The SPAB RESEARCH REPORT 2.

The SPAB Building Performance Survey 2014

Interim Report

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ArchiMetrics Ltd.

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The SPAB Building Performance Survey Interim Report 2014

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Acknowledgements

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

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This research is conducted on behalf of the SPAB by ArchiMetrics Ltd and Greenfootsteps, Cumbria. The SPAB Building Performance Survey arose from work previously carried out by ArchiMetrics for the SPAB which compared measured and calculated U-values for traditional buildings. The Building Performance Survey is a more comprehensive study which measures a wide range of aspects of building performance and has recently been extended to provide longer term interstitial hygrothermal performance monitoring in three properties as the SPAB Building Performance Survey II.

1.1 Introduction

This report is the fourth in a series which details the interim findings of the SPAB's Building Performance Survey, a research project that looks at the performance of traditional buildings before and after refurbishment designed to improve energy efficiency. Measuring across a range of parameters, the Survey looks at ways the energy performance and environmental behaviour of traditionally-built dwellings may be affected by retrofitting or refurbishment. Specifically the study looks at:

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

During a two-week period between January and April 2011 measurements were taken in seven properties whilst in an 'unimproved' condition. In 2012, measurements were repeated in four of the properties that had completed their refurbishment work and long-term interstitial measurements of temperature and relative humidity (interstitial hygrothermal gradient monitoring - IHGM) were installed in three of these buildings. Two previous editions of this report, 2012 and 2013, provide details of the findings of the post-refurbishment measurements carried out in four buildings; Shrewsbury, Drewsteignton, Riddlecombe and Skipton. This 2014 report provides findings from the long-term IHGM monitoring at Shrewsbury, Drewsteignton and Riddlecombe. Two of these properties are based in the South West of England - Drewsteignton and Riddlecombe - and the third is located in the city of Shrewsbury in Shropshire.

With the exception of Drewsteignton the refurbishment work undertaken at these properties has been directed by their owners. The house at Drewsteignton consists in part of a former barn constructed with solid granite walls and here the owner has allowed the SPAB to install an experimental section of polyisocyanurate (PIR) internal wall insulation (IWI). The house at Riddlecombe is of cob which has been re-rendered with an insulating render and at Shrewsbury the construction is solid brick with the addition of woodfibre IWI.

The 2014 report presents findings from the individual buildings followed by a discussion of these results and a brief conclusion. The measurements of temperature and humidity (IHGM monitoring) used in this study is analysed using a variety of terms described in section 1.2. Further background information, including details of the monitoring procedures and data processing used in the study can be found in the first version of this report, *SPAB Research Report 2: The SPAB Building Performance Survey 2011 Interim Report*.

1.2 Definitions & Analyses

<u>Absolute Humidity (AH) & Relative Humidity (RH)</u>

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 quantity of vapour present at a particular location at a particular point in time and thus is another 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 that particular temperature. It is given as a percentage in relation to saturation or dewpoint, i.e. at 100%RH the air has become saturated and vapour may begin to condense out as liquid water. High RH (80%+) is one of the conditions required for mould fungus formation. Dewpoint (100%RH) is the point at which the possibility of condensation may occur.

Relative and Absolute humidity behaviour is presented over time for the three walls within the study. Each property is provided with two graphical analyses; one based on full resolution data, that is each data point collected (measurements are made at 5 minute intervals) goes to make up the plot for each condition collected from the various sensors. The other, a daily aggregation of the data collected over the reporting period, that is an average of the values measured over a 24 hour period (288 values) is calculated and used as the basis for the plots of the individual conditions. The daily aggregation analysis allows for greater differentiation between sensor plots and thus a clearer overview of conditions. Full resolution provides a more detailed picture where specific characteristics of particular walls, such as porosity and air tightness, can be discerned.

Dewpoint & Dewpoint Margins

Dewpoint is the temperature at which air reaches vapour saturation. The difference between the measured temperature and dewpoint temperature we term the dewpoint margin and represents the temperature drop required for condensation to begin at the measured locations within the wall, Figure 1. Convergence of the measured temperature and dewpoint temperature indicates the possibility of interstitial condensation at a particular location. As such the dewpoint margin could be seen as an indication of the risk of interstitial condensation occurring within the wall fabric. Some interstitial condensation 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 condensation that does form can dry out without accumulating over longer periods of time.

Dewpoint and dewpoint margins are presented in the form of Hygrothermal Sections and plot averages of measured temperature and dewpoint temperatures for each of the walls on a monthly and annual basis.

Data Holes

During the extended periods of monitoring used in this study there are occasional losses of data. These occur of for a variety of reasons, most often due to interruptions to power supply. Where data is missing from an analysis values are shown as unchanging or as a gap and the absence is noted within the text.

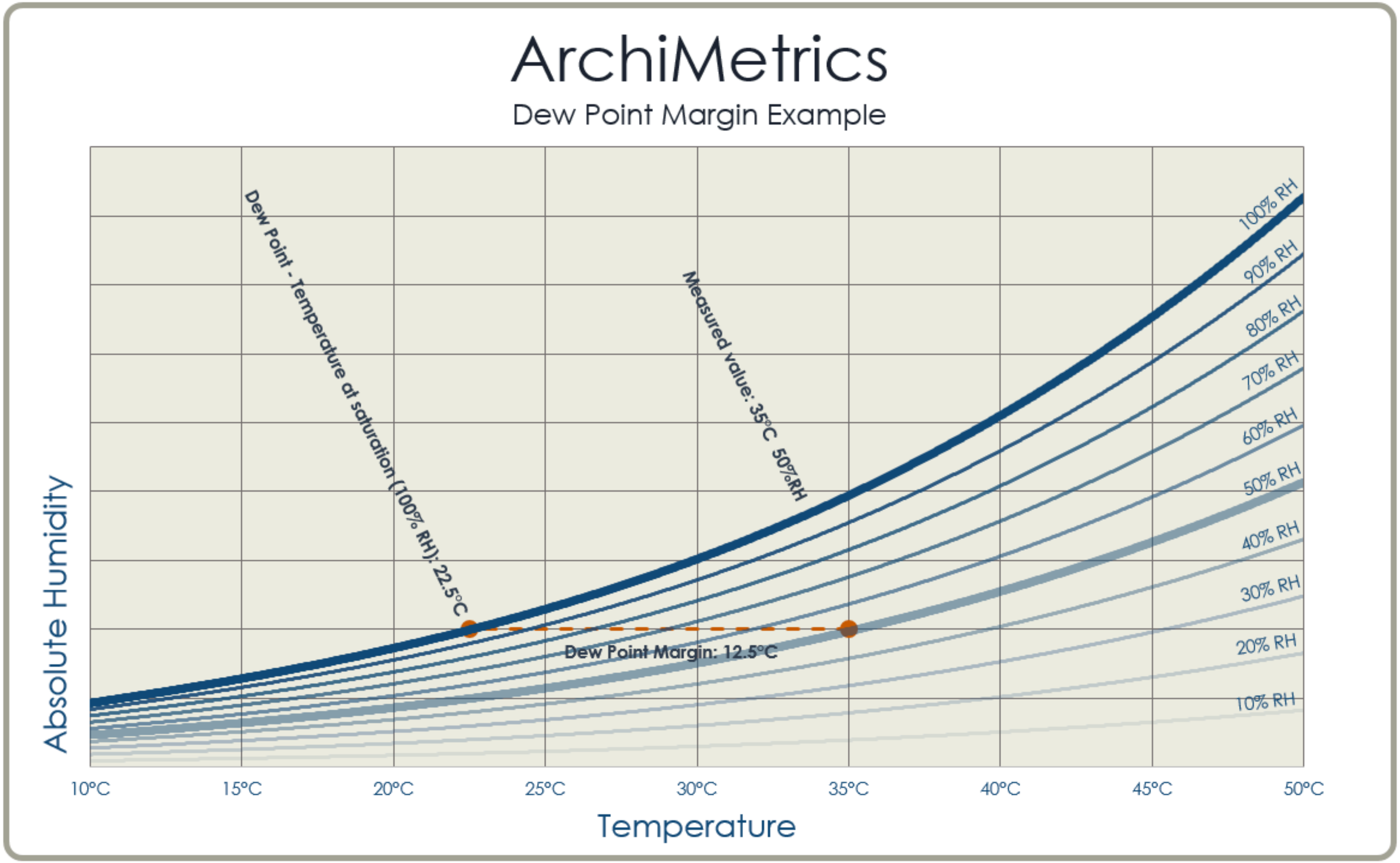


Figure 1. Illustration of Dewpoint Margin Principle.

2.1. 116 Abbeyforegate, Shrewsbury - 2013 - 14.

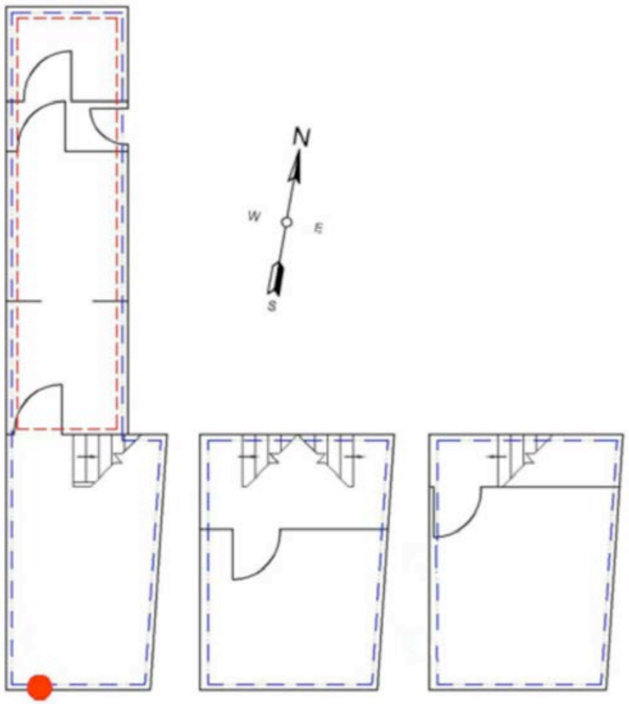


Figure 2. Plan of 116 Abbeyforegate, Shrewsbury, with ground floor on left hand side. The red dot indicates the location of the IHGM monitoring equipment.

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

Refurbishment: Between February 2011 - December 2012 the following refurbishment work was undertaken at Abbeyforegate: internal insulation of all external walls on the ground and first floor 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

Interstitial Hygrothermal Conditions

Figure 3. Interstitial Hygrothermal Gradient Monitoring, Shrewsbury.

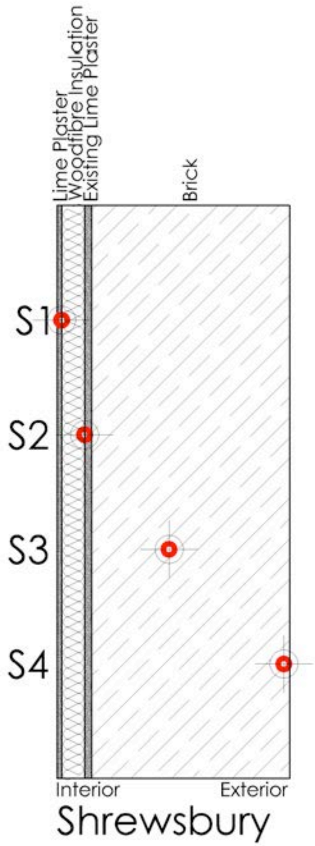


Figure 4. Position of sensors through wall section, Shrewsbury

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	385 mm
Overall	405mm			

Table 1. Interstitial hygrothermal gradient sensor positions for Abbeyforegate, Shrewsbury, 2012- 2013.

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 May 2013 - 30th April 2014, has been used as the basis for the following analysis.

Relative Humidity Over Time

Figures 5 and 6 show the RH responses measured in and around the test wall at Drewsteignton over the past year. Previously at Shrewsbury, Figure 7, we have found the %RH responses recorded in the wall to be quite dynamic in comparison to the granite wall at Drewsteignton and we have ascribed this to the condition and materials found in the wall's construction. The brick appears to be quite porous and the external pointing is in poor condition. In addition, the wall is south-facing so receives direct sunlight as well as the effects of the prevailing weather as the monitoring is located at the south-west corner of the front elevation. 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 vapour behaviour measured as RH. Of particular note are the extremes of response seen at sensor 4 which is located in close proximity to external conditions, 20 mm back from the external wall surface. This volatility continues to be evident in the 2013 - 14 monitoring (Figures 5 & 6) and is likely to persist as it is representative of the particular qualities of the construction and orientation of the wall and with regard to the extreme responses from sensor 4, the position of that particular sensor within the wall. In a similar way to the 2012 - 13 monitoring, it is also of note that despite this volatility the %RH responses measured deeper inside the wall, at sensor positions 2 and 3, fluctuate within quite a narrow range for the majority of the year, being around 70%. In a similar way to that of the previous year, in 2013 – 14, there is a period of time over winter where RH at sensor 4 reaches 100% or dewpoint, no doubt in response to the wet and cold weather. The extremity of conditions over the past winter can be seen in the RH behaviour at sensor 3 where, in the previous year, RH measured at this location peaked at 95%. For 2013 -14 the peak is 100%. An examination of weather records for Shrewsbury shows that the rise in RH seen at sensor 3, which starts week beginning 25th December, is commensurate with an extended period of rain and strong winds from the south west driving rain on and into the wall (Figures 8 & 9). This causes an associated rise in vapour quantities reflected in high %RH measurements at both sensor 4 and deeper within the wall at sensor 3, a phenomenon not seen in the previous year. However, as with the previous year, one can feel confident that despite the extreme wetting that has occurred to the fabric during an exceptionally wet winter, given the orientation and condition of the wall, its access to the drying influences of heat from the sun and plenty of air exchange, this wall material will dry out and RH responses moving into the summer of 2014 will reflect this accordingly.

By and large the wall continues to function within safe limits with regard to the risk of mould growth with average measurements of RH from sensors 1, 2 and 3 being below 80% and that of sensor 4, 81%, also representing little risk, conditioned as it is by its extreme proximity to external conditions. The responses of the two sensors positioned either side of the woodfibre insulation are of interest; during the summer months these track one another closely suggesting a good amount of vapour exchange either side of the insulation. On the whole the RH measured from sensor 1 is also lower than that recorded within the room reflected in the monthly averages of RH for the two locations as well as the averages found over the whole year, room humidity being 71% and sensor 1 being 66%, Table 2. (Although it should be noted that the record of internal room humidity is not complete for the full year). Sensor 1 is located on the internal face of the woodfibre insulation in close proximity to room conditions and the lower RH recorded at this location may reflect an element of hygroscopic buffering by the lime plaster finish which limits the degree of vapour penetration deeper into the wall.

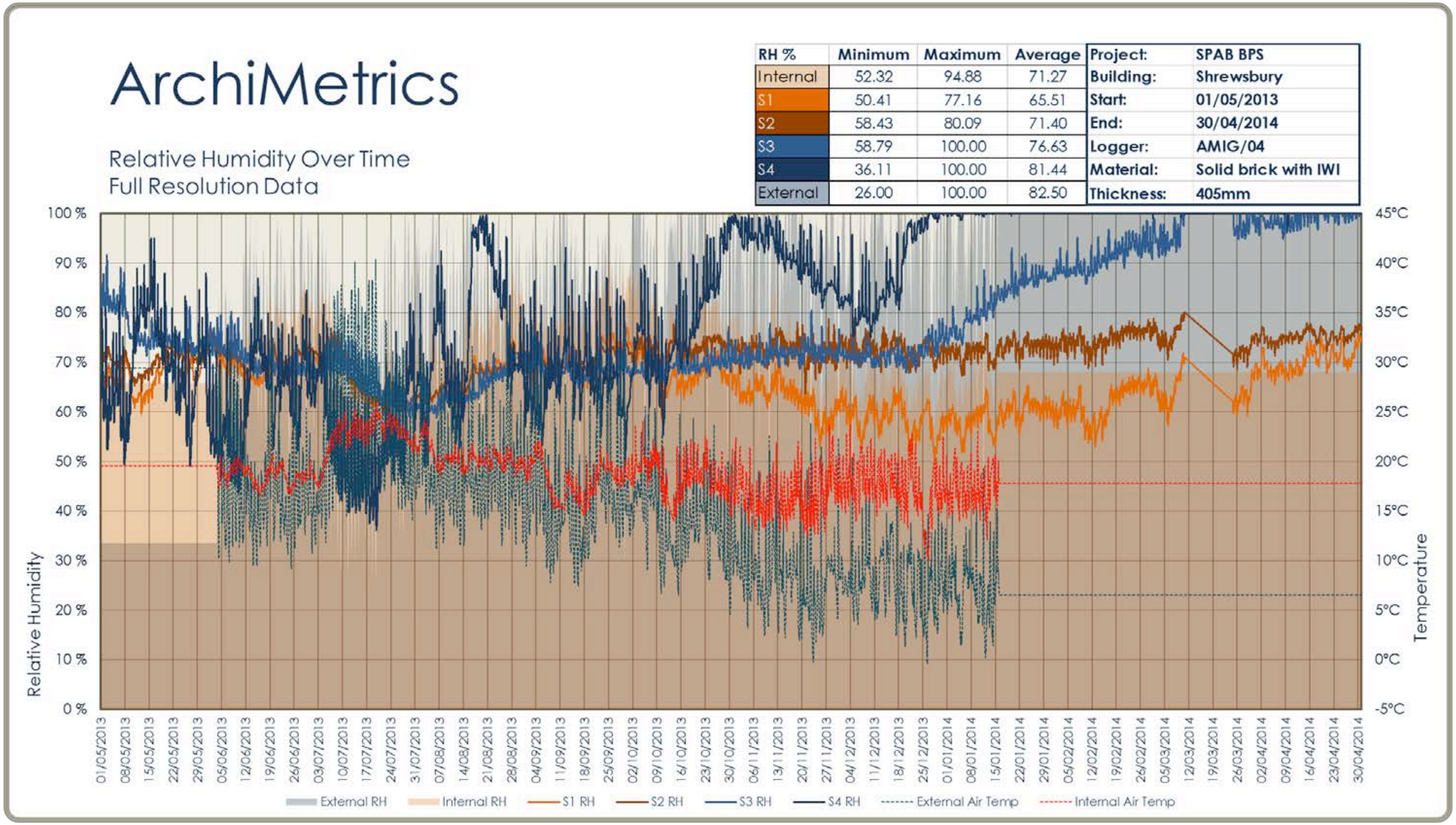


Figure 5: Relative Humidity over time, Abbeyforegate, Shrewsbury 2013 - 2014. Full Resolution.

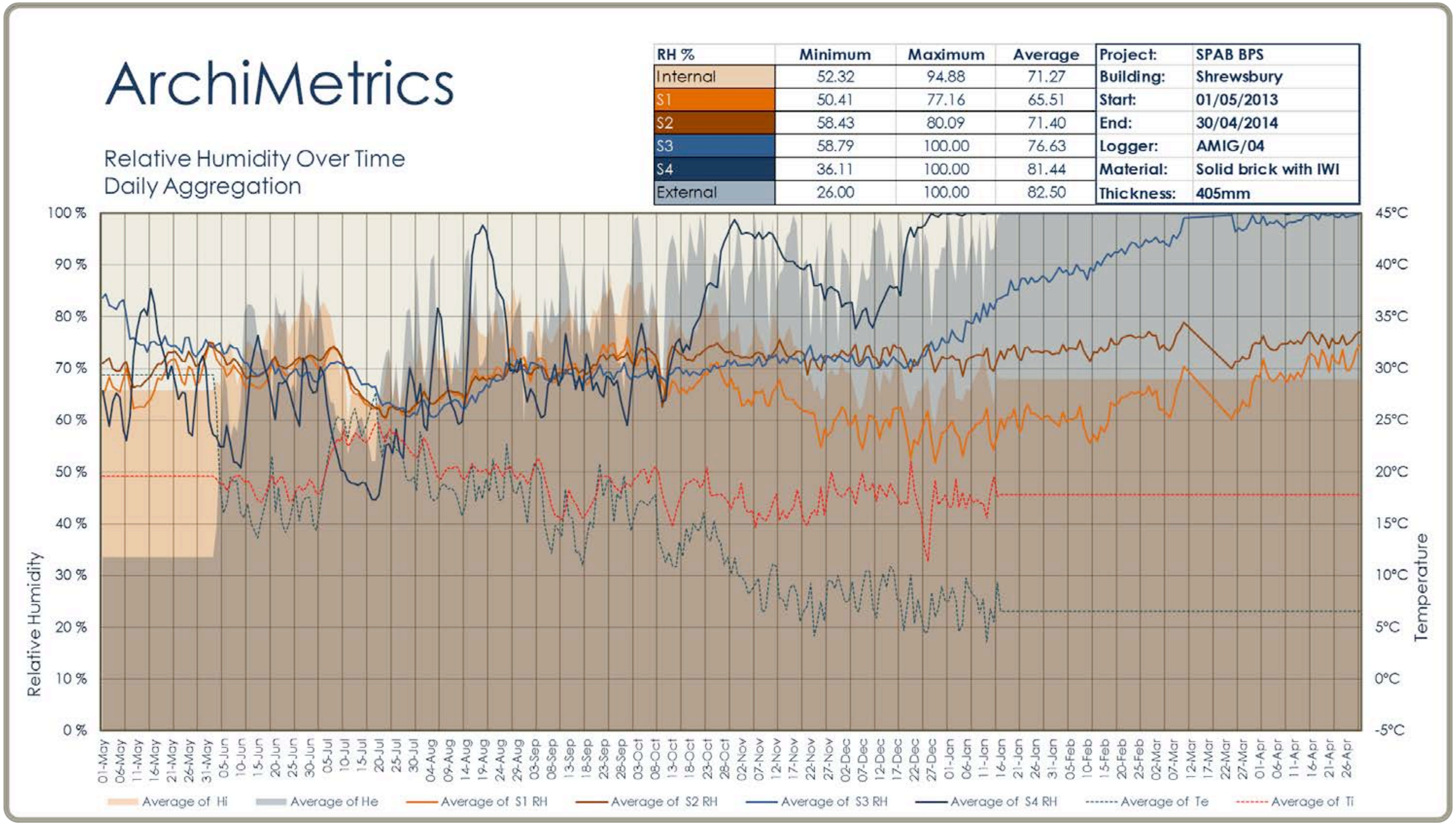


Figure 6: Relative Humidity over time, Abbeyforegate, Shrewsbury 2013 - 2014. Daily Aggregation.

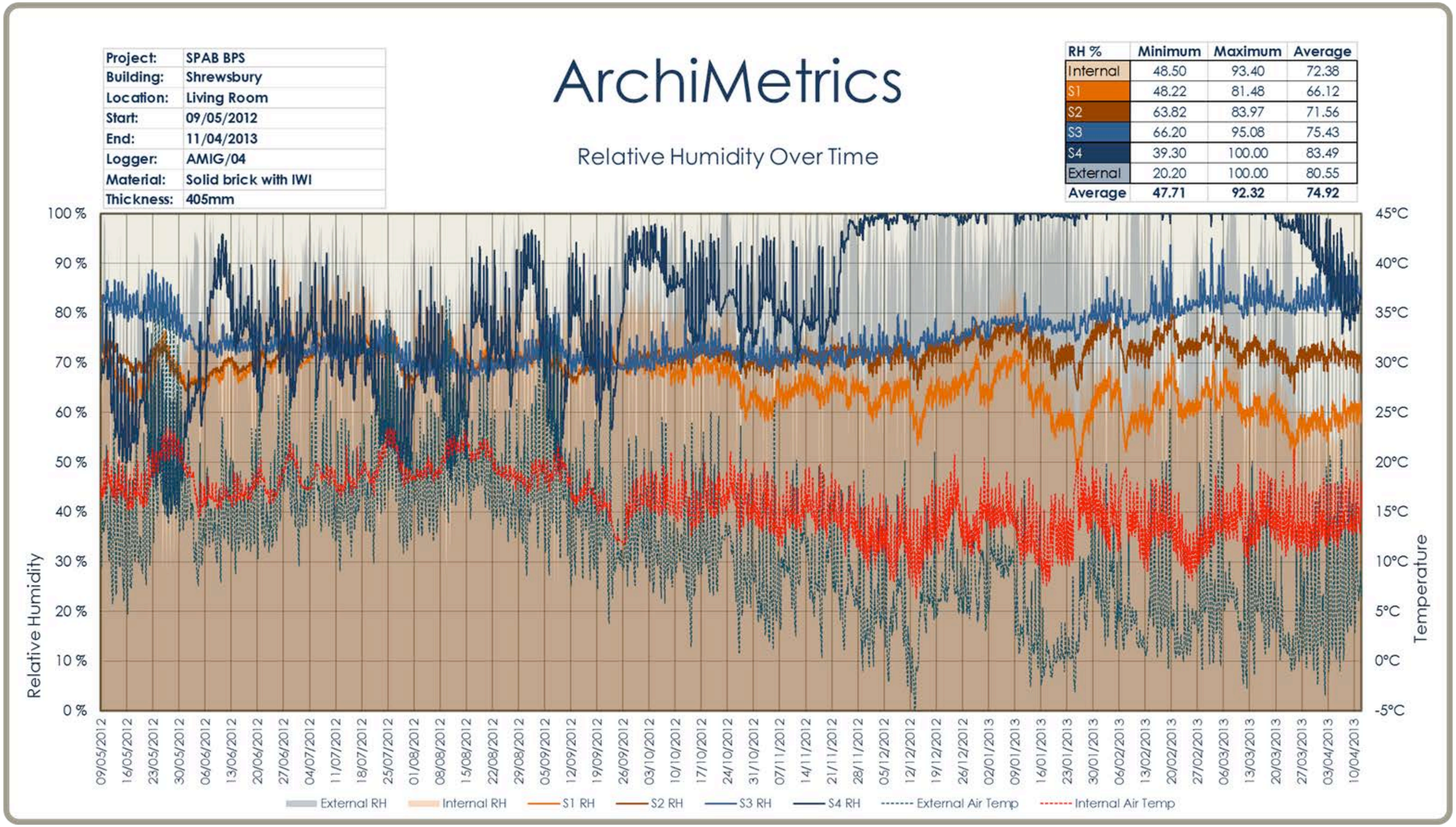


Figure 7: Relative Humidity over time, Abbeyforegate, Shrewsbury 2012 - 2013. Full Resolution.

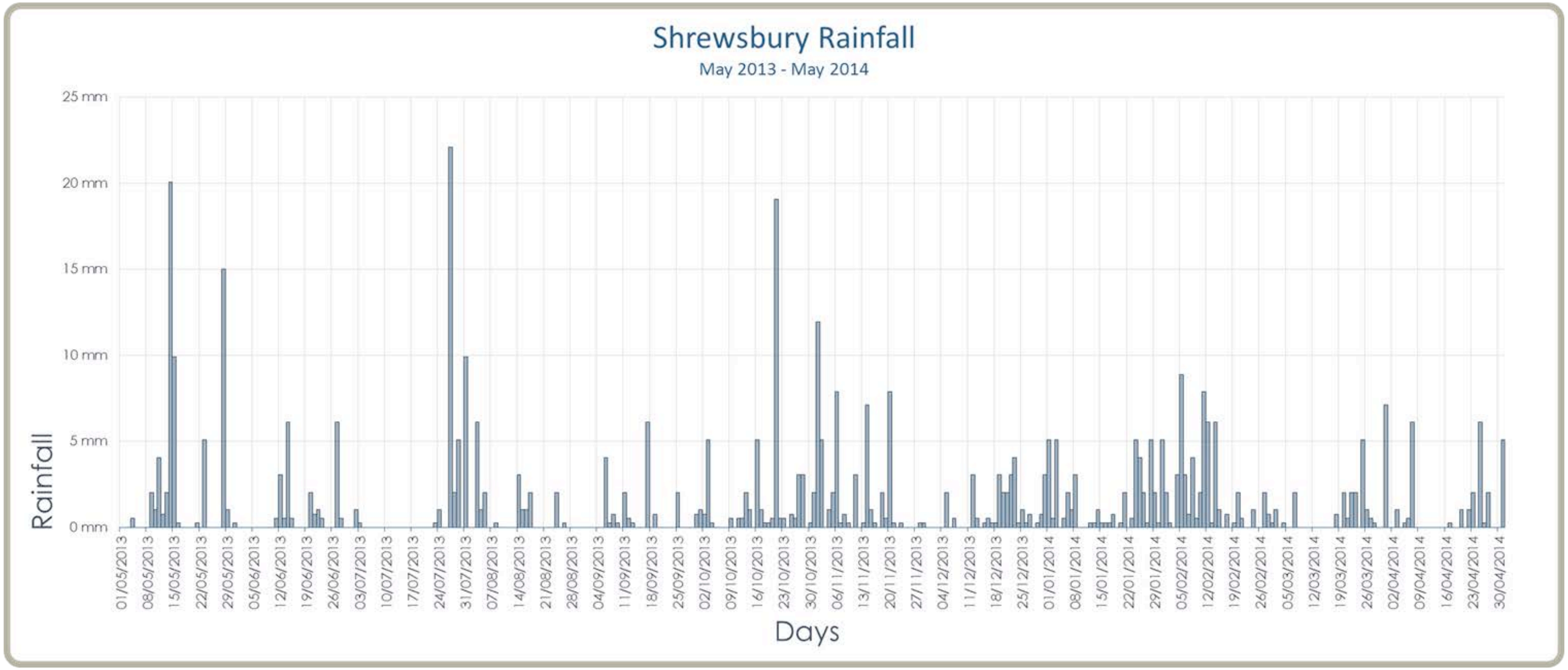


Figure 8: Daily Rainfall mm, Shrewsbury 2013 - 2014.

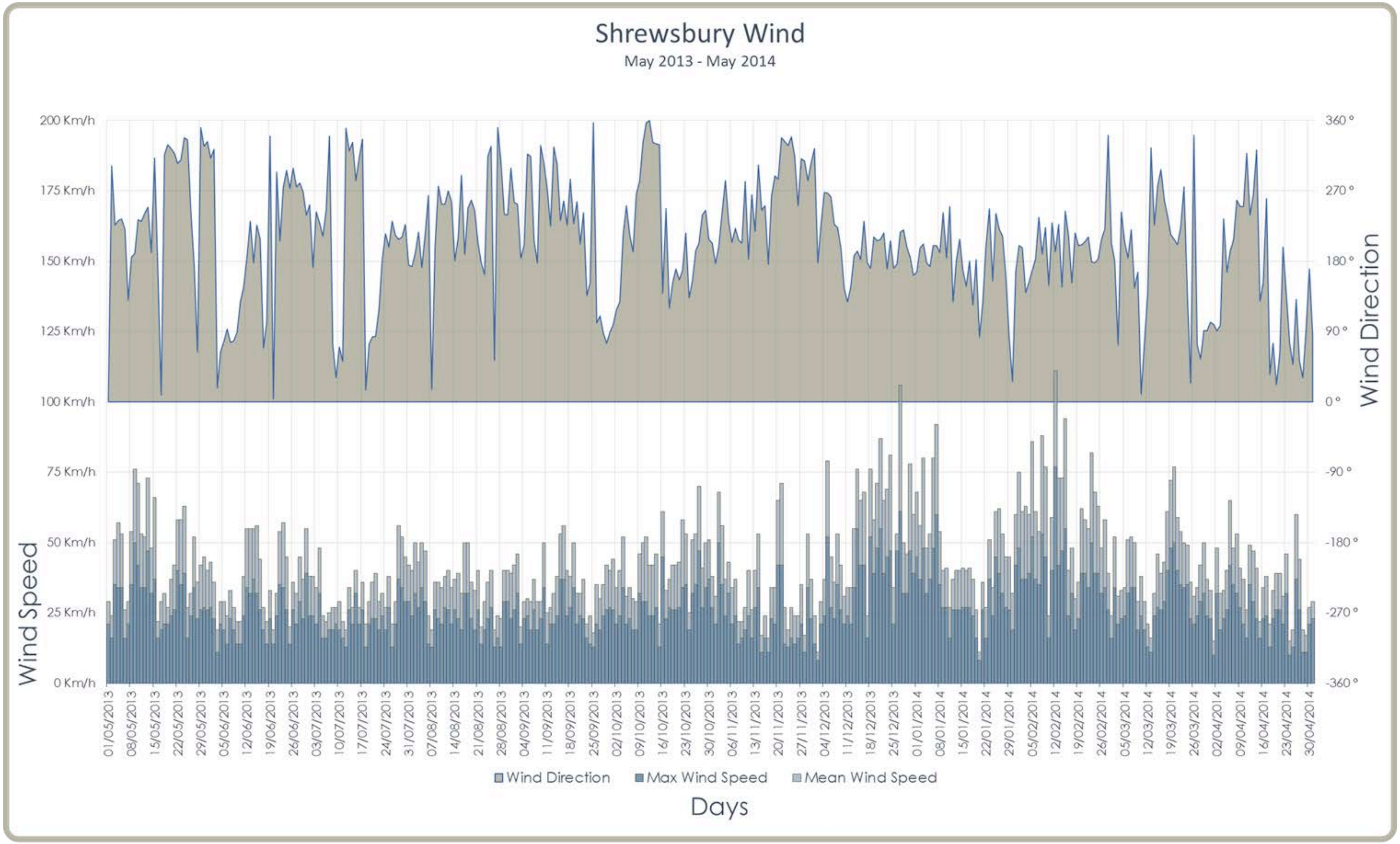


Figure 9: Annual Wind Speed (Km/h) and Direction, Shrewsbury 2013 - 2014.

Shrewsbury Monthly RH Averages						
	Internal RH	S1 RH	S2 RH	S3 RH	S4 RH	External RH
2013						
May	65.82	67.28	70.54	76.59	68.78	33.52
Jun	74.87	69.66	70.99	70.86	62.88	68.70
Jul	69.61	65.83	66.30	66.36	55.27	66.65
Aug	76.02	67.32	66.81	65.32	75.80	76.99
Sep	79.48	70.71	70.28	68.93	66.66	79.63
Oct	78.52	68.55	72.36	69.39	78.21	88.60
Nov	72.50	62.53	72.31	71.69	91.26	90.00
Dec	66.61	58.48	72.50	71.87	88.60	90.83
2014						
Jan	67.76	59.19	72.44	82.79	99.95	97.07
Feb	68.01	61.40	74.51	91.04	100.00	100.00
Mar	68.01	64.04	74.23	96.20	99.99	100.00
Apr	68.01	70.37	75.24	98.95	99.99	100.00
Average	**71.27**	**65.51**	**71.40**	**76.63**	**81.44**	**82.50**

Table 2. Relative Humidity Monthly Averages, Abbeyforegate, Shrewsbury, 2013 -14.

Absolute Humidity Over Time

Figure 10 shows an analysis of absolute humidity through the insulated wall section at Shrewsbury between May 2013 - April 2014. As expected the analysis of absolute humidity through the insulated wall section at Shrewsbury shows the same seasonal variation to that observed in the previous year (Figure 11), the weight of vapour within the wall increases with that of atmospheric humidity over the summer months. However, the pattern of vapour distribution through the wall, greater quantities towards the external face over summer reversed in winter time to higher quantities towards the internal face, is less obvious in this year's 2013 -14 analysis. This is largely a result of the extremely wet and windy weather experienced during the early part of 2014, which means that the normal pattern of winter distribution is reversed and the outside of the wall records higher weights of vapour as a response to the wetter conditions. The analysis for the year 2013 -14 also demonstrates a few other aspects of note with regard to vapour behaviour. At times during the months of May, June and particularly July, the highest weights of vapour recorded through the wall section are at sensor 3. In July external temperatures rise causing the vapour in proximity to sensor 4 to evaporate, hence records of vapour weight from this sensor become the lowest recorded through the wall section. The weights of vapour at the three other sensors climbs steeply, particularly at sensor 3, perhaps as a reflection of the general increase in atmospheric vapour over the same period but without the evaporation opportunities afforded to the external face of the wall. However, it is interesting to note to what extent these quantities of vapour exceed those recorded from both the internal and external environments during this period. This suggests another, more latent influence, the evaporation of the residual moisture held deeper within the fabric due to the warming of the wall over this period. Towards the end of July and into August levels of vapour return to the more usual pattern, lower than or tracking those found internally and externally, as presumably the vapour produced by the summer heating of the fabric has progressed to internal and external surfaces where it has evaporated. Shortly after this period, in August 2013, we also see an unusual event where weights of vapour at sensor 4 peak and are detached from measurements made at the other sensor locations. Once again, this can be ascribed to the direct influence of external conditions on responses at sensor 4, this time in the form of rain. The low levels of absolute humidity previously seen at this location are a reflection of the drying opportunities afforded to the fabric in close proximity to sun and wind. However, when it rains the pattern reverses and vapour increases due to the sensor's proximity to wet material. The beginning of August shows the highest quantity of rainfall over the full year in Shrewsbury and hence the high humidity found at this location over this time.

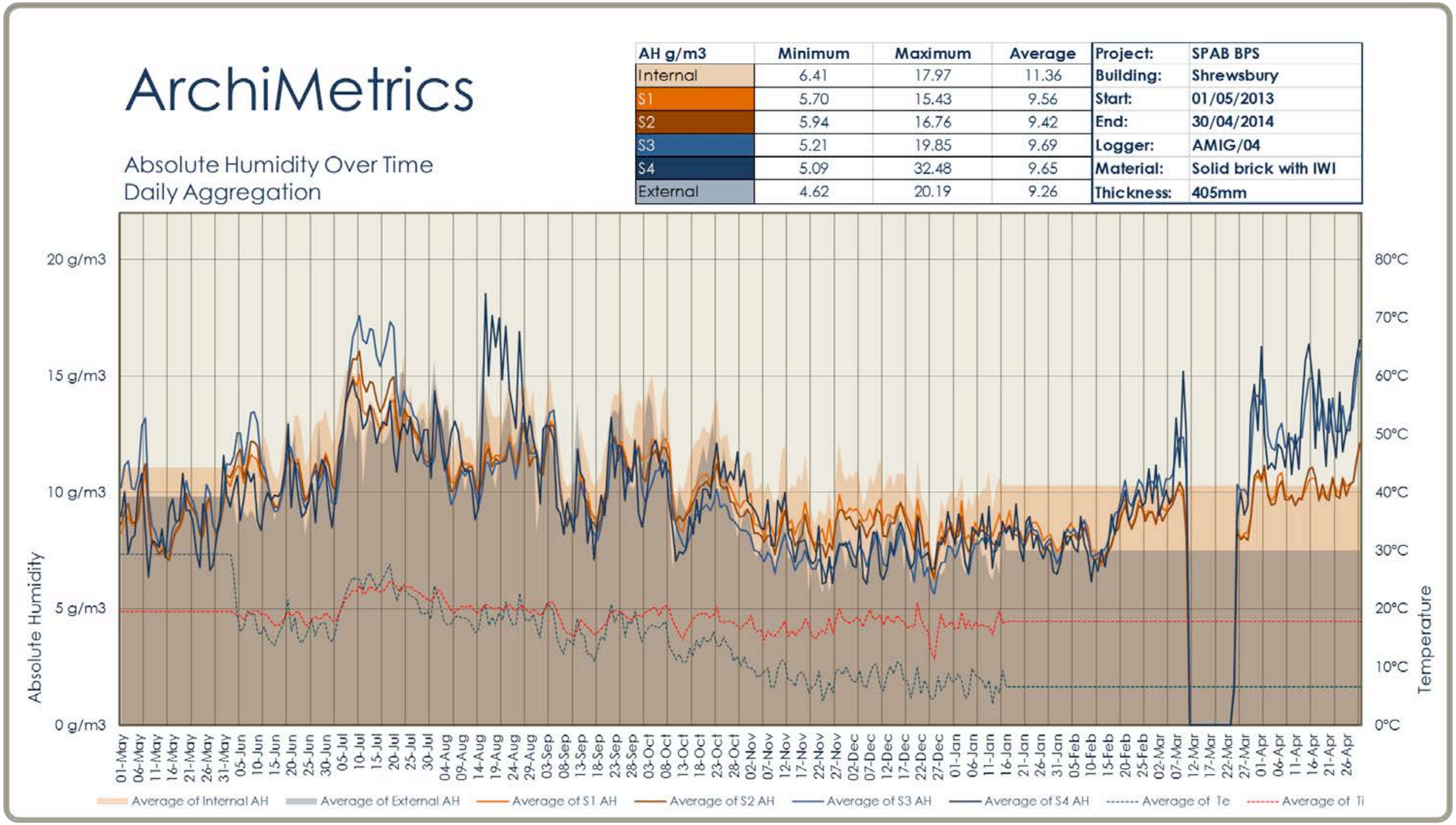


Figure 10: Absolute Humidity over time, Abbeyforegate, Shrewsbury 2013 - 2014. Daily Aggregation.

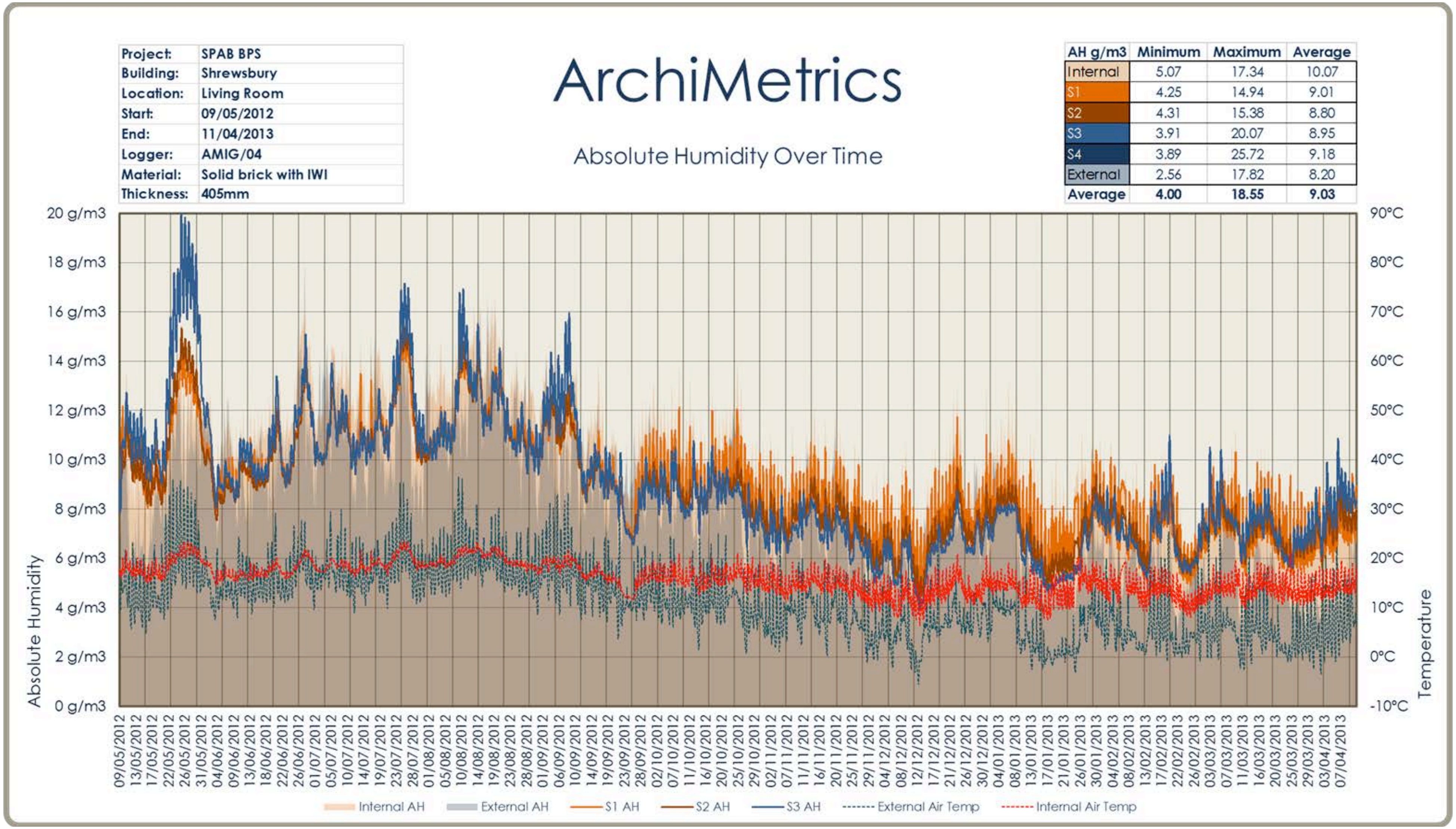


Figure 11: Absolute Humidity over time, Sensors 1 - 3, Abbeyforegate, Shrewsbury 2012 - 2013. Full Resolution.

Hygrothermal Sections & Dewpoint Margins

Measurements of temperature and RH are also used to plot annual and monthly averages of measured temperature and dewpoint through the wall section (Figure 12 and Figures 13 - 24). In Table 3 below, dewpoint margins are written as an average across all four measurement points within the section and also individually, showing the change in these average margins before and after the wall was insulated and over the following years.

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

Table 3. Dewpoint Margins & Pre & Post-insulation Difference, Abbeyforegate, Shrewsbury 2011 - 2014.

From this Table it can be seen that the dewpoint margins have narrowed somewhat following the insulation of the wall, but in comparison with other insulated walls in this study the margins are still quite large, being within whole degrees rather than points of a degree as is found at the other properties. The difference between the pre- and post-insulated margins is also smaller than those found for the other walls in the study. Both the margins and the difference compared with the pre-insulation calculations remain consistent between the first and second year post insulation or are slightly improved both on average and at sensors 3 and 4. This would seem to demonstrate a stable condition for the wall with little threat, on average, from interstitial condensation. Figure 25 present plots of the dewpoint margin from each of the four sensors through the wall section over time. In a similar way to the observations concerning relative and absolute humidity, this analysis shows the volatility of responses from sensor 4 conditioned as it is by the contrary influences of wind, rain and heat (sun). The analysis also clearly shows the effect of the wet winter weather which, come January 2014, quickly reduces the dewpoint margin at sensor 4 to 0˚C and is gradually followed by the margin at sensor 3 which reduces as the influence of the wet material on rates of humidity tracks back into the body of the wall. However, as before, given previously observed responses within the wall it is expected that the humidity measured at these locations will reduce with the onset of warmer temperatures.

An examination of the monthly averages for the wall section show some expected seasonal trends (Figures 13 - 24). Temperature gradients through the warmer summer months are flat through the wall fabric with similar temperatures internally and externally and over this period margins are pronounced. Moving into autumn and winter and the advent of the heating season, the pitch of the temperature gradient becomes steeper moving from the interior side of the wall to the exterior with the increase in internal and external temperature difference. Similarly the colder external conditions cause dewpoint margins to narrow, particularly at sensor 4 in proximity to colder conditions. The months January - April 2014 see a convergence of the temperature and dewpoint gradients reflecting the low temperatures and high RH measured over this period as a result of the persistent driving rain experienced by the wall. Also of note, the extremely high external surface temperature and a raised dewpoint gradient at sensor 3 plotted for the month of May 2013. This would seem to confirm a high degree of direct sunlight for the south-facing wall during this month which results in the evaporation of moisture and hence high vapour levels deep within the wall section as previous described in the absolute humidity section. In July 2013 the orientation of the wall is evident in the temperature gradient plotted for this month, where instead of flat lining the heat flow is, on average, reversed through the wall due to the effect of long periods of direct sunlight and the generally warm external temperatures.

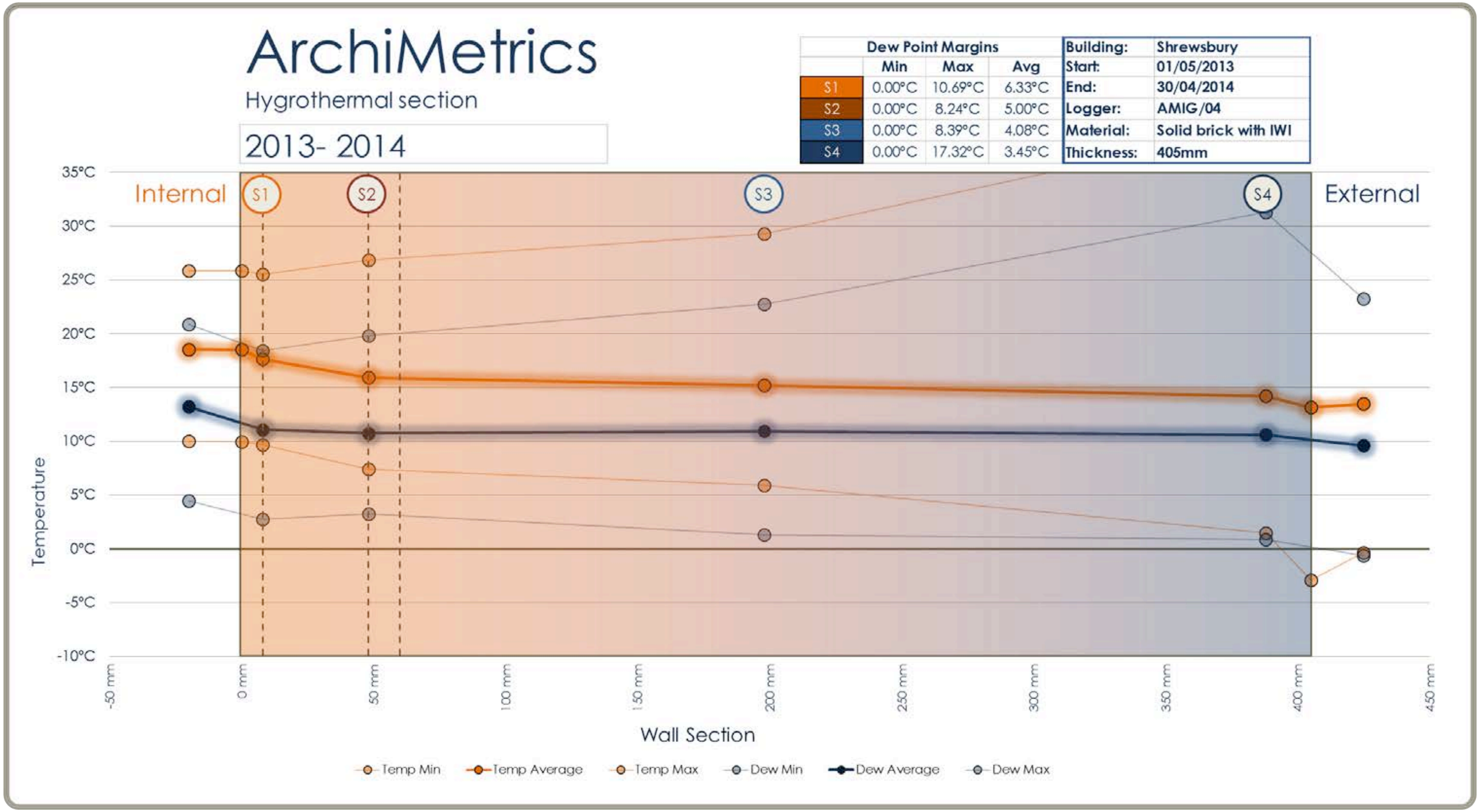


Figure 12. Hygrothermal Section, Abbeyforegate, Shrewsbury May 2013 - April 2014.

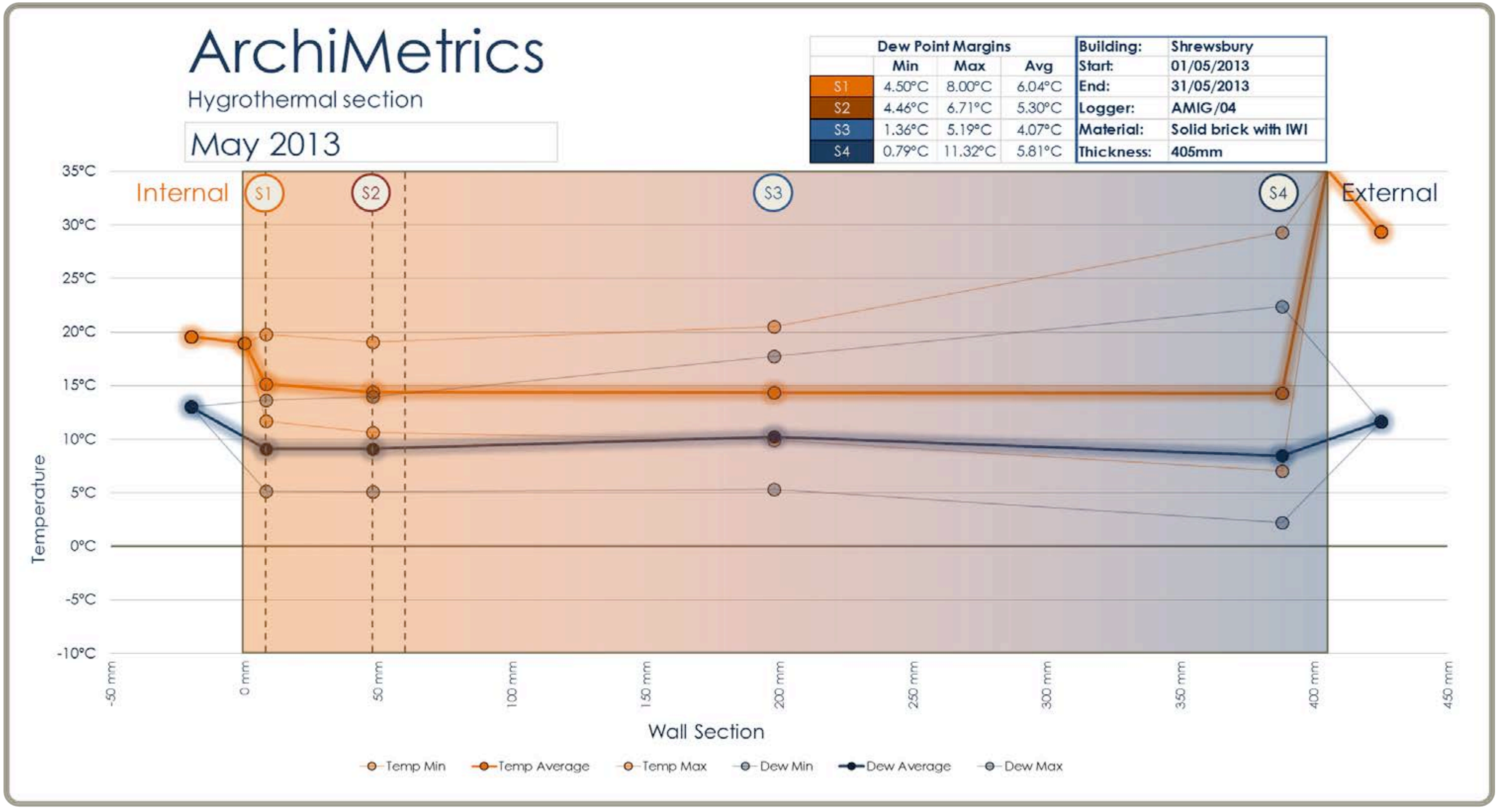


Figure 13. Hygrothermal Section, Abbeyforegate, Shrewsbury May 2013.

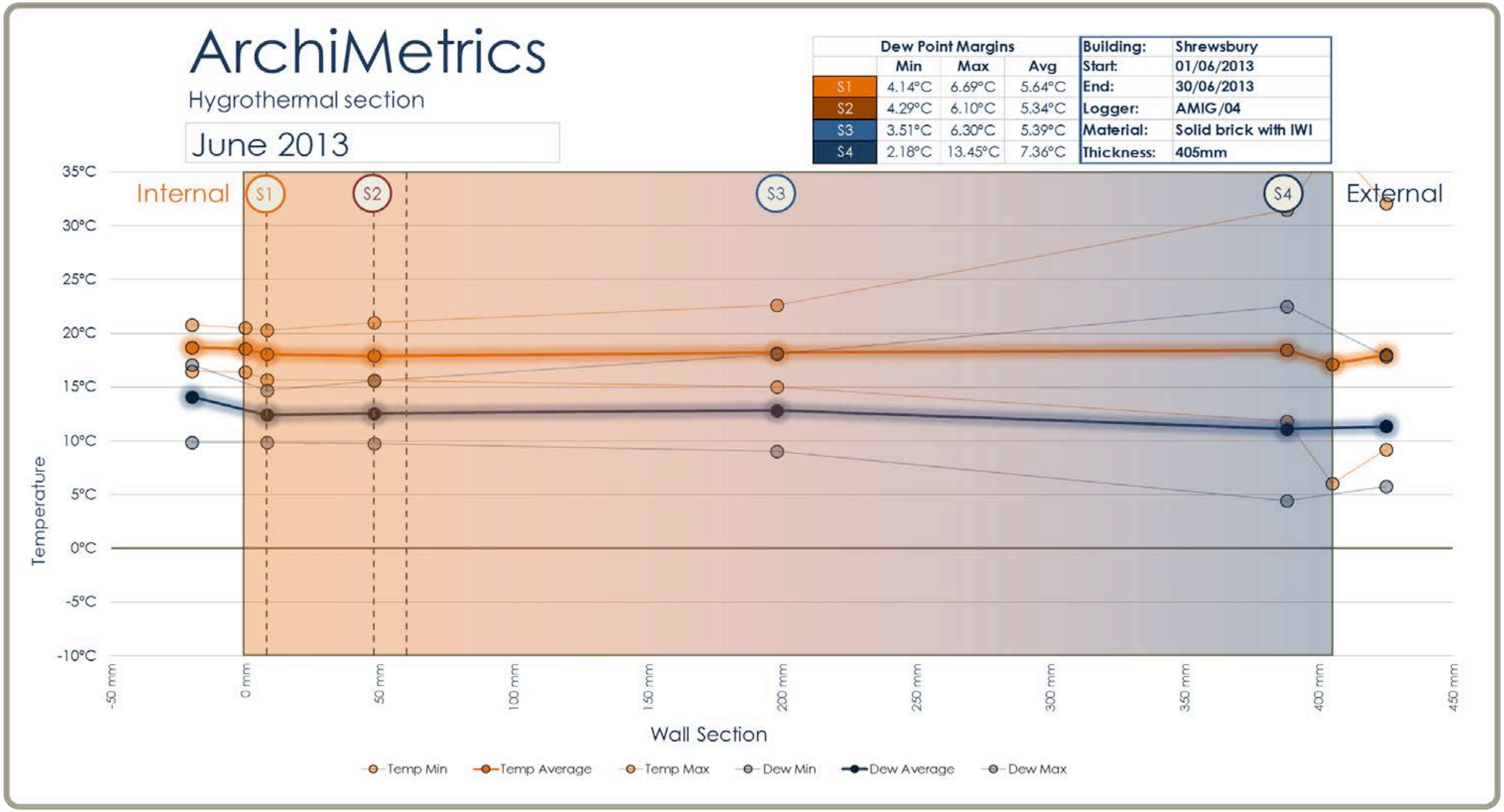


Figure 14. Hygrothermal Section, Abbeyforegate, Shrewsbury June 2013.

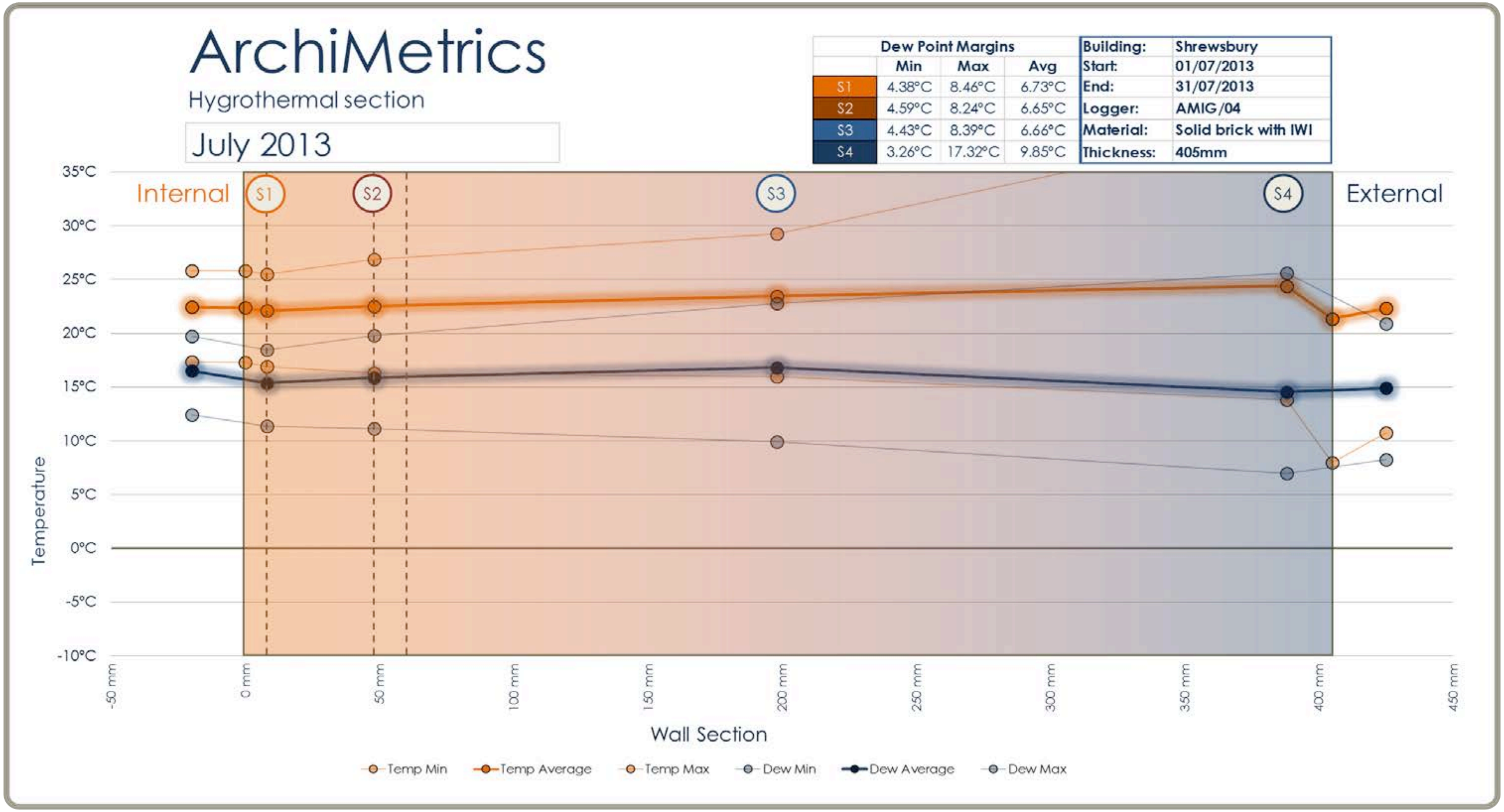


Figure 15. Hygrothermal Section, Abbeyforegate, Shrewsbury July 2013.

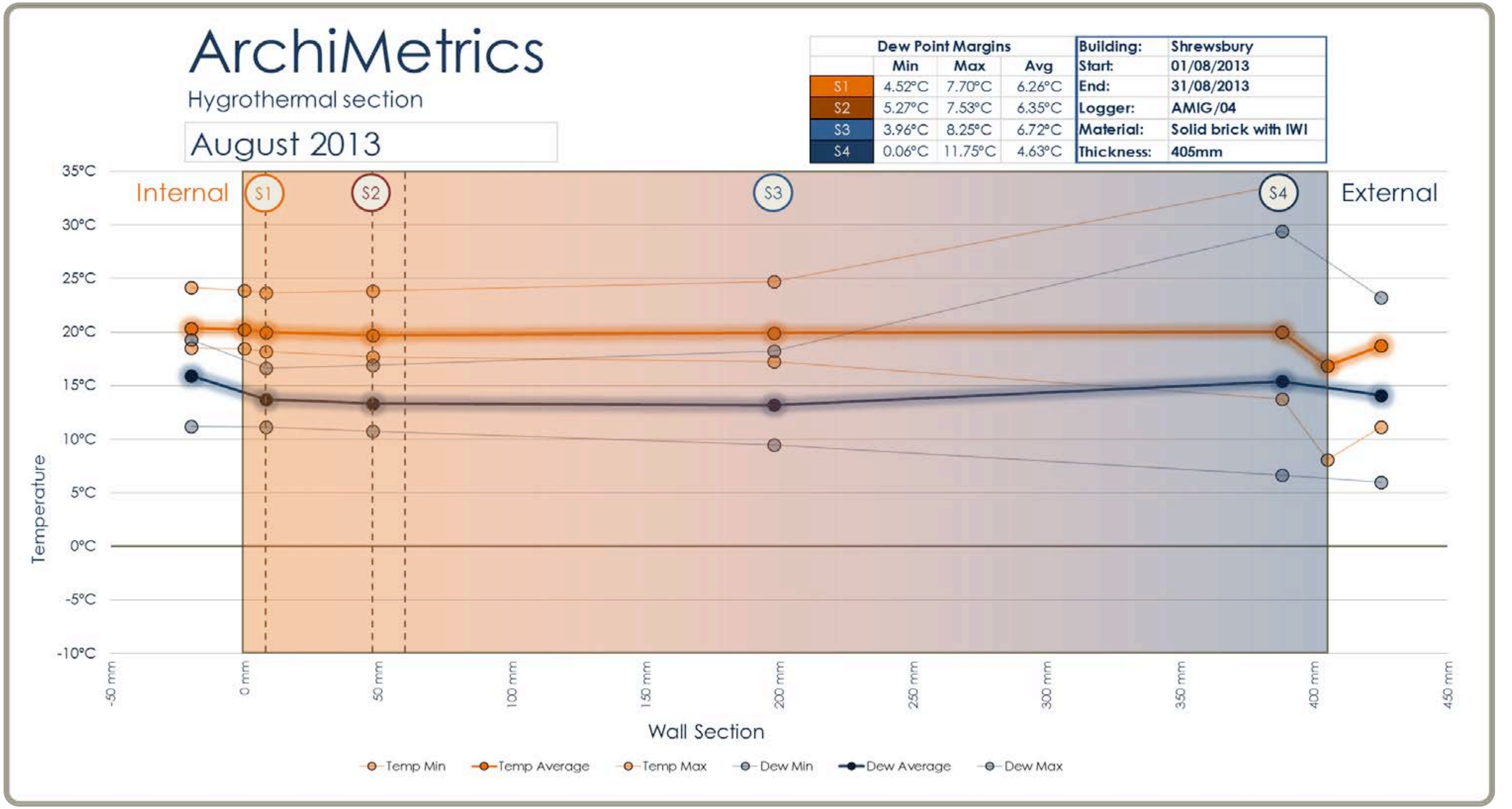


Figure 16. Hygrothermal Section, Abbeyforegate, Shrewsbury August 2013.

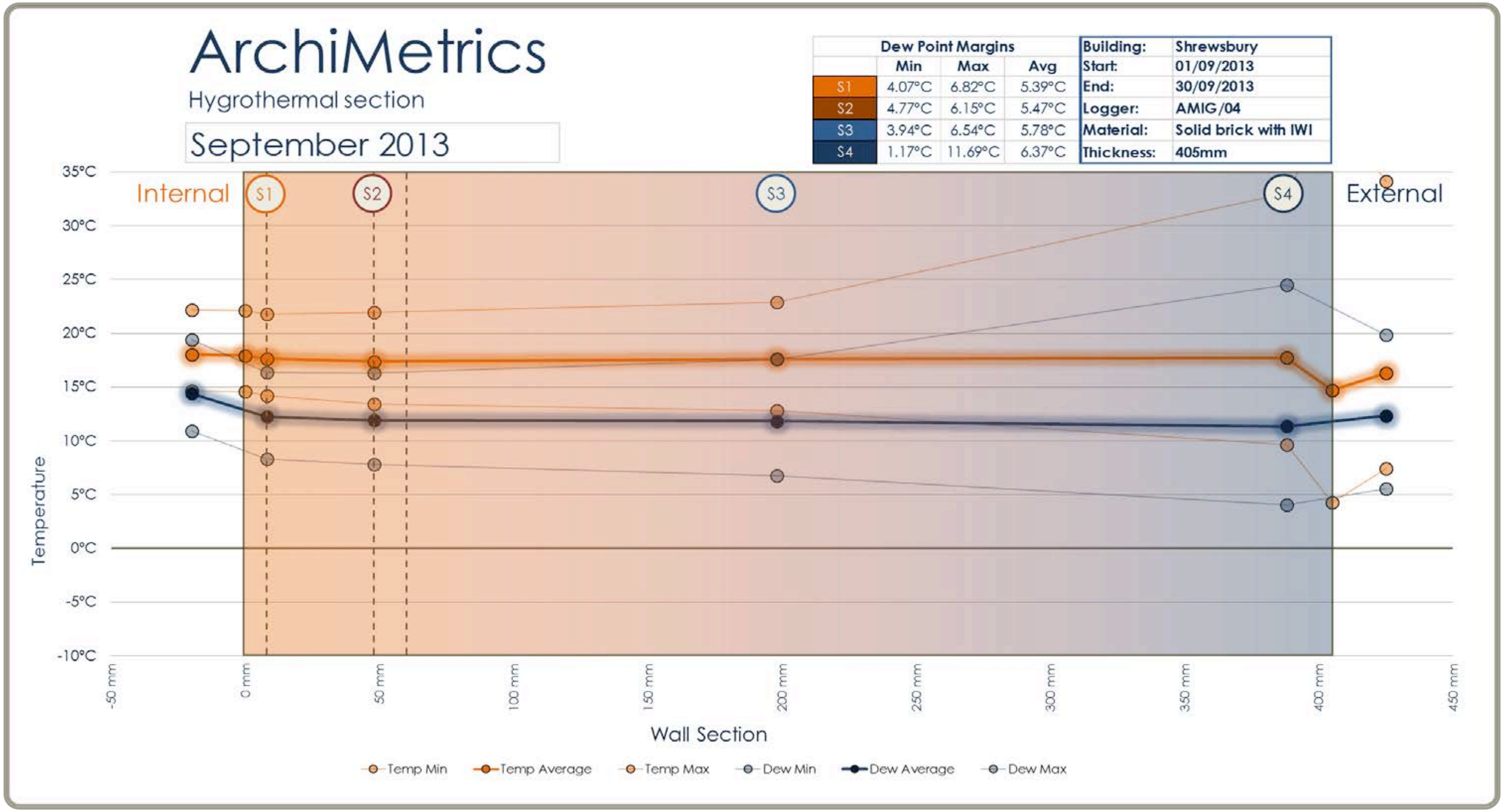


Figure 17. Hygrothermal Section, Abbeyforegate, Shrewsbury, September 2013.

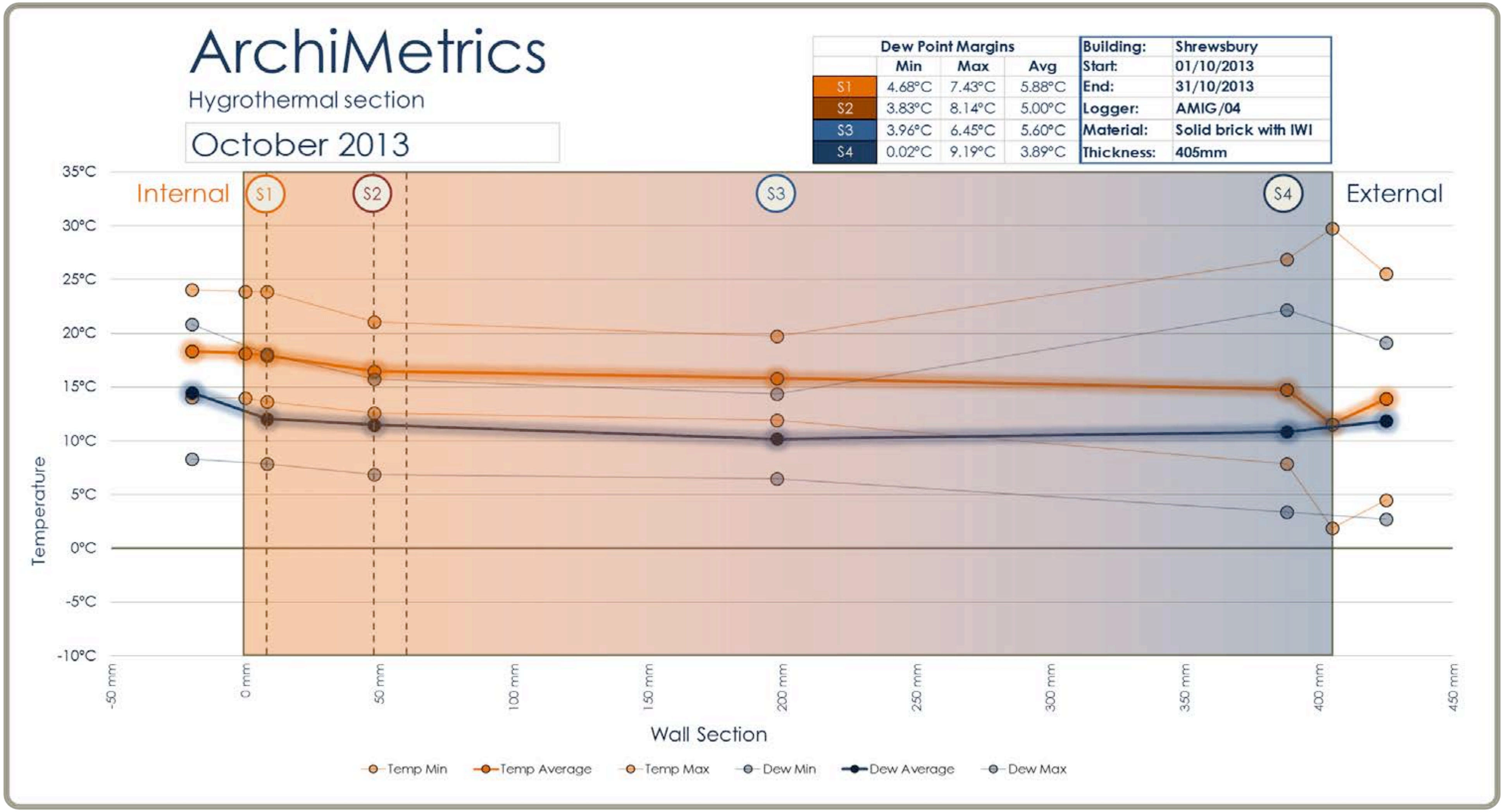


Figure 18. Hygrothermal Section, Abbeyforegate, Shrewsbury, October 2013.

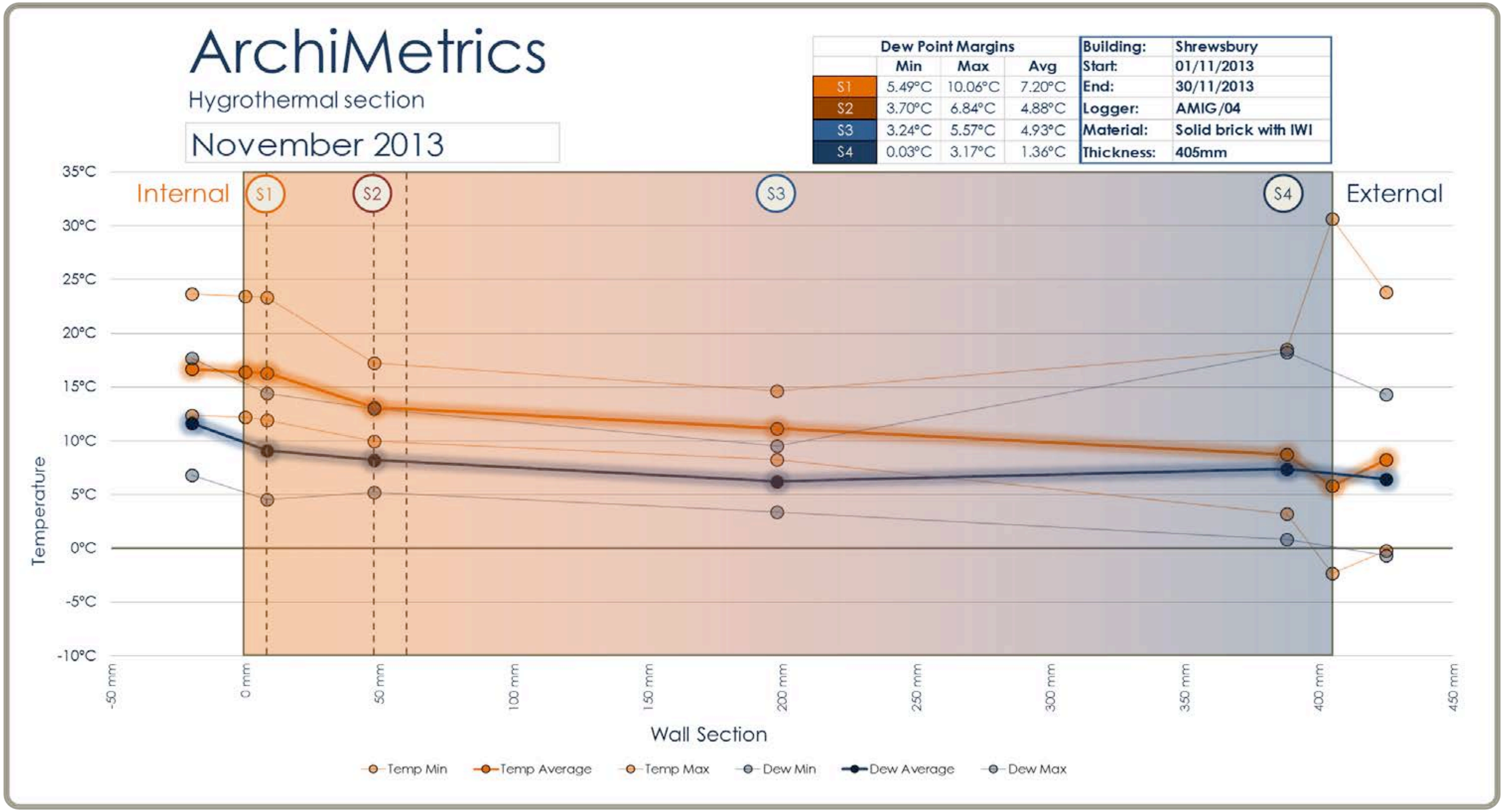


Figure 19. Hygrothermal Section, Abbeyforegate, Shrewsbury, November 2013.

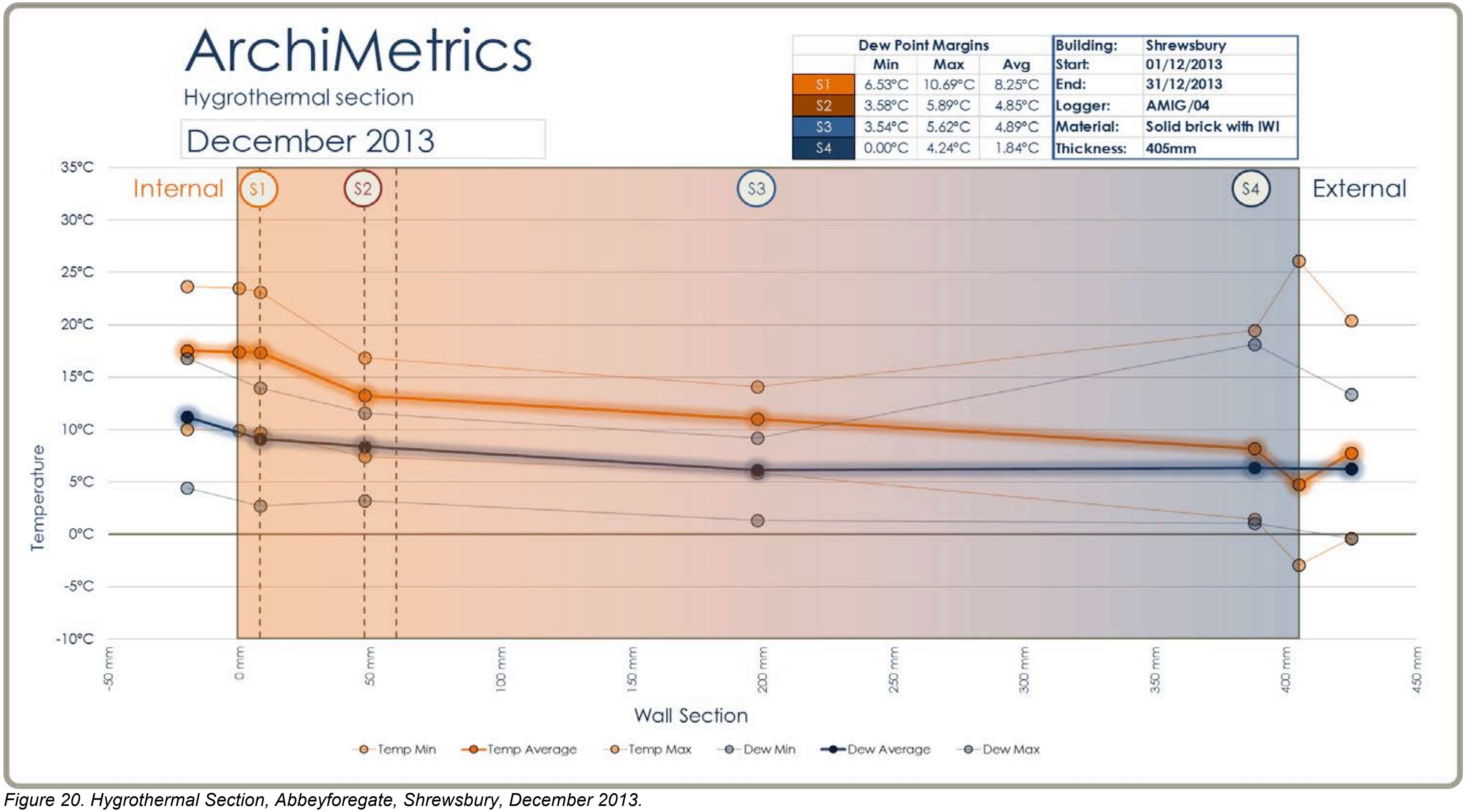


Figure 20. Hygrothermal Section, Abbeyforegate, Shrewsbury, December 2013.

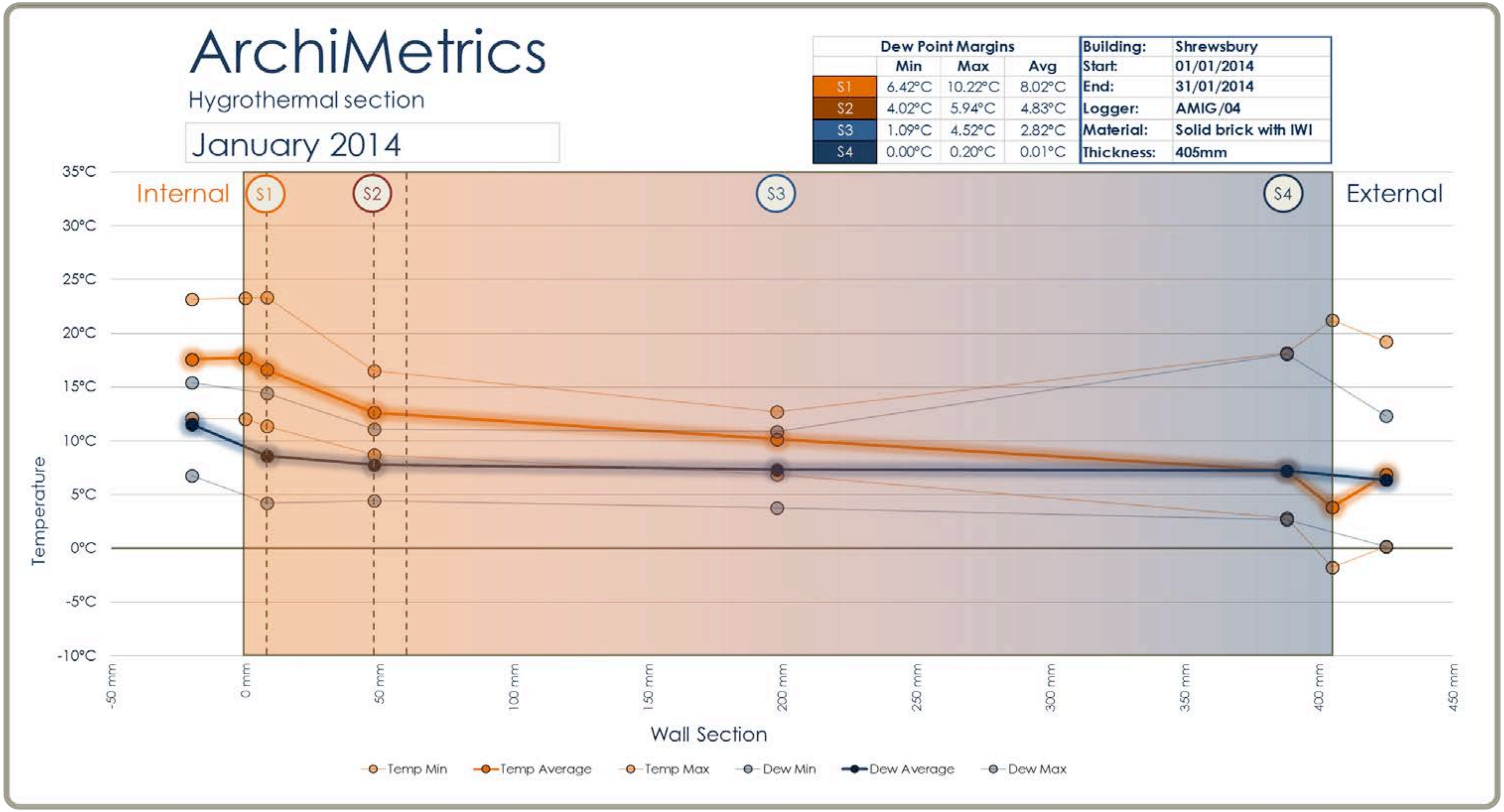


Figure 21. Hygrothermal Section, Abbeyforegate, Shrewsbury, January 2014.

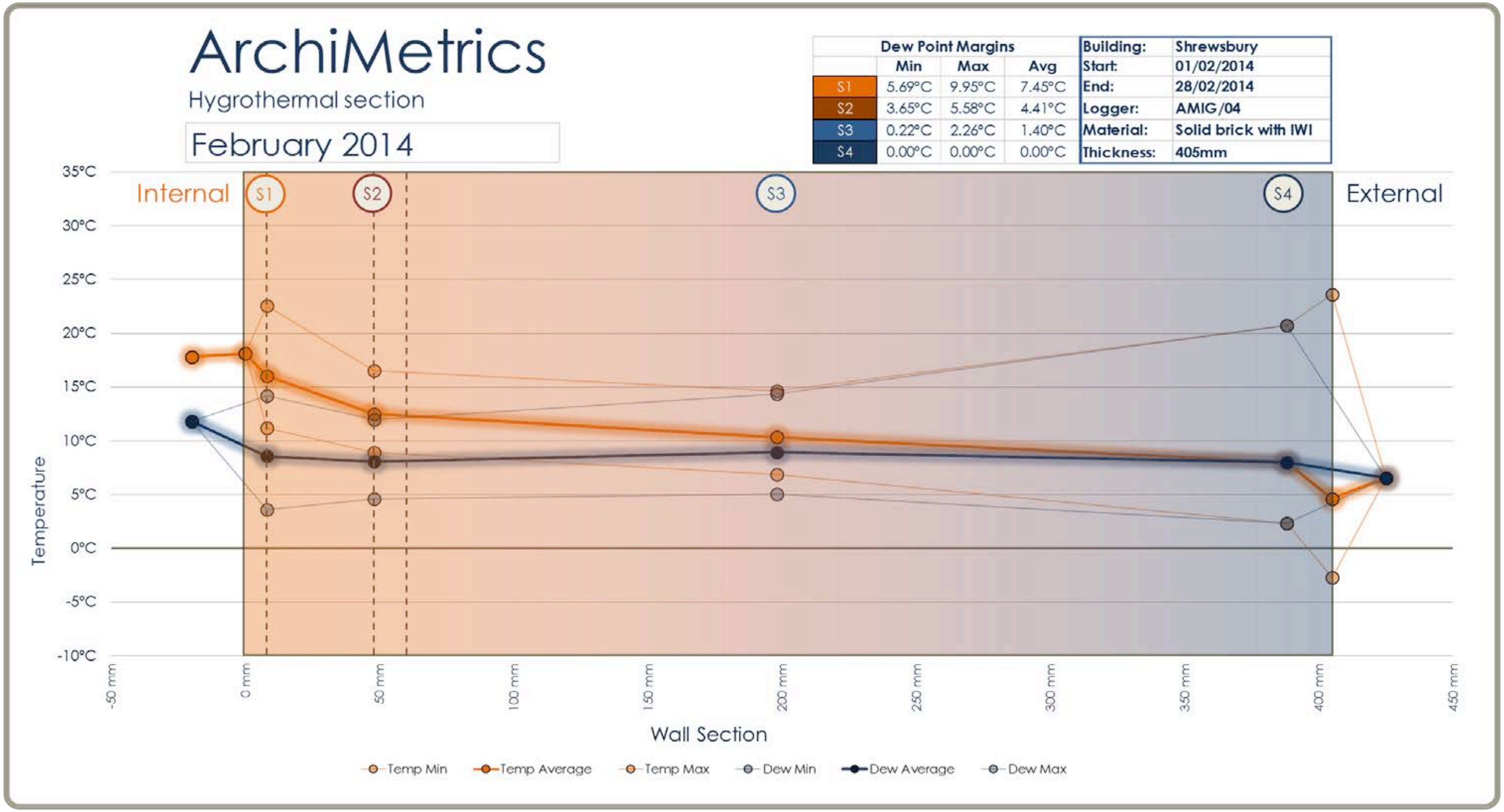


Figure 22. Hygrothermal Section, Abbeyforegate, Shrewsbury, February 2014.

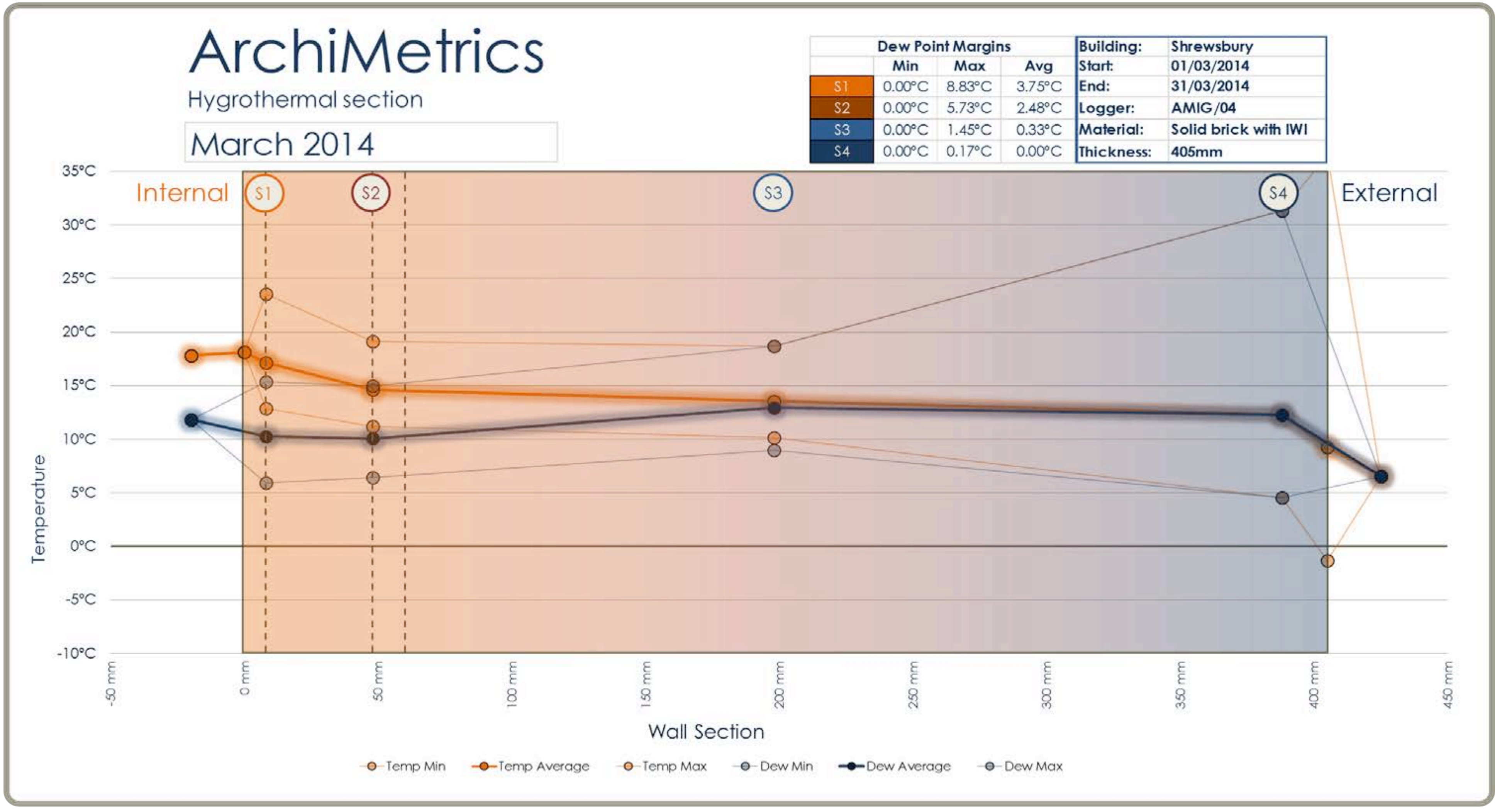


Figure 23. Hygrothermal Section, Abbeyforegate, Shrewsbury, March 2014.

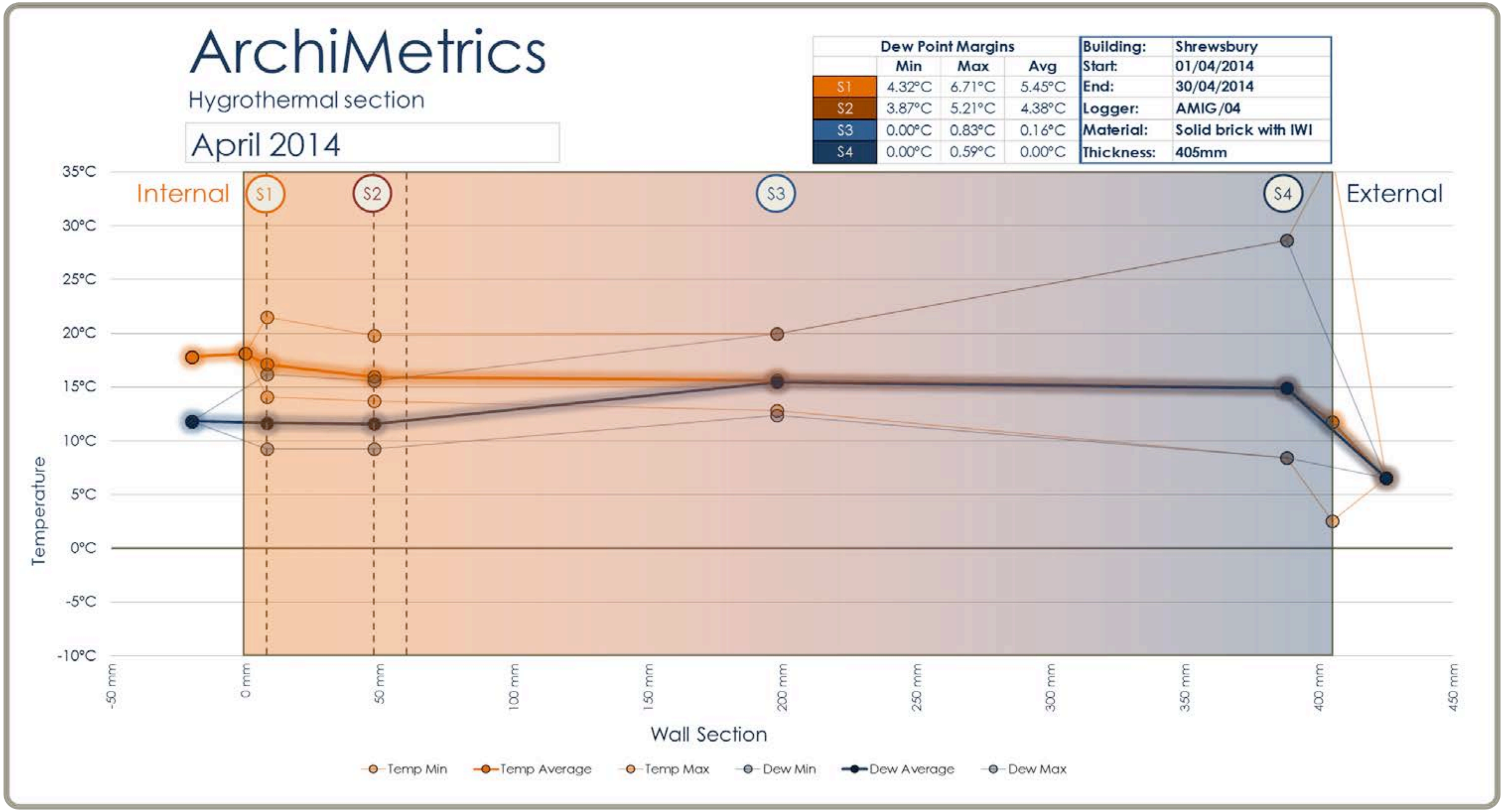


Figure 24. Hygrothermal Section, Abbeyforegate, Shrewsbury, April 2014.

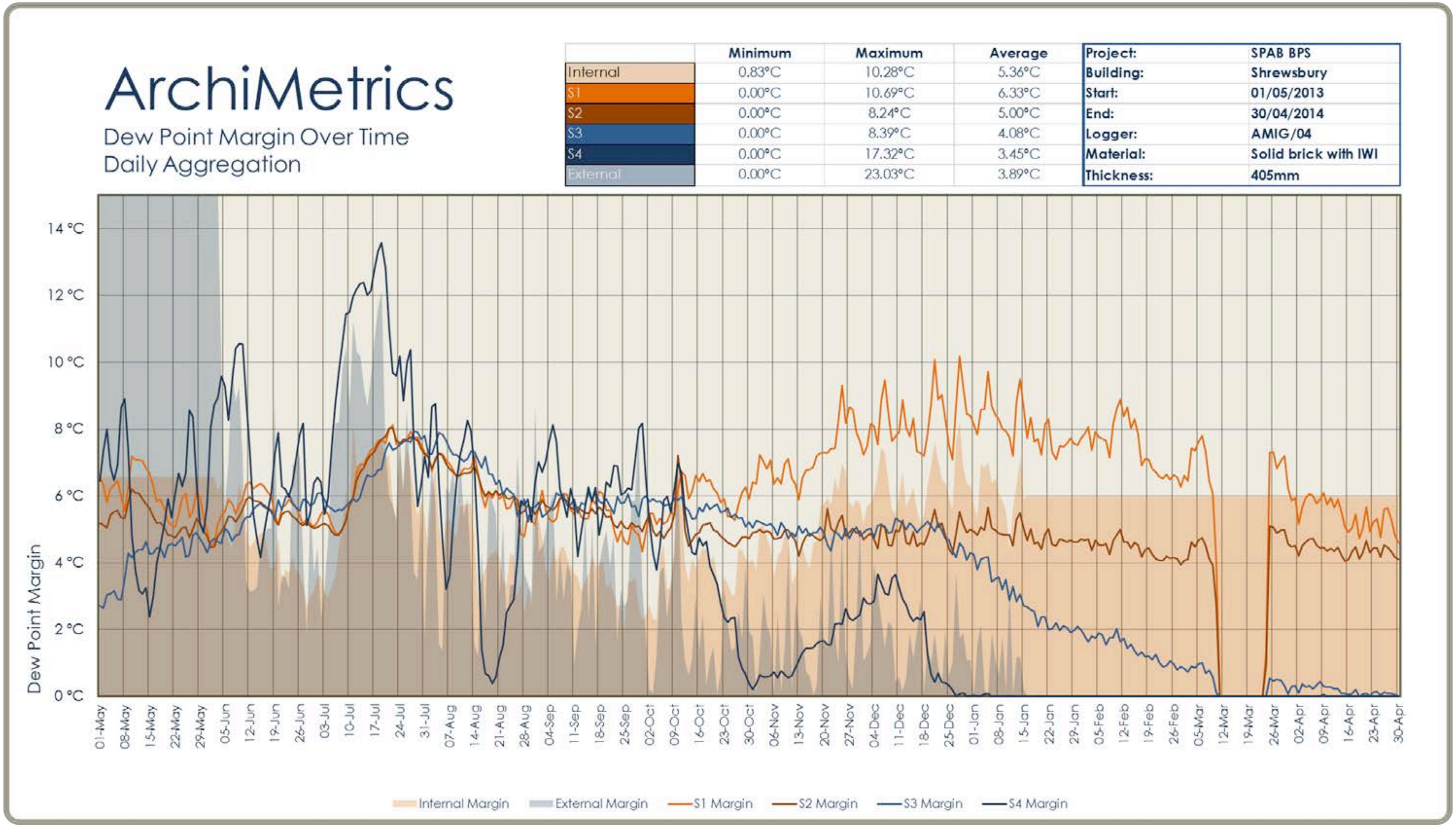


Figure 25. Dewpoint Margin Over Time, Abbeyforegate, Shrewsbury, May 2013 - April 2014. Daily Aggregation

Shrewsbury Monthly Dew Point Margin Averages						
	Internal	**S1**	**S2**	**S3**	**S4**	**External**
2013						
May	6.57	6.04	5.30	4.07	5.81	17.73
Jun	4.60	5.64	5.34	5.39	7.36	6.65
Jul	5.92	6.73	6.65	6.66	9.85	7.40
Aug	4.42	6.26	6.35	6.72	4.63	4.61
Sep	3.63	5.39	5.47	5.78	6.37	3.96
Oct	3.84	5.88	5.00	5.60	3.89	2.07
Nov	5.01	7.20	4.88	4.93	1.36	1.79
Dec	6.32	8.25	4.85	4.89	1.84	1.52
2014						
Jan	6.05	8.02	4.83	2.82	0.01	0.50
Feb	5.99	7.45	4.41	1.40	0.00	0.00
Mar	5.99	3.75	2.48	0.33	0.00	0.00
Apr	5.99	5.45	4.38	0.16	0.00	0.00
Average	**5.36**	**6.33**	**5.00**	**4.08**	**3.45**	**3.89**

Table 4. Monthly Dewpoint Averages, Abbeyforegate, Shrewsbury, May 2013 - April 2014.

2.2. Mill House, Drewsteignton, Devon - 2013 - 14.

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

Refurbishment: The 1950's extension to the rear of the building has been extensively rebuilt as a timber-frame construction, insulated with woodfibre insulation and has new double-glazed timber windows (the windows in the earlier 'barn' section of the house are in uPVC). In 2012, for experimental purposes, a short section of wall in a room in the older barn part of the dwelling 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 IHGM monitoring.

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

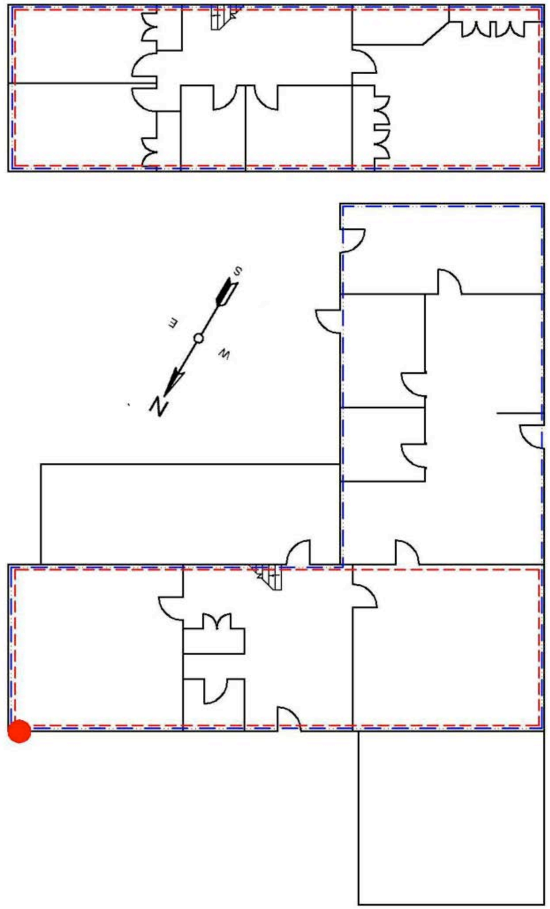


Figure 26. Plan of Mill House, Drewsteignton, the red dot indicates the location of the ground floor monitoring equipment.

Interstitial Hygrothermal Conditions

Figure 27. Interstitial Hygrothermal Gradient Monitoring, Drewsteignton.

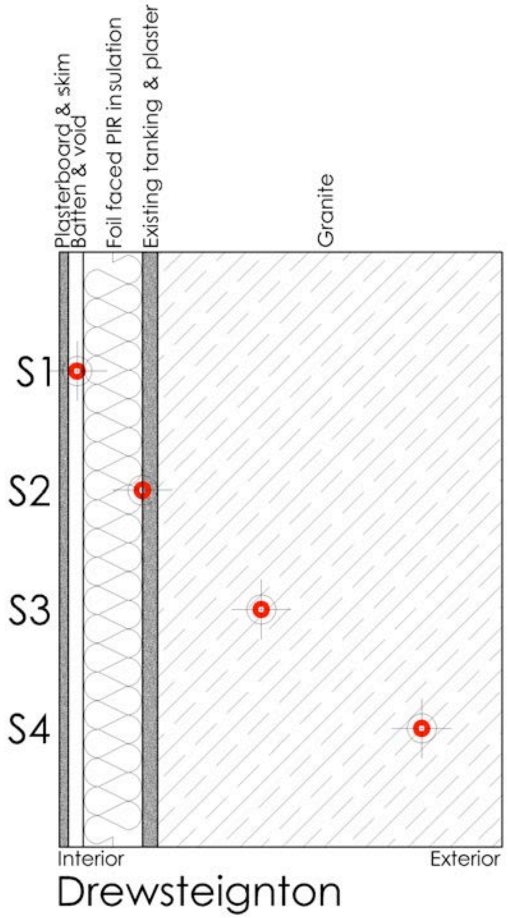


Figure 28. Position of sensors through wall section, Drewsteignton.

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 27 and 28). Combined temperature and relative humidity sensors are located at four points within the wall at the heights and depths given in Table 5. 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			
Plasterboard	12.5			
Air gap	25	Sensor 1	1730 mm	30 mm
PIR Board	100	Sensor 2	1580 mm	140 mm
Tanking & gypsum	3			
Lime Plaster	20			
Granite	580	Sensor 3	1430 mm	340 mm
		Sensor 4	1280 mm	610 mm
Total	**744**			

Table 5. Interstitial hygrothermal gradient sensor positions for Mill House, Drewsteignton, 2013- 2014.

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 April 2013 - 31th March 2014 has been used as the basis for the following analysis.

Relative Humidity Over Time

Figures 29 and 30 show the RH responses measured in and around the test wall at Drewsteignton over the past year. The granite wall at Drewsteignton provides a contrasting picture compared with that of Shrewsbury, as here the RH responses are more muted and do not have the volatility of those seen in Shrewsbury's brick wall. This suggests a different quality for the granite wall at Drewsteignton; it is thicker than that of Shrewsbury, constructed from more dense material, its pointing is in good condition and it has a north-west orientation rather than being south-facing. This construction is, therefore, less prone to the vicissitudes of the weather and RH responses are more muted as a consequence. (It should also be noted that at Drewsteignton, sensor 4, the sensor closest to external conditions within the interstitial array, is 135 mm back from the external face whereas at Shrewsbury this sensor is positioned only 20 mm back from the external wall face and is therefore more sensitive to changes in temperature and humidity caused by external conditions.) The measured responses from the wall at Drewsteignton post-insulation have, in the past, revealed a trend of rising RH over an annual cycle within the original masonry section of the insulated wall and we find this trend still in evidence and continuing to rise in this 2013-14 analysis. Table 6 provides the annual RH averages for the wall. When these are compared with the previous year's averages, a year-on-year increase for sensors 2 - 4 is found.

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

Table 6. Comparison of annual averages of RH measured through wall section, Drewsteignton 2012 - 2014.

From April through to June 2013 RH is at 100% or dewpoint at sensor 4. Dewpoint was first reached in February of that year (Figure 31) and RH remained at 100% for five months of the year and returns to 100% at the end of the analysis cycle for this year in March 2014. Table 7 provides a breakdown of the monthly RH averages measured through and either side of the wall section at Drewsteignton. As with the previous year 2012-13 there is a period over the summer months where RH at sensors 3 and 4 diminishes as the wall benefits from warmer external temperatures. However, as before, a similar reduction is not seen at the more deeply embedded sensor 2 positioned between the PIR insulation and the original masonry wall. Here, between June and July there is a brief stasis around 87% RH before measurements resume their climb peaking at 89% in November. Despite the overall annual trend of rising RH found for this wall it is interesting to note that peak %RH at sensor 2 occurs in November and thereafter decreases. This is the first time since post-insulation monitoring began that there has been a slight but sustained decrease in RH at sensor 2 and may mark the start of a another phase for the wall where a new equilibrium is established for the fabric at this location. Albeit %RH at sensor 2 is still above the 80% threshold limit given for mould growth, as is the average annual RH for all three masonry sensors, sensors 2 - 4. Sensor 1 is an exception to the humidity trends and values recorded for the wall at Drewsteignton. Conditions at sensor 1, positioned in the air gap between the plasterboard and PIR, are on average lower this year than in 2012 - 13 being 64%. Like the previous year the RH gradient here mirrors that of the internal RH profile suggesting a significant amount of vapour exchange between the two locations as was mentioned in the previous year's accounts (although it should be noted that the record for internal room humidity is not complete for this year).

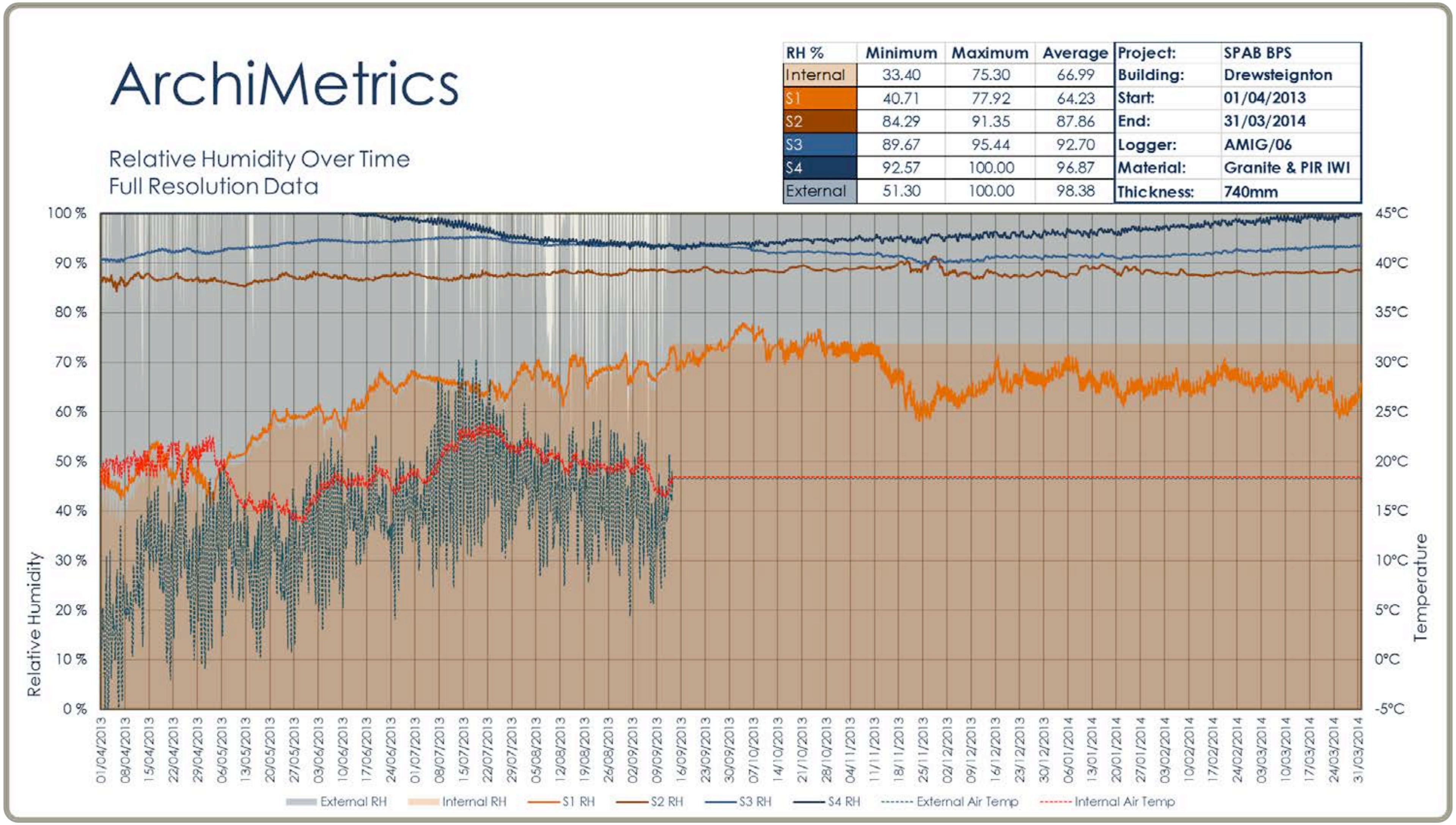


Figure 29: Relative Humidity over time, Mill House, Drewsteignton 2013 - 2014. Full Resolution.

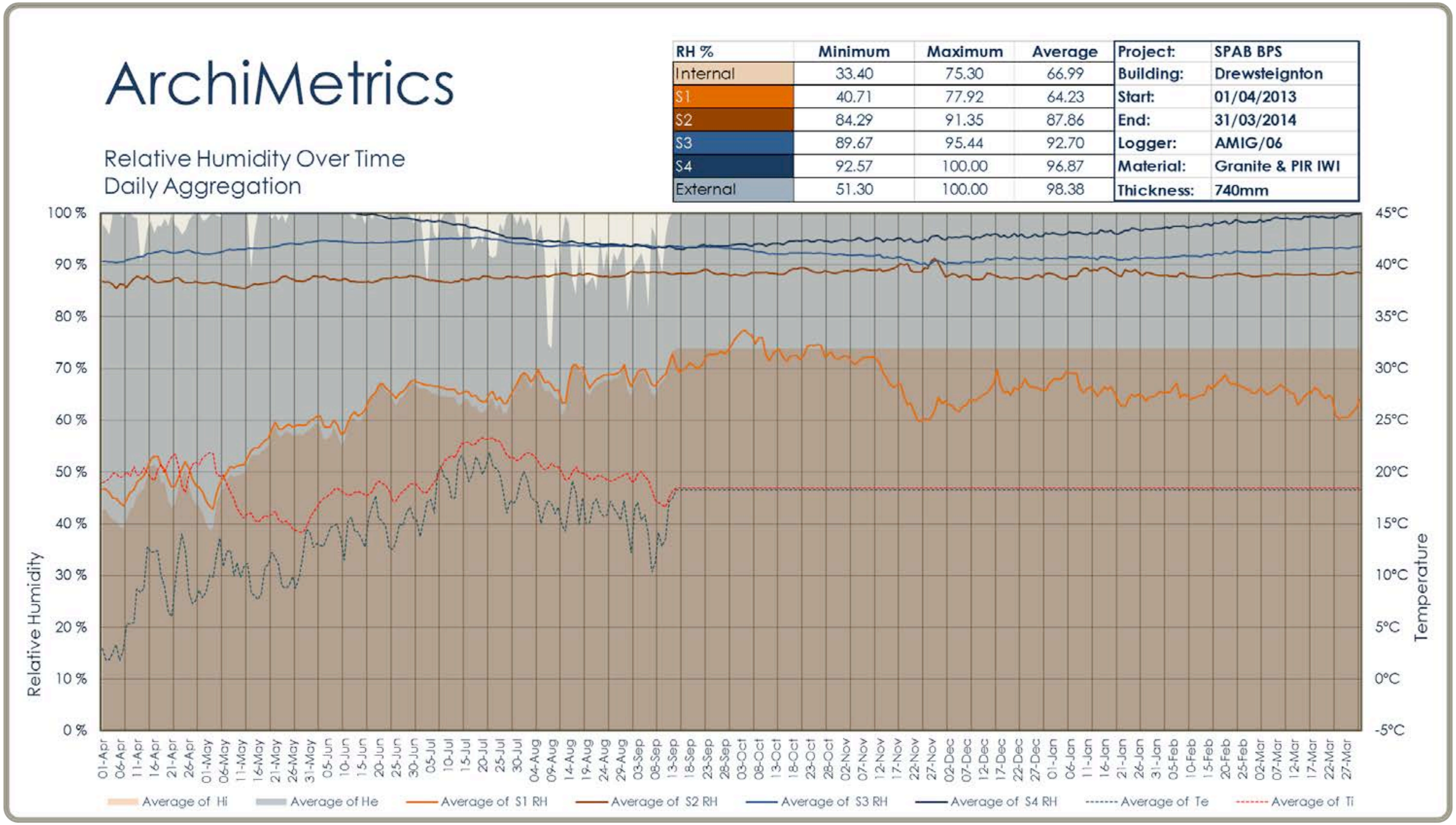


Figure 30: Relative Humidity over time, Mill House, Drewsteignton, 2013 - 2014. Daily Aggregation.

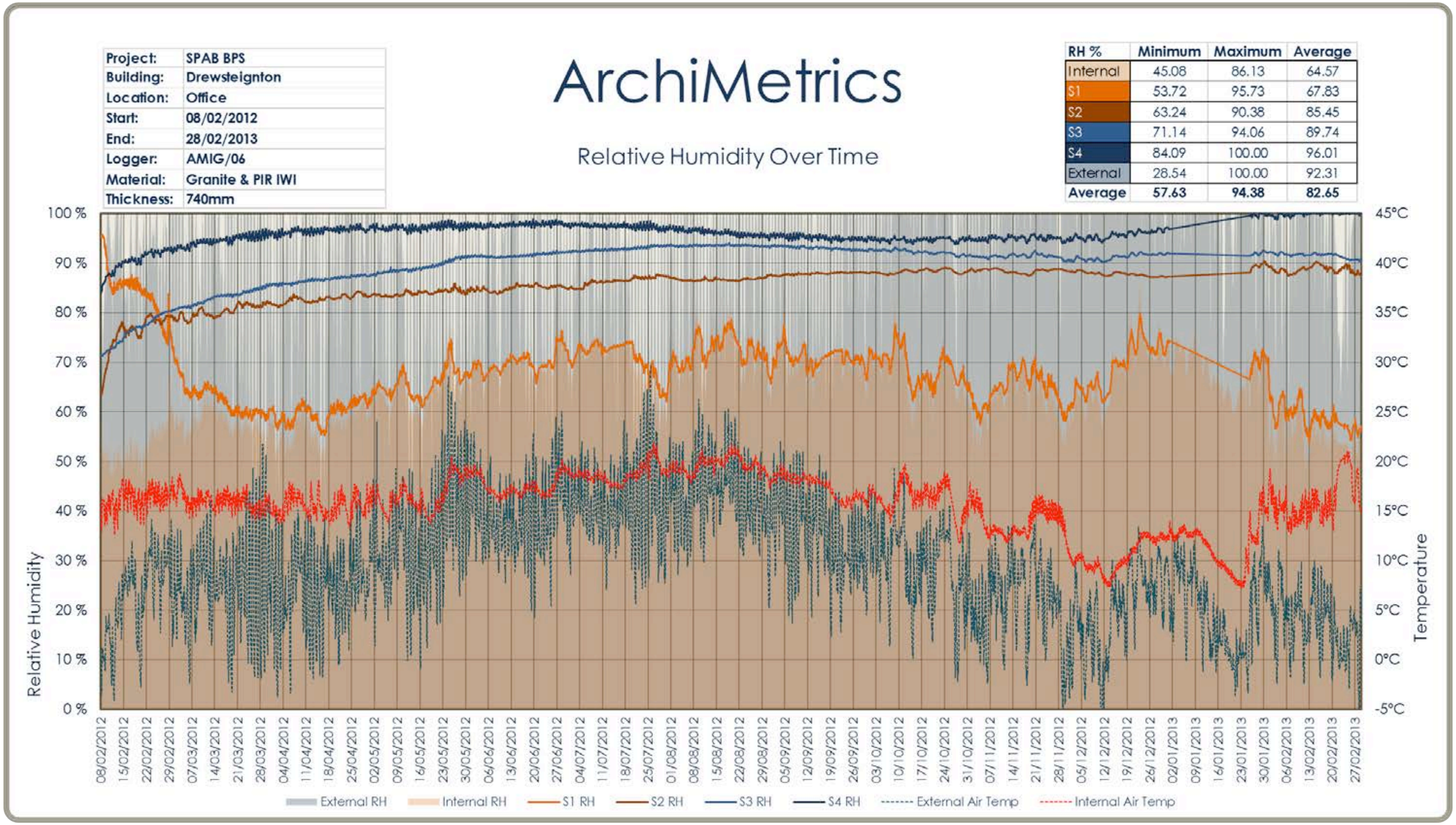


Figure 31: Relative Humidity over time, Mill House, Drewsteignton 2012 - 2013. Full Resolution.

Monthly RH Averages						
	Internal RH	S1 RH	S2 RH	S3 RH	S4 RH	External RH
2013						
Apr	45.00	48.19	86.78	91.79	100.00	97.93
May	52.13	53.87	86.51	93.26	100.00	99.24
Jun	61.62	62.61	87.26	94.42	99.60	99.59
Jul	64.10	65.53	87.27	94.89	97.15	96.71
Aug	67.08	68.05	87.91	93.71	94.31	90.60
Sep	71.23	70.37	88.47	93.48	93.52	96.71
Oct	73.80	73.84	88.57	92.36	94.28	100.00
Nov	73.80	66.94	89.28	91.24	94.88	100.00
Dec	73.80	65.17	87.71	90.91	95.55	100.00
2014						
Jan	73.80	65.88	88.46	91.33	96.38	100.00
Feb	73.80	65.95	87.89	91.96	97.77	100.00
Mar	73.80	64.24	88.16	92.99	99.11	100.00
Average	**66.99**	**64.23**	**87.86**	**92.70**	**96.87**	**98.38**

Table 7. Relative Humidity Monthly Averages, Mill House, Drewsteignton, 2013 -14.

Absolute Humidity Over Time

Figure 32 shows an analysis of absolute humidity through the insulated wall section at Drewsteignton between April 2013 - March 2014. The same seasonal variation that was noted in the previous report is in evidence once again; quantities of vapour within the wall increase with that of atmospheric humidity, are more dispersed through the wall section and peak towards the external face over the summer months. This pattern is reversed during the winter with lower quantities recorded, the gradients from all four sensors more aligned and quantities of vapour at their highest towards the internal wall leaf.

These patterns are reflective of the dominant source of heat over an annual cycle and its effect on humidity. This can be seen in the plots of external temperature over the summer where peaks in humidity mimic peaks in external temperature. Over the spring and summer months the plot of AH from the sensor installed in the air gap behind the plasterboard, sensor 1, is somewhat detached from those of the sensors installed on the other side of the PIR insulation. 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 'cold' masonry side of the wall (sensors 2 - 4) reveals the physical separation that has occurred in this wall a the installation of a vapour impermeable layer (the foil-faced PIR board). This distinction between sensor 1 values and those of the other wall sensors reduces as we move into the colder autumn and winter months where atmospheric humidity is reduced due to colder external temperatures. One can assume, based on this and the previous year's analysis (Figure 33) that the generally lower atmospheric humidity is reflected in the findings within the wall section where measured quantities of vapour also decrease. However, data for external AH is not available for the second part of this year. Over winter it is sensor 1 that provides the highest quantities of vapour through the wall section and once again one can assume that this is a reflection of AH conditions within the room where higher quantities of vapour are supported by warmer indoor temperatures as a result of central heating.

Year-on-year there has been an increase in the average quantities of vapour found in the insulated wall at Drewsteignton (Table 8) which may also correspond with the trend of rising %RH found for this wall.

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

Table 8. Average Absolute Humidity, Mill House, Drewsteignton, 2012 - 2014.

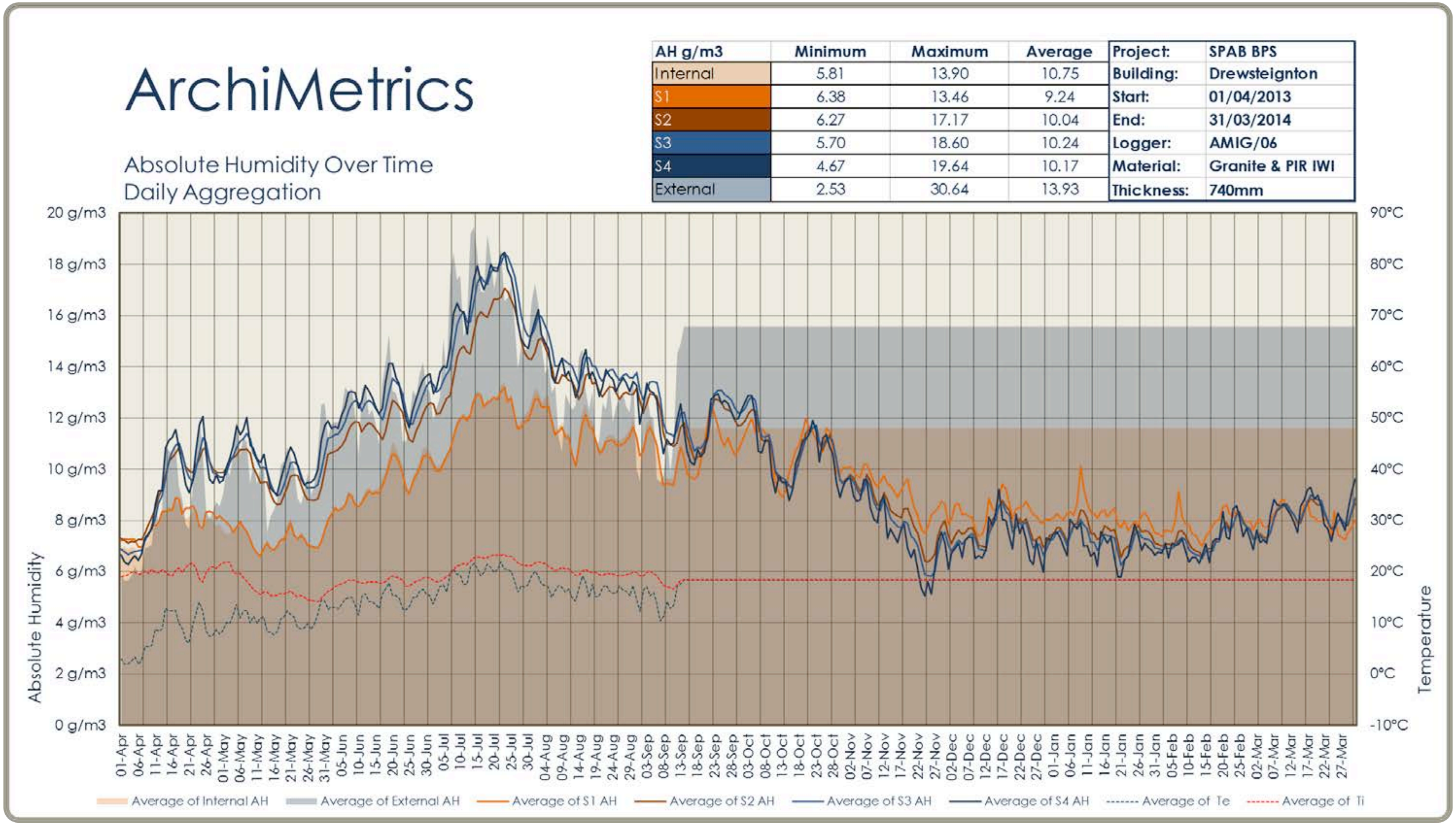


Figure 32: Absolute Humidity over time, Mill House, Drewsteignton 2013 - 2014. Daily Aggregation.

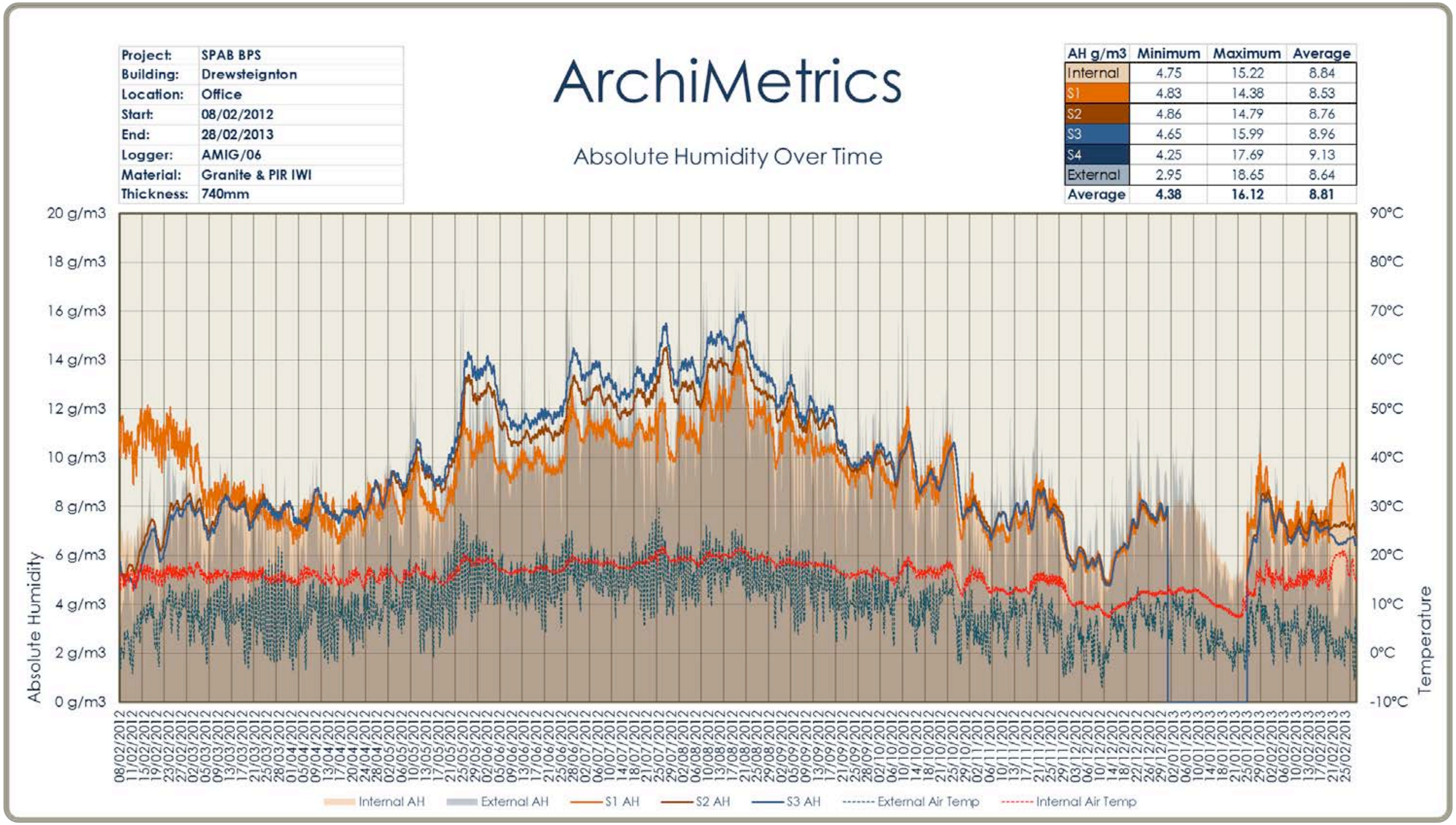


Figure 33: Absolute Humidity over time, Sensors 1 - 3, Mill House, Drewsteignton 2012 - 2013. Full Resolution.

Hygrothermal Sections & Dewpoint Margins

Measurements of temperature and RH are also used to plot annual and monthly averages of measured temperature and dewpoint through the wall section (Figure 34 and Figures 35 - 46). In Table 9 below, dewpoint margins are written as an average across all four measurement points within the section and also individually, showing the change in these average margins before and after the wall was insulated and over the following years.

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

Table 9. Dewpoint Margins & Pre & Post-insulation Difference, Mill House, Drewsteignton 2011 - 2014.

From this Table it can be seen that the dewpoint margins have narrowed considerably following the insulation of the wall and at the 4th sensor are on average below 1˚C. It can also be seen that there has been a further reduction in these margins between the first and second year of post-insulation measurements at the sensors located in the original masonry section of the wall, sensors 2 - 4. The continued narrowing of the dewpoint may be a consequence of the year-on-year rise in humidity (AH) found for this wall which also leads to the continuing trend of rising RH. Some reduction of the dewpoint margin is to be expected in an internally-insulated wall as the insulation deprives the majority of the wall fabric of heat from the interior during the colder winter months when %RH can increase (due to the colder temperatures) and therefore dewpoint is more likely to be reached. The margins for the wall, post-insulation, are calculated from a full year of data and therefore represent both colder winter conditions but also warmer summer months where margins may be much greater. In Table 9 these margins are compared with those calculated from the monitoring which took place prior to insulation. These were taken from data collected during the coldest part of the year, February 2011, and to this extent could be seen as 'worse case', i.e. the margins will be low due to cold temperatures. Therefore, despite the inclusion of warmer summer data in the post-insulation data set, the dewpoint margins found for the wall in Drewsteignton post-insulation would seem to be significantly lower than those calculated pre-insulation giving rise to extended periods of 100% RH (dewpoint) and hence the possibility of interstitial condensation within certain parts of the wall. The periods of time which the wall experiences high %RH and hence very narrow dewpoint margins or no margin at all, i.e. 100% RH, is indicated in Figure 47 - Dewpoint Margin Over Time.

The average, month by month, relationships between measured temperature and dewpoint for the wall are presented in Figures 35 - 46 and Table 10. During the early part of the year, April - June 2013, the margin between the temperature and dewpoint gradients between sensors 3 and 4 are extremely close and converge around sensor 4, where 100% RH (dewpoint) is found for these months. The margin between these two gradients thereafter opens out a little and is at it is greatest extent in September 2013 where the margin at sensor 4 is just over a degree - 1.04˚C - after which it begins to converge once again, being 0.13˚C at the end of this reporting period in March 2014.

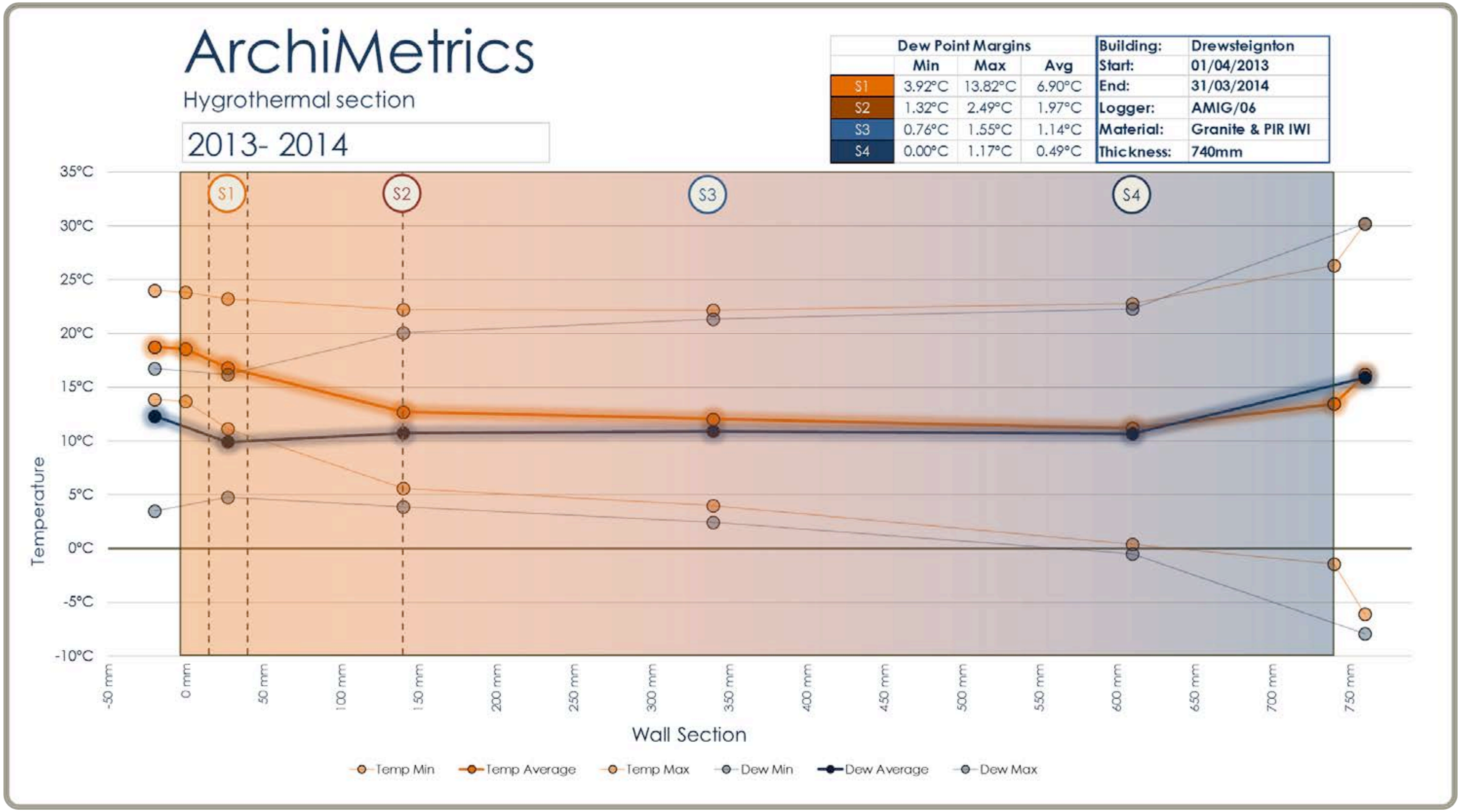


Figure 34. Hygrothermal Section, Mill House, Drewsteignton, April 2013 - March 2014.

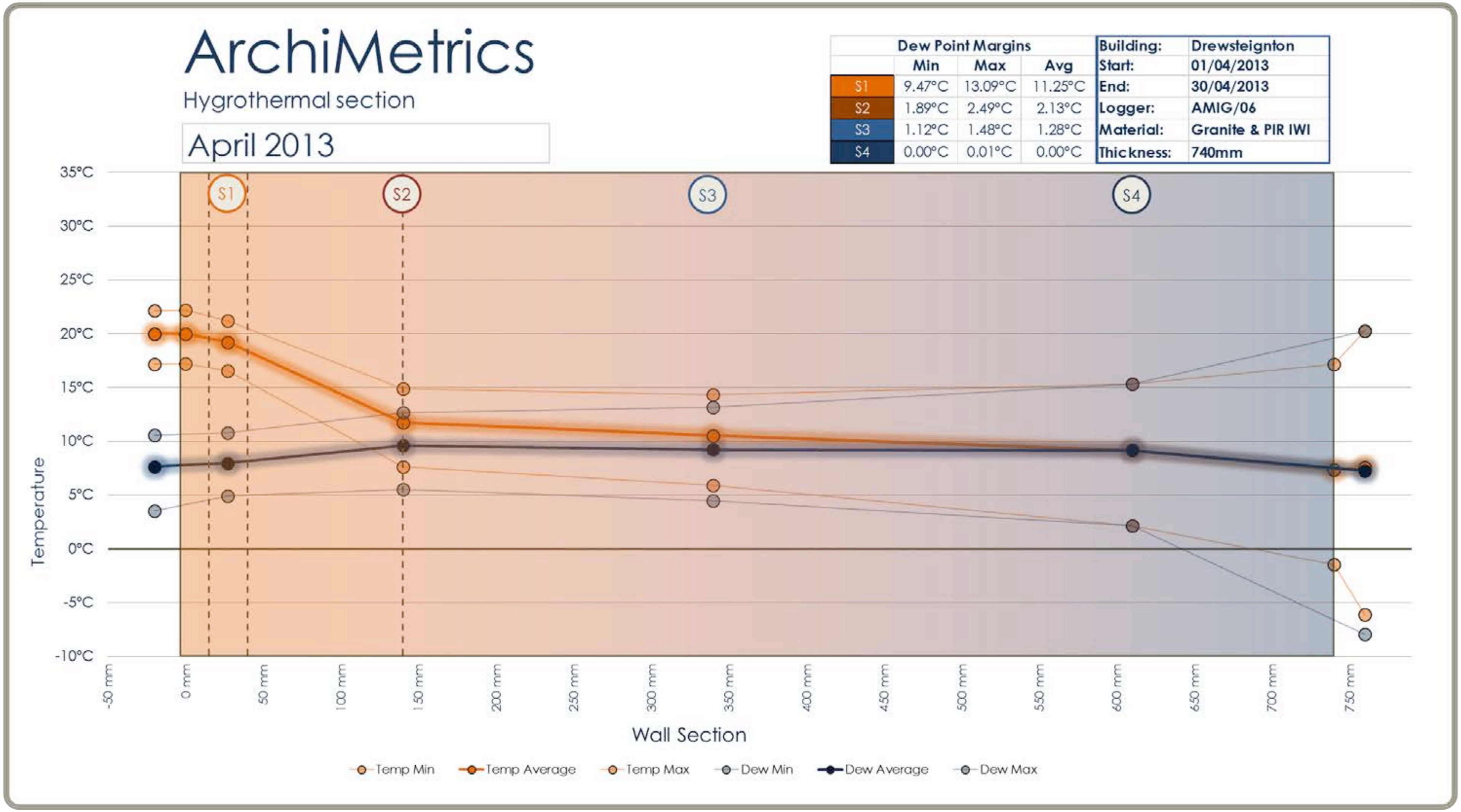


Figure 35. Hygrothermal Section, Mill House, Drewsteignton, April 2013.

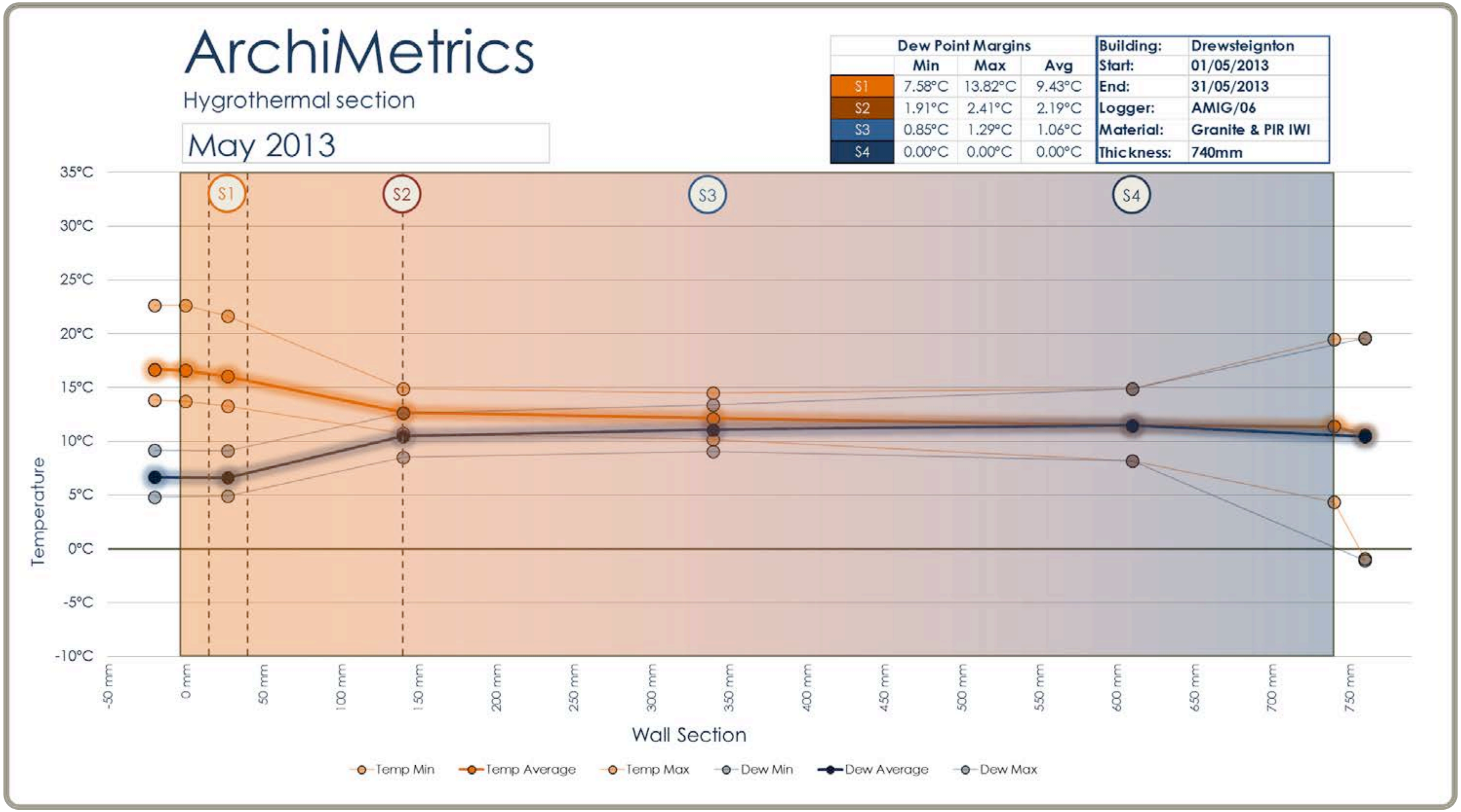


Figure 36. Hygrothermal Section, Mill House, Drewsteignton, May 2013.

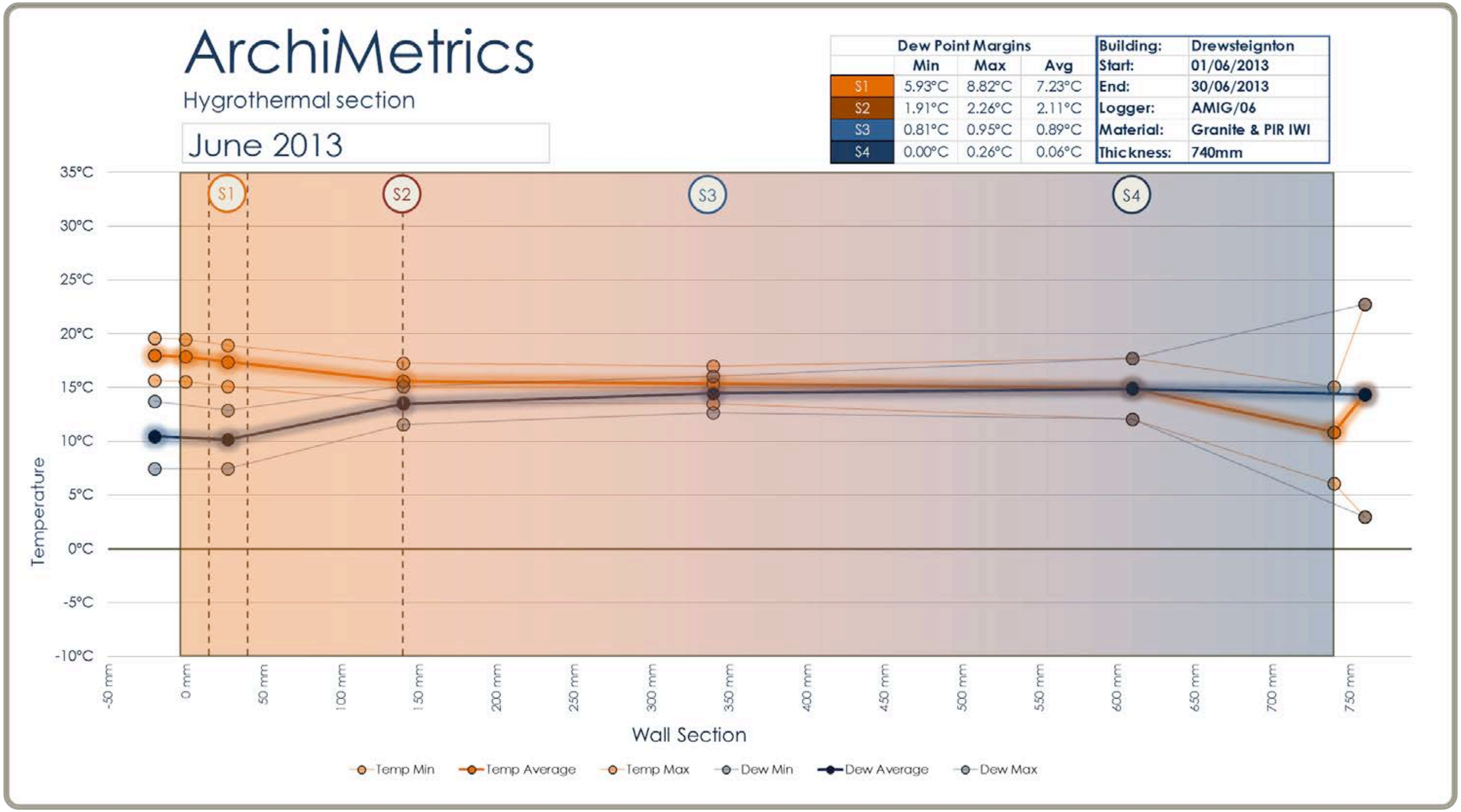


Figure 37. Hygrothermal Section, Mill House, Drewsteignton, June 2013.

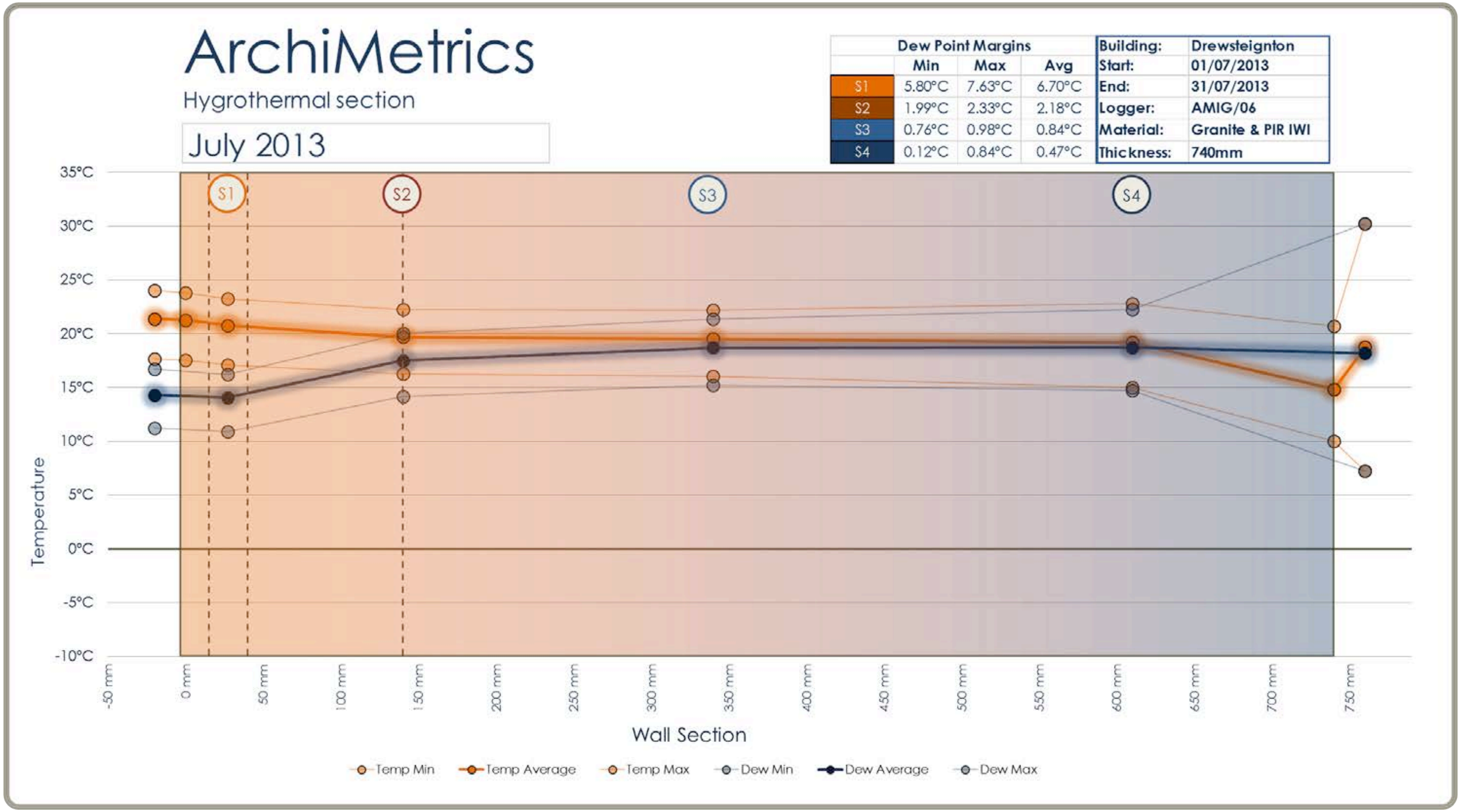


Figure 38. Hygrothermal Section, Mill House, Drewsteignton, July 2013.

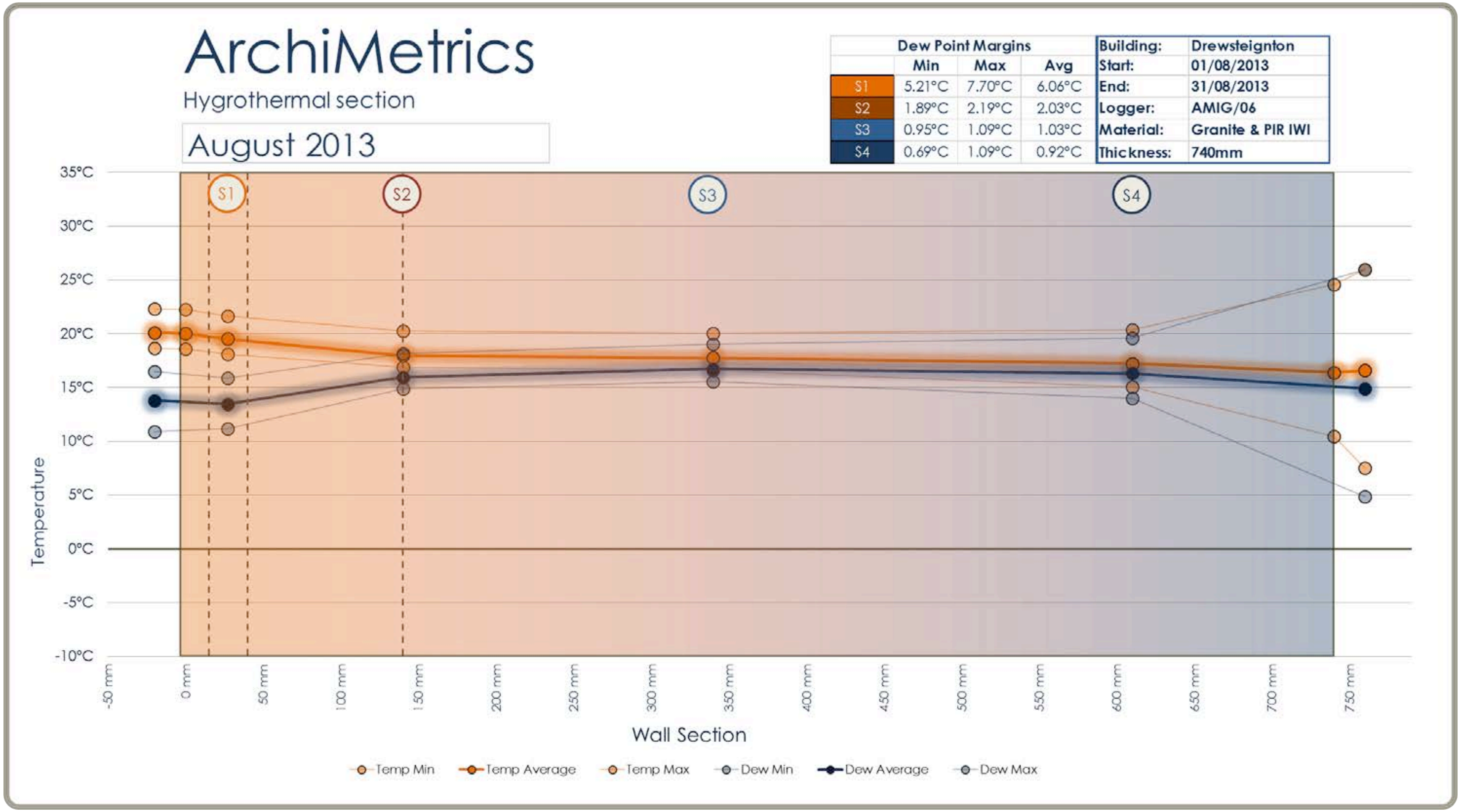


Figure 39. Hygrothermal Section, Mill House, Drewsteignton, August 2013.

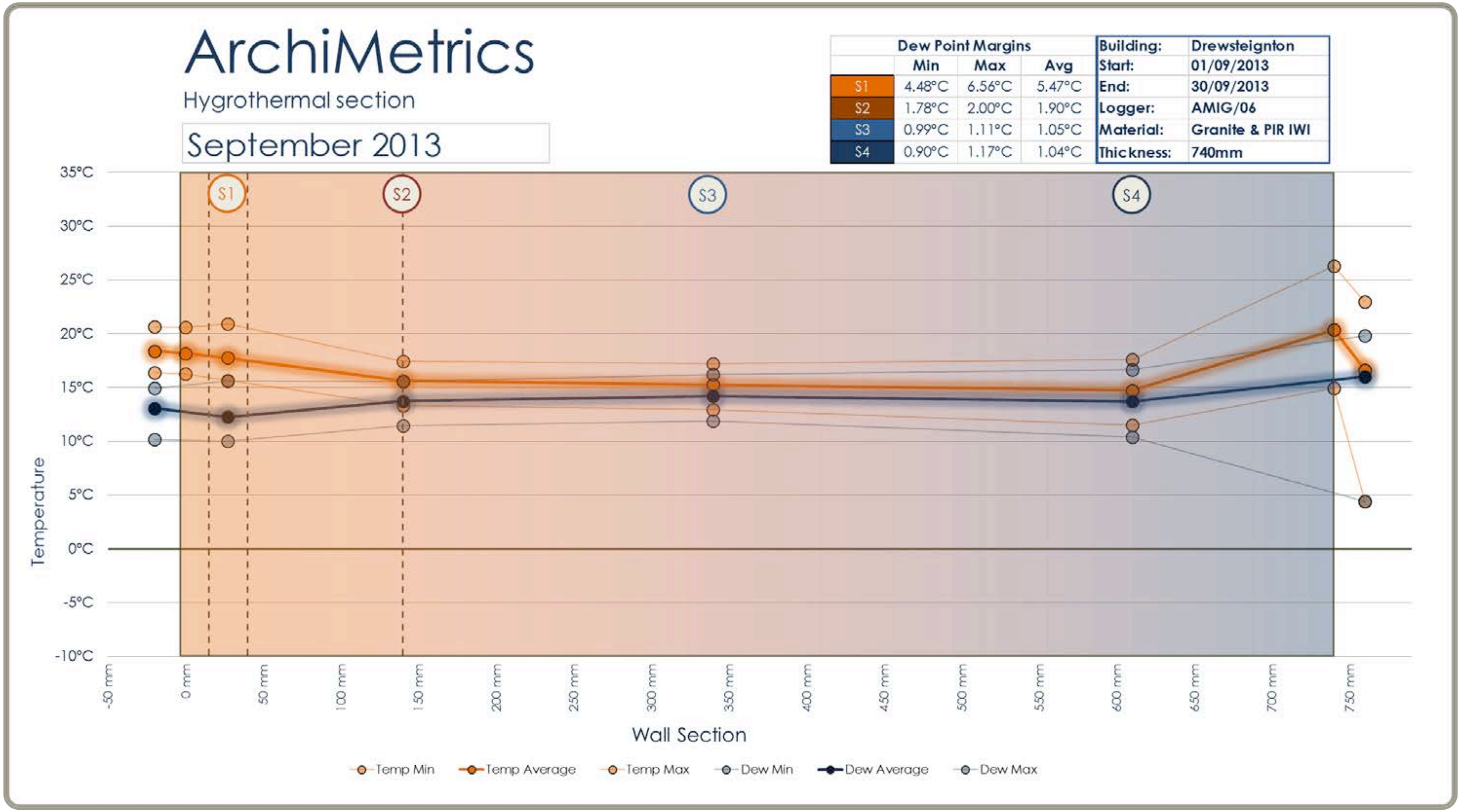


Figure 40. Hygrothermal Section, Mill House, Drewsteignton, September 2013.

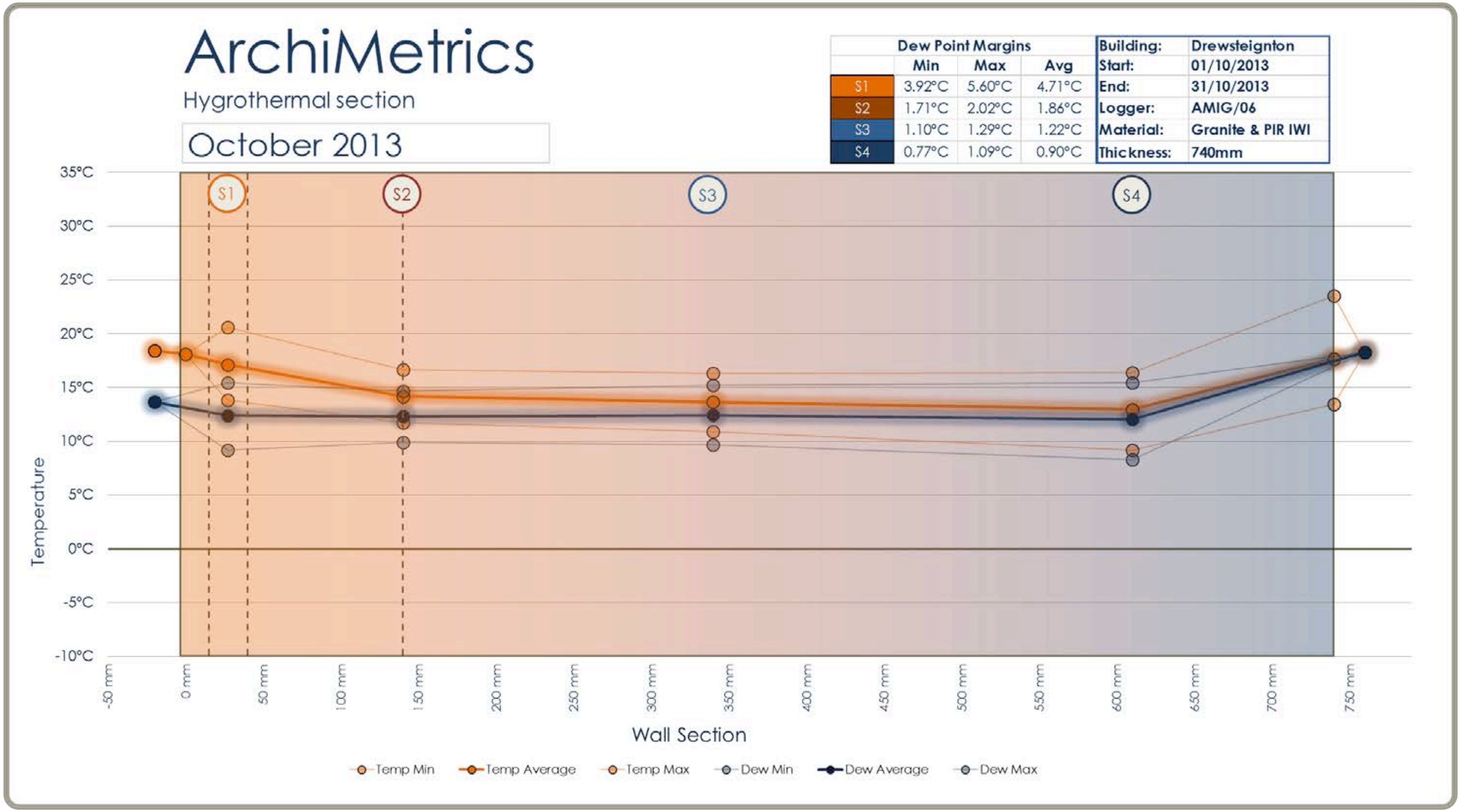


Figure 41. Hygrothermal Section, Mill House, Drewsteignton, October 2013.

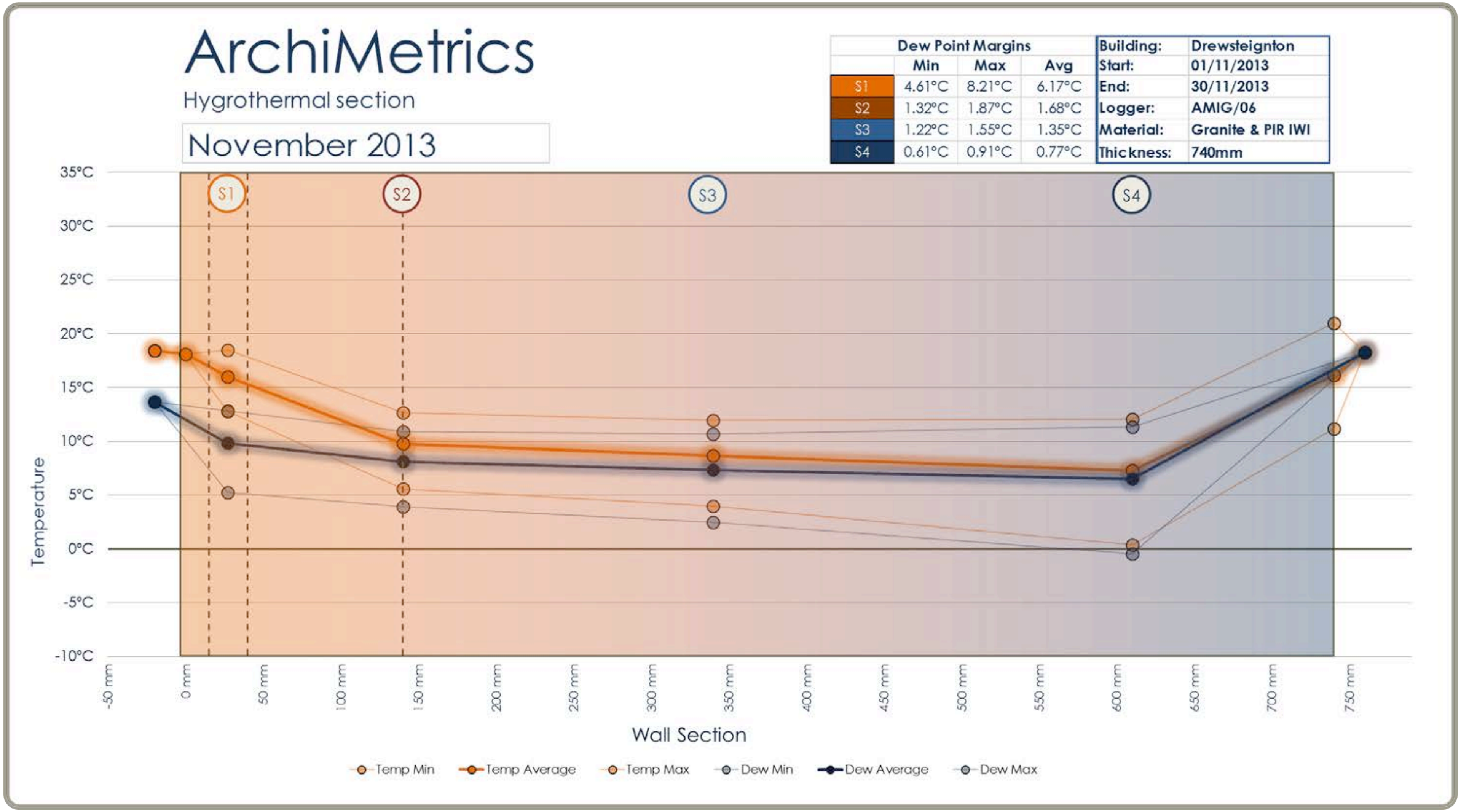


Figure 42. Hygrothermal Section, Mill House, Drewsteignton, November 2013.

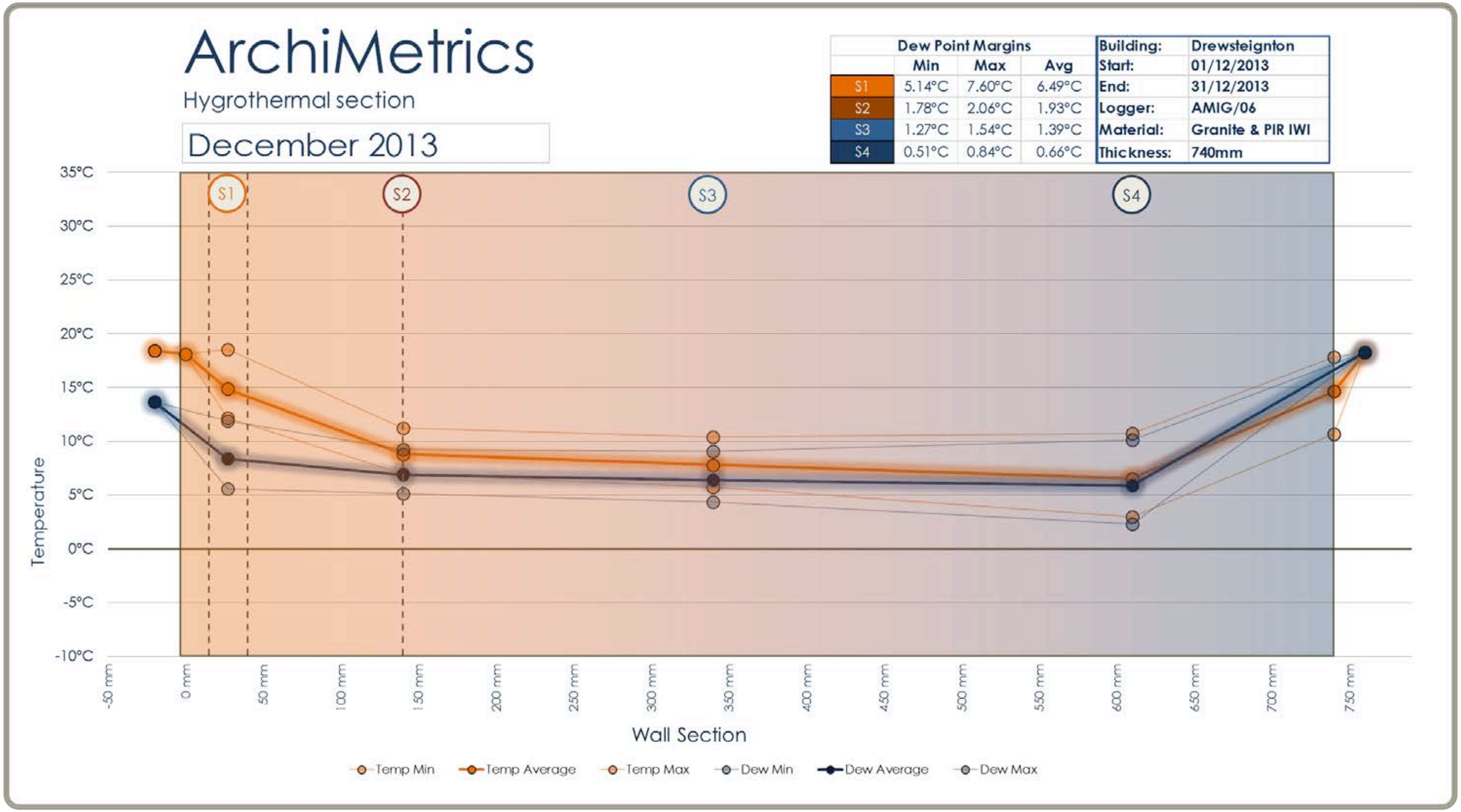


Figure 43. Hygrothermal Section, Mill House, Drewsteignton, December 2013.

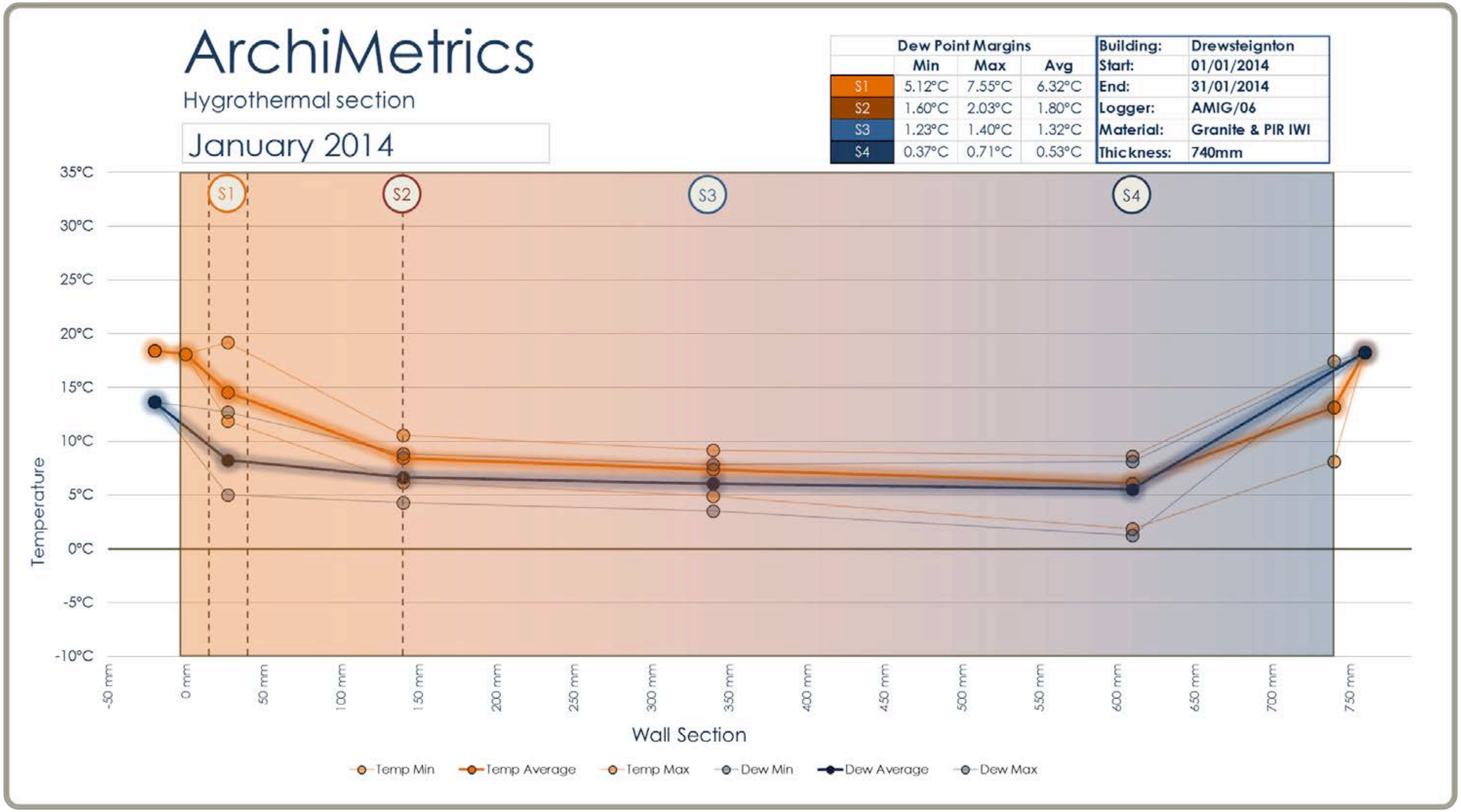


Figure 44. Hygrothermal Section, Mill House, Drewsteignton, January 2014.

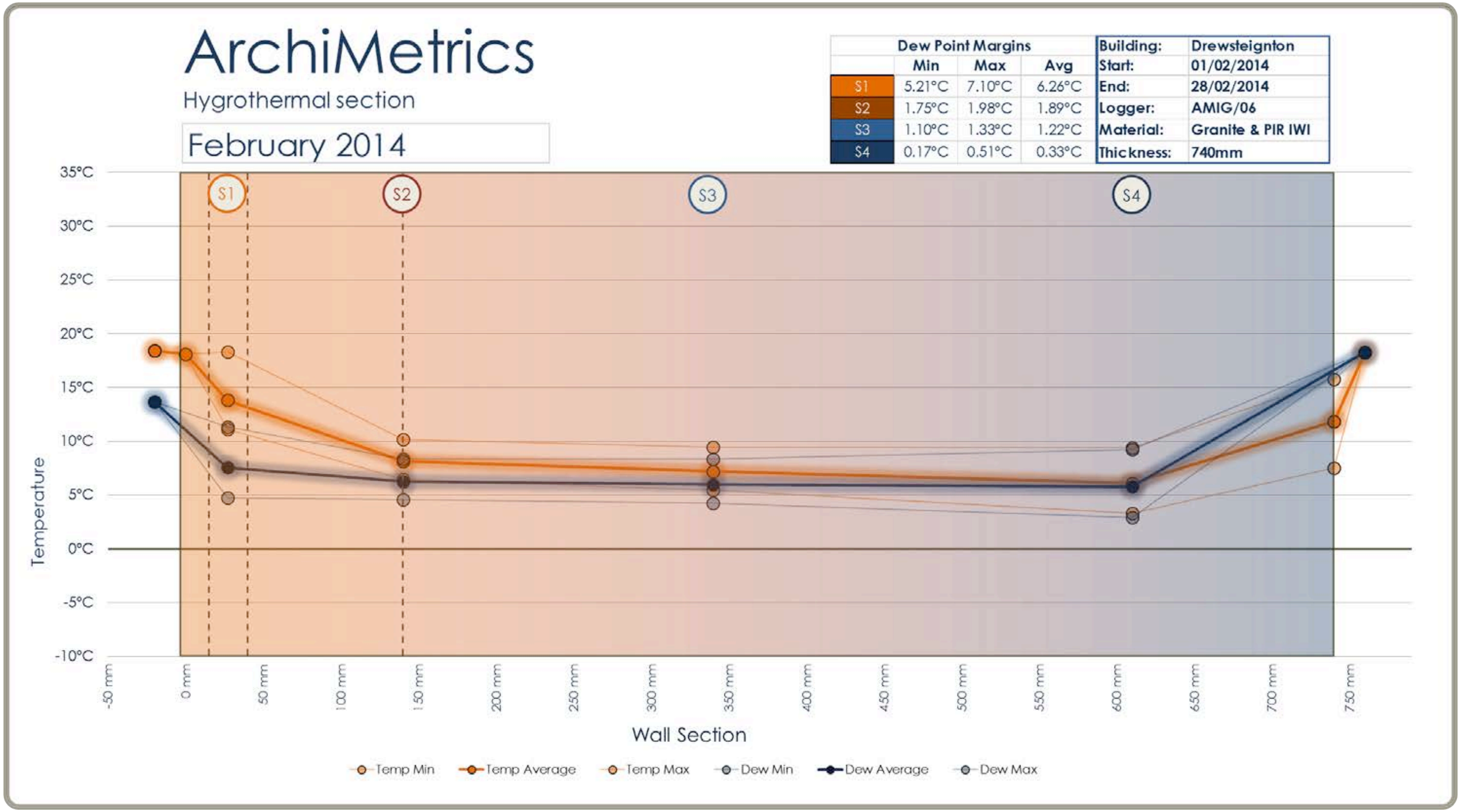


Figure 45. Hygrothermal Section, Mill House, Drewsteignton, February 2014.

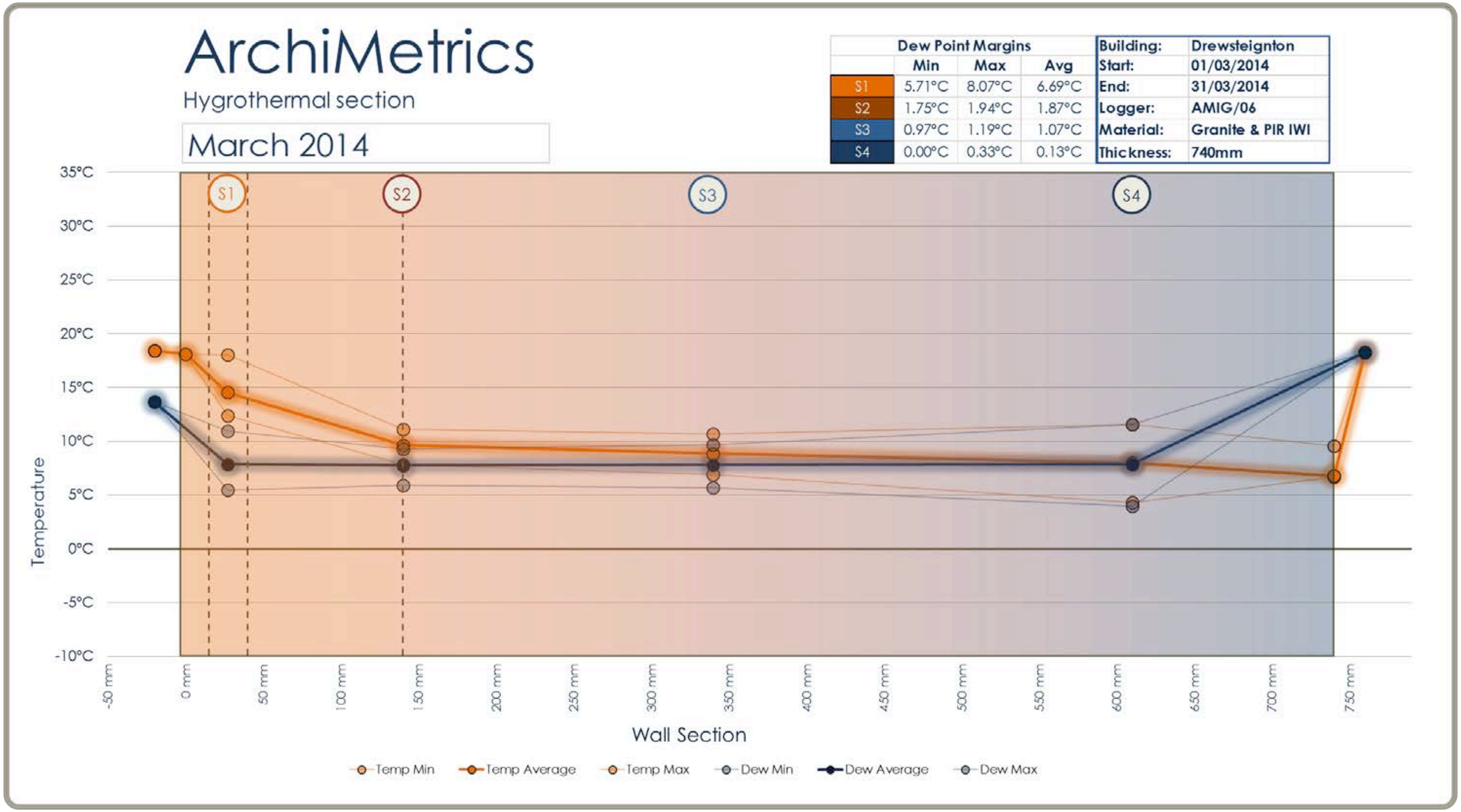


Figure 46. Hygrothermal Section, Mill House, Drewsteignton, March 2014.

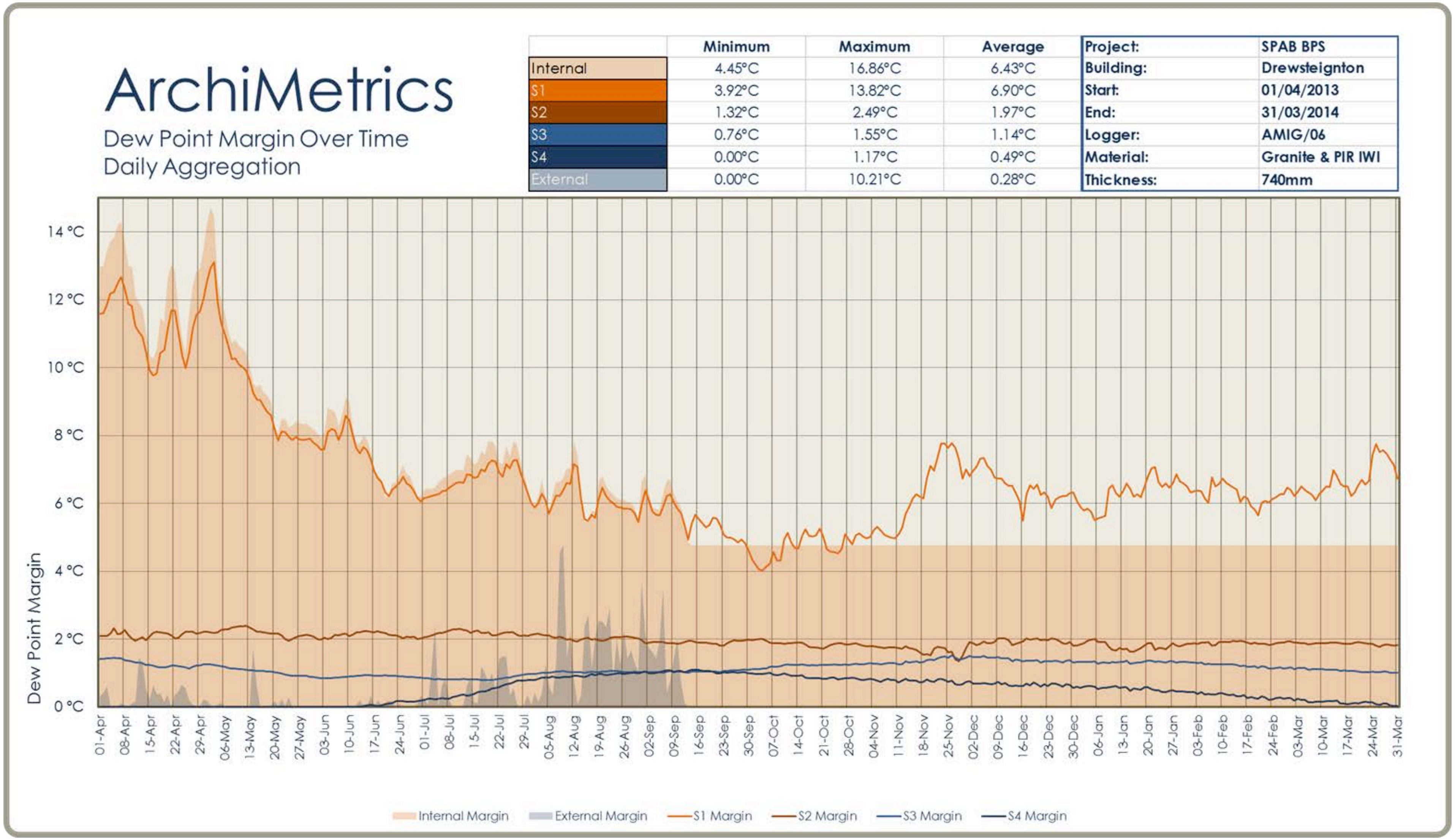


Figure 47. Dewpoint Margin Over Time, Mill House, Drewsteignton, April 2013 - March 2014. Daily Aggregation.

Drewsteignton Monthly Dew Point Margin Averages						
	Internal	**S1**	**S2**	**S3**	**S4**	**External**
2013						
Apr	12.35	11.25	2.13	1.28	0.00	0.32
May	9.99	9.43	2.19	1.06	0.00	0.12
Jun	7.51	7.23	2.11	0.89	0.06	0.06
Jul	7.08	6.70	2.18	0.84	0.47	0.56
Aug	6.32	6.06	2.03	1.03	0.92	1.70
Sep	5.32	5.47	1.90	1.05	1.04	0.59
Oct	4.76	4.71	1.86	1.22	0.90	0.00
Nov	4.76	6.17	1.68	1.35	0.77	0.00
Dec	4.76	6.49	1.93	1.39	0.66	0.00
2014						
Jan	4.76	6.32	1.80	1.32	0.53	0.00
Feb	4.76	6.26	1.89	1.22	0.33	0.00
Mar	4.76	6.69	1.87	1.07	0.13	0.00
Average	**6.43**	**6.90**	**1.97**	**1.14**	**0.49**	**0.28**

Table 10. Monthly Dewpoint Margin Averages, Mill House, Drewsteignton April 2013 - March 2014.

2.3. The Firs, Riddlecombe, Devon - 2013 - 14.

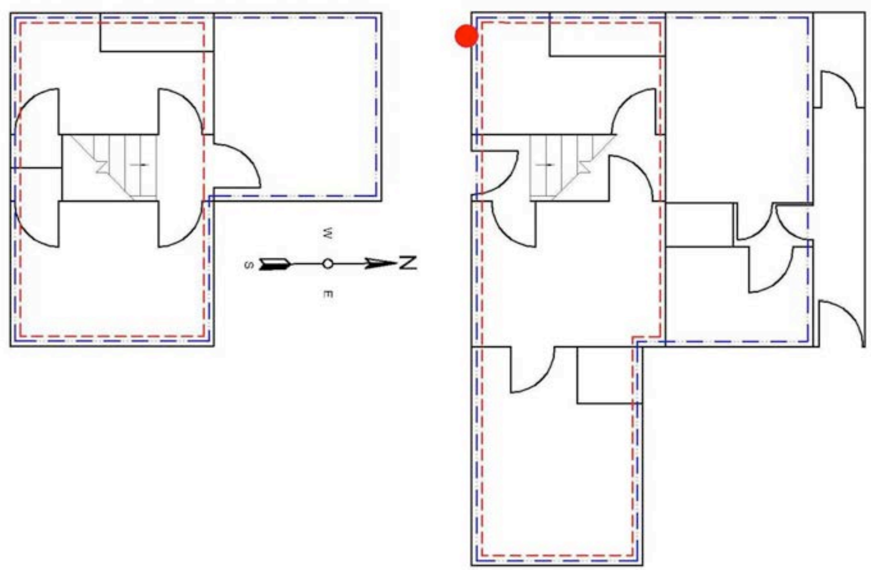


Figure 48. Plan of The Firs, Riddlecombe (ground floor on right hand side). Location of IHGM monitoring equipment shown by red dot.

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

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

Occupancy: Family of 5.
Floor Area: 86 m^2

Interstitial Hygrothermal Conditions

Figure 49. Interstitial Hygrothermal Gradient Monitoring, Riddlecombe.

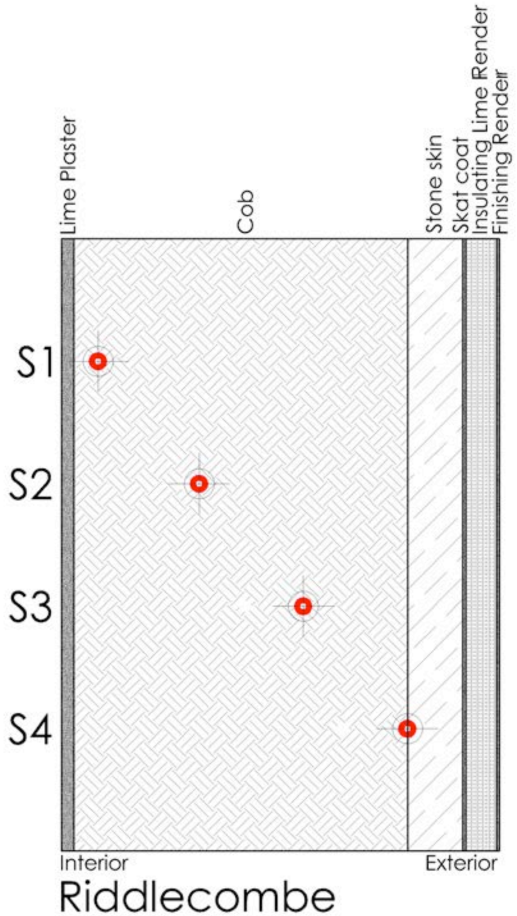


Figure 50. Position of sensors through wall section, Riddlecombe.

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 (Figures 49 and 50). Combined temperature and relative humidity sensors are located at four points within the wall at heights and depths given in Table 11. 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 11. Interstitial hygrothermal gradient sensor positions and wall build up for The Firs, Riddlecombe, 2013- 2014.

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 June 2013 - 31th May 2014 has been used as the basis for the following analysis.

Relative Humidity Over Time

Figures 51 and 52 show the RH responses measured in and around the wall at Riddlecombe over the past year. Findings of the unusual behaviour of RH in this cob wall have been discussed in previous versions of this report. At Riddlecombe, contrary to convention, RH rises during the summer months whereas normally one might expect RH to fall due to warmer summer temperatures which can reduce the relative humidity of the air. In the past, at Riddlecombe, we find sensor 4 rising quickly to 100% RH (i.e. saturation or dewpoint) over the summer, a pattern that is repeated by sensor 3 albeit for a less extended period of time (Figures 53 & 54). This year's full year analysis provided in Figures 51 and 52 features no gradient whatsoever for sensor 4 suggesting that values have remained at 100% for a full 12 months and this is confirmed by the average monthly RH values for the wall at Riddlecombe, Table 12. Measurements of moisture content and findings of damp material at this location have previously suggested that fabric may indeed be wet in this part of the wall. In prior reports the unseasonal rise in %RH has been ascribed to the heating effects of the sun on the south-facing wall causing moisture bound within the fabric (as a result of water applied during the re-rendering process) to evaporate or vaporise. If this is the mechanism by which high %RH is found within the wall we could maybe expect this effect to diminish during colder winter months (despite the lower temperatures which would normally cause RH to rise). Over the winter months it is indeed possible to see a fall in %RH across all three sensors, 1 - 3, with the lowest RH values for all 3 sensors being found in February 2014. These values then climb again with the onset of summer and direct solar incident on the wall. Whilst RH does decrease in the wall over winter overall rates of %RH remain very high with all annual averages, except for that of sensor 1 closest to the interior face, being considerably above 80% the threshold value for mould growth, Table 12. Indeed not even the minimum values measured over the year at sensors 2 - 4 show a value below 80% although it should be stated that there is no visual evidence of mould growth internally. The RH analysis from Riddlecombe displays another difference in comparison with the other two walls in the study; the RH gradient from sensor 1 seems to have a less direct relationship with internal room conditions and to be more broadly coupled to responses from the other sensors that are more deeply embedded in the wall. There is, of course, in this externally-insulated wall no change in material or interruption in the wall build up between sensors 1 and 2 as there is at Shrewsbury (insulation) and Drewsteignton (insulation and vapour barrier) which probably accounts for a more direct relationship between the internal side and the main body of the cob wall. Sensor 1 sits 60 mm in from the internal wall face within cob material rather than immediately behind internal finishes and so responses from this sensor are less affected by dynamic changes in internal conditions and more reflective of gradual trends within the wall itself.

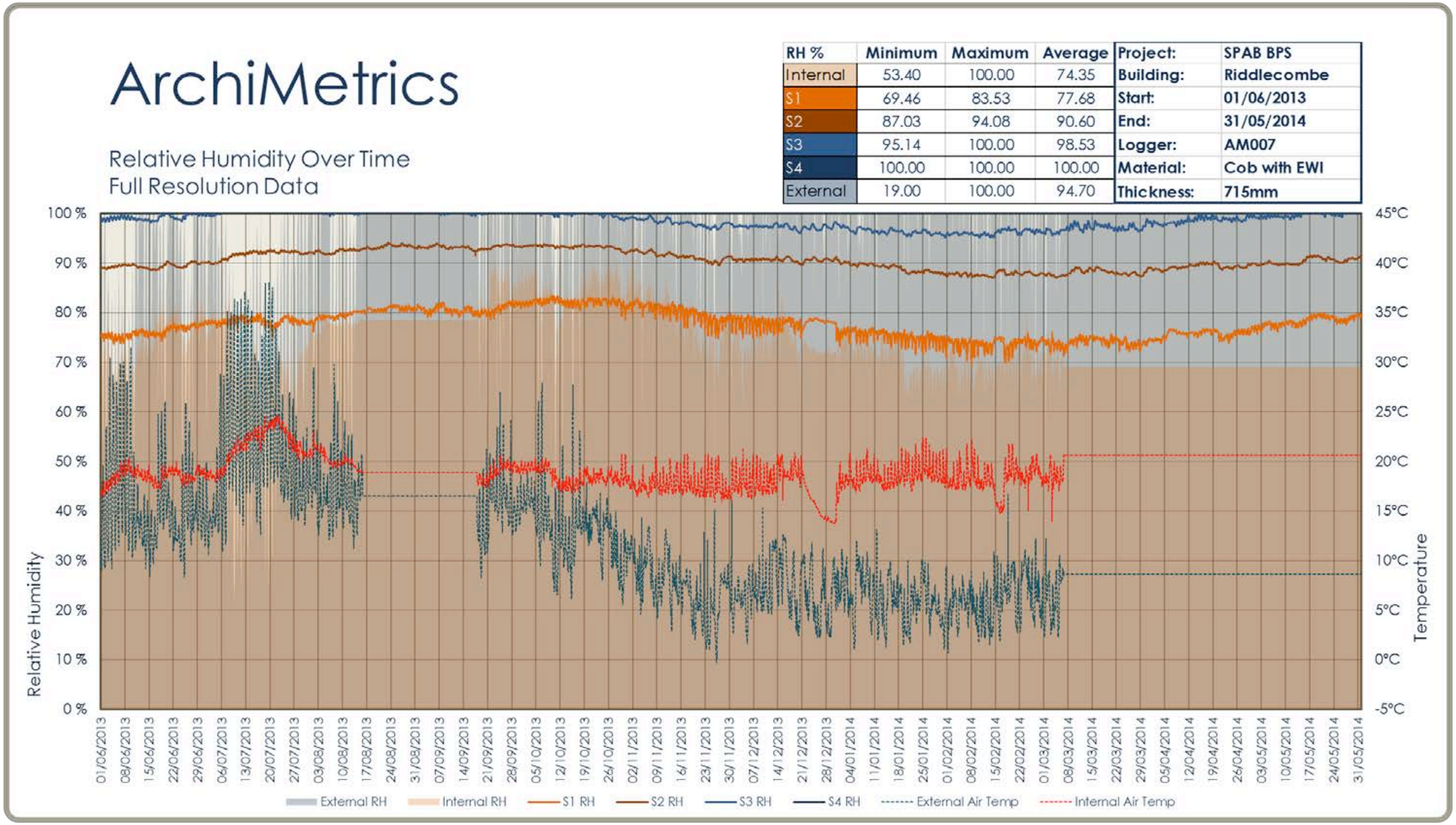


Figure 51: Relative Humidity over time, The Firs, Riddlecombe, 2013 - 2014. Full Resolution.

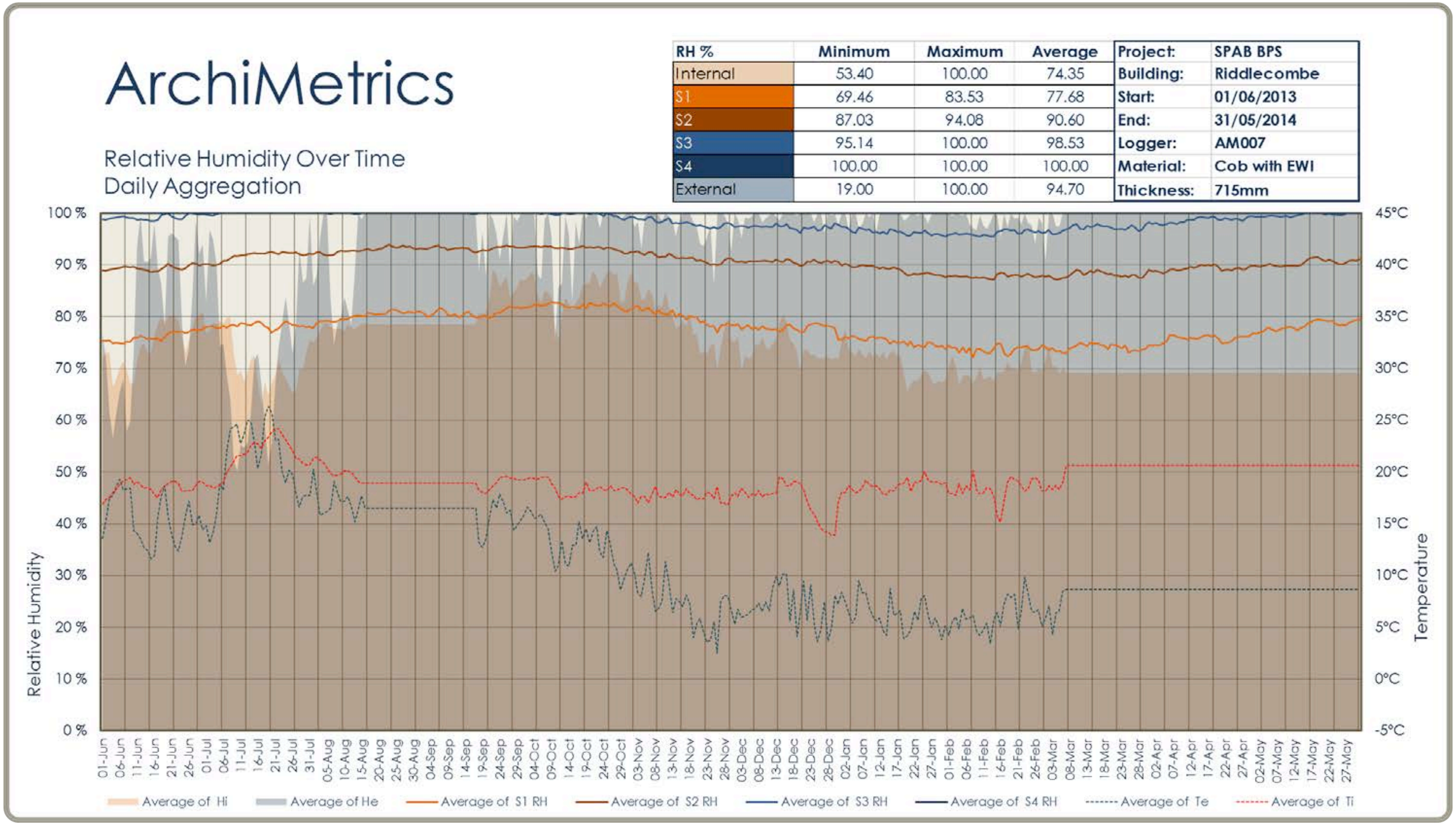


Figure 52: Relative Humidity over time, The Firs, Riddlecombe, 2013 - 2014. Daily Aggregation.

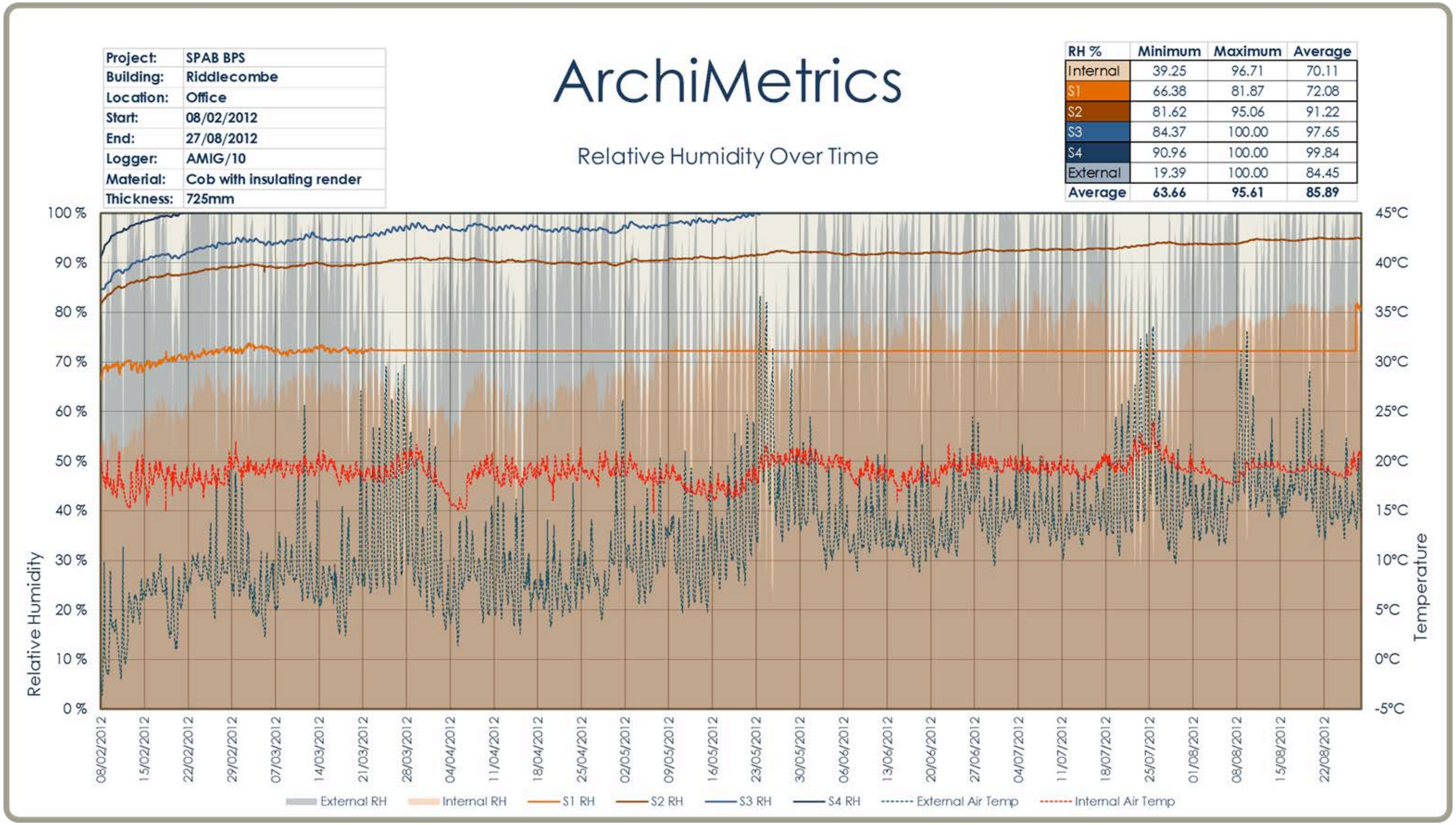


Figure 53: Relative Humidity over time, The Firs, Riddlecombe, February - August 2012. Full Resolution.

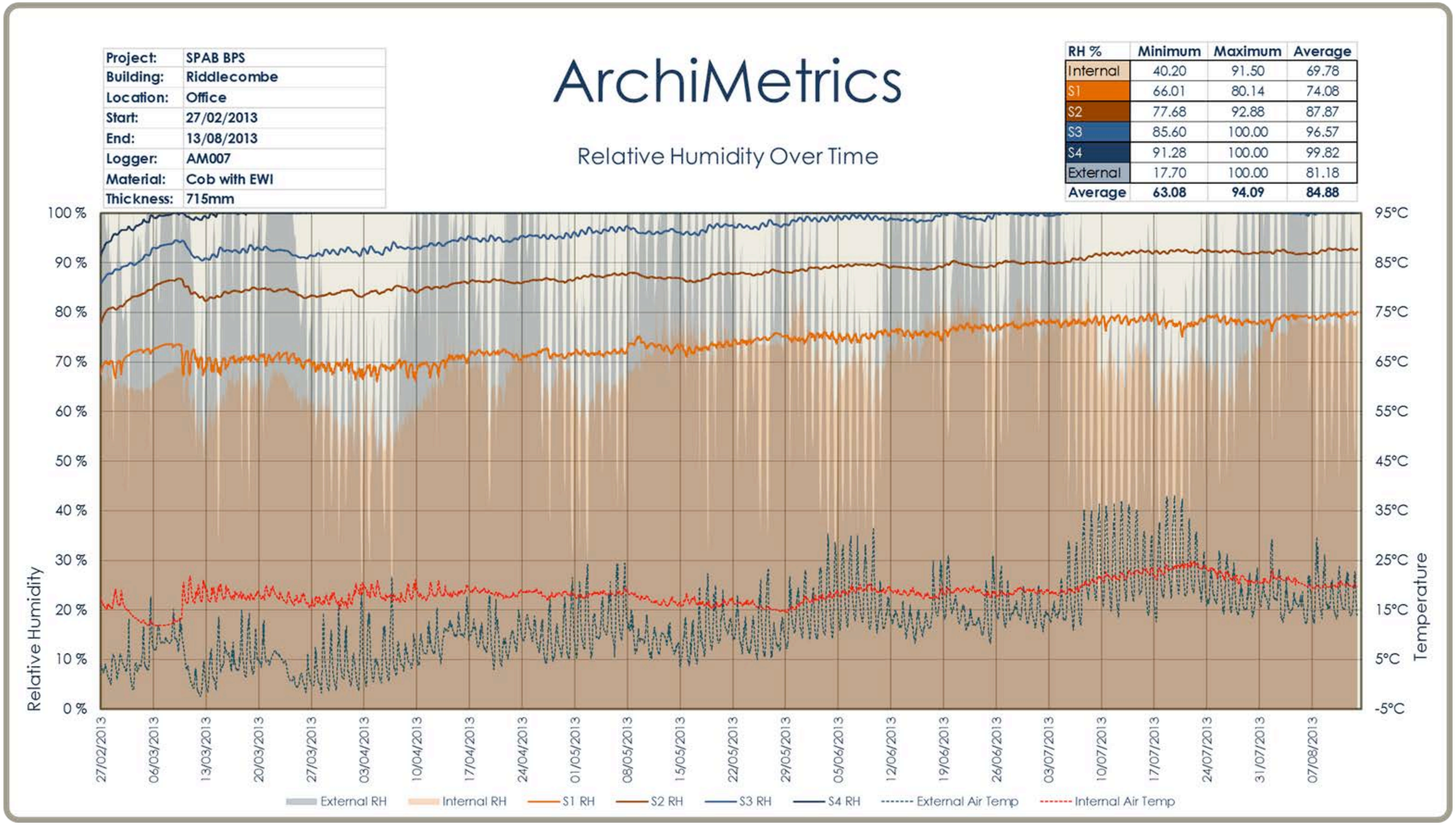


Figure 54: Relative Humidity over time, The Firs, Riddlecombe, February - August 2013. Full Resolution.

Riddlecombe Monthly RH Averages						
	Internal RH	S1 RH	S2 RH	S3 RH	S4 RH	External RH
2013						
Jun	74.70	76.11	89.40	99.16	100.00	81.41
Jul	71.44	78.22	91.68	99.96	100.00	72.70
Aug	78.08	80.08	92.85	99.98	100.00	94.06
Sep	81.31	80.68	93.19	99.97	100.00	98.04
Oct	84.95	82.10	93.25	99.77	100.00	96.17
Nov	79.40	79.94	91.38	98.15	100.00	97.69
Dec	73.80	77.86	90.63	97.31	100.00	99.24
2014						
Jan	70.94	75.17	89.00	96.37	100.00	99.38
Feb	69.69	73.66	87.78	96.14	100.00	98.48
Mar	69.46	74.02	88.09	97.10	100.00	99.54
Apr	69.10	75.72	89.28	98.63	100.00	100.00
May	69.10	78.30	90.39	99.67	100.00	100.00
Average	**74.35**	**77.68**	**90.60**	**98.53**	**100.00**	**94.70**

Table 12. Relative Humidity Monthly Averages, The Firs, Riddlecombe, 2013 -14.

Absolute Humidity Over Time

Figure 55 shows an analysis of absolute humidity through the insulated wall section at Riddlecombe June 2013 - May 2014. This analysis shows similar trends to that remarked on in previous reports, i.e. that there is an increase in absolute humidity throughout the wall during the summer period. This in itself is not confined to the wall at Riddlecombe but is something seen in all the monitored walls in the study most likely as a response to the lack of space heating and the increase in atmospheric humidity during the British summertime. Where Riddlecombe once again diverges from the norm is the extent of the AH response seen within the wall during these warmer periods. The gradients from all four wall sensors are detached from that of external AH and show considerably higher g/m^3 values than those measured for the external conditions. This suggests an additional source of moisture vapour beyond that found within the external or indeed internal room environments; i.e. construction moisture that is located within the wall fabric itself which is vaporising due to fabric heating in a south-facing wall over the summer months and creating higher quantities of vapour within the wall. Previously the rise in AH in the wall section over the summer has been seen to be cumulative (Figures 56 & 57). However, the full year's analysis in Figure 55 allows us to see that coming into the colder part of the year, October 2013 onwards, AH reduces and sits between the gradients of internal and external AH. Now the greatest quantities of vapour are found at the sensors closest to the internal side of the wall, sensors 1 and 2. Measurements at these two sensors are very similar and broadly mirror those of internal conditions. Quantities of vapour from sensors 3 and 4 decrease in proximity to external conditions and overall this arrangement, of diminishing quantities of vapour moving through the section towards external conditions, is what we find for other walls in the study over the winter period. The winter AH pattern at Riddlecombe, where AH measured within the wall replicates the physical reality of the wall itself, i.e. it sits between internal and external conditions, would also seem to suggest the additional summertime vapour-producing properties of the wall have reduced due to the lack of significant sun-driven fabric heating over the winter.

In an attempt to chart changes and trends in the wall over a longer period of time it is interesting to examine the average vapour quantities calculated for the wall since the new insulating external render was applied. However, it should be noted that the values given in Table 13 for the years 2012 and 2013 due to previous data losses are from data collected over a six-month period from February to August (during the summer where wall humidity is found to be high) whereas the data for 2013 - 14 is from a full year's worth of measurements and therefore includes summer and winter values. Table 13 shows a year-on-year (or summer on summer) increase in vapour weights within the wall at sensors 1 and 2 and a decrease at sensor 4. The greatest change has taken place at sensor 1 at the inside face of the wall and the increase in vapour quantities towards this side of the wall might suggest some migration of the vapour from within the fabric towards the internal face. This, in turn, may create the possibility of evaporation into the room?

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

Table 13. Average Absolute Humidity, The Firs, Riddlecombe, 2012 - 2014.

ArchiMetrics

Absolute Humidity Over Time
Daily Aggregation

AH g/m3	Minimum	Maximum	Average
Internal	7.65	17.38	12.25
S1	8.93	17.33	12.10
S2	9.08	20.05	12.96
S3	8.14	21.76	12.72
S4	6.76	22.85	11.75
External	4.75	17.78	9.69

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

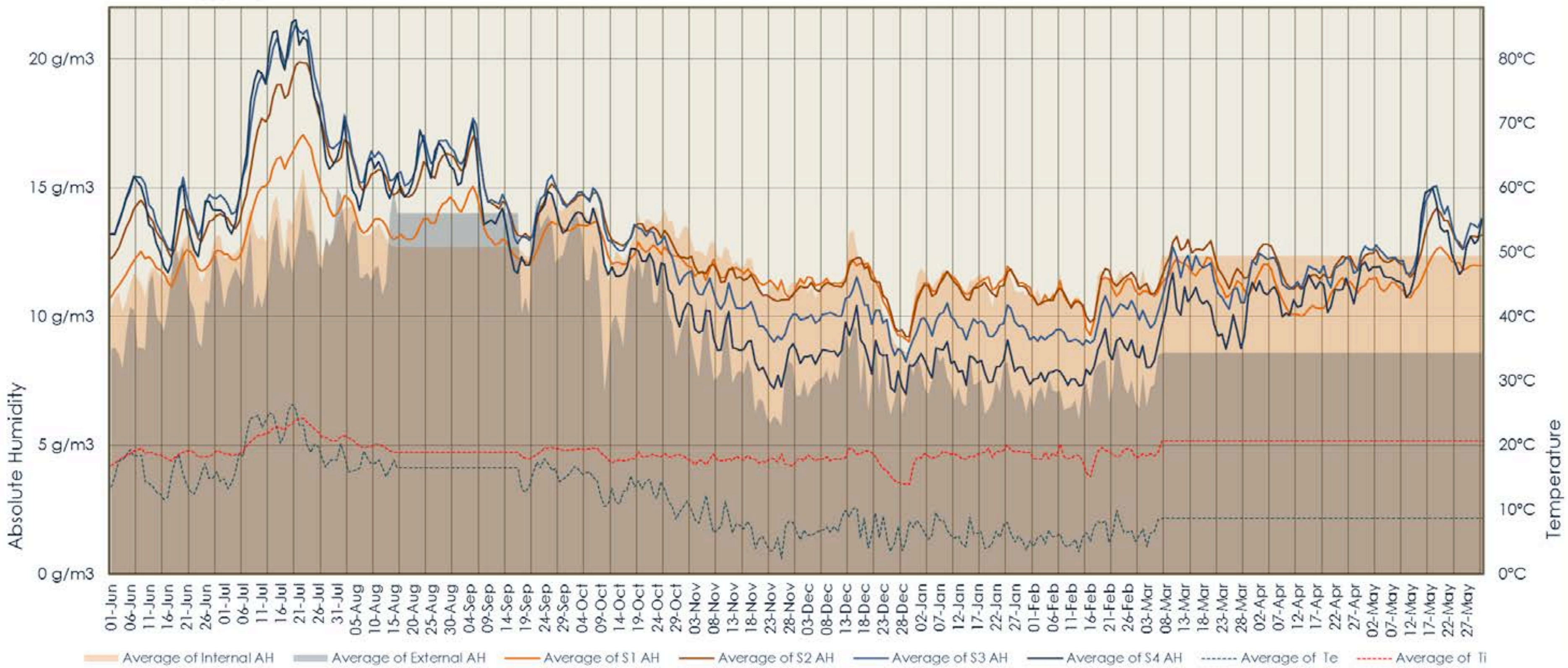


Figure 55: Absolute Humidity over time, The Firs, Riddlecombe, 2013 - 2014. Daily Aggregation.

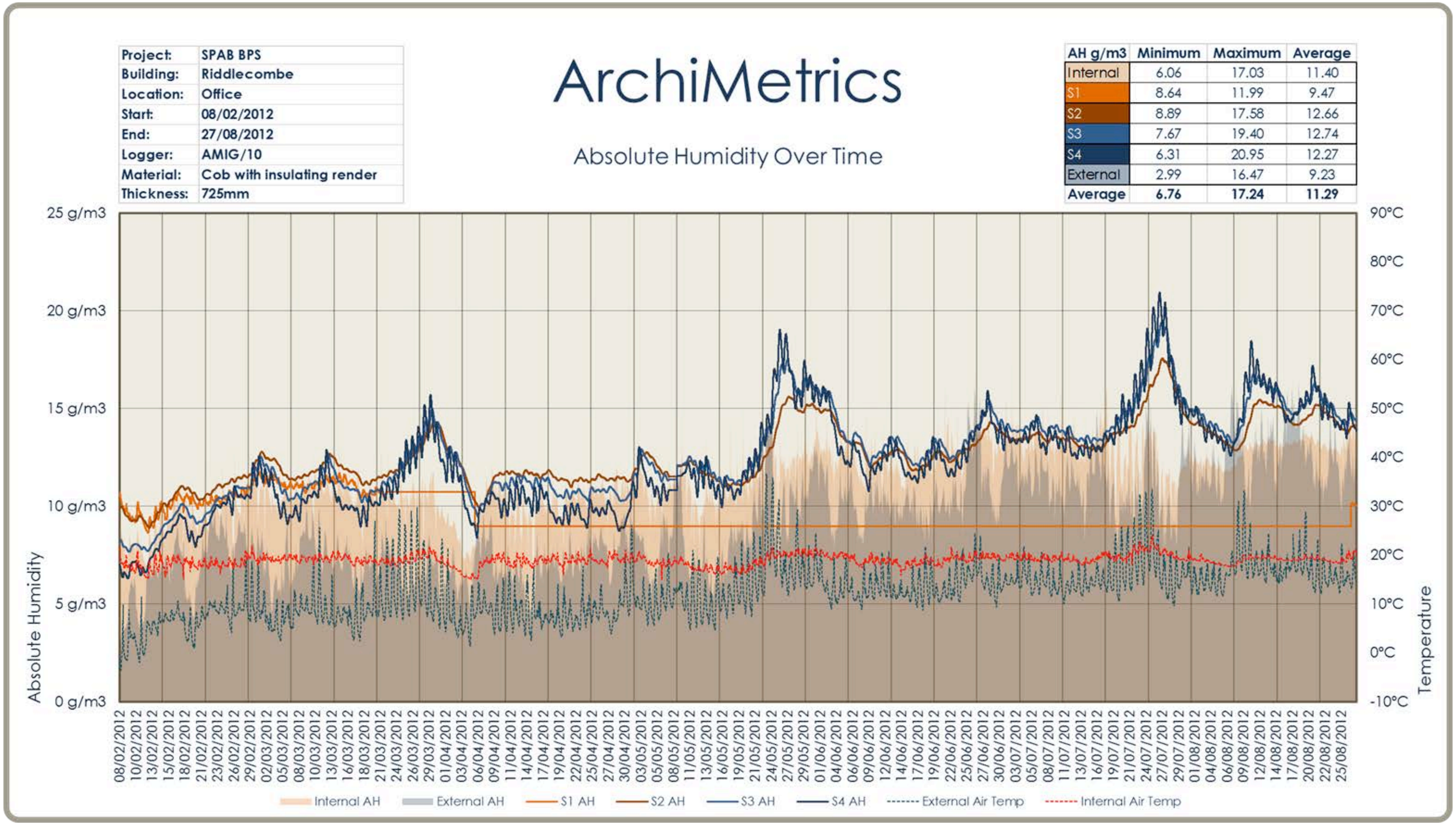


Figure 56: Absolute Humidity over time, The Firs, Riddlecombe Feb - Aug 2012. Full Resolution.

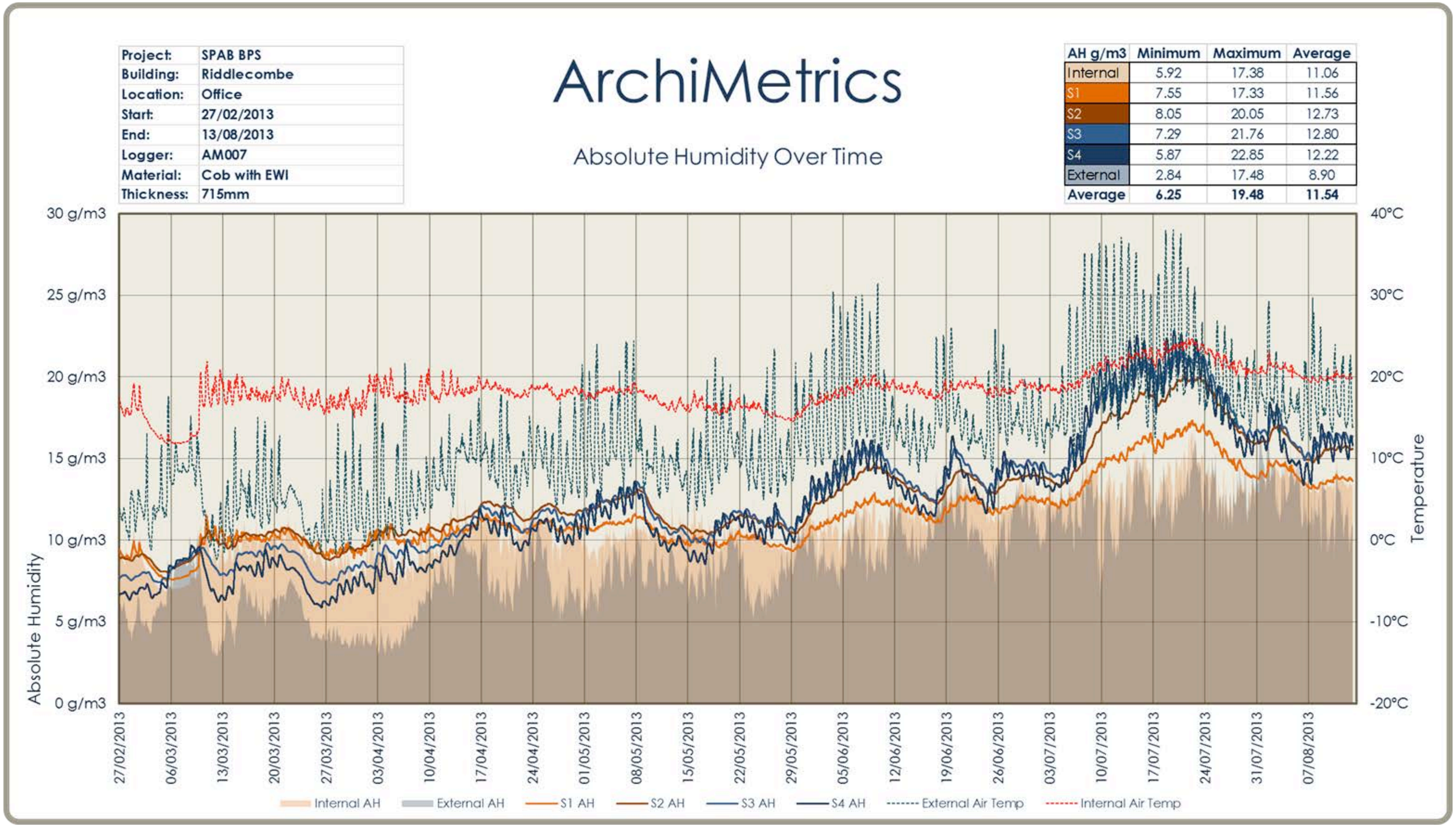


Figure 57: Absolute Humidity over time, The Firs, Riddlecombe Feb - Aug 2013. Full Resolution.

Hygrothermal Section & Dewpoint Margin

Measurements of temperature and RH are also used to plot annual and monthly averages of temperature and dewpoint through the wall section (Figure 58 and Figures 59 - 70).

Counter to convention, the monthly plots for Riddlecombe show that the wall is most at risk of interstitial condensation during the summer months where we see an extended period of convergence of the dewpoint and measured temperature gradients between sensors 3 and 4 and a narrowing of the margin between sensors 3 and 2 (Figures 59 - 70). This is most likely for the reasons previously discussed concerning summertime vapour generation from within the damp cob. Following this reasoning and once again counter to convention we see an improving picture over the winter period as the gradients between sensors 2 and 3 open up. Figure 58 provides a hygrothermal picture for the wall over the full year and shows the convergence of measured temperature and dewpoint between sensors 3 and 4 as the predominant feature, as well as the small annual average margin found at sensor 2 of only 1.55˚C. The difference between the measured temperature and dewpoint temperature we term the dewpoint margin and it represents the temperature drop required for condensation to begin at the measured locations within the wall. Figure 71 provides an analysis of the dewpoint margins for the wall at Riddlecombe over time. In Table 14 below, these margins are written as an average across all four measurement points within the section and also individually, showing the change in these average margins before and after the wall was insulated and over the following years.

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**

Table 14. Dewpoint Margins & Pre & Post-insulation Difference, The Firs, Riddlecombe, 2011 - 2014.

(It should be noted that in this Table the pre-insulation margins are calculated from a short period of winter monitoring, the 2012 data has been gathered over approximately seven months and the 2013 - 14 margins are calculated from a full years data set.) From Table 14 it can be seen that the dewpoint margin at the 4th sensor was already narrow prior to the application of the new insulating render (probably as a result of cracks in the old cement render admitting water to the structure). However, following the insulation of the wall, margins have narrowed considerably and are smaller than those found for the other walls in the study, for example, rarely being above 0.5˚C at sensor 3 and there is no margin at sensor 4 (0˚C = 100% RH) two and a half years after the work took place. A comparison of the difference between these margins, year on year, with the margins recorded for the wall prior to re-rendering suggests a slight decrease in margins once again between 2012 and 2013 -14, the exception being sensor 2 where the margin has increased to a small extent. However, overall there would seem to be an increase in the risk of dewpoint being reached within the wall.

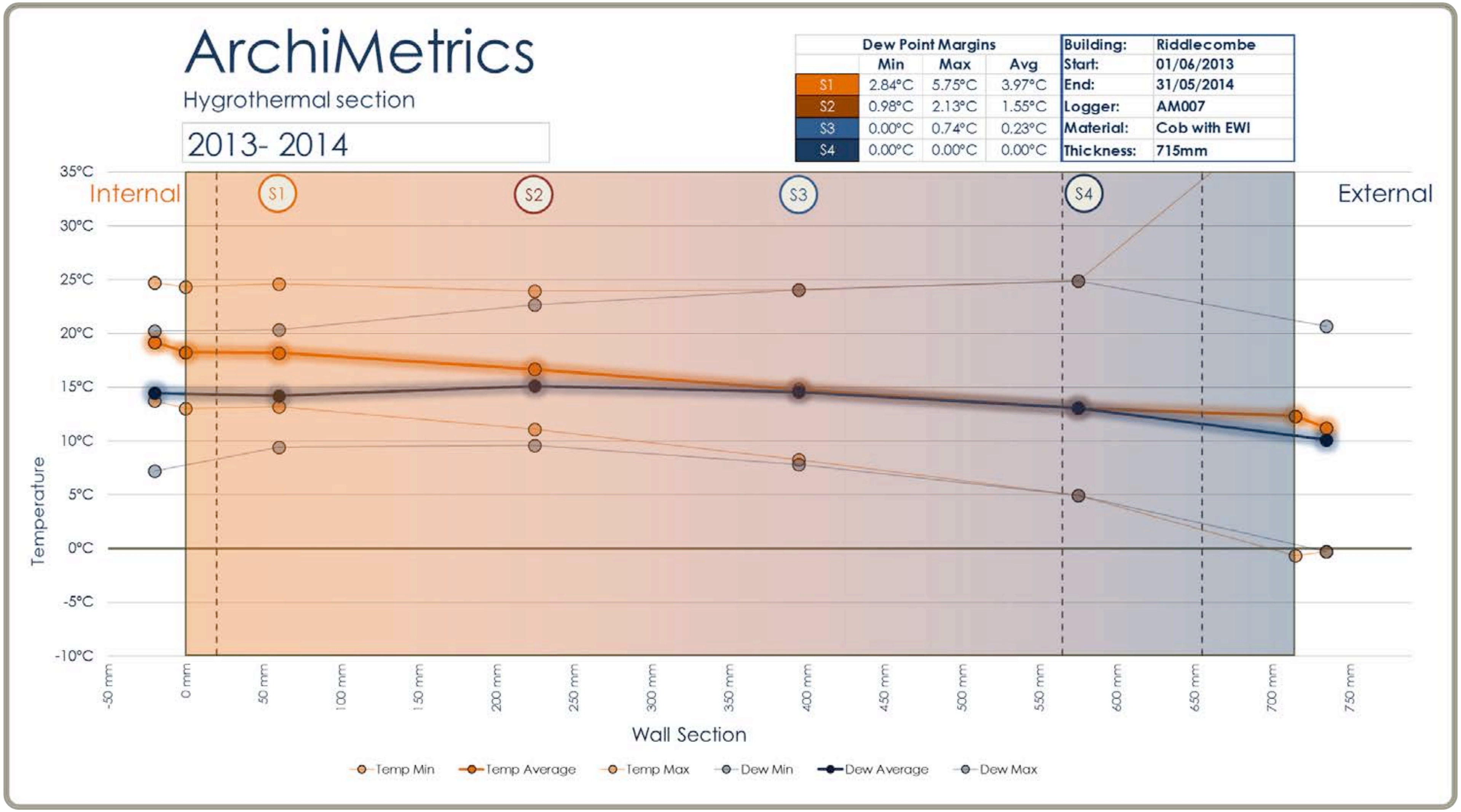


Figure 58. Hygrothermal Section, The Firs, Riddlecombe, June 2013 - May 2014.

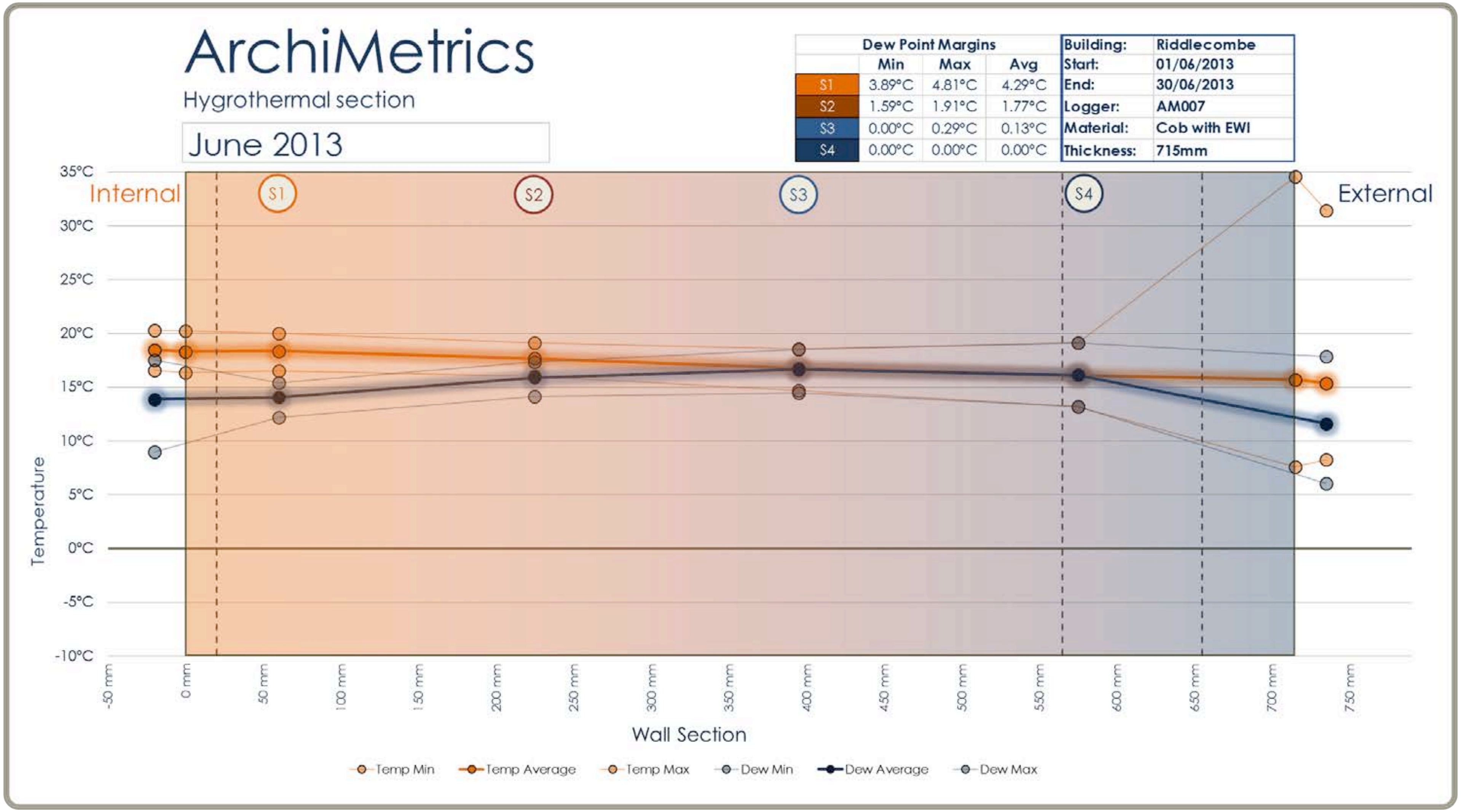
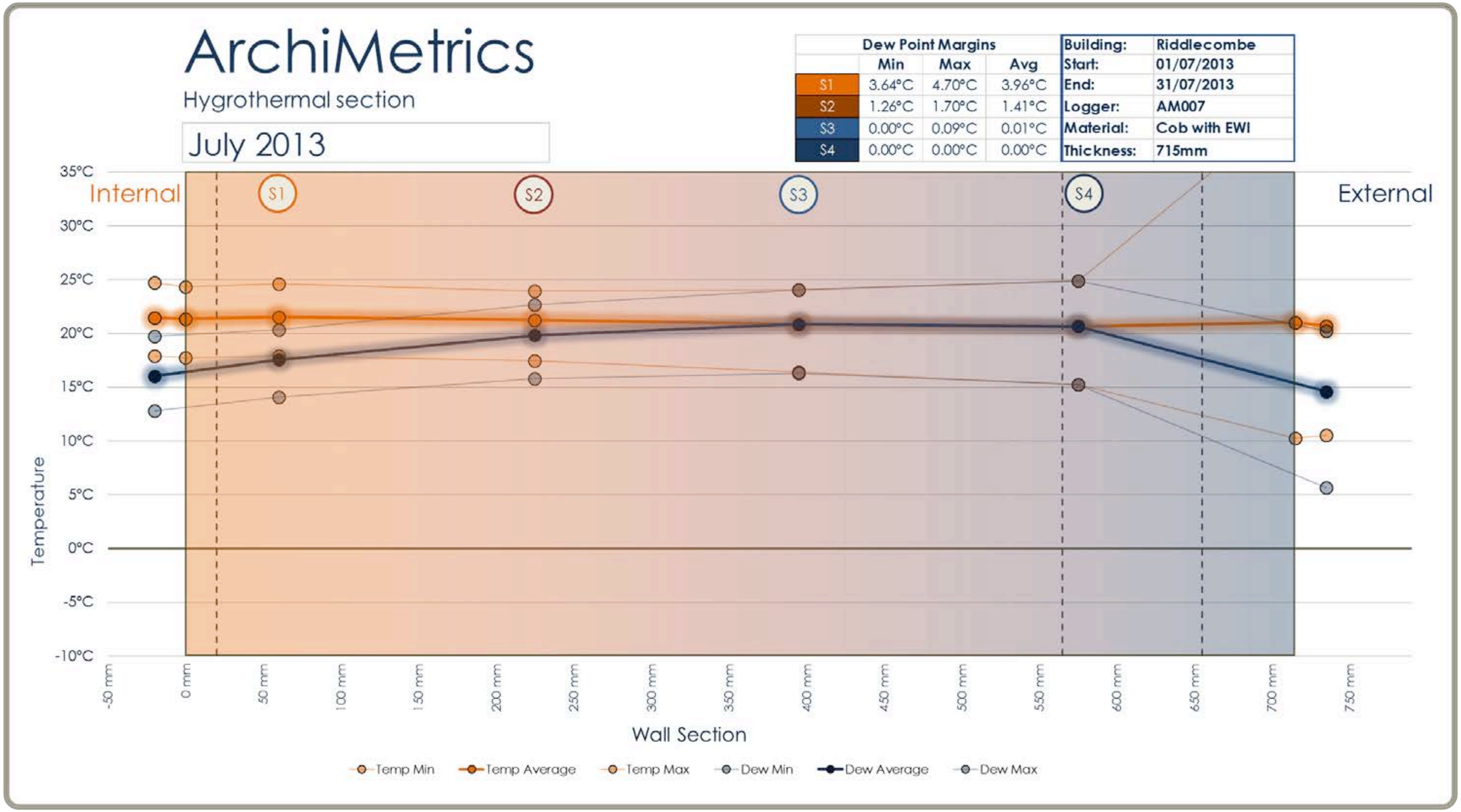


Figure 59. Hygrothermal Section, The Firs, Riddlecombe, June 2013.



	Dew Point Margins		
	Min	Max	Avg
S1	3.64°C	4.70°C	3.96°C
S2	1.26°C	1.70°C	1.41°C
S3	0.00°C	0.09°C	0.01°C
S4	0.00°C	0.00°C	0.00°C

Building:	Riddlecombe
Start:	01/07/2013
End:	31/07/2013
Logger:	AM007
Material:	Cob with EWI
Thickness:	715mm

Figure 60. Hygrothermal Section, The Firs, Riddlecombe, July 2013.

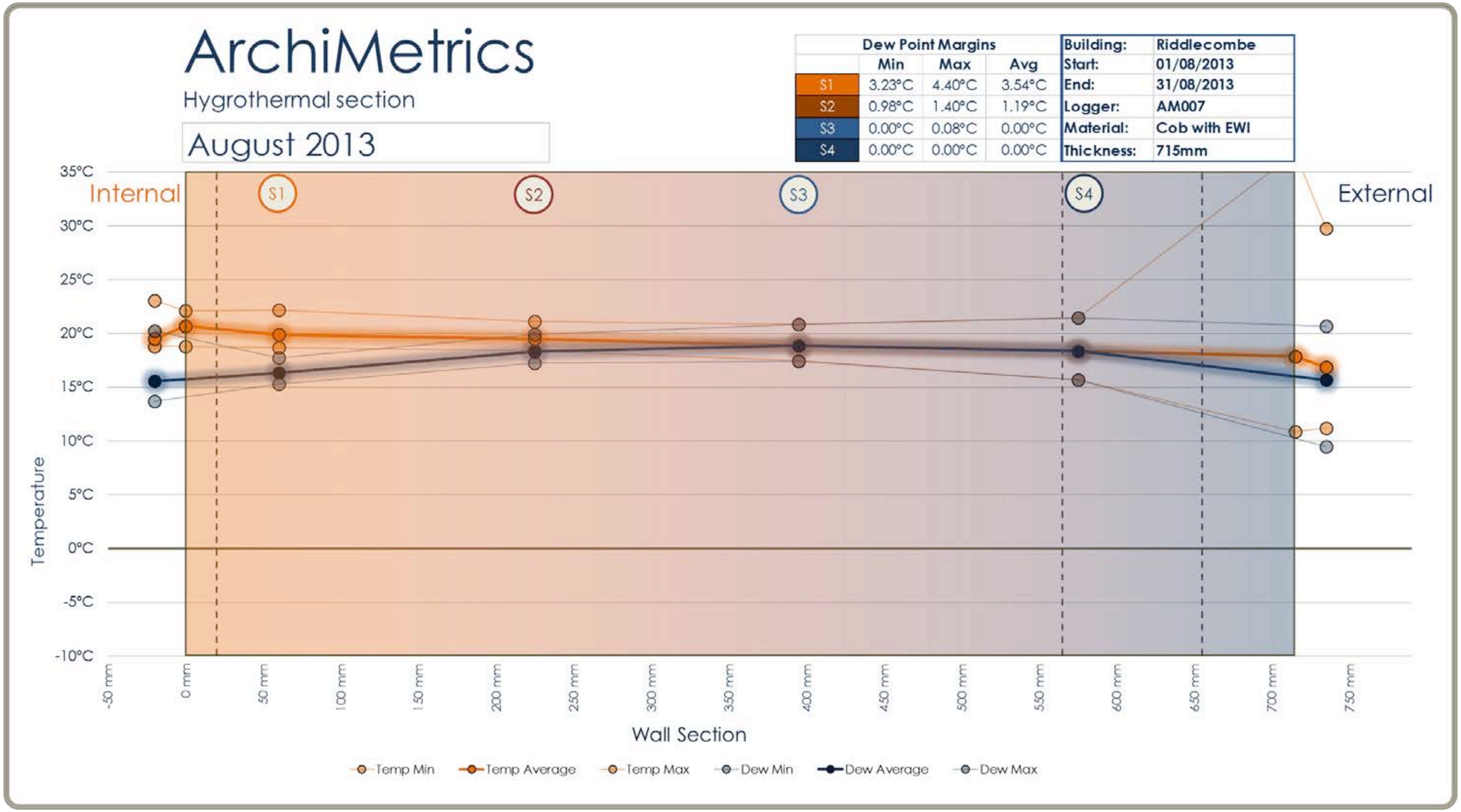


Figure 61. Hygrothermal Section, The Firs, Riddlecombe, August 2013.

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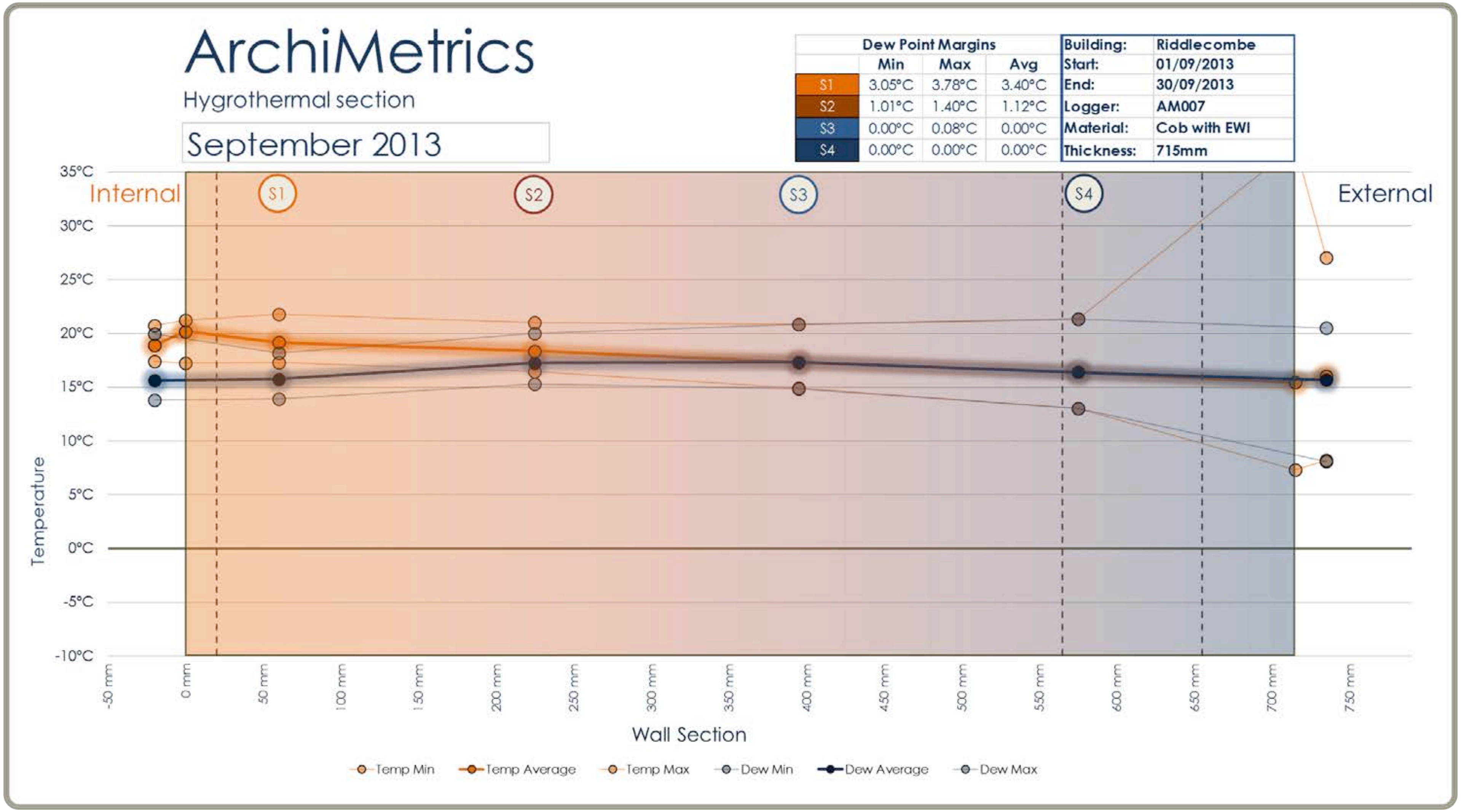

Figure 62. Hygrothermal Section, The Firs, Riddlecombe, September 2013.

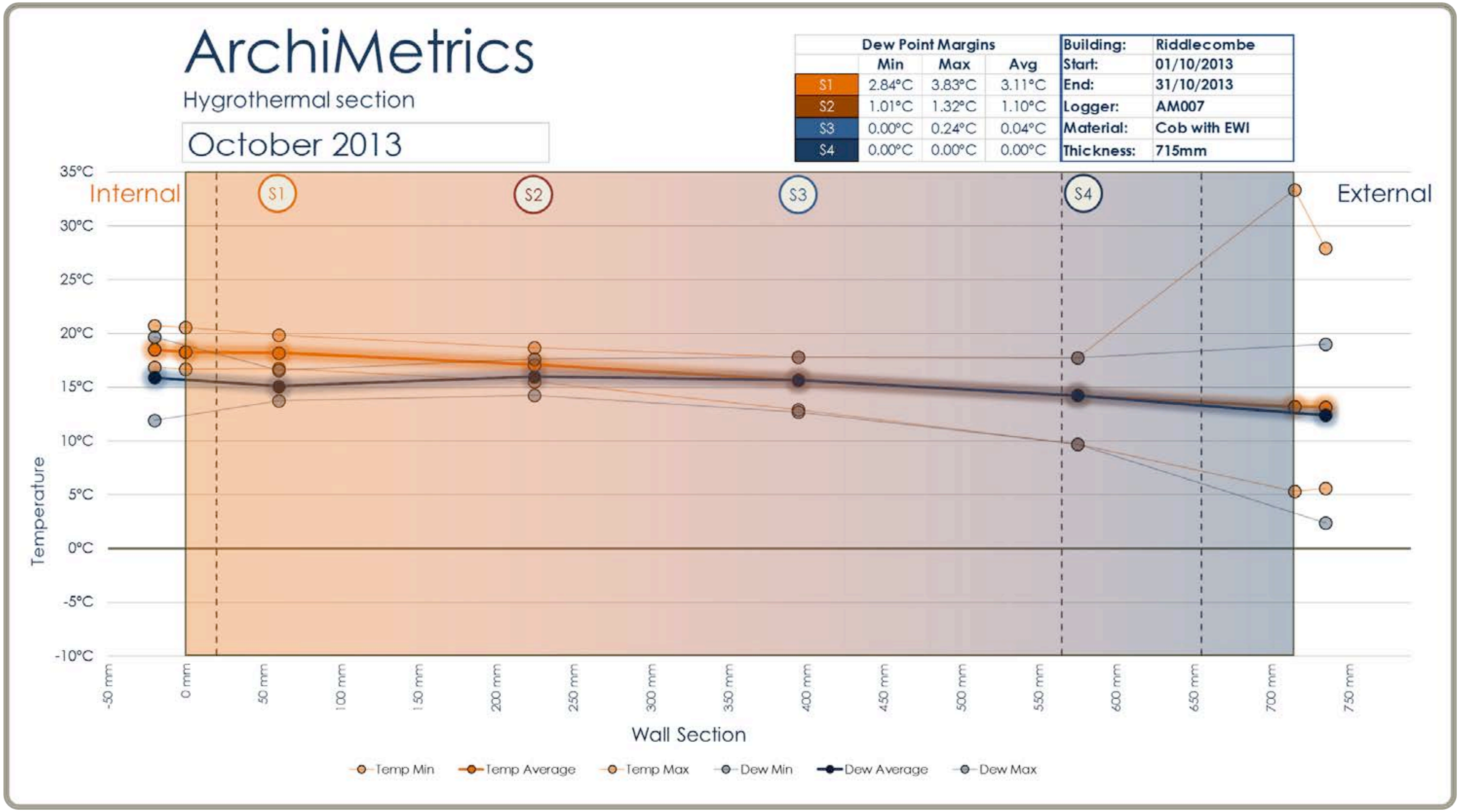

Figure 63. Hygrothermal Section, The Firs, Riddlecombe, October 2013.

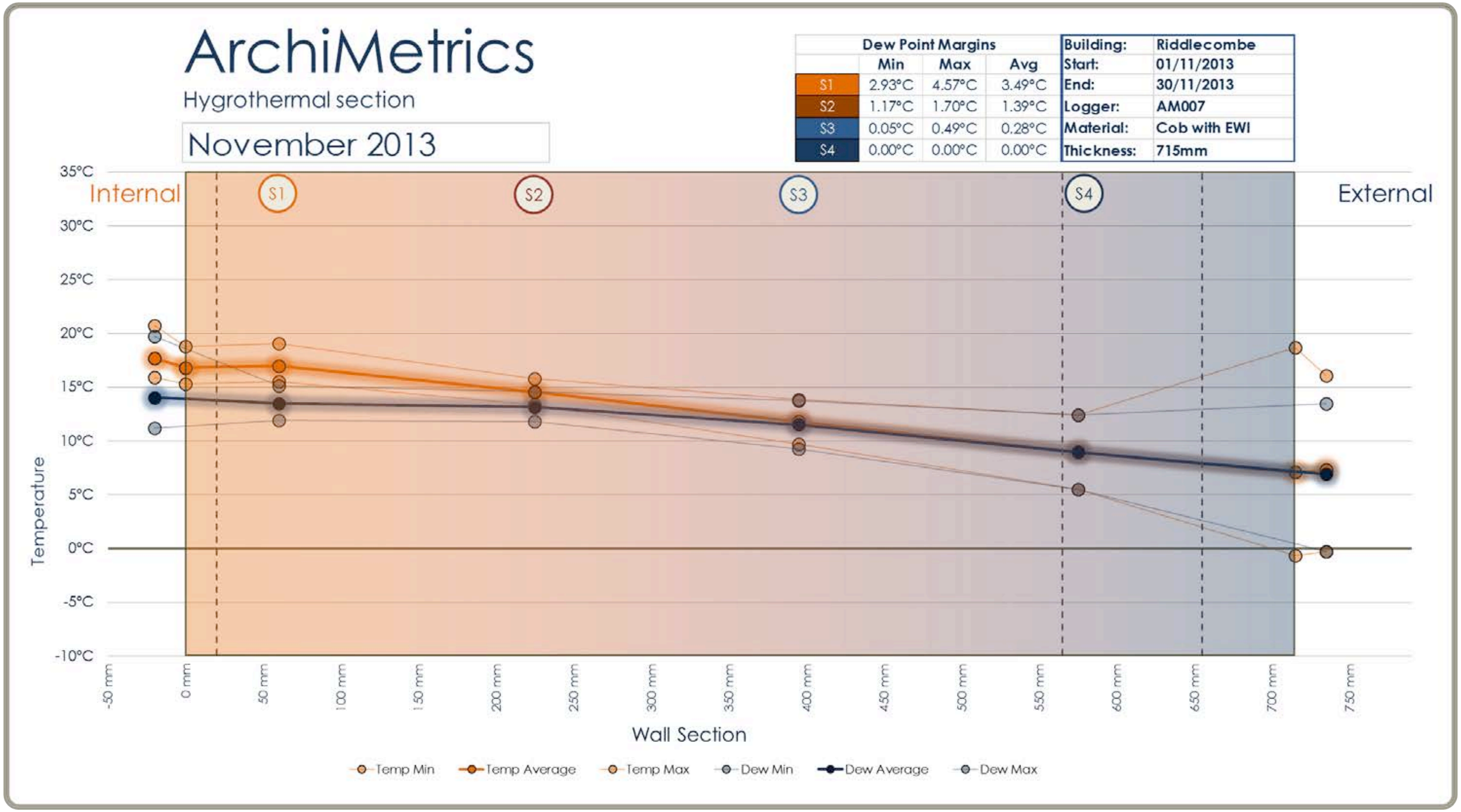

Figure 64. Hygrothermal Section, The Firs, Riddlecombe, November 2013.

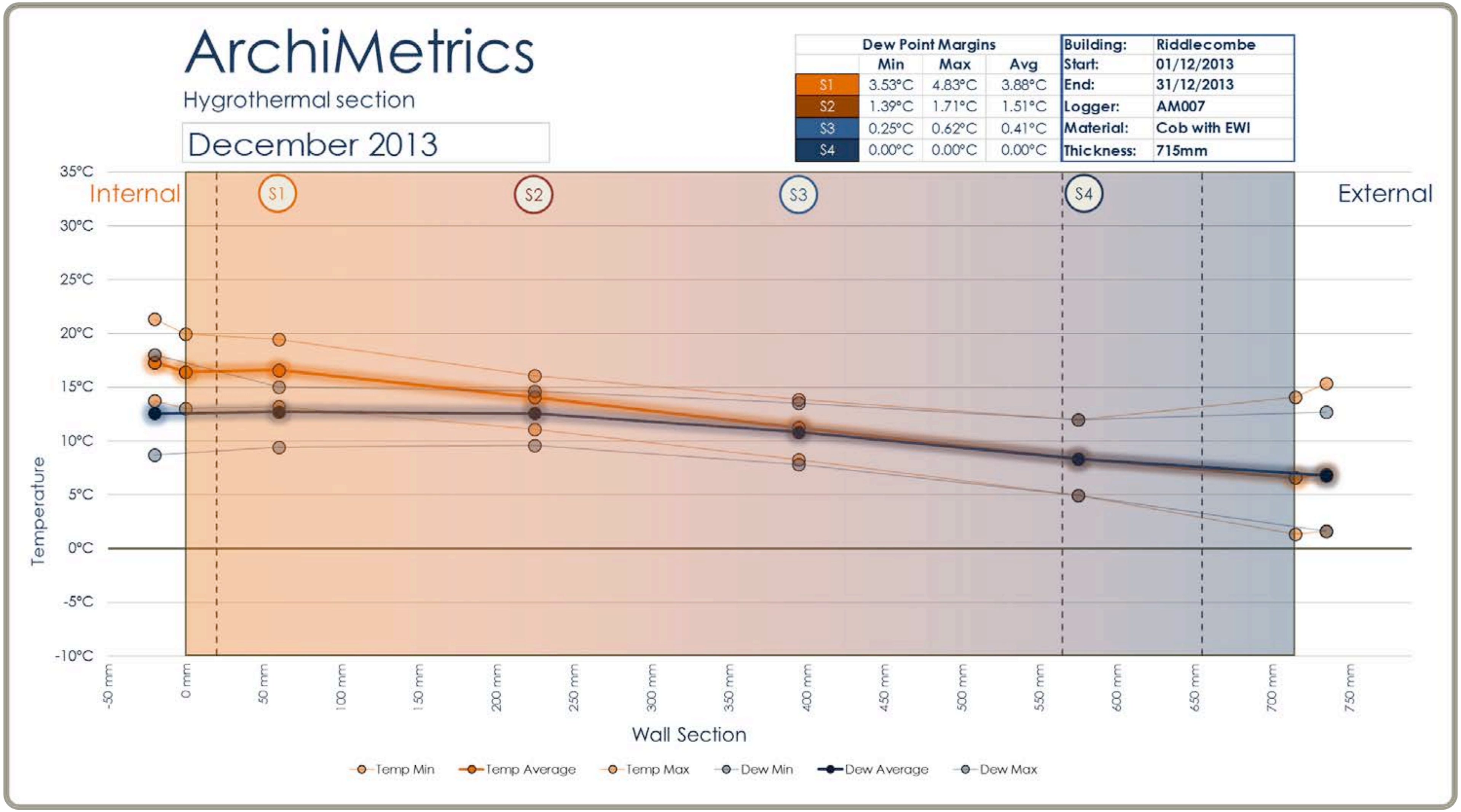

Figure 65. Hygrothermal Section, The Firs, Riddlecombe, December 2013.

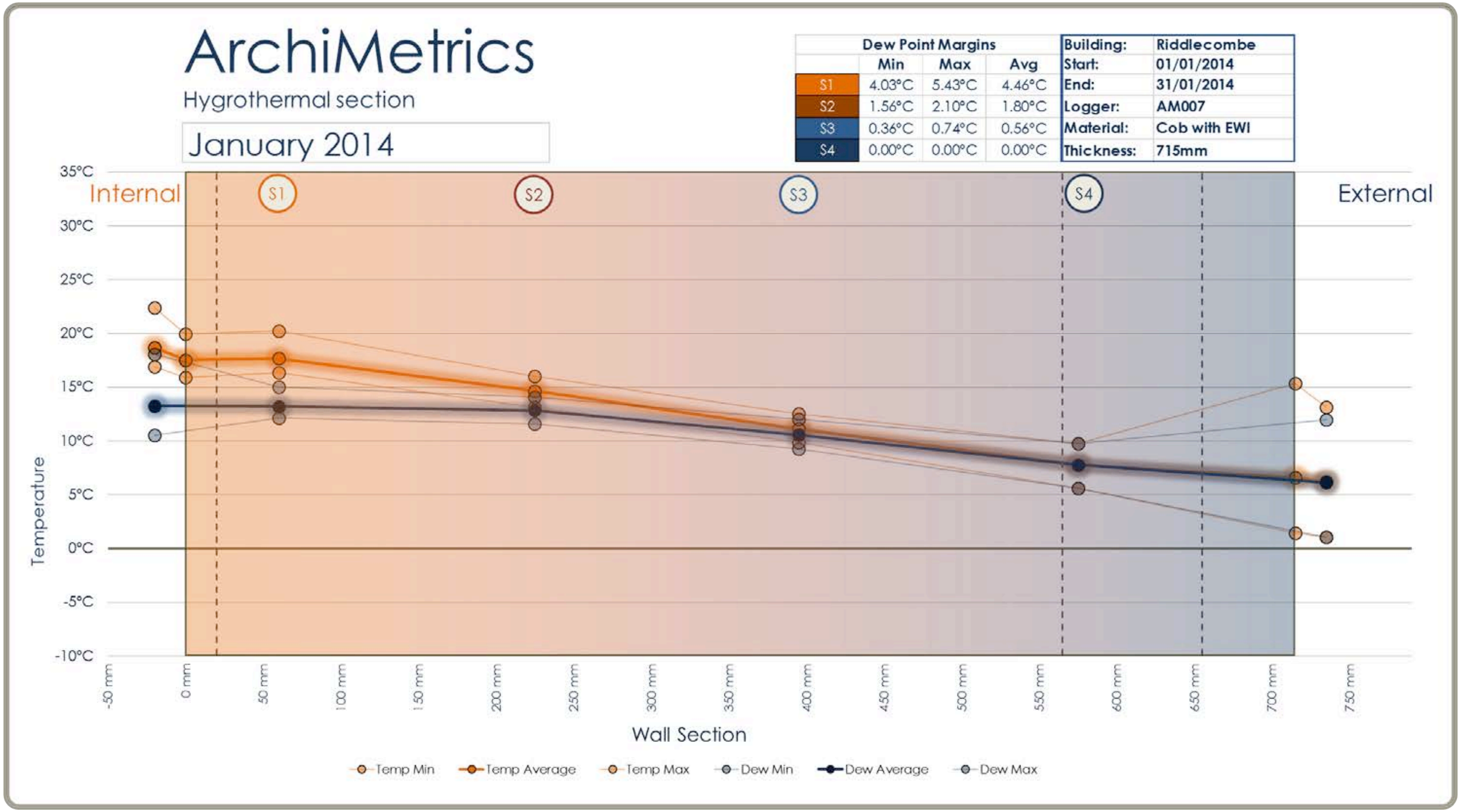

Figure 66. Hygrothermal Section, The Firs, Riddlecombe, January 2014.

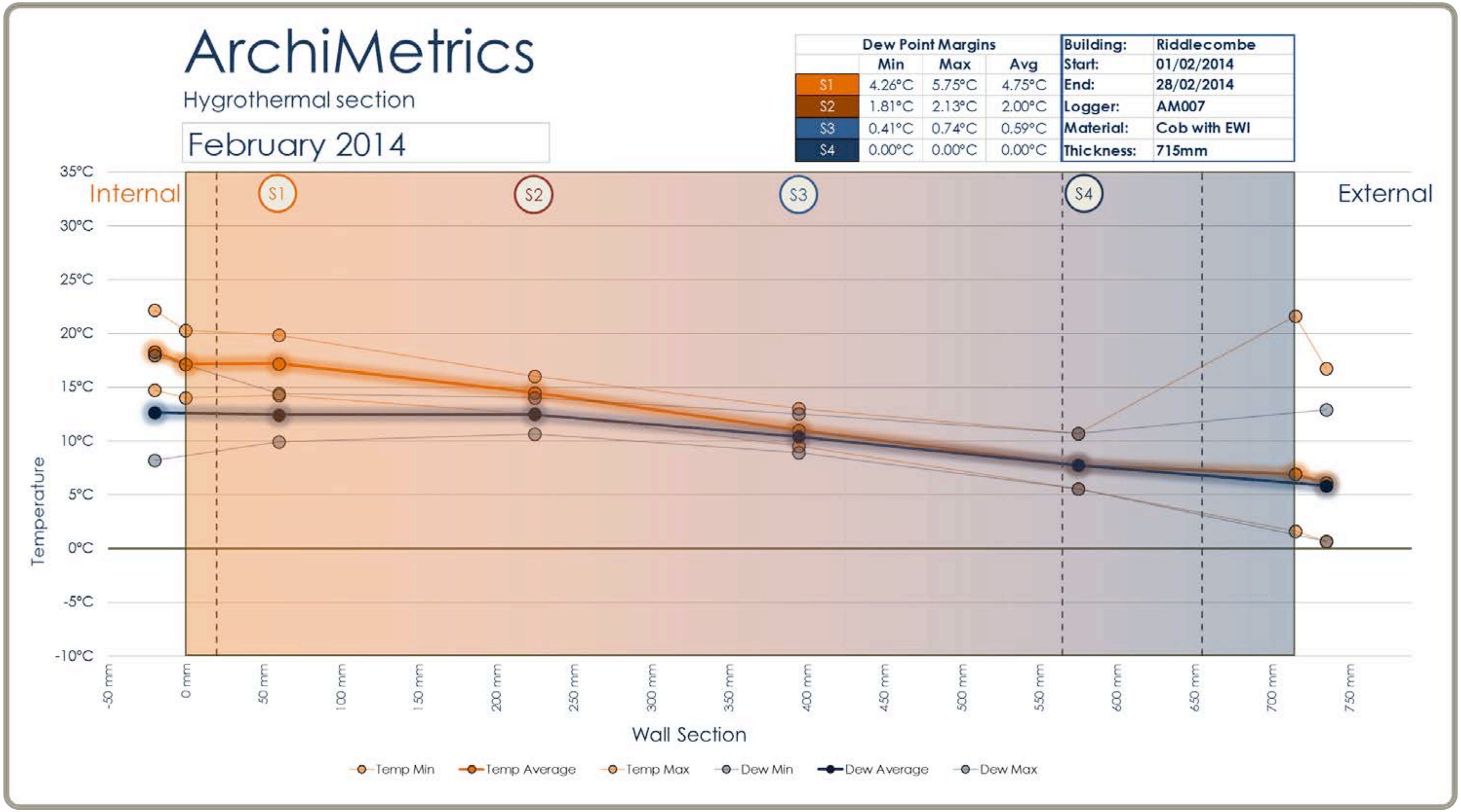

Figure 67. Hygrothermal Section, The Firs, Riddlecombe, February 2014.

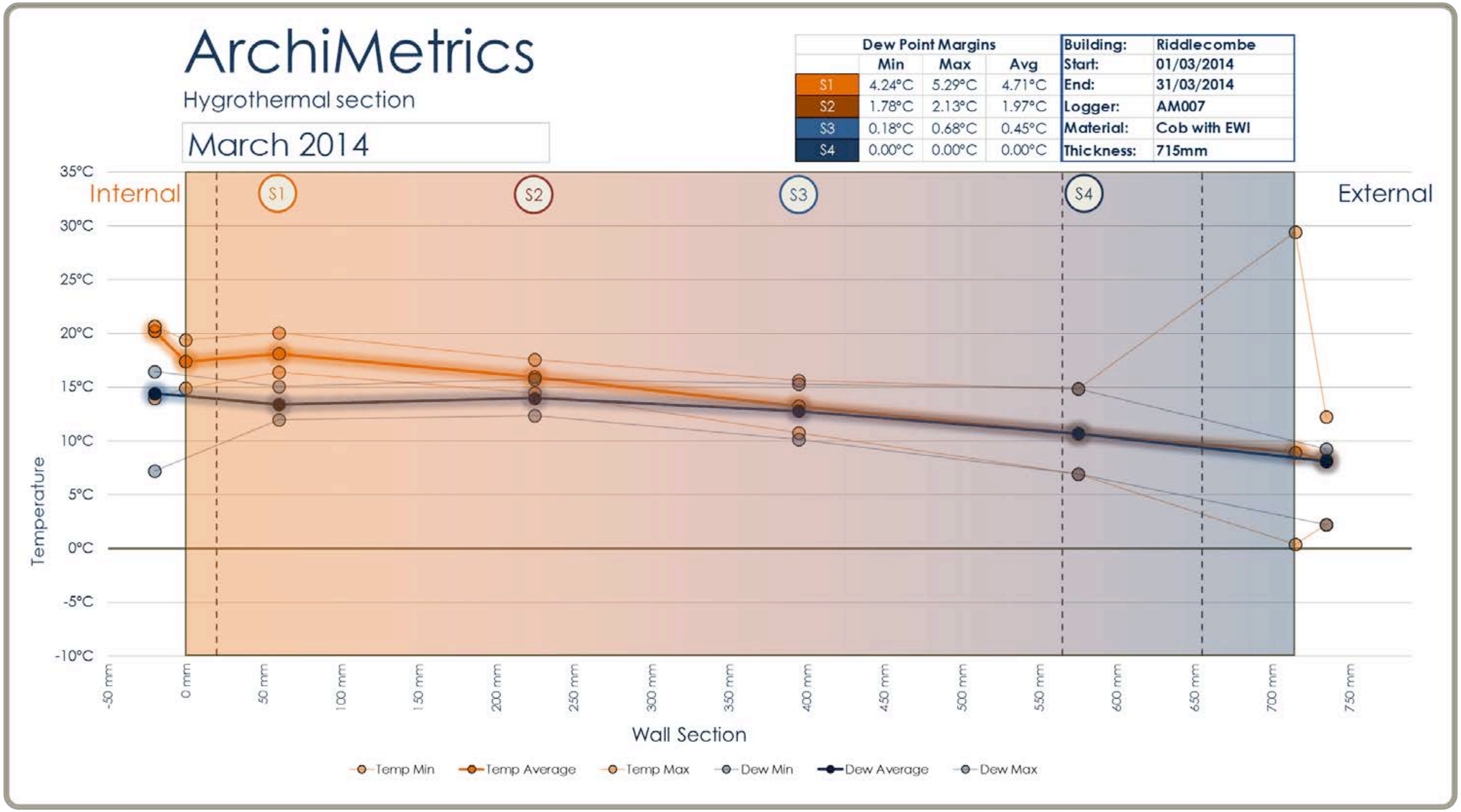

Figure 68. Hygrothermal Section, The Firs, Riddlecombe, March 2014.

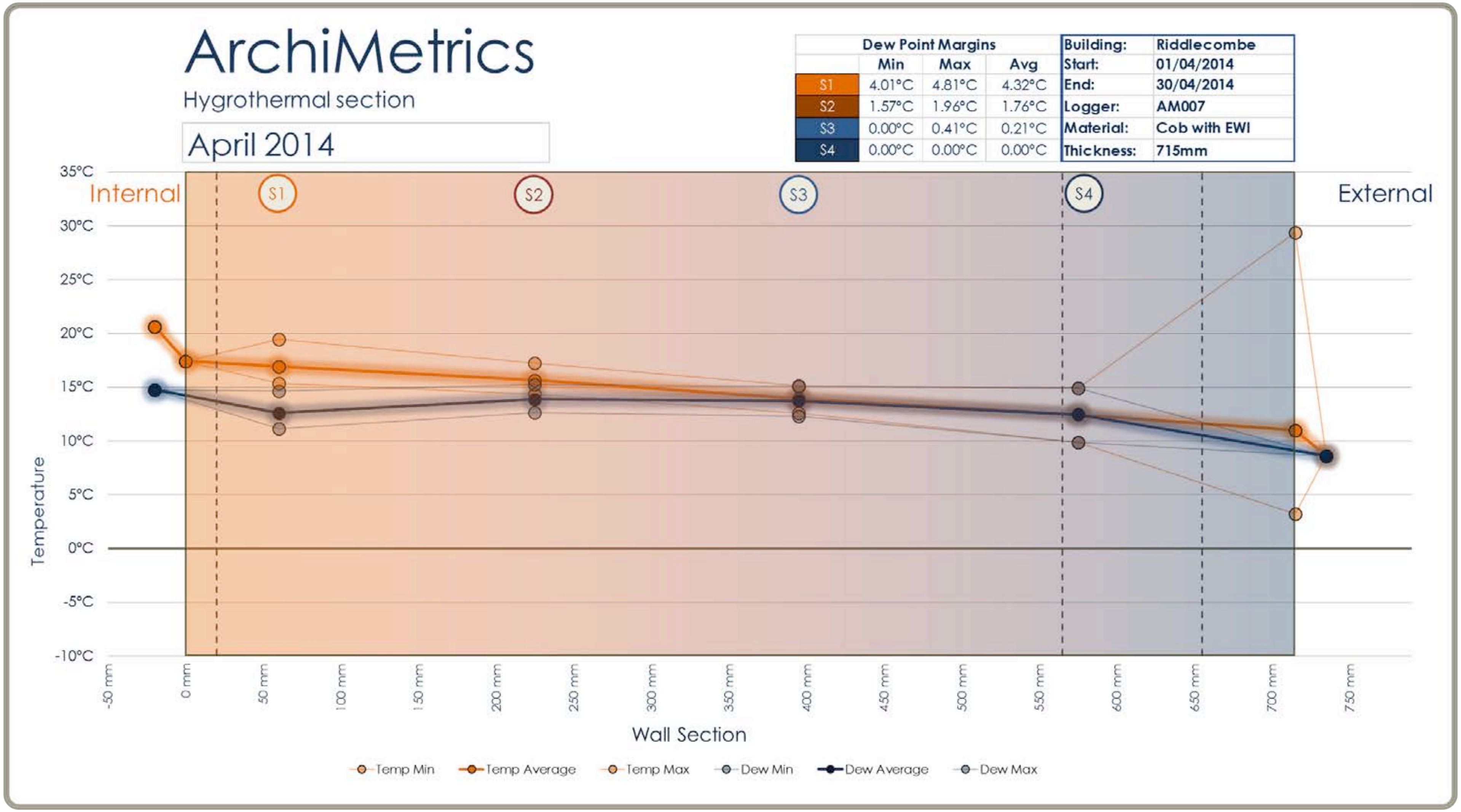

Figure 69. Hygrothermal Section, The Firs, Riddlecombe, April 2014.

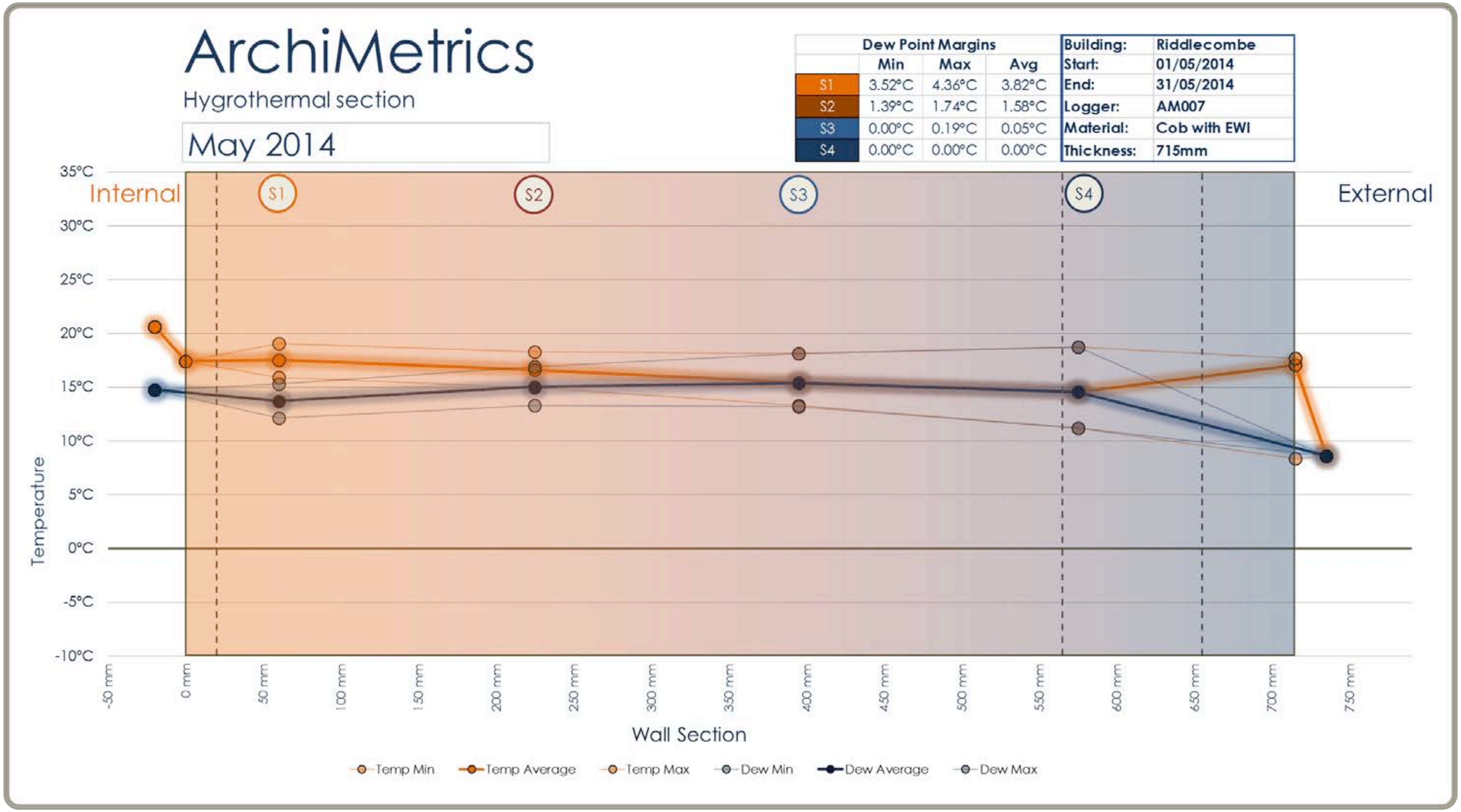

Figure 70. Hygrothermal Section, The Firs, Riddlecombe, May 2014.

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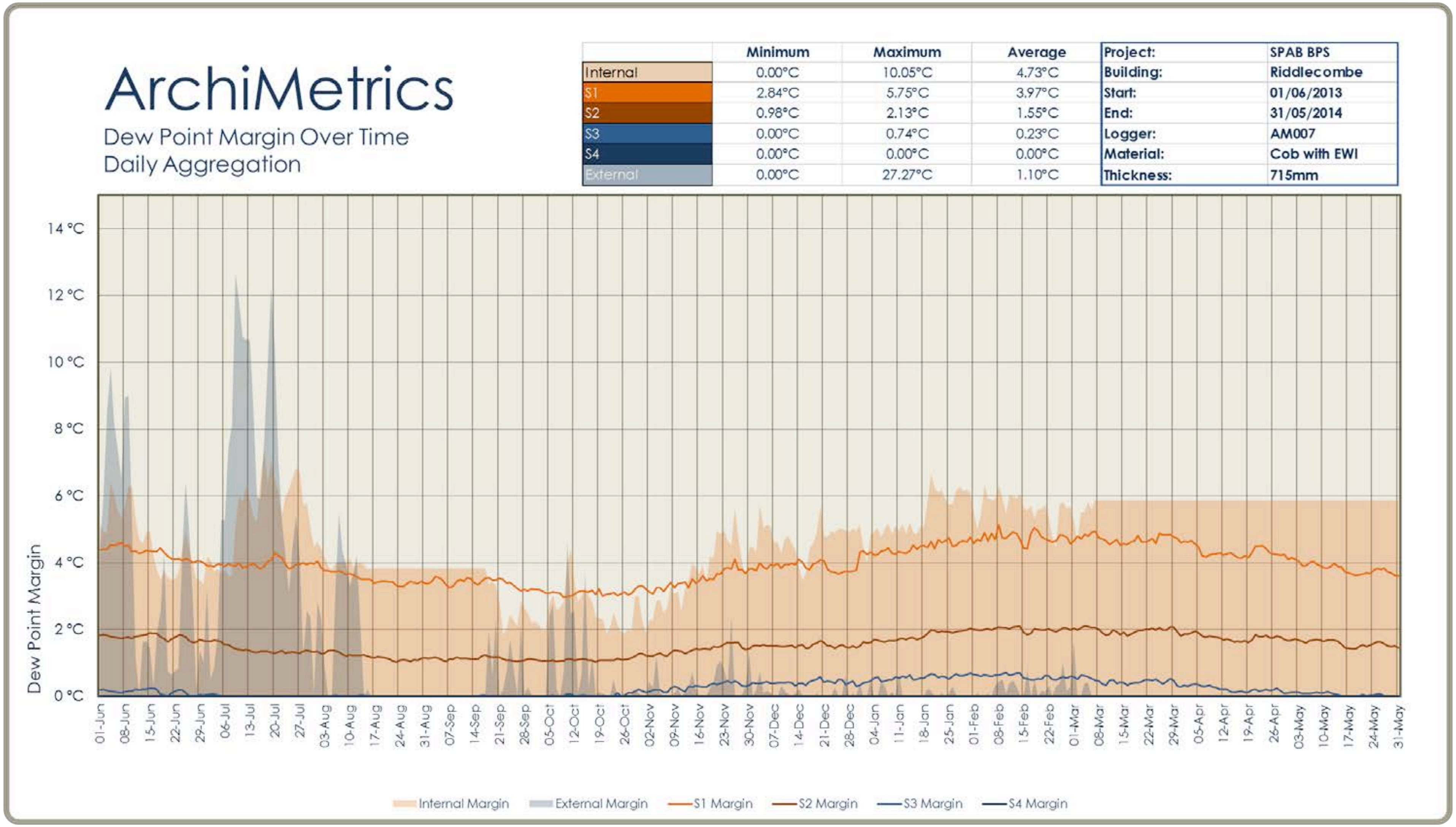

Figure 71. Dewpoint Margin Over Time, The Firs, Riddlecombe, June 2013 - May 2014. Daily Aggregation.

Riddlecombe Monthly Dew Point Margin Averages						
	Internal	**S1**	**S2**	**S3**	**S4**	**External**
2013						
Jun	4.61	4.29	1.77	0.13	0.00	3.77
Jul	5.44	3.96	1.41	0.01	0.00	6.12
Aug	3.93	3.54	1.19	0.00	0.00	1.17
Sep	3.29	3.40	1.12	0.00	0.00	0.36
Oct	2.60	3.11	1.10	0.04	0.00	0.73
Nov	3.65	3.49	1.39	0.28	0.00	0.38
Dec	4.74	3.88	1.51	0.41	0.00	0.12
2014						
Jan	5.40	4.46	1.80	0.56	0.00	0.10
Feb	5.65	4.75	2.00	0.59	0.00	0.24
Mar	5.78	4.71	1.97	0.45	0.00	0.08
Apr	5.87	4.32	1.76	0.21	0.00	0.00
May	5.87	3.82	1.58	0.05	0.00	0.00
Average	**4.73**	**3.97**	**1.55**	**0.23**	**0.00**	**1.10**

Table 15. Monthly Dewpoint Averages, The Firs, Riddlecombe, June 2013 - May 2014. Daily Aggregation.

3. DISCUSSION

Direct comparisons between the three properties included in the survey are problematic given the differences between the three 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 for points of similarity and difference.

3.1 Relative Humidity (RH)

Table 16 provides details of the annual average %RH values for the four interstitial sensors situated in the monitored walls at Shrewsbury, Drewsteignton and Riddlecombe post-insulation. Blue shading indicates decreases in %RH and orange increases in %RH year-on-year.

Annual Average RH	Sensor 1	Sensor 2	Sensor 3	Sensor 4
Shrewsbury				
2012 - 2013	66%	72%	75%	83%
2013 - 2014	66%	71%	77%	81%
Drewsteignton				
2012 - 2013	68%	85%	90%	96%
2013 - 2014	64%	87%	92%	97%
Riddlecombe				
2012	72%	91%	98%	100%
2013 - 2014	78%	91%	99%	100%

Table 16. Annual Average %RH for all Interstitial Sensors 2012 - 2014.

Despite the dynamic responses found in proximity to the external wall face at Shrewsbury, by and large the RH responses here appear to be quite stable and crucially largely below the 80% RH threshold for mould growth. This is particularly true for sensors 2 and 3 which are not situated at the periphery of the construction where responses are more likely to be directly affected by changes in internal and external conditions. Figure 6 shows a coupling of responses between sensors 1 and 2 indicating vapour exchange either side of the woodfibre insulation as well as possibly a hygroscopic buffering of the internal room RH taking place in proximity to sensor 1 behind the internal wall finish.

The wall at Drewsteignton records a more muted response and on average higher %RH values which show overall a rising trend for this wall post-insulation (Figure 30). There is a period during the summer where RH falls at sensors 3 and 4 but this 'recovery' does not occur at sensor 2 and averages at all three masonry sensors, 2 - 4, are considerably above the 80% mould growth threshold. There is clear vapour exchange occurring between the room and the air gap behind the internal plasterboard finish but the responses of the remaining sensors behind the PIR insulation are decoupled from the internal environment.

The wall at Riddlecombe shows a non standard RH response where %RH rises over summer and diminishes in winter (the opposite of the other two walls, Figure 51). This wall is externally insulated via perlite insulation bound within a lime render and has the highest of all %RH averages most likely as a result of construction moisture held within the cob material vaporising during periods of solar incident on the south facing wall. Sensors 2 - 4 all record averages above 80% RH and these are higher than those at Drewsteignton. These are in fact so high that sensor 4 is at dewpoint - 100% for the full 12 months of the year and sensor 3 averages 99% indicating long term vapour saturation within this part of the wall. Being an externally insulated wall however responses at sensor 1, towards the internal wall face, are more reflective of the mass of the cob wall than internal room conditions.

3.2 Absolute Humidity (AH)

Table 17 provides details of the annual average AH values for the four interstitial sensors situated in the monitored walls at Shrewsbury, Drewsteignton and Riddlecombe post-insulation. Blue shading indicates decreases in AH and orange increases in AH year-on-year.

Annual Average AH	**Sensor 1**	**Sensor 2**	**Sensor 3**	**Sensor 4**
Shrewsbury				
2012 - 2013	9.01 g/m^3	8.80 g/m^3	8.95 g/m^3	9.18 g/m^3
2013 - 2014	9.56 g/m^3	9.42 g/m^3	9.69 g/m^3	9.65 g/m^3
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
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

Table 17. Annual Average AH g/m^3 for all Interstitial Sensors 2012 - 2014.

All walls in the study show the same basic trend; that of higher AH over the summer with profiles that decrease in quantity from the external to the internal side of the wall, a pattern that reverses over winter with lower overall weights of vapour which are higher in proximity to internal conditions. To this extent AH behaviour is following the influences of lack of internal space heating and high summertime atmospheric humidity and lower (but higher than external) internal humidity over winter, supported by heating in internal spaces.

The walls do however, differ in other respects; the rise in AH seen for the cob wall in Riddlecombe over summer (Figure 55) far exceeds that of the external AH values in comparison with the other walls which points to an additional source of vapour for this wall of construction moisture vaporising via solar incident.

Similar behaviour albeit over a shorter time period is seen in the wall at Shrewsbury where damp material appears to be drying out during the month of July recording high weights of vapour deeper within the wall, Figure 10. There is an increase in quantities of vapour within the wall fabric for the walls at both Shrewsbury and Drewsteignton between 2012 - 13 and 2013 -14. In the case of Shrewsbury this could be explained as a consequence of the extremely wet weather experienced over the 2013 - 14 reporting period. Here the wall is relatively thin, porous and south-facing and the effect of the weather, both in terms of wetting and drying can be clearly seen penetrating quite deeply into the wall fabric. The wall at Drewsteignton is much thicker, less porous and faces north-west and changes in external conditions seem to have a less extreme effect with regard to humidity responses, Figure 32. Whilst the wet conditions which particularly affected the south west of England must have had an impact on the vapour profile of this wall we can see that the vapour quantity gain in this wall between 2012 - 13 and 2013 - 14 is about twice that of the wall at Shrewsbury (from a similar base in 2012 -13). This could be explained as the result of a lack of drying opportunities either due to the inherent characteristics of the wall at that particular location and/or as a result of the application of an impermeable layer of material within the wall build-up (the foil-faced PIR insulation) which has significantly reduced the quantity of heat passing into the masonry fabric and restricted vapour movement within the fabric. The year-on-year increase in vapour within the wall also provides an explanation for the trend of rising RH found for the wall at Drewsteignton.

Riddlecombe, however, has the greatest quantities of vapour found within the three walls (and perhaps as a result also the highest %RH averages) although here rather than a year-on-year increase at all four interstitial sensors an increase is seen at sensors 1 and 2 but a decrease at sensors 3 and 4. This is perhaps an indication that despite wet external conditions vapour has been able to evaporate from the wall in proximity to the external surface due to direct solar exposure during sunnier parts of the year (although not yet in sufficient quantity to lower %RH at sensor 4 where it is at 100% for a full year).

3.3 Dewpoint Margins

All walls in the study show the same pattern of temperature gradient passing through the walls over an annual cycle, i.e. the gradient is approximately flat through the summer months where there is little difference between internal and external temperatures. This gradient increases in pitch from inside to outside over the autumn and into the winter period where the advent of the heating season means that internal room temperatures exceed those of the exterior. With regards to dewpoint margins however there are some noticeable differences between the three walls, Table 18.

Annual Average DPM	**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
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
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

Table 18. Annual Average Dewpoint Margins for all Interstitial Sensors 2011 - 2014.

Table 18 shows the annual average dewpoint margins for the three walls subject to long-term IHGM monitoring. The 2011 pre-insulation margins were measured over a two week period between January - March 2011, the coldest part of the year and therefore potentially represent a 'worse case' scenario, i.e. margins may be quite narrow due to cold temperatures and possibly wet conditions. Post-insulation (2012 - 14) averages are calculated from annual records and therefore include both summer and winter data. The exception is Riddlecombe where, due to data losses the margins for 2012 are calculated from a seven-month period February - September. Blue shading indicates increases in dewpoint margins and orange shading decreases in margins year-on-year.

From the table it can be seen that all three walls have largely experienced a narrowing of dewpoint margins post-insulation although the reasons for this and the degree of change may be quite different for the different walls. The walls at Riddlecombe and Drewsteignton also seem to have experienced a further narrowing between the first and second years post-insulation. Shrewsbury has the widest margins post-insulation, being between 6 - 3 ˚C, with little change to these margins between 2012 - 13 and 2013 - 14. The magnitude of the change pre- and post-insulation is much greater within the masonry section (sensors 2 - 4) of the wall at Drewsteignton and at sensor 4 is on average around 0.5˚C. Riddlecombe has similarly experienced a considerable narrowing of its dewpoint margins post-insulation, margins here being the narrowest of all the three walls (although it should be noted that margins for this wall were found to be quite narrow prior to re-rendering particularly at sensor 4).

With reference to Figure 71 (DPM over time) Riddlecombe is seen to experience dewpoint (100% RH) at sensor 4 throughout a complete 12 month cycle and the narrowest or indeed no dewpoint margins (0.0˚C) during the summer for reasons previously explained. Conversely margins increase during the colder winter months. However, they remain much smaller than those calculated for the other walls in the study and are a reflection of the continuing extremely high vapour profile found for this wall. The picture at Shrewsbury appears to be quite stable. Despite periods of 0.0˚C measured at sensors 3 and 4 during times of extreme wet and/or cold weather, it would seem that the wall is able to recover over an annual cycle and maintain consistent margins of between 3 - 6˚C. Elsewhere, Drewsteignton presents a trend of rising RH and year-on-year increase in AH, both of which may lead to the year-on-year narrowing of the masonry section dewpoint margins seen for this wall. It is interesting here to note that the closest convergences between the temperature and dewpoint gradients, the period of narrowest dewpoint margins, start during the winter months (February 2013 see previous report) and persist into June and the beginning of summer. This is an indication perhaps of the slower drying time response of this granite wall, possibly due to excess damp material (and associated vapour) and perhaps lack of drying opportunities? This may be particularly the case for sensor 2 positioned in this wall between the PIR insulation and the granite masonry. At this sensor we see a narrowing of dewpoints continuing over the summer (unlike sensors 3 and 4) behaviour similar to that seen at Riddlecombe. It may be that vapour continues to accumulate at this point, deep within the wall, due to evaporation from damp material during the warm weather or indeed due to vapour from evaporation occurring elsewhere within the wall, principally at sensor 3 moving back towards sensor 2. The average quantities of vapour, Table 17, would suggest vapour might be moving from an area of high concentration at sensor 3 to an area of lower concentration at sensor 2 over the majority of the year.

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. The three walls are located in Drewsteignton and Riddlecombe in Devon and Shrewsbury, and IHGM measurements were made in these walls prior to insulation over a two-week period between January and March 2011. In 2011 the 360 mm-thick brick wall in Shrewsbury was internally insulated with 40 mm of woodfibre insulation finished with 8 mm of lime plaster, the 600 mm granite wall at Drewsteignton had an experimental section of 100 mm of PIR insulation applied to the internal wall face finished with an air gap and plasterboard dry lining. The 655 mm cob wall at Riddlecombe was re-rendered with 60 mm of a lime-based external insulating render. Following this work, beginning in the winter of 2012, measurements of temperature and RH have been made at four points through and either side of these three walls.

The long-term hygrothermal measurements show a stable picture with regard to the wall at Shrewsbury. The risk of interstitial condensation has slightly increased following insulation, as indicated by calculations of dewpoint margins for the wall. However, this might be expected for an internally-insulated wall and the risk is small. On average, dewpoint margins are wider (3 - 6˚C) with possible interstitial condensation occurring only during the wettest and coldest parts of the year followed by a period of recovery or drying out when margins open out once again. There seems to be no trend of rising relative humidity seen as yet within this wall as measurements of RH are broadly consistent between the first and second years post-insulation despite a slight rise in AH over the second year. Measurements of %RH are on average at or well below the 80% threshold required for mould growth and are particularly stable at sensor 2 embedded deep within the wall between the brick and the woodfibre insulation which average 71.4% RH over the year.

The picture for the other two walls in the study is somewhat different as both these walls, despite their differences, both show high and rising humidity within their wall fabric. Both walls record an increased risk of interstitial condensation following insulation. This could perhaps be expected for the IWI treatment at Drewsteignton but is more unusual for the externally-insulated wall at Riddlecombe. Dewpoint margins for the wall at Drewsteignton are narrower than those found for the wall at Shrewsbury being in the region of 0.5 - 2˚C, and the risk of interstitial condensation occurring in this wall is that much greater as a consequence. RH and AH values are also higher than those found at Shrewsbury being considerably above the 80% mould growth threshold at all 3 masonry sensors (2 - 4). These percentages also rise between the first and second year of post-insulation monitoring continuing the trend of rising RH previously found for this wall.

The cob wall at Riddlecombe has the highest of all humidity records and indeed dewpoint margins were already narrow in this wall prior to the application of insulating render. However, post-insulation, there is now no dewpoint margin at sensor 4 which is at 100% RH for the full year and margins are very narrow at the deeper wall sensors 2 and 3 being between 0.23 - 1.5˚C. A likely explanation for the records of very high vapour found for this wall stem from moisture bound within the wall fabric as a result of water penetration through the old cracked cement render significantly compounded by the addition of water to the wall from the wetting down process that is required prior to the application of the new render. It is understood that earth-based walls lose moisture very slowly and the new render, being a wet finish, also slows the drying that may take place deeper within the wall. The unusual pattern of high %RH and narrow dewpoint margins occurring in the summer months for this wall is accounted for by the evaporation of moisture bound within the cob during periods of incident solar radiation heating the wall material. The question is whether this vapour is able to migrate through the wall and be dispersed either within the internal or external environment? There is a slight decrease in quantities of vapour at the 3rd and 4th sensors recorded for this year as well as a slight increase in the dewpoint margin at sensor 2 which may suggest an improving picture. However, overall humidity levels remain very high within the construction and there is little year-on-year change to records of %RH which range between 91 - 100% between sensor 2 and 4.

The vapour picture at Drewsteignton seems to suggest retarded responses within the wall with regards to drying via evaporation which would account for the trend of rising RH, AH and increased risk of interstitial condensation within the construction. The wall is particularly monolithic and orientated north-west so does not benefit from extended periods of direct sunlight. The application of 100 mm of PIR insulation material has also radically reduced the U-value measured from this construction from 1.20 W/m^2K to 0.16 W/m^2K. The effect of this can be seen in the hygrothermal section plots made before the application of insulation which have considerably cooled the masonry side of the wall. In addition, this insulation material is encased in a foil membrane which acts as a vapour barrier and plots of RH overtime demonstrate an apparent lack of vapour exchange between sensor 1 and 2 positioned either side of this material. All these factors may contribute to reduced drying potential for this wall at this location.

By contrast there is no trend of rising %RH found for the wall at Shrewsbury suggesting, in comparison with Drewsteignton, improved potential for fabric moisture to evaporate. This wall is much thinner, more porous and south-facing and its ability to respond to the wetting and drying influences of the external environment is that much more evident (Figure 6). The insulation added to this wall is also thinner and a vapour control layer has not been part of this addition. Hence the cooling on the brick side of the construction is less extreme (the measured U-value has been reduced from 1.48 W/m^2K to 0.48 W/m^2K) and vapour exchange between sensors 1 and 2, positioned either side of the woodfibre insulation is also evident. The range of %RH responses measured at sensor 2 (58 - 80%) here may also be an indication of the hygroscopic properties of the woodfibre material and its ability to buffer vapour.

The walls within this study could not be considered as representative of refurbished solid walls in general. However, the notion of a 'representative' solid wall is problematic given the great diversity of traditional and historic construction forms within these Islands. Therefore, from a case study perspective, observations of changes within the fabric following various forms of insulation may be of use with regards to understanding the effects of refurbishment and an aid to decision-making for those considering energy efficiency improvement work for these buildings in the future.