SB&WRC Project

Installation report:

The Waste House Pilot Site Prototype 2

April 2019

Abstract of the project

The SB&WRC *(Sustainable Bio&Waste Resources for Construction)* project, an undertaking of more than two years, aims to conceive, produce and test three innovative, low-carbon, thermal insulation materials from agricultural co-products and recycled waste. The project is supported by the development program Interreg VA France (Channel) England and its budget, estimated to be 1.8M€, is co-financed by the ERDF (European Regional Development Fund) for 69% (1.26M€ contribution).

This project, led by Nomadéis, is carried out by a cross-channel partnership which gathers academic research laboratories, private research and consulting companies, manufacturers and professional non-profit organisation of the building sector:

- Nomadéis;
- Veolia Propreté Nord Normandie;
- University of Bath;
- Ecole Supérieure d'Ingénieurs des Travaux de la Construction de Caen (ESITC Caen);
- Construction21;
- UniLaSalle;
- University of Brighton;
- Alliance for Sustainable Building Products.

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Figure 2: The Waste House (pilot site for prototype 2) in Brighton.

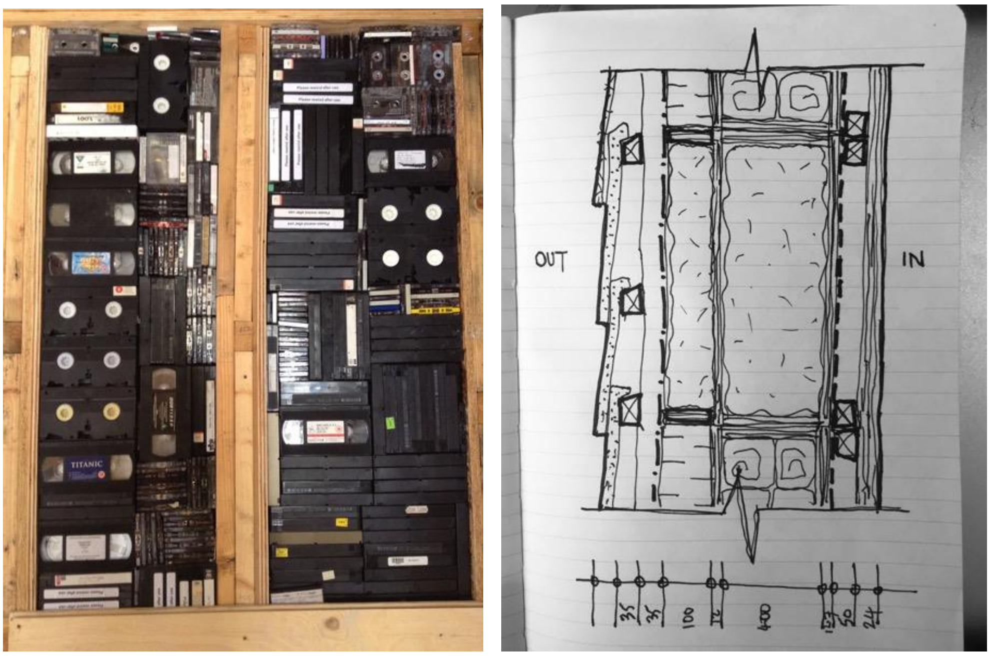

Figure 1: Left: Typical wall section before it was emptied, Right: Typical Waste House wall section drawn in section occupied by Prototype 2 at the Brighton Waste House

The SB&WRC project's wall prototype 2, consisting of two layers of waste duvet insulation, was installed in the downstairs office of the Brighton Waste House in November 2018. Monitoring of the wall was conducted from 8th of November 2018 to 3rd of January 2019. Temperatures and humidities within and around the wall were monitored along with the heat flux at the interior surface of the wall. From this data U-value and condensation risk for the wall were assessed. The U-value for the wall was calculated to be $0.138W.m^{-2}.K^{-1}$, and the duvets to have a thermal conductivity of $0.069W.m^{-1}.K^{-1}$. No condensation risk was detected during this monitoring period.

A $0.525m^2$ section of wall in the Brighton WasteHouse was selected to replace the existing insulation with folded duvets in both the inner 364mm deep cavity and outer 100mm cavity. The density of duvet installation was 21.4 and $11.3kg.m^{-3}$ for the inner and outer cavities respectively giving an overall density of $19.2kg.m^{-3}$. The duvet layers were pinned to the interstitial plywood layers at the top and allowed to hang in the cavities. The complete make-up of the test wall construction is shown in Figure 3 of the "*Facility Presentation Sheet: Waste House*" report. External conditions were ambient and internal conditions varied depending on occupancy and heating regime in the office room as shown in Figure 6 "*Facility Presentation Sheet: Waste House*" report.

2. Monitoring Equipment for Prototype 2

In addition to a heat flux mat placed on the inner surface of the wall a probe was constructed and inserted into the centre point of the wall section to monitor temperatures and humidities in the internal and external environments and at the mid-point of each duvet layer. Results were generated in accordance with ISO 9869-1:2014.

The SHT75 sensors are held in place with silicon sealant and the cavities within the tube filled with expanding foam to minimise air and heat transfer along the tube. The probe was built into the wall as the wall layers were constructed, as shown in Figure 3. This was done on the 6th of November 2018. The junction points between the probe and the hard construction layers were also sealed to minimise vapour transfer via this route.

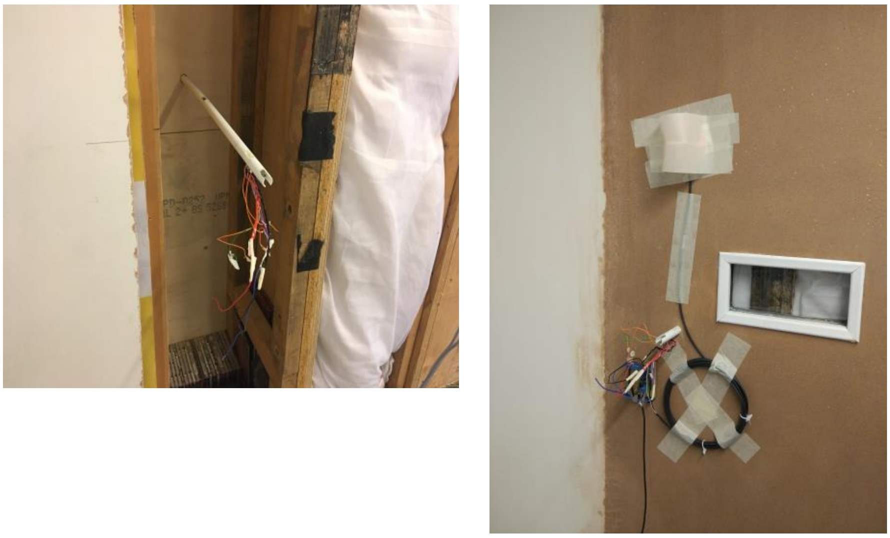

Figure 3: Probe installation and final equipment installation

For the heat flux measurement a recently calibrated Hukseflux HP01 heat flux sensor has been used. The calibration certificate for the sensor states 61.18μV output voltage per W.m^{-2}. This was positioned in-line and above the probe insertion point. The heat flux meter is attached to the wall and covered in masking tape to maintain a consistent emissivity with the rest of the wall (Figure 3).

As the heat flux mat produces voltage differentials in the μV range an analogue to digital converter is required to resolve these small differentials. An ADS1115 16-bit converter has been used here. The ADS1115 is programmed to use its lowest internal reference voltage of 0.256V. With 15bits of resolution (1 bit is used to sign the integer value) the ADS1115 can resolve down to 0.256/2^{15}V or 7.8125μV. As the heat flux meter has been calibrated at 61.18μV per W.m^{-2} this delivers a heat flux resolution of 0.128W.m^{-2}, or a U-value resolution of 0.0128W.m^{-2}.K^{-1} at a 10°C temperature difference.

The SHT75 sensors require a 3.3V power supply and both the SHT75 and the HP01 sensors require a platform to interpret the sensor values and to send them to the monitoring hub. For this, an Arduino Uno has been used as it has native support for the I^{2}C protocol used by both the SHT75 sensors and ADS1115 converter and libraries are available to allow the Uno to interface with an RFM69 transceiver chip. In addition, the Arduino supplies voltage (3.3V) and ground connections to the sensors. A custom circuit board was designed that interfaces the Uno's pin configuration with the ADS1115 and RFM69 chips. The schematic of the custom shield is shown in Figure 4.

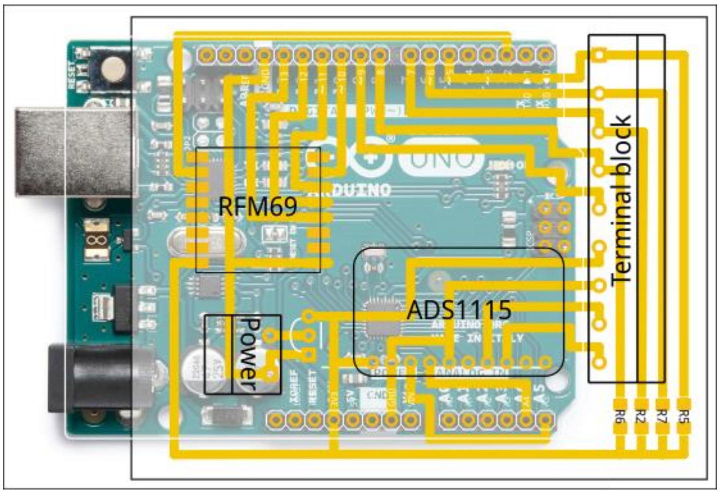

Figure 4: custom Arduino module

3. Issues encountered

As the duvets are permeable to moisture vapour, and the dew-point temperatures at all sensor points is similar, it is reasonable to assume that the moisture content at any point within each layer is similar. The worst case scenario for condensation risk is therefore at the coldest point, or exterior surface, of each layer. To asses this worse case scenario condensation risk the temperature at the external surface must be known. If the thermal conductivity of each of the insulated layers is similar, then the temperature gradient between the mid-points of the inner and outer insulation will be linear. By taking into the account the thicknesses to the two insulation layers, the temperature at the boundary point between the two layers can be estimated. If the temperature of this point is below the dew-point temperature of the inner insulation layer then condensation may form at this exterior surface point. For the outer insulation layer the outside surface can be considered to be at or near the external temperature and therefore if this external temperature is below the dew-point temperature of the outer insulation, condensation may again form at this outer surface.

Issues relating to testing Prototype 2 in an occupied building (The Waste House) including issues of air movement around the actual installed Prototype are discussed below.

4. Measurement of performance

The monitoring system was connected up and started on the 8th of November. Sensor readings since were taken approximately every 60 seconds and broadcasted to the monitoring hub. Results are later hour averaged.

Although the monitoring system was started on the 8th November and run continuously until the end of the calendar year, the general lack of heating (there is no dedicated heating system within the room) and occupancy in the space made a consistent and reliable U-value figure difficult to attain. Figure 6 shows the U-value over the entire monitoring period.

4.1 U-values

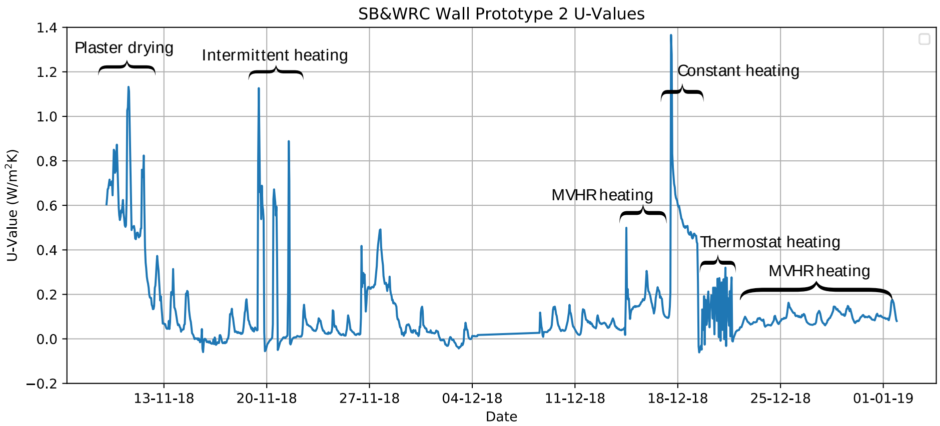

Figure 5 : Prototype 2 U-values (entire monitoring period)

Initially, the wall plaster was still drying causing the wall surface to absorb heat and inflate initial U-values. For the first 10 days the room temperature was allowed to free-float, i.e. no discrete heating was applied to the room, although occupancy was relatively high during the first few days. On the 19th, 20th and 21st of

November a fan heater was installed in the room and the room heated constantly during working hours. After this temperatures again free floated until the heating systems were turned on in the bathroom and upstairs room. As air to downstairs is supplied with an MVHR system, the heating in these other rooms was delivered to the downstairs office by proxy via the ventilation system. On the 17th of December a dedicated convection heater was placed in the room and the room heated constantly. This resulted in high room temperatures and resulted in a slow attainment of a thermal steady state within the room and wall constructions. The heating was therefore turned down on the 19th of December and the room heated to a thermostatically controlled temperature for three days. Over the Christmas period the room reverted to heating by MVHR air supply.

The temperatures within and around the wall prototype for the entire monitoring period are shown in Figure 6.

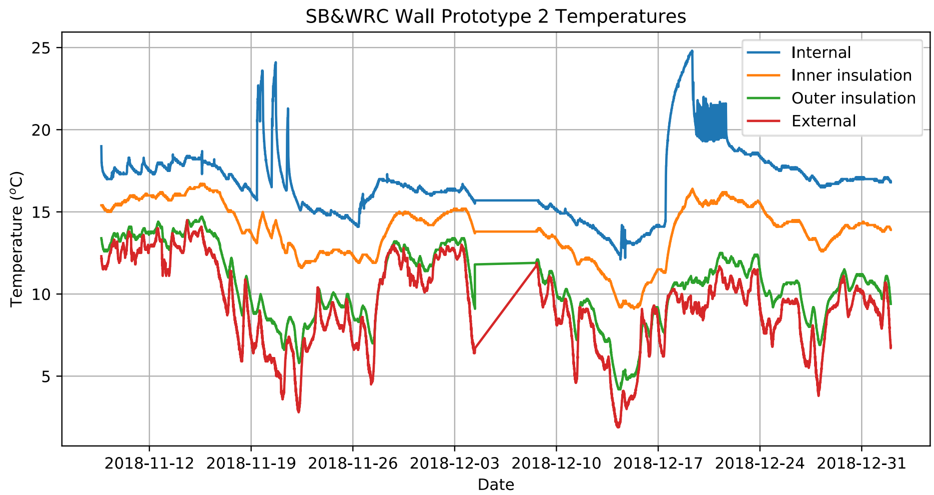

Figure 6: Wall temperatures (entire monitoring period)

The only period where the internal room temperature was controlled and relatively stable was the thermostat controlled heating period between the 19th and 21st of December. It is therefore this period that has been used to generate the wall U-value, the results for which are shown in Figure 7.

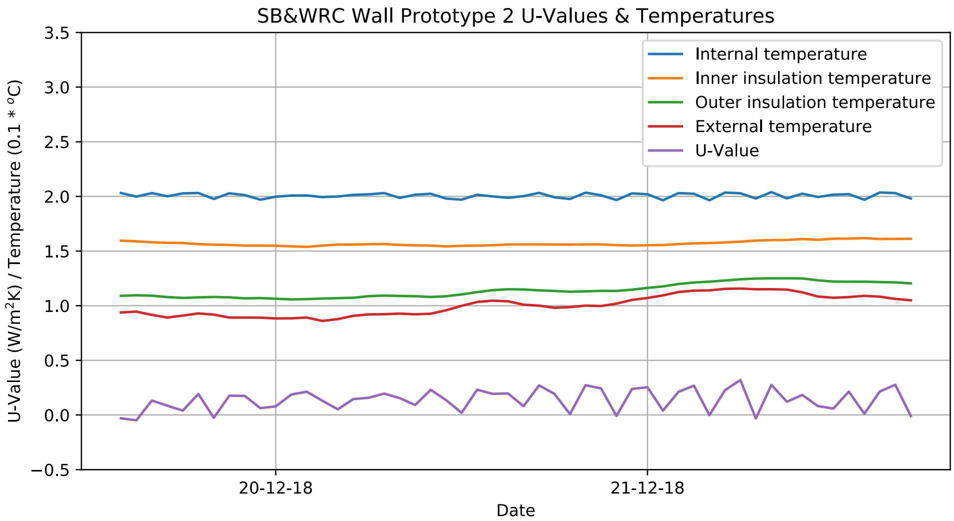

Figure 7: U-values and wall temperatures (calculation period)

Due to the intermittency of the thermostatically controlled heating, heat flux at the interior surface, and hence resultant U-value, still varies. This is however to be expected, and a U-value can be generated by averaging over the period. Although 72 hours is recommended in ISO 9869-1:2014 for the averaging in *in-situ* U-values compared to the 52 hours here, the strong heating of the room before this sampling period, and the subsequent consistency of the inner insulation temperature, coupled with the similarity between beginning and end of period external temperature would indicate that this period generates a valid U-value result as the overall heat content of the wall is does not change significantly. This average results in a final U-value of 0.138W.m^{-2}K^{-1}.

To put this in context, in cool/temperate climates the PassiveHaus standard for external walls is 0.15 W.m^{-2}K^{-1}and the U-value of the Prototype 2 is a slight improvement on this and therefore represents what could be considered a good U-value.

By rearranging the standard U-value equation and solving for duvet thermal conductivity, by assuming standard values for the other wall layers, a value of 0.069W.m^{-1}K^{-1} is attained. To put this in context many conventional insulation materials have a thermal conductivity of 0.04W.m^{-1}K^{-1}, and the duvets therefore overall achieve a conductivity 72.5% higher than this conventional value. Although the thermal conductivity is relatively high, the generous thickness of the insulation layers deliver the overall good U-value figure. Reasons for the higher thermal conductivity could include air circulation within and around the duvet layers, and the relatively low density of the duvet installation compared to conventional insulation materials.

A raw U-Value for the duvet material itself can be derived by dividing a chosen duvet thickness by the thermal conductivity. For 100mm of material this would result in a raw U-Value of 0.69W.m^{-2}K^{-1}, and at 150mm 0.46W.m^{-2}K^{-1}.

All the temperature and heat flux data generated for the SB&WRC project is available for download from: https://drive.google.com/drive/folders/1LVwFBVkMf5Fm5qgADbbomWf2vQEoOLIz.

An explanation of the data format of the monitoring files is given in Appendix 1.

4.2 Condensation Risk

Relative humidities for the whole monitoring period are shown in figure 8

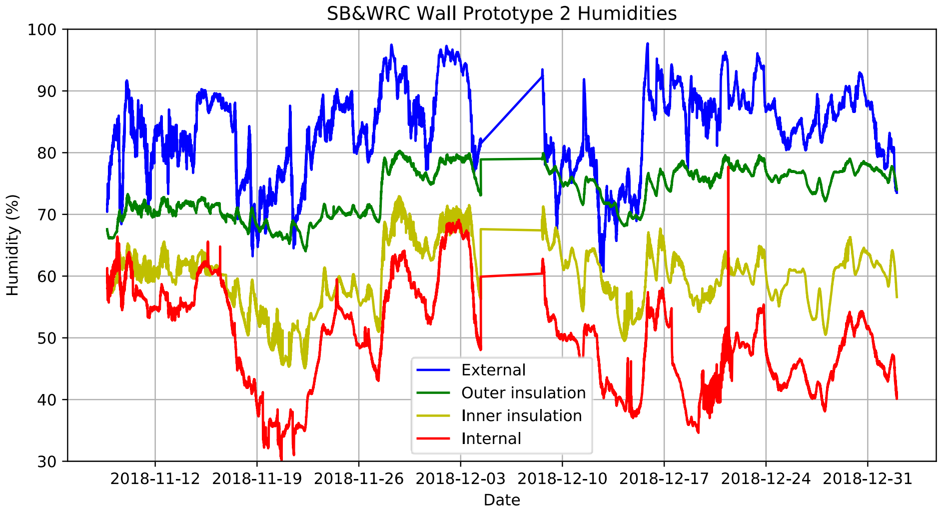

Figure 8: Humidity readings (entire monitoring period)

Relative humidities are generally higher towards the outside of the building, which is to be expected in the UK climate in Winter. Relative humidities within the wall, although different from the internal and external environments, do follow the trends of the internal and external environments. This suggests that water vapour is relatively free to move from either the outside or the inside of the building into both insulated sections of the wall. This is confirmed by looking at the dew-point temperatures within and around the prototype wall.

Dew-point temperatures with the two insulated layers not only vary significantly over time (if the moisture content within the layers were constant dew-point should be constant), but they also follow the dew-points of the internal and external environments quite closely. Water vapour does appear therefore to be able to move quite freely into, and out of, both the insulated layers from either or both of the internal and external environments. Raising the humidity within the room for a significant period of time could help determine which, if either, of the internal or external environments dominates in terms of this vapour exchange.

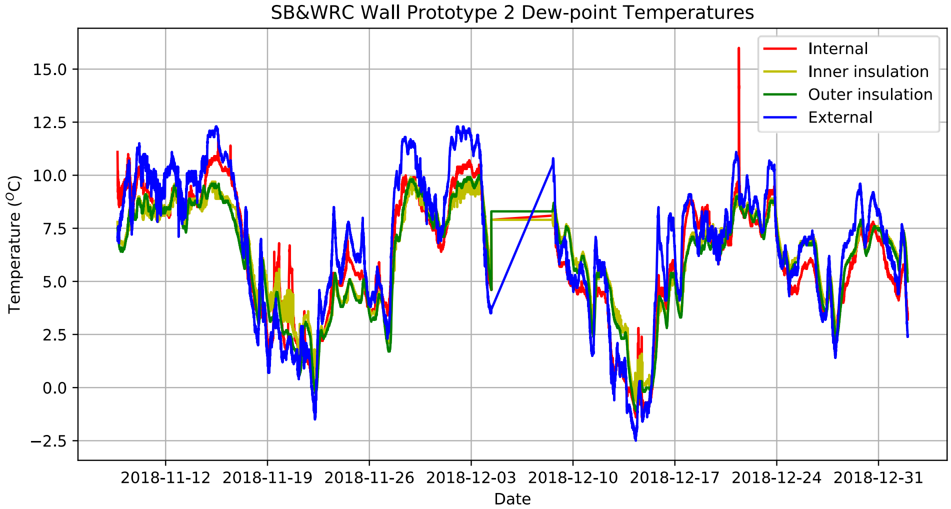

Figure 9: Dew-point readings

A basic assessment of whether condensation is likely to form at the centre point of the insulation layers (where the sensors are placed) can be made by comparing the sensed temperature and dew-point temperatures. If the temperature is greater that the dew-point temperature condensation is unlikely to form. Graphs in figure 9, 10, 11 and 12 are filled green where the temperature is greater than the dew-point temperature, and red where less. As can be seen the temperature difference at the centre of each layer is positive at all times, indicating that there has been no condensation risk at these points.

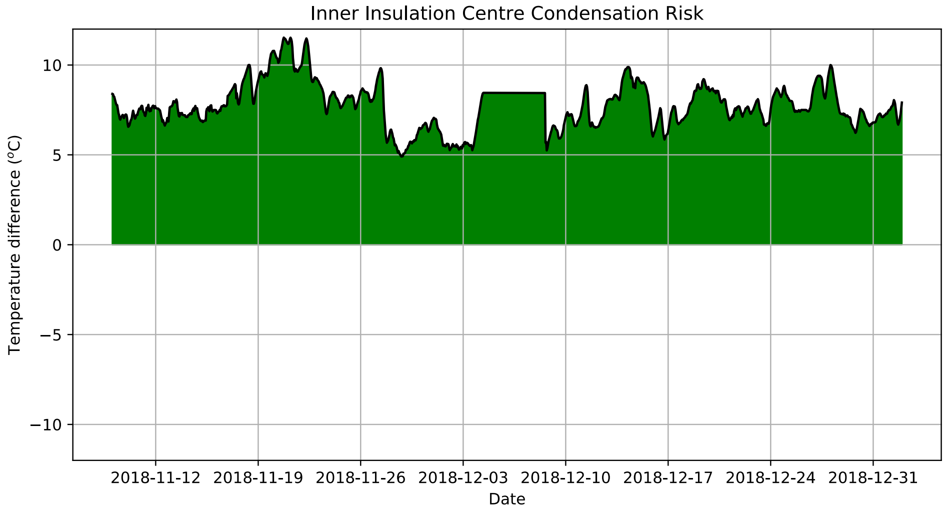

Figure 10: Inner insulation Centre condensation risk

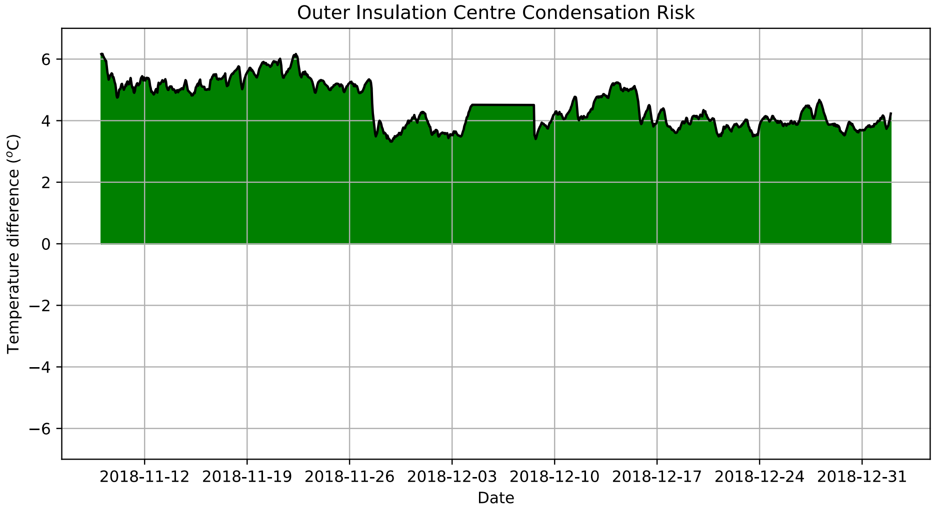

Figure 12: Outer insulation centre condensation risk

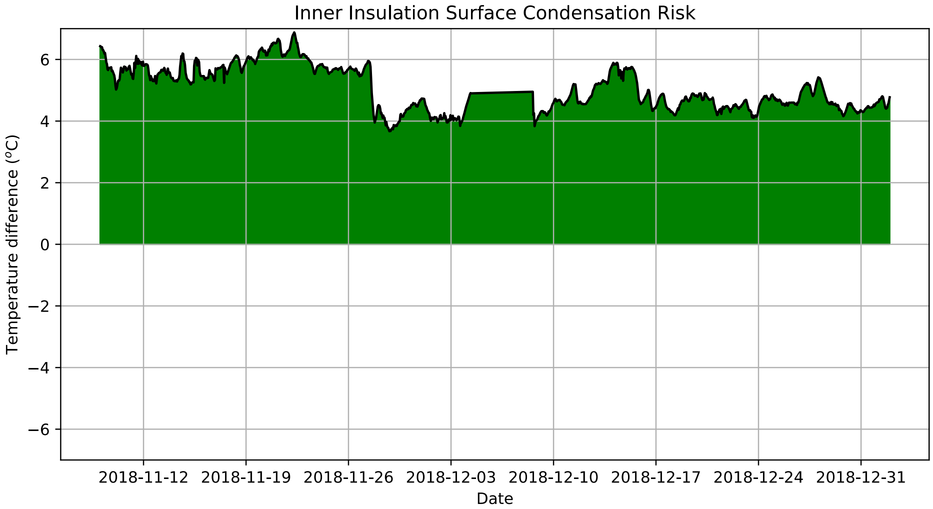

Figure 11 : Inner insulation surface condensation risk

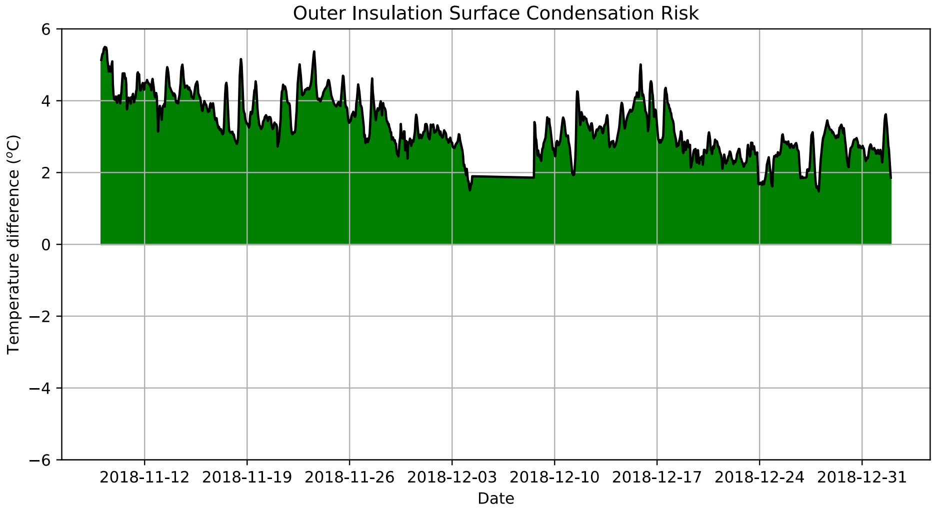

Figure 13: Outer insulation surface condensation risk

As the duvets are permeable to moisture vapour, and the dew-point temperatures at all sensor points is similar, it is reasonable to assume that the moisture content at any point within each layer is similar. The worst case scenario for condensation risk is therefore at the coldest point, or exterior surface, of each layer. To asses this worse case scenario condensation risk the temperature at the external surface must be known. If the thermal conductivity of each of the insulated layers is similar, then the temperature gradient between the mid-points of the inner and outer insulation will be linear. By taking into the account the thicknesses to the two insulation layers, the temperature at the boundary point between the two layers can be estimated. If the temperature of this point is below the dew-point temperature of the inner insulation layer then condensation may form at this exterior surface point. For the outer insulation layer the outside surface can be considered to be at or near the external temperature and therefore if this external temperature is below the dew-point temperature of the outer insulation, condensation may again form at this outer surface.

Again, there appears to be no risk of condensation at these exterior surfaces. As the water vapour content within the insulation layers is equalising with the external/internal environments, and the insulation layers are always warmer than the external environment, this is as expected. This relatively free movement of water vapour between the insulation layers and the external/internal environments could however indicate enough air movement between the layers to increase the thermal conductivity of the insulation layers to the relatively high value calculated in the U-value section.

5. Experimental Results

The dew-point temperature data suggests that the two insulation cavities are both able to exchange water vapour with either the external/internal environment. If this exchange is occurring with the external environment it may indicate enough air exchange with the outside to increase the effective thermal conductivity of the duvet layers and partly account for the relatively high thermal conductivity measured. Other potential reasons are the relatively low density of the of the duvet installation compared to conventional insulation materials, and the possibility of air circulation within the cavities. This exchange of water vapour has however ensured that there is no detectable condensation risk within the wall.

Despite the relatively high thermal conductivity the thickness of the wall, comprising a total of 464mm of insulation, has ensured a good U-value of 0.138W/m^{2}K, a figure better than would be required by, for example, by the PassivHaus standard.

The monitoring report concludes that although a good U-Value of 0.138 W/m^{2}K was attained, a large thickness of duvet material installation was required to achieve it, and the thermal conductivity of the duvet layers was significantly higher than conventional insulation materials. Dew-point data suggested water vapour exchange between the duvet layers and the internal/external environments indicating that significant air exchange may also be occurring. The low relatively low density of installation and the possibility or large air cavities within the duvet installations are also mentioned as potential reasons for the relatively high thermal conductivity.

6. Comparison of Monitoring results for Prototype 2 from ESITC Caen, University of Bath and University of Brighton

Below is a summary table of results for comparison purposes.

Table 1: Prototype 2 (waste polyester) thermo-physical properties in all three deployment sites

Institution	Thickness (mm)	Density	Thermal conductivity ($W.m^{-1}.K^{-1}$)	Raw U-Value 100mm ($W.m^{-2}.K^{-1}$)	Raw U-Value 100mm ($W.m^{-2}.K^{-1}$)
Caen	76	34	0.042	0.42	0.28
Bath	140	26	0.043	0.43	0.28
Brighton	464	19	0.069	0.69	0.46

There is quite a large disparity between the lab-based results produced by the Universities of Caen and Bath, and the *in situ* monitoring results produced by ARVEA Consultants at the University of Brighton's Waste House. The thermal conductivity of the duvet installation, as calculated from the overall heat flux measurements, is what one would expect a good insulative material to be in both of the lab tests. In the Waste House, however, the tests showed a thermal conductivity which was 64% higher.

Moving from a controlled lab experiment to a 'real world' test often results in some degradation in monitored performance due to the increase in variables and the attendant increase in possible factors that can decrease performance. There are however some specific factors that are believed to have contributed to this variation in performance:

- The very different densities of duvet installation is likely to have had an effect. The **higher density of installations in the lab would have resulted in less air being present** within the duvet installation. Although air can be a good thermal insulator, this is only the case when large convection currents within the air are not generated. In conventional insulation products this is usually achieved by having small, rather than large, pockets of air present within the insulation medium. **The larger amount of air within the Waste House installation would have given more opportunity for these convection currents to be generated**. It does however appear than **going above 26kg.m^{-3} of installed duvet density** used in the Bath tests **does not provide any thermal insulation benefits as they produced similar results to Caen 34kg.m^{-3}**.
- Placing a test sample in the external wall of a building will **expose the sample to wind-induced pressure differentials**. With a well-sealed construction unit, this would not, in itself, cause a degradation in thermal performance but the dew-point data generated by the Waste House testing would indicate that water vapour, and quite likely air, could move into and out of the layers of the test construction. This air movement, exacerbated by the wind pressure differentials, would have caused the heat resident in the construction to leave by air exchange and not just through conventional heat transfer mechanisms. This increase in heat loss would then be picked up by the heat flux mat placed on the interior surface of the wall.

In summary, **the duvet material** has clearly shown, in terms of pure insulative capability, to be **as effective as many commercial insulative materials**, but installation and implementation is a key parameter than can significantly degrade performance. This is obliquely noted in Caen's conclusions which mentions a support mechanism for the duvet fibres to present pooling of the insulation material.

Given that attention to relevant details during the construction process may be lacking, further work could focus on the pre-processing of the duvet fibres before installation e.g. placed within their own containing and supporting unit that guarantees minimal air exchange whilst maintaining material homogeneity and avoidance of large air pockets being formed.

The SB&WRC project is part of the Cross Border European Territorial Cooperation (ETC) Programme Interreg VA France (Channel) England and benefits from financial support from the ERDF (European Regional Development Fund).