RH values, which remain above the risk threshold, 80%, at all three sensors.

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. This year, 2016-17, we find this trend less evident towards the external side of the masonry wall, where annual average RH has reduced at sensor 4 and remains static at sensor 3. However, the trend still persists at the critical interface, that between the masonry of the original wall and the PIR insulation material, which despite improved, less wet, atmospheric conditions over the past twelve months once again sees a year-on-year increase in average RH.

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%
2016-2017	62%	91%	96%	97%

Table 10. Comparison of annual averages of RH measured through wall section, Drewsteignton 2012–2017.

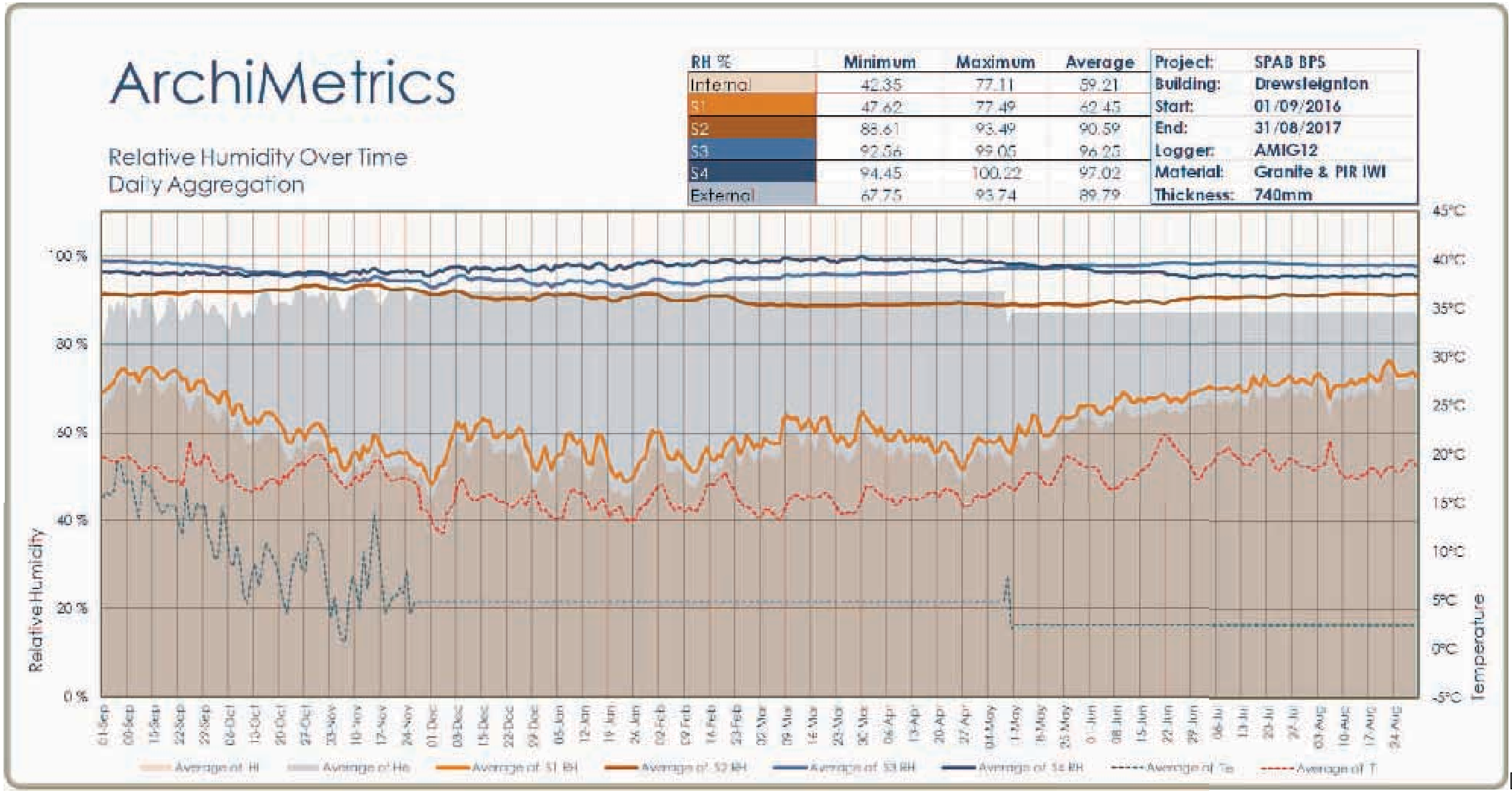

Figure 23. Relative humidity over time, daily aggregation, Mill House, Drewsteignton, 2016-2017.

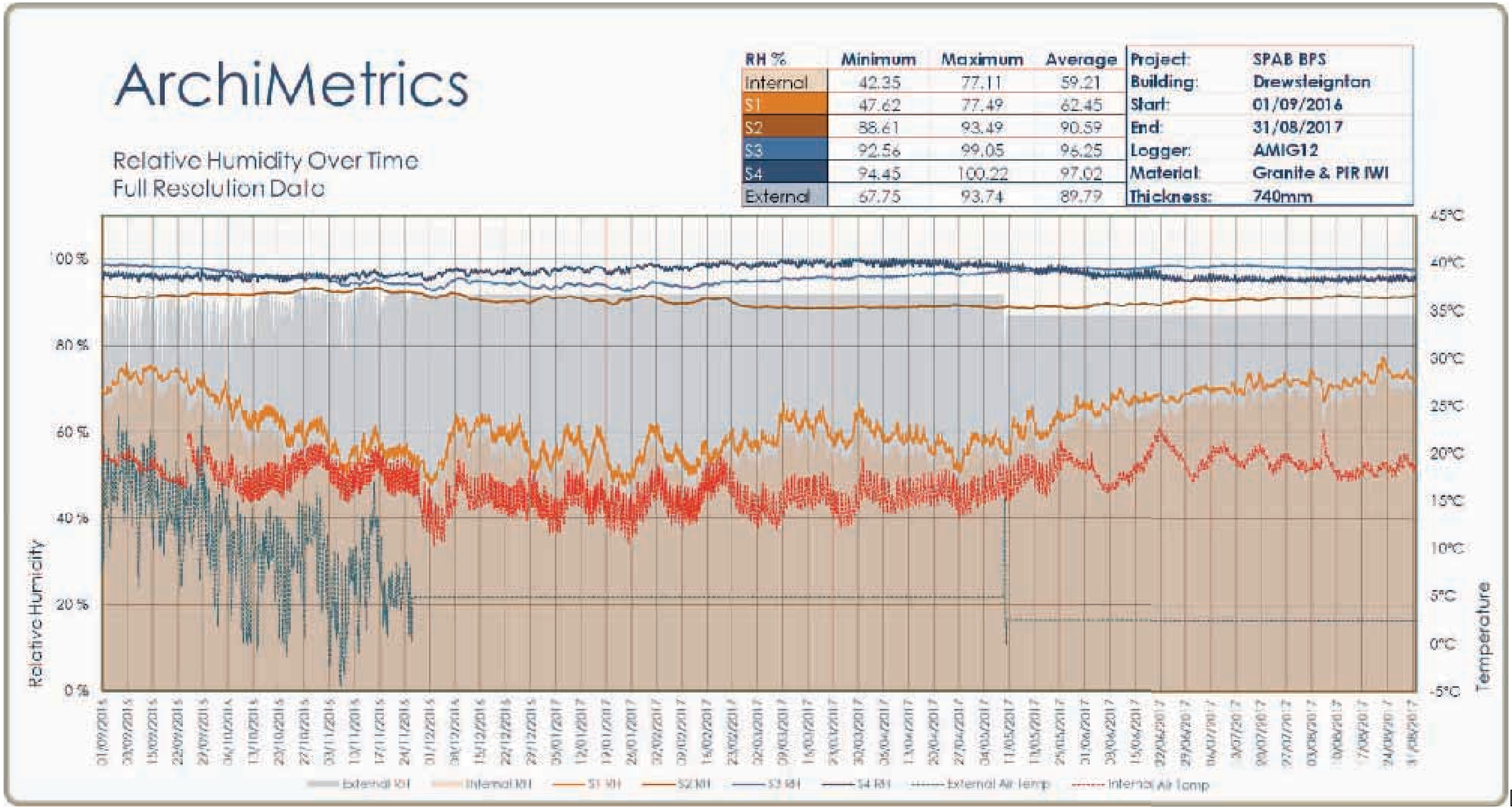

Figure 24. Relative humidity over time, full resolution, Mill House, Drewsteignton, 2016-2017.

Drewsteignton Monthly RH Averages						
	Internal RH	**S1 RH**	**S2 RH**	**S3 RH**	**S4 RH**	**External RH**
2016						
Sep	69.29	72.45	91.51	98.38	96.09	87.82
Oct	59.18	63.34	92.34	96.36	95.91	89.26
Nov	51.96	55.14	92.65	94.51	96.22	91.26
Dec	54.56	58.03	90.86	94.37	97.04	
2017						
Jan	51.44	54.83	90.89	93.73	97.76	
Feb	52.56	55.69	90.28	94.31	98.47	
Mar	57.03	60.57	88.86	95.52	99.13	
Apr	54.53	57.72	89.09	96.38	99.05	
May	57.94	60.80	88.95	97.30	97.90	
Jun	64.21	67.32	89.71	98.01	96.08	
Jul	67.92	70.76	90.74	98.28	95.35	
Aug	69.33	72.24	91.21	97.79	95.37	
Average	**59.21**	**62.45**	**90.59**	**96.25**	**97.02**	

Table 11. Relative humidity monthly averages, Mill House, Drewsteignton, 2016-2017.

Absolute Humidity Over Time

Figure 25 shows an analysis of absolute humidity through the insulated wall section at Drewsteignton 1st September 2016-31st August 2017. 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 different conditions either side of the wall due to the physical separation that has taken place via the installation of the PIR insulation board, air gap and plasterboard finish.

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. These weights are at their lowest throughout the section around 1st December 2016, which most likely coincides with a period of cold external temperatures. Unfortunately, external conditions data is lost but measurements of internal temperature, which fall to around 11˚C at this time, when the owners were on holiday, suggest colder weather and are compatible with the measured evidence, as less vapour will be present in colder air. From January 2017 onwards, there is an increase in AH measured through the section which is most likely driven by the shift from winter to spring and warmer atmospheric temperatures. The increase is erratic, driven - previous analyses would suggest - by spells of warmer weather (Figure 26, 2015 – 16).

A change in vapour conditions occurs mid-February when measurements from sensor 1, within the air gap, detach from those within the masonry part of the wall. AH here is now lower than that found within the rest of the wall and, as with RH records from the same location, comparable with that of the room interior. Weights of vapour measured by the other three sensors, 2–4, continue to be very similar until the end of April when sensor 2 develops a more distinct trace, recording lower weights of vapour than those of sensors 3 and 4. In the past, over this time, we have described these responses to be due not just to general increases in atmospheric vapour, but also indicative of evaporation taking place within the substrate. The weights of vapour measured exceed both those of internal and external conditions. If this is the case, then sensor 2, in the masonry adjacent to the insulation, is some distance away from the evaporative influences of warmth and air movement in the external environment. In these circumstances, perhaps it is not surprising that vapour generation is limited and less than that measured closer towards external conditions at sensors 3 and 4.

Another notable shift that takes place in the vapour profile of the wall occurs around 25th May. From this week onwards, the highest AH peaks measured within the wall occur at sensor 3, rather than sensor 4. This suggests that excess winter moisture present in materials towards the external wall face, has by now been sufficiently dispersed by evaporation, to the extent that when this process now takes place, higher concentrations of moisture vapour are found deeper within the wall, suggesting higher moisture concentrations at these greater depths. 25th May was also the week in the RH record where, possibly following a spell of warm external temperatures, plots of sensor 4 fell below those of sensor 3, reversing the wall's wintertime configuration. This also indicates that the process by which the wall disperses seasonally-accumulated moisture has begun to diminish to the extent that quantities of vapour within the external wall face are now lower than those around sensor 3.

Peak measurements, the highest being that from sensor 3 - 10.96 g/m^3, occur on the week beginning 22nd June, which, is known to have been a period of high temperatures throughout the UK (the 'mini-heat wave' previously referred to in the Shrewsbury section). Unsurprisingly, here vapour quantities are at their highest within the wall due to the evaporative effect of the high temperatures, coupled with the general increase in atmospheric moisture that occurs with warmer air temperatures.

Over the first three years following installation of the insulation, there has been a year-on-year increase in the annual average weights of vapour measured at Drewsteignton (Table 12). For the second year now, the annual average weights of vapour measured by all four sensors in the wall section have reduced. %RH levels in the centre of the wall (sensors 2 and 3) have largely increased year-on-year since 2012 and are well above the mould growth risk threshold which suggest high levels of vapour within the wall fabric. Last year it was suggested that the lower annual AH averages of 2015–16 were the result of an excessively wet year resulting in a lack of evaporative opportunities limiting the amount of vapour present within the air sampled within the wall. This year exceptionally dry conditions may also result in the same trend, in that not so much water was deposited within materials over the winter period so that less moisture is present or available for evaporation. This would result in a decrease in measured weights of vapour whilst - depending on ambient temperatures -, high %RH could still be measured 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
2016-2017	9.05 g/m^3	10.55 g/m^3	10.96 g/m^3	10.52 g/m^3

Table 12. Average absolute humidity, Mill House, Drewsteignton, 2012-2017.

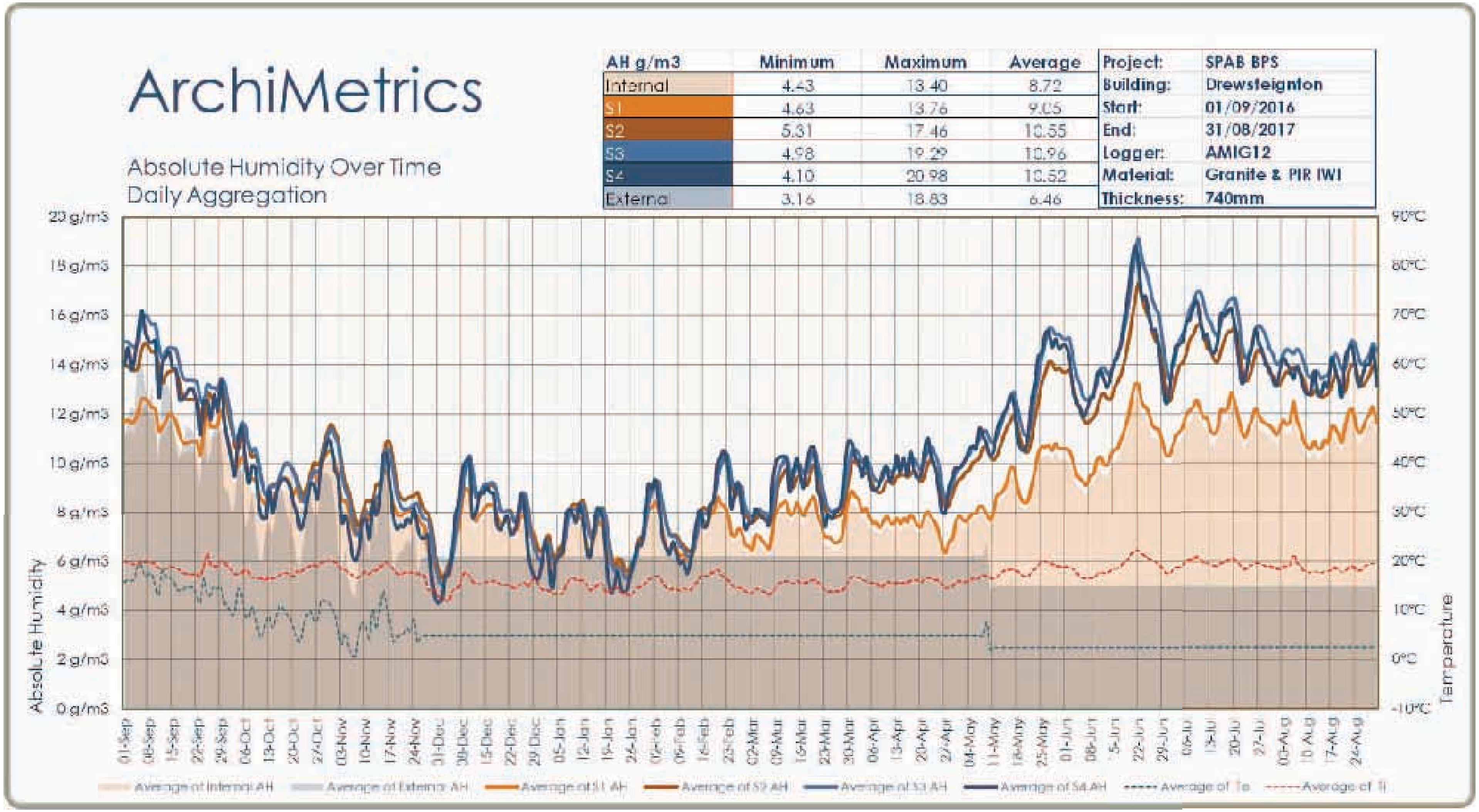

Figure 25. Absolute humidity over time, Mill House, Drewsteignton 2016-2017.

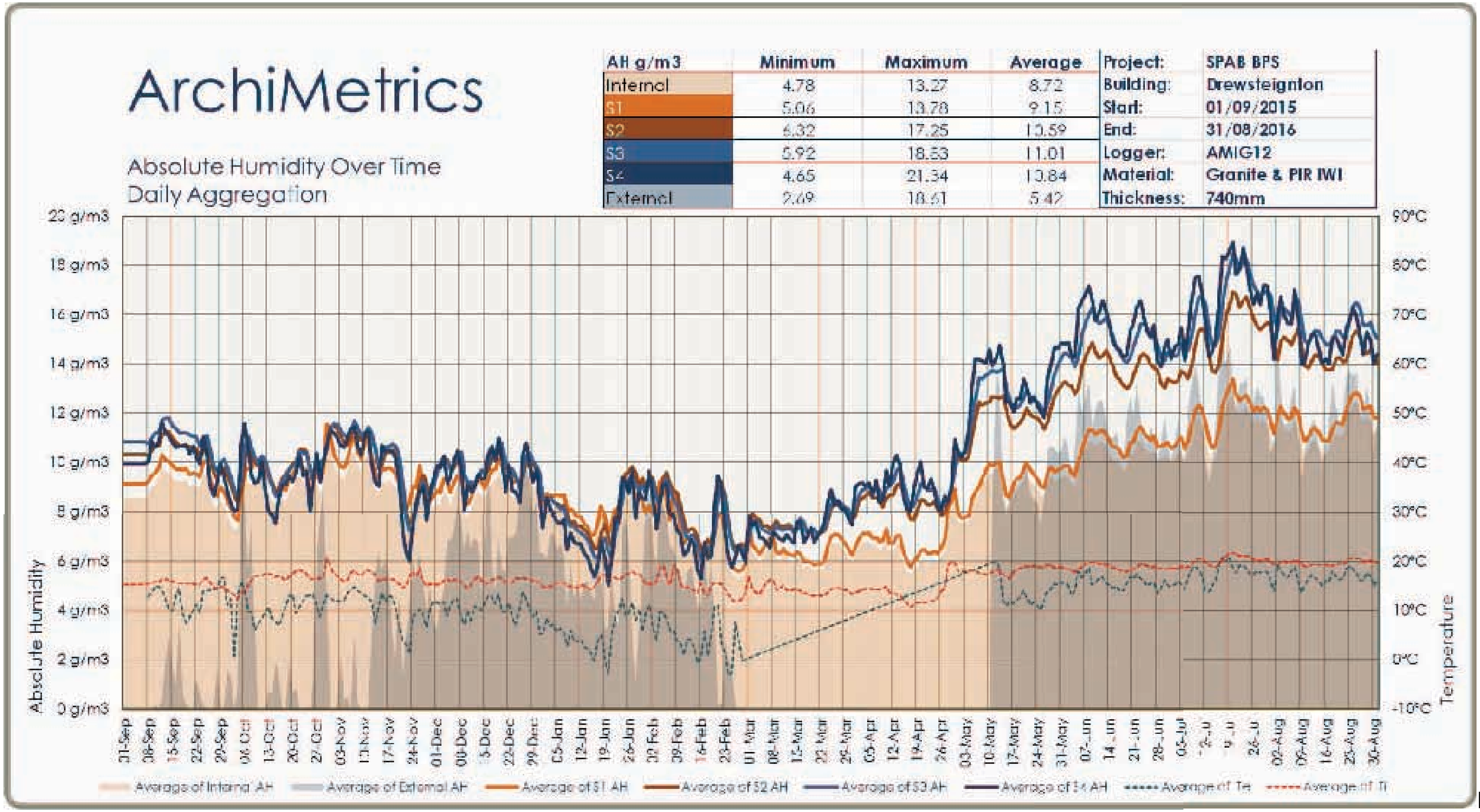

Figure 26. Absolute humidity over time, Mill House, Drewsteignton 2015-2016.

Drewsteignton Monthly AH Averages						
	Int AH	S1	S2	S3	S4	Ext AH
2016						
Sep	11.21	11.65	13.38	14.19	13.53	11.67
Oct	9.00	9.42	10.08	10.07	9.27	8.03
Nov	7.81	8.04	8.88	8.51	7.64	6.72
Dec	7.05	7.33	7.91	7.83	7.44	6.18
2017						
Jan	6.45	6.67	7.06	6.87	6.61	
Feb	7.04	7.27	8.20	8.17	7.84	
Mar	7.26	7.59	8.66	9.05	9.01	
Apr	7.29	7.59	9.35	9.82	9.62	
May	8.74	9.05	11.39	12.22	12.13	
Jun	10.39	10.83	13.85	15.06	14.51	
Jul	11.30	11.70	14.38	15.46	14.89	
Aug	10.98	11.36	13.33	14.14	13.55	
Average	**8.72**	**9.05**	**10.55**	**10.96**	**10.52**	

Table 13. Absolute humidity monthly averages, Drewsteignton 2016-2017.

Saturation Margins

Figure 27 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).

Figure 27 shows that within the masonry part of the wall air was close to saturation for much of the year. However, in contrast to last year, no negative monthly average margins are found for the wall suggesting conditions have not 'exceed' dewpoint for any significant period of time (Table 15). A negative minimum margin of -0.10˚C is recorded for sensor 4 at the end of March. This is a period where RH and AH records suggest that wall materials close to external conditions contain moisture in the form of vapour in quantities sufficient, when combined with springtime ambient air temperatures, to record its highest RH values. The widest margin found for the masonry part of the wall is that of 1.87˚C at sensor 2 during the warm summer month of June. As with the RH analysis we see saturation/dewpoint conditions shift through the wall depending on the time of year. Over winter the external side of the wall has narrower saturation margins (higher RH) whereas over summer and autumn margins are at their narrowest further back towards the centre of the masonry wall at sensor 3.

In Table 14, annual average saturation margins are written individually and as an average of all four sensors, they show the change in these margins before and after the wall was insulated. 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. This year, on average the saturation margin at sensor 1 is 7.23˚C, in contrast to those of sensors 2, 3 and 4 where margins remains below 1.5˚C. In Table 14, 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 have continued to narrow at sensors 2 and 3 deep inside the wall year-on-year. Margins at both sensor 4 and sensor 3 are below 1˚C for a third year, being 0.50˚C and 0.41˚C respectively. The sensor positioned closest to external conditions, however, does not always follow the trend that is prevalent elsewhere in the masonry monitoring. This year, the margin has remained unchanged from that of the previous year, rather than narrowing as it has done at sensors 2 and 3. The degree of change between pre- and post-insulation margins has also slowed and, of course, remains unchanged at sensor 4. This is perhaps a reflection of the influence of a drier year, where less moisture has been deposited in materials and less evaporation taken place? Or it maybe that the wall is beginning to approach a form of equilibrium where the trend of increasing RH is replaced by one of a dynamic equilibrium albeit of high %RH within the masonry?

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**
2016–2017 (1/9/16-31/8/17)	7.23˚C	1.44˚C	0.50˚C	0.41˚C	2.40˚C
Difference	**-1.93˚C**	**3.38˚C**	**3.03˚C**	**1.97˚C**	**1.62˚C**

Table 14. Saturation margins and pre- and post-insulation difference, Mill House, Drewsteignton 2011–2017 (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 (Figures 28-32). 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 shows how, over the past five years, actual temperature and dewpoint temperature have moved closer together year-on-year. Previously, this has most obviously been the case towards the external side of the wall around sensor 4. Here the annual average saturation margin has now been 0.41˚C for two years. However, it is possible to see in this year's analysis, 2016-17, a continuing narrowing of margins in the centre of the wall at sensor 3 and at the insulation/masonry interface at sensor 2. As with evidence from the saturation margins and %RH, this shows how, despite a drier year, with regard to indications of moisture performance, we continue to find a worsening picture for the wall at Drewsteignton.

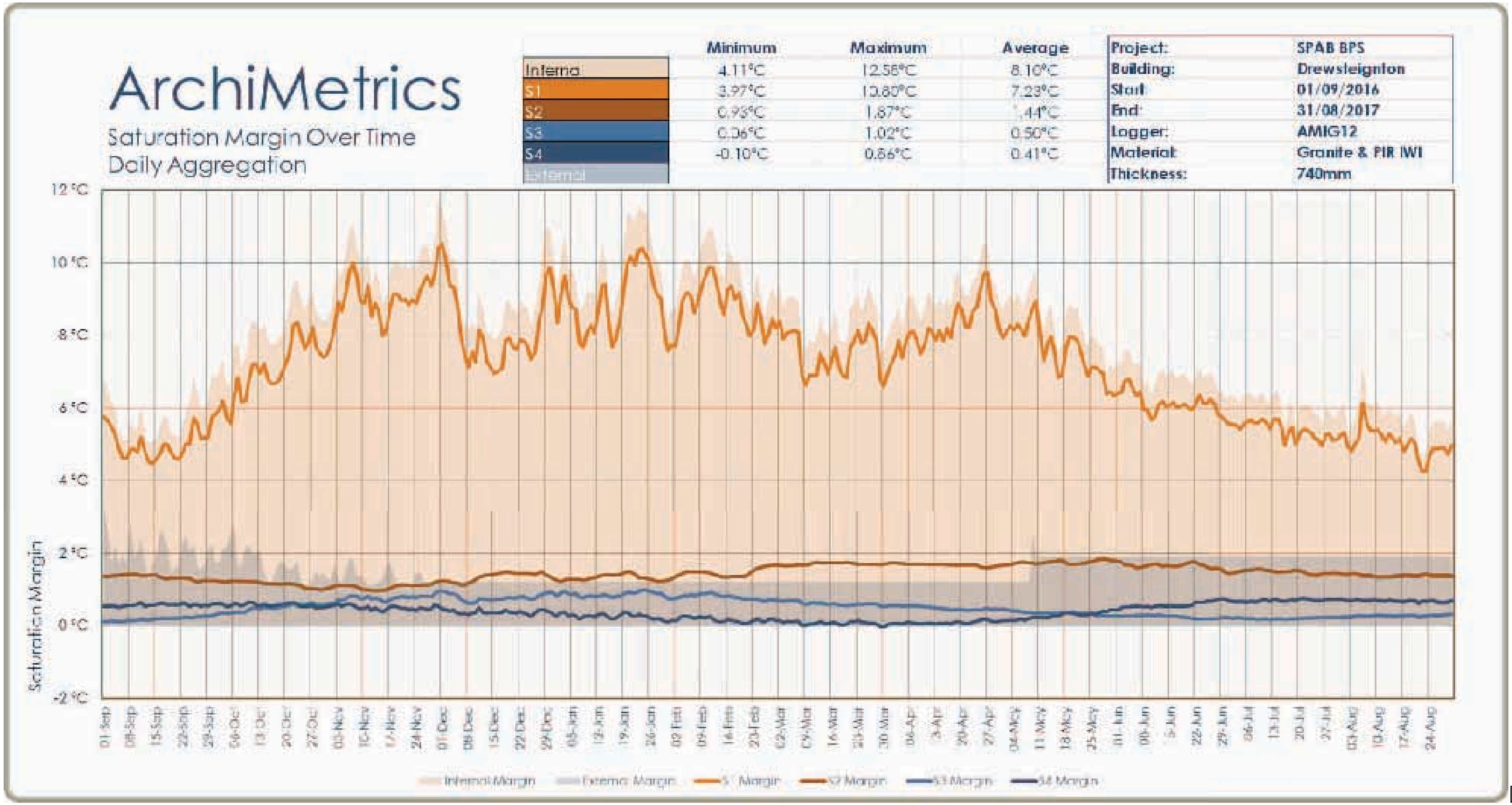

Figure 27. Saturation margin over time, Mill House, Drewsteignton, 2016-2017.

Drewsteignton Monthly Saturation Margin Averages						
	Internal	**S1**	**S2**	**S3**	**S4**	**External**
2016						
Sep	5.76	5.02	1.34	0.19	0.57	2.04
Oct	8.10	7.01	1.15	0.49	0.57	1.69
Nov	10.00	9.03	1.08	0.77	0.50	1.32
Dec	9.12	8.15	1.35	0.78	0.37	
2017						
Jan	9.93	8.93	1.32	0.86	0.26	
Feb	9.69	8.77	1.45	0.79	0.17	
Mar	8.45	7.50	1.70	0.61	0.07	
Apr	9.16	8.26	1.68	0.49	0.09	
May	8.40	7.61	1.75	0.35	0.27	
Jun	6.91	6.13	1.66	0.25	0.58	
Jul	6.08	5.39	1.48	0.21	0.70	
Aug	5.73	5.04	1.39	0.28	0.69	
Average	**8.10**	**7.23**	**1.44**	**0.50**	**0.41**	

Table 15. Monthly saturation margin averages, Mill House, Drewsteignton, 2016–2017.

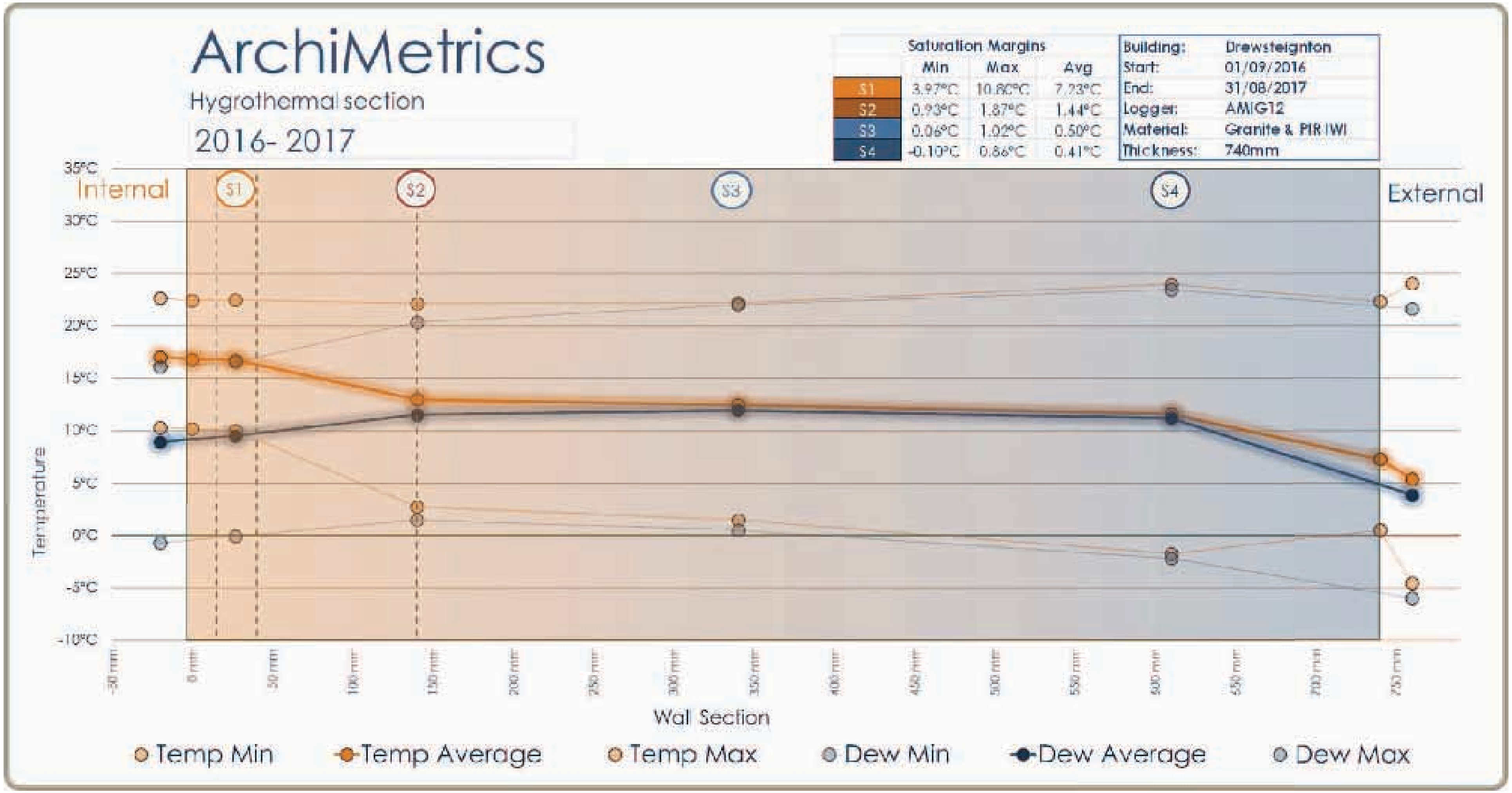

Figure 28. Hygrothermal section, Mill House, Drewsteignton, 2016–2017 (capped).

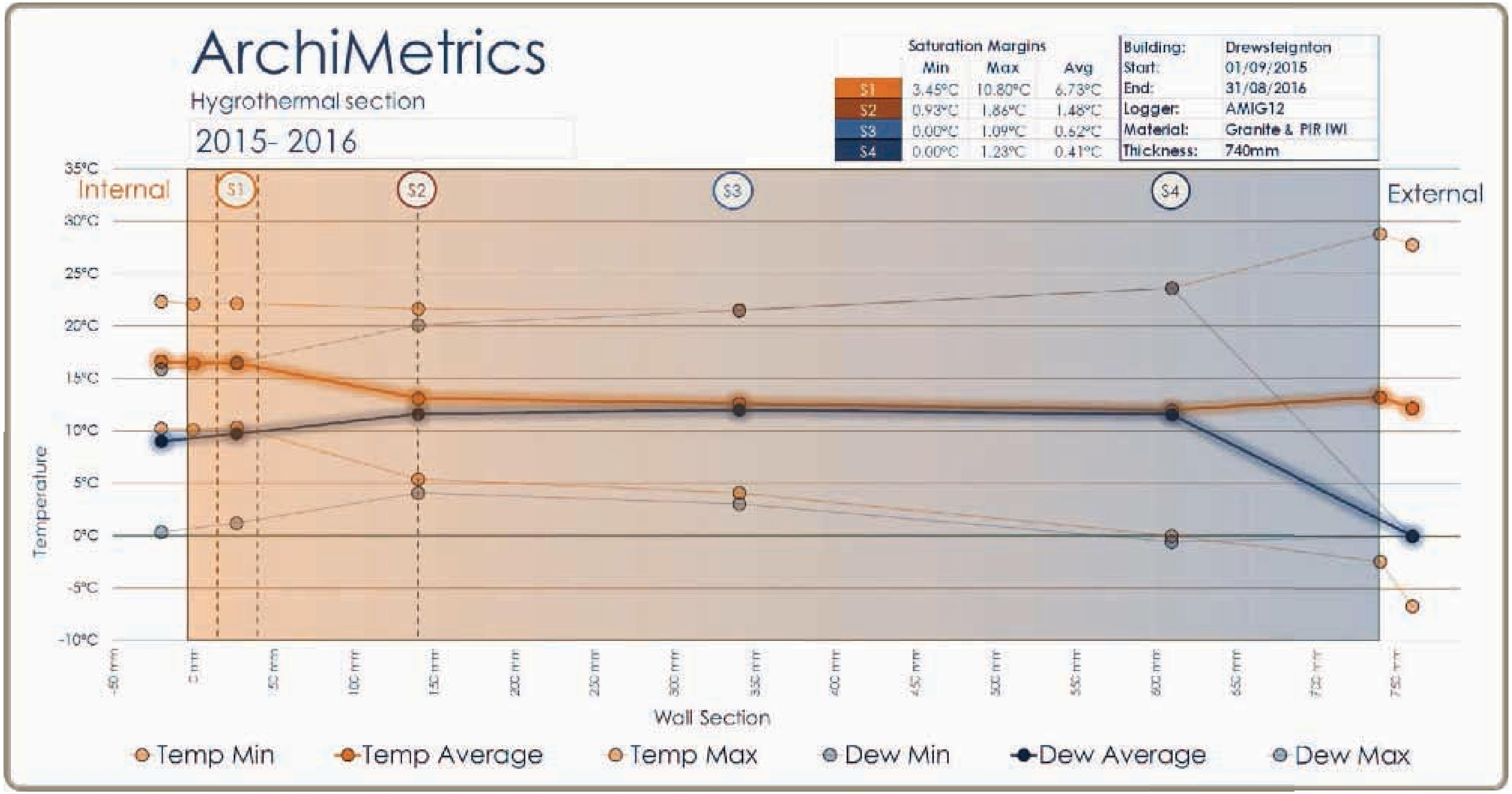

Figure 29. Hygrothermal section, Mill House, Drewsteignton, 2015–2016 (capped).

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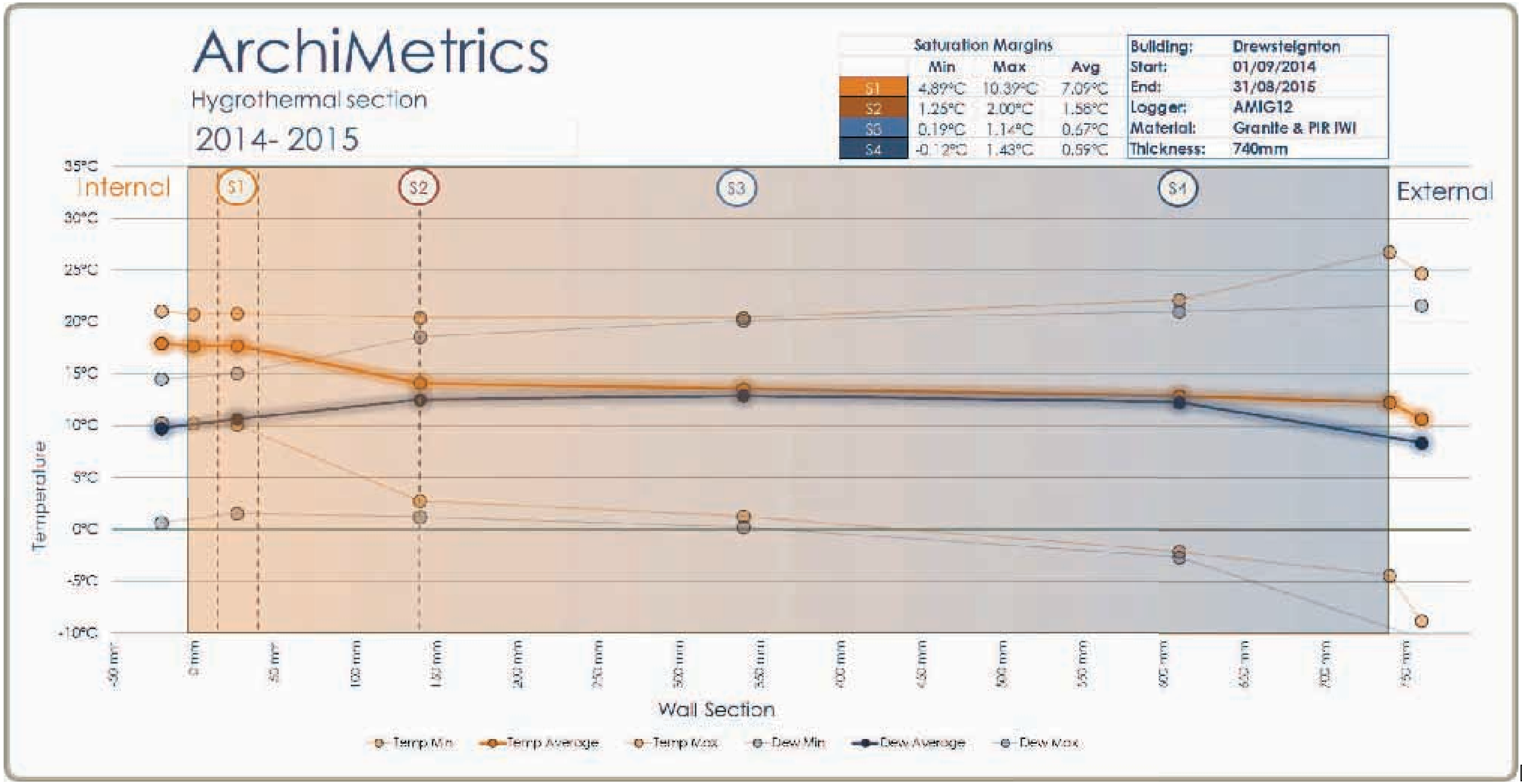

Figure 30. Hygrothermal section, Mill House, Drewsteignton, 2014–2015 .

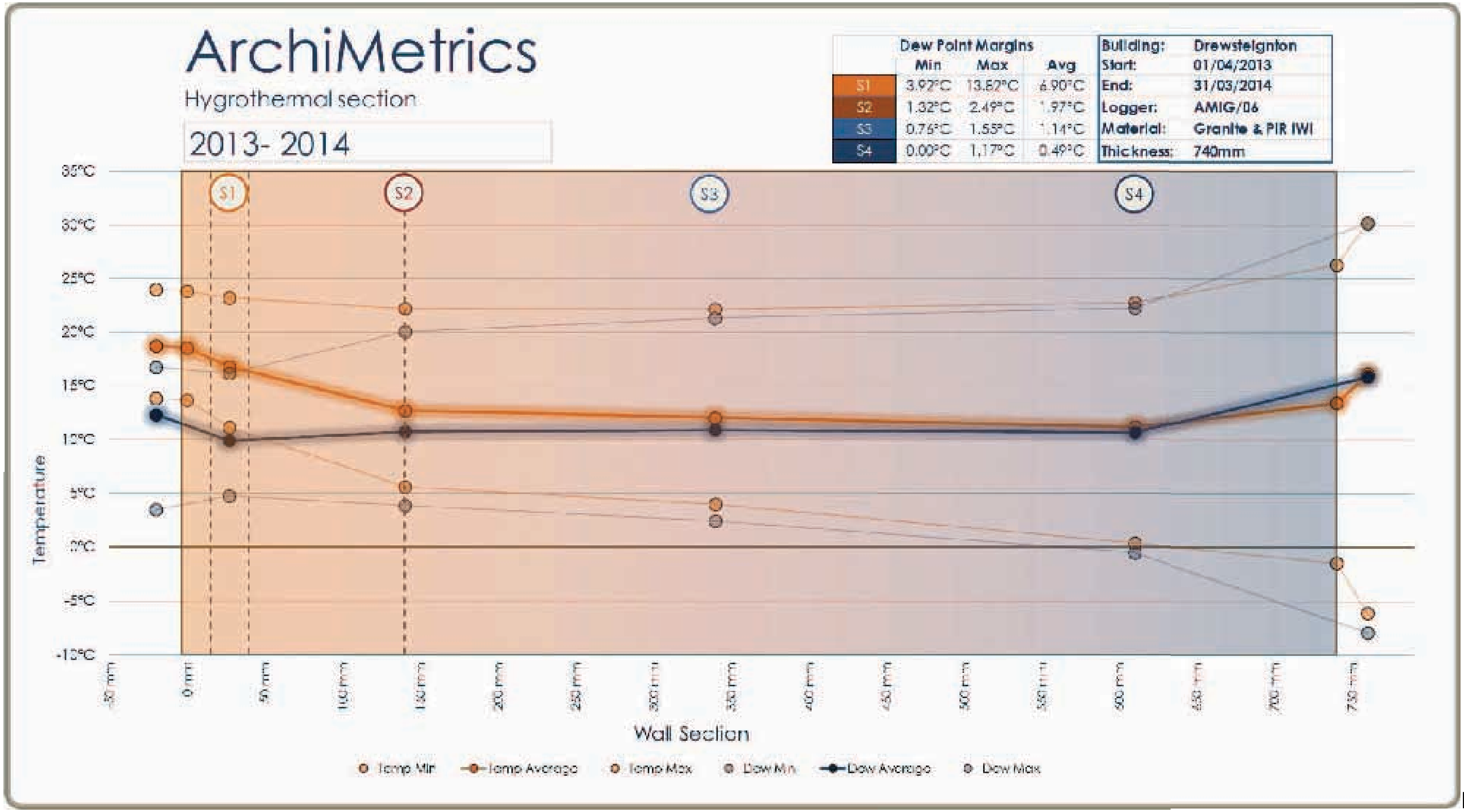

Figure 31. Hygrothermal section, Mill House, Drewsteignton, 2013-2014.

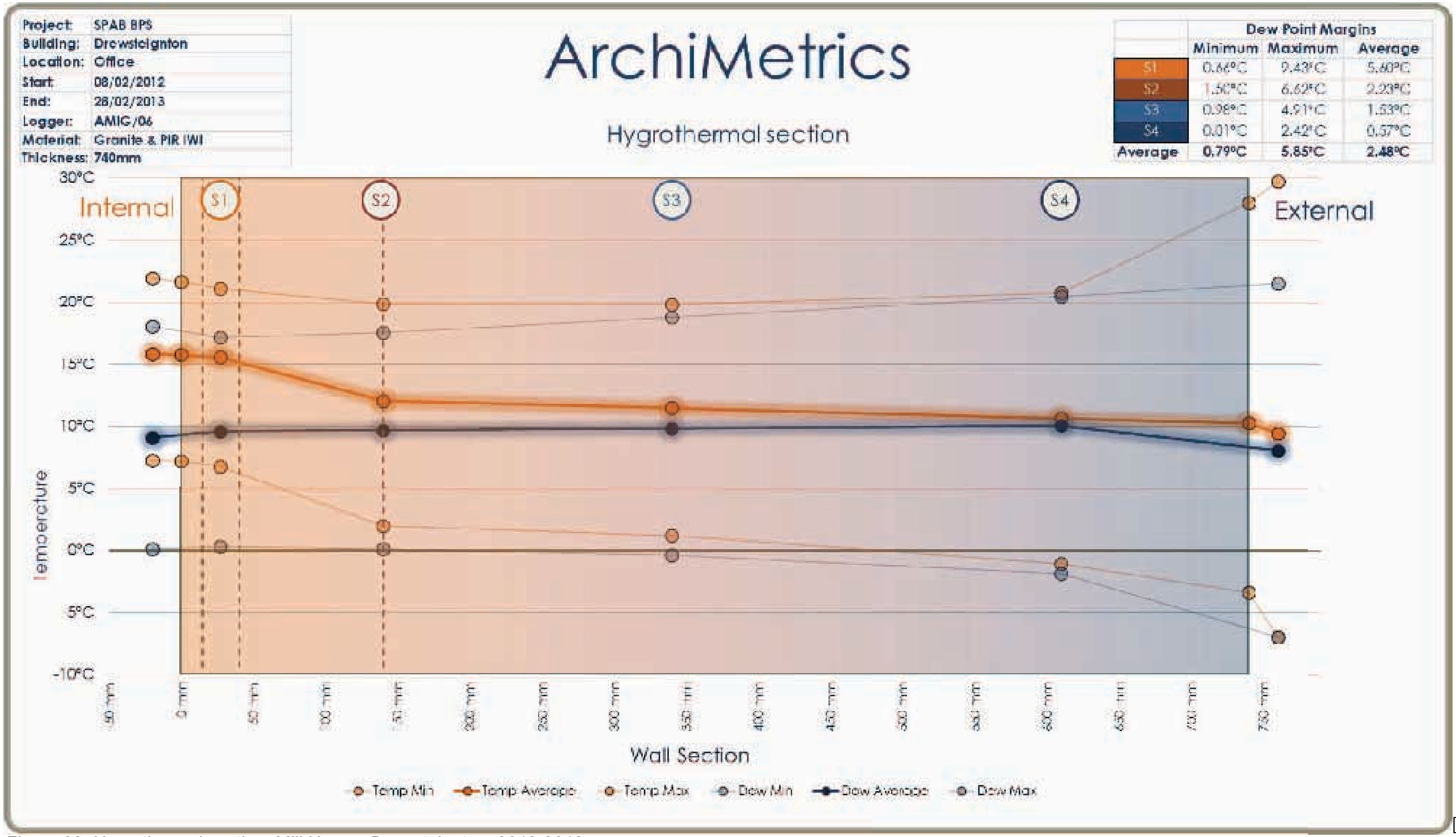

Figure 32. Hygrothermal section, Mill House, Drewsteignton, 2012-2013.

Material Moisture

The wall at Drewsteignton has higher % moisture measurements than that of Shrewsbury. This year, 2016-17, the annual average %MC for the granite wall - 0.99% - is more than double that at Shrewsbury, 0.43%

There are some interesting variations between this year's analysis, Figure 33, and those of the previous two years. The most striking being the different responses plotted for sensor 2 across the three years. In the first year, Figure 35, the range of %MC measurements recorded by sensor 2 was 0.71–1.65%, the average %MC over the year being 1.09%. In the second year of measurements, 2015–16, Figure 34, the range had narrowed, 0.50–1.10% and the average %MC was roughly half that of the previous year, 0.57%. This year, 2016 -17, the range is much wider again, 0.53–2.68% with the highest average value yet, 1.58 %MC.

Previously, we had ascribed some of the responses measured in the first year of material moisture monitoring to the presence of moisture introduced into the fabric during the placement of sensors, which are embedded in lime mortar. A general decline in %MC can be seen across sensors 2 and 4 through the first year's analysis and this might explain why at sensor 2 (and sensor 4) conditions appear 'drier', i.e. record a lower %MC in the second year as compared with year one. (There is also possibly a period of 'drying' which takes place at sensor 3 in the first year, where, until December 2014 %MC declines following the installation of sensors. However, from January 2015 onwards %MC starts to rise at this location, suggesting that the sensor from this time on is in equilibrium with surrounding wall materials and readings are now no longer influenced by moisture introduced during installation.)

In September 2016, a rapid spike in %MC readings is recorded at sensors 1 and 2. %MC at sensor 1 quickly reduces back to its previous ≈ 0.5% level following this, but %MC at sensor 2 remains higher, between 1–2% for most of the remaining analysis period. Coinciding with this peak, a service visit was paid to the property where the individual moisture measurement nodes were tested. This procedure involves the use of a resistance meter using a slightly higher voltage than that used by the logging unit and seems to have altered the state of the sensors in some way. Therefore, the change we see occurring in particular at sensor 2 from this time on is a result of the recovery of measurements rather than reflective of a change in moisture conditions within the wall. Importantly, it would seem that after this visit. the traces recorded at sensor 2 follow explicable patterns, driven largely by temperature, and are often compatible, if somewhat lower, than those measured at sensor 3.

Figure 33 illustrates that moisture conditions within the centre of the wall are higher than those towards the internal and externals surfaces, which is explicable as in theory greater evaporation takes places across these surfaces than can be achieved within the centre of the wall. Specifically, with regard to sensor 1, the moisture trace at this location is low, on average 0.58%, but probably not because of its proximity to an evaporative surface. This sensor is embedded within the PIR hydrophobic closed-cell foam material which insulates the wall. This material is encased in a foil moisture barrier and conditions within it could be expected to be 'dry'.

Sensor 4, on average, measures a slightly lower %MC content throughout the year, 0.53%, than that of sensor 1 and this could be due to its proximity to external conditions. Vapour records, factored as RH, show this section of the wall to have the highest annual average RH, 97%, but AH averages are lower here than those found for sensors 2 and 3, deeper within the wall. The vapour records can be an indication of evaporative activity from moisture within the substrate and high RH at this location is likely to be a product of vapour production and low temperatures, which over winter, in particular, will raise RH in proximity to external conditions. That records of AH are lower may suggest that less moisture is present here overall in comparison with that deeper within the wall as a result of more productive cycles of evaporation from the external wall face during the warmer months. In this way, the %MC measured at sensor 4 may remain quite low, whilst at different times of the year, vapour records may be quite high. The %MC measurements from sensors 2 and 3 show some accord with the vapour picture for the wall, where weights of vapour are higher and the long-term RH trend continues to increase. The %MC analysis shows peaks of %MC occurring alongside peaks in temperature, particularly noticeable around the June mini-heat wave. This suggests that during these times, which also often see peaks in vapour production, moisture is drawn through the substrate driven by the process of vaporisation and raising %MC accordingly.

However, there is a noticeable discrepancy between the high RH records for the wall at Drewsteignton and those of %MC which remain quite low. As has been previously noted, %RH is continuously high in the masonry section of the wall, well above the 80% mould risk threshold, whereas the peak %MC value recorded is 2.78%, which even for a heavyweight material such as granite may not really be considered to be 'wet', if, indeed, it is possible for granite to be wet. An explanation as to the difference may lie in the particular qualities of the granite wall. 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. 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 more permeable 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. Thus, in a wall constructed of granite blocks bedded in lime mortar, depending to some extent on the placement of sensors, it might be possible to measure relatively low material moisture contents whilst simultaneously deriving high records of vapour.

Annual Average %MC	**Sensor 1** %MC	**Sensor 2** %MC	**Sensor 3** %MC	**Sensor 4** %MC	**Average** %MC
Drewsteignton					
2014-2015	0.55	1.09	1.63	0.82	1.02
2015-2016	0.57	0.57	1.81	0.51	0.86
2016-2017	0.58	1.27	1.58	0.53	0.99

Table 16. Comparison of annual averages of %MC measured through wall section, Drewsteignton 2014-2017

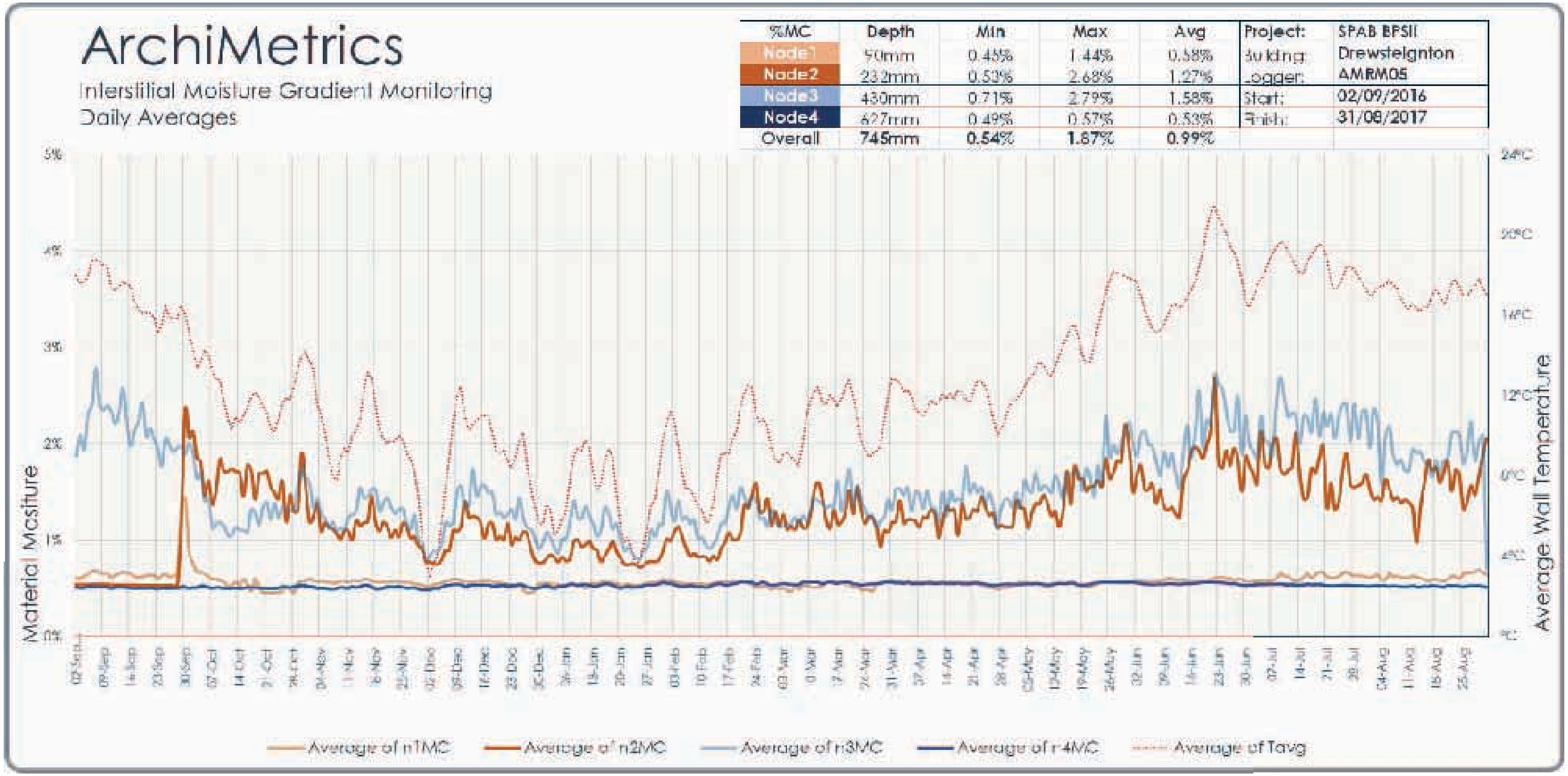

Figure 33. Material moisture content over time, Mill House, Drewsteignton, 2016-2017.

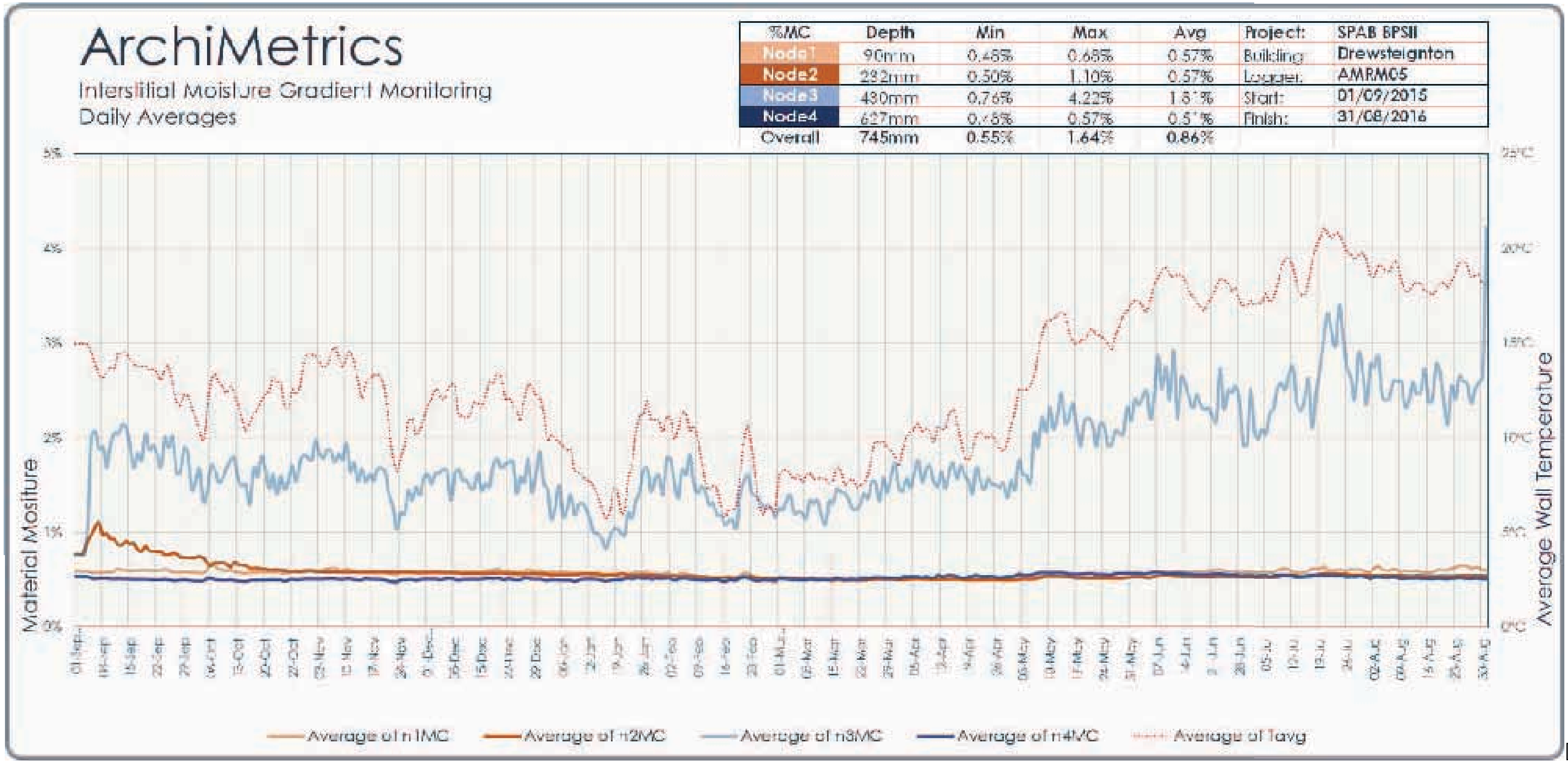

Figure 34. Material moisture content over time, Mill House, Drewsteignton, 2015-2016.

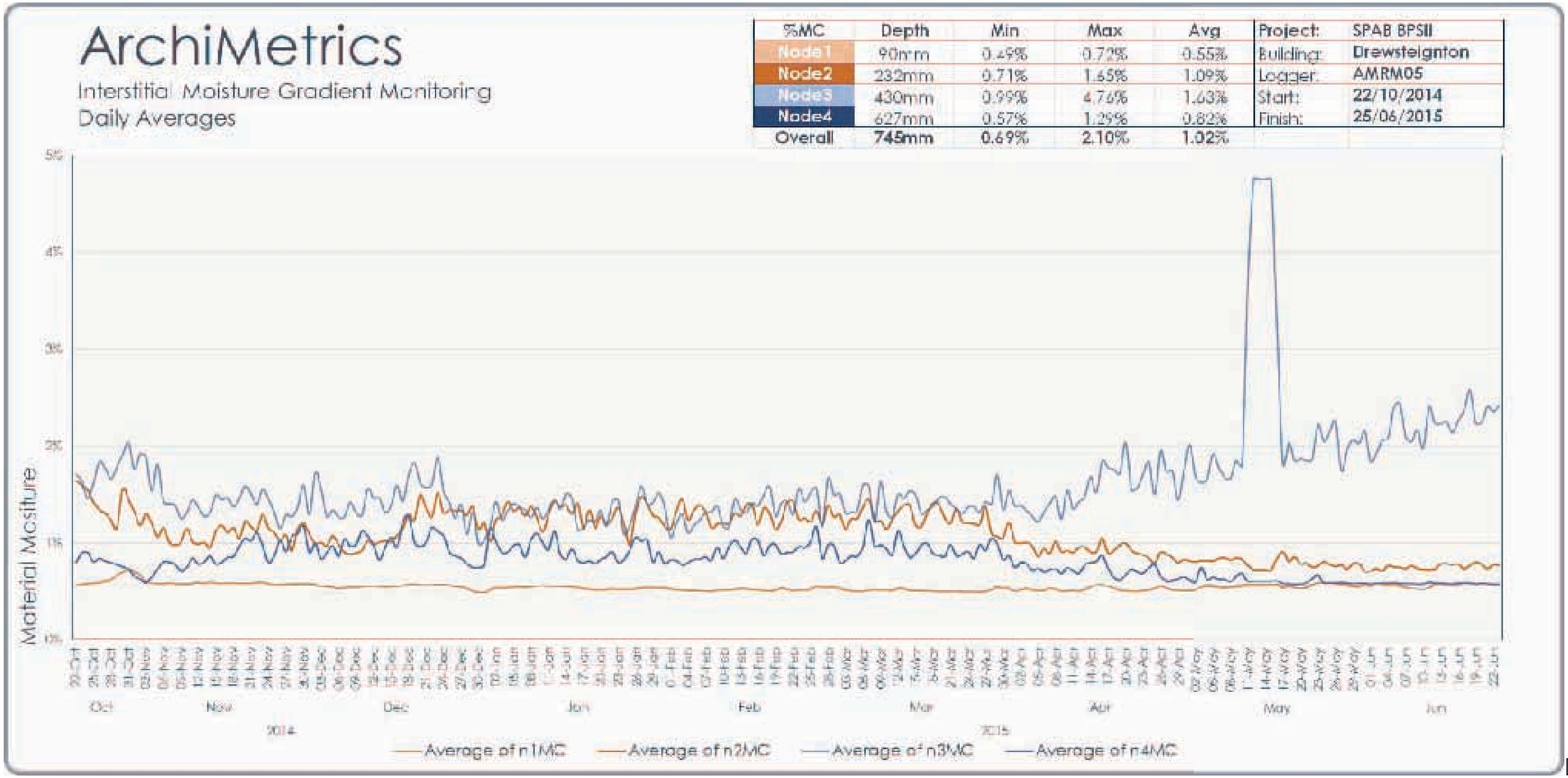

Figure 35. Material moisture content over time, Mill House, Drewsteignton, 2014-2015.

2.3. The Firs, Riddlecombe, Devon - 2016-17.

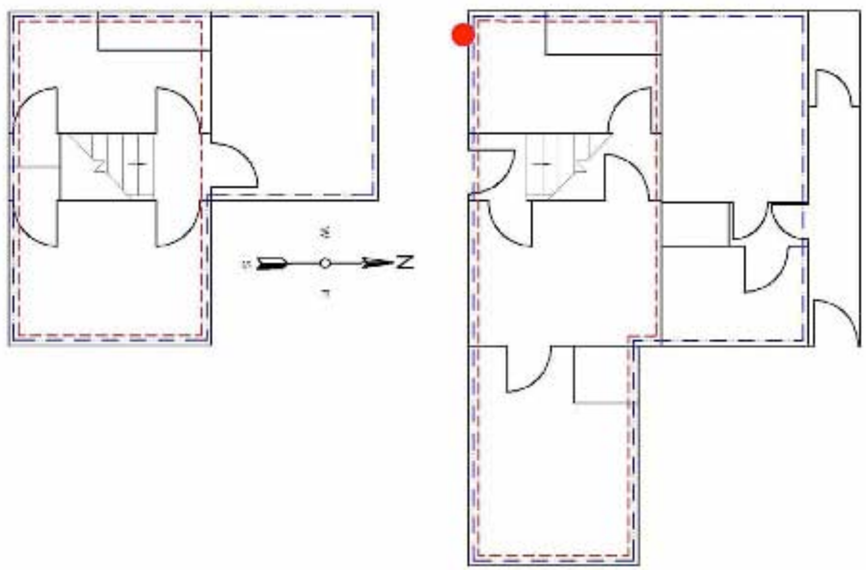

Figure 36. Plan of The Firs, Riddlecombe (ground floor on right hand side). Location of monitoring equipment shown by red dot.

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 airtightness detailing through the house.

Occupancy: Family of 5.

Floor Area: 86 m^2

Wall Condition Monitoring

Figure 37. Interstitial hygrothermal gradient and material moisture monitoring, Riddlecombe.

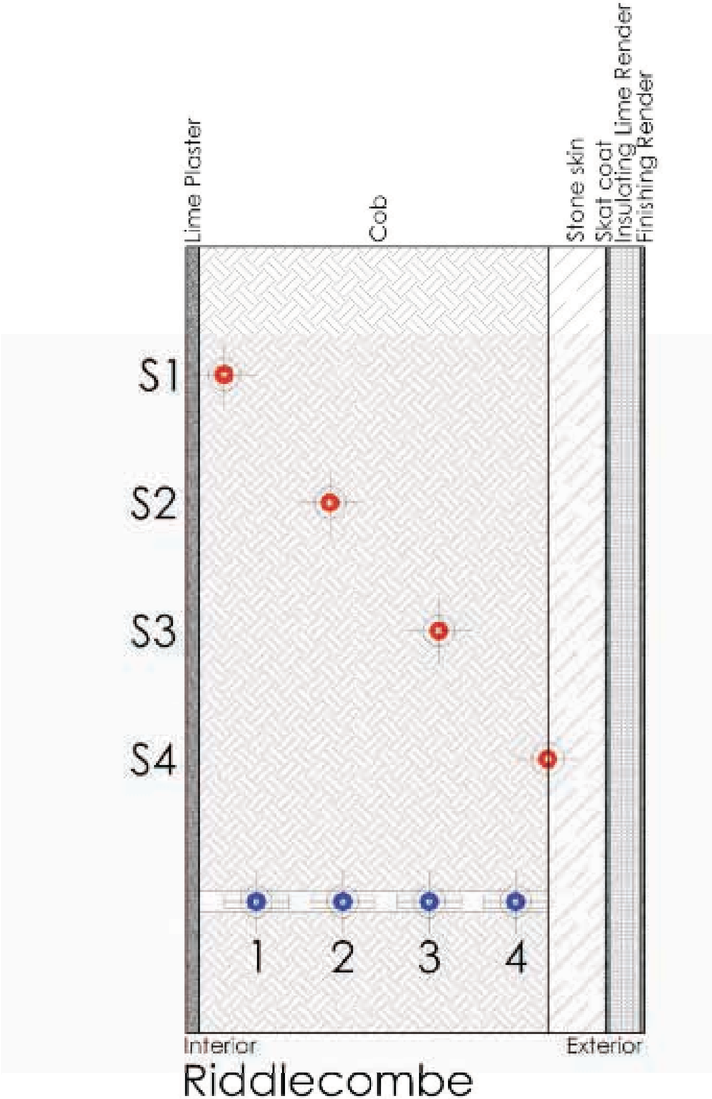

Figure 38. Position of sensors through wall section, Riddlecombe.

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 37 and 38). Combined temperature and relative humidity sensors are located at four points within the wall at heights and depths given in Table 17. 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 17. 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 2016–31st August 2017, has been used as the basis for the following analysis.

Relative Humidity Over Time

Figure 39 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 when factored as an average through the whole wall section 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.

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 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). This pattern is still in evidence in this 2016-17 analysis, which includes an example of peaks in RH at sensors 1–3 around 22nd June triggered by high external temperatures during the 'mini heat wave'. 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.

Overall, the annual average RH table, Table 18 does show a diminishing tendency which continues into this year for sensors 1 and 2. However, averages at sensors 3 and 4 remain unchanged from those of the previous year, 2015 -16, suggesting little change in this part of the wall.

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 continue to be above this threshold. Sensor 4 is above 100% which suggests 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 may be 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 from the external surface around sensor 4 causing moisture to accumulate. Is it also possible that if vapour is unable to exit at sufficient speed from the external side of the wall, vapour could also begin to accumulate further back toward sensors 3. Could this then be the reason that this year we see little change in the annual average RH recorded for sensors 3 and 4?

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%
2016-2017	76%	88%	95%	112%

*Table 18. Comparison of annual averages of RH measured through wall section, Riddlecombe 2013-2017. *Capped at 100%.*

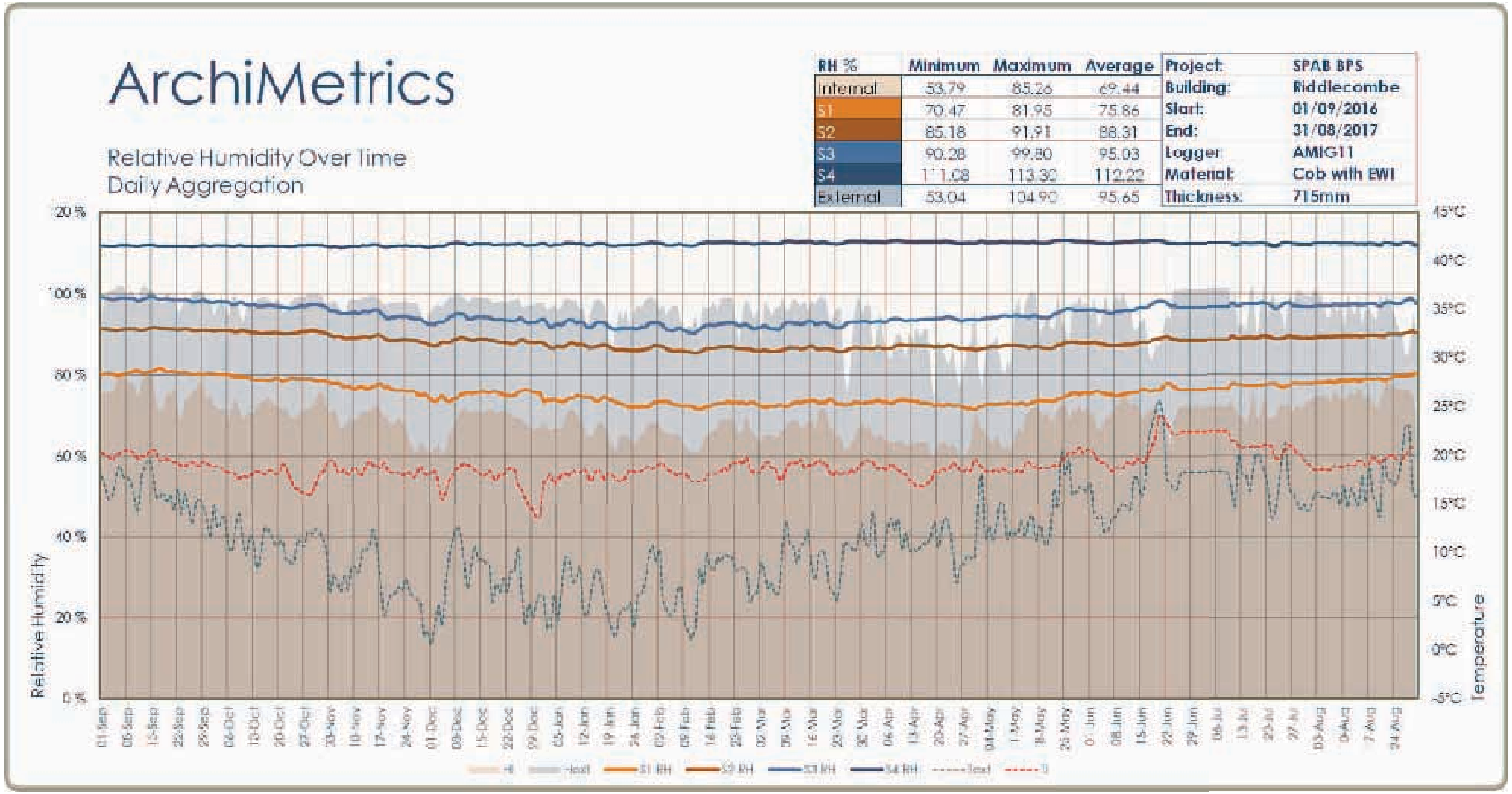

Figure 39. Relative humidity over time, The Firs, Riddlecombe 2016-2017.

Riddlecombe Monthly RH Averages						
	Internal RH	**S1 RH**	**S2 RH**	**S3 RH**	**S4 RH**	**External RH**
2016						
Sep	76.11	80.61	91.34	98.66	111.78	99.64
Oct	71.97	79.27	90.70	97.24	111.78	97.82
Nov	68.51	76.82	89.05	94.88	111.66	97.60
Dec	68.42	75.24	88.27	93.67	112.10	98.15
2017						
Jan	66.69	73.59	86.85	92.31	112.15	96.01
Feb	65.86	72.91	86.36	91.89	112.31	95.61
Mar	66.54	73.05	86.33	92.44	112.58	95.07
Apr	63.29	73.05	86.89	93.56	112.71	86.92
May	68.43	73.69	87.17	94.77	112.74	91.89
Jun	70.81	76.10	88.15	96.45	112.61	95.50
Jul	71.67	77.13	88.90	97.01	112.16	98.22
Aug	74.83	78.71	89.58	97.35	112.15	95.22
Average	**69.44**	**75.85**	**88.31**	**95.03**	**112.23**	**95.65**

Table 19. Relative humidity monthly averages, Riddlecombe, 2016-2017.

Absolute Humidity Over Time

Figure 40 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. This analysis shows a similar trend to that remarked on in previous reports for all walls in the study, ie 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 previously 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 and the warmth increases the amount of vapour measured in the air in the wall in proximity to internal conditions. (A similar phenomenon is seen to a lesser degree at Shrewsbury, Figure 9.) An inversion of this phenomenon can be noted around 29th December, where, for a short period the internal space was not heated. Over this time, weights of vapour measured by all four sensors through the wall section are quite similar before heat is restored again. The resumption of internal space heating causes an increase in AH at sensors 1 and 2 on the internal side of the wall and greater differentiation in measurements of AH through the section as a whole.

As was seen last year, 2015-16, there is a brief period in spring, at the end of March/beginning of April, when quantities of vapour are similar throughout the measured section before a summertime pattern begins to emerge and measurements towards the external side of the wall now show the highest weights of vapour. But, for a time, quantities of vapour are very similar within the centre of the wall, between sensors 2 and 3, until mid-May when a fully differentiated pattern emerges where weights of vapour are arranged through the section in relation to sensor proximity to external conditions. It is during the period April-May that vapour quantities in the wall appear much greater than those recorded either internal or externally. Peaks of vapour are provoked by peaks in external temperatures, but these peaks are quite dramatic and far in excess of those of the AH measured in the external environment suggesting evaporation of moisture bound within materials is taking place during this time. Responses are more extreme towards the external side of the wall which, being south-facing, receives direct solar radiation over the summer provoking a stronger vapour responses. The highest peaks for the year coincide with peaks in external temperature. These peaks also show higher weights of vapour within the wall than from the surrounding environment and suggest that vaporisation from damp materials continues to take place. The heat wave around 22nd June is particularly noticeable for this effect. Throughout the summer months, the homogeneity of the wall can be seen in the similarity of the plots between the four sensors.

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. This is the first year, since refurbishment measurements began where a decrease in average weights of vapour is recorded from all four sensor positions within the wall. This continues and extends the trend seen in the previous year, 2015–16, where three of the four sensors showed lower weights of vapour than those of the previous year, 2014-15. If weights of vapour are falling throughout the section, this might perhaps might be a reflection of the drying of construction moisture within the earthen material itself, i.e. that vaporisation over the preceding years has lead to a reduction in the moisture available for evaporation. It also perhaps suggests, that despite the evidence of a stasis with regards to RH levels towards the external side of the cob wall, that there has been a general reduction to the moisture load of the wall.

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
2015-2016	12.02 g/m^3	12.87 g/m^3	12.60 g/m^3	13.05 g/m^3
2016-2017	11.86 g/m^3	12.68 g/m^3	12.47 g/m^3	12.97 g/m^3

Table 20. Average absolute humidity, The Firs, Riddlecombe, 2012-2017.

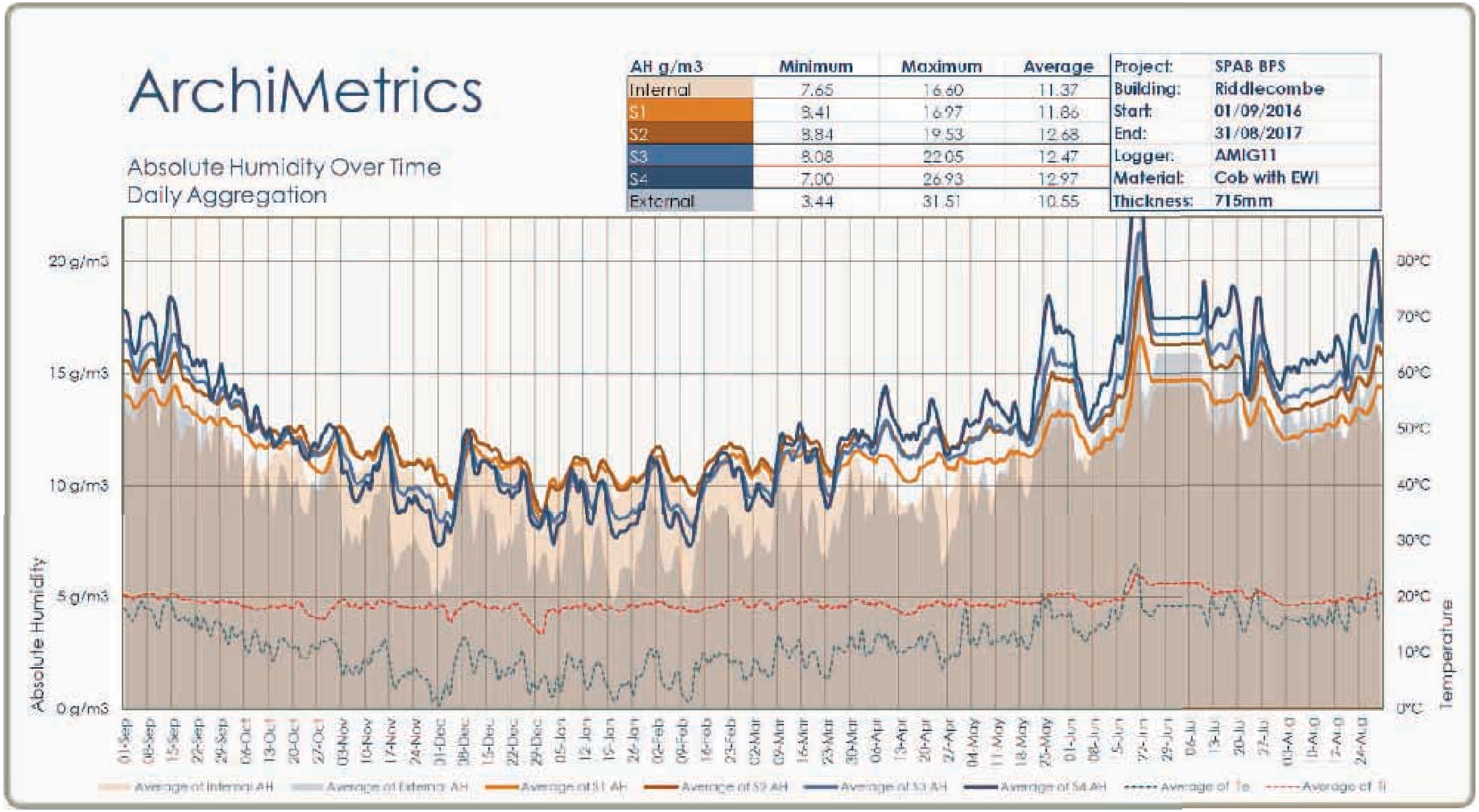

Figure 40. Absolute humidity over time, The Firs, Riddlecombe, 2016-2017.

Riddlecombe Monthly AH Averages						
	Int AH	S1	S2	S3	S4	Ext AH
2016						
Sep	13.01	13.58	14.80	15.33	16.28	14.14
Oct	11.03	11.76	12.49	12.32	12.57	10.34
Nov	10.91	11.47	11.54	10.48	9.92	7.84
Dec	10.24	10.56	10.88	9.97	9.80	7.84
2017						
Jan	10.31	10.46	10.45	9.29	8.96	6.92
Feb	10.42	10.67	10.97	9.90	9.70	7.50
Mar	10.72	10.97	11.47	10.72	10.97	8.62
Apr	9.97	10.97	12.01	11.79	12.53	8.89
May	11.27	11.67	12.91	13.10	14.26	11.52
Jun	12.84	13.45	14.98	15.71	17.15	14.39
Jul	13.24	13.90	15.43	16.04	17.09	14.69
Aug	12.41	12.81	14.08	14.83	16.29	13.83
Average	**11.37**	**11.86**	**12.67**	**12.46**	**12.96**	**10.55**

Table 21. Absolute humidity monthly averages, Riddlecombe 2016-2017.

Saturation Margins

Figure 41 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, -1.84˚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, once again increased to 0.73˚C from that of the two previous years, 0.68˚C and 0.52˚C.

A comparison of previous year's capped saturation margins, including a calculation of the difference between post-refurbishment margins and those calculated pre-refurbishment, is presented in Table 22. 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**
2016–2017 (1/9/15-31/8/16	4.28˚C	1.89˚C	0.79˚C	0.00˚C	1.74˚C
Difference	**1.29˚C**	**1.33˚C**	**1.27˚C**	**0.6˚C**	**1.12˚C**

Table 22. Saturation margins and pre- and post-insulation difference, The Firs, Riddlecombe, 2011–2017 (2015-2017 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 42 - 45). 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 reduction in %RH and AH measured within the wall, these changes indicate an improvement in the vapour profile for the cob wall at Riddlecombe.

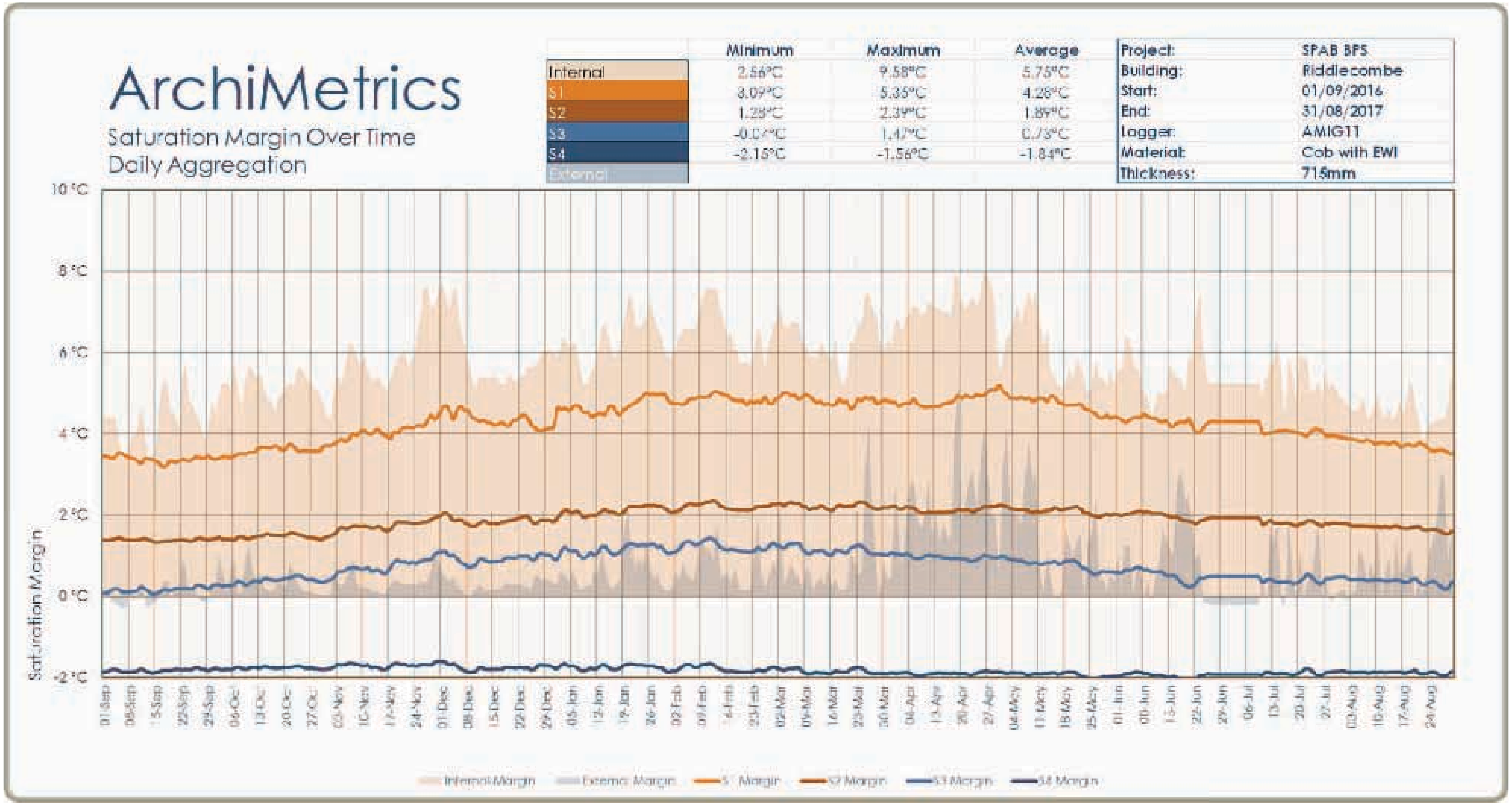

Figure 41. Saturation margin over time, The Firs, Riddlecombe, 2016-2017.

Riddlecombe Monthly Saturation Margin Averages					
	Internal	S1	S2	S3	S4
2016					
Sep	4.35	3.37	1.38	0.15	-1.83
Oct	5.14	3.57	1.46	0.37	-1.77
Nov	5.93	4.06	1.74	0.74	-1.71
Dec	5.90	4.35	1.86	0.93	-1.76
2017					
Jan	6.31	4.69	2.10	1.14	-1.75
Feb	6.52	4.85	2.20	1.22	-1.79
Mar	6.38	4.83	2.22	1.14	-1.85
Apr	7.12	4.84	2.13	0.97	-1.90
May	5.97	4.74	2.10	0.78	-1.93
Jun	5.51	4.30	1.96	0.51	-1.96
Jul	5.33	4.10	1.83	0.42	-1.90
Aug	4.59	3.73	1.69	0.37	-1.88
Average	**5.75**	**4.28**	**1.89**	**0.73**	**-1.84**

Table 22. Average monthly saturation margins, The Firs, Riddlecombe, 2016-2017.

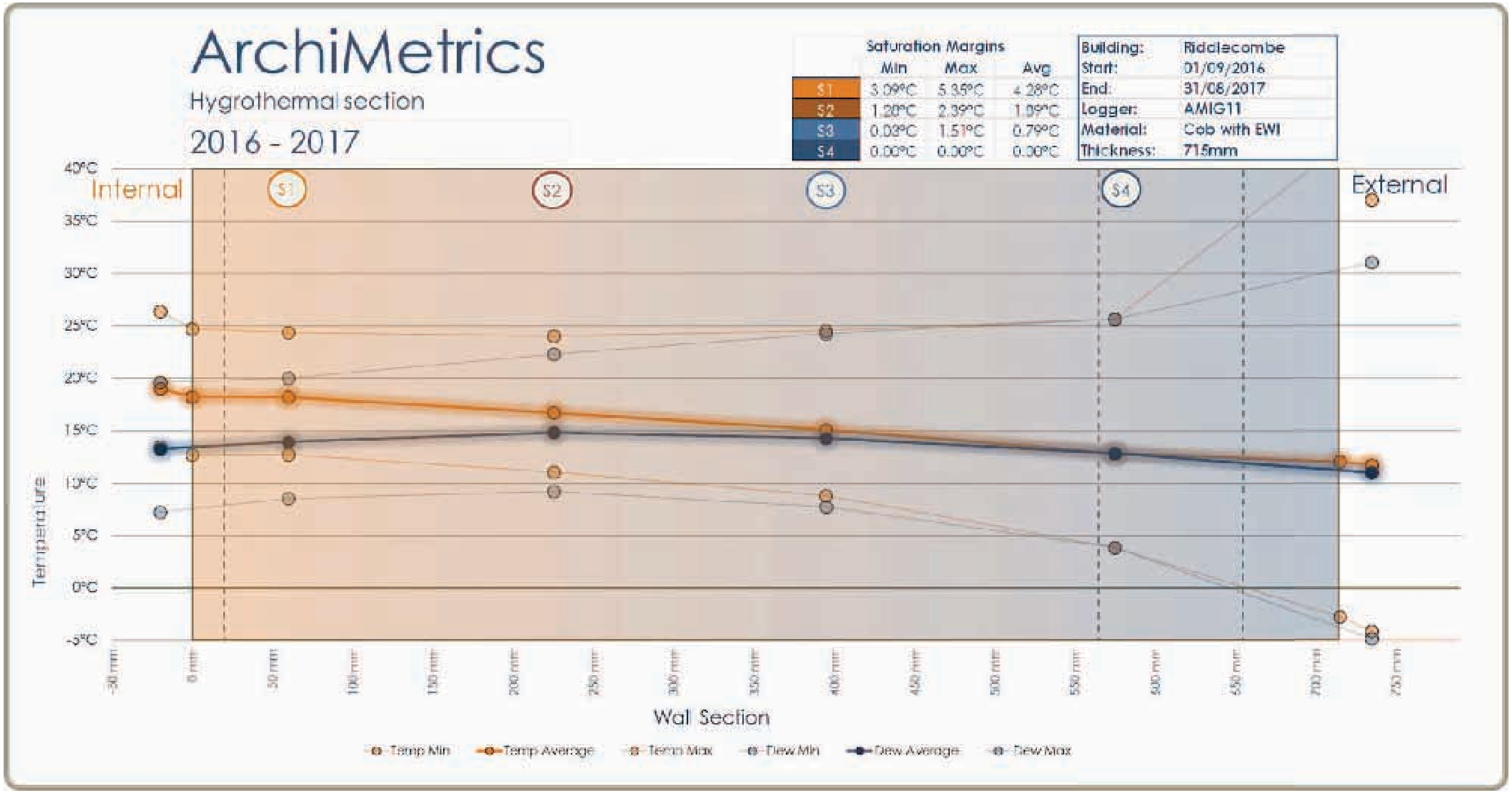

Figure 42. Hygrothermal section, The Firs, Riddlecombe, 2016-2017.

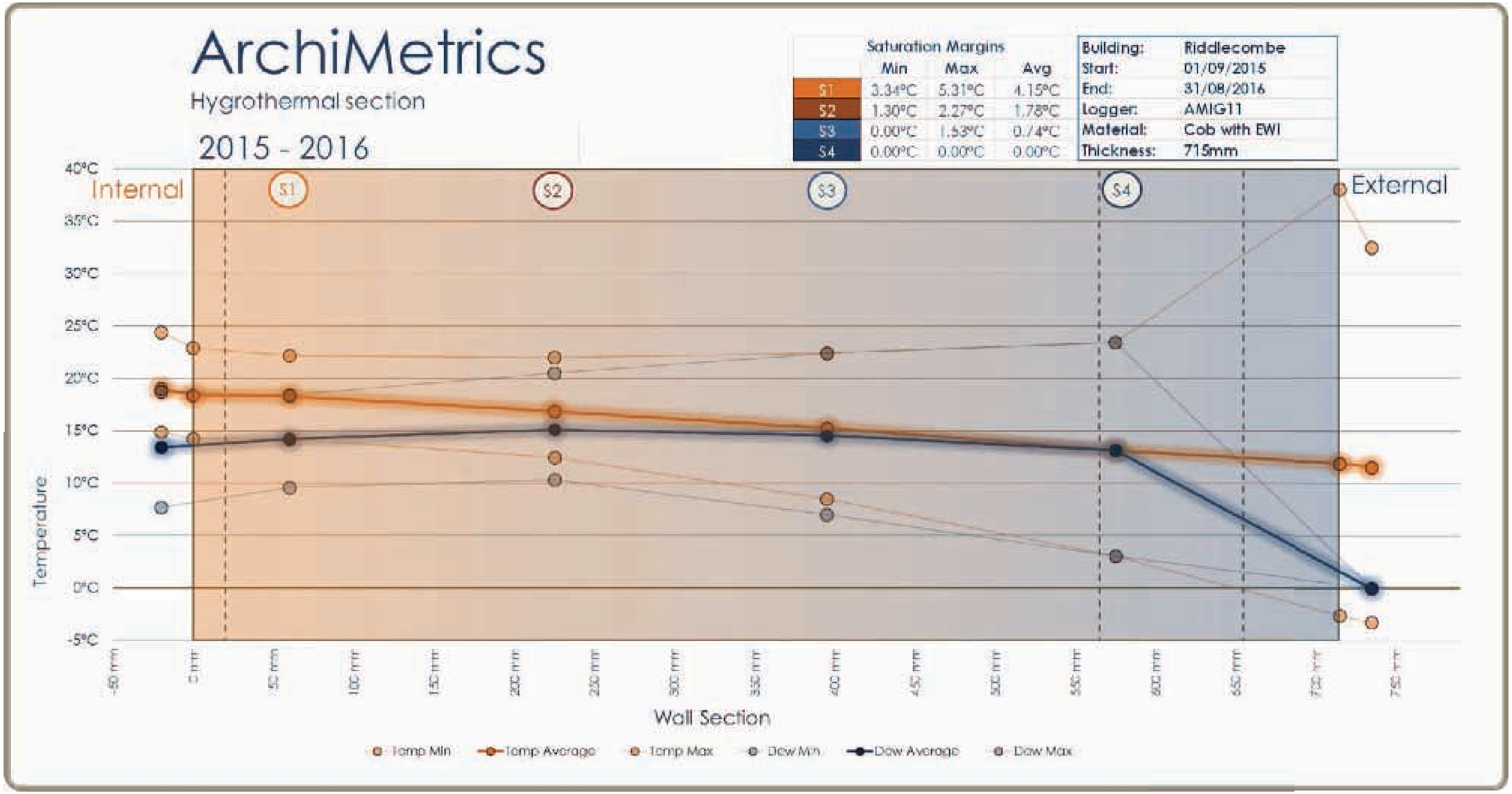

Figure 43. Hygrothermal section, The Firs, Riddlecombe, 2015-2016.

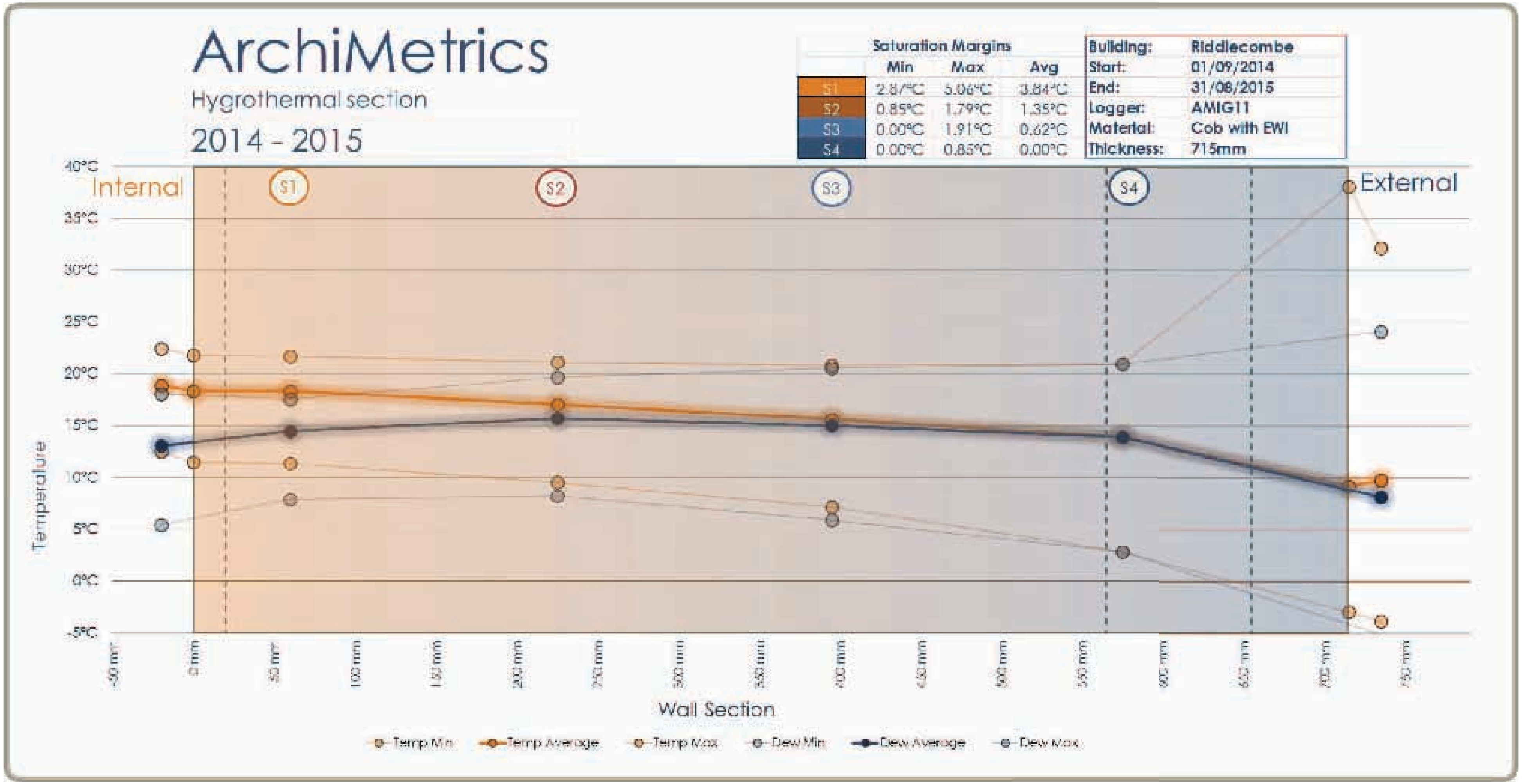

Figure 44. Hygrothermal section, The Firs, Riddlecombe, 2014-2015.

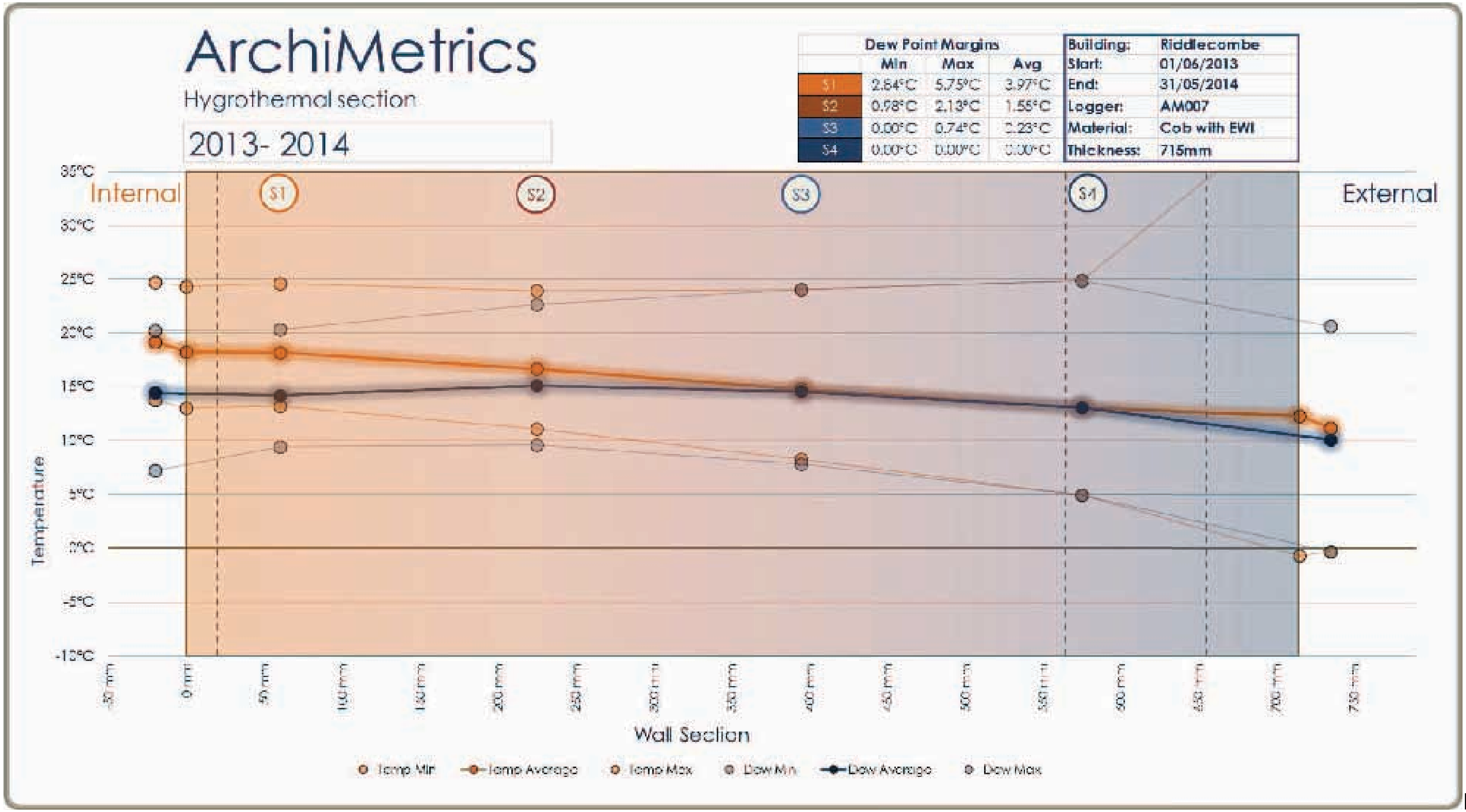

Figure 45. Hygrothermal section, The Firs, Riddlecombe, 2013-2014.

Material Moisture

Figures 46, 47 and 48 present an analysis of %MC in the wall at Riddlecombe over the past three years. The cob wall at Riddlecombe has the highest records of %MC of the three walls in the study. However, the annual average recorded from all sensors in the wall at Riddlecombe, for 2016 -17, 1.04 %MC is only slightly greater than that of Drewsteignton, 0.99 %MC, which in turn is more than double that of Shrewsbury, 0.43 %MC (Table 23). However, for a second year now, this year's average 1.04 %MC has reduced from that found for the previous year. 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.

Figure 46, the 2016-17 analysis is somewhat different from those of the previous two years. Sensor 1 measurements, which have always found the highest %MC of all the sensors through the wall section, shows a much greater range of %MC through the year and a higher annual average, 2.27 %MC. Sensors 2–4, though, mostly record %MC below 1%, with averages between, 0.56–0.78% MC. Sensors 2 and 3, towards the centre of the wall show very low %MC through the year and measurements from sensor 4, towards the external side of the wall are at a similarly low level, if slightly higher, particularly over the winter months. For the 2015 - 2016 recording period ,we noted in July 2016 a peak drying event which occurred during some high summer temperatures for the wall at Riddlecombe. We speculated that it would be interesting to see whether moisture quantities continue to decrease following this. It does indeed seem that from this point on moisture quantities at sensors 2–4 have remained quite low, the average %MC for sensor 4 being nearly half what it was in the previous year.

With the move into spring, where from the vapour record we think we have increased amounts of vaporisation occurring, we see levels of %MC rise in both sensor 1 and to a lesser extent in sensor 4, although they continue to be stable at sensors 2 and 3. The mini-heat wave in June, which has been a point of note throughout this report, produces a dramatic effect at sensors 1 and 4 (a muted response can also be seen at sensors 2 and 3). Here, as with the wall at Drewsteignton, the internal and external heat spike creates accelerated evaporation within the wall and concentrations of moisture in layers of substrate closest to the heat source and evaporative surfaces.

Once again, that records of RH are so high in this wall whilst %MC appears to be quite low (although what constitutes high %MC for cob material may be difficult to define) could be a puzzle. As with Drewsteignton, these peculiarities may be down to the features of particular building materials. Cob is considered to be hygroscopic and thus in theory has a high moisture capacity. Year-on-year %MC has reduced through the wall section, which does possibly lend credence to the theory that the wall is slowly evaporating excess construction moisture added during the application of the new insulating render to the external wall surface. The RH record suggests the wall continues to be at risk but the risk to the structural stability of the unfired earth material as a result of high %MC is not evident.

That the wall has the highest concentrations of moisture towards its internal wall surface is perhaps also not surprising given the nature of the airtight construction, relatively small room volume and high occupancy of the house, in comparison with others monitored in the study. Internally-generated vapour may be of greater quantities here and due to low rates of air exchange dispersed less easily. The room at Riddlecombe has the highest average AH of the three rooms. If it is also the case, posited elsewhere, that the thick external render retards or inhibits the evaporation of moisture vapour to some extent, perhaps moisture migrates towards the internal surface drawn by the improved evaporative potential of the thinner lime plaster finish? We know from observation that the cob at Riddlecombe was wet. We continue to see high vapour measurements made within the wall whilst simultaneously %MC appears quite low and both these quantities, RH/AH and %MC, are reducing year-on-year. Could it be that the wall material's capacity to hold vapour results in high vapour records whilst its %MC might be reducing due to evaporation leading to lower %MC values? The wall is 'buffering' the moisture in the form of vapour leading to less deposition of moisture in its liquid form. This process which is happening within a building element is the same as that often described for other historic building materials (timber, earth and lime plasters) used as internal surface finishes as a means by which moisture is managed in buildings to avoid damage to fabric.

Overall, it would seem from an examination of the years' analyses, Figures 46–48, and the annual average table, Table 23 that - as with the vapour responses (including measurements from sensor 1) - moisture within the fabric, measured as either a vapour or a liquid, continues on a downward trend.

Annual Average %MC	**Sensor 1** %MC	**Sensor 2** %MC	**Sensor 3** %MC	**Sensor 4** %MC	**Average** %MC
Riddlecombe					
2014-2015	3.98	0.63	0.63	1.24	1.86
2015-2016	2.74	0.84	0.59	1.33	1.38
2016-2017	2.27	0.56	0.57	0.78	1.04

Table 23. Comparison of annual averages of %MC measured through wall section, Riddlecombe 2014-2017

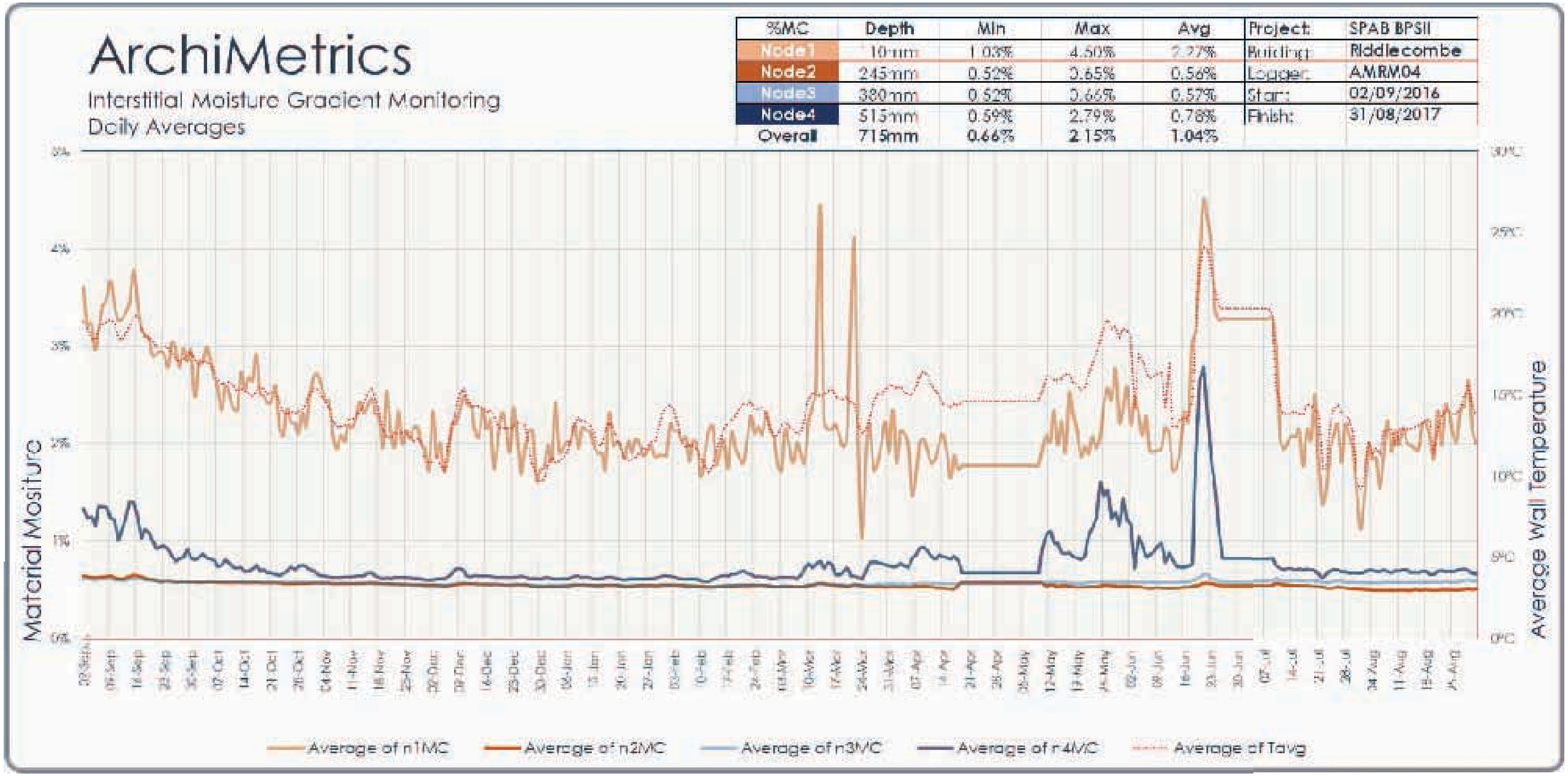

Figure 46. Material moisture content over time, The Firs, Riddlecombe 2016-2017.

Figure 47. Material moisture content over time, The Firs, Riddlecombe 2015-2016.

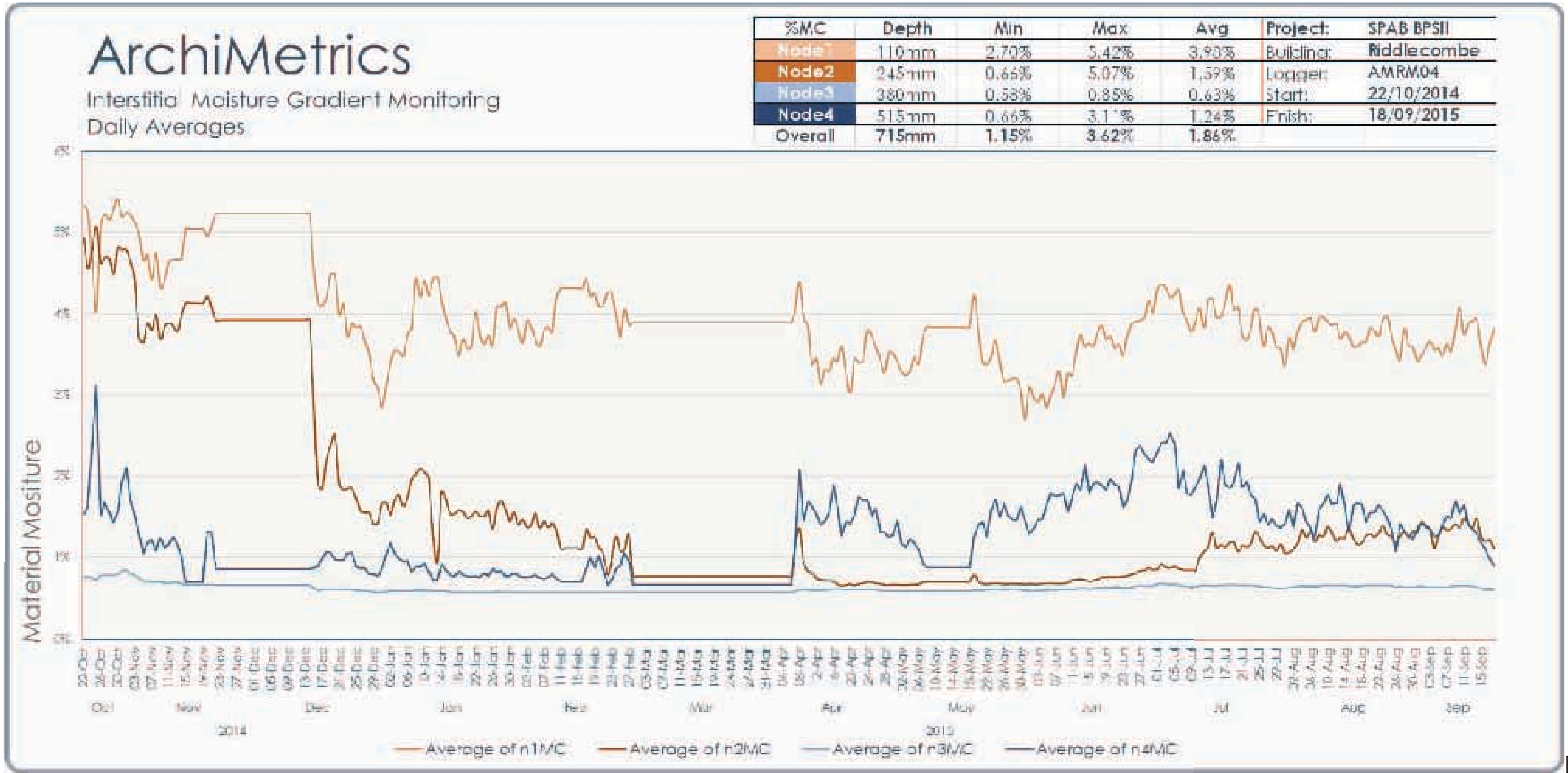

Figure 48. Material moisture content over time, The Firs, Riddlecombe 2014-2015

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 24 provides details of the capped 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. Figures 49–51 show the long-term RH trends for each wall. (In order to plot the full extent of the trend, a data set beyond the end of the analysis year, August 2017, has been used.)

The table shows the relative differences in %RH found between the three walls. Over the five years of monitoring, Shrewsbury has had the lowest rates of annual average %RH ranging between 63%-84%. Drewsteignton sits higher up the scale with a range between 62%-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%
2016-2017	63%	70%	70%	73%
Difference 2012-2017	-3.00%	-2.00%	-5.00%	-10.00%
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%
2016-2017	62%	91%	96%	97%
Difference 2012-2017	-6.00%	6.00%	6.00%	1.00%
Riddlecombe				
2012	72%	91%	98%	100%
2013-2014	78%	91%	99%	100%
2014-2015	78%	91%	96%	100%
2015-2016	77%	89%	95%	100%
2016-2017	76%	88%	95%	100%
Difference 2012-2017	4.00%	-3.00%	-3.00%	0.00%

Table 24. Annual average %RH for all interstitial sensors 2012–2017 (capped).

This reported year, September 2016–August 2017, has been particularly dry; autumn, winter and spring saw below average rainfall in the Midlands and south-west of England where our survey properties are located, only the summer period was wetter than average. Moisture behaviour within the walls is affected by the weather, not only in the form of rain but also heat from the sun and wind which encourages evaporation and/or drives moisture further into substrates. The degree to which the monitored walls are affected by, and respond to, changes in the external environment depends upon their individual circumstances.

The brick wall at Shrewsbury is a relatively open construction, porous and permeable, thin, dark and south-facing. Because of this, moisture behaviour within the wall is closely coupled to the weather. As this reported year, September 2016 – August 2017 has been particularly dry, there has been a relatively low moisture take up within the wall. This results in lower records of RH as there is less moisture within the wall. (Winter wetting, coupled with low temperatures has, over other winters created persistent and higher measurements of %RH. Likewise, when materials are wet and external temperatures increase, this can also for a time cause high %RH due to evaporation taking place within the substrate.) Because of the dry winter, the annual average RH figures for Shrewsbury this year are the lowest that they have been since post-refurbishment measurement began, particularly towards the external side of the wall, at sensors 3 and 4. The differences between this year and the first year, post-refurbishment, also show as negative numbers throughout the section as RH is lower this year, with bigger differences at sensors 3 and 4. The difference at sensor 2 is interesting in this respect as, contrastingly, its difference is quite small, -2%, and the annual averages over the years 2012–2017 are very consistent. These range between only 70–72% in this part of the wall over the five year period despite significant variations in weather patterns over that time.

The wall at Drewsteignton is very different from that of Shrewsbury; thicker, north-west-facing and constructed of less porous, impermeable, granite. The weather in this part of the country has also been drier than normal, particularly over winter (December 2016-February 2017) when rainfall was only 65% of the 1981–2010 average for these months. However, as has been the case since monitoring began, RH is much higher in this wall compared with that of Shrewsbury and we do not see the same responses to the drier weather that were found at Shrewsbury. In this wall, annual average RH has increased from that of the previous year at sensor 2 and remains unchanged at sensor 3. There have been decreases in both the sensor 1 and 4 annual averages but these are very slight, being only 1% or 2 %RH lower than the previous year. The only negative ‘difference’ value is found for sensor 1, in the air gap behind the plasterboard finish on the warm side of the insulation. As has been previously noted, this position is physically separated from the rest of the wall and conditions here normally track those of the internal room environment. The greatest difference through the section is found in the centre of the wall at sensors 2 and 3, where conditions are on average 6 %RH higher than they were in the first 2012–13 monitored year.

There is only a very slight change in the annual average RH values found for the cob wall at Riddlecombe (also located in the south-west of England) in comparison with those of 2015-16. None of the values have increased but annual average %RH has only decreased by 1% RH at sensors 1 and 2 and remains the same at sensors 3 and 4. (Values are capped in these tables, hence the repetition of 100% at sensor 4 over the years.) The lack of change at sensors 3 and 4 may be due to a slightly dull summer, with a below average number of sunshine hours, meaning less solar-driven evaporation has taken place from the south-facing wall over these months. If the primary driver for vapour changes in this wall is solar-driven summertime evaporation, then the retarding effect of the thick external render will be that much greater in a year when less vaporisation takes place. However, this is the third year where averages have either remained the same or decreased across all four sensors, a pattern of decline not seen in either of the other two walls. The ‘difference’ values also show this changing picture for the centre part of this wall, where negative values are found for sensors 2 and 3 as average RH is lower in 2016–17 in comparison with the higher annual average values found at the start of measurements in 2012.

As has been noted in previous reports, moisture behaviour factored as %RH has a closer relationship with weather patterns in the wall in Shrewsbury than that of the other two walls. The previous year, 2015-16, being warmer and wetter, shows higher records of %RH for this wall as there is more water and more evaporation within materials in comparison with this drier year with subsequently lower %RH. That this pattern does not repeat for Drewsteignton or Riddlecombe tells us something about the condition of these two walls. Drewsteignton is less directly affected by the weather - the wall does not face the prevailing weather and whilst water will enter the structure through the mortar beds, the masonry units will absorb less water as they are of less porous, impermeable granite. Because of its aspect the wall receives less direct ‘drying’ solar radiation and due to its heavyweight nature will be slow to warm up. The pointing is in good condition so there is likely to be less air movement through the structure which can also aid drying. These factors mean that whilst the wall must respond to its internal and external environment these responses may be slow, muted, not extreme. The rising %RH seen year-on-year in the centre of this wall also suggests that, unlike Shrewsbury, there are other factors which are influencing moisture behaviour in this wall.

Similarly, the trends in Table 24 show, too, that moisture behaviour in the wall at Riddlecombe is not driven solely by external conditions. Although these influences also seem to be different from those at Drewsteignton as here we have year-on-year reductions in %RH. This wall is thicker than that of Drewsteignton and its construction is quite different, being made of earth with a thick external render and a south--facing aspect. In previous reports, we have surmised that the predominant factor influencing moisture behaviour in this wall is not external heat and moisture but moisture that resides within the wall added when the cob was rendered (as well as residual moisture measured prior to the application of the render as the result of an older cracked cement render). Here %RH patterns do not match weather patterns as the principal source of vapour is construction moisture within the wall evaporating, over a number of years, from the damp cob substrate leading to a picture of annual declining %RH. The progress of the evaporative drying of the substrate can be looked at against the trend of rising %RH at Drewsteignton. For the first three years after refurbishment, %RH was higher in the wall in Riddlecombe but over the last two years this relationship has inverted. Annual average %RH at sensors 2 and 3 is now lower in the wall at Riddlecombe than that of Drewsteignton and has been for the past two years.

Figures 49–51 show, in the form of dashed trend lines, the consequences of changes in %RH through the wall sections since 2012. Shrewsbury, no doubt influenced by the mostly dry previous twelve months, shows a clear downward %RH trend across all four wall sensors. This may change in future years (as was indeed the case last year). However, despite this volatility, significantly the %RH trend values are low, quite closely grouped and have been below the 80% mould growth risk threshold for some years, since August 2014. Therefore, whilst %RH may increase during wetter years, this increase is likely to be only temporary and on balance %RH within the wall, particularly at sensor 2 at the critical interface with the woodfibre insulation board, is likely to remain below the risk threshold.

In contrast, the analysis for Drewsteignton, Figure 50, shows a trend of %RH from the three sensors within the masonry part of the wall which is high and rising. It is above 80% at sensor 2 and 90% at sensors 3 and 4 when post-refurbishment measurements begin and exceeds 90% at sensor 2 in August 2015. The rising trend is found, in particular, at sensors 2 and 3 in the central part of the wall and at the critical interface. The trend at the sensor closest to external conditions, sensor 4, is static at roughly 96-97% RH meaning that due to the trend of rising RH at sensor 3 %RH becomes higher in this part of the wall and crosses the sensor 4 trend line around December 2016. As has been shown, %RH is unlikely to reduce in response to a single drier year in this wall.

The long-term trend analysis for Riddlecombe clearly shows, whilst %RH is still high, above 80% in this wall, there is a declining trend of %RH for the central part of the wall at sensors 2 and 3 and trends at sensors 1 and 4 look to be quite static. Sensor 4 conditions are capped at 100% so the dashed trend line occupies the same line as that of the sensor values. A plot of the uncapped %RH values for sensor 4 is also given in Figure 51, represented by a dotted line. Once again, as with Drewsteignton, it is harder to discern the relationship between weather patterns and moisture behaviour in this wall at this scale. However, previous reports, within the individual property sections, have shown plenty of evidence of evaporation occurring within the wall section during periods of direct solar radiation heating the south-facing wall. Therefore, whilst weather of course does impinge upon the moisture profile of the cob wall, it is the moisture already inside this structure which dominates the moisture analysis. In particular, it is the vaporisation of this moisture which, over time, is reducing %RH within the central section of the wall but appears static towards either side of the wall's extremities, possibly due to vapour moving to these locations from the centre?

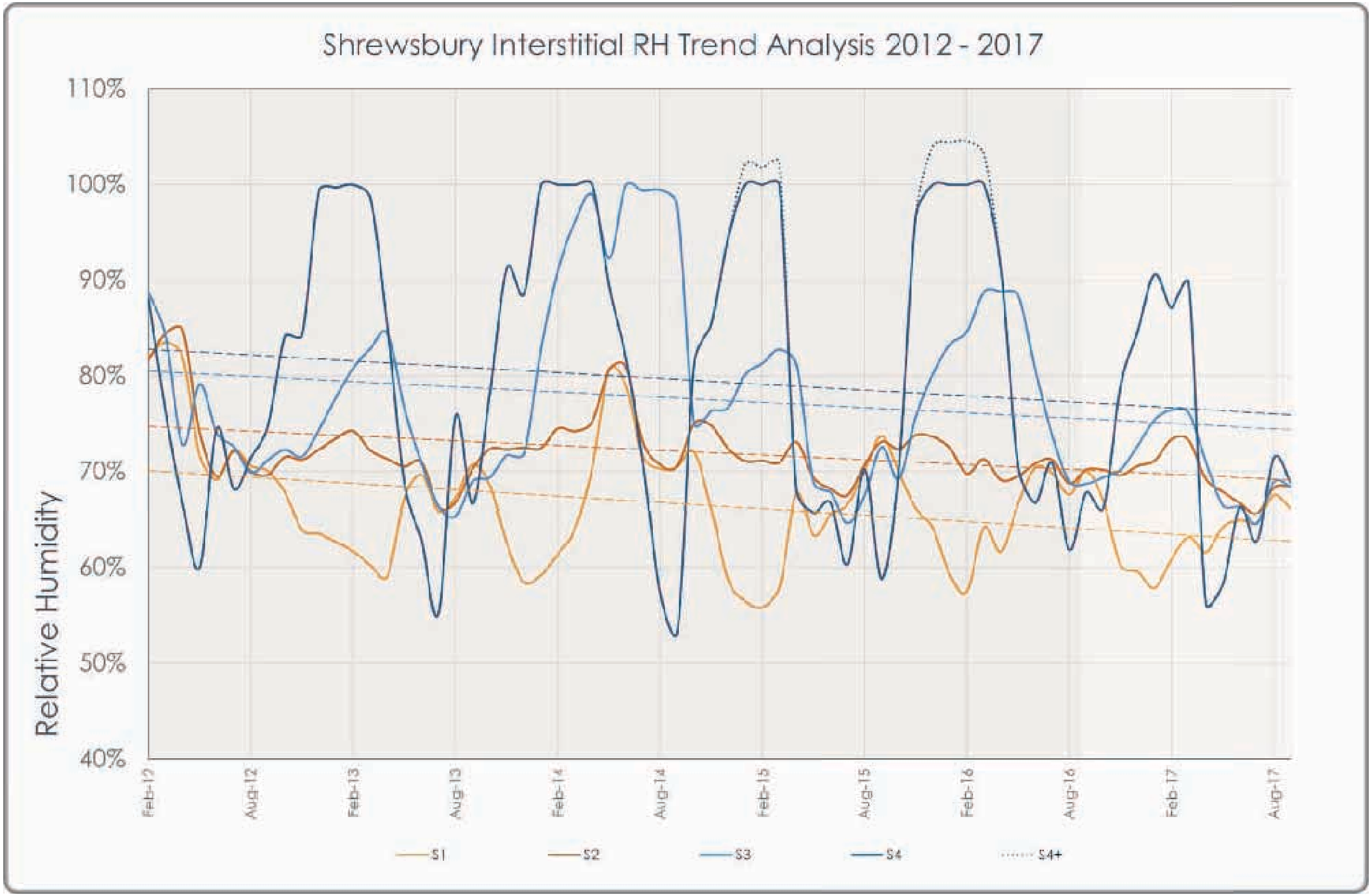

Figure 49. Relative humidity trends over time, Shrewsbury 2012-2017.

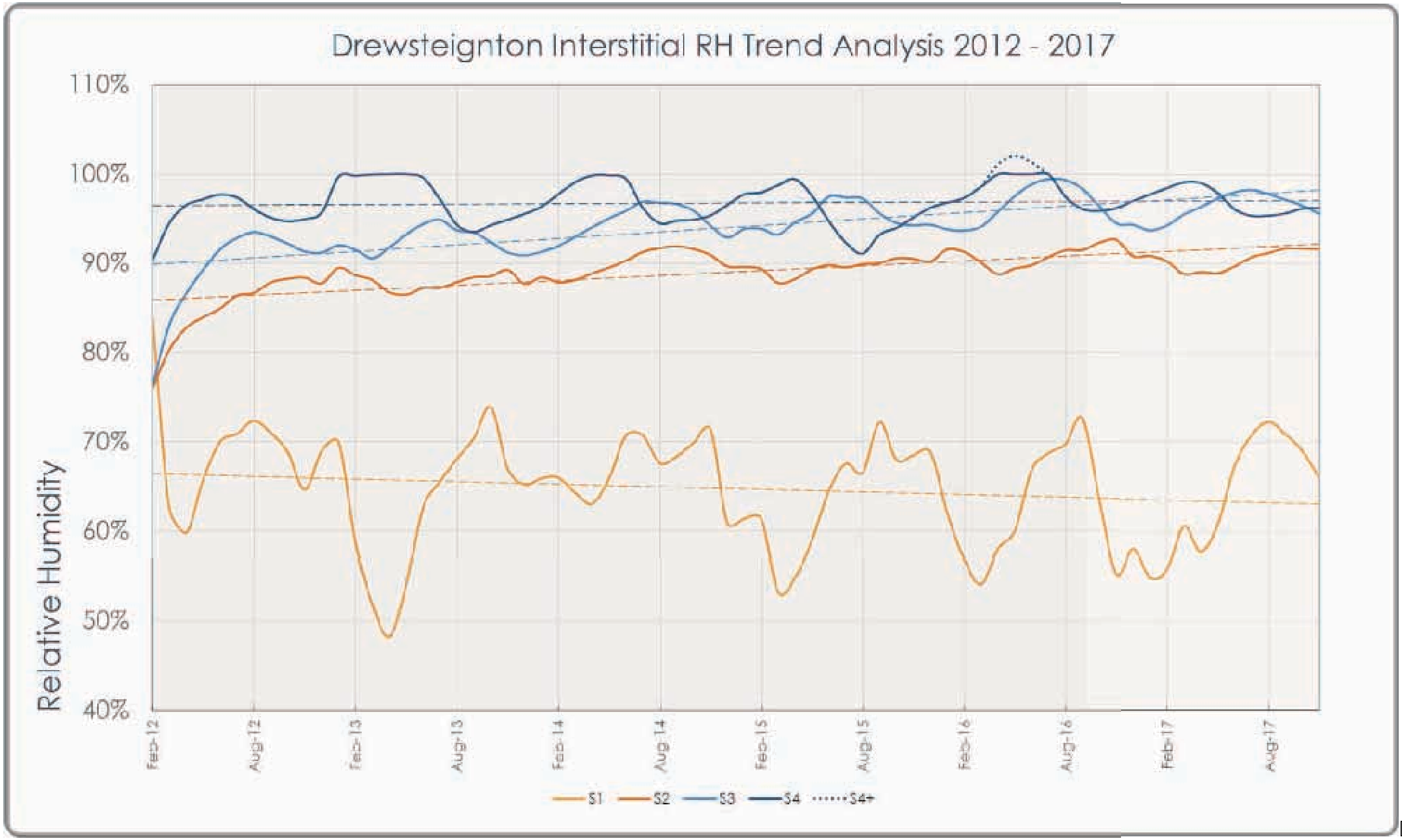

Figure 50. Relative humidity trends over time, Drewsteignton 2012–2017.

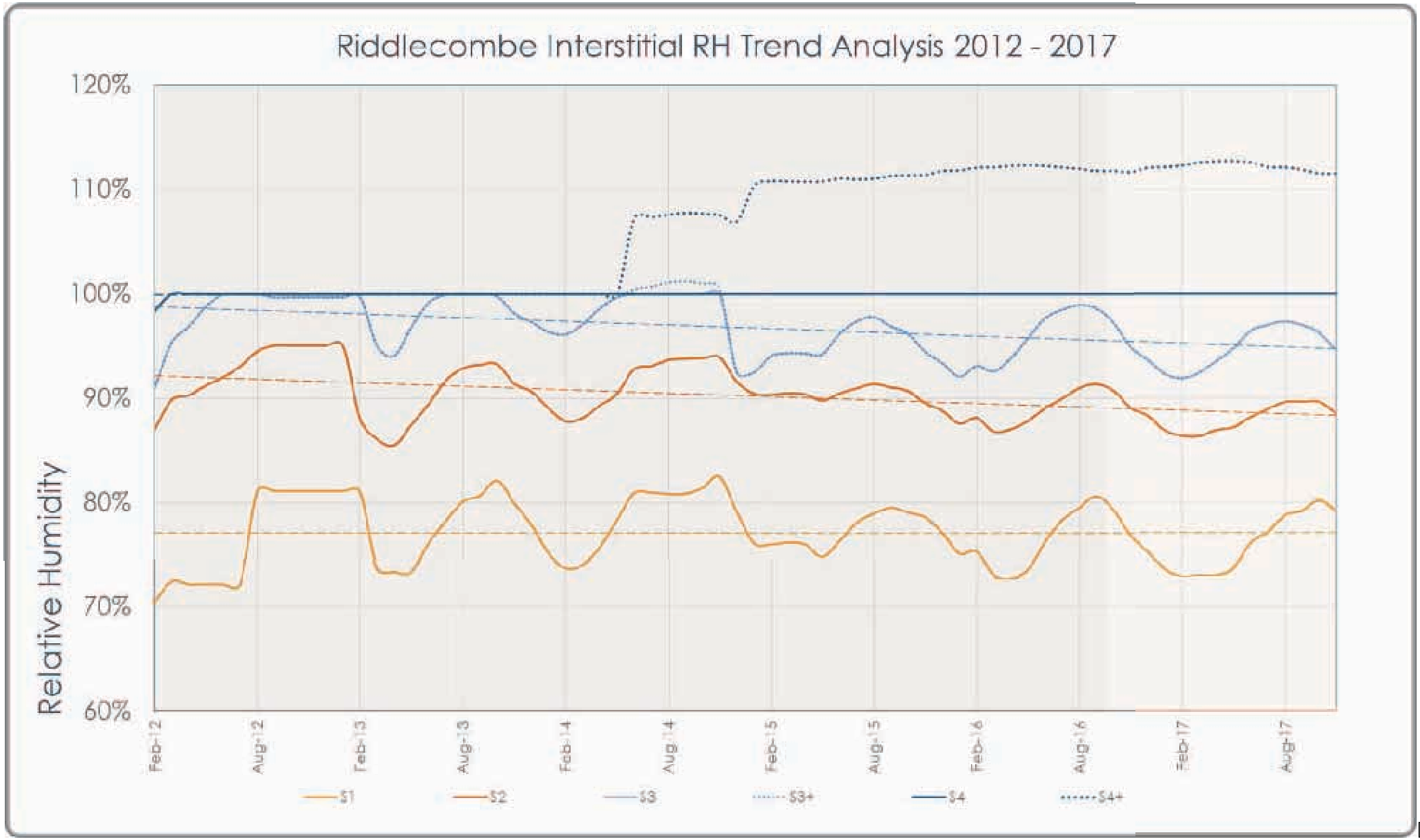

Figure 51. Relative humidity trends over time, Riddlecombe, 2012-2017.

3.2 Absolute Humidity (AH)

Table 25 provides details of the annual average AH values for the sets of 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
2016-2017	9.95 g/m^3	9.93 g/m^3	9.73 g/m^3	9.55 g/m^3
Difference 2012-2017	0.94 g/m^3	1.13 g/m^3	0.78 g/m^3	0.37 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
2016-2017	9.05 g/m^3	10.55 g/m^3	10.96 g/m^3	10.52 g/m^3
Difference 2012-2017	0.52 g/m^3	1.79 g/m^3	2 g/m^3	1.39 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
2016-2017	11.86 g/m^3	12.67 g/m^3	12.46 g/m^3	11.55 g/m^3
Difference 2012-2017	2.39 g/m^3	0.01 g/m^3	-0.28 g/m^3	-0.72 g/m^3

Table 25. Annual average AH g/m^3 for all interstitial sensors 2012-2017 (capped).

As has been previously noted, the walls with higher %RH measurements also, perhaps not surprisingly, provide higher measurements of weights of vapour, AH. Thus, over the monitored year, Shrewsbury, provides the lowest weights of vapour and Riddlecombe the highest. However, as has been recounted in the previous RH section, the same forces do not necessarily drive vapour behaviour within the three walls. As can be seen in the annual averages Table 25, for the second year in a row, weights of vapour have decreased across most of the wall sensors, with the exception of sensors 1 and 2 at Shrewsbury. But, the responses measured in each of the walls occurs for different reasons.

At Shrewsbury the dry year has meant less vapour is present towards the external wall face as less wetting of the substrate has occurred. In warmer, wetter years, this leads to increases in vapour records due to the presence of additional moisture and its associated evaporation from the south-facing and more permeable brick structure as was the case for the previous 2015–16 year. For both years, the direction of change at sensors 1 and 2 is contrary to those of 3 and 4. Year-on-year, weights of vapour have decreased towards the inside of the wall while increasing towards the external side and *vice versa*. However, this is not the same as behaviour seen between 2013–15 when the direction of change is unified through the wall section and weights increase year-on-year.

Although September 2016–August 2017 can be described as a predominantly dry year, the exception to this was the period June–August 2017 when there was above average rainfall across the UK. For the thinner wall at Shrewsbury summer conditions may not have such an impact on overall vapour weights, as we have seen in previous year's analyses as most winter moisture has already been evaporated from the wall by this time. However, for the two heavier weight walls with slower moisture responses, we still see 'drying' in the form of vapour production taking place through the summer months - particularly at Riddlecombe. It is likely then that these wet conditions have impinged on records of AH for these walls, resulting in lower annual weights of vapour, as their evaporative opportunities have been curtailed by the wetter weather. This is probably particularly the case for the north-west-facing wall at Drewsteignton, which already has limited opportunities for reducing its moisture load via evaporation due to its orientation.

However, there is probably an additional reason why the weights of vapour have reduced this year at Riddlecombe, as shown by the calculations of the difference between average weights measured in 2012 against those of this year. Although, overall, Riddlecombe measures the highest weights of vapour for the three walls, these weights have not changed much since 2012 and at two locations, sensors 3 and 4, have slightly reduced. This is different to the situation at Shrewsbury and Drewsteignton where 2016-2017 weights have increased from those of 2012, particularly at Drewsteignton where %RH is increasing. Although the weight differences at Riddlecombe are small, 0.72-0.01 g/m^3, this may again hint at the process of construction-moisture reduction which we believe has been taking place in this wall since it was re-rendered. Therefore, the lower average AH values measured this year may also reflect a slight reduction in the baseline moisture contained within the fabric of the wall. The exception to this is AH measured at sensor 1, which although it has decreased on average for two years now, is still higher than that measured back in 2012, possibly caused by vapour transiting in this part of the wall as it moves from the centre towards an evaporative surface.

Average AH section analyses have been produced for all three walls. For comparative purposes, this year's 2016-17 and last year's 2015-16 analyses are shown, Figures 52–57. In previous reports, the difference between the AH section profile for the brick wall at Shrewsbury, in comparison with those of Drewsteignton and Riddlecombe, has been noted. This difference is still evident this year and is related, once again, to the different, thinner/thicker, lighter/heavier characteristics of the walls. The profile for Shrewsbury, Figure 52, shows that average AH measured within the wall is in equilibrium with that measured in proximity to the wall's internal and external environments. AH through this wall is similar to that of its surrounding environment and more immediately affected by those environmental changes. The walls at Drewsteignton and Riddlecombe both measure higher AH inside the wall, resulting in an upwardly curved AH profile, with weights of vapour higher than those quantities measured from the surrounding internal and external environments. It may be that the materials these walls are made of - granite and earth - normally contain higher quantities of vapour. However, the rising %RH trend at Drewsteignton suggests a lack of equilibrium for this wall and a comparison of Figures 56 and 57 for Riddlecombe shows a change to the shape of the curved profile this year. AH has reduced in the central part of the cob wall, this difference being reflective of the reduction of vapour that has taken place at this location. It also suggests that these changes may be on-going, i.e. this wall is also not yet in a state of equilibrium.

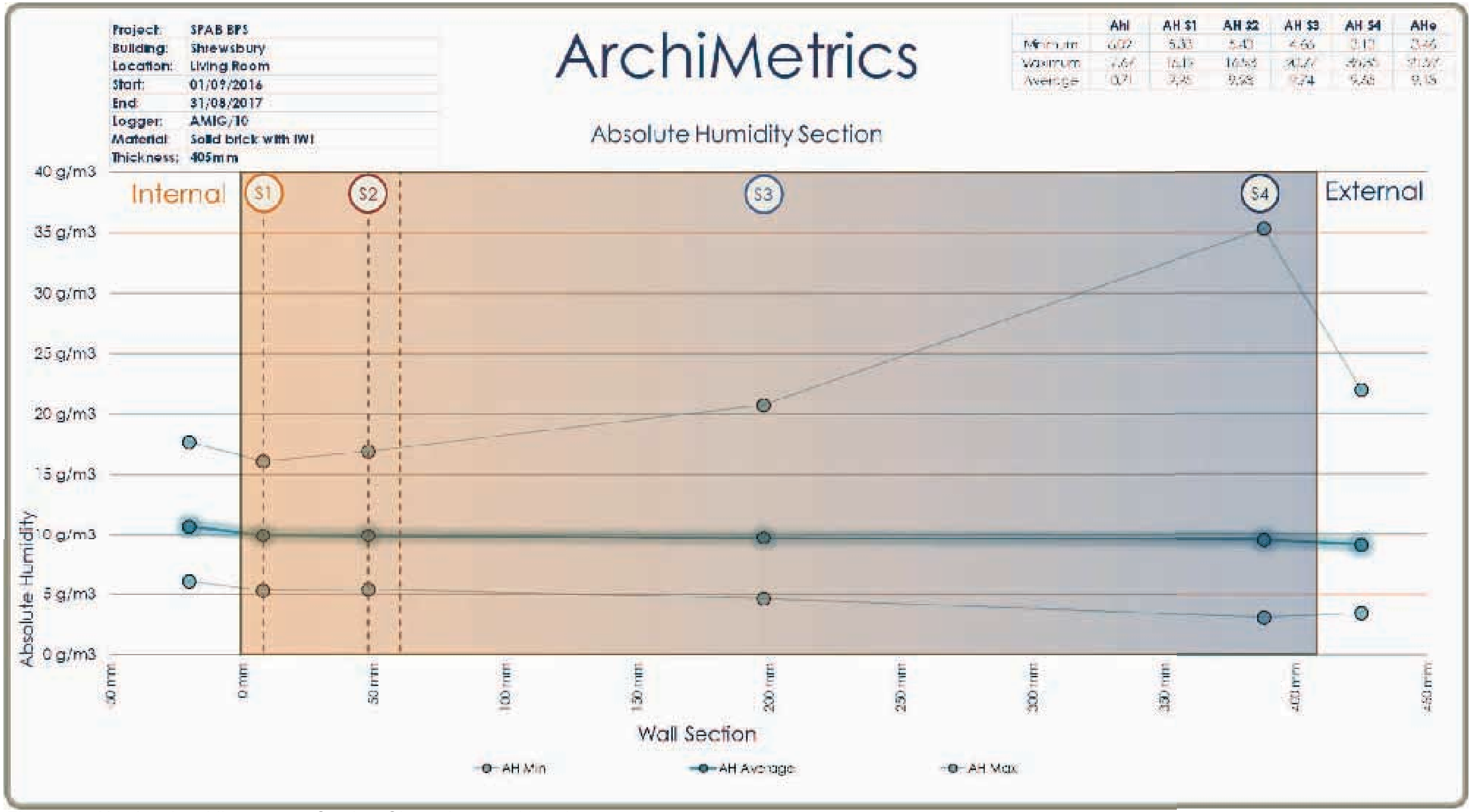

Figure 52. Absolute humidity average Section, Shrewsbury, 2016-2017.

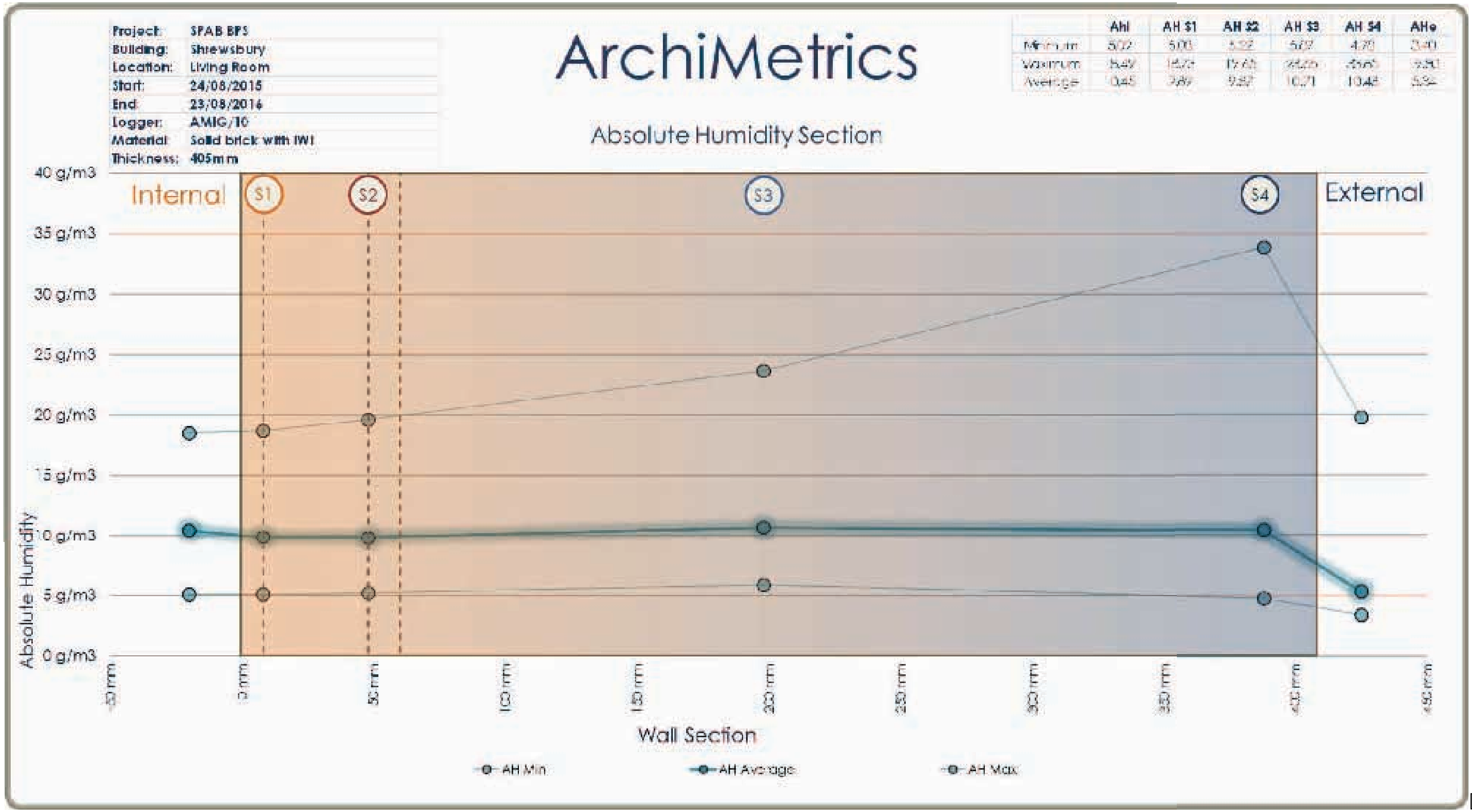

Figure 53. Absolute humidity average section, Shrewsbury, 2015 -2016.

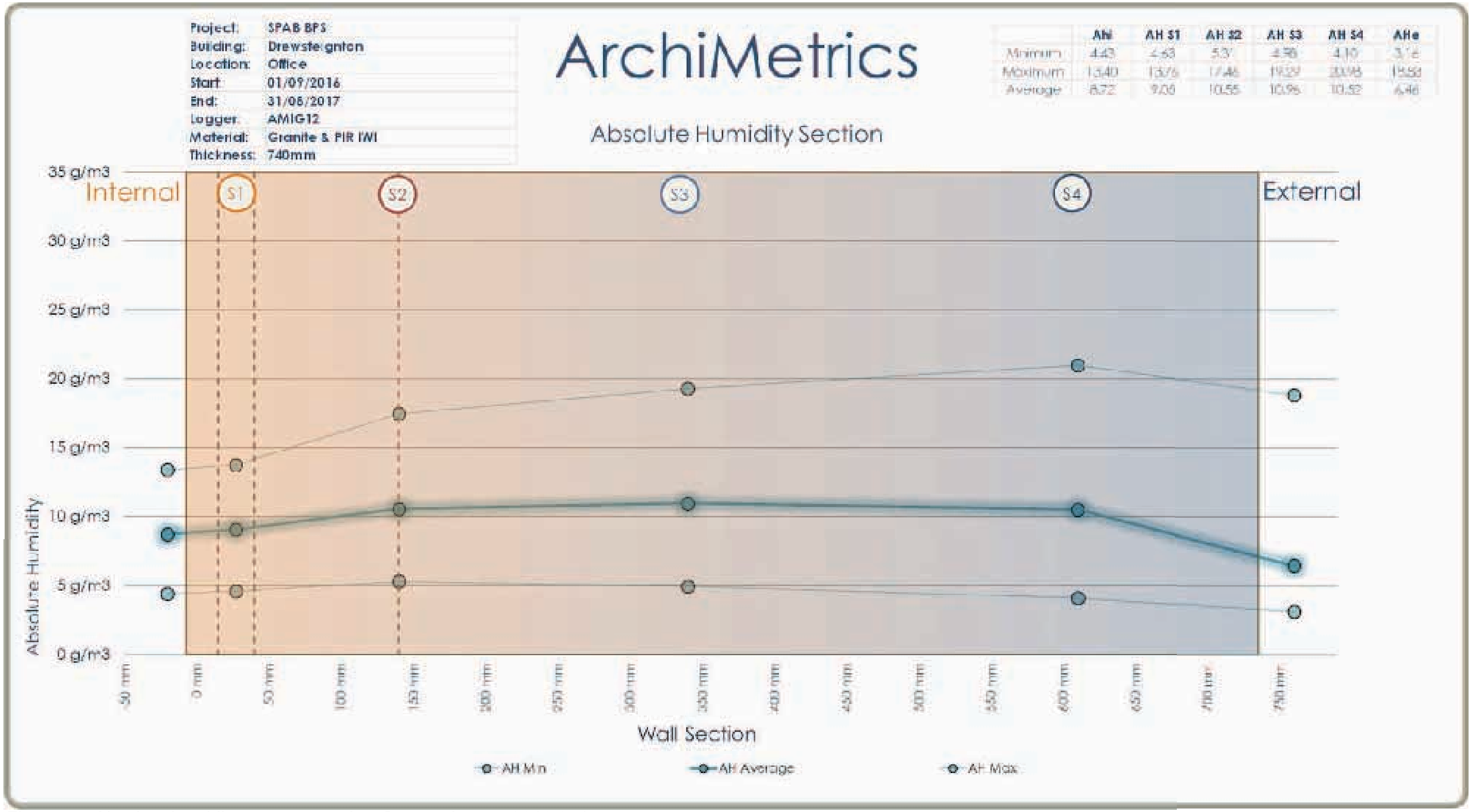

Figure 54. Absolute humidity average section, Drewsteignton, 2016-2017.

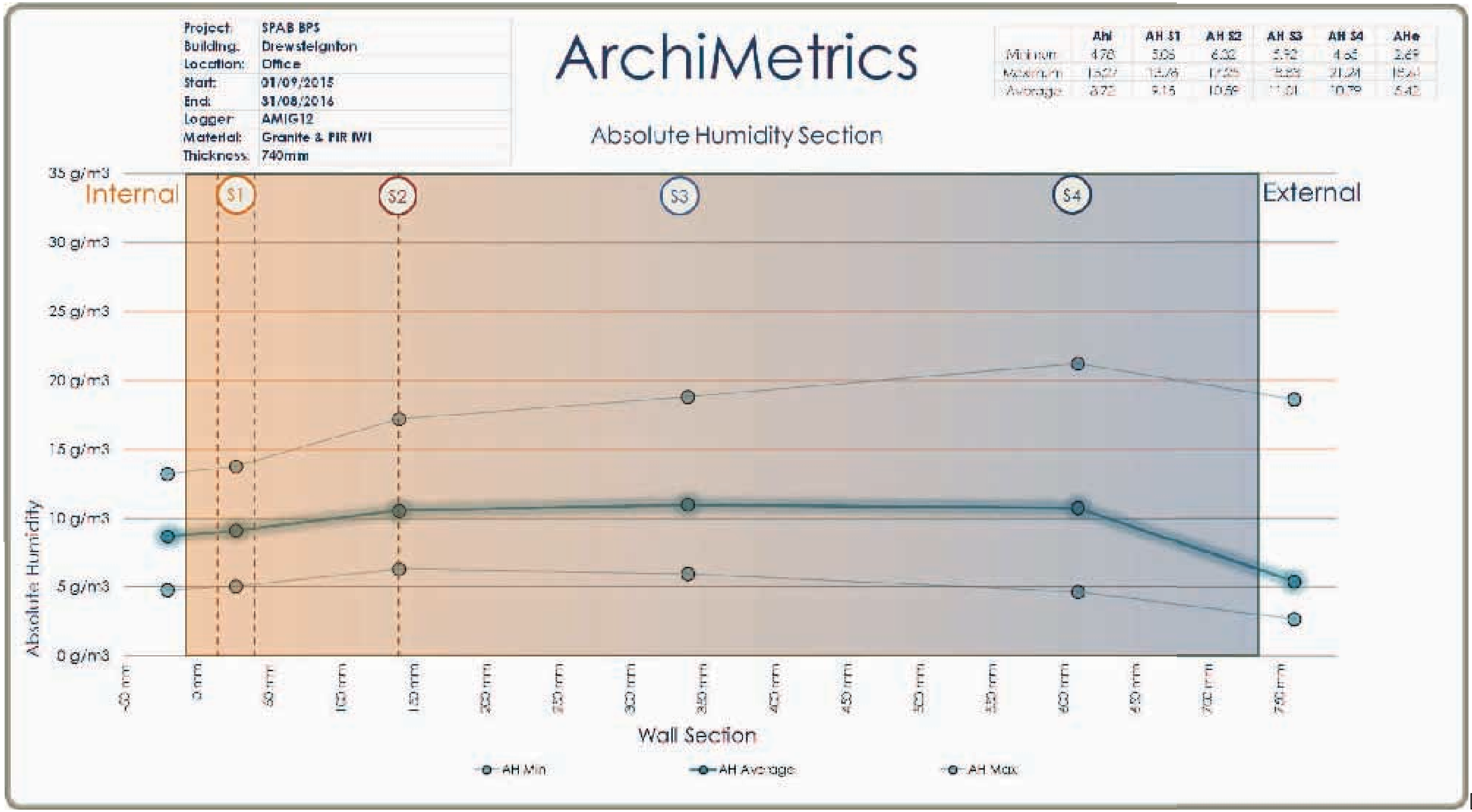

Figure 55.. Absolute humidity average section, Drewsteignton, 2015 -2016.

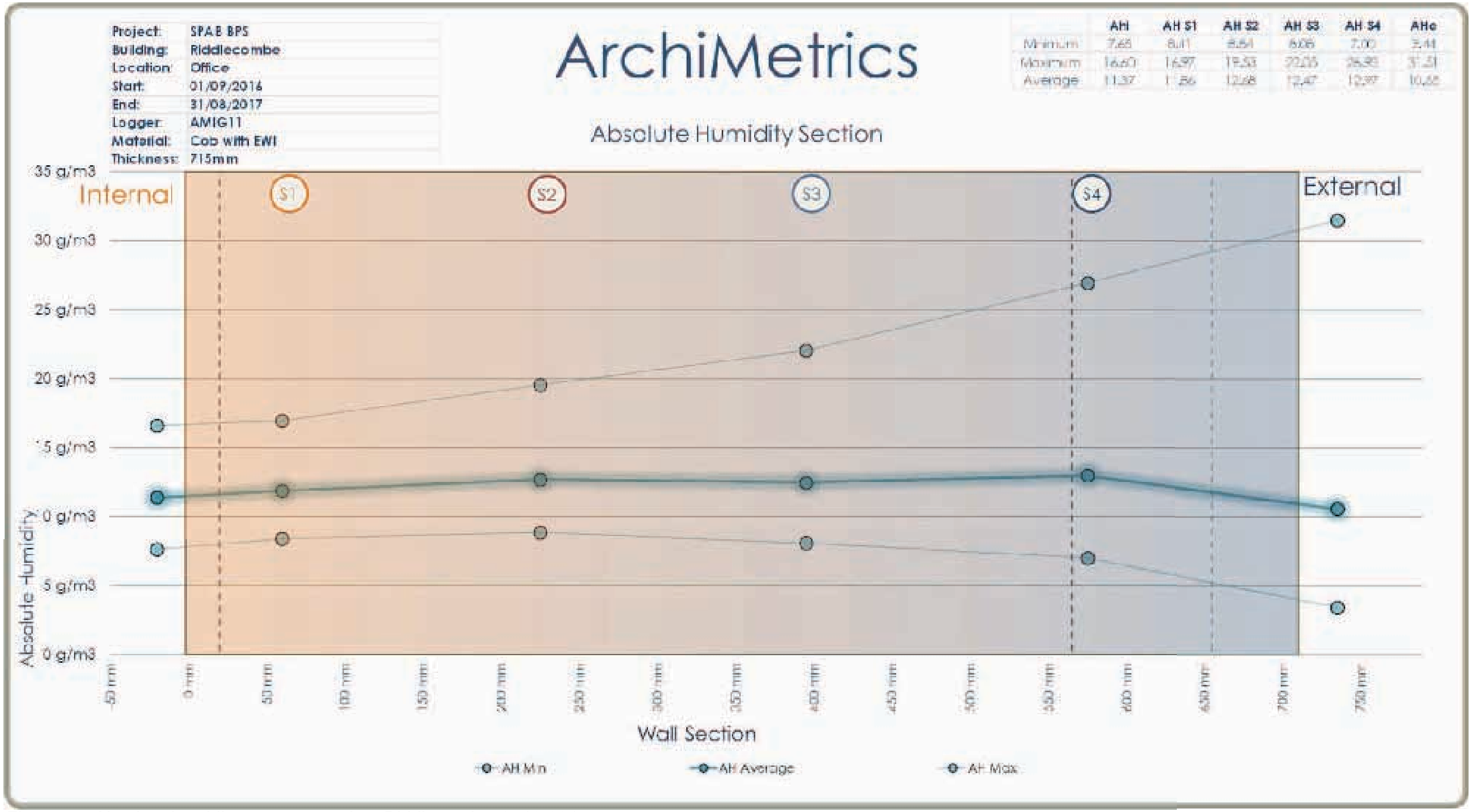

Figure 56. Absolute humidity average section, Riddlecombe, 2016-2017.

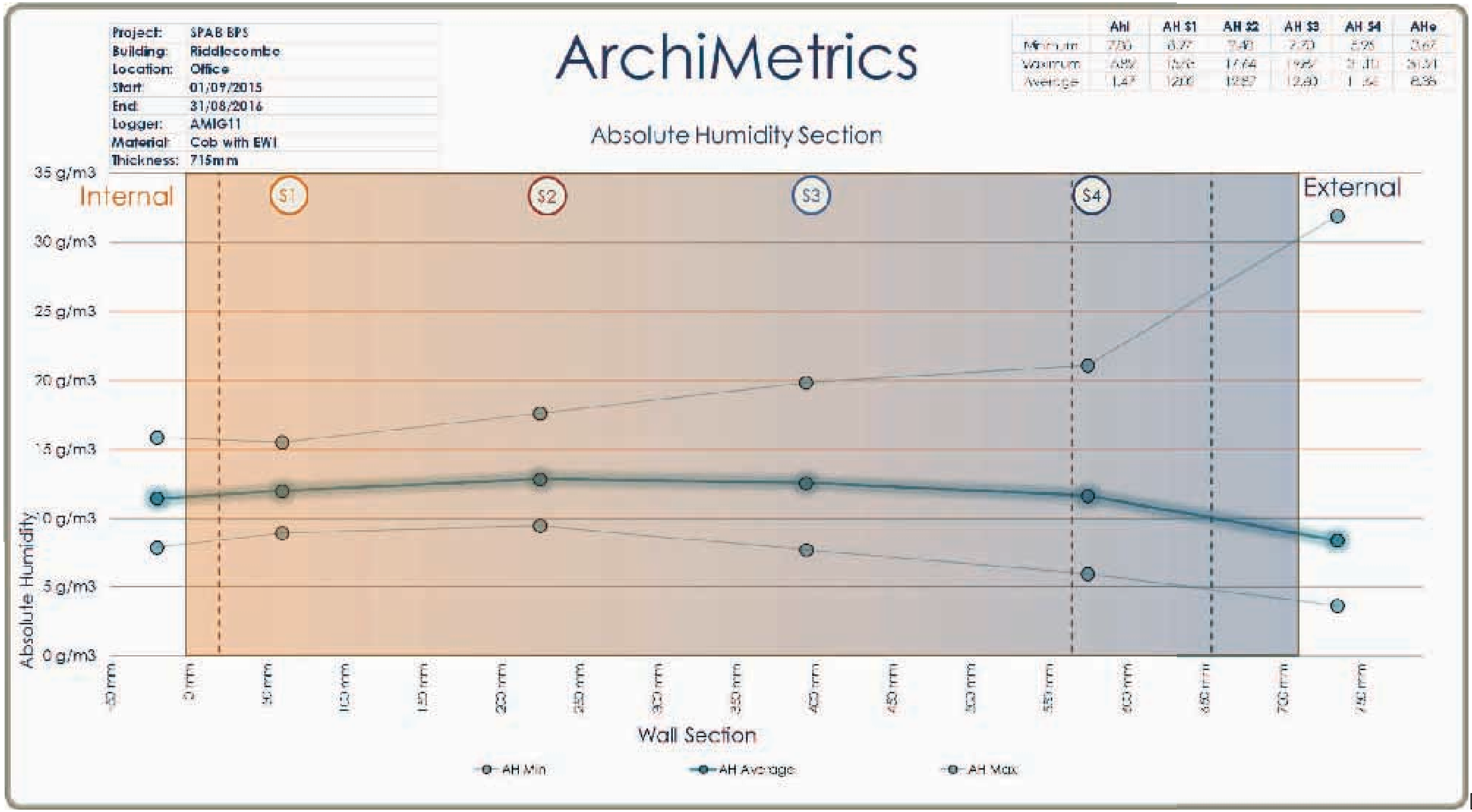

Figure 57. Absolute humidity average section, Riddlecombe, 2015-2016.

3.3 Saturation Margins

Table 26 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
2016–2017	7.02˚C	5.53˚C	5.35˚C	5.16˚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
2016–2017	7.23˚C	1.44˚C	0.50˚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
2016–2017	4.28˚C	1.89˚C	0.79˚C	0.00˚C

Table 26. Annual average saturation margins for all interstitial sensors 2011–2017 (capped).

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 deposition and/or accumulation of water in fabric in proximity to the measurement sensor. Table 26 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 records, post-insulation margins at Shrewsbury are greater than those at Drewsteignton and Riddlecombe (the lower the vapour quantities the less likely the air is to become saturated). This indicates '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 more frequently, particularly over the winter time, suggesting saturation occurs more often in these walls than that of Shrewsbury. 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). This year, noted to be a drier winter, margins have increased in the walls at Shrewsbury and Riddlecombe (or remained static in the case of the capped values for Riddlecombe's sensor 4). This is likely to be the result of the dry winter for the wall at Shrewsbury and - at Riddlecombe - the reduction in construction moisture, which has lessened the vapour load for the wall. The divergent wall in respect of this year's analysis is that of Drewsteignton where margins have remained static at sensor 4 but narrowed, once again, at sensors 2 and 3, in the central part of the wall. As with the %RH analysis, the increase in saturation margin measured this year for sensor 1 in this wall is largely a response to internal room conditions and not reflective of conditions within the masonry section of the wall. For the second year now, the average margins at sensors 2 and 3 are narrower in the granite wall than those of the cob wall at Riddlecombe. This is a factor of the rising %RH trend found for the wall at Drewsteignton, along with the decreasing trend plotted for Riddlecombe. This means it is likely that saturation margins will continue to be narrower at Drewsteignton than those of Riddlecombe unless there is a significant change in the circumstances of the wall which alter its moisture state. With regards to concepts of risk - whilst Riddlecombe still records the highest RH and AH profiles at present - the changes shown year-on-year by the saturation margins suggests that risks posed by high %RH may decrease in the cob wall whilst continuing to increase in the granite wall at Drewsteignton.

3.3 Material Moisture

For the past three years material moisture content measurements have been made as part of the SPAB Building Performance Survey in each of the three walls. These show - when quantities are averaged through each of the walls -that a similar relationship exists between them as that shown in the vapour records. That is, Shrewsbury records the lowest MC%, Riddlecombe the highest, with quantities at Drewsteignton lying between those of the other two walls (Table 27).

Annual Average %MC	**Shrewsbury**	**Drewsteignton**	**Riddlecombe**
2014-2015	0.50 %MC	1.02 %MC	1.86 %MC
2015-2016	0.47 %MC	0.86 %MC	1.38 %MC
2016-2017	0.43 %MC	0.99 %MC	1.04 %MC

Table 27. Annual average moisture content for BPS properties 2014-2017.

However, this year a shift has taken place which positions the averaged quantity of %MC found for the wall at Drewsteignton much closer to that of Riddlecombe. Whereas previous annual averaged quantities for Drewsteignton occupied an approximate mid-point between those of Shrewsbury and Riddlecombe, in 2016–17, the average is similar to that calculated for Riddlecombe. The shading in Table 27 shows that the only year-on-year increase in annual %MC has occurred at Drewsteignton, elsewhere values have declined over the past two years. No doubt this shift has, in part, been affected by the change in increased quantities of %MC measured by sensor 2 commencing in September 2016 (see p58 of the Drewsteignton individual property report for more details). Yet this finding accords with other observations we have made concerning the three walls in the study. Namely, that there is a trend of rising %RH found for the wall at Drewsteignton in contrast to declining trends mapped for both the walls at Shrewsbury and Riddlecombe. Whilst there may not be a straightforward relationship between moisture vapour behaviour and that of liquid moisture bound within building materials, in previous reports we have posited that moisture vapour behaviour at Drewsteignton suggests the possibility of the accumulation of moisture within the fabric. This might account for the increase in average %MC found for this year or, alternatively, this might be a reflection of the difficulty that this wall has in reducing its vapour load.

The increasing or decreasing trends indicated by the blue and orange shading in Table 27 match those of Table 24, annual average %RH. These annual average trends are conditioned by different things; at Shrewsbury it is the weather for the wall, and at Riddlecombe the evaporation of construction moisture. The lack - in particular - of winter rain produces low %RH records at Shrewsbury whilst the high %RH at Riddlecombe - which is a function of water added during refurbishment - continues to slowly decline via evaporation. %MC records show the same reduction for this year suggesting a general reduction of the moisture profile in general for both these walls. The monolithic nature of the granite stone wall at Drewsteignton and its north-west aspect lessens its ability to absorb water but also limits its potential to evaporate the moisture that it has absorbed. Although the 2016-17 winter was a relatively dry affair - the 2017 summer, when we might see some evaporation occurring - was wetter than average. AH quantities found for this year may be reduced because of this and the more overcast summer might also lead to an increase in %MC measured over the course of 2016-17.

What is interesting with regard to the %MC profiles for these walls is that walls with very high %RH do not seem to provide particularly high %MC values. In general, 5% MC is thought to represent a ‘high’ %MC value for masonry materials although what might be deemed a ‘high’ %MC for these particular materials - granite and cob - is not well defined and is likely to vary considerably with the natural variations in those materials. Ideally, to gain a better understanding we would profile samples from these two walls.

Alternatively, perhaps, depending on the properties of the individual materials that go to make up these walls - granite and cob - are both examples of materials that maintain relatively high quantities of vapour for low %MC. This might be possible in the case of unfired earth (cob) which is highly permeable and also has a high vapour-carrying capacity. Is this a form of moisture buffering, which means that the structure can contain large quantities of vapour without necessarily being wet? (although it should be remembered that at the start of this study, in 2011–12, wet cob material was retrieved from the wall at Riddlecombe during the installation of measurement sensors.)

Similarly, different qualities in the granite wall at Drewsteignton may produce divergent high vapour and low %MC readings. Whilst the lime mortar bedding joints of the stone wall will be both porous and permeable, this is most likely not the case for the less porous crystalline granite stone which makes up the majority of the wall surface. This material is still permeable and will allow the passage of water vapour but the lack of an interconnected pore structure means it does not readily take up or move moisture as a liquid. The high density of the material also means that there is less space within the material for water to reside. This wall has had a large quantity of impermeable insulation material added to its interior wall face. This has a number of effects: it deprives the masonry part of the wall of heat from the interior, particularly during the winter months; and also acts as a physical barrier to moisture in both a liquid and vapour form, preventing moisture penetrating the wall from the interior space as well as stopping moisture within the wall accessing the interior wall surface from where it might evaporate. The characteristic of this insulation material, coupled with those of the non-porous, heavyweight granite may combine to produce a picture where vapour builds up within the structure and is accompanied (this year) by an increase in moisture present as a liquid and thus measured as %MC.

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. Over the course of this research project, the value of long-term detailed measurements has become 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 and permeable 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, and AH g/m^3), the widest saturation margins and lowest %MC. Vapour responses in this wall are very dynamic and at times quite extreme, which 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, sensor 2, continues to decline. 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. 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. However, last year, for first the first time, we saw average quantities of %RH which were at, or exceed, the 80% threshold towards the external side of the wall face, at sensors 3 and 4. This produced an upward tendency in the long-term %RH trend for this section of the wall. This year, average quantities throughout the section have reduced and are at their lowest annual average values since post-refurbishment records began in 2012. The difference in the annual average quantities is also at its greatest between two consecutive years, being around 10%RH lower in 2016-17 than that of 2015-16. Once again, the reason for this difference is due to the contrasting weather patterns between the two years. Winter 2015–16 (December–February) was the second wettest in the UK since 1910. In contrast, the winter of 2016-17 was quite dry with the Midlands region receiving only about three-quarters of its average rainfall. (For a comparison of the rainfall for Shrewsbury for the two years see Figures 7 and 8, pp14-15). Last year, we speculated that the change in risk profile, to one of higher %RH and potentially greater risk towards the external side of the wall, was caused by weather patterns and would therefore be temporary. This year's long-term analyses shows that these trends have indeed altered. Figure 49 shows that the %RH trend at sensors 3 and 4, like those of 1 and 2, is now declining, which leads in turn to a change in direction for the overall average %RH trend for the wall that now proceeds downwards away from the 80% risk threshold.

The wall at Drewsteignton 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 five-and-a-half years, a trend of rising humidity within the centre of the wall (sensors 2 and 3), which, year-on-year, moves this part of the wall closer to saturation conditions. For the second year since post-insulation measurements began, average RH measured in the wall at sensors 2 and 3 now exceeds that found for the cob wall at Riddlecombe. The trend of rising humidity has been observed over a number of years now so we can surmise that the high vapour within the wall is not solely a response to atmospheric conditions but is also a function of certain qualities of the construction that might limit or inhibit drying in this wall. This may be down to the heavyweight nature of the wall and its aspect, but vapour profiles have climbed since the wall was insulated and have not returned to pre-insulation levels, suggesting that the insulation itself may be 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^2K to 0.16 W/m^2K) 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, so 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. In last year's report, we suggested that the two opposing RH trends seen at Riddlecombe and Drewsteignton would continue to the extent that, in an average trend analysis, the RH trend at Drewsteignton would supersede that of Riddlecombe. In this year's analysis, Figure 50, we can see that this occurred in autumn 2016, where the %RH trend line crosses that of Riddlecombe and from this point forward %RH is, on average, higher in the Drewsteignton 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 two years in succession we have now seen reduced AH and reduced or static %RH averages measured across all four wall sensors. 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 static trend at sensors 1 and 4 (once again, at sensor 4, due to the 100% cap). These static trends, indicating little change in %RH profiles at these locations, may, in part be due to moisture moving from the centre of the wall to surfaces from where it may evaporate and, in the case of the sensor 4 location, the movement of this vapour being inhibited by a less permeable, thick external render. There appears to be an improving moisture trajectory for the wall at Riddlecombe and indeed when sensors were removed from the wall in November, in contrast to their installation, there was no smell of dampness or obvious wetness. It should, however, be borne in mind that the RH is still high and well above the 80% risk threshold.

However, the cob wall at Riddlecombe, as with the granite wall at Drewsteignton, exhibits high %RH whilst simultaneously recording what appears to be low %MC values. The disparity between these two methods of moisture assessment raises questions about the moisture characteristics of these individual materials and what determines risk. From a %RH point of view, both walls appear at risk, with fabric measurements persistently above 80% which is the threshold above which mould growth may be triggered and sustained. The risk is particularly to organic materials embedded within the wall, such as joist ends, timber bearers, plates etc. Yet annual average %MC in these two walls over the past three years occupies a range of values, 0.86-1.86%, which suggests that their moisture content may be quite low. Cob and granite are very different materials, granite is a far denser material than cob and %MC is factored by weight; therefore does %MC between 0.86–1.02% (the range of average %MC for the years 2014 – 17 at Drewsteignton) equate to a high water content for this material, whereas 1.04 – 1.86% (the range at Riddlecombe) represent low moisture content in the cob? Cob is porous and permeable, granite much less so and as a consequence cob has a higher moisture-carrying capacity in contrast to that of granite. Both walls measure high %RH. This may be relatively normal for cob material because of its moisture-carrying capabilities, resulting in high %RH but low %MC. It may also not be unusual to measure low %MC in a wall made of a relatively non-porous, impermeable, stone which does not hold water but records high %RH as a result of the vapour load held within the much more porous and permeable mortar that surrounds the masonry blocks?

Currently, the most clearly defined risk framework for buildings is based on the %RH scale, so the measurement of this quantity is one way to provide information concerning likely risks. In an attempt to map long-term RH behaviour trends across all three walls in the study, Figure 58 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 58 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. These divergent trajectories are something that have been plotted since measurements began in February 2012, 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 a declining trend in %RH 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.

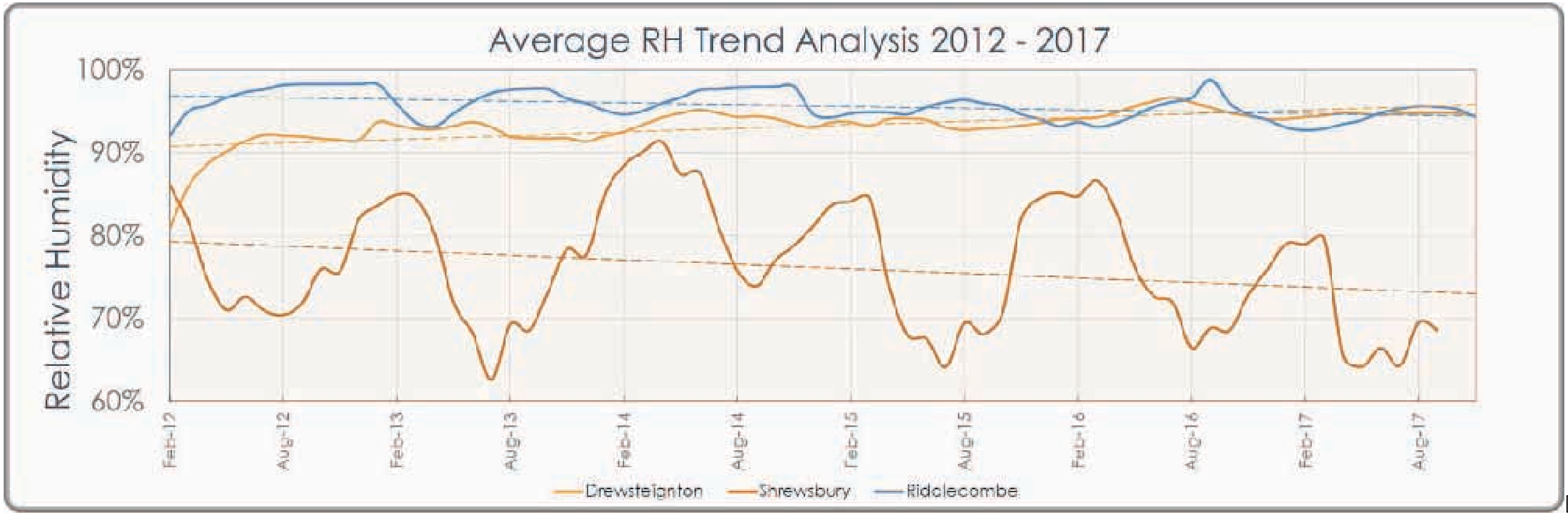

Figure 58. Average RH trend analysis, Shrewsbury, Drewsteignton and Riddlecombe, 2012-2017.

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.

In the past, within these walls, there has been a proportionate relationship between vapour quantities and those of material moisture content, with Riddlecombe exhibiting the highest, Shrewsbury the lowest and Drewsteignton somewhere between these two. Over the past few years, however, this relationship has slowly changed, as can be seen in Figure 58. Of the three measured walls, Drewsteignton now displays the highest %RH - and concomitantly the narrowest saturation margins - within the central part of the wall. However, using the other means by which vapour is quantified in this study – AH Riddlecombe continues to be the wall which measures the highest weights of vapour, as well as slightly higher %MC than that of Drewsteignton. The cob at Riddlecombe is a material which may be capable of containing high quantities of moisture as a vapour whilst simultaneously its %RH can reduce due to the drying of construction moisture bound within the wall. Indeed weights of vapour, whilst still the highest of the three walls, are reducing year-on-year. Therefore, the higher AH may be an anomaly caused by the particular characteristics of the earth wall material whilst the general trend of both the vapour and material moisture analysis suggest that moisture is reducing. %RH remains above the 80% risk threshold yet if the current trajectory is maintained perhaps we could expect it to eventually fall below this. Or perhaps, alternatively, an equilibrium will be reached when the wall has expelled the majority of its construction moisture, but vapour quantities will remain above those that are considered safe for other, more standard, building materials. Unfortunately, as this is the final year of measurements and monitoring equipment has now been removed in this wall, we will not see if and when an equilibrium state is reached and its resulting moisture profiles.

Average AH has also reduced this year in the wall at Drewsteignton but the wall has the highest %RH trend and its annual average %MC has increased this year. For this wall, the lower AH perhaps reflects a lack of evaporative opportunities over the annual period, whereas, assessment via the quantities of %RH or %MC suggests an increase in moisture at this location. Although the stone of the wall at Drewsteignton may not be able to hold or move much liquid water, other materials within the structure - principally the lime mortar, are capable of this and high vapour quantities may be present both within the mortar as well as the pores and microfissures of the granite. %RH records would suggest that vapour is accumulating within the central part of the wall to levels approaching air saturation. Whilst this may not pose a direct risk to the granite material, timber embedded in the wall sharing such conditions could be judged to be at risk, particularly because these conditions have been in existence for some years now (by extension, the same risk may pertain to timber materials currently within the wall at Riddlecombe.) Monitoring is continuing at this location and it is possible that the trend of rising %RH will continue until it reaches or exceeds 100%. Moisture behaviour in this wall appears to be less directly influenced by the weather patterns of individual years and possibly more associated with the refurbishment intervention which includes a moisture barrier that prevents moisture movement and has substantially cooled the masonry fabric, increasing the incidence of dewpoint. Therefore, it is possible that we will not see a change in this trend until alterations are made to the refurbished part of the wall.

In terms of its moisture profile, the wall at Shrewsbury is more positive – the %RH trends here being below the risk threshold and on a downward trajectory. We can also perhaps be more certain as to whether the %MC values, being well below 5%, represent a risk to this brick-built wall (albeit less dense, historic, low-fired, more porous, and permeable bricks, quite different from their modern equivalents). However, what the analysis does show is how moisture behaviour in the wall is dictated by weather conditions, in that a wet year can produce a temporarily risky vapour profile. That these conditions are not sustained over years is a reflection of the materials and the physical qualities of the wall, including its aspect, however - in this instance - the insulation material does not appear to have had a negative impact and perhaps helps ameliorate more extreme moisture responses in proximity to the critical interface and internal surface.