Appendix F: WP7 – U-value testing

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Section Contents

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1.1 Scope of WP7

The scope of this work package was to investigate the potential of waterproofing treatments in wind-driven rain exposed areas, both as an insulant in its own right and in combination with cavity wall insulation. To answer these questions, the thermophysical performance of six cavity-wall specimens (two untreated, two treated with an acrylic-based liquid product, and two treated with a silane/siloxane blend cream product) both in dry and wet conditions was tested in an environmental chamber, and with uninsulated and insulated cavity space as detailed in the following.

1.2 Methodology

1.2.1 Laboratory monitoring

Six cavity-wall specimens of approximately 1m^2 (to nearest brick dimensions) were built as part of this project and cured under controlled conditions in a curing room (see Appendix E for further details) for a minimum of six months. The specimen walls were constituted of two masonry leaves in a stretcher bond (see Appendices A, B and C for brick and mortar specification) creating an empty cavity of 75 mm.

A pair of specimen walls were tested side-by-side at a time in an environmental chamber. The specimens were moved from the curing room (where they rested when not in use for the testing) to the thermal chamber and placed in the middle of it such to separate the warm (simulating indoor conditions) and cold (simulating external conditions) sides. The cavity space of each specimen was perimetrically sealed with acrylic adhesive tape to minimise air flow; insulation boards of the same thickness as the specimens were placed all around them to fill the gaps between the specimens and the chamber walls to minimise lateral heat and moisture transfer. A daily dynamic temperature profile was repeated in the indoor and external chambers to replicate representative UK conditions (Table 1).

Table 1 Internal and external temperature daily cycle profiles set during the U-value test.

	Test 1 uninsulated	Test 2, 3 uninsulated and Test 1, 2, 3 insulated
External temperature, T_{ext}	11.0 ± 3.7°C	11.0 ± 3.7°C truncated for T<10°C
Internal temperature, T_{int}	18.4 ± 1.5°C	18.4 ± 1.5°C

For U-value testing, each specimen was instrumented with five Hukseflux HFP01 heat flux plates (HFP) [1] and four surface temperature thermistors [2], all wired to a DataTaker DT85 data logging system [3]. Two locations (referred to as “Top” and “Bottom” in the following) were monitored on each specimen by positioning the HFP and temperature sensors vertically aligned and in line with each other on the two sides of the specimen wall; a third location on the external surface of the outer masonry leaf was monitored as a control using the remaining HFP (Figure 1). The sensing parts of both HFPs and thermistors were located on brick stretchers. Additional temperature and RH sensors were in place in-wall in the inner and outer masonry leaves and inside the cavity space to monitor boundary conditions (see WP6 and WP8 for further details).

Figure 1 Cavity wall specimens instrumentation towards the external (left) and indoor (right) simulated environments.

U-value testing was performed as part of a longer monitoring programme in the environmental chamber, which included wind-driven rain testing (described in Appendix E). Specifically, the U-value testing sequence consisted of an initial monitoring period with the specimen walls just moved from the curing room exposed to the internal and external temperature profiles only (referred to as “dry condition” in the following and labelled as “Test a” in Table 2). Subsequently, a wind-driven rain wetting period of up to two days (refer to Appendix E for details on the wetting scenario) was started; during this period, the two vertically-aligned HFPs on the external masonry leaf were detached to ensure an even water distribution and penetration through the brick surface while the third sensor was left in place as a control. At the end of the wetting period, the external HFPs were remounted in their original location and a second U-value testing sequence (referred to as “wet condition” and indicated as “Test b” in Table 2) was started with the specimens exposed to the same internal and external temperature profile as in Table 1. The U-value testing sequence was initially performed on the six specimens leaving the cavity space empty (Tests 1 to 3 in Table 2), and subsequently repeated with the cavity space insulated with loose expanded polystyrene (EPS) beads (Tests 4 to 6 in Table 2). The polystyrene beads were poured into the cavity without the use of adhesives, compacted until full, achieving a nominal average density of 14 kg/m^3 ± 2 per installation to replicate industry guidelines.

Table 2 Summary of the testing sequence in the environmental chamber.

Test		**Specimen**	**Cavity condition**	**External masonry surface condition**
1	**a**	Wall A1 (untreated) Wall B1 (acrylic-based liquid)	Uninsulated	Dry
	b	Wall A1, Wall B1	Uninsulated	Wet
2	**a**	Wall A2 (untreated) Wall C1 (silane/siloxane blend cream)	Uninsulated	Dry
	b	Wall A2, Wall C1	Uninsulated	Wet
3	**a**	Wall B2 (waterproof coating) Wall C2 (masonry protection)	Uninsulated	Dry
	b	Wall B2, Wall C2	Uninsulated	Wet
4	**a**	Wall A1, Wall B1	Insulated	Dry

	b	Wall A1, Wall B1	Insulated	Wet
5	**a**	Wall A2, Wall C1	Insulated	Dry
	b	Wall A2, Wall C1	Insulated	Wet
6	**a**	Wall B2, Wall C2	Insulated	Dry
	b	Wall B2, Wall C2	Insulated	Wet

1.2.2 Assumptions of the laboratory testing

A number of assumptions were made while designing and performing the laboratory testing in this work:

- The wetting cycles (Appendix E) were designed to represent a worst-case wind-driven rain scenario, with high water pressure and flow. As a consequence, in-situ cavity walls in exposed wind-driven rain areas may have a better performance than observed in the laboratory testing.
- The specimen walls were built to replicate "As Designed Theoretical" (ADT) condition (Appendices A and E), with no specific objective to replicate common construction defects (*e.g.*, mortar snots, cavity debris, etc.) and detailing (*e.g.*, window reveals, services penetration, air bricks, etc.) that may be observed in cavity walls in situ ("As-Built, In-Service" condition, ABIS). Nevertheless, minor variability in the construction and local defects (*e.g.*, small cracks and gaps, uneven cavity space) were present in the six specimens as a consequence of the building process itself and the movement of the specimens between the curing room and the environmental chamber for the tests; some observable defects in the mortar joints were also identified and rectified (see Figure 18 in Appendix G as an example) as part of the wind driven rain laboratory testing (Appendix E). The presence of these defects and local variability has not been considered in the U-value analysis presented in Section 1.3 and they may in principle affect the estimates obtained.
- The minor variability in the construction and local defects of the specimen walls was assumed to have a negligible effect on the U-value estimates in the first approximation. Therefore, the thermal performance of the six specimen walls is compared as if these were equivalent replicates.
- The specimen walls were cured for a minimum of 6 months (for the specimens in Test 1 in Table 2) after construction, and it is assumed that after this length of time the specimens were representative of the conditions of a real wall in ABIS conditions. However, residual moisture from the building process, some long-term ongoing curing of mortar, and other effects [4] may have still been present in the structure at the moment of testing.
- The specimen walls were constructed using new bricks to reduce the variability of the properties of the materials used in the six specimens (as detailed in Appendix A). However, the use of new materials may provide different (hygro-)thermal performance compared to old existing walls. Similarly, the ageing and weathering process of existing materials may have an effect on the penetration of the waterproofing agent inside the structure. The potential magnitude of these effects is unknown.
- The indoor surface of the specimen walls was not treated (*e.g.*, plastered), leaving the brickwork exposed. This design choice may affect the overall thermophysical behaviour and moisture transfer of the specimens, potentially reducing their representativeness of the performance of in-situ walls.
- Loose EPS beads were used to insulate the specimens. While the absence of glue is assumed to have a negligible effect on the thermophysical performance of the insulation system in isolation, moisture and water transport within the structure may differ in the two cases with a potential effect on the overall thermophysical performance of the insulated specimens tested in this work compared to insulated cavity walls in situ.

1.2.3 Data analysis and U-value estimation

An initial investigation of the raw data collected in each test was performed to check for obvious issues in the data (*e.g.*, missing data, unrealistic trends, sensors faults, etc.). Subsequently, the U-value analysis was performed. The BS ISO 9496-1:2014 [5] Standard was used to analyse the data and estimate the U-value in each monitoring location. The fulfilment of the criteria in Section 7.1 of the Standard [5] was initially imposed to identify a sub-period of data within the time-series collected, leading to trustable U-value estimates. The time-series so obtained were subsequently used for U-value estimation by means of the average method (*i.e.* in steady-state conditions) described in [5]. Constant air film resistances of 0.13 m^2K/W for the internal surface and 0.04 m^2K/W for the external one [6] were added to the thermal resistance of the wall obtained from the surface-to-surface temperature measurements. Additionally, all the quantifiable uncertainties affecting the data-streams during the monitoring process were combined to calculate the relative and absolute systematic measurement error affecting the U-value estimates, as described in [7]. These uncertainties include: the accuracy of the equipment (*i.e.* sensors and data logging system(s) involved in the analysis, according to manufacturers' specifications); the effect of random variations caused by imperfect thermal contact between the sensor and the wall (i.e. 5% according to [5, p.13]); and uncertainty due to the modification of the isotherms caused by the presence of the HFP (i.e. 3% according to [5, p.13]).

1.3 Results and discussion

1.3.1 Uninsulated walls

The U-value estimates obtained in the top (labelled as "_T" in the figures) and bottom (labelled as "_B") locations for the tests detailed in Table 2 are reported and discussed in the following. The U-value for the wall specimens with uninsulated cavity space and untreated exposed surface (reference walls A) was always lower in dry conditions (ranging in [1.26, 1.46] $W/(m^2K)$) than in wet conditions (ranging in [1.54, 1.76] $W/(m^2K)$), although within the margin of the systematic measurement error in all cases (Figure 2, left). The specimens with uninsulated cavity and treated surface (*i.e*. acrylic-based liquid treatment, walls B, and silane/siloxane blend cream, walls C) showed similar behaviour to the untreated walls (Figure 2, right). Specifically, their U-values were in the range [1.06, 1.49] $W/(m^2K)$ in dry conditions and [1.28, 1.67] $W/(m^2K)$ in wet conditions. As a result, the percentage U-value difference between wet and dry conditions in each location (Figure 3) showed a slightly larger U-value increase in wet conditions for untreated specimens (between 17% and 24%) compared to the treated ones (between 7% and 15%), although within the margin of error propagation[a] in all cases and consequently with marginal effect in the context of reducing the energy demand of the building stock.

In summary, from the analysis of uninsulated specimens no strong evidence was observed about the insulation property of waterproofing agents as an energy efficiency measure in its own right. Additionally, no obvious difference was observed depending on the waterproofing agent used, suggesting a comparable thermophysical performance of the two treatments (walls B and C).

[a] The error associated to the percentage U-value difference between dry and wet condition was obtained as a first-order Taylor series expansion of the systematic measurement error associated to each U-value estimate involved in the calculation.

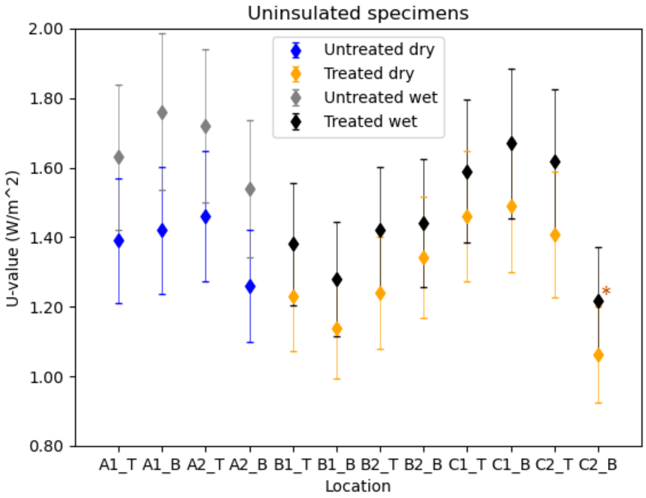

Figure 2 U-values for uninsulated untreated (walls A) and treated (walls B and C) cavity wall specimens exposed to dry and wet conditions (the external HFP was unintentionally slightly misplaced between wet and dry tests for location C2_B; this is denoted by the red star in the chart).

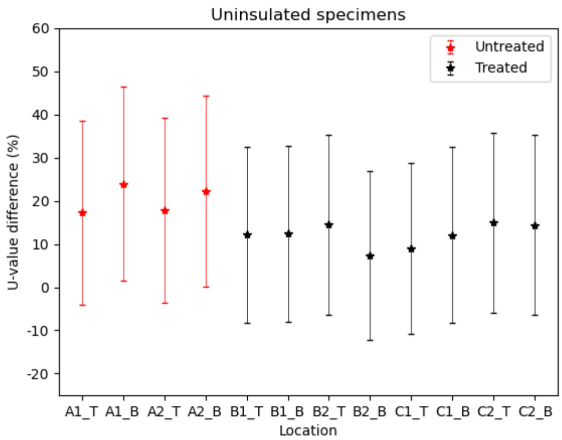

Figure 3 Percentage U-value difference between wet and dry condition on the uninsulated cavity wall specimens.

1.3.2 Insulated walls

Once the specimen walls were insulated with loose EPS grey beads, the untreated specimens still showed a distinct increase between the U-values obtained in dry and wet conditions (walls A in Figure 4). The values laid in the range [0.30, 0.38] W/(m^{2}K) and [0.38, 0.51] W/(m^{2}K) respectively. Conversely, the U-value increase was minimal for the treated specimens in the majority of cases (walls B and C in Figure 4) with no discernible differences between wet and dry conditions. Indeed, the U-values were in the ranges [0.31, 0.40] W/(m^{2}K) in dry condition and [0.30, 0.40] W/(m^{2}K) in wet conditions. The percentage U-value increase between wet and dry conditions was consequently generally around 31% for the untreated walls and between 0 % and 5 % for the treated ones (Figure 5), and always within the margin of error propagation.

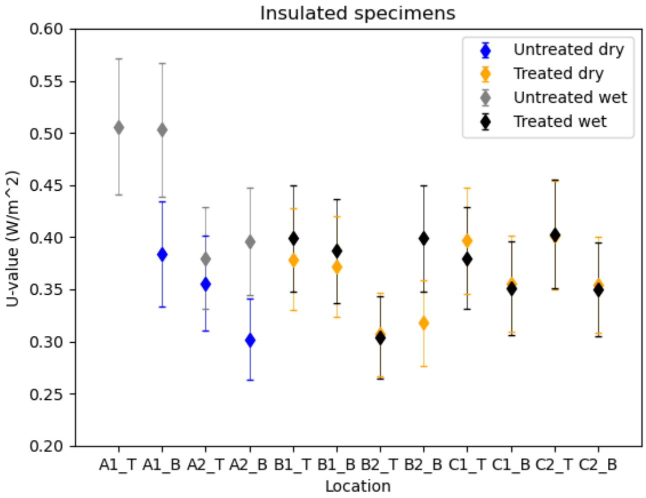

Figure 4 U-values for insulated untreated (walls A) and treated (walls B and C) cavity wall specimens exposed to wet and dry conditions (one of the temperature sensors in location A1_T had an issue during the dry condition testing, preventing the U-value estimation).

This analysis seems to suggest that waterproofing agents in combination with cavity wall insulation appear to have a more notable beneficial effect in reducing U-value variation between dry and wet conditions than in the uninsulated cases, provided that the wall system is in good state of conservation. This is likely to be in part a function of how the presence of the insulation changes the heat and moisture transfer across the whole wall.

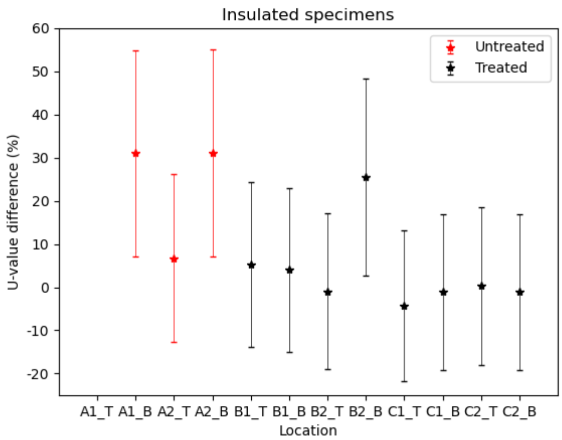

Figure 5 Percentage U-value difference between wet and dry condition on the insulated cavity wall specimens.

1.3.3 Comparison of treated and untreated walls in insulated and uninsulated configurations

U-value estimates for treated and untreated walls in insulated and uninsulated configurations (**Error! Reference source not found.** can be compared to assess whether waterproofing agents may improve the inherent thermal properties of the walls. Specifically, the insulant effect of the waterproofing treatment itself can be assessed comparing the U-values for uninsulated untreated (walls A in Figure 2) and uninsulated treated (walls B and C in Figure 2) wet walls, while the effect of cavity wall insulation alone can be assessed by comparing uninsulated and insulated untreated wet walls (walls A in Figures 2 and 4, respectively). From the first comparison, it can be observed that the U-value drops on average from 1.66 W/(m^2K) to 1.45 W/(m^2K); conversely, in the second comparison, the U-value drops on average from 1.66 W/(m^2K) to 0.45 W/(m^2K). The results show that the waterproofing treatment itself provides a marginal improvement of the thermal performance of the uninsulated walls compared to cavity wall insulation. Therefore these treatments cannot be considered as an energy efficiency measure in their own right.

1.4 Conclusions

A comparison of the U-value estimates obtained under different cavity (*i.e.* uninsulated and insulated with EPS grey beads) and external masonry leaf conditions (*i.e.* dry and wet, after exposure to wind-driven rain) presented above suggests that:

- Waterproofing treatments do not noticeably improve the thermophysical performance of uninsulated cavity walls, and as such they cannot be regarded as an energy efficiency measure in their own right. Given the extreme wetting scenario implemented (Section 1.2.2) this result is likely to be even more limited in-situ. However, the influence of the wetting scenario was not estimated, due to the limited evidence of the association between worst-case wetting scenario used in laboratory experiments and real wetting patterns.

- The two waterproofing treatments tested have similar thermophysical performance, although they provided different resistance to water penetration (Appendix E). While the results seem to suggest that U-values in wet walls may be improved to some extent with the application of waterproofing treatments to help keep the wall dryer (as discussed in Appendix E), they should be viewed with caution since the testing is based on a limited number of samples and the variation is often within the associated error of the testing apparatus. In particular, given the extreme wetting scenario implemented during the laboratory testing, the effect is likely to be more limited in-situ. It is also not possible to distinguish between the performance (i.e. whether better or worse) of the two different waterproofing treatments.

- In the case of walls in a good state of conservation (like those tested here), waterproofing treatments and cavity wall insulation might be a valuable combination as a measure to contain U-value fluctuations during wet periods and to enhance the performance of buildings in exposed areas. However, in the broader context of reducing the energy demand of the building stock, the addition of the waterproofing agent seems to have a minor effect compared to the installation of cavity wall insulation; alternative traditional retrofit solutions (*e.g.*, rain screens) may potentially be more durable, robust and cost-effective than waterproofing treatments, although the investigation of the performance of these measures was beyond the scope of this study and specific tests would be needed. Additionally, it is worth noticing that the waterproofing treatments were tested in isolation in this work and therefore, their effects and consequential impact at whole-house performance level is unclear. The durability of the performance and the potential degradation of waterproofing agents over time, and the consequent effects on the overall thermophysical performance of treated buildings, were not considered in this work.

1.5 References

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