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The Influence of Application Rate of Hydrophobic Treatments on the Drying Behaviour of Brick

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Abstract. Hydrophobic (or water repellent) treatments have been proposed as a means to mitigate rain ingress and therefore moisture risks associated with internal wall insulation (IWI) on solid (and hence, usually historic) masonry walls. Some practitioners and researchers point out that such interventions may cause unintended consequences, in particular damage to the external masonry surfaces from freeze-thaw or cryptoflorescence. Drying behaviour is important in both of these damage mechanisms. It is well established that hydrophobic treatments inhibit stage 1 drying. The depth of penetration also has a direct influence on the stage 2 drying, which is the focus of this work. Three types of treatment (silane-siloxane emulsion, silane only and siloxane only), with three different rates of application (resulting in varying depth of penetration and density of treatment) on a single type of brick, which were subjected to a drying experiment. This influence on stage 2 drying behaviour is explored.

1. Introduction

1.1. Context

Reducing space heating carbon is an essential part of reducing the UK's carbon dioxide emissions. This cannot be achieved through supply side technology alone; reduction in energy demand is essential (1). Energy retrofit of existing buildings is therefore essential. Many existing buildings are of solid wall construction, and of these, a significant proportion cannot be insulated externally. Internal Wall Insulation (IWI) is therefore an important intervention (2). IWI carries certain moisture risks because it reduced the ability of the wall to dry (3,4). In many situations, most moisture loading is from wind-driven rain. Many researchers and practitioners have proposed using hydrophobic (water repellent) treatments (HPT) to reduce rain absorption and therefore mitigate moisture risks (5–10).

1.1.1. Unintended consequences

However, the use of HPT may carry unintended consequences, including damage to the external surfaces (11,12). There are at least two possible mechanisms. Firstly, if the treatment is bypassed by e.g. cracking, leaks, this could compound with reduced drying and lead to a net increase in moisture content (as discussed below) which may lead to freeze-thaw damage. Secondly, treatments may cause the crystallisation of salts below the surface where before it occurred at/on the surface.



Both of these mechanisms are strongly linked to drying behaviour. A thorough understanding of the influence of HPT on drying behaviour will therefore support an assessment of the risk of these unintended consequences.

2. Background

2.1. *Drying in general*

From a capillary-saturated condition, drying of hydrophilic porous materials generally proceeds in two stages. Stage 1 is characterised by a constant rate of loss of mass (for constant boundary conditions) because the drying is defined by the rate of evaporation. Stage 2, by contrast, proceeds according to the square root of time. Stage 1 drying is therefore much faster than Stage 2 (13).

It is well established that HPT inhibit Stage 1 drying because they prevent liquid water being transported to the surface (14,15). If they are effective in the objective of preventing rain ingress, this is quite acceptable. However if the treated zone is bypassed, this reduction in drying rate could result in localised areas that are wetter than previously. In extreme cases this could lead to moisture-related damage.

2.2. *Cryptoflorescence*

A potential failure mechanism is cryptoflorescence. The growth of salt crystals can induce stresses large enough to overcome the strength of many masonry materials (16). When such crystallisation occurs on the surface, it is referred to as efflorescence and is not generally a threat to material integrity. If it occurs below the surface, within the pore structure, it is called cryptoflorescence and can lead to damage. Efflorescence is therefore characterised by stage 1 drying, and cryptoflorescence by stage 2. Because HPT enforce a regime of evaporation below the surface, they can promote cryptoflorescence (17).

Furthermore, it is recognised that the rate of crystallisation, driven by the rate of evaporation (18). Therefore, changes in the stage 2 drying behaviour are likely to influence the risk of crystallisation damage. If different treatments with different application rates influence the stage 2, as well as the stage 1 behaviour, the risk of damage from some treatments could be different to others.

2.3. *Expected results*

It is expected that increasing rate of application, which will lead to greater depth of penetration, reduces the stage 2 drying coefficient, because the hydrophobic zone will be thicker, resulting in greater diffusion resistance between the hydrophilic zone and the environment. Furthermore, the depth of penetration is not linear with rate of application (19), which implies that the (pore) surface density also increases with increasing rate of application. This is likely to further reduce liquid transport.

3. Methodology

3.1. Drying apparatus

Equipment to facilitate and precisely control a drying experiment was developed. At least two standardised methods exist (20,21). These call for specific, static conditions of temperature and humidity; 23°C and 50% RH are typical and adopted in this work. This is sufficient to give repeatable conditions for Stage 2 drying. However, evaporation from a surface film of water is dictated by the vapour pressure gradient at the surface; this depends on the air flow above the surface as well as the temperature and humidity (22). A small, low-speed wind tunnel was designed and built. This arrangement is comparable with other designs (23,24) but is intended to repeatably and precisely control the vapour pressure gradient, and therefore creating the possibility of studying Stage 1 drying in detail in the future. There is negligible pressure difference across the specimens.

The equipment consists of a shallow tunnel (to create a relatively wide central area with consistent velocity gradient). Below the tunnel is a chamber with load cells on which specimens can be placed such that the top surface is exposed to the laminar flow of air and flush with the bottom of the tunnel (see Figure 1). Five infra-red surface temperature sensors are mounted in the top surface. The design is such that each sensor covers a 50mm diameter specimen. A data logger records the loadcell outputs, as well as surface temperatures and ambient temperature and humidity. This allows the convenient, unsupervised repetition of drying experiments.

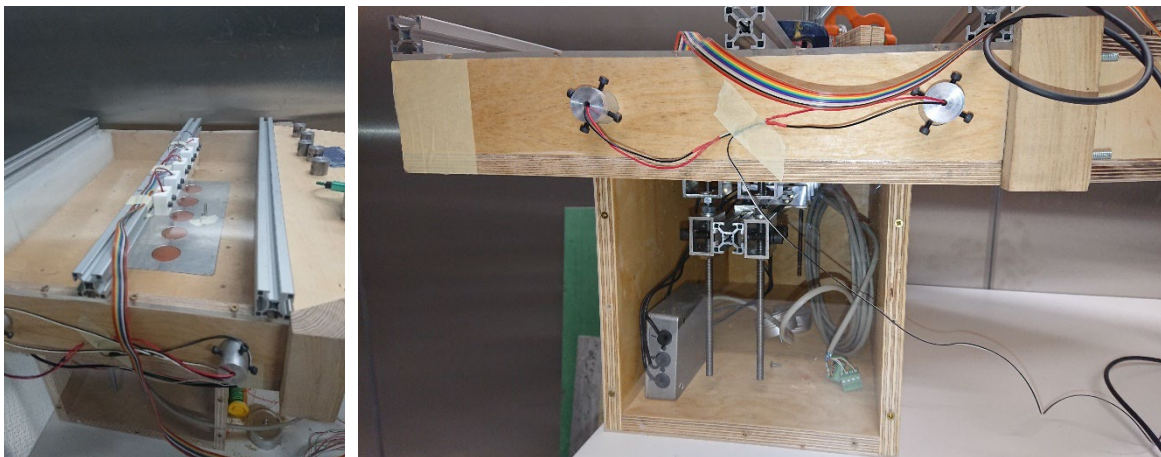


Figure 1: photographs of drying apparatus

3.2. Specimen material

Specimens were cut from ‘Atherstone Red’ bricks (by Forterra (25)) using a diamond abrasive core-drill. The cylinders were trimmed to a consistent length, keeping an original side (stretcher) face of the brick on one end. These bricks have been characterised by other researchers (26).

3.3. Hydrophobic Treatments

Three types of treatment were investigated: a silane-siloxane emulsion, a siloxane-only emulsion and a pure silane mixture. The two emulsions are commercially available and are sold into the UK consumer market. The silane-siloxane emulsion is made with a minimum of dispersant (water) such that the product is a stiff ‘cream’ which facilitates application with basic equipment (i.e. brushes or rollers). The siloxane-only product is an emulsion in water; it is supplied as a liquid. The silane mixture did not include a dispersant or solvent, and is not commercially available

3.4. Application

Specimens were dry and allowed to reach equilibrium with lab conditions prior to treatment. For each type of treatment, three different application rates were applied to different groups, summarised in *Table 1*. The area of each specimen was measured and the target amount of treatment calculated. The specimens were weighed to monitor the amount of treatment applied. The silane-siloxane emulsion was applied using a brush, the liquid products were applied with a household spray bottle.

For the commercially available products tested, there is a single recommended application rate irrespective of the substrate. The treatments were applied at a) the manufacturers recommended rate, b) double that rate and c) half that rate. In all cases the treatments were applied in one coat. The depth of penetration increases with increasing application rate, however the increase is not linear. The additional depth achieved reduces as the amount increases. This means that the final density of active treatment within the substrate is inconsistent between groups of differently treated specimens, and may also vary within the treated zone (19).

Table 1: Treatments applied at variable rate

	Silane-siloxane emulsion; cream	Siloxane emulsion; liquid	Pure Silane Mixture (no solvent/dispersant/surfactant; liquid)
Application factor	Application rate, g/m ²	Application rate, g/m ²	Application rate, g/m ²
0.5	85	100	100
1	170	200	200
2	340	400	400

3.5. Data analysis.

The data is filtered for erroneous values and the mass of water lost is calculated. The results are plotted against both the time elapsed and the square root of time to allow the identification of Stage 1 and Stage 2, and the fitting of straight lines for the respective stages. A genetic algorithm was used to fit a discontinuous function (consisting of a linear part and a part which is approximately linear with the square root of time)

4. Results

4.1. Depth of Penetration

The depth of penetration was measured after all drying experiments were completed. The depth of penetration in the specimens used here will be (destructively) verified after all experiments have been completed.

Figure 2 shows the results for a total of 22 specimens. Figure 2.a shows untreated specimens for comparison, which show the typical stage 1 – stage 2 behaviour. Approximately 10g of water was lost during stage 1. All treated specimens showed a significantly reduced stage 1 of drying. While close agreement between these two specimens might be expected, Figure 3.a shows there is a variation of around 14% in the stage 2 drying coefficient in the untreated material. An increased sample size would allow a better understanding of this variation. For this exercise, 14% is assumed to be indicative of the variability of the drying coefficient of the substrate material.

Figure 2.b shows four specimens with Stormdry applied at the recommended rate. There is almost no Stage 1 behaviour. Figure 3.b shows the Stage 2 drying coefficient is reduced by around 27% relative to the untreated specimens as the hypothesis predicts.

However, Figure 3.c shows that when applied at double the recommended rate, the Stage 2 drying coefficient is slightly higher than when applied at the recommended rate. This is contrary to the hypothesis, because the depth of penetration increases with rate of application.

Figure 2.c shows four specimens with double the recommended amount of silane-siloxane emulsion. There is a small amount of stage 1 drying, which may be a result of some residual surfactant (which is necessary in the formulation of the emulsion). This surfactant usually washes out over a period of perhaps a few months in real applications. To emulate rain washing, the specimens were soaked and rinsed repeatedly however the process was inconsistent. Further work will include a more consistent washing procedure.

Figure 2.d,e and f show that for all of the specimens treated with a silane mixture there is a reduced, but significant amount of Stage 1 drying. Figure 2.a indicates the critical moisture content (i.e. the moisture content corresponding to the transition from stage 1 to 2) is at around 12g of water lost, whereas it is at 2 to 3g for all specimens with silane. This suggests that there is some liquid transport remaining, because the silane mixture is providing only a partial hydrophobic effect. This could be due to insufficient density of active molecules on the pore surfaces, a contact angle greater than 90° , or inconsistent treatment across the range of pore sizes.

Figure 3.d and e show the stage 2 drying coefficient is larger in magnitude than the untreated specimens, meaning that the treated material is drying faster. This is likely to be related to the residual liquid transport, or is related to a greater moisture potential in the treated specimen. In contrast, Figure 3.d,e and f shows that increasing rate of application of this product causes slower Stage 2 drying.

Figure 2.g, h and i show results for the specimens treated with Siloxane-only. These indicate a small amount of stage 1 drying. As this is an emulsion type product, this may be the result of residual surfactant as discussed above, which could be verified by more consistent washing. Specimen E9 shows an unrealistic increase in mass at the beginning of the test. The source of this error is unknown; the results are included here as the stage 2 drying coefficient agrees with that of specimen D9 but further data should be collected to explore this. As with the silane only treatment, at the recommended and reduced rates of application, the Stage 2 drying coefficient is higher than the untreated material.

In many cases, it can be seen that during Stage 2, the loss of water was not strictly proportional to the square root of time. In some cases this could be due to a short stage 1 of drying followed by a long transition as water condensed in the hydrophobic region escapes via a combination of diffusion and capillary suction. However, when plotted against the square root of time the line in this region curves downwards, even after a distinct stage 1 has been completed. This is most obvious in Figure 3.e

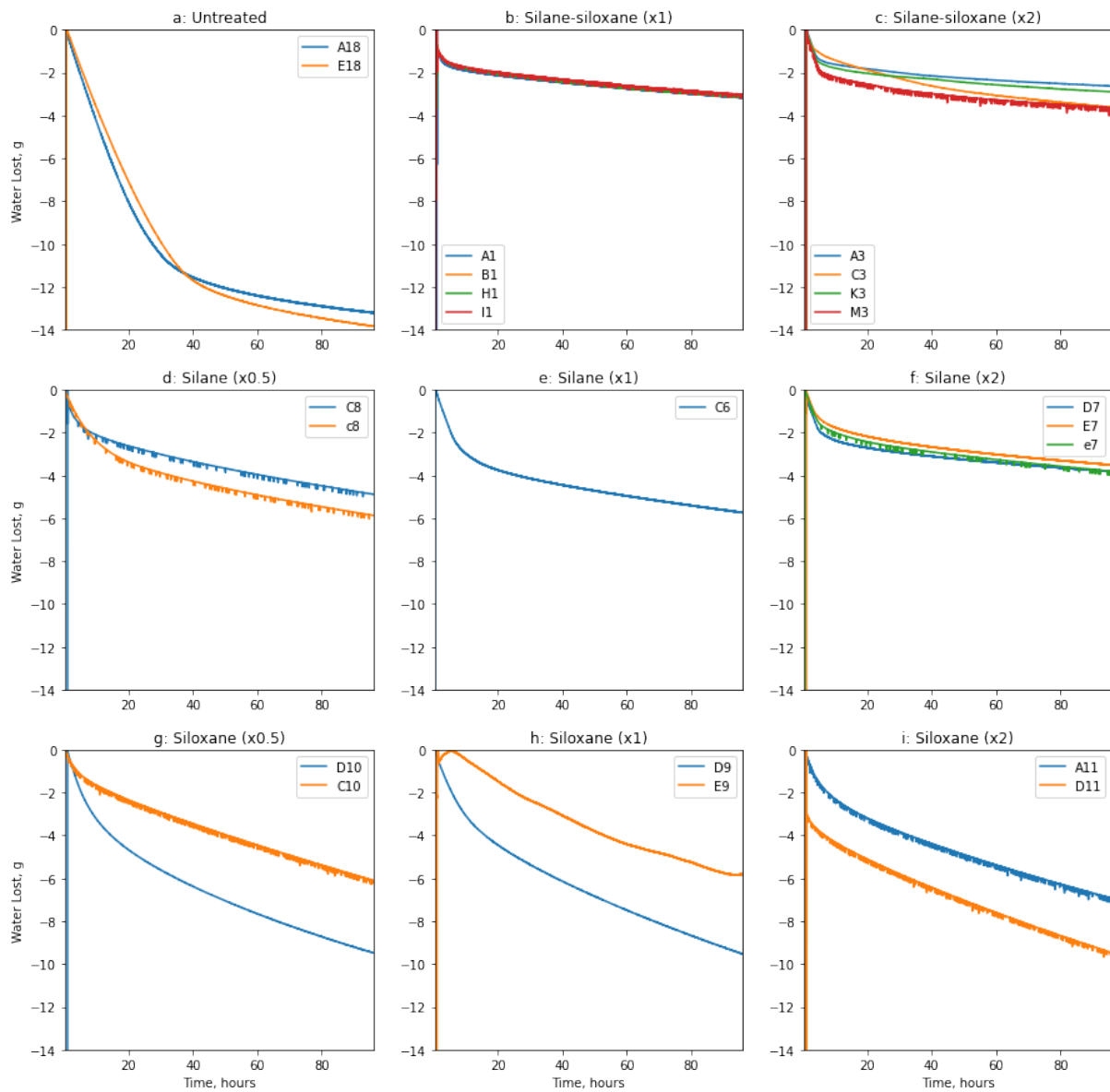


Figure 2: Loss of moisture against time for a variety of treatment types and rates

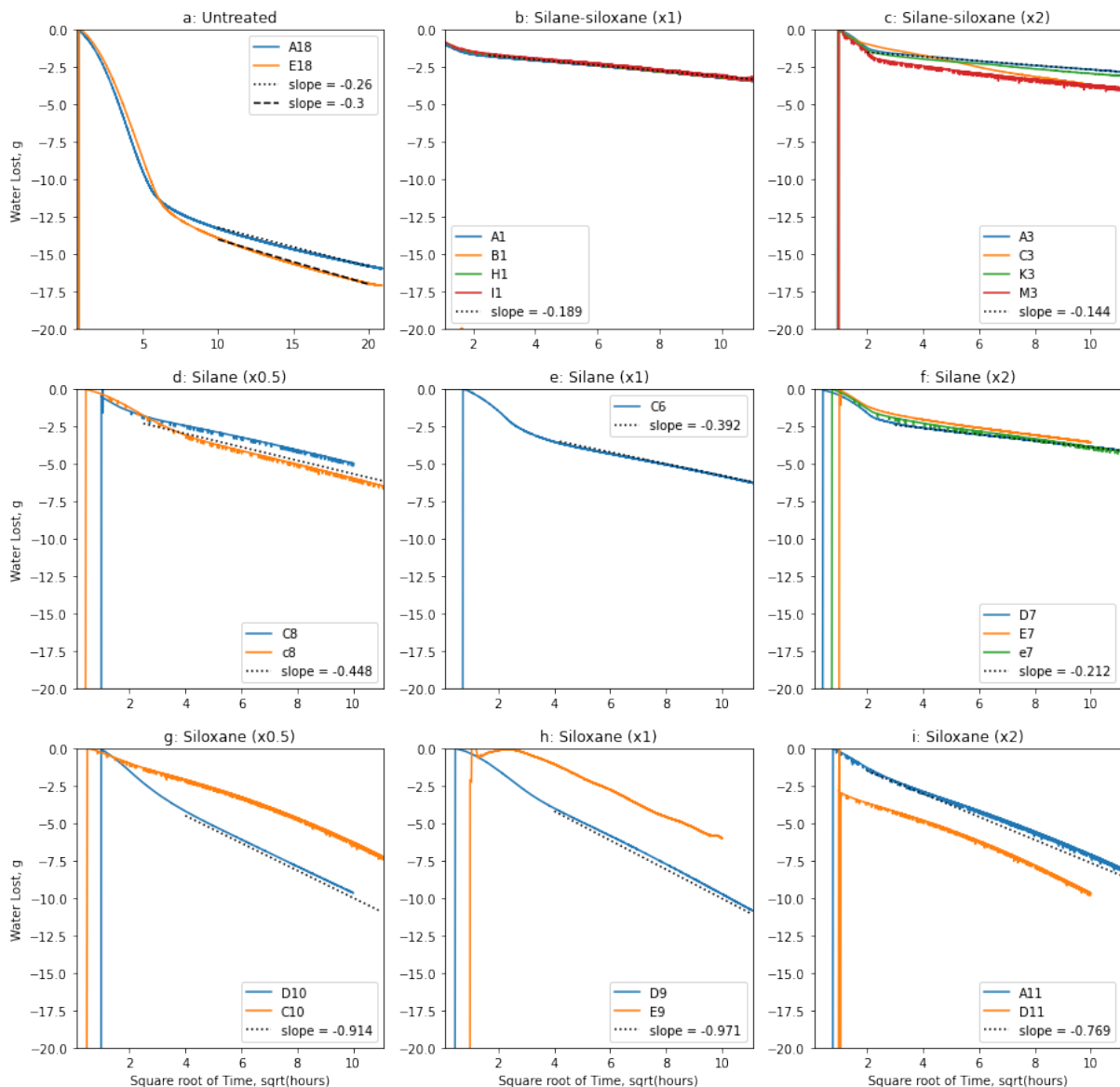


Figure 3: Loss of mass against the square root of time for a variety of treatment types and rates

5. Discussion

5.1. Stage 2 and HPT

The influence of HPT on Stage 2 drying is less thoroughly studied than that of Stage 1.

One of several factors in Stage 2 drying is the vapour diffusion resistance of the unsaturated zone between the drying front and the environment. This increases as Stage 2 progresses and the thickness of the unsaturated zone increases. However, although simple theory would predict zero capillary suction due to the inverted meniscus resulting from the contact angle >90 degrees, experiments to measure the liquid absorption of materials with a hydrophobic treatment often find a small residual amount of liquid absorption (19).

This behaviour is likely to be due to a combination of effects. Firstly, capillary condensation can still occur in hydrophobic pores; liquid ‘islands’ may grow and join up (during wetting) despite being repelled from the pore surfaces (27,28). Secondly, some compounds used for treatment consist of

molecules that are too large to enter the smaller pores. These pores are left untreated, and may or may not be blocked (14,28). In the latter case, they may permit some capillary transport of liquid water. This effect is likely to influence the stage 2 behaviour.

The process of absorbing the treatment into the substrate and curing is a complex combination of capillary suction and diffusion (the silanes in particular are relatively volatile) and depends on the chemical interactions between the substrate and the active ingredients (and with each other). It is therefore simplistic to consider a binary hydrophobic/hydrophilic pair of materials separated by a single plane at the depth of penetration.

5.2. Observations regarding Stage 2

While it might be expected that HPT tend to slow stage 2 drying, these data indicate that for the specimens treated here with Siloxane emulsion and pure silane, the stage 2 drying is in fact increased.

It is very unlikely that the 'dry cup' vapour resistance is reduced; the addition of some material to the pore structure will tend to increase it, if only slightly. However the 'wet cup' vapour resistance may be reduced if there is less multi-layer hygroscopic sorption, which would tend to block the path of vapour with liquid water(14,19). This is particularly the case if the hydrophobic treatment results in the blocking of capillary suction, whilst permitting capillary condensation.

A further observation here is that in some cases, stage 2 does not follow the square root of time precisely. This is visible as a downward curve when mass is plotted against the square root of time, and occurs in all cases. This downward curve suggests a component of non-Fickian diffusion.

6. Conclusions

Three different treatments were applied to specimens cut from a brick material at three different application rates/densities: a) according to the manufacturers guidance; b) at half that rate; and c) double that rate. The treatments were a commercially available silane-siloxane cream (emulsion), a commercially available siloxane emulsion (liquid) and a pure silane mixture, not on the market. The influence of the different types of treatment and their application rate (and therefore depth of penetration) was investigated via the drying behavior.

Increased rate of application increases the depth of penetration but not in a linear manner. This means the density of treatment within the substrate varies with the rate of application and depth of penetration. HPT significantly reduce the stage 1 drying behaviour because they prevent or significantly restrict liquid transport from the core of the material to its surface. HPT did not reduce the rate of Stage 2 drying; in fact the opposite appears to be the case for at least some of the combinations tested in this work.

This effect may be a result of the higher moisture potential during the middle of the experiment; for untreated specimens the total water content reduces rapidly; if stage 1 is inhibited, greater hydraulic potential remains to drive stage 2. HPT may reduce the vapour resistivity at high humidities, but this is insufficient to account for the difference between untreated and treated stage 2 coefficients.

Further work will involve: collecting more data to improve certainty in the observations; a more consistent technique for removing surfactants; measurement of the vapour resistance, particularly wet-cup (i.e. at high humidity conditions) and hygroscopic sorption to explore the influence of HPT on the vapor resistivity. The physio-chemical interaction between the treatment and the substrate during application and curing is little explored, and could yield insights into the more complex characteristics of the treated region.

In general, masonry walls are composites of brick (or stone) and mortar. Particularly for lime based historic mortars, there will often be differences in the interaction between the treatment and brick, versus the treatment and mortar. Given that lime based mortars are understood to have an important role in protecting the masonry units from surface damage, the three- way interaction between brick, mortar and treatment is an important area.

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