Waterproofing cavity walls to allow insulation in exposed areas

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Executive Summary

Introduction and approach to the study

UCL and BRE have investigated the effectiveness of waterproofing treatments to reduce rain penetration in unprotected masonry cavity walls on behalf of the Department for Business, Energy & Industrial Strategy (BEIS). The aim was to establish whether the use of such treatments could safely allow wall cavities to be insulated as a retrofit measure in exposed areas, where such insulation was otherwise deemed unsuitable due to the increased risk of moisture ingress. A key feature of this study has been to acknowledge and investigate the implications of contextual factors that give rise to 'As Built, In Service' (ABIS) conditions, as distinct from the 'As Designed Theoretical' (ADT) condition of walls. ABIS is defined as the physical state of real exposed walls of residential buildings at any given point in time post-construction, subjected to the environmental conditions found in-situ and to their ageiing, and has been a consideration for the assessment of waterproofing treatments during this work.

The study utilised a range of approaches to investigate the potential impact of waterproofing treatments on brick-faced cavity walls; from desk-based research to establish the most appropriate wall types and treatments for investigation, through bench testing of small scale samples to larger scale wind driven rain (WDR) testing in a dedicated environmental chamber. Site investigations were also carried out at cavity walled properties in locations of high WDR exposure to highlight the practical implications associated with the condition and features of real walls.

Simulation analysis has been carried out using results obtained from laboratory testing to validate hygrothermal models. In addition, data from various sources has been aligned and overlaid with mapping software to determine the likely number of cavity wall dwellings in exposed regions of the UK to which waterproofing treatments may be applied.

Findings

During the initial **desk-based investigations**, trends in UK cavity wall construction over time were explored to establish appropriate materials and techniques to be used in laboratory investigations. This highlighted that there could be high variability in the type of bricks used across the UK over time, so 3 different brick types with varying physical and mechanical properties were subjected to initial bench testing with waterproofing treatments. Subsequently, a single brick type was taken forward to larger scale WDR testing, with an established stretcher bond pattern, cement/lime blend mortar (M4 class) with concave joining, and with wall ties included at a density of 2.5/m^2.

Initial research also showed that there were no current standard test methodologies for WDR testing that would suitably replicate environmental conditions for exposed cavity walls. Subsequent WDR testing was therefore based on the standard deemed most relevant (ASTM E 514/C1601:2014) but adapted to provide exposure conditions in line with those from weather files from a known region of very severe WDR exposure (Swansea, Wales).

Market analysis was carried out to identify waterproofing products appropriate for the laboratory testing. Sixty potential products were identified, which fell into three main types based on their fundamental chemical components. Silane/siloxane products made up the vast majority of those identified, but it was decided that testing each of the different types at the bench testing stage would help to determine whether there are any fundamental differences in performance. A hierarchy was developed to select products for testing, which reflected the level of information available (and hence confidence) in the product. Four specific products were ultimately recommended for bench testing (note that the designation 'A' has been reserved for untreated reference samples):

- B: An acrylic-based liquid
- C: A silane/siloxane blend cream
- D: A silane/siloxane blend liquid
- E: A stearate-based liquid

At the **bench testing** phase, 3 types of tests were carried out.

i. Water vapour permeability tests established the overall water transmission rates across the 3 shortlisted brick types, bedded in mortar, with the exposed surface treated with the 4 waterproofing treatments. Here it was established that the water vapour resistance was dominated by the brick's own physical properties. Based on this testing, a single brick type – Atherstone Red – was subsequently chosen for any further testing as it provided the most consistent results (lowest standard deviation) and the highest permeability. The acrylic-based liquid (B) and the silane/siloxane blend cream (C) treatments offered the most consistent performance of the treatments.

ii. Wettability testing visually assessed the contact angle of liquid droplets on treated and untreated brick surfaces over time; the greater the contact angle, the less absorbent the sample surface. This testing found the silane/siloxane blend liquid (D) to be the least resistant to surface wetting and the acrylic-based liquid (B) the most resistant, though the remaining products performed similarly to treatment B.

iii. Water absorption testing considered the rate of water absorbed into brick, mortar and combined samples respectively over a 24-hour period. Only treatments B and C were assessed alongside an untreated control. Samples with treatment B took up between a third to half of the water absorbed by the untreated sample within 24 hours and did so more slowly compared to the untreated control samples. Samples treated with treatment C showed a very low and flat absorption profile with limited water uptake, two orders of magnitude smaller than the untreated samples.

Following the laboratory bench-scale testing, **larger scale WDR testing** was carried out on cavity wall samples in an untreated state and with two waterproofing treatments, B and C, with walls uninsulated, then subsequently insulated with EPS beads. Various measurements were taken during the WDR testing, including monitoring RH and temperature using sensors embedded within the inner and outer wall leaves to assess how moisture migrates through the walls, plus the assessment of absolute moisture uptake by weighing the wall samples using load cells.

When walls were tested in an uninsulated state, the outer wall leaves of those untreated (A) became saturated within the first wetting cycle. Those treated with the silane/siloxane blend cream (C) delayed moisture uptake in the bricks by 1 wetting cycle, with saturation reached in the outer leaf after 4 cycles. Those treated with the acrylic-based liquid (B) also delayed water ingress into the external leaf by 1 wetting cycle. The performance between the two B-treated samples then varied, with one becoming saturated in the outer leaf (via the bricks) after the second wetting cycle. It is possible this was due to ABIS defects (i.e. microcracks) which were not visible to the naked eye. The other B-treated sample retained lower RH in the external wall leaf compared to the control samples overnight but increasing with subsequent wetting cycles. This might be explained by potential reduction in the performance of the acrylic-based product due to the increased number of wetting cycles or duration of exposure to water.

When walls were tested in an insulated state, the untreated walls maintained a behaviour consistent with the uninsulated cases. Both brick and mortar in the external leaf of the test walls quickly became fully saturated after the first 2 wetting cycles and remained so throughout the test. However, treated walls showed a more pronounced improvement in performance when comparing the insulated tests to the uninsulated tests.

For the acrylic-based liquid treated samples (B), RH measurements in both mortar and bricks in the external leaf did not increase so significantly in the first two wetting cycles and the overall RH levels were 30% lower than the fully saturated untreated walls. After overnight conditioning and a further 8 wetting cycles, B-treated walls generally maintained 20% lower RH in the external leaf compared to the untreated walls. However, the B-treated bricks in the external leaf experienced increasing RH with every wetting cycle, resulting in a significant increase in the RH in B2 by the end of the testing. (This, as mentioned earlier, may be due to ABIS defects.)

The silane/siloxane blend cream treated walls (C) significantly improved in performance when insulated, with no obvious RH gain in the external leaf mortar throughout the test and only a 6% increase within the external leaf bricks by the end of the test. RH readings of C-treated walls were 45% lower in mortar and 30% lower in bricks compared to the untreated walls at the end of the test. This significant improvement between the insulated and uninsulated C-treated walls might indicate that the waterproofing capability improves over time and/ or with exposure to high levels of moisture, as experienced during the first round of testing when uninsulated. However, this hypothesis should be further investigated.

Load cell readings were also available for the insulated WDR test cases. The untreated samples experienced a significant weight gain over the duration of the tests, up to 20kg on the outer wall leaf and 10kg on the inner wall leaf. B-treated walls showed a reduced weight gain, but varied between the two tested samples; one sample gained 8kg in the outer wall leaf and had no appreciable gain in the inner leaf, while the other gained 18kg in the outer wall leaf and 5kg in the inner leaf – still a notable reduction compared to the control samples. Meanwhile, the C-treated walls showed limited weight gain in the outer wall leaves of up to 5kg, and up to 2kg in the inner wall leaves. This supports the overall findings observed from the RH sensors in the insulated WDR test and also the findings from the earlier absorption bench testing; untreated samples showed the most significant weight gain, the B-treated samples showed an intermediate weight gain and with the most variability between samples, while the C-treated samples showed virtually no weight gain.

Hygrothermal modelling was carried out, incorporating data from the laboratory bench testing experiments as inputs for the properties of the bricks and the waterproofing treatments, to compare model predictions about heat and moisture transfer in walls with measurements obtained during the WDR testing. It was found that the accuracy of the modelling is highly dependent on closely matching the characteristics of construction products. When the material properties of untreated bricks were known and could be replicated in the models, results from simulations were quite representative of the laboratory findings. However, if alternative bricks from the modelling software database were instead used, they led to a notable discrepancy from the laboratory behaviour.

Simulation of the behaviour of the waterproofing treatments did not align with laboratory findings. Model predictions suggested that there would be no moisture uptake in treated bricks, whereas in practice, the laboratory samples did show some moisture uptake. It is likely that the presence of small cracks in the laboratory samples allow moisture to effectively ‘bypass’ the treatment to some extent, whereas the modelling assumes perfect construction and thus absolute resistance to the passage of moisture. It is for these reasons that in reference literature ‘engineering conditions’ or ‘safety factors’ are sometimes added to simulation models to attempt to allow for otherwise unquantifiable conditions experienced in practice. For example, modelling can be set up to assume that a defined percentage of moisture will penetrate the external construction layer. However, there is no real agreement on what correction factors should be applied, and indeed they are likely to be variable for different construction systems. Overall, while the reliability of untreated wall models may be improved by ensuring the parameters of the construction products are accurately represented, it is not possible to reliably model the impact of waterproofing treatments without identifying suitable ‘rules of thumb’ for safety factors that could be consistently applied. Further research is required to derive such ‘rules of thumb’, considering the several factors and ABIS conditions that could affect the behaviour of waterproofing on cavity walls.

U-value testing was carried out before and after the WDR testing on the same samples, in both a dry and wet condition to assess if the waterproofing treatments would help to improve the overall thermal performance of the walls. The tests showed that U-values were systematically lower in dry conditions than in wet conditions, and the waterproofing treatments in combination with CWI appeared to have the most notable beneficial effect in this regard. However, the results 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. When comparing treated and untreated walls in insulated and uninsulated configurations, it was observed that the U-values marginally improved between uninsulated untreated and uninsulated treated walls. Conversely, the U-value substantially improved between uninsulated and insulated untreated walls. These results show that the waterproofing agents themselves provide marginal improvement to the thermal performance of uninsulated walls compared to cavity wall insulation, and therefore the treatments cannot be considered as an energy efficiency measure in their own right.

The intention had been for laboratory performance of waterproofing treatments to be compared with real-world **site trials** on brick-faced cavity walls in areas of severe WDR exposure. However, when surveying properties in potential locations it was found that facing brickwork in exposed locations was not typical, or in significant numbers; the majority of properties were fully or partially rendered. Closer inspection of the condition of the external walls identified high levels of cracking and defects. For any application of waterproofing treatment, it is essential that the condition of the external facade is in a sufficiently good condition to allow the treatment to have any chance of reducing the risk of moisture penetration (as per manufacturers guidance). Due to the number of ABIS faults identified in properties during the site investigations, if any were to be tested with waterproofing treatments it would not have been possible to determine whether any failure was due to the treatment itself or a result of potentially multiple other failure routes. The proposed site trails of waterproofing treatments therefore unfortunately had to be abandoned as they would not have offered any additional insights compared to the laboratory testing. This and previous site investigation work suggests that cavity wall constructions in the UK – particularly those of facing brickwork rather than rendered – are unlikely to be of sufficiently good condition to expect such treatments to offer the intended reduced risk of moisture penetration without first having defects rectified.

There is no existing data source indicating the number of dwellings in the UK that are of brick-finished cavity wall construction, let alone those within high exposure zones. **Models** have been developed to predict the probability of a cavity wall dwelling in the UK having brick faced walls (masonry pointing) based on sources of available data, including NEED and EPC databases and EHS survey data. Mapping of WDR exposure zones according to BS 8104 in the form of GIS shapefiles now allows any geo-referenced data source to be overlaid with exposure zones. Unfortunately, due to lack of access to a geo-referenced version of the NEED database, it was not possible to run the full process of comparing brick cavity wall probability with exposure zones within the project. However, the process can be carried out by BEIS, where geo-referenced NEED data is available, to determine the likely number of cavity wall dwellings in exposed regions of the UK to which waterproofing treatments may be relevant.

Conclusions

Reduced moisture ingress was evident in the treated insulated wall samples during WDR testing compared to untreated walls, though the extent of moisture reduction varied between the two main products tested. U-values were also systematically lower in dry conditions than in wet conditions, and the waterproofing treatments in combination with CWI appeared to have the most notable beneficial effect in this regard.

While this is a positive finding in the context of the potential for such treatments to protect CWI, it is based on a small number of test samples and some discrepancies in performance between tests cannot readily be explained. Further WDR testing would therefore be recommended to provide additional supporting data for these conclusions, and solar exposure and freeze/ thaw testing would additionally be beneficial to simulate potential ageing effects on the treatments.

While overall moisture uptake in treated, insulated walls is reduced, there is still some moisture uptake over time. Had suitable in-situ case studies been available, it may have been possible to assess the robustness of deterministic hygrothermal modelling for the analysis of treated, insulated cavity walls in very exposed locations to see if the accumulation of wetting were likely to ultimately lead to failure, or if intermediate dry periods were likely to offer sufficient opportunity for walls to recover before being subjected to further wetting.

In any case, underlying ABIS conditions found during site investigations to be common in existing brick-faced cavity wall dwellings, could undermine the performance of the waterproofing treatments, allowing them to be effectively bypassed by cracks or other openings in the external façade. It would be essential that detailed and rigorous surveys were undertaken on any property where these waterproofing treatments were being considered and any defects rectified before application, so they are not undermined by underlying faults within the wall.

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Table of abbreviations

Abbreviation	Definition
ABIS	As built, in service
ADT	As designed, theoretical
CWI	Cavity wall insulation
DSA	Drop Shape Analyser
EHS	English Housing Survey
EPC	Energy Performance Certificate
EPS	Expanded polystyrene
GIS	Geographic Information System
HFP	Heat flux plates
LASSO	Least Absolute Shrinkage & Selection Operator
NEED	National Energy Efficiency Data-framework
RH	Relative humidity
WDR	Wind driven rain

Waterproofing treatment referencing

The following referencing is used throughout the report when discussing the waterproofing treatments under test:

Reference	Treatment type
A	Reference/ Untreated
B	Acrylic-based liquid
C	Silane/siloxane blend cream
D	Silane/siloxane blend liquid
E	Stearate-based liquid

1 Introduction and background

UCL has partnered with BRE to investigate the effectiveness of waterproofing treatments to reduce rain penetration in unprotected masonry cavity walls on behalf of the Department for Business, Energy & Industrial Strategy (BEIS). The aim was to establish whether the use of such treatments could safely allow wall cavities to be insulated as a retrofit measure in exposed areas, where such insulation was otherwise deemed unsuitable due to the increased risk of moisture ingress. If insulating such cavities were possible, it could offer a far less costly solution than the installation of externally or internally applied wall insulation, which would otherwise be the only alternative approach.

The government has a duty to implement a fuel poverty strategy for England and has a fuel poverty target and interim milestones that requires improving the energy efficiency of fuel poor homes. Moisture is increasingly a concern in all refurbishment and construction projects because as buildings become more energy efficient and particularly where they have lower air infiltration rates, they become more sensitive to moisture risks.

Cavity wall insulation (CWI) is one of the most cost-effective energy efficiency measures that can be implemented in UK dwellings that are appropriate to receive it. However, it has been long established as unsuitable for brick-finished cavity walls (i.e. not rendered or otherwise clad) in regions of high exposure to wind driven rain, since the insulation can facilitate moisture penetration across the cavity from the external to internal wall layers, leading to damp within homes.

A number of water-repellent surface treatments are available on the market that aim to reduce water penetration of walls. This study, therefore, sought to investigate a number of issues, including:

- Whether the water protection offered by such treatments to brick-finished cavity walls was likely to be sufficiently reliable in practice long term to enable the cavities to be safely insulated;
- To what extent reducing moisture ingress into walls (even uninsulated) could maintain their thermal properties simply by being dryer, since the presence of moisture aids heat transfer and dry walls should therefore help to reduce potential heat loss;
- The accuracy and reliability of hygrothermal modelling tools compared to real walls, since such tools may be relied upon going forward to assess the potential risk of moisture transfer across existing walls;
- The benefits, in carbon terms, if such treatments were deemed to be an appropriate measure to help reduce heat loss from existing brick-faced cavity wall dwellings in exposed regions of the country;

A key feature of this study has been to acknowledge and investigate the implications of contextual factors that give rise to 'As Built, In Service' (ABIS) conditions, as distinct from the 'As Designed Theoretical' (ADT) condition of walls. A well-constructed brick cavity wall should provide satisfactory resistance to moisture ingress. Modern standards and guidance for brickwork ensure cavity walls, constructed with appropriate materials and incorporating a suitable cavity width for the expected environmental conditions, remain a barrier to moisture, even in areas of very high exposure. These standards represent the ADT conditions. However, during construction, workmanship could be sub-standard and after construction walls can settle and age, thus becoming subject to ABIS conditions that can temper the efficacy of the ADT performance. ABIS is defined as the physical state of the wall at any given point in time post-construction, subjected to the environmental conditions found in-situ, and has been a consideration for the assessment of waterproofing treatments during this work.

2 Approach and methodology

A number of departments from UCL and BRE collaborated under the partnership of the UK Centre for Moisture in Buildings (UKCMB) to provide specific expertise to deliver this research work. This included UCL's Institute for Environmental Design and Engineering (IEDE), the Energy Institute (EI) and the Department of Civil, Environmental & Geomatic Engineering (CEGE).

This study utilised a range of approaches to thoroughly investigate the potential impact of waterproofing treatments on brick-faced cavity walls; from desk-based research to establish the most appropriate wall types and treatments for investigation, through bench testing of small-scale samples to larger scale wind driven rain (WDR) testing in a dedicated environmental chamber. Site surveys were also carried out at cavity walled properties in locations of high exposure to highlight the practical implications associated with the condition and features of real walls.

Simulation analysis has been carried out using results obtained from laboratory testing to validate hygrothermal models. In addition, data from various sources has been aligned and overlaid with mapping software to determine the likely number of cavity wall dwellings in exposed regions of the UK to which waterproofing treatments may be applied. This, combined with the outcomes from laboratory investigations, will allow the potential carbon impact to the UK to be assessed.

The project is organised in nine work packages, which respond to the aim and objectives of the tender. The first two work packages (see section 2.1 and 2.2), led by BRE, determined 1) relevant parameters to classify cavity wall construction in the UK in the last 50 years, including a realistic representation of defects, and 2) waterproofing products available on the market and suitable for application to exposed masonry cavity walls. The output of these two work packages is essential to ground the rest of the research and to inform the design and delivery of the laboratory work packages. The laboratory work packages (see section 2.3 and 2.5) led by UCL-CEGE, were designed to first determine, through a series of bench tests, the applicability of the waterproofing products in relation to specific bricks and mortar types representative of UK cavity wall construction, then to expose real size walls to variable environmental and wind-driven rain conditions to determine the effectiveness and detailed response of the products and walls to cycles of wetting and drying and to establish the combined effect of waterproofing and cavity insulation on the moisture uptake of these walls and effect on their thermal performance. To this end monitoring of heat flow and temperature, led by UCL-IE, (see section 2.6) was carried out on the wall specimens to determine the U-values of the cavity walls. To extend the applicability of the results obtained with the laboratory testing, UCL-IEDE led first a thorough review of the literature on hygrothermal modelling, to determine relevant parameters to be included in the testing (see section 2.4), then detailed modelling of the tested cavity walls for both heat flow and wind driven rain (see section 2.7). The objective of the eighth work package, led by BRE, was to provide further validation of the laboratory test by performing a number of onsite tests on existing insulated and waterproof exposed buildings (see section 2.8), while the objective of the final work package, led by UCL-EI, (see section 2.9) was to determine the benefit in carbon terms, that could be delivered by rolling out such treatments at the national scale.

The extent to which the proposed methodology was adhered to and the specific objectives and overall results delivered is discussed in each of the following sections for each work package and in section 3 of the report, respectively.

2.1 Wall analysis (led by BRE, see Appendix A)

This involved a desk-based literature review to establish how walls should be constructed and tested during the laboratory experiments so they may be as representative as possible of typical cavity wall construction in the UK, and it covered:

- Brick types, sizes, manufacturing techniques and resulting physical properties
- Mortar types, wall ties, brick bonding patterns and jointing techniques

These would represent ADT conditions. Data from recent site investigations was additionally assessed to understand the range of ABIS conditions that may be present in real walls that could lead to cavity wall failure. The various moisture transfer mechanisms and environmental factors to which a cavity wall may be subjected were explored, including those resulting from ABIS conditions.

Existing testing standards relating to exposure and water penetration of walls were reviewed to consider whether their methodologies would be suitable for the testing of cavity walls, or whether any testing parameters were of relevance and worthy of replicating during the proposed laboratory testing phase.

Based on the combined analysis, materials and construction approaches were proposed for subsequent laboratory testing to be representative of likely cavity wall constructions in exposed parts of the UK, along with recommendations for exposure testing that would allow the relative performance of samples with and without waterproofing treatments to be determined.

2.2 Treatments analysis (led by BRE, see Appendix B)

A desk-based analysis was carried out to gain a better understanding of the range and nature of wall waterproofing products available in the UK, with the aim of selecting representative products for subsequent laboratory testing. The approach taken was to identify as many relevant products as possible, starting initially with internet searches as many potential customers would do. Certification bodies and professional product selector services were also explored to expand on those initially identified (e.g. RIBA Product Selector, Barbour Index, BBA Certification).

Product literature was then investigated, and enquiries made with manufacturers to establish whether products fell into different groups based on their chemical composition, effective mechanism, application method, or any other parameters. Further requests for information were sent via email directly to 33 manufacturers/ suppliers for which contact details could be found. This particularly focussed on aspects that were not readily available in the public domain, such as the chemical base of the product and market information that may help provide a picture of the most commonly used products in the UK. Manufacturers were asked the following questions of their products:

Please list the wall waterproofing treatment products you supply that are both:

1. Clear once dried (i.e. not paints or renders)
2. Breathable in nature (i.e. allow moisture within a wall to dry out)

For each of the above products:

3. For categorisation purposes, what is the fundamental chemical component, e.g. siloxane, silane, aluminium stearate, etc
4. Has the product performance been independently certified by a third party, e.g. BBA? If so, please provide relevant certificate information.
5. Do you have any statistics on the market share of each product, or the typical volume of sales, e.g. litres per year?
6. Is the product suitable for use on brick/ stone/ concrete/ calcium silicate/ cement mortar/ lime mortar (please list as appropriate)?
7. If possible, please provide statistics for the effectiveness of the product(s) to the resistance of moisture ingress (e.g. % reduction in water absorption)
8. Do you propose an expected lifespan/ effective duration for the product(s)? If so, how long?
9. Does the product need to be reapplied at a given frequency to ensure continued durability? If so, what is the typical period of recommended reapplication?

Unfortunately, the majority of manufacturers did not respond at all, or did not reply directly to the questions raised. Information was received from only 10 contacts representing 16 relevant products. In particular, no meaningful data could be established regarding market share, hence this could not be used to help select products for laboratory testing. A hierarchy was developed to select products for testing, which reflected the level of information available (and hence confidence) in the product:

1. Those with declared performance data relating to moisture resistance, preferably with third party certification

2. Whether a lifespan/ durability is declared and guaranteed (with preference to those offering longer lifespans)
3. Whether the product is readily available online, to aid with confidentiality when sourcing products
4. If the same manufacturer is put forward for more than one product, an alternative should be sought for a more balanced market spread

If remaining products otherwise appear to have the same criteria, the cost per m^2 wall coverage will be considered

2.3 Bench testing (led by UCL, CEGE, see Appendix C)

CEGE undertook bench testing of small masonry specimens with three different types of brick and four waterproofing treatments selected from the earlier tasks, with the aim of identifying the best performing to progress to the full masonry specimens test. The bench testing investigated the ability of waterproofing treatments to cover/ penetrate into the masonry surfaces thoroughly and evenly by two different application techniques, i.e. brushing and spraying. Specimens were made up of a 28 mm deep sections of the external face of 2 bricks bonded with a 10 mm mortar bed joint. The purpose was to determine the characteristic of the resulting masonry assembly rather than just the material components. Three sets of tests were performed:

- Water vapour permeability test, ISO 12572:2016, 'Hygrothermal performance of building materials and products - Determination of water vapour transmission properties - Cup method.'

  (3 brick types, 4 treatments, 1 reference untreated) Test specimens were sealed to the open side of a test cup containing an aqueous saturated solution (wet cup) with their external surface facing down towards the solution. The assembly was then placed in a temperature and humidity-controlled test chamber for 72 hours. Because of the different partial vapour pressure between the test cup and the chamber, a vapour flow occurs through the permeable brick and mortar specimens. The assembly was weighed periodically to determine the rate of water vapour transmission under stable conditions.

- Hydrophobicity test, BS EN ISO 19403-2:2017, 'Paints and varnishes - Wettability Part 2: Determination of the surface free energy of solid surfaces by measuring the contact angle.'

  (1 brick type, 4 treatments, 1 reference untreated) Test specimens of treated (waterproofed) and untreated brick had drops of liquid applied to their surface using a needle dosing system. According to the standard, and consistently to the other two tests, water was used. An optical system (KRÜSS Drop Shape Analyser (DSA) 100 apparatus) was used to study the behaviour of the drops and calculate their contact angle as they rest on the surface. The contact angle indicates the extent to which the drop is absorbed into the material, with the behaviour assessed over time; the greater the contact angle, the less absorbent the sample surface. An average of 3 measurement points was taken to assess the homogeneity of the test specimen. The surface tension, polar and dispersive fractions, and the surface free energy of the solid test sample were subsequently determined from the contact angle measurements.

- Water absorption test, BS EN ISO 15148:2002, 'Hygrothermal performance of building materials and products - Determination of water absorption coefficient by partial immersion'.

  (1 brick type, 2 treatments) The absorption test indicates the speed and amount of water specimens take up when immersed in water. Tests were carried out on brick and mortar samples separately, plus assembled 28 mm sections of brick bonded with mortar as used for the water vapour permeability tests, in both untreated and treated (waterproofed) conditions. Sample sides were sealed using waterproof tape, with silicone sealant applied at the joint between the tape and the specimen. Samples were placed exposed side down on a raised mesh support within a tray of water so the water level remained 5mm above the base of the specimen. The change in mass of the samples was measured at increasing time intervals over a 24-hour period to determine the rate of absorption of the samples through the unsealed surface.

2.4 Hygrothermal modelling review (led by UCL, IEDE, see Appendix D)

A literature review of the state of the art of hygrothermal modelling was carried out to understand how it may support moisture risk analysis and to identify how information obtained from the laboratory testing could be integrated so as to validate such models. The aim was to understand the limitations of existing modelling methods, particularly related to:

- The characteristics of cavity walls (e.g. convective heat loss, the presence of insulation, the presence of debris, etc)
- The availability of information related to material properties
- Appropriate indoor and outdoor moisture loads
- ABIS conditions

The findings would help to steer the appropriate collection of data from the laboratory testing and inform subsequent hygrothermal modelling activities.

2.5 Wind Driven Rain (WDR) laboratory testing (led by UCL, CEGE, see Appendix E)

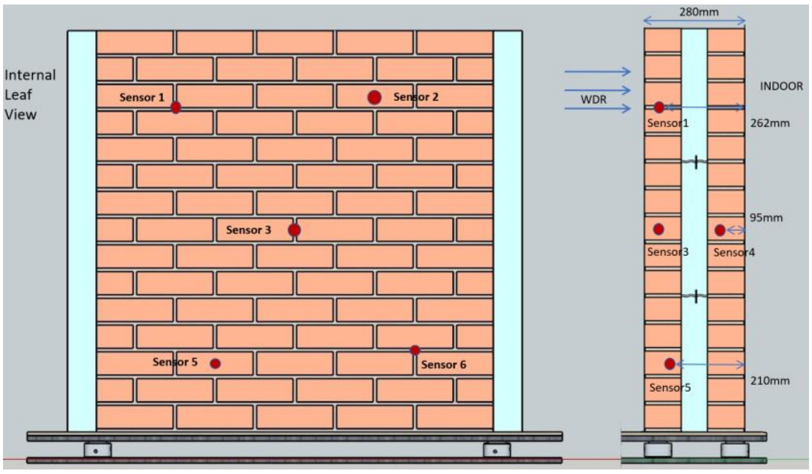
Six cavity wall specimens of approximately 1m^2 (to nearest brick dimensions), first uninsulated and subsequently insulated with loose expanded polystyrene (EPS) beads, were built by trained bricklayers. The Polypearl Platinum polystyrene beads were poured into the cavity without use of adhesives, compacted until full, achieving the manufacturer recommended density of 14 kg/m^3 ± 2 per installation.

Samples were tested in a double environmental chamber allowing control of internal and external environmental conditions. Walls were intended to represent ADT conditions, though minor variability in the construction and local minor defects (e.g. small cracks, uneven cavity space) were present in the walls as a consequence of the building process and movement of the walls between the curing room and the environmental chamber. Two wall samples could be tested side-by-side at a time. During the test, the specimens were placed at the centre of the environmental chamber with internal and external hygrothermal conditions simulated on either side of the test walls.

The cavity space of each specimen was 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. The external chamber also contained a water spraying apparatus and fans capable of driving a given quantity of water at a desired pressure towards the walls to represent the effects of wind driven rain.

Two waterproofing treatments - one liquid and one cream - were selected based on the outcome of the bench testing described in section 2.3. These were used to coat the outer surface of the external wall leaf of two cavity wall samples each, i.e. the wall samples consisted of 2 untreated (reference) samples (A), 2 treated with an acrylic-based liquid product (B), and 2 treated with a silane/siloxane blend cream product (C). During the WDR tests the walls were subjected to wetting/drying cycles to determine the response of the coating products to extreme wind driven rain conditions. Water uptake in the walls was measured by relative humidity (RH) sensors in the wall fabric and by weighing on load cells to systematically measure and record the moisture movement within the cavity wall and the wall mass. Each wall specimen sat on a set of two steel plates, though isolated from direct contact with the plates by strips of insulation to prevent thermal bridging of the inner and outer wall leaves, with four loadcells interposed at the four corners of each wall, to determine separately the increase in weight due to water uptake of the external and internal leaf, respectively. Six temperature and RH sensors were installed in-wall in the two masonry leaves for the purposes of this testing, as shown in Figure 1.

Current standards regulating wind driven rain testing protocols of building construction elements are not conceived to determine the durability of superficial treatments, and hence are not directly applicable to the present study. The most relevant standard is the ASTM E 514/C1601 (2014), ‘Standard test method for water penetration and leakage through masonry’, however testing conditions were adapted to surveyed exposure conditions as discussed in detail in section 3.1.



Sensor type	Position	Depth(mm)
T&RH 1	Mortar	262
T&RH 2	Brick	262
T&RH 3	Mortar	265
T&RH 4	Brick	95
T&RH 5	Brick	210
T&RH 6	Mortar	210

Figure 1: Location of temperature and RH sensors within WDR wall samples.

WDR tests were performed as part of a longer monitoring programme in the environmental chamber, which included U-value testing outlined in section 2.6. Specifically, WDR tests were run over 2 days after 'dry' U-value testing had been carried out. On the first day, 2 wetting cycles were applied to the walls. On the second day, a further 8 cycles were applied, or testing was concluded when water was observed to penetrate the wall cavity and reach the inner leaf. Each wetting and drying cycle consisted of 20 minutes wetting at a rate of 2.25 litres/m^2/minute then 40 minutes drying. Samples then remained in the chamber for the 'wet' U-value testing before being moved back to the curing room.

2.6 U-value testing (led by UCL, EI, see Appendix F)

Heat flow and temperature measurements were carried out on the wall specimens during the monitoring programme in the environmental chamber to determine the U-values of the cavity walls. Specifically, U-value tests were performed before and after the WDR wetting cycles, i.e. in 'dry' and 'wet' conditions respectively. In addition to the sensors described in section 2.5 for use in the WDR testing, each wall was instrumented with five heat flux plates (HFP) and four surface temperature thermistors, as shown in Figure 2, for the purposes of the U-value testing. Two locations were monitored on each specimen by positioning the HFP and temperature sensors vertically aligned and opposite each other on the two leaves of the wall. A third location on the external surface was monitored as a control using one additional HFP. The two vertically aligned HFP on the external surface were temporarily detached from the specimens to ensure an even water distribution and penetration through the wall surface during the WDR test; the third sensor remained in place at all times. The sensing parts of both HFPs and thermistors were located on brick stretchers.

The U-value testing sequence consisted of an initial monitoring period of at least 3 full days prior to WDR wetting cycles with the specimen walls (just moved from the curing room) exposed to the simulated internal and external dynamic temperature and RH profiles (referred to as 'dry condition') specified in Table 1. After a maximum of 2 days of wetting cycles as part of the WDR testing, there was a second U-value testing period of a further 3 full days (minimum) with the wet specimens (referred to as 'wet condition') exposed to the same internal and external temperature and RH profiles as in the previous U-value test. Testing was carried out for all wall samples in both the uninsulated and subsequently insulated condition. Analysis followed BS ISO 9869-1:2014, 'Thermal insulation. Building elements. In-situ measurement of thermal resistance and thermal transmittance. Heat flow meter method', using the average method (i.e. in steady-state conditions).

Figure 2: Cavity wall specimen instrumentation for the external (left) and internal (right) simulated environments

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

	Test 1 uninsulated	Test 2, 3 uninsulated and Tests 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

2.7 Hygrothermal modelling (led by UCL, IEDE, see Appendix G)

Hygrothermal modelling was carried out using Delphin software in accordance with BS EN 15026:2007, ‘Hygrothermal performance of building components and building elements - Assessment of moisture transfer by numerical simulation’. The aim was to utilise data from laboratory experiments (bench testing and WDR testing) as inputs to the simulation models to compare the measurements and the model predictions about heat and moisture transfer in walls. A comparative analysis was also carried out to evaluate the influence of the selection of appropriate material files on the predictions.

The cavity wall samples tested within the WDR laboratory testing and U-value testing were instrumented to measure temperature and relative humidity at varying depths across the walls, i.e. the inner and outer surfaces of each of the two wall leaves, so this could be compared with findings from equivalent simulation models.

The boundary conditions in the models were set to match those used in the laboratory testing, considering both the U-value test and WDR test. These boundary conditions consisted of (at least 4) daily cycles of T and RH under dry conditions (as described in the U-value testing), followed by wetting (as described in the WDR testing) and by (at least 4) daily cycles of T and RH under wet conditions.

The comparative analysis was carried out using material files from the in-built Delphin[1] software database and MASEA database[2] (the result of a research project to characterise a number of German construction materials). Such material files are likely to be the only reference sources available to hygrothermal modellers at this time.

The comparisons between measurements and model predictions were performed considering material files representative of the materials used in the WDR laboratory testing. Furthermore, the material

[1] DELPHIN 6 (2020), Bauklimatik Dresden. Accessed: 30/04/2020 [Online] http://www.bauklimatik-dresden.de/delphin/index.php

[2] MASEA - Material Property Database of Old and New Building Materials for Software Tools in Building Construction, 2007. [Online] Available: http://www.masea-ensan.de/

properties measured in the laboratory bench testing (described in section 2.3) were integrated in the software database for the characterisation of each element of the modelled wall construction (i.e. the brick and the treatments).

2.8 Site testing (led by BRE, see Appendix H)

The initial aim of the site investigation work was to carry out a range of tests on uninsulated and insulated brick-faced dwellings with waterproofing treatments applied. Testing was expected to include:

- Confirmation of the localised exposure rating according to BS 8104, 'Code of practice for assessing exposure of walls to wind driven rain'*
- Investigations to assess the condition and suitability of cavity walls for filling according to BS 8202, 'Assessment of suitability of external cavity walls for filling with thermal insulants'*
- Infrared camera imaging*
- Moisture testing with calcium carbide
- Internal and external temperature and humidity measurements
- Extraction of test samples for laboratory analysis

BRE undertook extensive searches to try to identify properties constructed of facing brickwork that were located in exposed locations according to BS 8104 and in a physical condition that would be suitable for the application of waterproofing treatments. Six Housing Associations were approached to assess their housing stock for potential properties. 100 properties underwent external surveys, 50 of which also included internal investigation of the cavity space. Unfortunately, it was not possible to find any suitable dwellings in an appropriate condition to accept the application of a waterproofing treatment with any chance of a successful outcome – all were found to have problems requiring fundamental repairs, making them unsuitable even for calibration of simulation models in the untreated state. It was therefore not possible to implement the full extent of site testing originally envisaged, instead only focussing on the initial surveying aspects used to identify suitability (or in practice, the lack thereof) as indicated with a star (*) above.

2.9 Carbon modelling (led by UCL, EI, see Appendix I)

The original aim of this task was to estimate the contribution that could be made to UK carbon emission savings if it were deemed acceptable to insulate brick-finished cavity walls in regions of high WDR exposure. In order to do this, information would be required on:

- The number of such brick-finished cavity wall dwellings in exposed areas (zones 3 and 4 according to BS 8104)
- The energy and therefore carbon savings that may be achieved by insulating such dwellings if waterproofing treatments were deemed sufficiently successful to allow it

The latter is explored in the wider research, i.e. the principle of whether waterproofing treatments are deemed effective at reducing moisture ingress in cavity walls, but most specifically via the U-value testing, which aims to quantify any changes in the thermal performance of walls. In this analysis, the focus was on identifying the number of brick-finished cavity wall dwellings using different residential buildings data sources.

There is no robust existing data source indicating the number of dwellings in the UK that are both of brick-finished cavity wall construction and within high exposure zones. The focus of this task therefore became the development of a methodology that could help to better understand the potential scale of the housing stock to which treatments may be relevant to facilitate CWI.

The resulting stock analysis comprised 3 parts:

i) Predicting whether a dwelling was likely to have a brick-finished cavity wall according to available data on the housing stock

ii) Mapping dwellings according to their wind driven rain exposure zone

iii) Combining the above to estimate the number of relevant dwellings in severe or very severe exposure zones

Data sources available for dwelling analysis include the National Energy Efficiency Data-framework (NEED), the Energy Performance Certificates (EPC) bulk access database (held within NEED), and the English Housing Survey (EHS). NEED and EPC information includes several data points useful for applying a predictive model, including the EPC band of the property, the wall construction, the presence of CWI and the year of its installation where known. However, it does not include information on wall finishes. The EHS includes information on a number of energy performance and physical characteristics, including wall construction and wall covering, which could identify masonry pointing (i.e. brick finish). However, this sample set represents only a relatively small number of dwellings. It was therefore necessary to develop a model to predict the probability of properties in the NEED data having a brick-finished cavity wall, based on identified patterns between NEED and the smaller EHS sample set. A process was developed to train a statistical model based on logistic regression, generalised linear regression and Least Absolute Shrinkage & Selection Operator (LASSO) selection to predict the probability of a cavity wall having masonry pointing (i.e. brick finished).

ArcGIS and QGIS Geographic Information Systems were used to create a map layer of the wind driven rain exposure zones (according to BS 8104). This could be overlaid on geo-referenced property data of chosen criteria.

It is understood that BEIS have a geo-referenced version of NEED, but this was not available to the project team for this research. Instead, this project demonstrated the ability to assign exposure zones via GIS to an alternative geo-referenced building database, namely the Geofabrik and OpenStreetMap database[3] as a proof of concept.

Although it is not possible to determine the number of brick-finished cavity wall dwellings in given exposure zones as part of this research, a predictive model is now developed that would allow BEIS to identify dwellings in the NEED database with a likelihood of having a brick-finished cavity wall, then overlay exposure zones against that data (using the geo-referenced version of NEED) to help identify most likely properties for the consideration of waterproofing treatments.

[3] Geofabrik OpenStreetMap database available at: https://www.geofabrik.de/geofabrik/index.html

3 Results

Key findings from each of the tasks are presented here. The full detailed analysis for each is included in the respective Appendix.

3.1 Wall analysis

The desk-based investigation explored the range of wall components and construction techniques that may be applicable to cavity walls across the UK so they could be best-replicated in the laboratory investigations. These are summarised in Table 2.

Table 2: Characteristics/ variables of cavity wall construction

Characteristics	Performance (variable extremes, where relevant)	
Brick size	215 x 102.5 x 65 mm (or equivalent Imperial)	
Manufacturing technique	Machine made clay bricks (pressed/extruded)	
Density/ porosity	Low absorption	High absorption
Brick texture	Smooth	Heavily textured
Brick bond	Stretcher bond	
Brick joint	Weather struck or concave	
Wall ties	Stainless steel wall ties @ 2.5/m^2	
Mortar binder	Cement/ lime blend mortar, M4 class	
Sand	Standard building sand	

Investigations into existing standard test methodologies for WDR showed that no single current test would adequately deliver all the environmental conditions relevant to exposed cavity walls, based on example weather data for a known severely exposed location (Swansea, Wales). It was therefore necessary for the project team to develop a new testing approach for the large scale laboratory WDR analysis incorporating the most relevant exposure factors identified from the literature, as indicated in Table 3.

Table 3: Environmental conditions for cavity wall testing

Characteristics	Performance (variable extremes, where relevant)	
Cavity width	50 mm	75 mm
Water exposure volume	0.13 litres/m^2.min for >13h (or equivalent)	
External pressure	185 Pa	
External temperature	10 °C	
Internal temperature	20 °C	
Internal relative humidity	65%	

A range of common ‘real world’ ABIS features that may reasonably be expected to be present in an otherwise seemingly good quality cavity wall were identified from the literature and from recent site investigation reports. During the preparation of samples for laboratory testing it was therefore acknowledged that the walls could include cracking at the interface between bricks and mortar, of approximately Category 1 classification, i.e. up to 1mm, and minor mortar accumulation on wall ties. Other, more significant faults should be avoidable so as to represent ADT 'best case' conditions during laboratory testing to give the waterproofing treatments a fair analysis.

3.2 Treatments analysis

Detailed analysis of waterproofing products available on the market identified 60 potential products for consideration to take forward to the laboratory testing. These products fell into three main 'types', namely acrylic based, stearates, or silane/siloxanes (or blends). Silane/siloxane products made up the vast majority of those identified. Additionally, some products took the form of liquids while others were supplied as creams, and some were solvent based while others were solvent free. Notably, some solvent-free examples suggested they may be applied to damp walls rather than insisting that the wall be dry before application, which could be a useful practical feature when the aim of the products is to reduce dampness in walls.

Although silane/siloxane blends appeared to be the most common product type of those identified, it was decided that testing each of the different types at the bench testing stage would help to determine whether there are any fundamental differences in performance, even though silane/siloxane blends were most likely to be taken through to the larger scale WDR testing as being most representative of the market. In addition, testing both a cream and liquid version of the silane/siloxane type at the bench testing stage would allow comparison of the ease and relative merits of their application method and whether this fundamentally impacts on subsequent performance.

Following the hierarchy developed to select products for testing discussed in section 2.2 and the considerations above, four specific products were ultimately recommended for bench testing (note that the designation 'A' has been reserved for untreated reference scenarios):

- **B:** An acrylic-based liquid, with 10 years lifespan but no resistance performance claims
- **C:** A silane/siloxane blend cream, with 25 years lifespan and BBA certificate with claimed resistance rates
- **D:** A silane/siloxane blend liquid, with 10 years lifespan and with claimed resistance rates. This product was solvent free and claimed it could be applied to damp walls
- **E:** A stearate-based liquid, with10 years lifespan and independent performance testing with claimed resistance rates

3.3 Bench testing

3.3.1 Water vapour permeability test

The aim of the water vapour permeability measurements was to test the overall water vapour transmission of the combination between bricks and mortar to simulate a real-life scenario. Samples were comprised of two brick sections (28mm thick) cut from the external surface of whole bricks bonded together with a 10mm mortar joint, as shown in Figure 3.

Figure 3: Water vapour permeability test set up, with the mortar and brick samples placed over wet cups

For each combination of brick and waterproofing treatment identified, 5 replications were tested. Samples were placed over a wet cup containing salt solution to maintain a relative humidity of 93%, then weighed periodically over a 72-hour period with a curve of change in mass against time plotted to facilitate recognition of the constant mass change rate as the samples take up moisture. This was then used to determine the water vapour resistance factor (μ) of the sample, as reported in Figure 4. The error bars on the columns are the standard deviation between the 5 replications. A higher water vapour resistance factor indicates lower permeability.

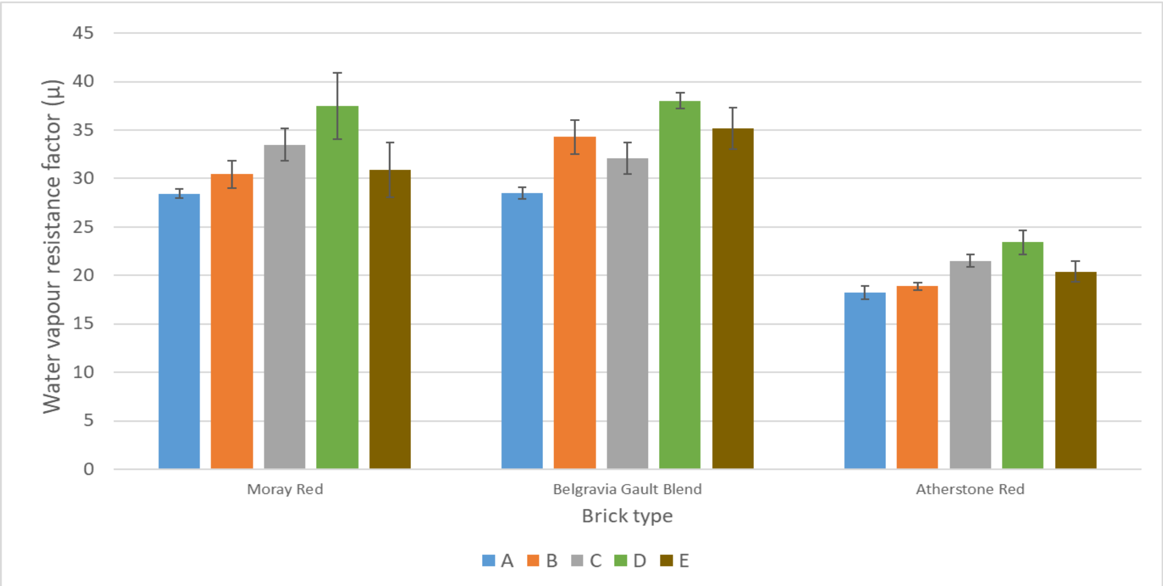


Figure 4: Water vapour resistance factor (μ) of masonry specimens with different brick types and various waterproofing treatments

The water vapour resistance was mainly dominated by the brick's own physical properties. Nonetheless the trend of the relative performance of the treatments for each substratum is consistent across the three brick types.

Results obtained from untreated specimens are very consistent with relatively little standard deviation. The highest variability for the treated cases is observed in specimens built using Moray Red. This is likely due to the visibly more heterogeneous structure of Moray red, with larger particles, leading to a lower uniformity (see Figure 4). Atherstone Red results, for both untreated and treated cases, demonstrate the highest consistency. The Atherstone Red was therefore deemed the preferred brick type to take forward to the subsequent bench tests and the larger scale wind driven rain testing.

A comparative review of the results obtained for specimens treated with individual products shows that among the waterproofing products, D led to standard deviations relatively high among all treatments except in combination with Belgravia Gault Blend. On average, the product provides the highest impact on water vapour resistance over all 4 products but also importantly, there was less consistency compared to other products. B and E have shown similar performance: they both have a relatively low impact on the water vapour resistance while B held a more consistent performance over all brick types. Differently from the other 3 aqueous products, C is a cream product. It was the second strongest waterproofing product in providing additional water vapour resistance for two out of three brick types.

3.3.2 Wettability test

The wettability of the untreated and treated brick surfaces was determined via the contact angle associated with drops of water at the sample surface. The contact angle indicates the extent to which the drop is absorbed into the material, with the behaviour assessed over time; the greater the contact angle, the less absorbent the sample surface.

Similar to the previous test, first the untreated specimens were tested to provide the reference case, where the water drops were absorbed fully within 1-3 seconds, depending on surface roughness, uniformity and density of bricks. Due to the rapid absorption, the DSA100 was not able to capture the image and the contact angle could not be measured.

The results obtained from hydrophobicity tests are summarised in Figure 5. B and E treated specimens showed very similar results with no obvious absorption in the 20 minutes duration that they were observed after the drops were dosed on the surfaces, and the contact angles were very consistent over all brick types. The average contact angles were also very close with 113.5° for the B specimens and 114.1° for E specimens (Figure 5a and 5c,) respectively

Compared to other specimens, the ones treated with product C have shown some unique characteristics. On the centre of the brick specimens, the absorption started 3 minutes after leaving the droplets on the surface and the water droplets were completely absorbed in 10-15 seconds. After repeated tests on the whole specimen surface, it was seen that the absorption starting time reduced radially from centre to the edges of the specimen. On the edge water drops absorption started in 0-5 seconds and they were fully absorbed in 10-15 seconds. In most of the surface between the centre and the edges, the absorption started around 1 minute after dosing on the surface, and the droplets were fully absorbed in 10-15 seconds. The average contact angle before the start of absorption was 102.8° (Figure 19b). This rather unique characteristic of the specimens treated with this product is considered to be due to its consistency as cream. It can be assumed that the difference was caused by the lack of uniformity of the application caused by the nature of the product and the size of the specimen. Despite all efforts towards best practice in application under ideal lab conditions using a paint roller, the centre of the specimen was rolled over more times than the edges. It should be borne in mind however that this uneven distribution of the product over the surface of the specimen is due to the small specimen size and might not reflect the product spread over a real-life façade when applied with good workmanship. For specimens treated with product D, the absorption started within 5 to 15 seconds after dosing the drops on the surface, and the droplets were fully absorbed between 1 to 3 minutes (Figure 5d). However, the contact angles before the absorption started were very consistent with an average of 91.9°, which demonstrated a relatively high wettability of surfaces treated with the blend liquid.

Combined with the findings in the water vapour transmission test, apart from the wettability difference caused by the roughness of the brick surfaces, the quality and uniformity of the application can influence the amount of product penetrating the surface. From the results of both tests, the C product is showing relevantly higher sensitivity in application quality on smaller scale specimens, therefore it can be assumed that good workmanship is necessary to achieve a satisfactory coating with consistent performance on real scale applications.

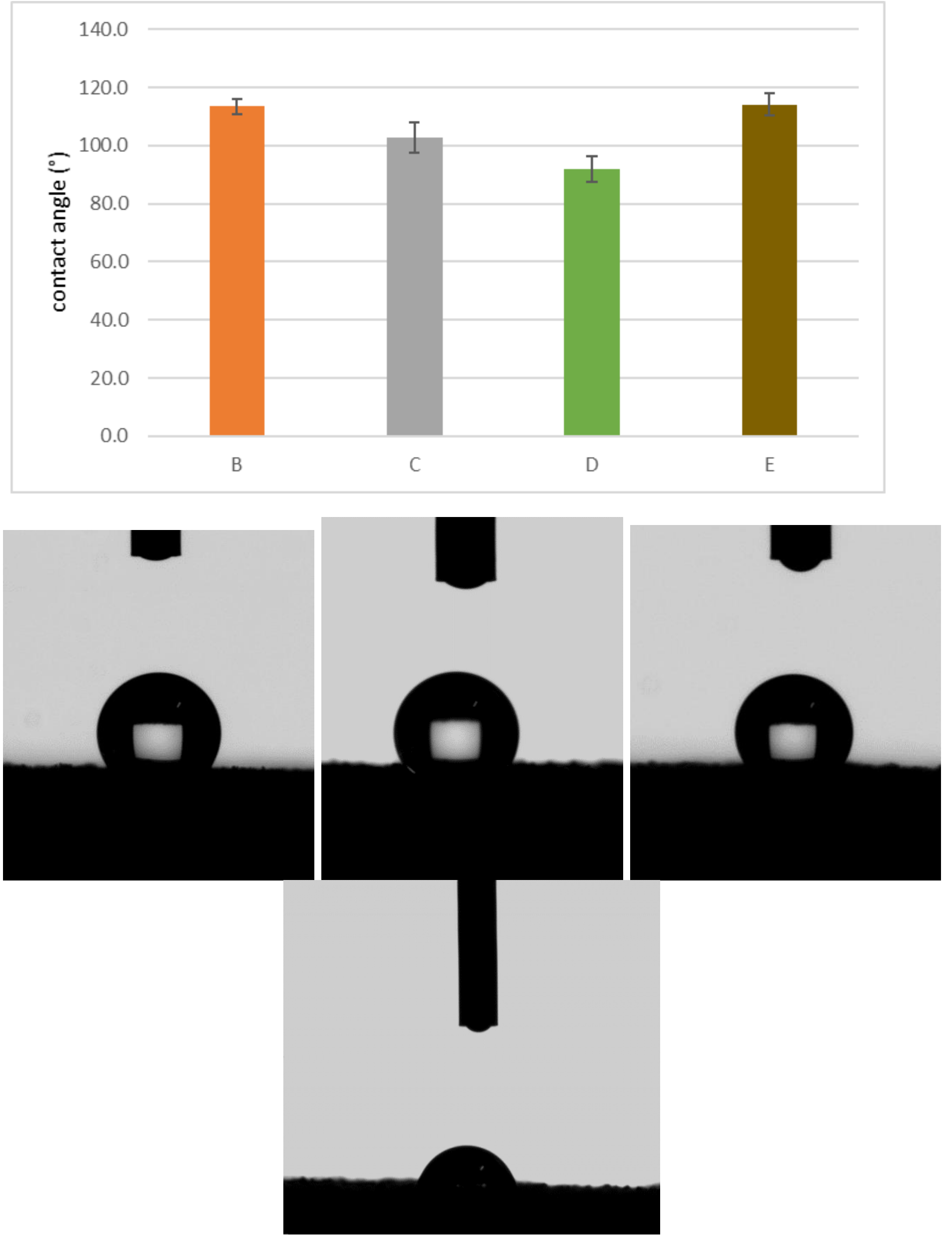


Figure 5: Average water contact angles for each treated specimen and water drop on specimens treated with a) product B b) product C, c) product D, d) product E

3.3.3 Water absorption test

The aim of an absorption test is to measure the rate and amount of water absorption in specimens when in water. The results in the graphs shown in Figure 6 were averaged from three samples for each building material and waterproofing treatment condition. Weight gain on untreated bricks reduced significantly after 2h, mortar samples in about 4h and combined samples also in about 2h, although modest weight gain is still visible up to 5 hours. The water absorption coefficients calculated for the B-treated samples were considerably lower than the ones for untreated samples, indicating a slower absorption, but similarly to the untreated samples the brick had a faster rate of absorption than the mortar, while the combined sample had a rate of absorption similar to the mortar. The C-treated samples show a flat curve with almost no water absorption over all three types of sample. In terms of weight gain over 24 hours, the untreated specimen shows a weight gain of 17% in the mortar, 11.6% in the brick and 10.7% for the combined specimens. For B treated specimens the uptake was roughly halved at 5.9%, 7.6% and 6.7%, in mortar, brick and combined respectively. The C treated specimens had weight gain two orders of magnitude smaller at 0.14%, 0.29% and 0.37% in mortar, brick and combined respectively.

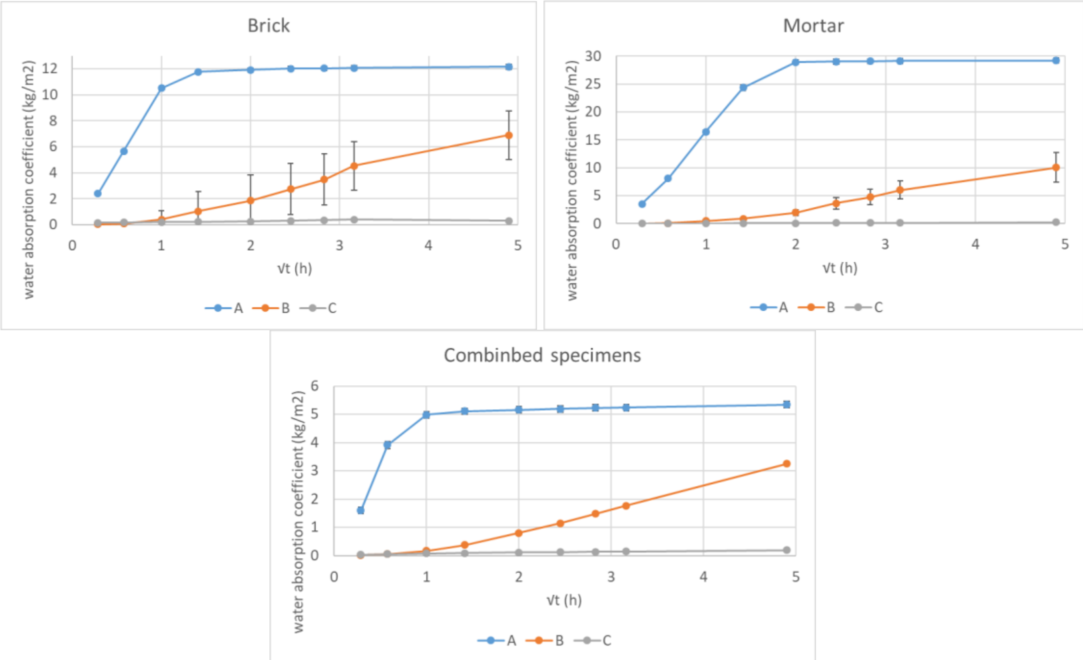


Figure 6: Weight change of various samples in absorption test

From the error bars shown in Figure 6, it can be observed that the performance of the B-treated samples was less consistent and had larger scatter for the brick and mortar samples, when compared to the combined specimens, which showed high consistency. This can be explained by the fact that the combined samples were treated 12 months before the test, while the brick and mortar samples only 28 day before the test, hence the curing time having an effect on the absorption of the sample. Therefore, the long-term performance of the treatment should be further investigated, and it is recommended repeating the above set of tests at 6 months intervals.

On the other hand, all C treated samples have shown little water absorption compared to untreated and samples treated with B. The results were also very consistent, with very minor error values. However, it is noted that the rate of weight gain in the first 5 minutes is higher than the rate for subsequent time intervals on the brick samples and the water absorption coefficient curve grew gradually flatter.

The results of the absorption test are supportive of the findings from the WDR tests on insulated walls in WP6. The water absorption coefficients of the B-treated samples were considerably lower, and the water absorption rate was slower than untreated ones while C treated samples almost absorb no water over all three types of sample. Additionally, the combined samples treated with B showed higher consistency in performance than freshly treated brick and mortar samples, possibly indicating an improvement in performance with longer curing time or exposure to high RH environment. Hence the long-term performance of the treatment could be usefully confirmed by repeating the above set of tests at 6 months intervals.

Similar to the WDR test results obtained from insulated walls, all C treated samples have almost no water gain in the absorption test. Furthermore, the increase in water absorption coefficient was faster in the first 5 minutes than the rest of the 24h test.

3.3.4 Summary and comparisons

Table 4 summarises the performance of each of the treatments as it can be determined through the results obtained across the three bench tests. These are interpreted in terms of the relationship with the cycle of wetting and drying, from first contact of the wind driven rain with dry surfaces (hydrophobicity test), to the absorption of liquid water within the body of the walls (absorption test), once surfaces are thoroughly wetted by wind driven rain, to the consequent process of drying by evaporation (water vapour transmission test).

Table 4: Summary of the findings from hydrophobicity, water absorption and water vapour transmission test through the lifecycle of a wall response under exposure (green, yellow and red indicate comparatively significant, some/inconsistent and little/insufficient improvement, respectively, and SD stands for standard deviation)

FIRST CONTACT WITH WATER	WETTING PROPENSITY	EASE OF DRYING

Treatment	Hydrophobicity test		Water absorption test			Water vapour transmission test	Performance summary and implications
	Brick III (cured for 1 week)		Brick III (cured for 2-4 weeks)	Mortar (cured for 2-4 weeks)	Masonry with brick III (cured for 12 months)	Masonry made with brick III* (cured for 2-3 days)	
	Average contact angle / SD	Time to the start of / for completion of sorption	Average water absorption coefficient at 24h / SD Performance in reference to base-case			Average μ / SD Performance in reference to base-case	
Untreated (base-case)	Could not be measured	0 / 1-3 sec	12.15 / 0.18	29.23 / 0.42	5.34 / 0.12	18.23 / 1.35	Low hydrophobicity, very quick absorption, good vapour transmission.
Acrylic-based liquid	113.5° / 5.07°	No obvious absorption after 20 min	6.89 / 2.02 -43.3%	10.08 / 2.66 -65.5%	3.25 / 0.05 -39.1%	18.89 / 0.80 +3.6%	Good hydrophobicity, low water resistance under intense rainfall, good vapour transmission. Comparatively less likely to trap water within the fabric to lead to moisture induced damage.
Silane/siloxane blend cream	102.8° / 10.33°	0-5 s on edge, 3 min in centre, 1 min between / 10-15 sec	0.30 / 0 -97.5%	0.23 / 0.01 -99.2%	0.20 / 0.01 -96.3%	21.5 / 1.32 +17.9%	Inconsistent performance in hydrophobicity due to difficulty of applying on small specimens, very effective liquid water absorption resistance, low vapour transmission.
Silane/siloxane blend liquid	91.9° / 8.81°	5-15 s / 1-3 min	0.27 / 0.03 -97.8%	0.22 / 0.02 -99.3%	3.45 / 0.16 -35.4%	23.41 / 2.48 +28.4%	Lowest surface water repellence, absorption results suggesting performance decay with time, lowest vapour transmission capacity indicating possible moisture trapping.
Stearate-based liquid	114.1° / 7.37°	No obvious absorption after 20 min	2.37 / 0.79 -80.5%	2.70 / 1.47 -90.8%	2.29 / 0.48 -57.1%	20.39 / 2.11 +11.8%	Good hydrophobicity can provide some resistance to liquid water ingress, low vapour transmission. Comparatively less likely to trap water within the fabric to lead to moisture induced damage.

3.4 Hygrothermal modelling review

Hygrothermal simulations can be used in moisture risk analysis to consider the effects of the external climate and occupant behaviour on the moisture balance of the building fabric. It is desirable to be able to rely on such modelling to assess the impact of energy efficiency retrofit interventions on existing constructions to avoid the potential for moisture accumulation and subsequent adverse consequences. However, as with all simulations, the outcome of each simulation largely depends on the representativeness of the input data used in the models.

Several methods for moisture risk analysis were identified and reviewed. Methods often consider average and worst-case scenarios. The accepted standard relating to hygrothermal simulations is BS EN 15026:2007. This relates to tools that consider one-dimensional moisture movements, with the most common being WUFI[4], developed by the Fraunhofer Institute, and Delphin[5], developed by the Dresden University of Technology. Simulations use building physics to model the combined heat and moisture transfer of a system subject to defined moisture loads, to estimate moisture levels within a building component. The standard describes the moisture transfer mechanisms and the necessary parameters to be considered in hygrothermal simulations.

Key inputs required include material properties (i.e. the resistance of a material to liquid transfer, vapour diffusion, heat conduction, etc.) along with indoor and outdoor moisture loads. There are currently limitations associated with each type of input parameter:

- There is little measured data relating to typical UK construction materials available for use in hygrothermal simulations. In particular, as was explored in the detailed wall analysis (Appendix A), the properties of bricks used in UK construction over time have varied considerably due to local availability of materials, enhancements in manufacturing techniques and quality control, which can vary their relative hygric properties. Research studies have identified that the porosity and thus water absorption of bricks is related to their strength and density, which is linked to the mineralogical composition of the brick and its firing temperature. Using average values can therefore lead to risks being over or underestimated in simulations.

- The influence of waterproofing treatments on hygrothermal properties is rarely available. In the literature, it has been considered in hygrothermal simulations by reducing the fraction of rain available for absorption, or reducing the absorption coefficient while increasing the vapour diffusion resistance factor of building materials. Also, the effectiveness of waterproofing treatments depends on several characteristics of the substrate that are not considered during laboratory measurements, such as the potential influence of contaminants absorbed into bricks due to air pollution, and the moisture content of the substrate during the application of the treatments, amongst other potential ABIS conditions. It is also acknowledged in manufacturer's literature that these products have a limited effective lifetime (for example, 5 or 10 years), but the change in overall hygrothermal performance over time has not been reported.

- Climate parameters used for analysis are typically for 'reference years' intended to represent weather conditions found at a location over a long period (either typical or worst-case scenarios) for the purposes of energy assessment. Not all weather stations collect all potential parameters needed for hygrothermal simulation, requiring the integration of data from different sources. The conditions measured at the closest station to the site of interest can substantially differ from the microclimate conditions to which the building of interest is subjected to. This can again lead to an over or underestimation of moisture risk, and that is before the potential impacts of future climate change are considered.

- Buildings can be subject to significant changes in occupancy and use. Internal boundary conditions are therefore typically selected for the most severe likely use.

It was found that the majority of moisture risks in insulated cavity walls were associated with ABIS conditions. It therefore follows that hygrothermal simulations for moisture risk analysis should consider these conditions. This is often done via an 'engineering' approach. According to the ASHRAE standard 160, 'Criteria for Moisture-Control Design Analysis in Buildings', adding 1% of the incident WDR load (by weight) could represent a 'best estimate' scenario for rainwater infiltration. Review of the available

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[4] WUFI® Pro 6.4 (2019), Fraunhofer Institute for Building Physics. Accessed: 30/04/2020 [Online] https://wufi.de/en/software/wufi-pro/

[5] DELPHIN 6 (2020), Bauklimatik Dresden. Accessed: 30/04/2020 [Online] http://www.bauklimatik-dresden.de/delphin/index.php

literature suggests this is a reasonable approach for walls with an outer brick leaf, but the sensitivity of the walls to rainwater infiltration should be verified considering rates between 0-10%.

3.5 WDR lab testing

Following the laboratory bench-scale testing (section 3.3), larger scale WDR testing was carried out on cavity wall samples in an untreated state and with two waterproofing treatments, with walls uninsulated then subsequently insulated with EPS beads. Various measurements were taken during the WDR testing, including monitoring RH and temperature using sensors embedded within the inner and outer wall leaves as shown earlier in Figure 1, to assess how moisture migrates through the walls, plus the assessment of absolute moisture uptake by weighing the wall samples using load cells.

3.5.1 Change in RH and temperature

3.5.1.1 Uninsulated tests

Figure 7 shows readings from within mortar and bricks in the external wall leaf, and within bricks in the inner wall leaf when the cavity wall samples were subjected to the 2-day WDR testing protocol. The charts include 2 untreated reference samples (A), 2 samples treated with the acrylic-based liquid product (B), and 2 samples treated with the silane/siloxane blend cream product (C). In each case, the RH within the sample is indicated in the top half of the chart (left axis) while the temperature is indicated in the bottom half of the chart (right axis).

In the first test pair (A1 and B1) two cycles of wettings were performed followed by an overnight conditioning period and a further set of eight wetting cycles.

In the second test pair (A2 and C1) during the overnight conditioning period, the outdoor chamber was shut down due to a power cut and this resulted in a temperature rise in the walls up to 30°C. Before starting the second day wetting, the temperature in the outdoor chamber was reconditioned down to 20°C. Two wetting cycles were then applied, at which point it was found that water had penetrated both walls and was present in the indoor chamber so the test was concluded.

For the third test pair (B2 and C2), since no reduction in humidity was observed in the outer leaf sensors after the overnight conditioning period, the external chamber was conditioned at 25°C, 50% RH for a further 4.5 hours. However, RH readings remained unchanged. Two wetting cycles were then performed. On untreated walls (A, orange and red lines in Figure 7), RH sensors in both brick and mortar on the outer leaf reached full saturation within the first 2 cycles of wetting and remained saturated to the end of the test.

On acrylic-based liquid treated samples (B, grey and yellow lines in Figure 7), water ingress into mortar joints on the external leaf was delayed by one wetting cycle. RH within the external mortar was 20% lower than that of the untreated walls after 2 cycles, while within bricks in the external leaf the RH was 25% lower than untreated in B1; B2 reached saturation after the initial two wetting cycles. After overnight conditioning and 8 cycles on the second day, RH values for the external leaf mortar joints in the B1-treated walls (grey) remained 6-8% lower than the untreated walls to the end of the test, while RH gain accelerated in external bricks after the first 4 cycles on the second day. This might be explained by potential reduction in the performance of the acrylic-based product due to the increased number of wetting cycles or duration of exposure to water, besides possible ABIS defects (i.e. microcracks) which were not visible to the naked eye. The final RH within the B treated external brick was 5% lower than that of bricks in the untreated walls.

The silane/siloxane blend cream treated walls (C, green and blue lines in Figure 7) did not show a reduced RH increase in either mortar or brick in the external wall leaf throughout the test. The start of water ingress was delayed by one cycle in the brick, but the behaviour of the mortar was very similar to the untreated external wall leaf. Saturation was reached very quickly in both wall samples after 2 cycles on the second day, at which point the test was concluded.

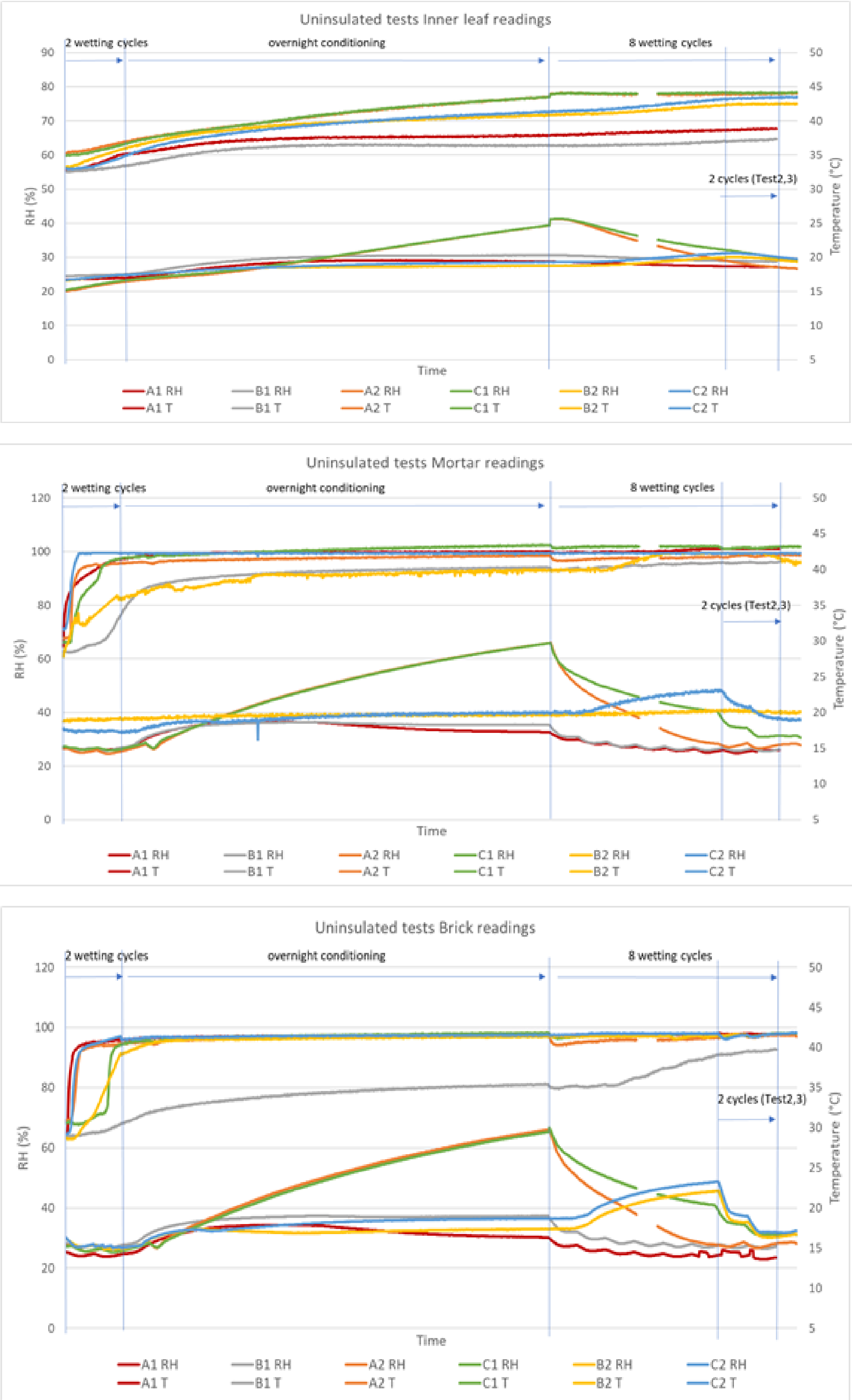

Figure 7: RH and temperature variation in outer leaf mortar and brick, and inner leaf brick in **uninsulated** walls

Due to the inner leaf of the walls having no direct contact to the wind driven rain, the change in RH at the inner leaf is a result of water vapour migrating across the air cavity. RH increases are much reduced compared to the external leaf and more gradual across all samples. There are no obvious trends in RH levels between the treated and untreated samples evident within the inner leaf, with all increasing to some extent in the range 10-20% (Figure 7).

The temperature sensors in the outer leaf show variations caused by the presence of water in the pore network of the walls. The temperature reduces with the number of wetting cycles and reflects the uptake of moisture. The temperature profiles across the uninsulated walls and their respective sensor locations were not straightforward to compare due to the differences in test regime described above compared to the originally proposed 'standard' sequence of 2 wetting cycles with the external chamber at 15°C, overnight conditioning with the external chamber at 20°C, followed by a further 8 wetting cycles with the external chamber at 15°C. Consequently, behaviour is most similar in pairs of samples that were tested together.

By the end of the testing, the temperature in the B1 and C1 treated samples were 1-2°C higher in both internal and external leaf brick sensors than their respective reference samples, A1 and A2. For B2 and C2 tested together, C2 retains a marginally higher temperature compared to B2 (1-2°C over the duration of the testing). In the external leaf mortar sensors, there is no temperature difference between B1 and its paired reference A1 by the end of the test, while C1 mortar shows a 2°C temperature increase compared to its paired reference A2. Overall, the temperature measurements suggest the treated bricks experience less in-wall temperature reduction from the action of external wetting than the untreated bricks, despite most walls becoming saturated over the duration of the WDR testing. Temperature reductions are less evident in mortar with treatment B than treatment C.

It is worth noting that, defects in the sealing of the cavity space in the test of uninsulated walls A1 and B1 led to possible unintended air infiltration into the cavity. This was reflected in fluctuations of relative humidity within the cavity (particularly during the initial dry period). While this may have caused local effects on the measurements in the cavity, no obvious anomalies were noticed in other measurements (e.g. U-value).

3.5.1.2 Insulated tests

Figure 8 shows equivalent charts to Figure 7, with results of the 2 reference samples (A), 2 samples treated with the acrylic-based liquid product (B), and 2 samples treated with the silane blend cream product (C) after they have been insulated with EPS beads.

For all samples, two cycles of wettings were performed followed by an overnight conditioning period and a further set of eight wetting cycles.

In the insulated wall tests, untreated walls maintained a behaviour consistent with the uninsulated case (A, orange and red lines in Figure 8). Both brick and mortar in the external leaf of the test walls quickly became fully saturated after the first 2 wetting cycles and remained so throughout the test. However, treated walls showed a more pronounced improvement in performance when comparing the insulated tests to the uninsulated tests.

For the acrylic-based liquid treated samples (B, grey and yellow lines in Figure 8), RH measurements in both mortar and bricks in the external leaf did not increase so significantly in the first two wetting cycles and the overall RH levels were 30% lower than the fully saturated untreated walls. After overnight conditioning and 8 wetting cycles on the second day, B-treated walls generally maintained 20% lower RH in the external leaf compared to the untreated walls. However, the B-treated bricks in the external leaf experienced increasing RH with every wetting cycle, resulting in a significant increase in the RH in B2 by the end of the second day of testing.

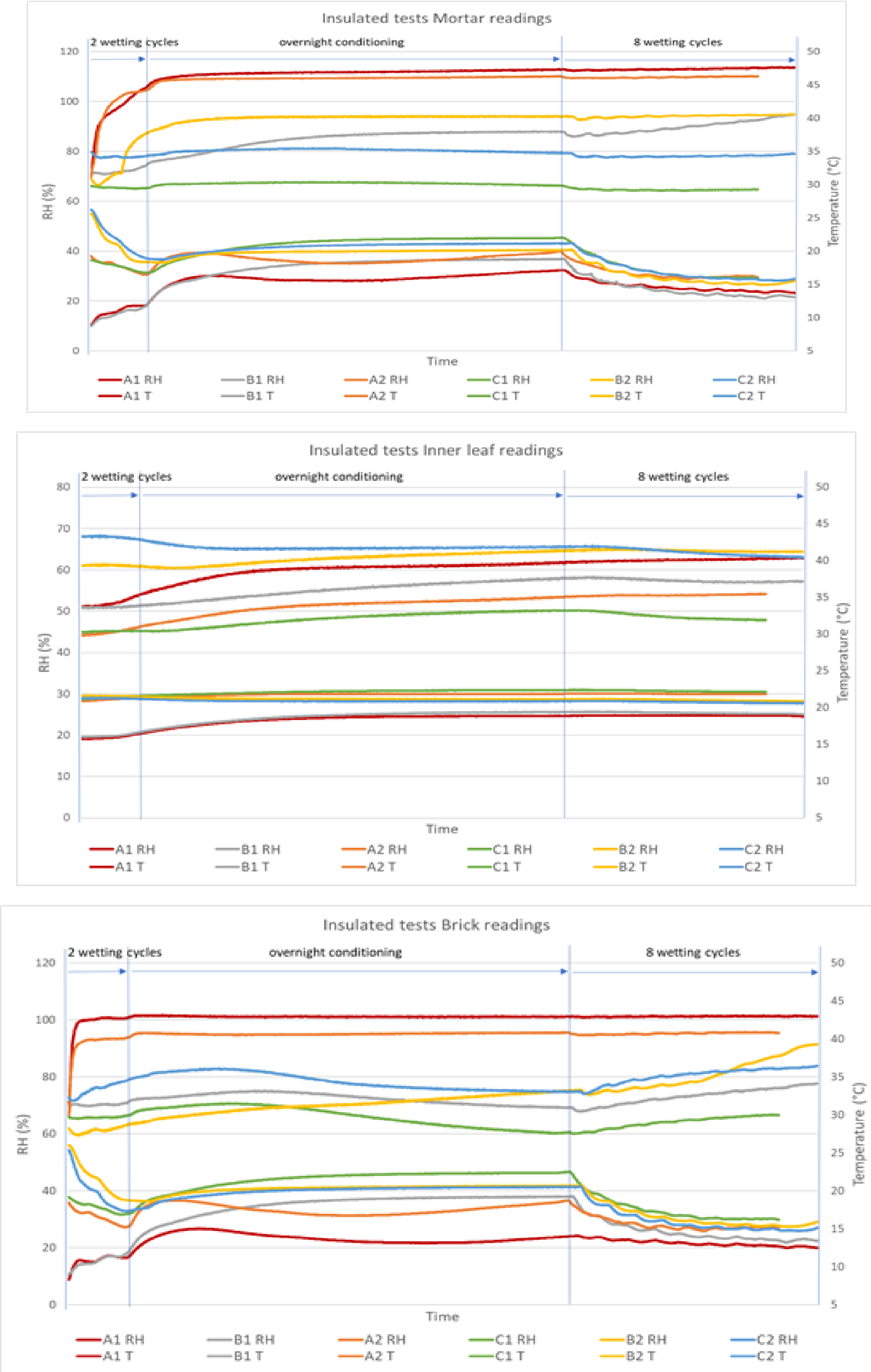

Figure 8: RH and temperature variation in outer wall mortar and brick, and inner leaf brick in **insulated** walls

The silane/siloxane blend cream treated walls (C, green and blue lines in Figure 8) significantly improved in performance when insulated, with no obvious RH gain in the external leaf mortar throughout the test and only a 6% increase within the external leaf bricks during the 8 wetting cycles on the second day. RH readings of C-treated walls were 45% lower in mortar and 30% lower in bricks compared to the untreated walls at the end of the test. This significant improvement between the insulated and uninsulated C-treated walls might indicate that the waterproofing capability improves over time and/ or with exposure to high levels of moisture, as experienced during the first round of testing when uninsulated. However, this hypothesis should be further investigated.

The behaviour of the temperature and RH within the inner wall leaf when walls are insulated is distinctly different to when the walls were uninsulated; there appears to be no direct link between the behaviours in the inner and outer wall leaves, suggesting the presence of the insulation fundamentally changes the moisture transfer mechanisms. A 10% RH increase is experienced in the internal leaf bricks of the untreated walls, A, by the end of the test, whereas the B-treated walls increase by only approximately 5%. Due to shorter drying times following the uninsulated testing for walls B2 and C2, their RH is higher within the inner leaf at the beginning of the test compared to all other samples tested. This meant that treated wall C2 experienced an overall RH drop within the inner leaf bricks over the course of the testing, while the B2 inner brick leaf showed an initial RH drop during the first 2 wetting cycles, followed by an RH increase of approximately 5% during the overnight conditioning period, which was maintained over the subsequent 8 wetting cycles on the second day.

As with the uninsulated test cases, the temperature sensors in the outer leaf show variations caused by the water dispersion on the walls. The temperature reduces with the number of wetting cycles and reflects the uptake of moisture. The treated walls B and C generally show higher temperatures in the external wall leaf compared to the untreated walls, A, during the overnight conditioning period, with the difference narrowing by the end of the test. Within the inner wall leaf, the treated walls remain 1-2°C warmer than the untreated walls over the duration of the testing.

As with the uninsulated cases, the temperature measurements again suggest the treated bricks experience less in-wall temperature reduction from the action of external wetting than the untreated bricks.

3.5.2 Moisture uptake/ weight gain measured via load cells

Load cell readings are reported here for the **insulated** test cases only (Figure 9), since unfortunately the load cells did not work correctly during the uninsulated test cases. The results indicate the amount of water the test walls absorbed during the WDR test and are separately reported for the inner and outer wall leaves in each case.

- The untreated walls, A, are represented by the red and orange lines in the charts
- The acrylic-based liquid treated walls, B, are represented by the green and yellow lines in the charts
- The silane/siloxane blend cream treated walls, C, are represented by the dark and light blue lines in the charts

An obvious weight gain is observed during the first 2 wetting cycles of both wall leaves in the untreated samples, A (red and orange lines). This further increased during the 8 subsequent wetting cycles the following day. Over the course of the test, the outer leaves gained between 16.5-20.0 kg of water, while the inner leaves gained 7-10 kg.

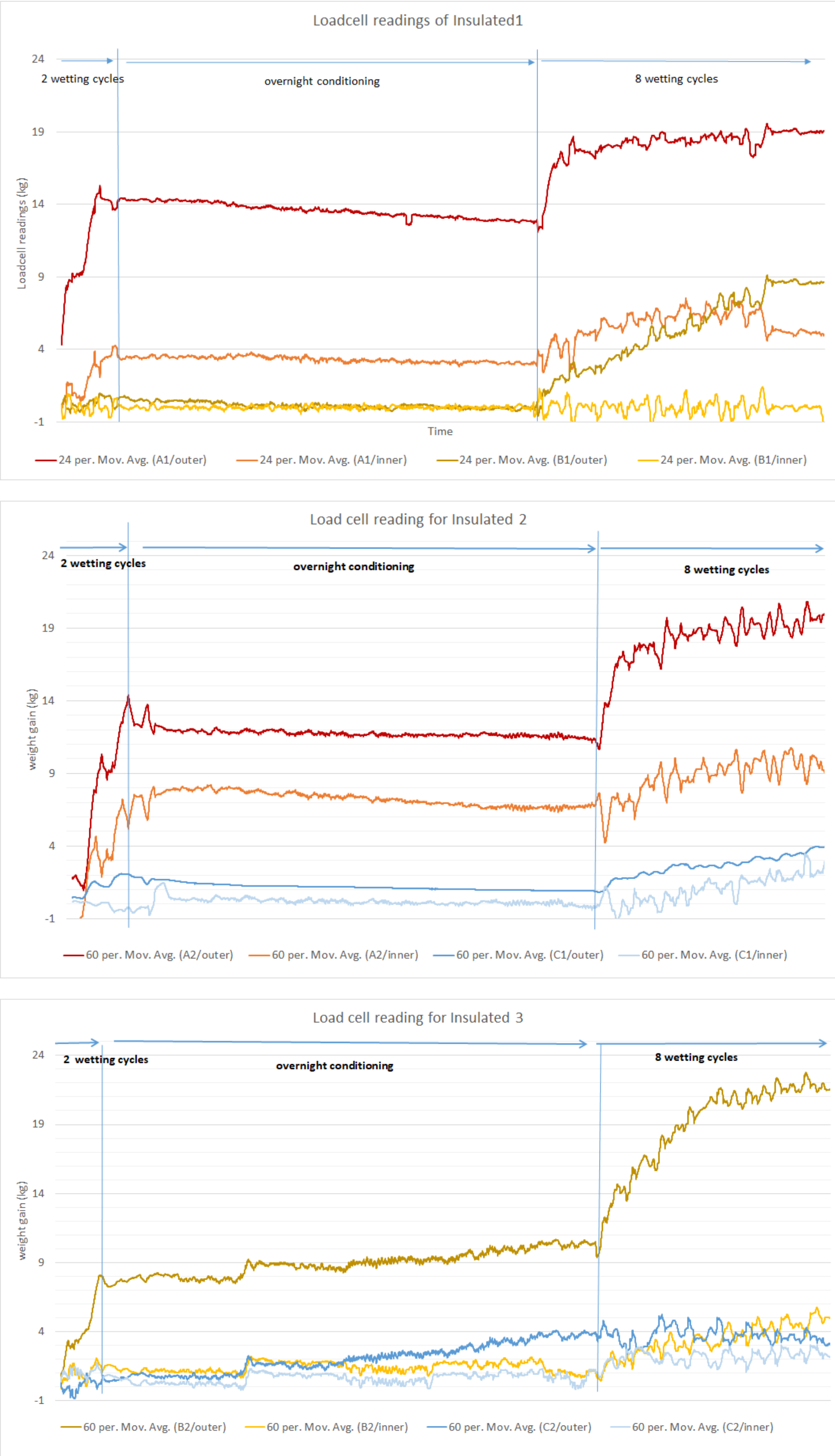

Figure 9: Load cell weight gain of outer and inner wall leaves in **insulated** walls

The B-treated walls showed varying weight gain between samples, with B1 experiencing a relatively modest gain of 8 kg in the outer leaf over the course of the test and no appreciable gain at the inner leaf, while B2 experienced a more significant gain of 18 kg in the outer wall leaf and 5 kg at the inner leaf.

The C-treated samples show limited weight gain in the outer leaves of up to 5 kg, and up to 2 kg in the inner leaves.

These trends are in line with the earlier findings from the absorption testing (Section 3.3.3), where the untreated samples showed the most significant weight gain, the acrylic-based liquid treated (B) samples showed an intermediate weight gain and with the most variability between samples, while the silane/siloxane blend cream treated (C) samples showed virtually no weight gain.

3.6 U-value testing

The main purpose of U-value testing the sample walls in both a dry and wet condition was to assess if the application of waterproofing treatment would help to improve the overall thermal performance. (Note that lower U-values represent improved thermal resistance).

3.6.1 Uninsulated walls

Figure 10 shows the U-values obtained for uninsulated wall samples in both dry and wet conditions, along with the associated systematic measurement error of the testing. The U-values were consistently lower in dry conditions than in wet conditions for all samples, although within the margin of the error. U-values in the untreated walls (walls A) ranged from 1.26-1.46 W/m²K in dry conditions and 1.54-1.76 W/m²K in wet conditions. The samples treated with the two different types of waterproofing treatment (walls B and C respectively) showed a similar thermophysical behaviour to the untreated walls, with U-values in the range 1.06-1.49 W/m²K in dry conditions and 1.28-1.67 W/m²K in wet conditions. The percentage U-value difference between wet and dry conditions was larger for untreated walls (between 17% and 24%) compared to the treated walls (between 7% and 15%).

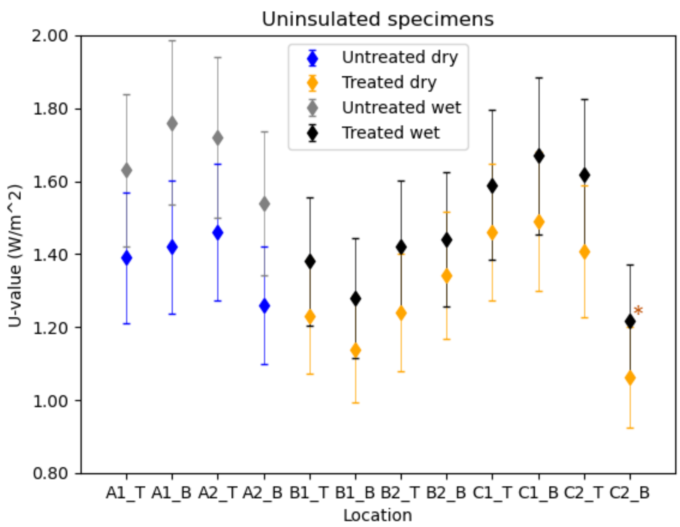

Figure 10: U-values for uninsulated untreated (walls A) and treated (walls B and C) wall samples

3.6.2 Insulated walls

Figure 11 shows the U-values obtained for walls insulated with EPS beads in both dry and wet conditions, along with the associated systematic measurement error of the testing. As would be expected, all U-values are significantly reduced when the walls are insulated. U-values in the untreated walls (walls A) again showed a distinct increase from dry to wet conditions, ranging from 0.30-0.38 W/m²K in dry conditions and 0.38-0.51 W/m²K in wet conditions. Conversely, the samples treated with two different types of waterproofing treatment (walls B and C respectively) showed a minimal change, with U-values in the range 0.31-0.40 W/m²K in dry conditions and 0.30-0.40 W/m²K in wet conditions. The percentage U-value difference between wet and dry conditions was notably larger for untreated walls (around 31%) compared to the treated walls (between 0% and 5%).

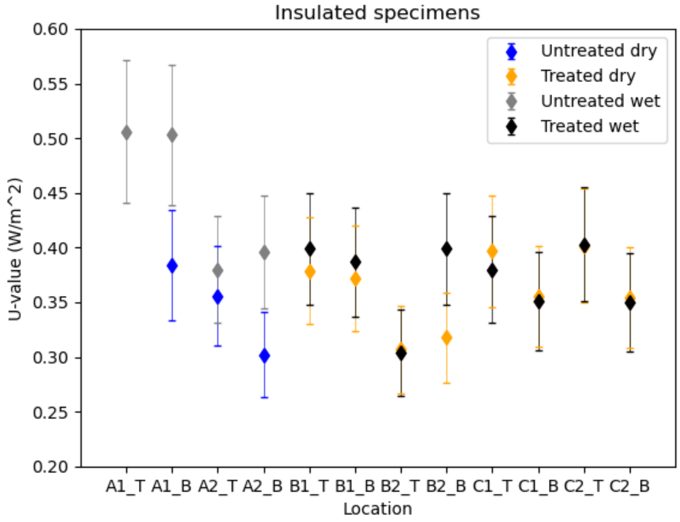

Figure 11: U-values for insulated untreated (walls A) and treated (walls B and C) wall samples

The waterproofing treatments in combination with CWI appear to have a more notable beneficial effect in reducing U-value variation between dry and wet conditions than in the uninsulated cases. This is likely to be in part a function of how the heat and moisture transfer across the whole wall is changed by the presence of the insulation.

Although 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, 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.

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

U-value estimates for treated and untreated walls in insulated and uninsulated configurations (Figures 10 and 11) 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-value for uninsulated untreated (walls A in Figure 10) and uninsulated treated (walls B and C in Figure 10), while the effect of cavity wall insulation alone can be assessed by comparing uninsulated and insulated untreated wet walls (walls A in Figures 10 and 11 respectively). From the first comparison, it can be observed that the U-value drops on average from 1.66 W/(m2K) to 1.45 W/(m2K); conversely, in the second comparison the U-value drops on average from 1.66 W/(m2K) to 0.45 W/(m2K). 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 and therefore these treatments cannot be considered as an energy efficiency measure in their own right.

3.7 Hygrothermal modelling

3.7.1 Comparative analysis of example bricks

Hygrothermal modelling software tools tend to include an in-built database of material properties for use in simulations. However, it is known that the properties of bricks can vary significantly depending on their composition, manufacturing technique, etc. To assess the variability that could be introduced into simulation modelling depending on the selection of brick characteristics, a comparative analysis was conducted using various brick entries available in the Delphin software database while imposing equivalent boundary conditions to those measured throughout the duration of the laboratory testing, considering both U-value and WDR testing. 2 wetting cycles followed by overnight conditioning then 8 further wetting cycles.

Figure 13 indicates that bricks 1, 1a, 2, 4 and 6 (in blue) show a fast uptake, some with a more marked reduction during the dry period occurring overnight after the first 2 wetting cycles. Similar behaviour is found for bricks 3 and 5 (in green). Meanwhile, lime-sand bricks represented by 8, 9 and 10 (in orange) showed a very different behaviour under wetting, characterised by a slow or no uptake. However, another 'lime-sand brick', number 7 (in yellow), shows the fastest uptake of other bricks. This initial analysis emphasises the importance of knowing the type, or *cluster,* that a particular brick belongs to. In new buildings, it is possible to identify the right cluster by looking at product datasheets, although not all datasheets contain relevant hygrothermal properties that could be used for this purpose. In existing buildings, identifying the correct cluster is more difficult due to the lack of information historically available on the bricks used.

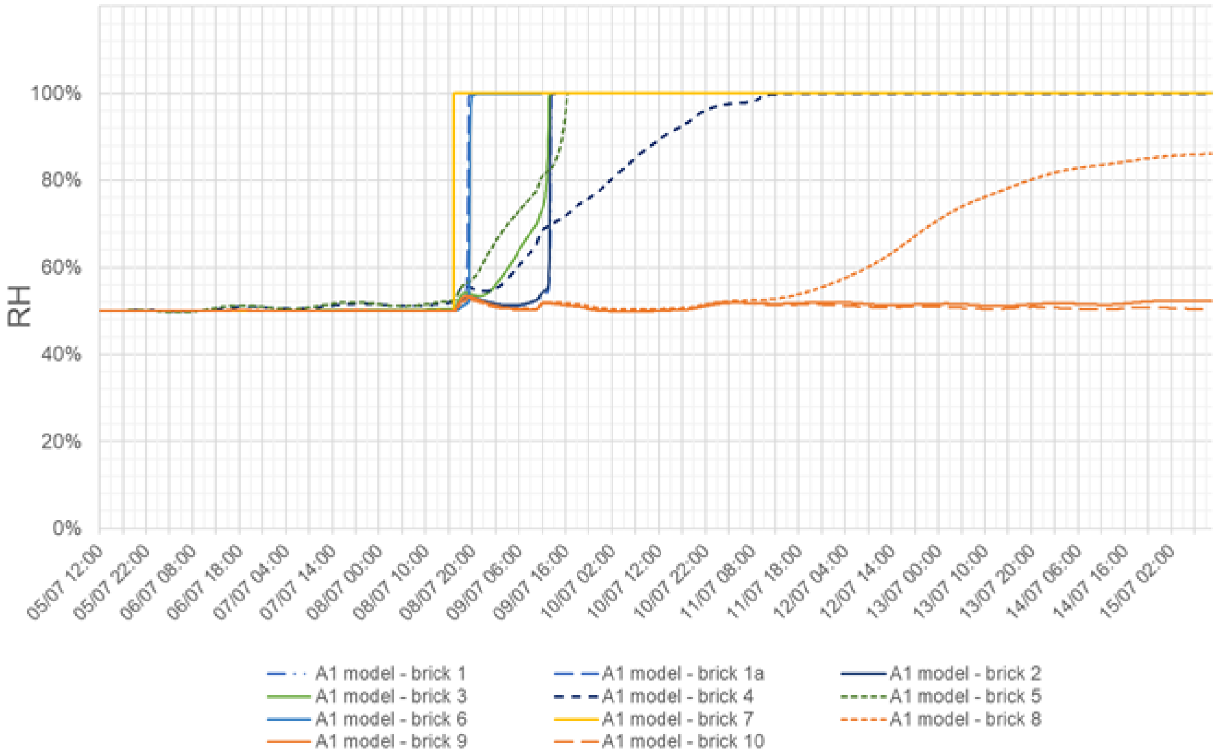

Figure 13: Simulated RH behind an external wall leaf, assuming untreated bricks from the Delphin software

3.7.2 Direct simulation comparisons with uninsulated wall samples

3.7.2.1 Untreated wall

Figure 14 compares the laboratory measurements with model predictions using 3 example bricks with most closely represented properties to the bricks' datasheet and integrating the material properties measured in the laboratory bench testing. The model predictions for the three similar bricks show an increase of relative humidity up to 100% at the (internal surface of the) external leaf during wetting, in agreement with the experimental results for untreated brick. Also, the model predicted an increase in RH at the internal leaf, in line with experimental results. However, this increase was higher than observed in the experimental results for the three similar bricks considered. Moreover, the speed of moisture uptake is different among the similar bricks and it is not possible to identify what brick best represents the laboratory behaviour.

During wetting, the experimental results show variability in water accumulation at various locations of the wall (i.e. the top and bottom of the wall), which cannot be captured by deterministic hygrothermal modelling; this is expected and in agreement with other studies.

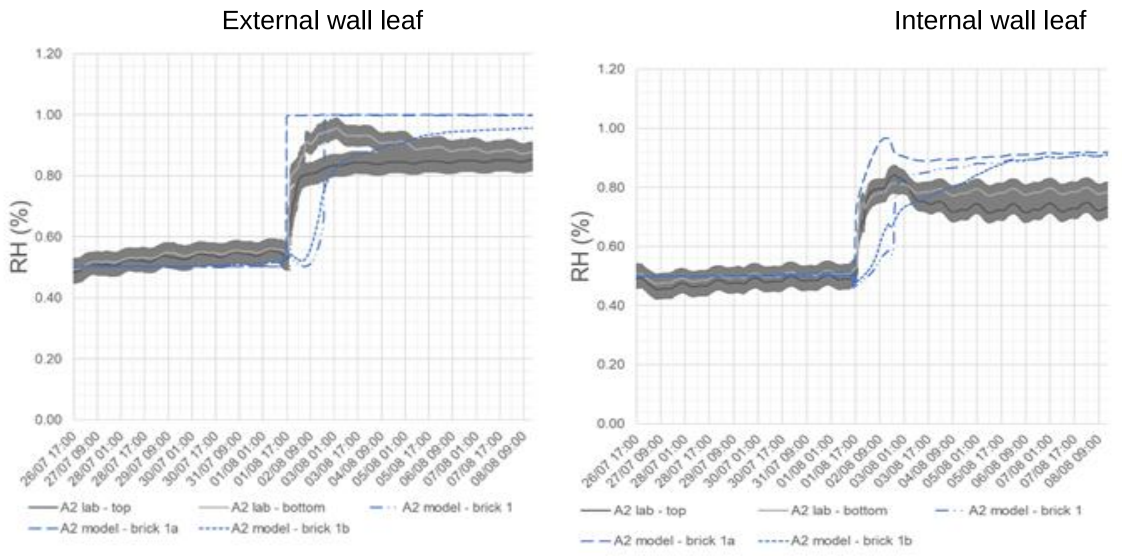

Figure 14: Model predictions (dashed lines) versus laboratory measurements (solid lines, with ±3.5% declared RH measurement error) of RH behind the external wall leaf (left), and internal wall leaf (right), assuming untreated bricks in an uninsulated wall

3.7.2.2 Treated walls

Although four treated wall samples were tested (2 walls x 2 treatments), only one is presented here as an example. The individual performance of the treated laboratory wall samples varied between the treatment types and was explained in more detail in section 3.5 on WDR testing and section 3.6 on U-value testing. However, the overall findings relating the hygrothermal modelling results to the laboratory measurements are similar in all cases and are reported fully in Appendix G.

The material properties assumed for the treated bricks in the simulation models were taken from the bench testing results (section 3.3). Despite this, Figure 15 shows that there is a substantial deviation between the modelled behaviour and the laboratory measurements. Hygrothermal modelling showed little to no uptake in moisture over time as a result of the treatment, whereas in practice, the laboratory samples did experience an increase in RH. This was witnessed with all treated wall scenarios.

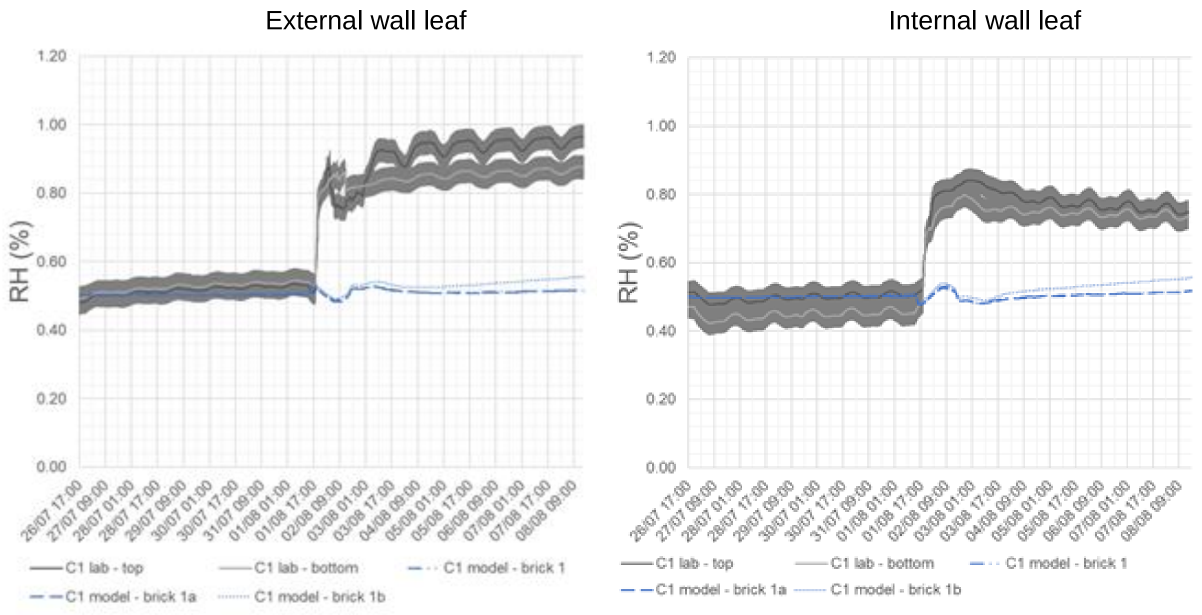

Figure 15: Model predictions (dashed lines) versus laboratory measurements (solid lines, with ±3.5% declared RH measurement error) of RH behind the external wall leaf (left), and internal wall leaf (right), assuming treated bricks in an uninsulated wall

3.7.3 *Direct simulation comparisons with insulated wall samples*

3.7.3.1 Untreated wall

The results in Figure 16 that the insulation offers some protection to the inner brick leaf compared to the uninsulated case in Figure 14, although the model prediction implies there should be virtually no change in RH whereas some increase is experienced in the laboratory samples. By contrast, the behaviour of the external leaf is similar between the model predictions and the laboratory measurements.

External wall leaf | Internal wall leaf

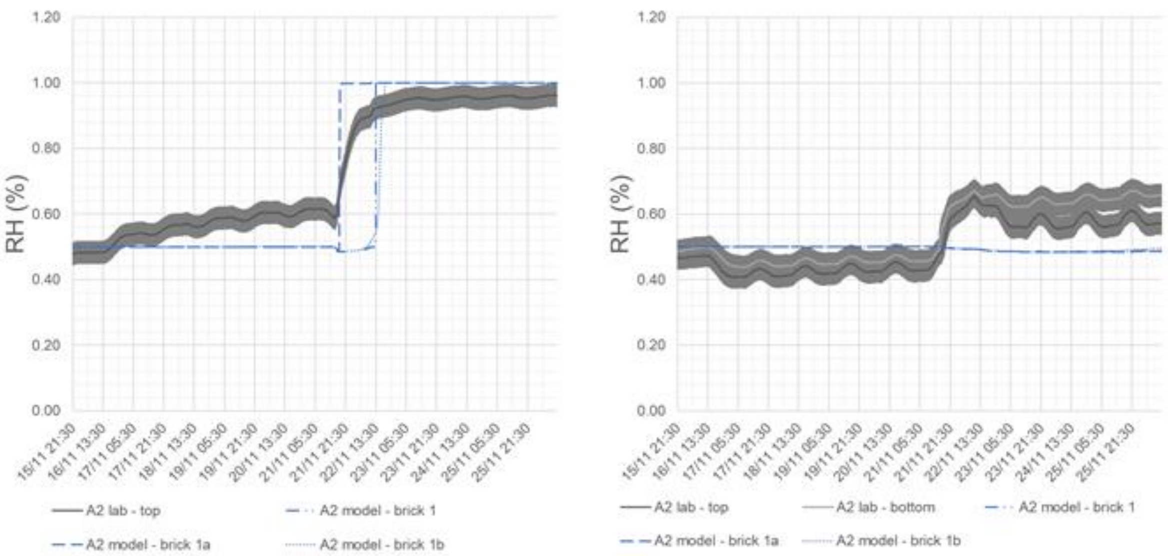

Figure 16: Model predictions (dashed lines) versus laboratory measurements (solid lines, with ±3.5% declared RH measurement error) of RH behind the external wall leaf (left), and internal wall leaf (right), assuming untreated bricks in an insulated wall

3.7.3.2 Treated walls

As with the uninsulated treated samples, the material properties assumed for the treated bricks in the simulation models were taken from the bench testing results (section 3.3), and only one example wall treatment is presented here. Figure 17 shows that there is a substantial deviation between the modelled behaviour and the laboratory measurements for the treated walls. Simulations showed little to no uptake in moisture over time as a result of the treatment, whereas in practice, the laboratory samples did experience an increase in RH. This was witnessed with all treated wall scenarios (Appendix G).

External wall leaf | Internal wall leaf

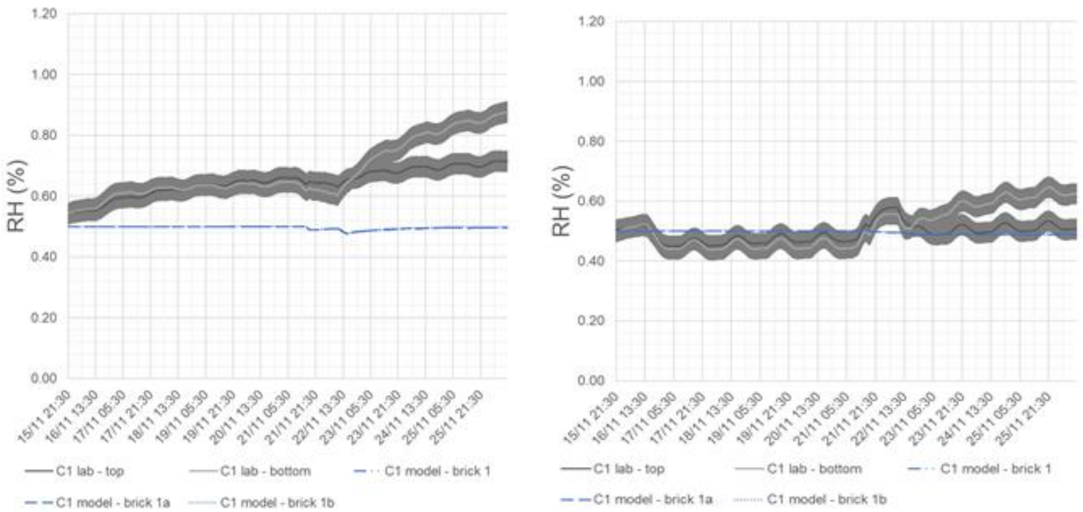

Figure 17: Model predictions (dashed lines) versus laboratory measurements (solid lines, with ±3.5% declared RH measurement error) of RH behind the external wall leaf (left), and internal wall leaf (right), assuming untreated bricks in an insulated wall

3.7.4 Summary of simulation model comparisons

In the untreated case, it was possible, knowing some basic properties of the brick, to perform hygrothermal simulations that were fairly representative of the behaviour of the laboratory wall assemblies. However, when bench testing samples were treated with waterproofing products, the measured absorptivity of materials was not representative of the behaviour of the laboratory wall assemblies.

The water absorption coefficients measured respectively for bricks, mortar and the combination of brick and mortar (section 3.3.3), reveal a value that is too low: the simulations suggest there should be little to no water uptake, but the laboratory results show some uptake. This suggests that the moisture behaviour is not governed by the material properties themselves in these cases, but by the properties at the interface between building materials and by the hairline cracks formed within the actual walls.

The model, representing As Designed, Theoretical (ADT) conditions, was unable to satisfactorily replicate the tests in the climate chamber. The results suggest that the hygrothermal behaviour of the cavity wall might be influenced by moisture transfer mechanisms other than the ones considered in the hygrothermal simulations, i.e. the mechanisms related to As Built, In Service (ABIS) conditions such as water infiltration. These findings agree with the literature (Appendix D) and the modes of failure (Appendix A) identified on site, which showed that failure is due to ABIS conditions. As a result, this analysis shows that the values of absorption provided in the software libraries, would not be sufficient for the description of the behaviour of walls treated with waterproofing agents.

'Engineering approaches' assuming a certain percentage of WDR will penetrate the wall might be an appropriate way for considering the influence of water infiltration and such techniques are increasingly used in the literature. However, as indicated in section 3.4, there are no exact parameters for such techniques that can reliably simulate given ABIS conditions.

3.8 Site testing

Since the project aimed to assess the suitability and effectiveness of waterproofing treatments readily available on the market for brick-faced cavity walls in high exposure conditions, it was essential that properties located in exposure zones 3 or 4 (according to BS 8104) were identified that were constructed of facing brickwork, either fully or substantially. Only properties with full facing brickwork or half rendered/ half facing brickwork, and in good condition were selected for an internal inspection of the cavity to then, if suitable, be considered for the waterproofing treatment stage.

Figure 18: Examples of faults identified in facing brickwork: Left – Eroded mortar beds, Right – Saturated bricks caused by erosion or face damage

The first main observation when surveying the potential property locations was that full facing brickwork in exposed locations was not typical, or in significant numbers; the majority of properties were fully or partially rendered. Closer inspection of the condition of the external walls identified high levels of cracking and defects. Some exploratory work was undertaken, including the use of an infrared camera to identify underlying faults or cracks that would preclude their suitability for the study. Some examples are shown in

Figure 18. Other identified issues included cavities that were blocked at the base with debris, cavity trays not in place or damaged, and seals around windows in poor condition or absent.

For any application of waterproofing treatment, it is essential that the condition of the external facade is in a sufficiently good condition to allow the treatment to have any chance of reducing the risk of moisture penetration (as per manufacturers guidance). The site investigation work suggests that cavity wall constructions in the UK – particularly those of facing brickwork rather than rendered – are unlikely to be of sufficiently good condition to expect such treatments to offer the intended reduced risk of moisture penetration.

If any of the properties identified during the site investigations were to be tested with waterproofing treatments, it would not be possible to determine whether any failure was due to the treatment itself or a result of potentially multiple other failure routes. The proposed site trails of waterproofing treatments were therefore abandoned as they would not offer any additional insights compared to the laboratory testing. It would be essential that detailed and rigorous surveys were undertaken on any property where these waterproofing treatments were being considered and any defects rectified before application, so they are not undermined by underlying faults within the wall.

3.9 Stock modelling – approach to determining the scale of potentially relevant dwellings

Stock modelling using two forms of regression analysis focused on using readily available features from the NEED and EPC databases and using EHS data to predict the probability of buildings having brick finished (masonry pointed) cavity walls.

Logistic regression found that many data variables had low predictive power to estimate the probability of a cavity wall construction having a masonry pointed wall; only ‘dwelling age’ and ‘government office region’ were shown to have any significant predictive power. Dwellings built between 1919 to 1944 were deemed most likely to have masonry pointed walls, as did those in London, the south-east and the north-west. This supports the expectation that dwellings in severe and very severe exposure zones are more likely to have some form of wall covering (e.g. render) to provide additional protection rather than only masonry pointing.

The analysis was therefore re-run using only the western regions of England, i.e. those areas with greater moisture severity, to determine whether features of buildings would help predict exposed brick walls. The results showed that as dwelling age increased compared to 1919-1944 dwellings, so did the probability of a cavity wall being masonry pointed. However, most properties built before 1919 are likely to be of solid brick construction, and those noted as having a cavity may not be a ‘true’ cavity wall that would be suitable for insulating. That is not to say that they may not be candidates for waterproofing treatments, but such walls are out of the scope of this study, which focusses on cavity walls that could potentially be retrofitted with insulation if not restricted by exposure.

Dwellings in EPC bands C to E had a higher probability of a cavity wall being masonry pointed than those in band F. Properties with higher EPC scores (i.e. C and D) are more likely to already have insulated cavity walls in order to achieve this level of energy performance, and in the case of more modern dwellings, are likely to have been constructed with an adequate residual cavity adjacent to the insulation rather than being fully filled so as to avoid the risk of moisture ingress on brick-finished walls. Many of these dwellings are therefore unlikely to be candidates for additional insulation or waterproofing treatments. Those of EPC bands E and F are likely to be more relevant.

The generalised linear regression and LASSO selection method offered a slightly improved statistical fit compared to the logistic regression and offered additional variables that have explanatory power when estimating the probability of a cavity wall having facing brickwork. Dwellings built after 1965 and in mid and north-eastern government regions tended to have increased likelihood of exposed brick masonry pointed walls. As with the logistic regression, the analysis was re-run using only the western regions of England. Results showed that dwellings built after 1990 and with an EPC band of C in the west midlands and in urban areas larger than 10,000 units were more likely to have brick finished walls, while those built before 1964 and in the south-west were less likely to have brick finished walls. This generally agrees with the findings from the logistic regression; the dwellings identified as most likely to have a brick finish cavity wall are most likely already insulated and would not be candidates for waterproofing treatments.

The stock modelling results, and the variables identified within, can be used to identify properties whose features would suggest a higher probability of having a wall type that warrants further investigation. While the overall model predictive power was low, both the logistic and LASSO regression identified variables that were significantly associated with wall types of concern. These variables could be used to filter NEED properties and EPC data to add a wall features flag.

The following variables could therefore be filtered to identify properties with a likelihood of having exposed brick walls:

Identified variables:

- Dwelling age: 1919 to 1944, 1945 to 1964, post-1990
- EPC Band: C
- Region: South West, West Midlands
- Loft insulation thickness: none
- Rurality classification: urban > 10k

From the GIS shape files produced of the WDR exposure zones, Figure 19 shows an example of buildings in England within the Geofabrik database located in exposure zone 2 (i.e. Moderate exposure).

Since BEIS have access to geo-referenced NEED data, it will be possible for BEIS to similarly apply the GIS exposure zones to pre-sorted NEED data, based on the predictive modelling outlined above, to identify properties and locations where the waterproofing treatments may be relevant, then filtered to exclude any properties already recorded as being insulated. However, this could not be done as part of this research since geo-referenced NEED data was not available.

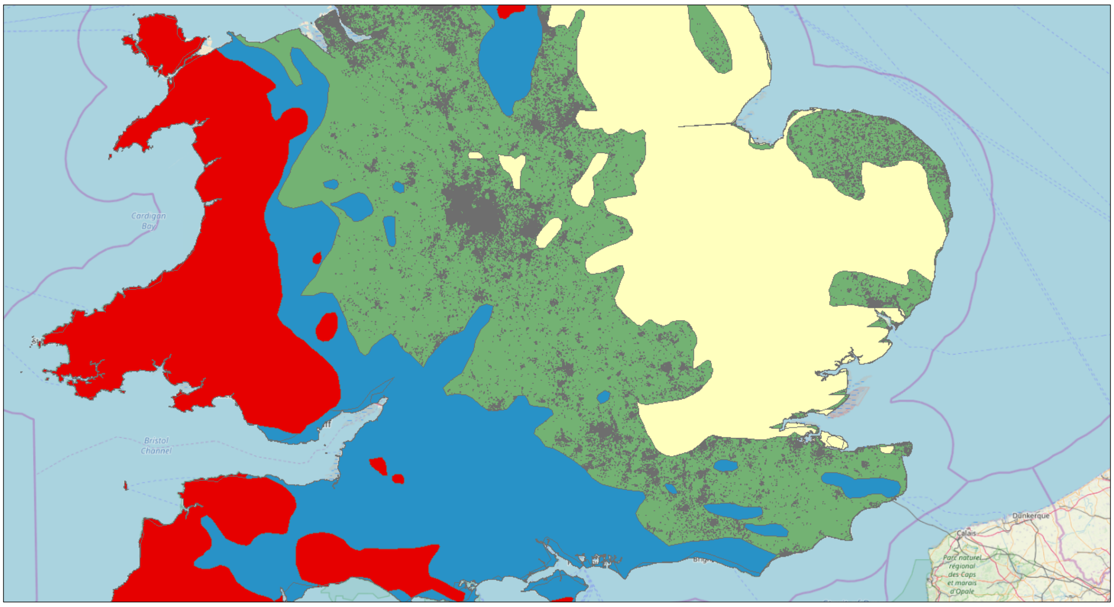

Figure 19: Buildings in England (grey, from Geofabrik database) located in exposure zone 2 (green zone)

4 Discussion of findings

A number of research questions were proposed at the outset of the project. These are addressed here based on the findings of the research.

1. Under what exposure conditions does waterproofing keep CWI dry?

WDR testing has simulated very severe exposure conditions on untreated and treated cavity wall samples, in both uninsulated and insulated states. It has consistently shown that waterproofing treatments reduce moisture uptake more in the external leaves of cavity wall samples that are insulated than in uninsulated wall samples. This may in part be a function of how the heat and moisture transfer across the whole wall is changed by the presence of the insulation. The resistance to moisture ingress varied between the waterproofing treatments tested. For one of the treatments, the performance was so markedly different between the uninsulated and insulated scenarios, that it has led to the hypothesis that the product performance may improve with extended curing time (since the insulated tests were carried out after the uninsulated tests) or improves after initial exposure to moisture (or indeed both). This is however only based on a very small number of samples, and further testing would be required to confirm or dispute this behaviour.

In general, both treatments tested tend to cause a delay in the onset of moisture uptake in the earliest wetting cycles, suggesting they may be more effective at lower levels of exposure than at the most severe levels represented by the additional wetting cycles.

2. How do such treatments affect the permeability of the wall, and do they cause problems by trapping moisture (including from sources other than rain) in the wall? (e.g. How well can waterproofed cavity wall insulation and thermophysical performance recover from moisture ingress following masonry drying out?)

There is no evidence from the testing that the waterproofing treatments assessed ‘trap’ moisture within the wall, although the WDR testing was not explicitly set up to assess drying behaviour.

3. What are the adverse impacts on the integrity of the wall (using accelerated aging techniques if necessary), particularly the external leaf, following waterproofing and the installation of CWI?

During the WDR testing, no adverse impacts on the integrity of the walls were observed in samples that had received waterproofing treatment. This was the case for both uninsulated and insulated walls. Although the WDR testing has simulated very severe exposure conditions over a number of simulated wetting cycles, it does not represent the long-term experience of a wall over many years, nor the effects of solar exposure or freeze/thaw that may be expected over extended periods of time, nor the impact of other ABIS conditions. Unfortunately, such testing was not possible within the scale of the testing programme.

4. What is the potential of both waterproofing as an insulant in its own right, and waterproofing plus CWI, in exposed areas in the UK, using measurements of the U-values of: a. A wet uninsulated cavity wall, b. A dry uninsulated cavity wall, i.e. following waterproofing, c. A dry insulated cavity wall.

From the U-value tests carried out on uninsulated sheltered (dry) and exposed (wet) walls, results from different test samples fall within each other’s error margins, with some treated samples having higher U-values and some lower than the untreated walls. There is, therefore, no evidence that treated walls perform better thermally than untreated walls and thus no suggestion that the waterproofing treatments could act as insulants in their own right.

When waterproofing treatments are applied to insulated wall samples, the situation is similar in the sheltered (dry) state, with some treated samples having higher U-values and some lower than the untreated walls. When treated insulated walls are wetted, their U-values generally deviate less from the dry U-values than is the case with untreated walls (varying between 0-5% treated compared to approximately 31% untreated), suggesting that the treatments in combination with CWI may help to preserve the thermal performance of the insulated wall. However, this 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.

5. For a given wall type, is there a significant variation in the U-value for different exposure levels?

This study has effectively tested the U-values of wall samples at opposite extremes of the exposure spectrum, with dry walls representing sheltered conditions, through to cyclically wetted walls representing very severe exposure conditions. The measurements at these extremes generally show a systematically lower U-value when walls are dryer (i.e. sheltered/ low exposure) than when they are wet, although this difference is narrowed in the case of treated, insulated walls. However, despite this observable trend, the dry (sheltered) and wet (exposed) U-values fall within each other's error margins, hence the difference cannot be deemed significant, but instead within the variability of testing.

6. Establish a best practice in waterproofing treatment applications to maximise the effectiveness and minimise risks in CWI in exposed areas.

For the laboratory testing, the waterproofing treatments were applied in line with the manufacturers' instructions so far as possible. In the case of smaller bench test scale samples, there was some evidence from the testing that the application of the treatment was disproportionate across the sample surfaces, with the centre of samples ultimately receiving a higher dose of the treatment than the edge of samples due to the size of the roller used for the application, resulting in some doubling up of passes in the centre. The application appeared somewhat more consistent in the larger scale WDR samples. Ensuring the minimum recommended product application across the whole wall surface will be important to ensure consistent behaviour of the treatments.

Attention is however drawn to the observations from site investigations of brick-faced dwellings (research question 9), which identified numerous ABIS conditions in practice, such as cracking and degradation of mortar beds. Even best practice application of waterproofing treatments in these cases could not be expected to overcome the elevated risk that such conditions pose to moisture ingress in cavity walls.

7. How accurate is moisture risk modelling in the UK? How could existing hygrothermal models be improved?

This research has allowed hygrothermal modelling simulation to be directly compared with results from laboratory testing. It has also been possible to use results established from the bench testing that characterise brick and mortar samples to refine the model inputs. The accuracy of the modelling is highly dependent on closely matching the characteristics of construction products; when material properties of *untreated* bricks were known and could be replicated in the models, results from simulations were quite representative of the laboratory findings. However, if alternative bricks from the modelling software database were instead used, they led to a notable discrepancy from the laboratory behaviour.

Simulation of the behaviour of the waterproofing treatments did not align with laboratory findings. Model predictions suggested that there would be no moisture uptake in treated bricks, whereas in practice, the laboratory samples did show some moisture uptake. It is likely that the presence of small cracks in the laboratory samples allow moisture to effectively 'bypass' the treatment to some extent, whereas the modelling assumes perfect construction and thus absolute resistance to the passage of moisture.

It is for these reasons that in reference literature 'engineering conditions' or 'safety factors' are sometimes added to simulation models to attempt to allow for otherwise unquantifiable conditions experienced in practice. For example, modelling can be set up to assume that a defined percentage of moisture will penetrate the external construction layer. However, there is no real agreement on what correction factors should be applied, and indeed they are likely to be variable for different construction materials.

Overall, while the reliability of untreated wall models may be improved by ensuring the parameters of the construction products are accurately represented, it is not possible to reliably model the impact of waterproofing treatments, or derive 'rules of thumb' for correction factors that could be consistently applied, as these could be case-study dependent.

8. This project aimed to quantify the potential contribution to meeting the UK carbon budgets that CWI in exposed areas could provide. If waterproofing treatments are viable how many more CWI installations could there be in the UK and what would be the impact of this on policy targets?

There is no existing data source indicating the number of dwellings in the UK that are of brick-finished cavity wall construction, let alone those within high exposure zones. Statistical models have been developed to predict the probability of a cavity wall dwelling in the UK having brick faced walls (masonry pointing) based on sources of available data. Mapping of WDR exposure zones according to BS 8104 in the form of GIS shapefiles now allows any geo-referenced data source to be overlaid with exposure zones. Unfortunately, due to lack of access to a geo-referenced version of the NEED database, it was not possible to run the full process of comparing brick cavity wall probability with exposure zones within the project. However, the process can be carried out by BEIS, where geo-referenced NEED data is available.

9. How do the results from testing a house differ from laboratory results and what lessons does this hold for the wider use of waterproofing treatments?

As described in section 3.8, unfortunately, it was not possible to test the waterproofing treatments in actual houses to compare with the laboratory findings. However, this in itself reflects the differences between testing in a laboratory and testing in-situ and offers lessons for the use of waterproofing treatments in real-world situations.

Laboratory wall samples will offer the closest representation to ADT conditions likely to be experienced due to the high level of attention and control that can be committed to the construction within a laboratory setting. Even if the same degree of construction quality was achieved in a real building, that building is then subjected to a variety of environmental conditions – ABIS conditions – that can influence the long-term quality of the wall. In particular, poorly sealed openings will introduce potential penetration points into the construction that were not replicated in the laboratory samples. Also, degradation caused by ageing and weathering can lead to new or widened cracks in real walls that again would not be experienced by laboratory samples unless subjected to accelerated conditioning. Even in these cases, it is difficult to equate a particular regime of accelerated conditioning to the actual environmental conditioning that may be experienced by any given wall.

Manufacturers of waterproofing treatments invariably state that their products must be applied to walls in a good state of repair. Notable faults, including a wide range of ABIS features, would promptly undermine the effectiveness of the treatment by, for example, allowing water to bypass the brickwork and mortar directly due to cracking or other gaps in the construction. The site investigation work suggests that cavity wall constructions in exposed areas of the UK – particularly those of facing brickwork rather than rendered – are unlikely to be of sufficiently good condition to expect such treatments to offer the intended reduced risk of moisture penetration.

5 Conclusion

The following key project conclusions align with, and address, the objectives from the original project brief.

Objective 1: Assess the effectiveness of waterproofing treatments in allowing CWI to be safely installed in exposed areas.

Reduced moisture ingress was evident in the treated insulated wall samples compared to untreated walls, though the extent of moisture reduction was varied between the two main products tested. While this is a positive finding in the context of the potential for such treatments to protect CWI, it is based on a small number of test samples and some discrepancies in performance between tests cannot readily be explained. Further WDR testing (verified ultimately by in-situ testing) would therefore be recommended to provide additional supporting data for these conclusions, and solar exposure and freeze/thaw testing would additionally be beneficial to simulate potential ageing effects on the treatments.

While overall moisture uptake in treated, insulated walls is reduced, there is still some moisture uptake over time. Had suitable in-situ case studies been available, it may have been possible to assess the robustness of deterministic hygrothermal modelling for the analysis of treated, insulated cavity walls in very exposed locations to see if the accumulation of wetting were likely to ultimately lead to failure, or if intermediate dry periods were likely to offer sufficient opportunity for walls to recover before being subjected to further wetting.

Treatments may provide additional assurance for CWI in lesser exposure conditions, i.e. zone 2. However, in any case, underlying ABIS conditions in walls could likely undermine the performance of the waterproofing treatments, allowing them to be effectively bypassed by cracks or other openings in the external façade. Reliance on waterproofing treatments as a ‘do it yourself’ solution may not achieve the desired effects if the underlying condition of the wall has not been assessed by professional survey and confirmed to be of appropriate quality or rectified accordingly.

Objective 2: How can the reliability of hygrothermal models be improved?

The hygrothermal modelling investigation has confirmed that the properties and characteristics of construction products need to be represented as closely as possible within models for them to be reliable. This is likely to require specific laboratory testing of components for the purposes of characterisation. This could be financially restrictive, since a key advantage of hygrothermal modelling is to support designers in decision-making with minimum need for practical sampling and testing. Knowing the specific product properties was found to be particularly important for bricks, since they experience wide variations in physical properties such that it would not be appropriate to simply select software database entries at random. A more robust approach would require considering the variability of the hygrothermal properties of building materials in the moisture risk analysis.

Note that **no way has been identified to reliably model the real-world behaviour of waterproofing products**, largely because models cannot reliably account for minor cracks in bricks and mortar, or indeed any more substantial ABIS conditions that may be found in real walls. Therefore, future research efforts could be made towards the development of a representative ‘engineering approach’ for the characterisation of waterproof treated walls.

Objective 3: Validate laboratory and modelling findings with demonstration buildings.

Unfortunately, it was not possible to validate the performance of the waterproofing treatments in the laboratory testing against real demonstration buildings. However, this in itself is quite insightful for the potential future applications of such treatments in practice.

It is apparent that relatively few buildings in regions of severe or very severe WDR exposure have brick-faced cavity walls – the majority instead employ an additional protective external finish, such as render. Where examples of brick wall dwellings were identified in high exposure zones, they were found to have high levels of cracking and other defects, including cavities that were blocked at the base with debris, cavity trays not in place or damaged, and seals around windows in poor condition or absent (i.e. ABIS conditions).

The site investigation work suggests that cavity wall constructions in the UK are unlikely to be of sufficiently good condition (as per manufacturers guidance) to expect waterproofing treatments to offer the intended reduced risk of moisture penetration in practice.

Objective 4: Estimate the increased potential for lower cost CWI savings (i.e. by 'drying out' walls to improve U-values). Also comment on how U-values versus wall wetness may explain the performance gap in CWI insulation savings.

There is no evidence from this research that walls treated with waterproofing products perform better thermally in like-for-like conditions (e.g. whey dry) than untreated walls, and thus no suggestion that the waterproofing treatments could act as low-cost insulants in their own right. Results of U-values from different test samples fall within each other's error margins, with some treated samples having higher U-values and some lower than the untreated walls.

The U-values still vary with moisture content when walls are untreated or treated. However, the percentage U-value difference between wet and dry uninsulated walls was larger for untreated walls (between 17% and 24%) compared to treated walls (between 7% and 15%). The treatments do therefore appear to help to reduce the wetness of the wall to some extent, which in itself is beneficial since dryer walls appear to systematically have a lower U-value. However, this 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 possible that wall wetness influencing U-values could make some contribution to the performance gap often experienced between predicted savings from installing CWI and real-world savings. However, equally, some ABIS conditions could compromise the performance of CWI to some extent, (e.g. debris in cavities leading to enhanced thermal bridging, settlement of insulation leading to uneven thermal performance). It is also likely that a performance gap could be introduced by users 'taking extra comfort' from the new insulation, by heating their homes to a higher temperature than they were able to before, thus not creating like-for-like occupancy conditions for comparison before and after the insulation measures.

Appendices

A: WP2 - Wall analysis

B: WP3 - Treatments analysis

C: WP4 - Bench testing

D: WP5 - Hygrothermal modelling review

E: WP6 - Wind driven rain laboratory testing

F: WP7 - U-value testing

G: WP8 - Hygrothermal modelling

H: WP9 - Site testing

I: WP10 - Stock modelling