Impact of surface waterproofing products on the performance of brick masonry through the moisture exposure life-cycle

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ABSTRACT

Moisture is one of the major causes of damage to building systems, affecting the hygrothermal performance and durability of building systems. Surface treatment products are available in the market that can influence the hygric performance of masonry facades under water exposure. These are of a wide range of chemical compositions, and they claim to waterproof the masonry surfaces while not diminishing vapour transmissibility. This paper presents and discusses the findings from a series of benchtests carried out to measure hydrophobicity, water absorption and water vapour transmission following the relevant codes for an appraisal of the hygric behaviour change in brick masonry induced by waterproofing through three distinct phases of the life-cycle of moisture exposure, i.e. first contact with water, wetting and drying. To this end, 4 waterproofing products including silane/siloxane blend liquid and cream, and acrylic and stearate-based liquids were selected for testing, along with 3 brick types common in the 50s and 60s to be representative of the majority of the UK building stock. The findings show that the treatment products indeed enhance the surface hydrophobicity and reduce water absorption while allowing water vapour transmission, to differing degrees: silane/siloxane blend cream overall was found the most effective throughout the moisture-exposure life-cycle, with an average of ~96% reduction in water absorption and 18% of increase in water vapour resistance in comparison to the untreated case, followed by the stearate-based liquid with 57% reduction in water absorption and 12% increase in water vapour resistance. The acrylic-based product demonstrated good performance in hydrophobicity and water vapour transmission tests, however led to a comparatively higher water absorption capacity than the other treatment products with only ~40% reduction in comparison to the base-case. Finally, silane/siloxane blend liquid was found to lead to the lowest contact angle, demonstrating a lower-than-others capacity to developing surface hydrophobicity, and led to 35% reduction in water absorption and 28% increase in water vapour resistance, making it the poorest product in the dataset to lead to watertight and vapour open systems under water exposure. Based on the test results it was also deemed beneficial to use masonry specimens to account for its composite nature, rather than using results obtained from brick and mortar separately to infer the wall response under exposure.

Keywords: waterproofing, water repellence, surface treatment, brick masonry, water vapour transmission, hydrophobicity, absorption, wind-driven rain (WDR)

1. INTRODUCTION

Masonry is the traditional and most common construction method (Barlow, 2000; Ross, 2002), representing some 91% of all homes in the UK (MHCLG, 2013). A sizable portion of these, however, including some more recent cavity wall typologies, remain uninsulated, as various insulation options to tackle their poor energy performance have been shown to have important potential unintended consequences in case of moisture enrichment through capillary action or water ingress through building defects. The 'Hard to Treat Homes' report by BRE (2008) indicates that, due to the high permeability of conventional masonry walls, most commonly used insulation materials are not suitable for facades subjected to moisture ingress due to exposure. Wind-driven rain (WDR), which affects the hygrothermal performance and durability of building facades (Lacasse & Vanier, 1999, D'Ayala & Aktas, 2016; Stephenson et al., 2016), is a critical source of moisture ingress into exposed masonry. Moisture enrichment and water penetration into the building fabric composed of porous building materials can lead to serious problems such as ineffective insulation, freeze-thaw damage, biodeterioration and indoor mould growth, and cracking due to thermal and moisture gradients, which are common problems exacerbated by WDR (Franke et al., 1995; Lü, 2002; Aktas et al., 2017).

The UK government has a fuel poverty target and interim milestones that require improving the energy efficiency of fuel poor homes, which are estimated to account for more than 10% in England, 12% in Wales, 18% in Northern Ireland and 25% in Scotland of the residential building stock (Hinson and Bolton, 2020; BEIS 2020). Therefore enhancing the energy efficiency and hydrothermal performance of the existing UK building stock has been the focus of intense governmental efforts: In the last five years, the Energy Company Obligation (ECO; the current scheme launched in 2018 and runs to 2022), Warm House Discount (WDH; extended to 2021) and the Private Rented Sector Regulations were released to address fuel poverty by requiring building performance to meet the Minimum Energy Efficiency Standards: Following the consultation reports issued by the Department of Energy and Climate Change (DECC, 2015a&b), Department for Business, Energy & Industrial Strategy (BEIS) released the Domestic and Non-Domestic Minimum Energy Efficiency Standard (MEES) Regulations in 2017 and 2019, respectively (BEIS, 2017; BEIS 2019). All these efforts call for energy efficient retrofit measures to be implemented, which, however, should rule out adverse impacts of increased insulation and airtightness.

As buildings become more energy efficient through insulation and particularly where their ventilation is not upgraded leading to lower air infiltration rates, they become more sensitive to moisture risks. Certain commercially available water-repellent surface treatment products applied directly to the outer surface of the walls have been proposed as a solution to reduce moisture ingress, WDR-induced or otherwise, while not impairing walls' capacity to permeate water vapour, protecting the fabric from associated risks. That these products are colourless and therefore do not change the appearance of the wall they are applied on resulted in a significant amount of work examining their potential for use on historic stone facades especially from the 1960s onwards (e.g. Charola, 1995; Tsakalof et al., 2007). This paved the way for more recent studies to focus on their application on existing buildings with specific emphasis on minimizing moisture induced risks accompanying insulation and other retrofit measures, and the subsequent enhancements in thermal performance, energy efficiency and comfort (e.g. Odgaard et al. 2018; Jensen et al., 2020).

Some of the previous research on the hygric behaviour of treated brick and mortar specimens showed that these products were successful in increasing the hydrophobicity of the tested materials: Soulios et al. (2020) in their study focus on common silicon-based water repellents confirmed that they were successful in impregnating brick and mortar to reduce water ingress with minimal impact on the overall pore structure, while keeping permeability to water vapour in place (Soulios et al., 2020). Esteves et al., (2019) investigate the impact of three different types of hydrophobic treatments on stone, render and an external thermal insulation composite system, concluding that while the surface treatments indeed improved surface water repellence, they adversely affected the drying speed and "breathability", drawing attention to the product-substrate compatibility. This is in broad agreement with the findings of Biscontin et al. (1995) and de Witte et al. (1996), and later of Borsoi et al. (2020) on the durability and long-term implications of such treatments. Slapø et al. (2017) in their study based on testing of full brick masonry walls under WDR exposure conclude that surface water repellents are unable to improve the wall performance under exposure, while the results obtained by Hansen et al. (2018) indicate significant reductions in moisture ingress into brick solid masonry walls under rain, especially when treated using silane-based products. Similarly, a cream emulsion product has been shown effective to reduce water enrichment under exposure, and to subsequently improve thermal performance and the associated energy demand through reduced thermal conductivity (MacMullen et al., 2011). Surface waterproofing by water repellent treatment products was also shown by hygrothermal simulations to potentially make capillary active insulation feasible (Finken et al., 2016), by ruling out the moisture induced risks associated with its use (Vereecken and Roels, 2015), which highlights their benefits possibly extending to reduction of energy demand in buildings.

As seen, there is contradictory evidence regarding the performance of walls treated with surface waterproofing products depending on the product's chemical composition and the wall characteristics. Even when the obtained results are favourable, the extent of performance improvement of treated walls exposed to WDR is highly debated and therefore, the extent to which it can be considered a viable option to meet the governmental targets on reduction to fuel poverty and increase of energy efficiency, at the national scale, remains substantially undefined.

To this end, a research project was commissioned in 2017 by the Department for Business, Energy & Industrial Strategy (BEIS) to a consortium comprising UCL and BRE. The aim of the project was to examine if cavity walls treated with surface waterproofing products indeed provide a safe barrier to WDR-caused moisture ingress, and hence could potentially allow the introduction of insulation materials in the cavity as an effective retrofitting measure for a significant number of UK properties (Energy Savings Trust, 2016). The study utilised a range of assessment methods to investigate the potential impact of waterproofing treatments on brick-masonry cavity walls; from desk-based research to establish the most appropriate wall types and treatments for investigation, and through benchtesting of small size specimens, to larger cavity walls tested under WDR exposure and environmental conditions in an indoor-outdoor environmental chamber.

This manuscript reports on the findings from the desktop research and benchtesting stage of the project preceding the full scale WDR testing of cavity walls. The aim of the benchtesting was to quantify the variation in performance of water-repellent surface treated materials under exposure through water vapor resistance, hydrophobicity and water absorption testing of the selected waterproofing products on brick, mortar cubes and small size masonry specimens. To this end, 4 waterproofing treatment products of different compositions and 3 brick types representative of the UK cavity wall building stock built in the '50s and '60s were used. The findings of the benchtesting were used to inform which treatment product(s) were to be used at the full-size wall testing stage – it is intended that the findings of this second stage are reported in a separate paper.

This paper is organised as follows: Following the introduction and problem definition in Section 1, the selection of brick, mortar and waterproofing treatment products for the testing scheme is detailed in Section 2, and the specimen preparation and testing protocols for water vapour transmission, hydrophobicity and water absorption tests in Section 3. The results are presented and discussed in conjunction with the previous literature in Section 4 along with the potential mid- to long-term implications under actual service conditions, and the paper is concluded in Section 5.

2. SELECTION OF MATERIALS

Given the national ambition of the project, prior to the commencement of the testing, a thorough desk-based investigation was carried out to identify the most appropriate wall materials (brick and mortar) for the study to ensure relevance of the findings to a significant portion of the UK building stock, and to also represent a good cross-section of the commonly used commercially available waterproofing products of different chemical compositions. The criteria used for the selection of building materials and surface waterproofing products are discussed in the rest of the section.

2.1. Brick

In order to identify the bricks for the study, characteristics of the existing masonry cavity wall constructions across the UK were examined to ensure that the testing scheme would be representative of the majority of the stock, focussing on sizes, types, manufacturing techniques and physical properties as follows:

Size: RIBA and Brick Makers Association set standard dimensions for kiln fired clay bricks in 1904, which were later adopted by BSI. These sizes were slightly reduced to the metric units as 215 x 102.5 x 65 mm in 1970. Bricks typically in use from the time at which cavity walling was introduced (late 1800s) onward are all standard bricks (Hammett, 2013), therefore this was the size chosen for the study.

Type and manufacturing technique: Research reports from BRE (then BRS) indicate that by the 1950's advanced wire cutting processes were in use (BRE, n.d.). Despite improvements in manufacturing, brick production includes poor- and high-quality bricks (also known as stock and facing grade bricks), although the quality and consistency of both are subjected to much improved quality control. It was therefore assumed that bricks typically used for cavity construction were produced via controlled manufacturing processes of pressing or extruding similar to modern bricks. These also had a 'frog' or holes to reduce the amount of clay used and aid firing, making them cheaper and lighter to handle, and to help the mortar adherence.

Physical properties: It is not apparent from the literature if bricks with particular physical properties have dominated construction since the introduction of cavity walls, although due to regional variation in raw material supplied it is highly likely that bricks covering a wide range of properties will be present across the UK. Based on this, and since the application of the waterproofing treatments were anticipated to alter the hygric performance of bricks, it was considered valuable to test treatments on bricks with both high and low water absorption rates. Similarly, texturing can be very diverse in bricks and because it defines resistance to the runoff of water and therefore is potentially a contributing variable towards the effectiveness of waterproofing treatments, it was deemed appropriate to test both smooth and textured bricks.

Therefore, in this study machine-made clay bricks with standard size 215 x 102.5 x 65 mm with frogs or holes were chosen. In order to account for the variations in the density and surface finish properties within the building stock the following 3 representative brick types shown in Figure 1 were adopted: (I) A more porous/less dense brick with a rough surface finish (manufacturer's reported gross density equal to 1600 kg/m^3); (b) A less porous/more dense brick (low moisture absorption) with a smooth surface finish (manufacturer's reported gross density equal to 1700 kg/m^3); and (c) A more porous/less dense brick with a smooth finish (manufacturer's reported gross density equal to 1550 kg/m^3).

Figure 1: Brick types: I. more porous/less dense brick with a rough surface finish (perforated); II. a less porous/more dense brick with a smooth surface finish (frogged) and III. a more porous/less dense brick with a smooth finish (frogged)

2.2. Mortar

While prior to 1930s lime mortar was the norm, by the mid-1930's concerns started to arise on the quality of lime mortars due to regional variations in production and a lack of standards for materials and methods of mixing them. The move towards cavity walls also required stronger mortars due to single skin thicknesses, and hence between the 1930s and 1960s cement mostly replaced lime for mortar production. BRE (then BRS) Digest 58, 'Mortars for jointing', suggests that in areas of severe exposure as defined by BS 8104, mortar of a 'designation 3' standard was recommended for external walls; ratios of 1:1:5-6 cement : lime : sand (non-hydraulic lime) or 1:6 cement : sand would meet this standard (BRS, 1965). The traditional mortar designations were then superseded in 2002 by mortar 'classes' in BS EN 998-02. Comparison between The Mortar Industry Association Dataset 03 and BS EN 998-02: 2010 shows that the current mortar class equivalent to the designation 3 mortar is M4, which is recommended for moderate exposure areas, as defined by BS 8104, since 2010. In any case it follows that certainly for external walls built from the 1960s onward, but also likely from the mid-1930s onward for cavity walling, cement-based mortar will have been used to deliver the required strength and speed of building. It was therefore proposed that in this study a predominantly cement mortar be used in the laboratory testing, with the addition of non-hydraulic lime to improve workability of the mix and assist in achieving the required jointing finish. Cement-lime mortar has good working, water-retention and bonding qualities, and also develops early strength without an excessively high mature strength. These advantages made it the most useful general-purpose mortar (Seeley, 1974) and was found most suitable for the tests in this study as it is very common in the building stock under examination.

Limited historic information has been found relating to sand granulometry and composition, and any potential variation in its use across the UK. Although there may be some regional variation in locally sourced sand, it would be expected that soft sand with smoother particles (also known as builder's or bricklayer's sand) would always have been favoured to provide the workability required for bricklaying.

In this study, in addition to individual brick and mortar specimens, small masonry specimens were used to account for the composite nature of masonry while investigating the impact of surface waterproofing on its performance under WDR exposure. This required a decision on the shape of jointing to adopt. Although no references have been found to indicate the most common jointing/pointing type on cavity walls over the last century, weather struck or concave (also known as bucket handle) joints should have been the dominant type in areas of high exposure to rain, as both techniques encourage the runoff of water from the joint surface. The latter was chosen for this study due to its relative ease of implementation.

2.3. Waterproofing products

A market analysis of available waterproofing treatments was carried out to identify representative product(s) for laboratory testing. Information was obtained, where available, on the product composition, expected coverage, indicative cost (per litre), performance claims and any relevant certification achieved (e.g. BBA - British Board of Agrément Certification). Initial internet searching was supplemented with requests for further information directly to manufacturers. Overall, 60 products were identified with varying levels of information. Of these 43 had an identifiable product "type" which broadly fell into one of the following three categories:

- Acrylic (n=3)
- Stearates (n=3)
- Silane/Siloxanes (or blends) (n=37, 11 of which were creams)

Although silane/siloxanes or blends appeared to be the most common type, it was decided to use 3 different products, one from each of these three categories, plus an additional silane/siloxane cream to allow comparison of the ease and relative merits of the application of creams versus liquids and whether this fundamentally impacted on subsequent performance.

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 was declared and guaranteed (with preference to those offering longer lifespans);
3. Whether the product was 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;
5. If remaining products otherwise appear to have the same criteria, the cost per m^2 wall coverage would be considered.

The above factors resulted in the selection of four specific products for benchtesting. Basic characteristics of these, incorporating also the limited amount of information disclosed by the manufacturers, are summarised in Table 1.

Table 1: Products selected for testing in this study

Product type	Service life	Number of coats	Amount of product per application	Notes
Acrylic-based liquid	10 years	2 if the substrate is absorbent	2-6 l/m^2	No resistance performance claims
Silane/siloxane blend cream	25 years	1	5 l/m^2	BBA certification with claimed resistance rates
Silane/siloxane blend liquid	10 years	1	10 l/m^2	No resistance performance claims. Solvent free and can be applied to damp walls
Stearate-based liquid	10 years	2	2.4-3 l/m^2	Major component polyoxoaluminium stearate. Independent performance testing with claimed resistance rates

Surface hydrophobisation via **acrylic**-based repellents, commonly used in the past for conservation purposes (Charola, 1985) is done through (co)polymerisation of mainly acrylic acid, and then esterified using alcohol, the type of which affects the appearance of the repellent on the substrate (i.e. the level of sheen or gloss; see McGettigan, 1995). Acrylic resins are film-formers, i.e. their waterproofing impact is achieved through a continuous film on the substrate surface, as opposed to penetrants also lining the substrate pores near the external surface, such as silanes and siloxanes (Bader et al., 2019; Christodoulou et al., 2013). These latter are silicon-based materials and they irreversibly bond with the substrate (Roos et al., 2008). **Silane** treatments usually form a thin hydrophobic film, i.e. a physical barrier on the substrate surface by polymerizing and linking chemically through -Si-O- bonding to the hydroxylated surfaces of siliceous building materials (e.g. brick, concrete, granite, sandstone), providing anchorage between the hydrophobic film and building substrate to act as a coupling agent (Lyons, 2014). The monomeric low-weight molecules and low reactivity of silanes often gives great penetration depths, even in alkaline substrates such as concrete (Roos et al., 2008). At the same time, silanes are highly volatile. To meet the desired performance rates high concentrations of active content are required, mostly higher than 25% and up to 100% (Soulios et al., 2020; de Vries and Polder, 1997). **Siloxanes** are similar to silanes in that that they irreversibly bond with siliceous or aluminous materials. As chemical compounds with alternating Si and O atoms, the dimensions of siloxane molecules are larger than those of silanes, and the structure is more complex. Thus, siloxane treatments have more difficulties in penetrating building materials. Siloxanes are mostly used in more porous and more pH neutral mineral substrates (e.g. brick, natural stones, and aged concrete) as they are not able to penetrate deep into highly alkaline substrates due to the fast curing process. Siloxanes are less volatile than silanes so the needed active content is usually no more than 10–20% (de Vries and Polder, 1997), and using higher concentrations will raise the risk of darkening the surface (Roos et al., 2008). Silanes and siloxanes do not plug the pores of the porous building materials they are applied on, but change their surface tension with respect to water. This is what makes these water repellents liquid water-tight but vapour-open, as water vapour does not have a surface tension (McGettigan, 1995; Roos et al., 2008; de Vries and Polder, 1997). Silane/siloxane blends such as the two products used in this study are common, and the silane to siloxane ratio in these is determined based on the density and permeability of the substrate: for dense, less permeable surfaces a high silane content is preferred, and vice versa (Lyons, 2014). Finally, **stearates** are commonly known as metallic soaps (metal salts of fatty acids), and act as a water repellent by reacting with free salts in the building materials they are applied on, and filling their pores (McGettigan, 1995; Roos et al., 2008) proving therefore effective in reducing water ingress when applied on the surface and added into the mixture (e.g. of adobe; see Lanzón et al., 2017).

3. TESTING

The performance of construction elements to environmental moisture and specifically to WDR is best understood by considering the continuous and holistic process composed of 3 distinct stages, as shown in Figure 2: first the extent of contact and adherence of water droplets at the wall surface (A), then wetting and absorption once the water repellence of the treated wall surface is surpassed (B), and finally drying by evaporation of the water within the wetted wall (C). Correspondingly, the benchtesting in this study includes hydrophobicity, water absorption and water vapour transmission tests on brick, mortar and masonry specimens. The methodologies of each of these tests and corresponding findings are provided below in the reverse order to reflect the relative importance of the 3 phenomena in terms of long-term performance and potential unintended consequences of surface waterproofing.

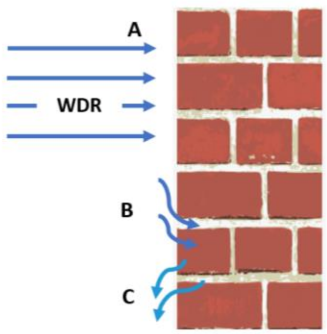

Figure 2: Diagram showing the lifecycle of the wall response to WDR exposure in the form of a 3-stage process: A – First contact of water droplets with the wall surface. Performance appraised via hydrophobicity testing in line with BS ISO 19403-2:2017, B – Wetting and absorption once the hydrophobic capacity of the wall surface is surpassed. Performance appraised via water absorption testing in line with EN ISO15148:2002, C –Drying by evaporation. Performance appraised via water vapour transmission testing in line with BS EN ISO 12572:2016.

3.1. Water vapour transmission test

3.1.1. Specimen design

Similar to the semipermeable coating for building materials proposed by Ruid et al. (2005), the waterproofing products tested here are claimed to be essentially watertight but water vapour permeable, which is a critical property in determining the propensity to envelope decay in case of water ingress through defects in the fabric or capillary suction. In order to define the overall water vapour resistance, small-size masonry specimens were used to ensure a better representation of the composite nature of masonry constructions than brick or mortar alone (Binda et al., 2000; Larbi, 2004) and hence a more accurate representation of the actual vapour transmissibility of the composite. To this end, two sleeves were cut from the external surfaces of bricks were then bonded together with a 10 mm mortar joint to produce specimens for the water vapour transmission testing.

In order to measure the water vapour transmission properties of the treated and untreated masonry specimens, BS EN ISO 12572:2016 was used. By considering the different frog/perforation locations on each type of brick, 28 mm final thickness was targeted for the specimens, which is larger than the 20 mm minimum thickness enforced by the BS EN ISO 12572 to ensure that there was no brittle failure of the brick, or development of cracks during cutting. The bricks were cut with a wet saw to the desired dimensions and subsequently dried at 22°C and 45% RH until a constant weight was reached (Figure 3).

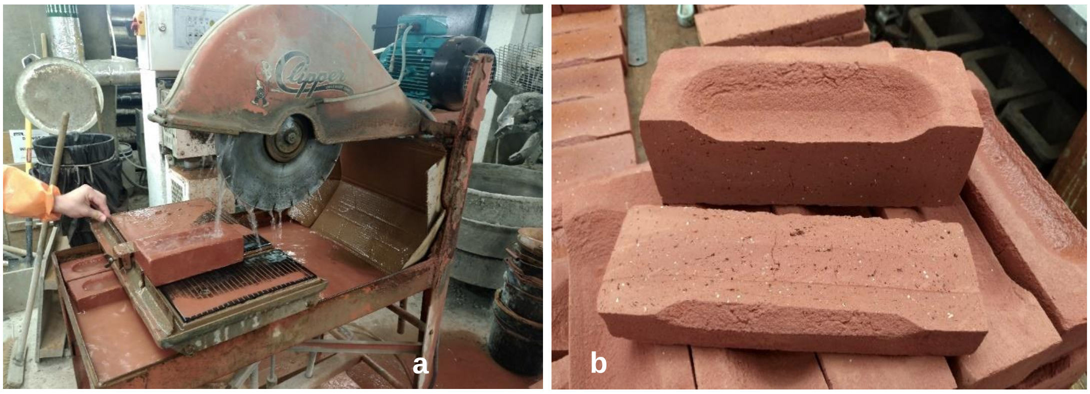

Figure 3: a) Brick wet saw cutting, b) 28 mm thick specimens cut from one side of brick

While preparing the mortar mixture, in order to ensure that the particle content was suitable to the requirements of the standard that was in effect when the building stock under examination was being built, BS 1199 and 1200 (1976) were used for the sieve analysis. A sample was taken from each bag of sand for grading. The grading curves for the two batches of the sand used in the test as well as reference grading curve, and upper and lower limits for the grading of building sands from natural resources for mortar for brickwork from the mentioned standards are shown in Figure 4.

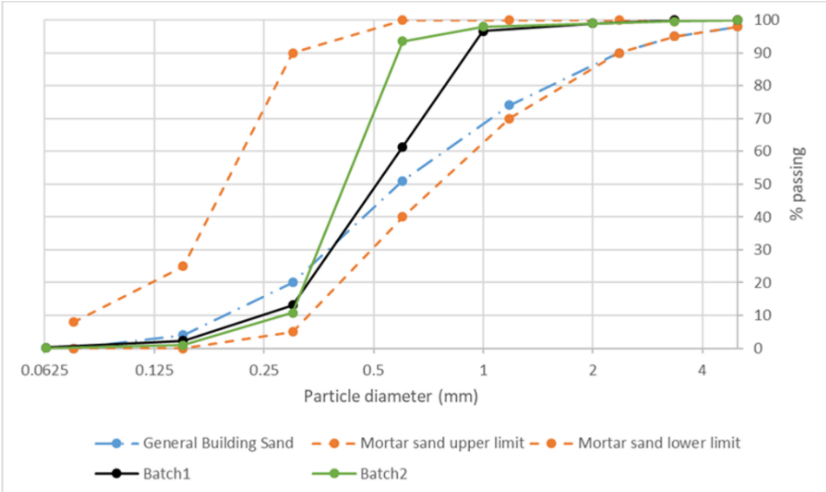

Figure 4: Grading curves for 2 bags of sand and reference sand, and upper and lower bounds as per BS 1199 and 1200

In general, the grading curve of both bags of sand were within the range provided by the abovementioned codes. However, it is also observed that both bags had fewer sharp particles of large size and the content size was more concentrated on the medium size particles. In relative terms, more fines in a sand will demand more water, due to higher surface area to be wetted. A higher proportion of fines in sand and the consequent high-water content in the mortar will promote shrinkage and would lead to higher risks of de-bonding and cracking in lime mortars (Reddy and Gupta, 2008). As a result, particular care was taken during the curing of the mortar to avoid cracking. Bricks were moistened during the assembly, in line with the general practice of building a masonry wall. Once assembled using concave joints of 10 mm thickness, all masonry specimens were covered with an impermeable sheet to act as a vapour barrier for 3 days, and then stored for 25 days at 23±2°C and 50±5% RH for curing covered with a hessian cloth. The dimensions of the specimens were measured after the curing and were used in the calculation of the vapour flow rate. 15 specimens were prepared for each treatment case, leading to 75 specimens in total with average dimensions (L x W x d) equal to 137.9 mm (±2.0) x 214.3 mm (±1.2) x 27.4 mm (±1.05). The specimens were carefully cleaned to remove small particles before applying the selected waterproofing treatments as per the application procedure recommended by the manufacturers (Figure 5).

Figure 5: Masonry specimens

In this study, instead of the standard cup detailed in BS EN ISO 12572:2016, a box (wet cup) was designed to accommodate the larger size masonry specimens. The box was built of plexiglass for transparency and durability, and cut by a laser cutter to ensure precision and hence the airtightness of the boxes once the masonry specimens were fitted, as shown in Figure 6a&b. Screws and silicon sealing were used on the box frame to add additional reinforcement and pre-compression to avoid moisture leakage and keep the box perfectly sealed during the test. Silicone and foam tape were used to provide connection and airtightness between the specimen and the plexiglass frame. Foam tape acted as a buffer to transfer the compression evenly from the frame to the specimen avoiding damage to the specimen, while the silicone helped seal the edges of the foam tape to form an airtight layer around the frame. This was essential as each specimen is slightly different due to the nature of brick manufacturing. With the combination of foam tape and silicone, a well-defined upper specimen surface area without "masked edges" could be provided as per the BS EN ISO 12572:2016 requirements.

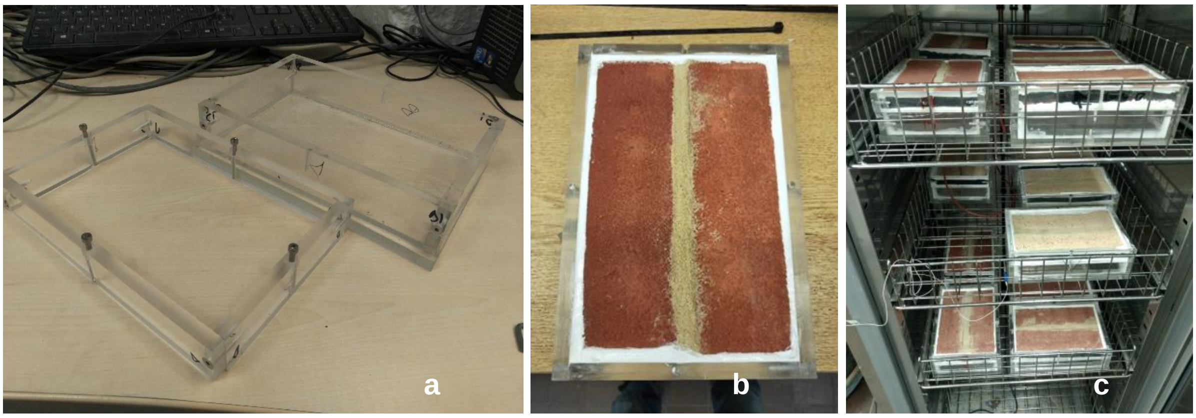

Figure 6: a) Plexiglass box, b) Top frame of the box with specimen installed, c) Temperature and humidity control chamber with testing boxes

3.1.2. Test process

As the aim of this test was to study the water vapour transmission properties in high moisture conditions, the 'wet cup' method was considered the most suitable of the two proposed by the standard. The test setup was composed of the specimen with surface of interest facing down sitting on top of a cup containing an aqueous saturated solution based on ammonium dihydrogen phosphate ($NH_4H_2PO_4$) maintaining the target humidity level, i.e. wet state (93±5% RH according to BS EN ISO 12572:2016).

The test was divided into 5 batches with 1 reference batch without waterproofing treatment and 4 additional batches, each treated with a selected waterproofing product. Each batch consisted of 15 boxes with every 5 boxes using one of the three brick types as a minimum of 5 specimens of the same material is required by the standard.

Before assembling the whole box, the specimens encased in the top frame were kept in an environmental chamber for 2 days for conditioning at 23°C temperature and 50% relative humidity (RH). Then, 15 boxes were fully assembled for each batch, with $NH_4H_2PO_4$ solution at the bottom of the box maintaining 93%, weighed and placed back in the test cabinet (Figure 6c). Due to the humidity difference between the test box and the chamber, a vapour flow driven by the partial vapour pressure occurred through the specimens.

A total of 72 continuous hours of mass change were recorded with a weighing interval of 24h, thus 4 values were used in the calculation of water vapour resistance for each box. Each box was weighed 5 times at each interval. BS EN ISO 12572:2016 suggests carrying out the weighing of the specimens in an environment with a temperature within ±2°C difference of the test condition, and wherever possible, within the test chamber. In this study the weighing was carried out on a stable bench next to the chamber using a scale with accuracy of 0.01g, as required by the code. The boxes were exposed to the lab relative humidity and temperature for approximately 5 minutes in each weighing cycle. This was not considered to lead to any significant alteration in the specimens' moisture content.

For each set of successive weighing of the specimens, the mass change rate (*G*, kg/s) was calculated and averaged over five measurements. Then, water vapour permeance (*W*, kg/(m^2.s.Pa)) was calculated for each test case by dividing the average mass change rate (*G*, kg/s) by surface area of the specimen (arithmetic mean of the free top and bottom surfaces) (*A*, m^2) and water vapour pressure difference across the specimen (Δp, Pa), which was chosen as 1207 Pa as recommended by Table 2 in BS EN ISO 12572:2016 for set C defined as 23°C and 50/93% RH testing conditions. Based on this, water vapour permeability (δ, kg/(m.s.Pa)) was calculated by multiplying water vapour permeance (*W*, kg/(m^2.s.Pa)) by the specimen thickness (*d*, m). Finally, the water vapour resistance factor (μ, unitless) was calculated by dividing the water vapour permeability of air (δ_{air}) by the calculated water vapour permeability of the specimen (δ), producing the equation shown below:

$$\mu = \frac{\Delta p * A * \delta_{air}}{G * d} = \frac{\Delta p * \delta_{air}}{g * d} \tag{1}$$

where *g* is the density of water vapour flow rate (kg/(m^2·s)), calculated by dividing water vapour flow rate through the specimen (G, kg/s) to surface area (A, m$^{2)}$ for each specimen, and *d* is the mean thickness of specimen (m).

The water vapour permeability of air (δ_{air}) was estimated as 1.95×10^{-10} kg/(m.s.Pa) using the standard barometric pressure based on Figure 2 of BS EN ISO 12572 titled "Water vapour permeability of air as a function of barometric pressure at 23°C". This value is further verified using the two versions of the Schirmer formula shown in Eq(2) (Maillard et al., 2014), and Eq(3) (Slanina et al., 2009) adjusted to the units used in the present study.

$$\delta_{air} = \frac{2.306 \cdot 10^{-5} \cdot p_0}{R \cdot T \cdot p} \left(\frac{T}{273}\right)^{1.81} \tag{2}$$

$$\delta_{air} = \frac{1.97 \cdot 10^{-7} \cdot T^{0.81}}{p} \tag{3}$$

where *R* stands for the gas constant of water vapour and is equal to 462 Nm/(g.K), *T* stands for temperature and is equal to 296.15K (equivalent to 23°C), p_o stands for standard barometric pressure equal to 101325 Pa and *p* stands for barometric pressure in the lab. This last parameter was measured during all water vapour transmission tests and was taken equal to p_o in the calculation as it was observed not to diverge more than 0.001% from the standard barometric pressure in the environmental chamber.

3.2 Hydrophobicity test

3.2.1. Specimen design

This test aimed to quantify the level of hydrophobicity (or wettability) of the masonry surfaces after treatment with waterproofing products. The specimen sizes were dictated by the testing equipment chosen for the test, the Drop Shape Analyzer (DSA) 100 manufactured by KRÜSS, whose testing platform allows specimens of a maximum size 100 x 56 x 28 mm. Therefore, brick specimens of this size were used. Mortar specimens were not tested for this parameter as producing specimens of this size was not possible.

3.2.2. Test process

The method in BS ISO 19403-2:2017 requires determining the surface free energy of a solid surface by measuring the contact angle of different liquids on it. The contact angle is representative of the surface tension and the surface free energy of the specimen, hence providing a quantitative basis for the "wettability" of the surface. The higher the contact angle the higher the hydrophobicity is, i.e. the lower the wettability is. The

DSA100 allowed the surface tension to be calculated automatically with successful determination of the contact angle.

The test was carried out at the UCL electrochemical lab, where the ambient temperature and relative humidity levels were constantly controlled at 23 ± 2°C and 50 ± 5% RH in line with ISO 3270 (1984), to ensure all test media were under the same hygrothermal conditions. The flat surfaces of all 15 specimens, 3 of each brick types untreated or treated with one of the 4 different surface waterproofing products, were each dosed with 8 water drops on different parts of the surface, and for each drop the contact angle was measured.

3.3. Water absorption test

3.3.1. Specimen design

The absorption test was performed following EN ISO 15148:2002, with the aim of determining the level of absorption of different substrates, untreated and treated with the 4 different waterproofing products. The standard suggests using at least 3 specimens of a surface area of 100 cm^2. For this test, three different types of specimens were used for each treatment: 100 x 100 x 100 mm mortar cubes, 215 x 102.5 x 65 mm standard dimension full bricks, 215 x 140 x 28 mm brick and mortar masonry specimens, as described in section 3.1. Three specimens of each type for each waterproofing treatment and one untreated set were dried and stored in the curing room at 22°C and 55% RH after being carefully cleaned of small particles then brushed with the selected waterproofing treatments.

3.3.2. Test process

The test was carried out inside the curing room where the environment is controlled at 22°C and 55% RH. A layer of mesh was placed at the bottom of a tray to support the specimens and ensure the surfaces of interest were in full contact with water. The water level was maintained at 5±2 mm above the base of the specimens during the test as required by standard (Figure 7).

Figure 7: 3 different types of specimen during absorption test

To prevent water from being absorbed via the side of the specimens, duct tape was used to seal the edges with an extra layer of silicone at the joint between the tape and specimen to ensure the seal was waterproof. To measure the mass change of the specimens, after removal from contact with water, the wet surfaces were blotted with a damp paper wipe and weighed with a scale accurate to 0.1g on a level platform. The procedure of immersion, removal, surface drying, and weighing was repeated at intervals of 5 min, 20 min, 1h, 2h, 4h, 6h, 8h, 10h and 24h.

4. Results and Discussion

4.1 Water vapour transmission test results and analysis

The weight change and calculated water vapour resistance factors (μ) for each different brick type without and with the four waterproofing treatments are shown in Figure 9 and Figure 9. The error bars on the columns are the standard deviation of the 5 masonry test cases with for each brick type and surface waterproofing product.

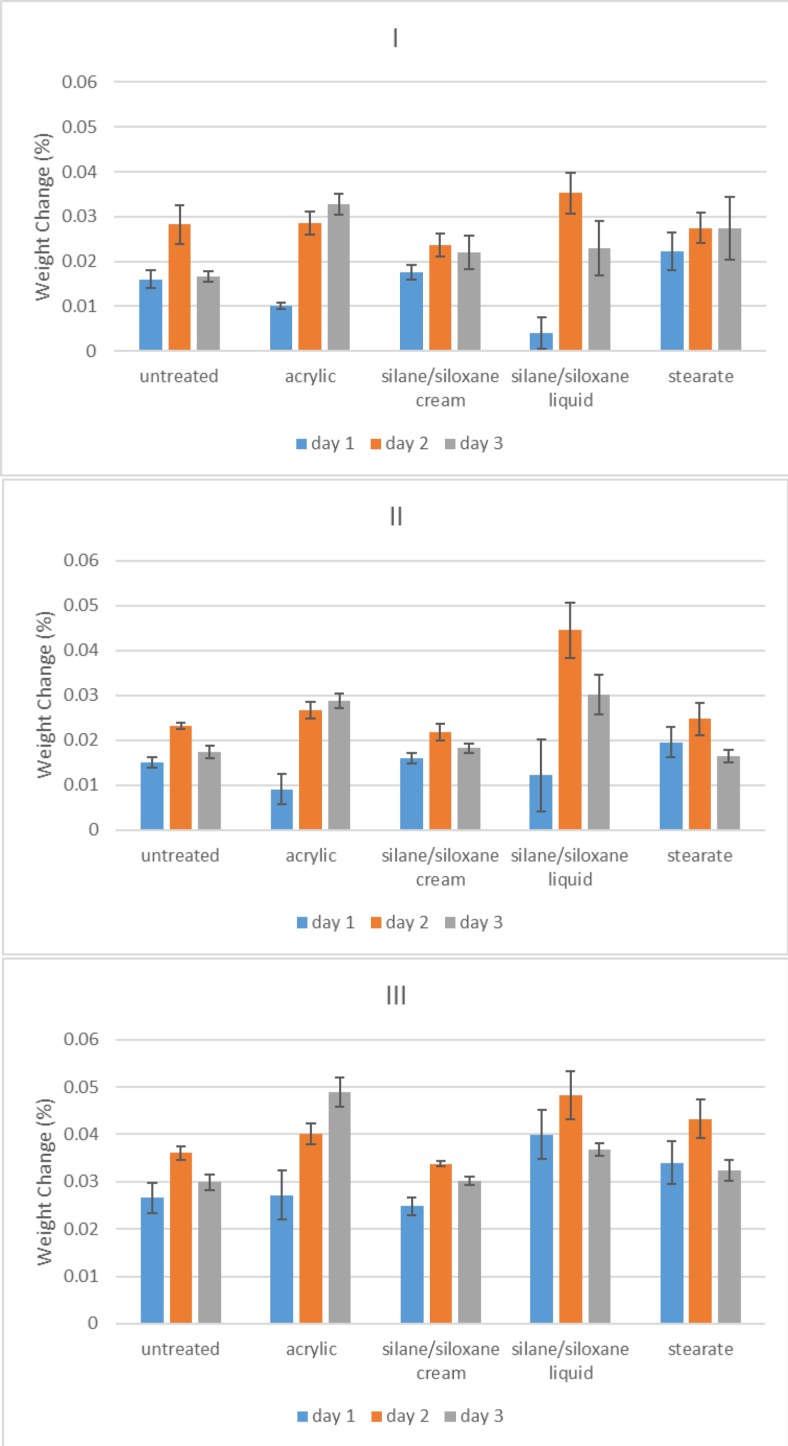

Figure 8: Weight change in three day-long intervals (0-24 h, 24-48 h and 48-72 h) for brick types I, II and III for each treatment case

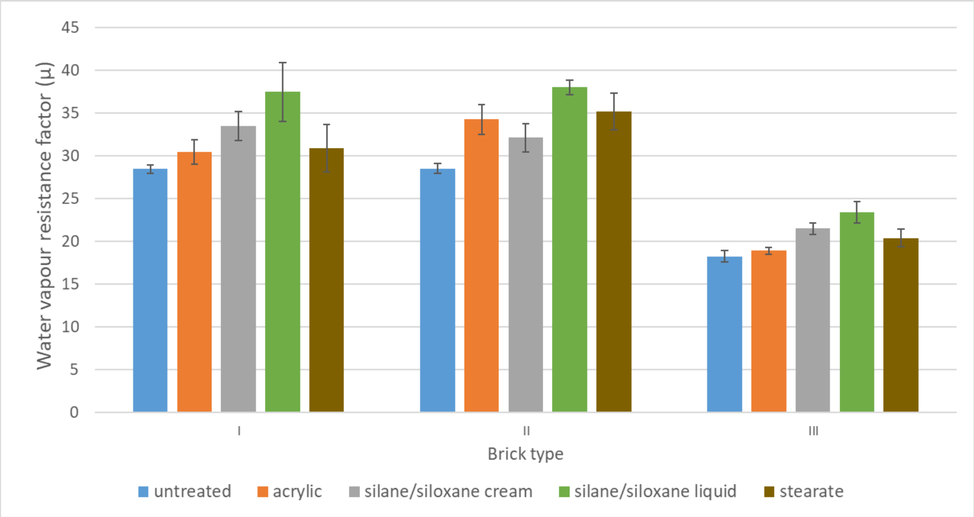

Figure 9: Water vapour resistance factor (µ) of masonry specimens with different brick types and various waterproofing treatments

From the results it is obvious that the water vapour resistance of the test is dominated by the bricks' 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 brick type I. This is likely due to the visibly more heterogeneous structure of brick I, with larger particles, leading to a lower uniformity (see Figure 1). Brick III results, for both untreated and treated cases, demonstrate the highest consistency, with small standard deviation values compared to those reported by previous research (e.g. Soulios et al., 2020).

A comparative review of the results obtained for specimens treated with individual products shows that the silane/siloxane blend liquid led to standard deviations relatively high among all treatments except in combination with brick II. On average, the silane/siloxane blend liquid provides the highest impact on water vapour resistance over all 4 products. Acrylic- and stearate-based products have shown similar performances: They both made a relatively low impact on the water vapour resistance of the treated bricks while the acrylic-based product held more consistent performance over all brick types. On the other hand, the silane/siloxane cream was, by a small margin, the second-best waterproofing product with minimal additional water vapour resistance in case of all brick types.

The water vapour transmission test results indicated that among the three brick types tested, brick type III was the one with the lowest water vapour resistance and showed the impact of various waterproofing treatments most consistently. This brick type was also the less dense among all three brick types used, and therefore it was deemed most critical and was chosen as the only brick type to be employed in the hydrophobicity and water absorption tests.

4.2 Hydrophobicity test results and analysis

Similar to the previous test, first the untreated specimens were tested to provide the reference case, where the water droplets were absorbed fully within 1-3 seconds, depending on surface roughness, uniformity and density of the brick specimens they were dropped on. 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 10. Acrylic- and stearate-based products showed very similar results with no obvious absorption within 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 angle was 113.5° for the acrylic-based product and 114.1° for the stearate-based product (Figure 11a&b).

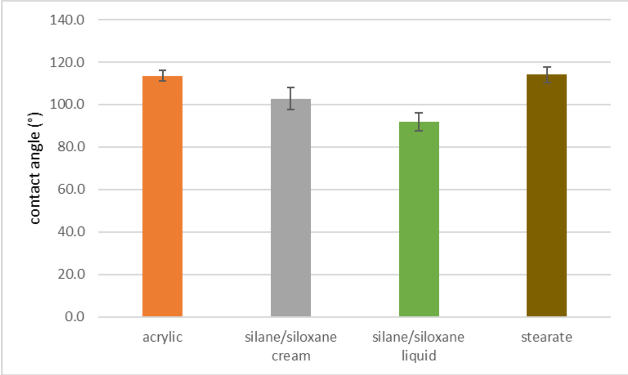

Figure 10: Water contact angles measured for each treated specimen

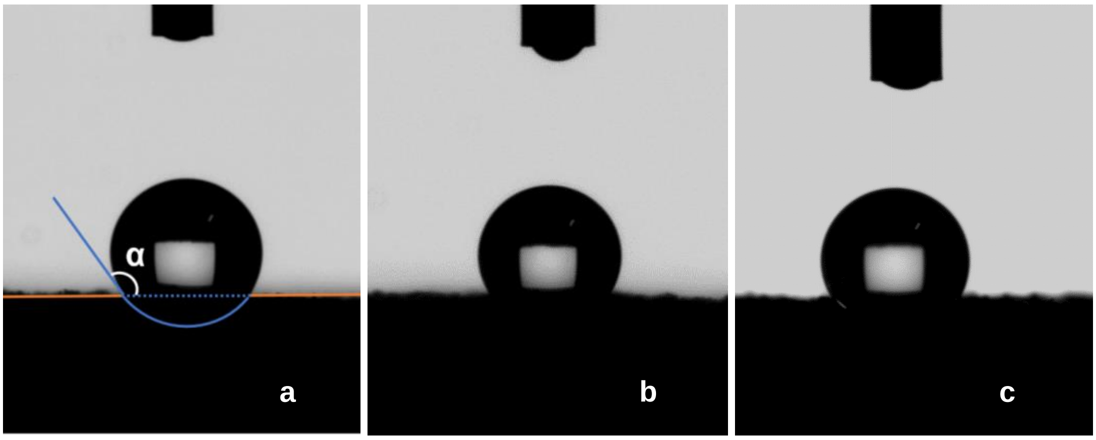

Figure 11: Water drop on specimens treated with a) acrylic-based liquids b) stearate-based liquids, and c) silane/siloxane blend cream. The measurement of contact angle (shown as α) is shown in (a)

Compared to other specimens, those treated with the silane/siloxane blend cream showed 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 brick surface, it was seen that the absorption starting time reduced radially from the centre to the edges of the specimen. On the edge water drop 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 11c). This rather unique characteristic of the specimens treated with this product is considered to be due to its consistency as cream. It can be inferred that the difference was caused by the non-uniformity of application caused by the nature of the product. 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 is acknowledged that this uneven distribution of the product over the surface of the specimen might potentially be due to the small specimen size, and may or may not reflect the product spread over a real-life façade.

In the case of specimens treated with the silane/siloxane blend liquid, 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 12). 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. The contact angle measured and the absorption time for the four products are consistent with the mechanism of hydrophobisation described for each of them in Section 2.3.

Figure 12: Water drop getting absorbed on brick surface treated with silane/siloxane blend liquid

4.3 Absorption test results and analysis

The results obtained from absorption tests are summarised in Figure 13 and Table 2 for brick, mortar and masonry specimens. Each data point is an average of 3 test results for each building material and waterproofing treatment condition. As seen, untreated bricks reach capillary moisture content in about 2h, while for mortar specimens this takes about 4h and masonry specimens also about 2h, although a marginal weight gain is still visible up to 5 hours. Looking into the capillary absorption coefficients (A_{cap}, equal to the initial slope of the curves, calculated using the one tangent method described by Feng and Janssen (2018)), it can be seen that it is higher for mortar (16.5 kg/m^{2}h^{½}) than for brick (10.5 kg/m^{2}h^{½}) and, by a higher extent, than for masonry (8 kg/m^{2}h^{½}). The weight gain measured for the acrylic-treated specimens were considerably lower and flatter than those for untreated specimens, indicating lower and slower absorption. The initial capillary absorption coefficients obtained for the acrylic-treated specimens were ~0.13 kg/m^{2}h^{½} for masonry and brick, and 0.37 kg/m^{2}h^{½} for mortar specimens. Specimens surface treated using a silane/siloxane blend cream show a flat curve with almost no water absorption over all three types of specimens as indicated also by the weight gain figures. The capillary absorption coefficients for cream-treated brick, mortar and masonry were the lowest within the dataset with 0.03-0.10 kg/m^{2}h^{½}. The silane/siloxane blend liquid-treated specimens show very similar performances to those treated with the cream in the case of both brick and mortar, both in terms of amount and rate of absorption, however masonry specimens show the highest absorption among all four waterproofing treatments with a capillary absorption coefficient equal to 0.4 kg/m^{2}h^{½}. The performance of the stearate-based liquid was between that of the acrylic-based liquid and silane/siloxane blend cream. On brick and mortar specimens, their water absorption was closer to the cream-treated specimens, while the masonry specimens' absorption was closer to the acrylic-treated specimens. The capillary absorption coefficient for stearate-treated brick, mortar and masonry were calculated as 0.16, 0.05 and 0.07 kg/m^{2}h^{½}.

Both the weight gain and capillary absorption coefficient values show that the surface treatment is more efficient to reduce capillary absorption in mortar than in masonry. The 24-h long testing protocol in line with the EN ISO15148:2002 is not sufficient to demonstrate the capillary moisture content of the treated brick, mortar and masonry specimens, as the surface waterproofing significantly decreases the rate of water absorption. The standard deviation (S.D.) values obtained here seem generally in line with what reported by previous research: While Borsoi et al. (2020) gives the S.D.s for the A_{cap} values for untreated and treated mortar as 0.031 and 0.001 kg/m^{2}min^{½} (0.24 and 0.008 kg/m^{2}h^{½}), which are mostly consistent with our calculated values although substantially lower than those found in our study for acrylic-treated specimens with the highest S.D.s, Duarte et al. (2020), in their study looking into water absorption through the Karsten tube tests for different types of walls gives values within a wide range from 0.2 to 4.53 kg/m^{2}min^{½} (1.55 to 35.1 kg/m^{2}h^{½}), the lower end of which covers or exceeds our calculated S.D. range.

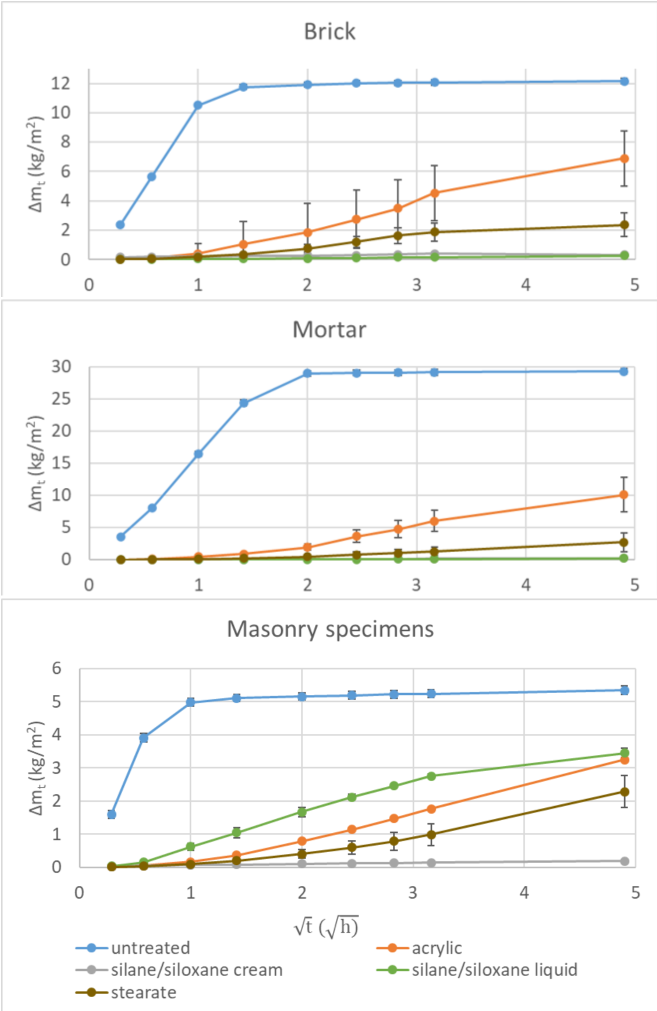

Figure 13: Variations in weight gain due to absorption of brick, mortar and masonry specimens (standard deviation is shown for all cases although this is very low and hard to read for some)

Table 2: Specimen weight gain due to water absorption of brick, mortar and masonry specimens at 24h (%) and the associated standard deviation (%)

Specimen weight gain (%) at 24h / standard deviation						
Waterproofing	**Brick**		**Mortar**		**Masonry**	
Untreated	11.6	0.35	17	0.50	10.7	0.49
Acrylic	7.6	3.52	5.9	3.12	6.7	0.22
Silane/siloxane blend cream	0.29	2.49	0.14	0.01	0.37	0.04
Silane/siloxane blend liquid	0.26	4.73	0.13	0.03	7.1	0.65
Stearate	2.2	1.49	1.6	1.75	4.5	1.90

From the error bars shown in Figure 13, the performance of the acrylic-treated specimens was less consistent as made clear by the large range of standard deviation values obtained for brick and mortar specimens, compared to the masonry specimens, which showed a higher consistency. This can be explained by the fact that the masonry specimens were treated 12 months before the test, while the brick and mortar specimens only 2-4 weeks before the test. We can therefore conclude that the curing time likely has a significant impact on the waterproofing capability of the acrylic based treatment and hence water absorption characteristics of the specimens.

On the other hand, all silane/siloxane blend cream-treated specimens showed little water absorption compared to all other specimens for all specimen types. The results were also very consistent, with very minor standard deviation values, making the blend cream the most effective and consistent product of all selected treatments in terms of water absorption. The silane/siloxane blend liquid-treated specimens showed very close performance and consistency in mortar and brick specimens. However, the absorption by the masonry specimens are noticeably higher. Considering the consistency of the results obtained from the masonry specimens was well maintained, this can be indicative of performance decay as the masonry specimens were treated 12 months before the test and had been exposed to a high RH environment during the water vapour transmission test.

4.4. Discussion

The present paper examined the hydrophobicity, water absorption and water vapour transmission properties of brick, mortar and small masonry specimens for an appraisal of the performance change induced by various waterproofing treatment products under exposure. The three benchtests were intended to simulate different stages of water ingress in real-life as shown in Figure 2. Hydrophobicity test results are representative of the response when rain drops first hit the surface of the walls: the larger the surface contact angles and the longer the water absorption times the more hydrophobic (or the less wettable) the surface is. Surface hydrophobicity, promoting surface run-off, shortens the duration of contact between the surface and the water droplets, and is therefore the first barrier to capillary suction and water penetration into porous building materials. Absorption tests are indicative of the propensity for water ingress once the surface water repellence is surpassed and capillary action is possible. Finally, the water vapour transmission test results show the impact of surface treatment on the capacity of building materials to permeate water vapour back into the external environment, and therefore indicates ease of drying under suitable conditions: the lower the water vapour resistance the easier for the water vapour to escape into the external environment – a mechanism which helps make unintended consequences of insulation less probable in a building context. These 3 benchtests give a thorough and holistic understanding of the essential performance indicators of various water-repellent surface treatment products under water exposure. A summary of the results obtained from these tests are given in Table 3 with a colour-coding adopted to indicate relative performances of different waterproofing treatment products – green and red shows the most and the least favourable outcome within this particular dataset for a given test, while yellow indicates intermediate performance.

The results obtained from untreated specimens exhibit a highly wettable base-case (immediate surface absorption) with a high water absorption capacity with more than 10% weight gain in masonry specimens (Table 2), and water vapour resistance factor (μ), equal to 18.23 on average, comparable to generic values assumed by WUFI for lime-silica brick, i.e. μ=18 (WUFI, 2009) (Figure 9). Considering the 28 mm thickness (t) of the specimens used for water vapour transmission tests, the equivalent air layer thickness (S_d) for untreated masonry can be calculated as μ*t = 18.23*0.028 = 0.510 m, confirming that these are materials with high vapour permeability (Pihelo et al., 2016).

In light of this base-case, the acrylic-based liquid, with a quoted 10-year life span with “no resistance performance claims”, significantly improved the surface hydrophobicity, by inducing a high water-repellence as indicated by the contact angle equal to 113.5°, and by forming an effective physical barrier on the surface which can hold the water droplet for the 20 min test duration. However, its performance in the absorption test was poorer compared to other products. The masonry specimens treated with the acrylic-based product were cured for longer periods, and these showed a lower reduction in water absorption compared to the base-case, with, however, a higher consistency than freshly treated brick and mortar specimens. This may be due to longer curing time or exposure to high RH environments, although Chen et al. (2020) suggests a viscoelastic recovery of acrylic coatings under elevated RH due to water uptake. Therefore, the impact of curing and long-term performance of the treatment under weathering agents should be investigated systematically beyond the current, rather limited, state-of-the-art (see Kozak, 2015; Bader and Lackner, 2020). Acrylic-treated specimens exhibited the best performance within the test-set by a large margin in terms of water vapour transmission with only 3.6% increase in the vapour resistance factor in reference to the base-case (for a similar finding see Bader et al., 2019). This suggests that acrylic-based products are able to keep the water out for the entire test duration (20 min) and more efficiently thanks to the strong surface repellence they help build, and although they allow rapid and high water absorption once the surface hydrophobicity is surpassed, they still allow efficient drying with “breathability” levels almost equal to an untreated surface, reducing the risk of long-term damage to building fabric as a result of moisture ingress.

The silane/siloxane blend cream was the only cream product among the 4 tested products, and it has a longer quoted life span of 25 years as opposed to 10 years for other products. It is also the only one with BBA certification and claimed resistance rates. This treatment led to a significant improvement in surface hydrophobicity with 102.8° average contact angle, but not as good as the acrylic treatment. The performance of the blend cream in the water absorption tests was excellent: the results show up to 96.3% reduction in the water absorption by masonry specimens with respect to the untreated ones, with very good consistency. Silane's and silane/siloxane blends' strong capacity to reduce water absorption under immersion has been reported also by other scholars (e.g. Pinto and Rodrigues, 2000 and Roos et al., 2008). It however led to the second highest average water vapour resistance within the test-set, with an approximately 18% increase in the resistance factor. These results indicate overall good performance through the lifecycle of a wall response under exposure, considering first contact with water, wetting propensity and ease of drying. Critically, in the hydrophobicity test, the silane/siloxane cream treated specimens showed higher sensitivity than others to consistency of application.

The silane/siloxane blend liquid is solvent free and can reportedly be applied to damp walls. It performed comparatively poorly in two stages of the modelled exposure lifecycle: It led to the smallest contact angle and earliest start of absorption, indicating poorest water repellence and highest wettability, respectively. It also achieved the highest increase in the average water vapour resistance on all brick types with an average of 28.4%, indicating a relative increase in the prevention of the diffusion that the untreated bricks were shown to be capable of. Importantly, brick and mortar specimens with a shorter curing time than the masonry specimens, showed consistently almost no water gain in the absorption test with the highest reduction in the average water absorption at the end of 24 hours of immersion. However, the masonry specimens treated 12 months before, and having been exposed to high RH environment, showed significant performance decay compared to these specimens. This, similarly to the acrylic-treated specimens, suggest a strong potential role played by the curing duration and exposure history in the performance of silane/siloxane blend liquids on brickwork, which should be systematically examined in the future, also in light of the contradictory findings reported in the literature with regards to their long-term behaviour (cf. Baltazar et al., 2013, Christodoulou et al., 2013, and Stefanidou and Karozou, 2016 for durability features of blends on concrete and brickwork). The poorer-than-others performance during hydrophobicity and water vapour transmission tests and better-than-others performance during water absorption tests is a pattern common to both silane/siloxane products, although the cream outperforms the liquid on all fronts. Further, the response of the blend liquid in all three stages suggests that despite relatively high resistance to water absorption, in case of moisture enrichment it is more likely to trap moisture than the other products, which could lead to moisture induced damage within the fabric.

The stearate-based liquid showed a very similar performance to silane/siloxane blend cream in all three tests. A good surface water repellence was achieved with this product with the highest average contact angle within the test-set at 114.1°. The water absorption reduction was lower but still kept at significant levels with up to >80 and 90% respectively for brick and mortar specimens compared to the base-case. Critically, the water absorption of masonry specimens was higher with only around 57% reduction in reference to the base-case – a pattern observed with all products except for the blend cream – which, once again, highlights the potential impact of curing time and exposure history on test results. The vapour resistance factor was increased by around 12%, the second lowest within the test-set.

Overall the findings are in favour of the manufacturers' claim that surface waterproofing treatment products can be used to produce watertight but vapour-open systems, but to varying degrees. Results show that within the test-set reported here, the highest improvement is provided by silane/siloxane blend cream, followed by the stearate-based liquid product. The current study does not include durability under solar radiation and cyclic freeze and thaw, among others, and the long-term implications of surface waterproofing treatments, which have been reported to vary depending on the chemical composition and the underlying substrate (Borsoi et al., 2020). Of the two best performing product types, silane/siloxane blends (or only silanes) were widely reported to outperform in the long-term stearate-based products (e.g. Roos et al., 2008 and Silva et al., 2011). Furthermore, the applicability of the present findings to real-life service conditions may be compromised by surface defects common in existing buildings, such as cracks and eroded joints, and by poor application practices (without cleaning dusty, dirty surfaces prior to implementation, on damp surfaces etc.) which could increase the scatter in performance observed during the tests.

Table 3: Summary of the findings from hydrophobicity, water absorption and water vapour transmission tests 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 weight gain due to water absorption at 24h / SD Performance in reference to base-case			Average vapour resistance factor (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.

* This test has been conducted with masonry specimens built with all three brick types, but only those with brick III are reported in this summary table. For the other results refer to Figure 9.

The testing protocols used in this study following BS ISO 19403-2:2017 for hydrophobicity testing, EN ISO15148:2002 for water absorption testing, and BS EN ISO 12572:2016 and water vapour transmission testing have certain limitations in explaining the phenomena at hand. For instance, the 24-h protocol used for the water absorption testing is not sufficient to quantify the capillary moisture content of the treated specimens, while it still shows the water absorption behaviours of specimens when untreated and treated with different products. Similarly, our adopted 72 h protocol for the water vapour transmission testing could be extended further.

Finally, the masonry specimens tested in the water vapour transmission and absorption tests intended to better reflect the composite nature of masonry. Although testing of individual materials seems to dominate the literature, the difference in porosity and permeability of brick and mortar constituting masonry plays an essential role in its overall performance, which cannot be directly obtained by simple regression of results obtained from these individual materials. Therefore accounting for the composite nature of masonry accurately was deemed beneficial to infer the actual wall response under exposure.

5. Conclusions and Future Work

The aim of this paper was to determine how different waterproofing treatments affected the hygric performance of common masonry construction materials through the entire lifecycle of water exposure, by examining water vapour transmission, hydrophobicity and liquid water absorption through small-scale benchtests. The relative performances of the tested materials in these three tests can be used to infer the overall resilience of surface treated wall systems under moisture attack. The selected four products based on different chemical composition classes demonstrated various levels of efficiency to reduce or even stop water and moisture ingress into the fabric, while the results indicated that the curing time and exposure history was influential on the achieved performance.

Among tested treatments, the silane/siloxane blend cream was capable of achieving almost no water absorption while slightly sacrificing water repellence and water vapour transmission. Stearate-based liquids were identified to demonstrate the second-best performance within the test-set here, with excellent surface water repellence, but somewhat diminished performance in terms of water absorption and water vapour transmission. These findings also informed the scope and content of the second part of this study: full-scale testing of brick masonry cavity walls under wind-driven rain simulations, the findings of which will be published in due course. Future research should target different types of masonry reflecting the As-Built-In-Service (ABIS) characteristics of the existing building stock to establish the real-world potential of these products to assist in achieving carbon emissions reduction targets, with specific emphasis on product-substrate compatibility, and durability features.

Acknowledgements

This work has been carried out as part of the 'Waterproofing cavity walls to allow insulation in exposed areas' project, funded by the UK Department for Business, Energy and Industrial Strategy (BEIS) (TRN 1303/04/2017), in collaboration with the UK Centre for Moisture in Buildings (UKCMB), UCL Institute for Environmental Design and Engineering (IEDE) and Building Research Establishment (BRE). The authors are grateful to BEIS and its advisory team for funding and assistance throughout. We also cordially thank BRE's Colin King and Andy Sutton, and the rest of the project team for the invaluable discussions.

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