Appendix E: WP6 – WDR testing

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Section Contents

1. Introduction

This report presents the analysis of the results obtained from the test campaigns developed in WP6: "*Wind Driven Rain (WDR) Simulation Tests on Real Size Cavity Walls Specimens*".

Details of the test setups, procedures, specimens' preparation and data collection protocols are reported in the following sections.

For the *WDR Simulation Test,* six cavity wall specimens were built and tested in the CEGE-HE double environmental chamber in two different configurations, uninsulated and insulated cavity. Two waterproofing products selected among the ones tested in WP4 were used for coating the external surface of the external leaf of the cavity walls. These were treatment B and C. The products were selected based on the water vapour transmission and hydrophobicity performance results in WP4's bench tests. The results for each of these products are available in

The aim of the WDR test is to determine the response of the coating products when exposed to extreme wind driven rain conditions, as suggested from national and international standards BS 4315-2:1970, BS EN 13050:2011 and ASTM E 514/ C1601 (2014), (see Figure 1). Specifically, the objective is to determine the uptake of water of the external leaf and any breach of water to the internal leaf, when the panels are subjected to subsequent cycles of wetting and drying.

Test method	Test purpose	Water application	Pressure/ wind	Duration	Nature of result
BS EN 12155:2000	Curtain walling static lab test	2 l/min	150-600+ Pa *(35-70 mph)*	Up to 50 min	Pressure limit to failure
BS EN 13050:2011	Curtain walling dynamic lab test (pulses every 5 sec in vertical passes across wall)	2 l/min	Design pressure	Time required for vertical passes	Pressure limit to failure
BS EN 13051:2001	Curtain walling site test	5 l/min	-	30 mins	'Pass' after 30 min
ASTM E 514/ C1601 (2014)	Masonry lab/ site test	2.6 l/min	480 Pa *(60 mph)*	4 hours	Absorbed litres/hour
BS EN 12865:2001	External wall tested under pulsing air pressure (every 15s)	1.5 l/m^2 surface *plus* 1.2 l/m at top	150-600 Pa *(35-70 mph)*	1 hour [(a)] 5 hours [(b)]	Pressure limit to failure [(a)] Absorbed kg/m^2 [(b)]
BS 4315-2:1970	Permeable wall water penetration test (1min every 30 min[(a)], 6 hr in 24 hr [(b)])	0.5 l/m^2	250 Pa *(45 mph)*	48 hours [(a)] x days [(b)]	% absorption
Weather data	Swansea 2012-2017 (WDR index = 116 l/m^2 spell)	0.13 l/m^2 min	185 Pa *(39 mph)* hour av	13 hours (to 100 litres)	-

Figure 1: Available test standards for WDR testing

The heat-flow tests delivered under WP7 were also carried out at the same time, to determine the U values of the cavity walls, for treated and untreated walls in uninsulated and insulated conditions and in dry and wet conditions, These results are compiled in Appendix F.

2. Test setup

2.1 WDR Test

The coupled environmental chambers of UCL CEGE at Here East shown in Figure 2 were used in the WDR test to simulate indoor and outdoor environments simultaneously. The two chambers face each other and have a common mounting area interface of size 5m x 4m in elevation and 0.4m deep. To ensure the wall specimens can be fully and evenly impacted by the wind driven rain created by the rain simulator in the outdoor chamber, two wall specimens are tested simultaneously. In all, a repetition of three set of tests is conducted for insulated and uninsulated conditions, so as to expose six wall specimens. The first two tests consisted of a treated wall and an untreated reference wall, the third test compared directly the performance of treatments *B and C.*

Figure 2: UCL CEGE External-Internal coupled environmental Chambers at UCL-Here East

The wind driven rain simulation system consists of 2 major components. The first component is the built-in rain simulation system in the outdoor chamber. Rain is simulated using a 3.5 m wide and 3.0 m high frame composed of 3-layers with a total of 18 60° nozzles. Only the 6 nozzles of the bottom layer at a height of 600mm from the chamber floor were used in this study, to match the height of the walls. The second component is a couple of horizontal fans placed at the back of the nozzle frame to provide extra velocity to the raindrops to reach the standards' requirements in Figure1. The wind speed during the test was set to 3 m/s measured at the nozzles.

The walls specimens were built in dimensions 1.1m x 1.1m x 0.28m, with two leaves of bricks in stretcher bond and 75mm cavity in between. The brick type is Atherstone red in standard dimensions of 215x102.5x65mm, selected based on the bench test results on three different brick types, reported in Appendix C. Atherstone red bricks showed good consistency and performance gain during the bench test, besides having characteristics reproducing bricks kilned in the 1960s to 1980s and being still very popular in current construction practice. The mortar type used in the test was hydrated lime M4 mortar with a lime, cement, sand ratio of 1:1:6, which well represented typical mortars used in the period of reference in the UK.

Six wall specimens were built by professional bricklayers and later cured in controlled environmental conditions at 22° C temperature and 55% relative humidity. The specimens were built in December 2018 and the first test was conducted in July 2019, providing a six-month curing period for the lime mortar. During this period the weight of the walls was monitored by placing load cells under each specimen. (see Figure 3)

Figure 3: Six wall specimens in the curing room, being cured for six months. The double set of plates with interposed loadcells can be seen under the first row of walls. Each specimen is built on insulating material to prevent temperature bridges from the plates

Each wall specimen sits on a set of two steel plates of thickness 17.5 mm, 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 leaves. The loadcells have a capacity range from 3kg to 100kg, linearity ±0.02% RO and an IP66 rating which makes them resistant to moisture penetration, essential given the testing condition and environment. (see Figure 4).

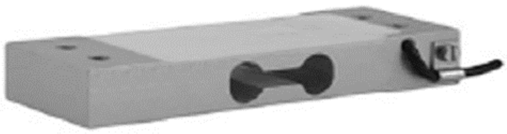
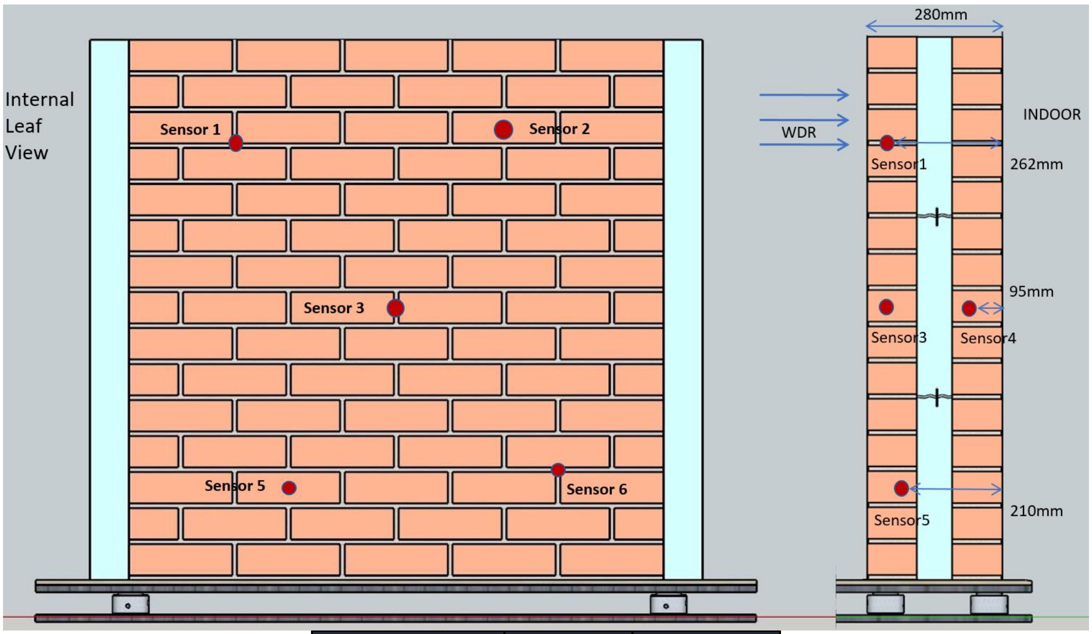


Figure 4: Typical loadcell, model SP-1022, supporting the 4 corners of the wall plates.

To systematically measure and record the movement of moisture inside the wall, RH and temperature sensors were placed both in-wall and on both surfaces of the two leaves, external and in cavity, in addition to heat flux plates used to measure the U-value.

For the purpose of determining the moisture uptake of the walls, each wall was monitored using 5 in-wall sensors with RH calibrated within +/-2% @55%RH and temperature measurement through NTC 10kOhms +/-1% direct output. Each wall was also equipped with one high accuracy sensor with humidity calibrated within ± 0.5%RH / 0.1 K at 10-90 %RH and 23 °C respectively. The detailed positioning of the in-wall sensors whose readings were logged using the CEGE NI LabView data acquisition system are shown in Figure 5 and Figure 6.



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 5: Layout of the in-wall T&RH sensors, and their depth into the panel with respect to the internal leaf. Sensor 3 is a high accuracy sensor.

Figure 6: Position of the in-wall T&RH sensors seen from the internal leaf

3. Test Process

3.1 WDR Test specimen's preparation

Before the start of the test, walls were instrumented and insulated at the sides and top to prevent any thermal bridge to develop during the test and sealed with special insulating tape from Pavatex all round to prevent any water ingress from the sides into the cavity

The specimens were preconditioned for at least 4 days with a dynamic program with 75% of RH and temperature oscillating between 10 °C and 15 °C in the outdoor chamber and between 17°C and 20°C in the indoor chamber, for measurement of heat flow and U values (see Table 1). Further to this, three hours of conditioning at 20 °C and 50% RH in the external chamber were conducted before start of the wind-driven rain test.

Time (h)	EXT T (°C)	EXT RH (%)	INT T (°C)	INT RH (%)
1	14.7	75	18.8	58
2	14.4	75	18.9	57
3	13.9	75	19.3	53
4	13.3	75	19.7	50
5	12.5	75	19.7	47
6	11.8	75	19.9	45
7	11.1	75	19.8	43
8	10.6	75	19.4	43
9	10	75	18.9	38
10	10	75	18.3	39
11	10	75	17.9	39
12	10	75	17.7	39
13	10	75	17.3	39
14	10	75	16.9	40
15	10	75	17.1	40
16	10	75	17.2	43
17	10	75	17.6	44
18	10.5	75	17.9	46
19	11.3	75	18.1	48
20	12	75	18.2	50
21	14.1	75	18.2	58
22	14.4	75	18.4	58
23	14.4	75	18.4	58
24	14.5	75	18.6	58

Table 1: Dynamic program used in outdoor and indoor chambers for U-value testing

The first batch of 3 tests were carried out using six wall specimens without insulation. After completion of this first batch, the specimens were brought back in the curing room where they were left to dry for 90 days at 22° C and 55% RH before filling the cavities with insulation beads. To accomplish this the sides of the walls were sealed with special insulating tape from Pavatex, and the Polypearl Platinum polystyrene beads from Polypearl Ltd were poured into the cavity without use of adhesives, compacted until full, for a total of 1.4 kg of beads per cavity, achieving the manufacturer's recommended density of 12 kg/m^2 ± 2 per installation.

The product specification can be found at
https://polypearl.co.uk/wp-content/uploads/2015/11/POLYPEARL-PLATINUM-MSDS-JULY-2015.pdf

A second batch of 3 tests were then run with the six insulated specimens. All other conditions and instrumentation were maintained the same as the first batch of tests.

3.2 WDR Test protocol

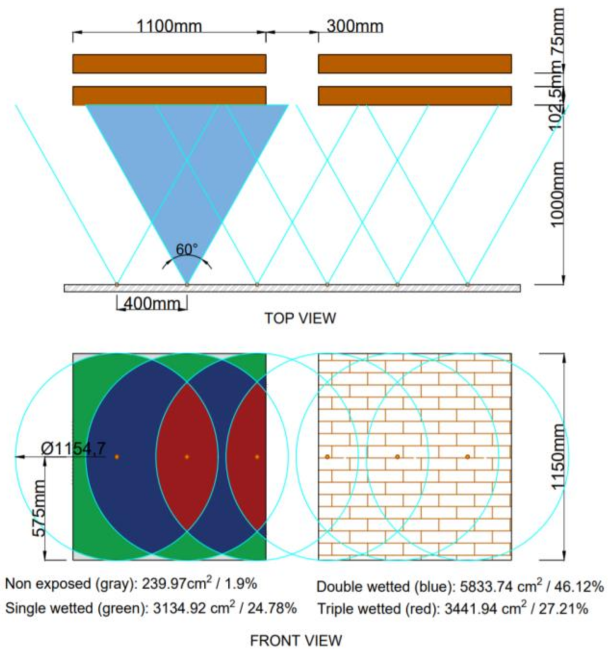
Wind driven rain tests were run over two days after 4 days of conditioning to determine the U values in dry condition and were followed by another 5 days of conditioning to derive U values in wet condition.

For the wind driven rain test duration, the temperature was set at 15°C in the external chamber and 20°C in the internal chamber. Each wind driven rain wetting and drying cycle consists of 20min wetting and 40 min drying. The flow rate of rainwater was controlled at 9 L/min by a flowmeter at the inlet of the water to the wind-driven rain system.

On the first day of the test, 2 cycles were applied to the walls. This first day represents the wetting of the walls from dry conditions. The walls were then dried overnight for 14 hours at 20°C in both chambers. On the second day, up to 8 more cycles were applied or the test was concluded when water penetrated the walls' cavities and was observable on the interior surface of the interior leaf. Figure 7 shows that the bottom layers of brick and mortar were darker in colour compared to other layers due to water penetration. Liquid water can also be observed on the top surface of the upper steel plate.

Figure 7: Example of water penetration to the interior surface of the interior leaf

During each wetting period, WDR gauges were placed in between the edges of the walls to confirm that a consistent amount of water was dispersed within the chamber and onto the external surfaces of the walls in each test. This confirmed repeatability of the test conditions throughout the testing programme.

a)


b)


Figure 8: a) Theoretical patterns of wetting of walls during WDR tests b) Calibration of water distribution with WDR gauges

Results of these measurements show that an average of 450ml of water was dispersed on 3 gauges over 400cm^2 surface area over 5 minutes. Based on this, the amount of rain dispersed on each wall can be calculated as 2.25 L/m2/min. (see Figure 8). This value compares well with the conditions specified in ASTM E 514/C1601 (2014) for masonry walls.

During the test, after each wetting cycle, pictures of the wall surfaces were taken to record the wetting condition of the walls. The readings of the in-wall sensors were recorded every minute to quantify the trend of moisture ingress into the outer leaf and transmission into the inner leaf, if any.

4. Analysis of WDR test specimen hygrothermal response

4.1 Introduction

Test results are presented below for each test (performed for a couple of walls) and for uninsulated and insulated cases separately to allow a comparative assessment. Each chart includes T and RH for the two wall specimens tested together under the same wind driven rain loading protocol, which includes an initial set of two wetting cycles, overnight drying and the following up to 8 wetting cycles. Three sensors were mapped for each set of walls, providing the response of the mortar (S1 or S3) and brick (S2), respectively, on the external leaf and the response of the internal leaf (S4), buried in brick. Cross-comparison among the three sets of tests is then presented to derive general trends. This is repeated for the insulated walls. The increase in weight recorded by the loadcells for the insulated walls is discussed in section 5. All variations in RH are considered in terms of % points over 100% RH.

4.2 Uninsulated Test 1

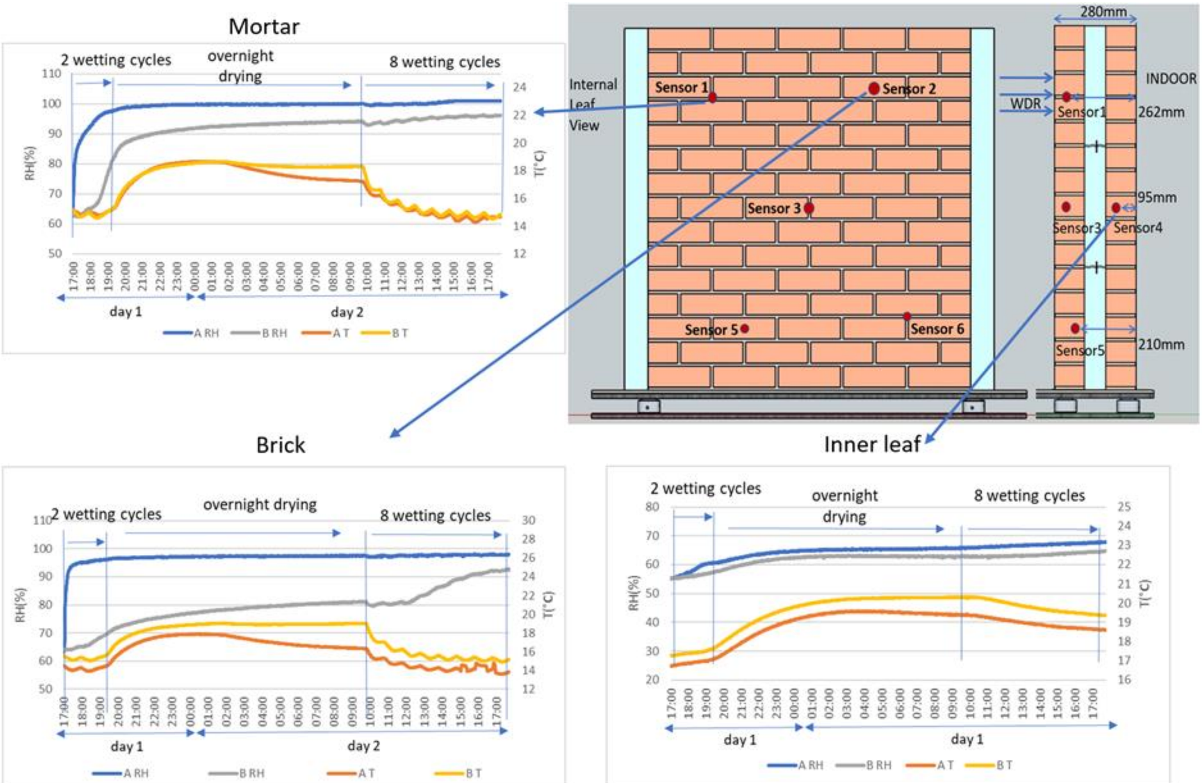


Figure 9: Variation of in wall temperature and RH for the untreated (A1) and B-treated1 (B1) walls in uninsulated test 1

The first test is to study the performance of treatment B by comparing the readings to an untreated wall. Two cycles of 20 min rain and 40 min drying at 15°C constant temperature were applied, and then the walls were left to dry overnight for 14 hours at 20°C, with no RH control. The indoor chamber was kept at 20°C constant through the entire test.

After applying six cycles on the second day, water was observed to have penetrated the untreated wall as evident from the water at the lowest course of the wall’s inner surface and onto the underlying steel base plate.

As seen in Figure 9, for the wall treated with B product, the readings on S1 located in mortar show an increase in RH of 15% (ie from 65% to 80%) after the first two cycles, while the untreated wall had an increase of 23%. For S2 on the brick, the RH readings reached almost 100% after one cycle for the untreated wall, remaining then constant, while for the B-treated wall the increase was about 6% after two cycles. During the overnight drying, a further increase of 13% in the mortar and 10% in the brick RH sensors was observed for the B-treated wall. The eight cycles on the

second day did not have much impact on the RH reading for the untreated one, while the B-treated mortar had a low increase of 1% from a starting value of 95%. S2 in brick showed no increase in the first three cycles and then an increase of 12% during the following five cycles, taking the total RH to 92%. This might be explained as a deterioration of the performance of the B product after a certain number of cycles of wetting and drying. However, the final total RH in the treated wall according to all instrument was still 5% lower than the untreated one.
The sensors S4 on the interior leaf of both walls had a gain of 13% RH over the whole test with a maximum difference of up to 5% in RH and 2°C in T between the untreated wall and the B-treated wall. The sensors on the outer leaf have shown temperature variations caused by the water dispersion on the walls. The reduction in temperature with the number of cycles reflects the uptake of moisture. The reduction in temperature due to the moisture absorption of the external leaf was recorded also at the internal leaf, notwithstanding the air cavity. However, the total reduction in temperature on the external leaf was about 4 to 5 °C while it was less than 2 °C on the internal leaf.

Overall the B treatment has shown its ability in reducing water ingress as no moisture was observed in the inner leaf of this wall, while also showing slightly better thermal performance.

4.3 Uninsulated Test 2

Figure 10: Variation of in wall temperature and RH for the untreated (A2) and C-treated (C1) walls in uninsulated test 2

The second test was to study the performance of C-treated wall in comparison to the performance of an untreated wall (Figure 10).

The initial testing protocol was as in the first test. During the first two cycles both sensors S1 and S2 reached values in the range of 100% RH for both walls with a slightly higher RH level in the case of C1.

During the overnight drying, the outdoor chamber was shut down due to a power cut in the lab 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 conditioned down to 20°C. Two wetting cycles were then applied until water penetrated into both walls and was observed on the inner leaf. Considering that all sensors on the external leaf for both walls measured RH readings around 100%, it was decided to conclude the test.

The sensors on the internal leaf for both walls show an increase of about 18% of RH (12 percentage points) during the night period in correspondence with the shutdown, with a slight decrease following the conditioning and the cycles of wetting in the following day.

Overall the wall treated with C did not show much difference compared to the untreated wall. The RH gain was very similar over all sensors, however the temperature difference especially on the outer leaf shows that the C-treated wall has a better thermal performance than the untreated, with an overall 2°C higher T value.

4.4 Uninsulated Test 3

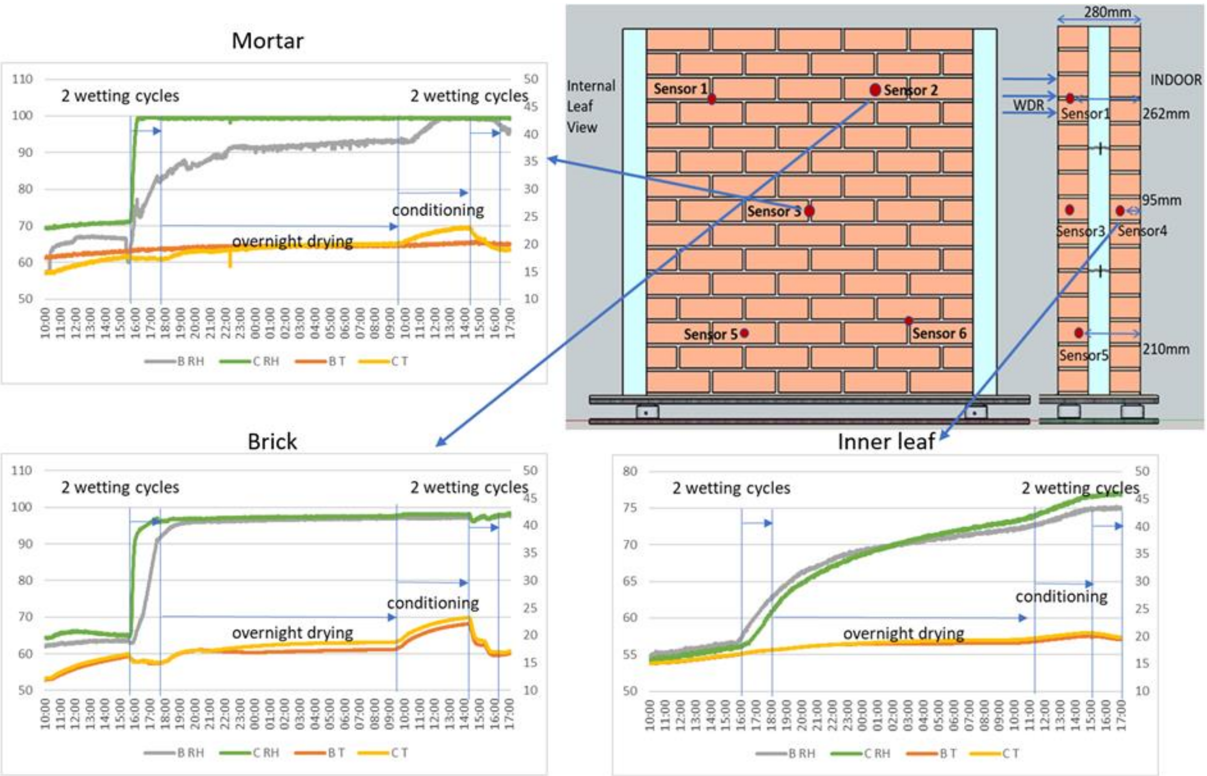


Figure 11: Variation of in wall temperature and RH for the C- (C2) and B-treated (B2) walls in uninsulated test 3

The third test compared the waterproofing performance of the two different products B and C and to confirm the findings from previous tests.

Two wetting cycles were applied to both walls on the first day and resulted in 100% RH readings of the C wall's external sensors and, for the B-treated wall, in substantial uptake of moisture during the 2 cycles up to 20% of RH increase at the mortar sensors S3, with a further increase of 11% RH during the dry period. The sensor S2 for the B-treated wall, reached 90% RH after the 2 cycles and 100% RH is attained during the drying period. After the overnight drying at 20°C, no humidity drop was observed on the in-wall sensors, so the outdoor chamber was conditioned at 25°C, 50% RH for 4.5 h. However, RH readings remained unchanged. During this period the RH sensor in mortar for the B-treated wall reached 100% RH. Two wetting cycles were then performed, which resulted in a slight loss of RH in the B-treated wall mortar sensor, while other sensor readings remained unchanged.

The inner leaf sensors showed an increase in RH overnight of about 15% during the dry period and then a further increase of 3% during the last two cycles. The B-treated wall showed a marginally better behaviour over the C-treated wall. However, the behaviour in temperature between the two walls was very similar, showing a constant behaviour overnight and loss of 3°C during the wetting cycles, as already observed in the previous tests.

The performance of the C-treated wall remained very similar to the previous test while the B-treated wall performed less effectively than in the first test.

4.5 Uninsulated Tests Cross-comparison

To compare the performance and consistency of the treatments across the three uninsulated tests, the RH and temperature readings of the in-wall sensors are presented for Mortar (S1), Brick (S2) and Inner leaf (S4) respectively. Each chart presents both RH and T readings of each wall. Each wall is labelled in different colours. In drawing the comparison, allowance has to be made for the variance in overnight events, such as the shutdown of the chamber in the second set of tests and the reduced number of cycles for the second day due to the attainment of 100% RH of sensors I the outer leaf of the walls or leakage observed in the internal chamber.

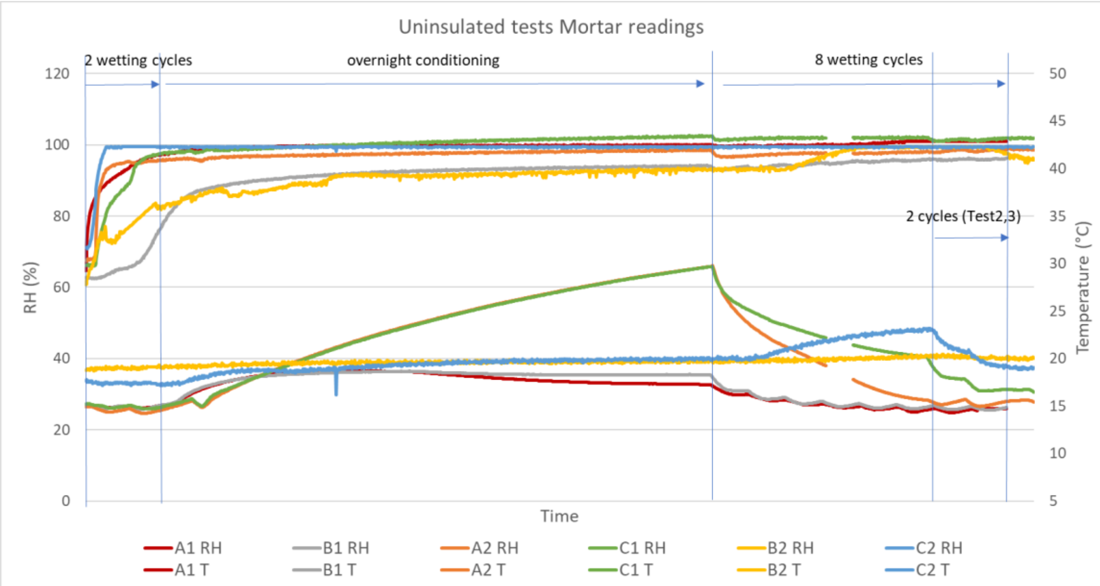


Figure 12: Variation in mortar T and RH for all walls in uninsulated tests

Figure 12 presents the RH and T readings of the sensors in mortar for each wall in the uninsulated tests. The total six walls contain two untreated walls, two B-treated walls and two C-treated walls. Both untreated walls reach 100% RH after the 2 wetting cycles on the first day with an increase of 35% RH, which remain unchanged to the end of the test. B1 and B2 started at same level of RH at around 60% but B1 has a slower and more stable RH gain compared to B2. RH increased by 8% at the end of 2 wetting cycles in day one and kept increasing after two hours into the overnight conditioning on B1. The 8 wetting cycles on the second day did not had much impact on B1 and only had a low increase of 1%. The performance of B2 was different from B1, in the first day, with an increase of RH by 22% during the first 2 cycles with spikes during wetting. The readings stabilized during the overnight conditioning but increased by 6% before the wettings on the second day, with no further increase during the 2 wetting cycles on the second day. C1 treated wall reached 100% RH by the end of the first 2 wetting cycles, on day one, while C2 sensor reached 100%RH within one wetting cycle.

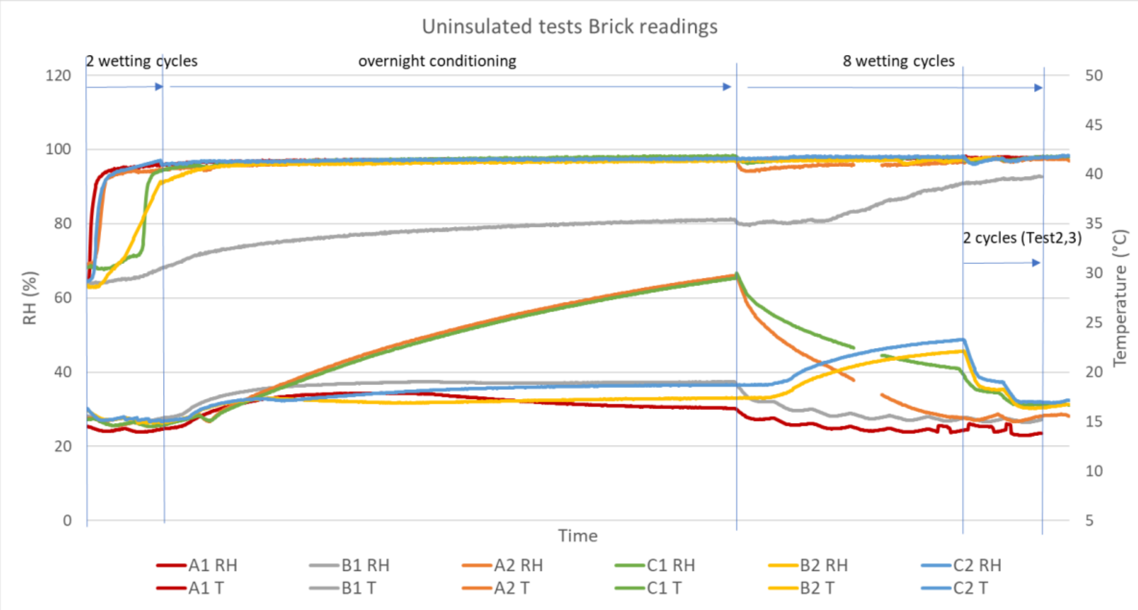


Figure 13: Variation of in brick T and RH for all walls in uninsulated tests

Figure 13 presents the RH and T readings of the S2 sensor in brick for each wall in the uninsulated tests. Both untreated walls maintained the consistency in the readings on mortar, both increased 35% in RH after the first cycle on day one and reached near 100% RH readings which remained to the end of the test. The performance between B1 and B2 was very different. B1 merely increased by 6% RH after two cycles and further gained 10% during the overnight conditioning. In the first three cycles of the 8 wetting cycles on the second day, B1 showed no obvious increase but increase by 12% in the following five cycles. This might be explained as a deterioration of the performance of the B product after repeated wetting and drying. B2 however, reached 100% RH readings after the first 2 wetting cycles on the first day and remained constant. C1 experienced a slow RH gain by 4% at the first wetting cycle but gained 25% in the second wetting cycle and reached nearly 100% RH. C2 did not show obvious differences compared to the untreated walls on brick.

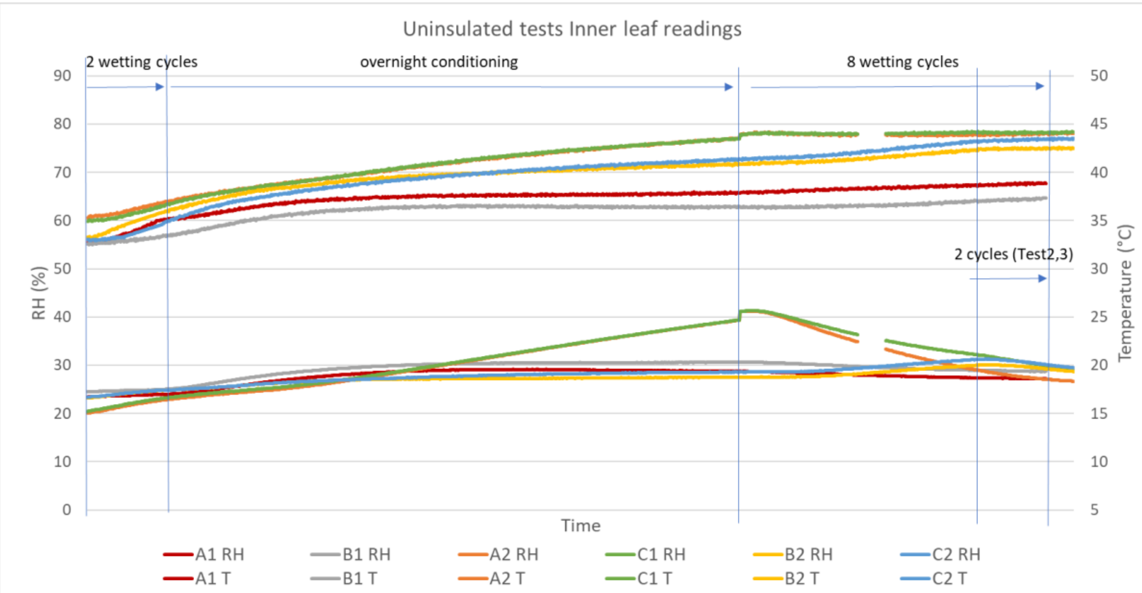


Figure 14: Variation of inner leaf T and RH for all walls in uninsulated tests

Figure 14 shows the RH and temperature readings of the sensors in the inner leaf of each wall in the uninsulated tests. Due to the inner leaf of the walls having no direct contact to the wind driven rain, the change in RH is considered a result of moisture vapour migrating across the air cavity. In test 1, after an initial increase in the first two cycles, A1 remained 5% higher in RH than B1 throughout the test. In test 2, the shutdown of the outdoor chamber raised the temperature to 30°C and this greatly accelerated the water transport. Both C1 and A2 have the same RH reading throughout the test but comparably higher than the other walls. In test 3, C2 was initially 2% lower than B2 but slowly increased overnight to a value of 2% higher than B2 by the end of the test.

The thermal performance difference was less obvious for the inner leaf than the outer leaf. The temperature on every two walls from each test was very close. Both B and C treated walls inner leaves maintained a T about 1°C higher than the untreated walls.

4.6 Insulated test 1

The insulated test is to study the influence on water resistance and thermal performance of the treatments of insulated cavities, as prescribed by the Green Deal policy and as described in section 3. Two cycles of 20min wetting and 40min drying at 15°C constant temperature were applied, and then the walls were left to dry overnight at 20°C, 40%RH. The following day 8 wetting cycles were applied with the same regime. The indoor chamber was kept at 20°C constant through the entire test.

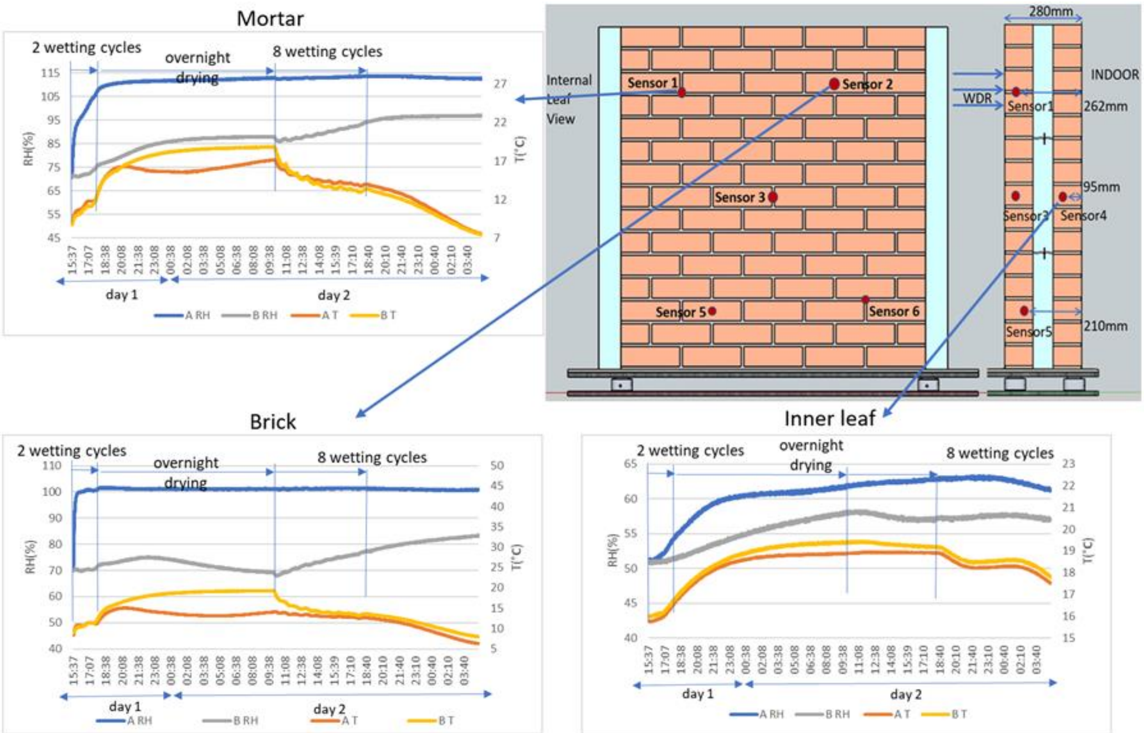


Figure 15: Variation of in wall temperature and RH for the untreated (A1) and B-treated (B1) walls in insulated test 1

Compared with the results from *uninsulated test 1*, better performance can be witnessed on all sensor readings on the *B1-treated* wall in Figure 15. Both sensors in mortar (S1) and brick (S2) have increased by 1-2% RH in the first 2 cycles while the sensors on untreated wall have shown readings corresponding to the saturation of the sensors in the range of 100% RH, similarly to the uninsulated. During the overnight dry conditions, a further increase of 11% was observed on the mortar RH sensor for *B1*. The brick sensor (S2), RH showed an increase of 5% in the first 5h and then decreased by 6%, resulting in a 1%RH decrease at the end of overnight drying. The temperature difference between *B1* and *A1* wall increased by up to 5 °C on both brick and mortar sensors during the overnight dry conditions. The 8 cycles on the second day did not have much impact on the total RH reading for the untreated one, while the B-treated mortar and brick show a steady increase of 10%.

The sensors on the interior leaf of *B1-treated* wall had a gain of 7% RH over the whole test while the untreated wall shows a 12% RH gain, resulting in a difference of up to 5% in RH and 1°C in T between the two walls.

4.7 Insulated test 2

In Figure 16, the second insulated test studies the performance of *C1* after installation of insulation in comparison to the *A2* wall. A more substantial improvement in performance can be observed on all sensors in the *C1* wall compared to the previous uninsulated test while the sensors on the untreated wall reached their RH saturation in the first 2 cycles as both in the previous test and in the *A1* wall. Sensor S1 in mortar on *C1* showed no obvious RH gain throughout the whole test, while the sensor in brick showed no gain in RH in the first two cycles, then during the overnight dry conditions it first increased by 6%RH in 7h and then dropped by 10%. During the 8 cycles on the second day the RH increased again by 6% more.

The sensors on the interior leaf of *C1* wall had a gain of 7% RH over the whole test while the *A2* wall gained 11% RH resulting in up to 4% difference in RH and 1°C in temperature between walls *A2* and *C1*. Compared to the uninsulated test, wall *C1* has shown substantial performance improvement in this test on both brick and mortar with significantly reduced RH gain.

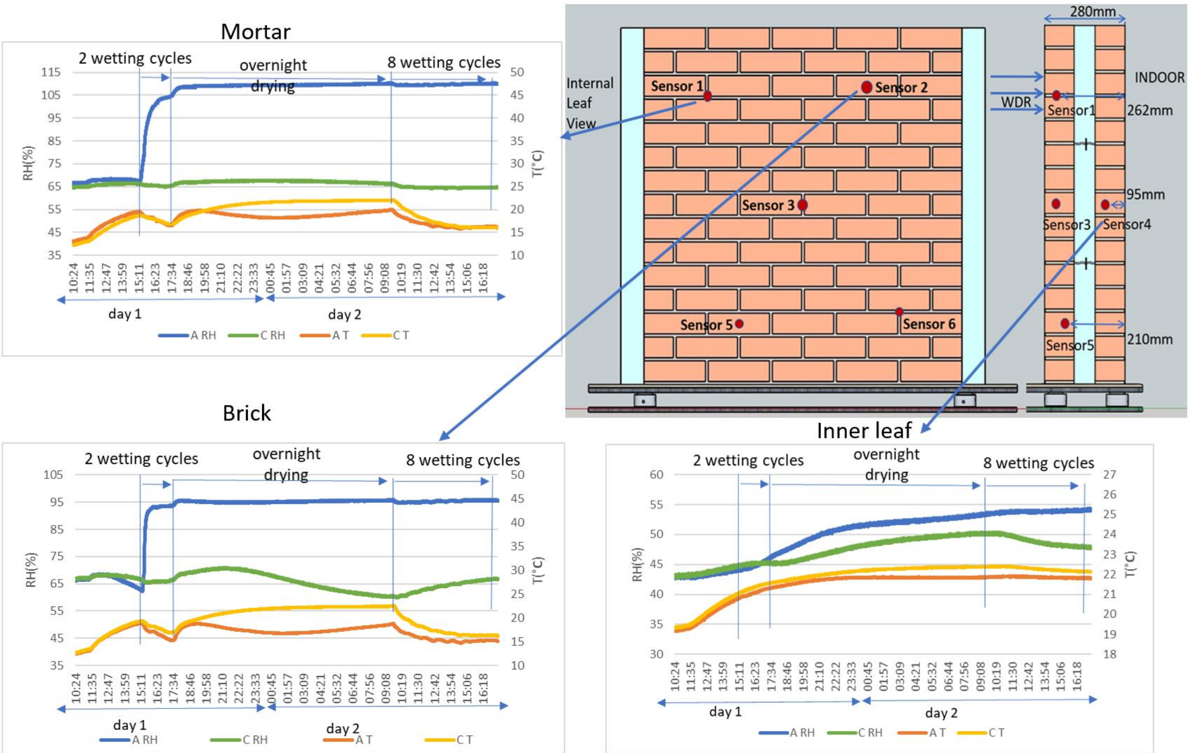


Figure 16: Variation of in wall temperature and RH for the untreated (A2) and C-treated (C1) walls in insulated test 2

4.8 Insulated test 3

To compare the performance between the two different products B and C directly and to confirm the findings from the previous 2 insulated tests, the readings of the sensors in the two walls *B2* and *C2* are compared in Figure 17. The two wetting cycles on the first day resulted in a 20% RH gain on S3 located in the *B2* mortar, and further increase during the drying period to reach 95% RH, while the mortar sensor in *C2* although starting at a higher RH of 75%, had no obvious gain throughout the test.

For the brick sensor S2, a fluctuation of 3% occurred on the *B2* wall during the first two wetting cycles but resulted in no obvious difference in RH compared to the starting condition. A 15% increase in RH was later observed during the overnight dry conditions. During the 8 cycles on the second day, wall *B2* first gradually gained 4% RH in the first 4 cycles, then the RH started to climb during the last 4 cycles resulting in 13% RH increase.

On the other hand, the readings of S2 on wall *C2* shows an increase by 5% in RH in the 2 cycles on the first day. Then in the overnight dry conditions, the RH first rose by 5% then dropped by 7%. A further 10% RH gain was recorded after the 8 cycles on the second day. On inspection of the graph in Figure 17 it can be seen that, the overall gain for wall C2 was 20% lower than for wall B2. The temperature behaviour is very similar for the two walls, with differences in the range of sensitivity of the sensors.

The inner leaf sensors showed an increase in RH of about 5% throughout the test on *B2* wall and 5% decrease on the *C2* wall. The steady dry conditions in the indoor chamber during the test have accelerated the RH decrease on the interior leaf. The temperature of two walls remained very close throughout the test while *C2* remained about 0.5°C higher than *B2* wall in the interior leaf.

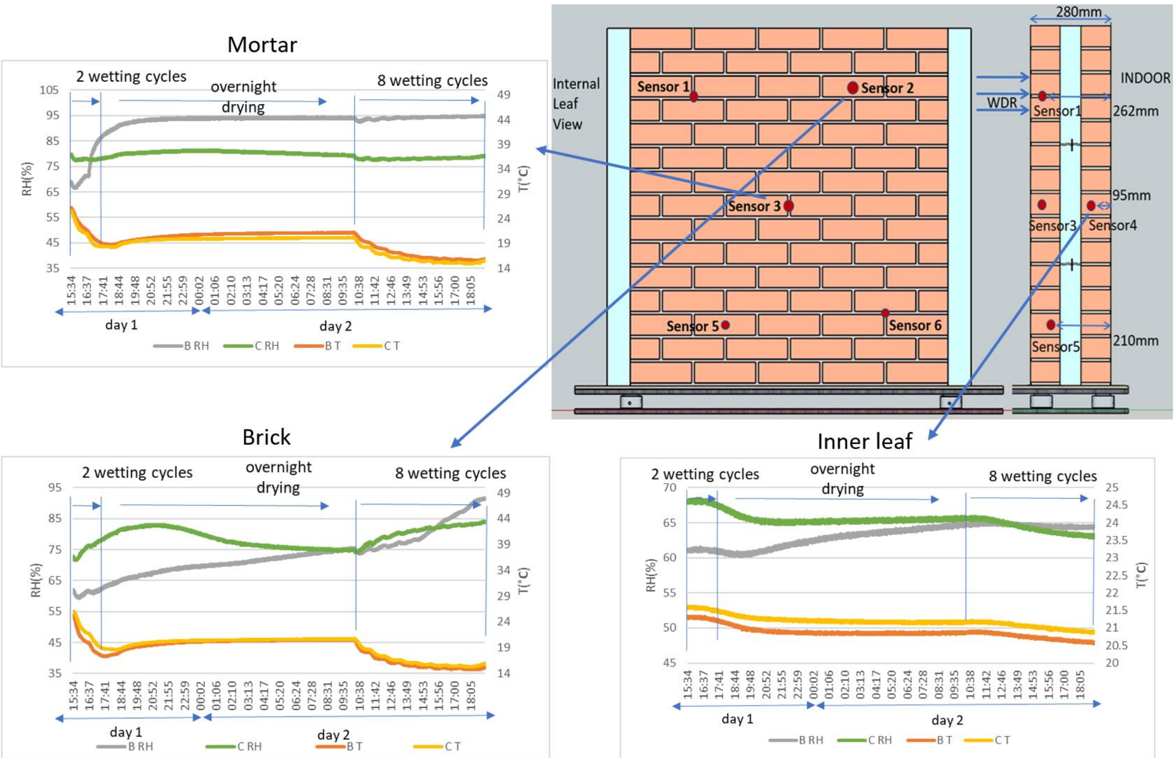


Figure 17: Variation of in wall temperature and RH for the B2 and C2 walls in insulated test 3

4.9 Insulated Tests Cross-comparison

To compare the performance and consistency of the treatments across the three insulated tests, the RH and temperature readings of the in-wall sensors are presented for Mortar (S1), Brick (S2) and Inner leaf (S4), respectively. Each chart presents both RH and the temperature readings of each wall. This second set of three test was much more consistent than the first set hence comparison is easier to draw and more meaningful.

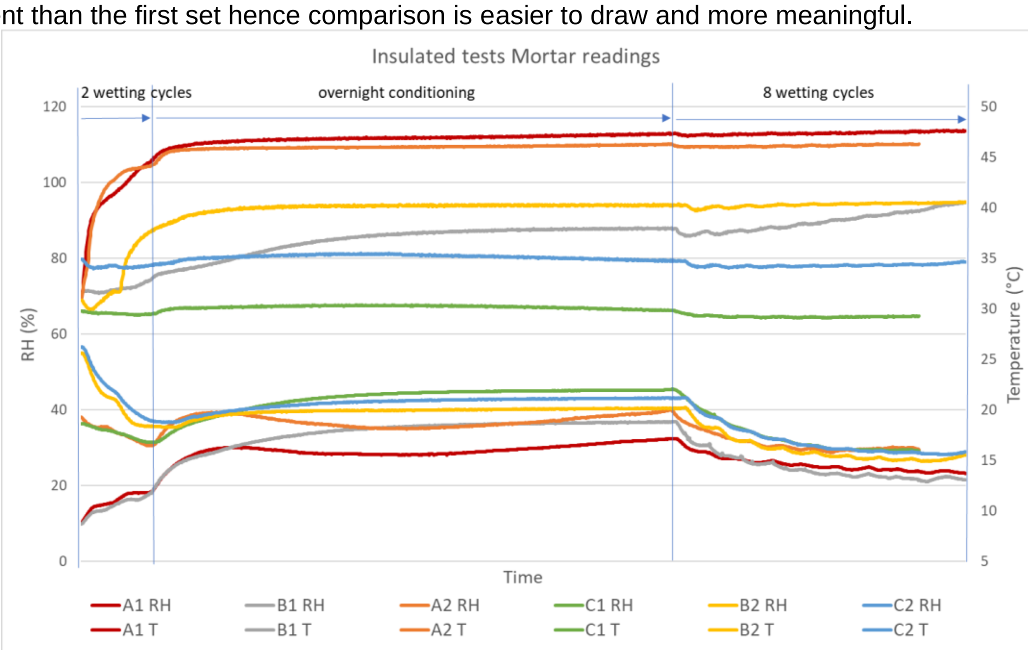


Figure 18: Variation in mortar T and RH (sensor 3 readings) for all walls in insulated tests

Figure 18 presents the RH and temperature readings of the sensors in mortar for each wall in the insulated tests. The total six walls contain two untreated walls, two B-treated walls and two C-treated walls. The *untreated walls* have maintained good consistency, both reached 100% RH readings after the 2 wetting cycles on the first day. RH on both untreated walls have increased by 40% in the first 2 wetting cycles over initial RH readings, then maintained the same level to the end of the test. The two *B-treated walls* performed differently although reaching the same ultimate 95% RH. B1 increased 5% in RH during the first 2 wetting cycles while B2 increased by 20%. While the RH of B2 maintained the same level to the end of the test, B1 gained 11% in RH during the overnight conditioning and steadily increased by 10% during the 8 wetting cycles on the second day, resulting in the same final value of RH as B2. On the C-treated walls, though the level of RH at beginning had a difference of 15%, both walls had no obvious RH gain throughout the test.

Although the temperature reading was different at the beginning of each batch of tests, due to slightly different periods of conditioning, the temperature differences between treated walls and untreated ones were very close between tests. The differences in temperature start to appear at the beginning of the overnight conditioning and reached a maximum during the middle of the conditioning. Both B and C treated walls were up to 5°C warmer than the untreated walls. For all walls, the temperature dropped during the 8 cycles test on the second day by 4°C degrees on average.

Figure 19 presents the RH and temperature readings of the sensors S2 in brick for each wall in the insulated tests. Similar to the behaviours in mortar, bricks on both untreated walls have shown the same pattern in RH gain with a difference of 5% RH between the two. B1 shows no obvious RH gain in the 2 cycles on the first day while a fluctuation of 3% occurred on B2. During the overnight conditioning, B1 first increased 5%RH in the first 5h, then decreased by 6%, resulting in 1%RH decrease at the end of overnight drying while B2 experienced a 15% increase. The 8 cycles on the second day produced a steady increase of 10% on B1, but on B2 it gradually gained 4% RH in the first 4 cycles, then the RH gain accelerated during the second 4 cycles resulting in 13% RH increase. C1 maintained a good performance in brick during the first 2 cycles, showing no obvious RH gain while RH on C2 increased by 10%. In the rest of the test, the two C-treated walls have shown very similar performance regardless of the difference in RH before start. They both increased by 5%RH in the first 4h and decreased by 10% during the rest of the conditioning period, resulting in circa 5%RH decrease at the end of overnight drying. During the 8 wetting cycles on the second day, RH on C1 increased by 6% while C2 increased by 10%.

The temperature difference was very close to the performance of the S1 in mortar. Regardless of the difference in temperature at the start of each batch of tests, the thermal performance between B and C treated walls were very close and were up to 5°C higher than the untreated walls.

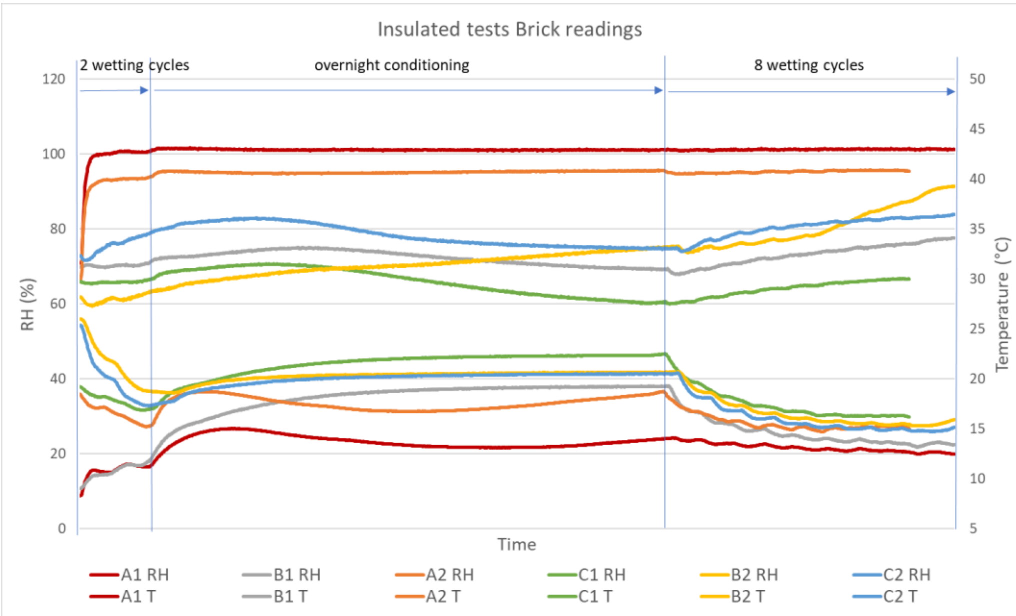


Figure 19: Variation in brick T and RH (S2 readings) for all walls in insulated tests

Figure 20 presents the RH and T readings of the sensors in the inner leaf of each wall in the insulated tests. Differently from the mortar and brick on the outer leaf, the inner leaf of the walls has no direct contact to the wind driven rain, so the changes in both RH and temperature were less obvious. Except for the difference in RH at the start of the tests, both untreated walls have a 10% increase in RH throughout the test. The increase was not immediate, it started at the end of the first cycle and lasted about 5 hours, then the increase slowed down towards the end of the test. The 8 wetting cycles on the second day made no obvious impact on all test walls. The performances of both B-treated walls were very similar on the inner leaf, with a gradual increase by 5% from the end of the second cycle until the end of the overnight conditioning. No obvious changes during the 8 cycles on the second day. Due to the shorter drying time on wall B2 and C2, their RH were higher at the beginning of the test, the RH on C2 dropped by 3% in four hours and remained constant until the start of the 8 cycles. C1 had 5% increase during the overnight conditioning, then the RH of both C-treated walls dropped by 2% during the 8 wetting cycles.

The thermal performance difference was more obvious on brick and mortar on the outer leaf than on the inner leaf. The temperatures on every two walls from the same batch were very close; both B and C-treated walls were 1°C higher than the untreated walls.

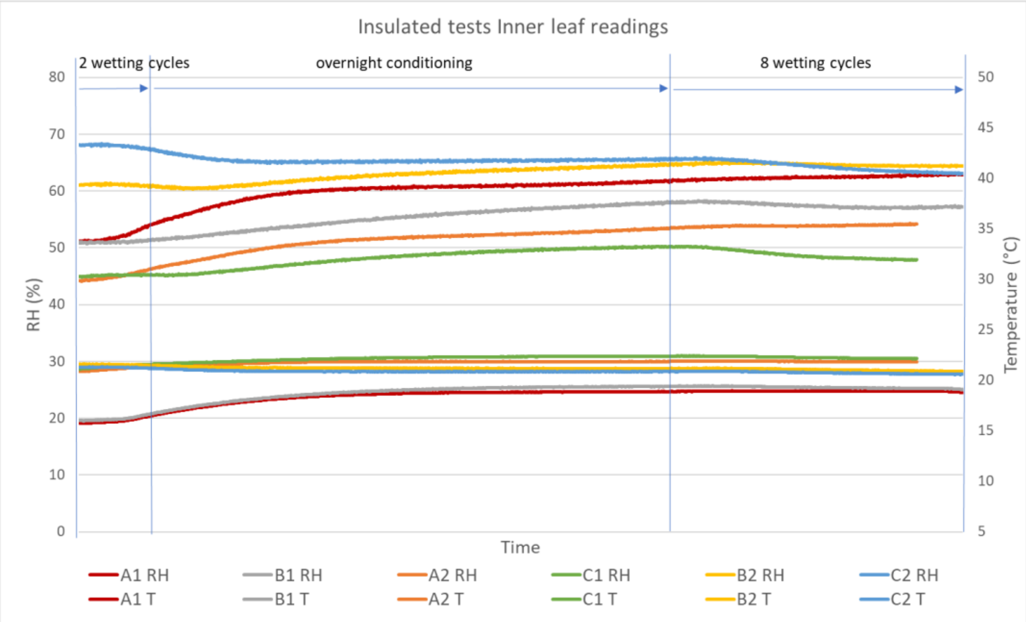


Figure 20: Variation in inner leaf T and RH (sensor 4 readings) for all walls in insulated tests

5. Analysis of WDR test specimens weight gain

The graphs below show the loadcell readings of each test batch during the WDR insulated test. Loadcell readings indicate the amount of water the test walls have absorbed during the WDR test. The results are presented for the three batches of tests separately and for each wall the measurements of load cell under the outer leaf and under the inner leaf are presented separately.

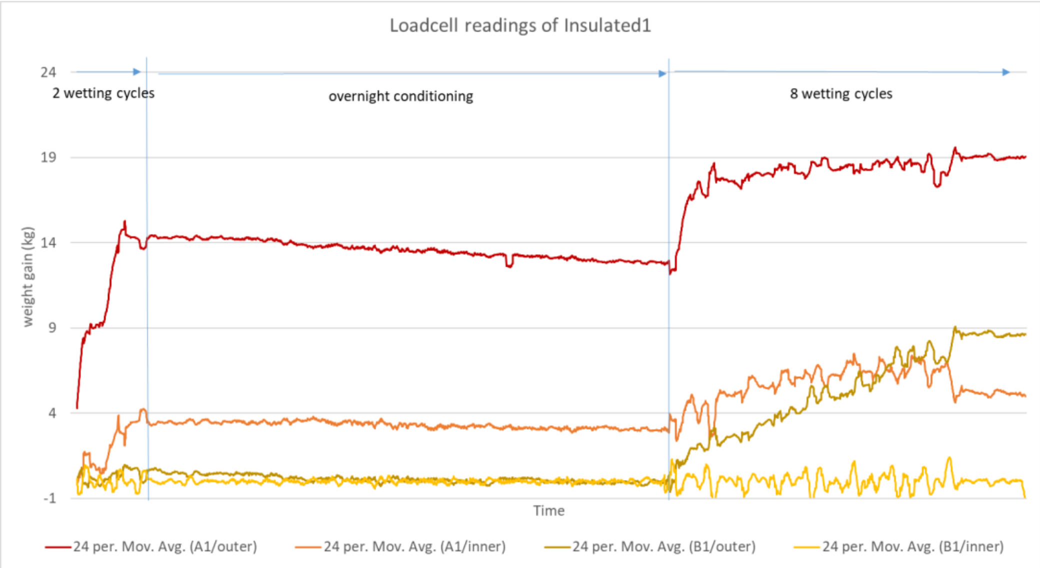


Figure 21: Loadcell readings of inner and outer leaves of walls in insulated test 1 A1 and B1

Figure 21 presents the loadcell readings of inner and outer leaves of *A1* and *B1* walls, respectively. An obvious weight gain can be observed during the first 2 cycles on both the inner and outer leaves of the *A1* wall. The outer leaf gained about 10kg of water while the inner leaf gained 4 kg. During the overnight conditioning, the outer leaf of the *A1* wall lost 2 kg of water while the inner leaf remained constant. On the following 8 wetting cycles on the second day, the outer leaf increased by 6kg while the inner leaf increased by 3 kg. The total change in weight by the end of the test is 16.5 kg gain on the outer leaf and 7 kg on the inner leaf of *A1*. Conversely, wall *B1* shows very modest weight gain, with the outer leaf fluctuating about 1 kg during the first 2 wetting cycles but had no change during the overnight conditioning. During the 8 wetting cycles on the second day, the outer leaf of *B1* absorbed 7 kg of water. The impact has remained on the outer leaf of B1 while the inner leaf had some fluctuation during wetting cycles but recorded no obvious weight gain. The total gain for the outer leaf of the untreated wall is 1.5% of its weight, while for the inner leaf the gain is just 0.65 %. The gain of the B1 wall's outer leaf at the end of test is 0.75%.

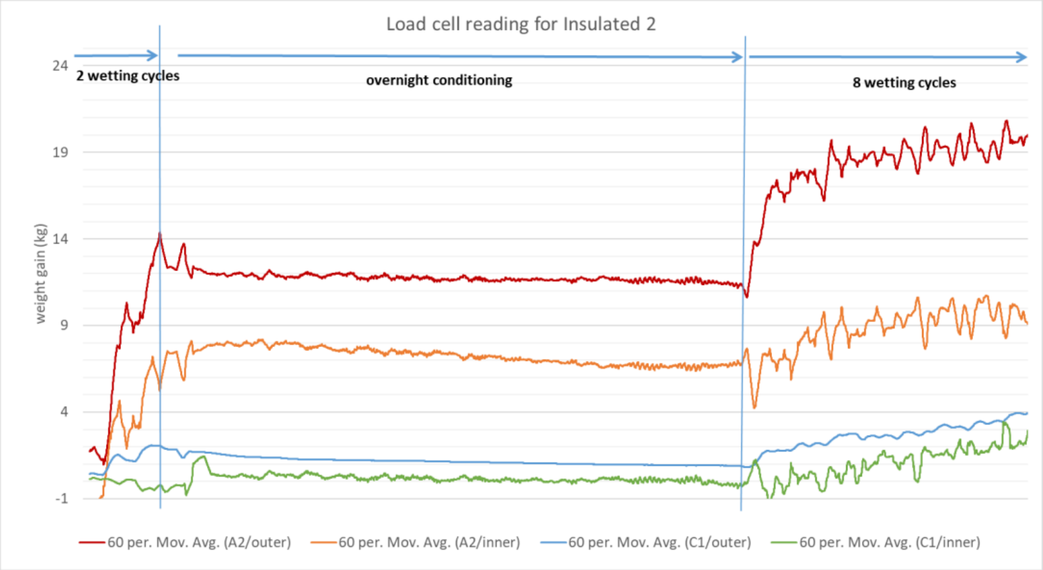


Figure 22: Loadcell readings of inner and outer leaves of walls in insulated test 2, A2 and C1

Figure 22 presents the loadcell readings of *A2* and *C1* walls of insulated test 2. The outer leaf of *A2* received 12.5 kg of weight gain after the first 2 wetting cycles, the inner gained 7.5 kg. The overnight conditioning reduced the weight by 1.5 kg on the outer leaf and 0.5 kg on the inner leaf. After 8 cycles on the second day a further 9 kg were gained by the outer leaf and 3 kg by the inner leaf, with total of 20 kg weight gain on the outer leaf and 10 kg on inner leaf of *A2*. On the wall *C1*, a slight gaining trend can be identified by looking at the 8 wetting cycles of the second day, the readings on the outer leaf marking an increase by 3 kg while the inner leaf remained flat with some noise. The total gain for the outer leaf of the untreated wall is 1.9% of its weight, while for the inner leaf the gain is 0.93 %. The gain of the C1 wall outer leave after the whole test is 0.28%.

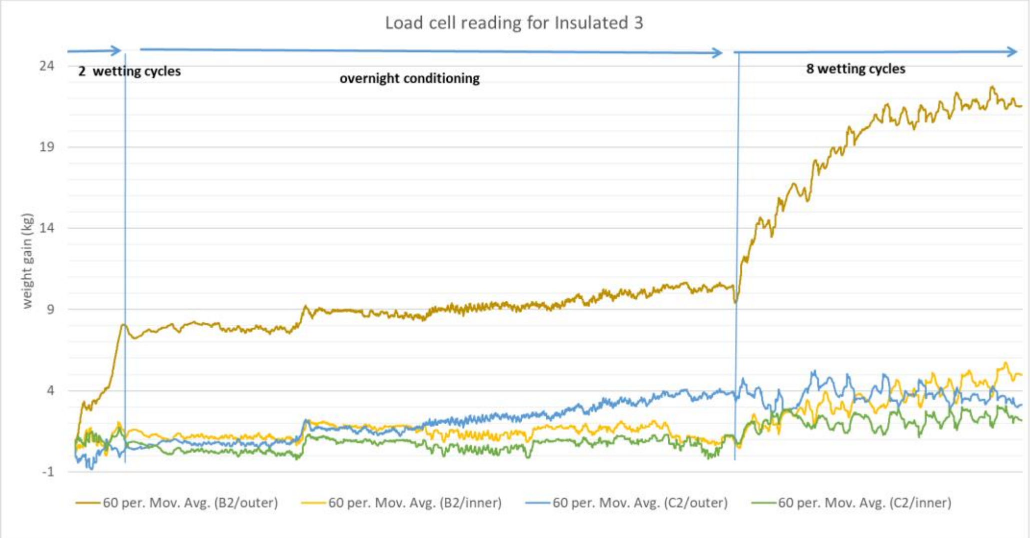


Figure 23: Loadcell readings of inner and outer leaves of walls in insulated test 3

Figure 23 shows the loadcell readings of *B2* and *C2* walls of insulated test 3. The outer leaf of *B2* gained 7.5 kg of weight in the first 2 wetting cycles, lost 0.5 kg during overnight conditioning and gained another 11 kg in the 8 wetting cycles, for a total gain of 18 kg . The inner leaf of *B2* had around 2 kg of fluctuation during the 2 wetting cycles and gained 5 kg in total at the end of the test. By comparing the trend between inner leaf and outer leaf of the *C2 outerleaf shows a slight gain in weight overnight and fluctuation over the 8 cycles during the second day, while the inner leaf records no increase overnight but a slight increaseof about 2 Kg during the second day.* The total gain for the outer leaf of the *B2* wall was 1.7% of its weight, while for the inner leaf the gain is just 0.47 %. No gain in weight for the *C2* wall can be computed with confidence as the trend is not clear.

6. Discussion and Conclusions

The aim of the WDR testing was to determine the response of the brick masonry cavity walls, insulated and uninsulated, coated using waterproofing treatment products when exposed to wind driven rain conditions, simulated in the form of cyclic wetting and drying. Specifically, the objective was to determine the uptake of water of the external leaf and any breach of water to the internal leaf through the readings of the loadcells and RH sensors. This uptake of water is a critical measure, as it also affects the temperature in both the external and internal leaf walls, ultimately affecting the indoor ambient conditions and comfort for occupiers. To this end, a total of 12 walls were tested in 6 sets of two walls, 3 uninsulated and 3 insulated, as follows: 1. Untreated and B-treated (uninsulated and insulated), 2. Untreated and C-treated (uninsulated and insulated) and 3. B- and C-treated (uninsulated and insulated). The same walls used for the first set of tests were insulated and used in the second set of tests. The change in temperature and water content on external and internal leaves, both in brick and mortar joints were measured in insulated and uninsulated walls to calculate U-values in WP7. All RH and T sensors measured in-wall conditions rather than surface conditions, therefore they provide a more accurate representation of the moisture uptake in the outer leaf and hence a direct measure of the effectiveness of the superficial treatments as barrier to water absorption. A summary of the findings and conclusions on the performance of the two products tested are listed thereof.

Uninsulated tests

On untreated walls, RH sensors in both brick and mortar on the outer leaf reached 100% RH within the first 2 cycles of wetting. Their RH increased by 35% and remained unchanged to the end of the test.

On B-treated walls, water ingress into mortar joints has been delayed by one wetting cycle. RH in mortar was 20% lower than that of untreated walls after 2 cycles, while in bricks RH was 25% lower than untreated. After overnight drying and 8 cycles on the second day, RH values for the mortar joints in the B-treated wall remained 6-8% lower than the untreated to the end of the test, while RH gain accelerated on bricks after the first 4 cycles. This might be explained with a potential deterioration of the performance of the B product after a certain number of cycles of wetting and drying. However, the final RH in the B treated wall was 5% lower in RH than the untreated ones. B-treated walls remained 1-2°C warmer on both inner and outer leaf than the untreated walls throughout the test.

On the other hand, C treated walls did not show lower RH gain on either mortar or brick throughout the test. The start of water ingress was delayed by one cycle on brick but the behaviour of the mortar was very similar to the untreated wall. 100% RH was reached very quickly after 2 cycles on the second day and the test was concluded. Thermal performance on C-treated walls was also better with a constant 1-2 °C higher temperatures on both inner and outer leaf compared to the untreated walls.

Insulated tests

In the **insulated** wall tests, untreated walls have maintained a behaviour consistent with the uninsulated. Both walls quickly reached 100% RH after the 2 wetting cycles on the first day and remained so throughout the test. The total weight gain at the end of the test is also consistent ranging from 1.5% to 1.9% of the original weight, for the two specimens. The inner leaf also showed a weight gain in both tests, of 0.65% and 0.93%, respectively.

Treated walls with either B or C have shown a more pronounced improvement in performance when comparing the insulated tests to the uninsulated tests.

On B-treated walls RH measurements in both mortar and bricks did not increased significantly in the first two wetting cycles and the overall RH levels were 30% lower than the untreated walls. After overnight drying and 8 wetting cycles on the second day, B-treated walls maintained 20% lower RH on both mortar and bricks than the untreated walls. However, B2-treated specimens had a significant increase in RH on the second day, not observed in the other treated specimens. On temperature, B-treated walls showed up to 5°C higher on the outer leaf while remained at a constant 1-2 °C higher on the inner leaf than uninsulated walls. The difference in hygrothermal behaviour of the two B-treated specimens is reflected in the weight gain, 0.75% and 1.7%, respectively at the outer leaf.

C-treated walls significantly improved in performance with no obvious RH gain on mortar throughout the test and a 6% increase during the 8 cycles on the second day on bricks. RH reading on mortar on C treated walls were 45% lower and 30% lower on bricks compared to untreated walls at the end of the test. Thermal performance also has improved on C-treated walls, reaching up to 5°C higher on the outer leaf than uninsulated walls while remained at a constant 1-2 °C higher on the inner leaf. The weight gain was also negligible at 0.28% for the first specimen and virtual no gain for the second specimen.

To shed light on the inconsistencies observed in the outcomes from uninsulated and insulated tests with regards to the performances of B and C treated walls, further investigation will be carried out on the two existing untreated walls and four new built walls, which will be tested in batches of twos in the following conditions: a) untreated, uninsulated; b)untreated, insulated; c) treated, insulated; d) treated, uninsulated. This combination will allow 2 more reference untreated walls and provide a measure of the effect of treatment on the same untreated substratum. By testing in the proposed sequence also the influence of the insulation will be measured independently of the treatment on all specimens.

In conclusion, treatment *B* and *C* have shown various levels of improvement on the water resistance and thermal performance of masonry cavity walls. The overall performance change following waterproofing is positive, as both treatments were capable of lessening moisture enrichment and improve thermal performance of masonry cavity walls under cyclic wind driven rain (WDR) loading. The results show that installing insulation in cavities can improve the thermal performance of masonry cavity walls while waterproofing treatments are able to provide additional resistance to water ingress contributing to maintain insulation dry and effective.

Between the two waterproofing products, *C* can provide more effective and consistent waterproofing performance compared to *B*. However, the findings from the WDR tests suggest that *C* may allow some initial water absorption before becoming effective. This initial behaviour should be further investigated with the new set of tests.

Given the additional questions that our findings so far have led to, and in order to improve the robustness of our conclusions, we consider it vital to extend the testing programme to include the additional proposed tests.

Importantly, the findings of this study should be used with caution when the existing building stock is concerned as it has been observed that the surface characteristics of the walls to be waterproofed are very influential on the performance improvement that these treatment products can offer. Further, our conclusions do not apply to the long-term performance of the examined waterproofing treatment products and their durability under various action such as freeze-thaw and solar radiation.