# Appendix A: WP2 – Wall analysis

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# 1. Introduction and background

## 1.1 Definition of failure

In the context of this study, the definition of a wall failing will be:

*Primary failure is liquid water arriving at the inner leaf of the cavity wall. Secondary failures are due to excessive moisture levels (liquid or vapour) in any part of the wall or connective elements.*

We will consider mechanisms that can cause failure relevant to empty and full-fill cavities for brickwork walls in the UK.

## 1.2 Scope of cavity dwellings in England

Data is available on types of wall construction for various property ages from the 2015 English Housing Survey[1]. Unfortunately data of an equivalent level of detail is not available for the other UK regions. However, the English data highlights trends that may be largely representative of the whole of the UK.

Table 1 shows the number of cavity masonry dwellings for each age band compared with the total number of dwellings reported in 2015. Note that this data does not reflect the number of dwellings built in a given period, but instead the number still in use in 2015. Half the cavity wall dwellings were constructed between 1945 and 1980, with only approximately a third constructed after 1980. From 1945, cavity masonry is by far the most prominent construction method.

Table 1: Cavity dwellings as portion of all dwellings from 2015 English Housing Survey

| | **Number of dwellings (thousand)** | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Pre 1919 | 1919-1944 | 1945-1964 | 1965-1980 | 1981-1990 | 1991-2002 | Post 2002 | **Total** |
| **Cavity masonry** | 706 | 2,010 | 3,874 | 4,392 | 1,798 | 1,848 | 1,723 | **16,352** |
| **All dwellings** | 4,865 | 3,850 | 4,548 | 4,698 | 1,840 | 1,903 | 1,839 | **23,543** |
| **Cavity %** | 15% | 52% | 85% | 93% | 98% | 97% | 94% | **69%** |

Further examination of the data indicates the wall finish for the cavity dwellings over time. Note that this data is reflective of England only. It may not be representative of the other UK regions in the way the construction trends above might, particularly since the wall finish used may depend on the localised exposure level experienced, which would be expected to vary across the country and particularly for Wales and Scotland, as discussed in section 2.1. Table 2 shows that masonry pointing has been the dominant wall finish on cavity dwellings for over 100 years in England compared to render or other types.

Although the English Housing Survey data confirms that the majority of existing dwellings in England are of cavity wall construction and have a masonry pointing finish, it is unfortunately not possible to determine their location and hence how many of these may be in areas of severe exposure and potential candidates for water proofing treatments.

## 1.3 Boundaries and limitations of the study

**Hollow walls:** Note that any walls with cavity spaces less than 50mm wide are considered 'hollow walls', rather than true cavity walls. It is generally accepted that it is not advisable to retrospectively install insulation in such walls for various reasons, particularly since such narrow spaces often do not allow for effective retrospective filling with insulation. It is also deemed unsuitable due to the elevated risk of rain penetration across such a narrow cavity if insulated.[2] While this research study specifically sets out to challenge the premise that cavities should remain unfilled, spaces below 50mm will not be specifically considered. However, depending on the findings of the laboratory and field studies, reflection will be made on the applicability of water proofing treatments to hollow walls if they are shown to impart beneficial properties to the walls in an uninsulated state.

Table 2: Reported wall finish for cavity dwellings from 2015 English Housing Survey

| | Number of cavity masonry dwellings (thousand) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Pre 1919 | 1919-1944 | 1945-1964 | 1965-1980 | 1981-1990 | 1991-2002 | Post 2002 | **Total** |
| **Masonry pointing** | 510 | 1,277 | 3,289 | 3,960 | 1,624 | 1,725 | 1,441 | **13,825** |
| **Rendered** | 148 | 646 | 495 | 299 | 143 | 108 | 221 | **2,060** |
| **Other** | 48 | 87 | 90 | 133 | 31 | 15 | 61 | **467** |
| **Masonry pointing %** | 72% | 64% | 85% | 90% | 90% | 93% | 84% | **85%** |

## 2. Analysis of cavity walling in areas of high exposure

### 2.1 Defining high exposure conditions

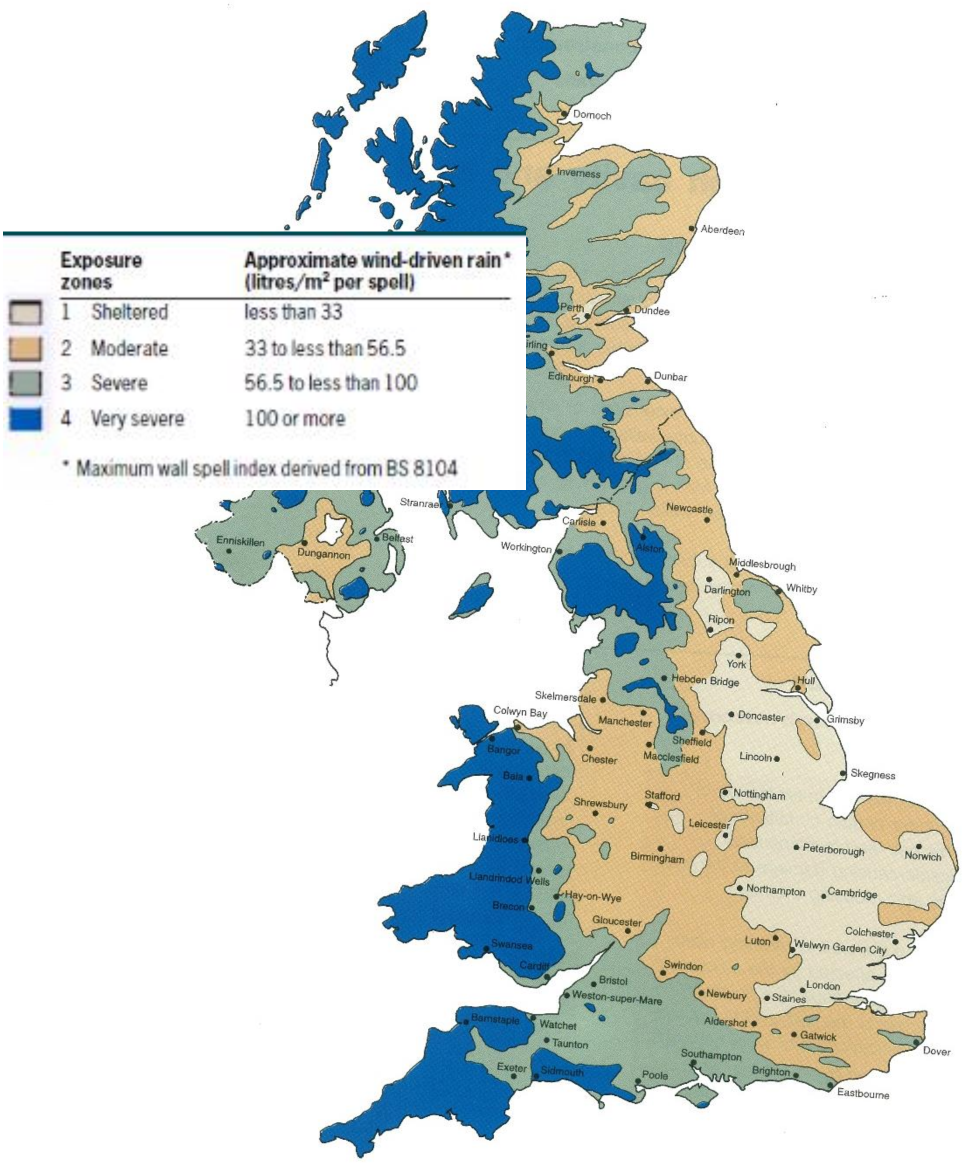
A key element of the scope of this research is the assessment of buildings in areas of high exposure. It is therefore necessary to define the criteria for exposure that will be used in this study.

Part C of the Building Regulations (England and Wales)[3] sets requirements for masonry walls based on their exposure rating to wind driven rain. The exposure rating will influence the external finish that may be used (e.g. facing masonry, render, impervious cladding) and the corresponding thickness of filled or unfilled cavity that should be present to avoid moisture ingress. It follows that smaller cavities can be tolerated in lower exposure conditions, while wider cavities are required for more severe exposure conditions. These standards refer to BRE Report BR 262[4] on the avoidance of risks with thermal insulation, and the British Standard BS 8104: that sets out the calculation procedure for assessing exposure of walls to wind driven rain.

The report BR 262 is a useful reference source for building regulations as it includes an indicative map of the UK showing typical exposure ratings for wind driven rain (Figure 1). The zones range from 1 to 4, from sheltered to very severe. The map is based on the exposure calculation method from BS 8104, but obviously cannot take account of specific local site conditions. Additional guidance provides rules of thumb whereby the exposure rating may be increased or decreased if some particular local features are known to be present. While this is a useful indicator of regional exposure ratings, more accurate exposure assessments can be made for specific locations using the calculation method in BS 8104:1992[5] based on specific site features and characteristics.

This study will consider high exposure areas as those classified as zones 3 and 4, i.e. subject to wind driven rain in excess of 56.5 and 100 litres/m$^2$ per spell respectively.

Figure 1: Map of UK exposure zones from BR 262, based on BS 8104 calculation methodology



## 2.2 Identifying brick walls for further testing

The purpose of this section is to identify the characteristics of existing cavity walls across the UK that may be considered as candidates for waterproofing treatments. The most common features and/ or ranges of characteristics (i.e. across a variable spectrum of material properties) will be estimated in order to recommend representative constructions for laboratory testing.

The evolution of construction techniques over time has gone hand in hand with material availability and enhancements in quality introduced by developing manufacturing processes. By examining the changing trends, it is possible to develop an overview of the likely range of construction situations within the housing stock that may be considered for testing. Since no sufficiently detailed data is available to determine what the statistically most common construction arrangements may be, and due to regional variability meaning that even the most common scenario may only represent a relatively small proportion of all cavity walls, testing the effectiveness of water proofing treatments on what may be seen as the most diverse range of potential variables is believed to be the most robust approach.

This section therefore first explores the nature of bricks used in external leaves of cavity walls, then the bonding and jointing techniques and finally the mortar, to give a cumulative overview of wall constructions that should be given further consideration.

### 2.2.1 Bricks

Traditionally walls were built of stone and brick and were generally solid in construction, the width of the wall fundamentally dictating its ability to resist water ingress, i.e. thicker walls offer greater resistance. Advancements in engineering sophistication and improvements in material properties led to the introduction of walls that included a cavity between two leaves to prevent the movement of moisture, as well as providing improved thermal properties and more efficient use of materials. This began towards the end of the 1800’s but gained significant popularity from the 1920’s and became the ‘norm’ from the 1930’s, as evidenced by housing data for England reported in section 1.2. Certainly at times while traditional solid walls and cavity walls were both being constructed, the bricks used for each would have been from the same sources.

Before the introduction of more extensive mass transport (via railways), it was more economic to use local materials for the production of bricks. Although all were composed of clay, this resulted in considerable variability in colour and texture of bricks from different brick makers across the country, creating distinctive regional appearances and variations in quality.

#### 2.2.1.1 Brick sizes

Prior to the introduction of the brick tax in 1784, there was significant variation in the dimensions of bricks, although all fundamentally embraced the principle that they needed to be held in one hand by bricklayers without tiring, while applying mortar with the other. Introduction of the brick tax favoured larger bricks, since fewer would be required to create a given wall. After the tax was lifted in 1850, since many machine-made processes had been established in that time (rather than bricks being handmade), particularly in the north of England, the same sizing continued. Measurements of bricks made across the country indicate that larger brick sizes were typically found in the north of the UK, with smaller sizes to the south, reflecting their respective manufacturing processes.

RIBA and the Brickmakers Association set standard dimensions for bricks in 1904, which were later adopted by the British Standards Institute. Originally in Imperial measurement, these sizes were slightly reduced to the metric standard brick size of 215mm x 102.5mm x 65mm in 1970. It follows that *bricks typically in use from the time at which cavity walling was introduced (late 1800’s) onward will all essentially be of equivalent size to modern standard bricks*.[6-10]

#### 2.2.1.2 Manufacturing techniques

Brick quality could be quite variable, even from the same producers, with the best quality bricks being used for visibly exposed areas of wall (i.e. external leaves) known as facing bricks, and poorer quality bricks being used out of sight, (i.e. inner leaves, party or internal walls, or beneath render), known as commons or stock bricks. Relatively thick layers of mortar would be used to effectively regulate any unevenness in lower quality bricks. Over time, handmade bricks gave way to machine made bricks using various techniques (although handmade bricks are still made today and typically command a price premium). In particular, machine made techniques included ‘pressed’ bricks, which were made by pressing clay into individual moulds, and ‘wire cut/ extruded’ bricks, which were made by forcing a column of clay through a series of wires to cut the shape. Holes were introduced into the extrusion process to reduce the amount of clay used and aid firing, making them cheaper and lighter to handle, and to help the mortar adhere. For handmade and pressed bricks, this was achieved by including an indent known as a ‘frog’ on one or both largest brick surfaces.

Research reports from BRE (then BRS) indicates that advanced wire cutting processes were in use by the 1950’s. Despite improvements in manufacturing, stock and facing grade bricks are still produced today, although the quality and consistency of both are subject to much improved quality control.[11-15] It may therefore be assumed that *bricks typically used for cavity construction are likely to have been produced via a controlled manufacturing processes of pressing or extruding similar to modern bricks, rather than being hand made*.

#### 2.2.1.3 Physical properties

Enhancements in manufacturing allowed improved quality and consistency and the ability to produce higher strength and highly moisture resistant engineering bricks. Research studies[16,17] have identified that the porosity and thus water absorption of bricks is related to their strength and density, which is linked to the mineralogical composition of the brick and its firing temperature. For example, the presence of carbonates within the clay mix promotes the presence of fissures and pores during firing. Modern processes can carefully control the composition of raw materials and firing conditions so that strengths and densities can be tailored for different applications. The range of physical properties currently available across the brick market is consequently vast, as shown in Table 3, which gives examples of brick properties from a prominent supplier.

Table 3: Properties of a range of example bricks[18]

| Brick type | Compressive strength, N/mm$^2$ | Water absorption, % by mass of brick when dry | Bulk density, kg/m$^3$ |
|---|---|---|---|
| **Engineering brick (BS EN 771 Class A)** | ≥125 | ≤4.5 | ≥2200 |
| **Engineering bricks (BS EN 771 Class B)** | ≥75 | ≤4 | ≥2100 |
| **London white glazed** | 125 | 4.5 | 1820 |
| **Tonbridge Pastone (handmade)** | 30 | 15 | 1670 |
| **Brunel blue** | 75 | 6 | 1660 |
| **Staffordshire slate blue** | 75 | 7 | 1650 |
| **Bexhill Red Stock** | 30 | 15 | 1610 |
| **Aldridge multi rustic** | 35 | 12 | 1470 |
| **London Stock reclaim** | 12 | 21 | 1450 |

From the research carried out, it is not apparent whether any particular type of brick may have dominated construction since the introduction of cavity walls, although due to regional variation in raw material supplies it is highly likely that bricks covering a wide range of properties will be present across the UK and any particular brick may only represent a small proportion of those. Since the application of water proofing treatments will inevitably alter the absorption behaviour of bricks, *it would seem valuable to test the treatments on walls with both high and low water absorption rates, to see if this influences their effectiveness*. A knowledge of specific physical properties will be required to choose appropriate bricks, so *modern bricks for which such data is readily available would be a logical choice, unless specific testing can be carried out to obtain this data*.

#### 2.2.1.4 Alternatives to clay bricks

Although it is reported that 96% of UK bricks are manufactured from clay, alternatives include concrete bricks (4%) and calcium silicate bricks (<1%).[13] Non-clay bricks found popularity particularly in areas where quality clay for brick making was not available. They can also offer additional benefits, as discussed below.

**Calcium silicate bricks** (also called sand lime or flint lime bricks) are a mixture of lime, siliceous or crushed flint aggregate and water. They are cured under steam and pressure in an autoclave causing the lime and sand to combine chemically. Their density varies in the range 1750-1950 kg/m$^3$, with an average water absorption of 12%. Due to their strength, which is typically only around 10 N/mm$^2$, they should be used with lime mortar rather than cement mortar to avoid shrinkage or expansion cracking. They should not be used in combination with clay bricks, since calcium silicate bricks will tend to shrink, while clay bricks will tend to expand. They do however offer good frost resistance compared to clay bricks and may be preferable in areas of severe freeze/thaw exposure, for use where bricks may be persistently wet, e.g. below DPC level, and may be suitable in sulfate bearing soil. They are also generally cheaper than clay bricks.[13,19-22]

**Concrete bricks** are made from Portland cement and aggregates and are machine moulded. Their compressive strength ranges between 7-40 N/mm$^2$ and they are typically 30-40% heavier than clay bricks of equivalent dimensions. They are often used with concrete blockwork products to infill small areas and prevent the need to cut blocks; the use of the same material helps to reduce differential thermal insulation properties and differential movement, which could be a risk with clay bricks. They can also be used as coursing bricks. They can be supplied as flush bricks or with the inclusion of a frog and may be lightweight, suitable for internal wall leaves above DPC level (density ~1550 kg/m$^3$) or dense, suitable for use either above or below DPC level internally or externally (density ~2100 kg/m$^3$). Concrete bricks typically have low rates of water absorption.[13,23]

Since these alternative bricks are much less common across the UK and clay bricks are available covering the range of variables discussed, it would appear appropriate that *the focus of the laboratory testing should be on clay bricks*.

#### 2.2.1.5 Surface finishes

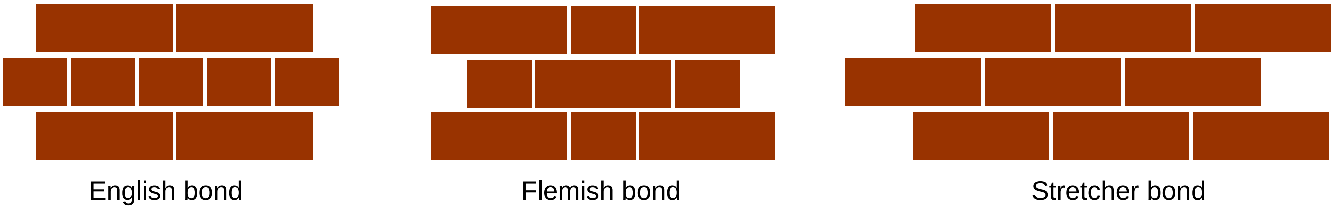
Whether bricks are handmade or machine made, different techniques give rise to different surface textures on the brick faces, fundamentally ranging from smooth finishes to sometimes heavily textured finishes. While historically texturing may have been representative of the manufacturing technique used, modern bricks can typically be made to any required finish.[24,25] Texturing will offer resistance to the runoff of water from walls and hence may be a contributing variable towards the effectiveness of water proofing treatments. As such, *it may be appropriate to test both smooth and heavily textured bricks to assess their impact.*

#### 2.2.1.6 Brick bonding

Linked to wall construction techniques, brick bonding techniques have also varied over time. Solid brick walls needed to have sufficient thickness that they could support their own weight and any additional dead loads (e.g. floors, roof). Brick length therefore typically dictated ultimate wall width, with bricks laid in patterns with various combinations of their sides (stretchers) and ends (headers) exposed to create a number of bond techniques that are commonly recognised, including Flemish and English bonds for example, as shown in Figure 2.

When cavity walling was introduced, there was no longer the requirement for bricks to be placed perpendicular to the wall, though this practice occurred briefly with some intermediary hollow wall bonds, such as ‘rat trap’, where the occasional perpendicular brick was retained to anchor the wall skins together across a very narrow cavity (<50mm). With anchoring being replaced by cavity wall ties, all bricks were laid lengthways in a ‘stretcher bond’ arrangement. Although some variations occurred, largely to falsely simulate some of the more interesting patterns historically created in solid wall bonding arrangements, *stretcher bond is most representative of typical cavity wall construction since approximately the 1940s.*[6]

Figure 2: Example brick bonding patterns



English bond

Flemish bond

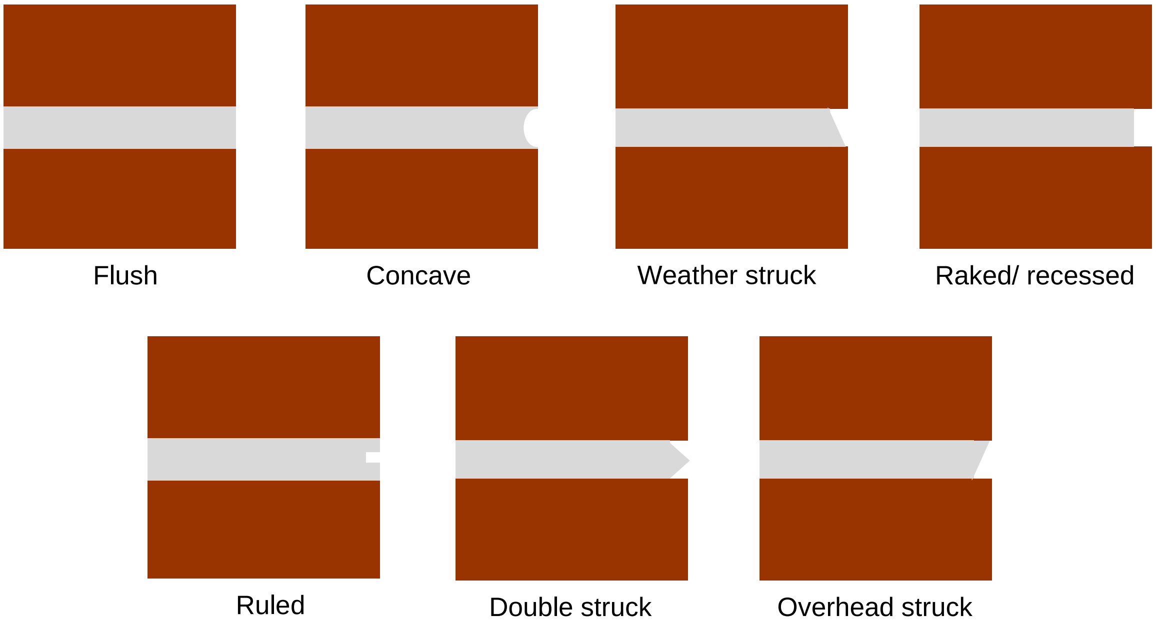
Stretcher bond

#### 2.2.1.7 Brick jointing

Tooling of joints to compact the mortar, thus closing up shrinkage cracks, improves its durability and rain shedding properties. Mortar will generally be left flush at the inner faces of cavity walls. Externally, various shapes are used, as shown in Figure 3. If they remain flush, they are not well suited to areas of high exposure because the joint has not been compressed by a finishing tool. Hence more robust tooled joints for weather resistance in areas of high exposure include concave joints (e.g. bucket handle, keyed) or weather struck, where mortar is compressed at the top of the joint and slopes outward towards the bottom; both techniques encourage the runoff of water from the mortar. By comparison, a recessed, or raked-out style creates a full depression of a few millimetres depth. This 'shelf' can allow water to accumulate, so such jointing is not recommended in modern construction in areas of moderate to high exposure or where full fill cavity wall insulation is present.[26]

Some traditional styles of jointing included ruled/ penny round joints, where a 2-3mm wide groove was formed in the centre of the line of mortar, double struck joint, where the mortar was cut inwards at both the top and bottom of the bed to create a raised centre line, and overhead struck joints. Overhead struck joints are the inverse of the weather struck joint (i.e. sloping inwards towards the bottom of the mortar bed), which was traditionally done as a way of emphasising the straightest, upper edge of the bricks and hiding the more uneven lower edges of poorer quality bricks. It may be expected that this practice would not be necessary as brick quality improved over time and, indeed, weather struck joining became the more popular choice in the 19th century.[27]

Figure 3: Example brick jointing types



It is most likely that these latter forms of jointing, while common on older traditional construction, would not have been common at the time when cavity wall construction was becoming the most popular brick construction form. No references have been found to indicate the most common jointing/ pointing type on cavity walls over the last century, *though it would be expected to include weather struck or concave joints in areas of high exposure to rain*.

### 2.2.1.8 Wall ties

Wall ties are used to join the inner and outer wall leaves together so they act as a homogeneous unit. Building Regulations Part A[28] requires that ties should be located at a minimum horizontal spacing of 900mm and vertical spacing of 450mm, resulting in at least 2.5 ties per $m^2$ (though more frequent around openings). Their design has changed over time, including different materials, shapes and strengths.

Issues often associated with wall ties are discussed later in section 2.3.3.12. If ties fail it is necessary to replace them to maintain the integrity of the wall. Ties used in cavity walls built prior to the 1980's were shown to experience corrosion that limited lifespans to between 12-26 years.[29] It follows that those dwellings are likely to have had their wall ties replaced within their lifetime.

Ties are usually embedded into the mortar during construction. When they fail, mortar may be removed around ties in the outer leaf to enable them to be isolated so they no longer connect the wall leaves. New ties will generally need to be of a ‘self-tapping’ design to be installed into the inner wall leaf from the outside, though the outer heads may be re-fixed into the mortar bed in the outer wall. Modern replacement wall ties are essentially self-tapping at either end and are installed through the face of the brick rather than through the mortar to ensure a good grip. The outer face of the brick will then need to be repaired with a like-coloured mortar to re-fill the hole created by drilling the tie into place.

When considering the application of water proofing treatments to cavity walls, it would be expected that any signs of wall tie failure would need to be rectified prior to treatment. As such, walls considered for filling should contain ties in good, sound condition. For the purposes of the laboratory wind driven rain testing, the presence of ties will fundamentally offer structural support to the test samples and may also act as a potential bridging point between the inner and outer wall layers. Any impacts of rusting will not be considered, since this should be remedied beforehand. It follows that any type of modern wall tie should be suitable for use in laboratory samples to carry out their basic function. While replacement ties may in fact be common in the current cavity wall stock due to the prominence of pre 1981 cavity dwellings shown in the English Housing Survey (section 1.2), test walls would need to be built with standard ties for safety during construction. Replacement ties could subsequently be added, but these would not allow for the testing of mortar dropping build-up on ties as a potential ‘as built’ condition, discussed further in section 2.3.3.12. *Use of common design, modern stainless steel wall ties should therefore be adequate*.

### 2.2.2 Mortar types

Unnecessarily strong mortar concentrates the effects of any differential movement into fewer larger cracks, while weaker mortar will accommodate small movements and result in much finer cracks. Disproportionately strong mortar can also promote cracking through weaker bricks, rather than within the mortar itself. The strength choice of mortar should therefore match that of the chosen brick to eliminate such disproportionate effects.

Prior to 1930s, lime mortar was common and particularly suited to use in solid brick or stone walling. Lime mortars develop their strength slowly by reacting with air (carbonation). Initial stiffness is from drying out rather than ‘setting’. Lime mortars would typically have ratios of 1:3 lime to sand, but this may vary slightly according to the aggregate grading used to ensure adequate workability but prevent shrinkage and cracking. Semi hydraulic lime has some cementitious properties and so partly develops strength by reaction with water, rather than only through carbonation.

By the mid-1930s concerns were arising (expressed in the RIBA journal at the time) on the quality of lime mortars, due to regional variations in production and a lack of standards for materials or methods of mixing them. The move towards cavity walling also placed higher stresses on masonry (due to the single skin thickness) creating a need for stronger mortars. The quality and strength requirements were more reliably met with cement mortars. Hence, between the 1930s and the 1960s, cement based mortars therefore became most common due to their faster setting time, which allowed faster construction.[30]

BRE (then BRS) Digest 58, ‘Mortars for jointing’, from 1965 indicates that lime mortars were no longer commonly used by that time due to their slow set, with cement-based mortars (including combined cement/ non-hydraulic lime mortars for improved workability) favoured instead for use with clay, concrete or calcium silicate bricks. (Note that English Housing Survey data from section 1.2 indicates that in 2015 60% of the existing cavity wall dwellings in England were constructed after 1965.) In areas of severe exposure, mortar of a ‘designation 3’ standard was recommended for external walls; given ratios of 1:1:5-6 cement:lime:sand (non-hydraulic lime) or 1:6 cement:sand would meet this standard. Hydraulic lime was only advised for use in mortars of designation 4 or 5, which were deemed suitable for use in sheltered or moderate exposure conditions or for internal walls or partitions.[31]

The traditional mortar designations were superseded by mortar ‘classes’ in BS EN 998-2. Appropriate mix ratios relevant for the classes and for use in different environmental conditions were also updated. Traditional mortar designations, equivalent modern mortar classes and acceptable mortar ratios are given in Table 4, taken from the Mortar Industry Association Data sheet 03 on mortar for masonry and BS EN 998-2:2010.[32,33]

Table 4: Mixes for masonry mortars and mortar classes

| Mortar designation | Prescribed mortars (traditional proportion of materials by volume)[a] | | | | Mortar class that may be assumed | Suitable for use in environmental conditions |
|---|---|---|---|---|---|---|
| | Cement[b] : lime : sand with or without entrainment | Cement[b] : sand with or without entrainment | Masonry cement[c] : sand (organic filler, not lime) | Masonry cement[d]: sand (lime) | | |
| (i) | 1 : 0 to 0.25 : 3 | 1 : 3 | Not suitable | Not suitable | M12 | Severe |
| (ii) | 1 : 0.5 : 4 to 4.5 | 1 : 3 to 4 | 1 : 2.5 to 3.5 | 1 : 3 | M6 | Severe |
| (iii) | 1 : 1: 5 to 6 | 1 : 5 to 6 | 1 : 4 to 5 | 1 : 3.5 to 4 | M4 | Moderate |
| (iv) | 1 : 2: 8 to 9 | 1 : 7 to 8 | 1 : 5.5 to 6.5 | 1 : 4.5 | M2 | Passive |

a When the sand portion is given as e.g. 5 to 6, the lower figure should be used with sands containing a high proportion of fines, while the higher figure should be used with sands containing a lower proportion of fines.
b Cement or combinations as detailed in the National Annex BS EN 998-2
c Masonry cement (organic filler other than lime) as detailed in the National Annex BS EN 998-2
d Masonry cement (lime) as detailed in the National Anne1965 and x BS EN 998-2

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 build. *It is therefore proposed that a predominantly cement mortar is 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.*

Ratios in line with the severe mortar classes from BS EN 998-2 (M6) shown in Table 4 may have only been applied after the British Standard was updated in 2010. Prior to this, the mortar ratios of ‘designation 3’, i.e. class M4 are more likely to have been used.

#### 2.2.2.1 Sand

In addition to the necessary binder, mortar is comprised of sand. Primarily, two types of sand are used in construction:

- Sharp sand (washed sand, river sand) is coarse, contains angular particles and is generally used in concrete and screed or for laying blocks or slabs. It is generally not favoured for use in mortar as the coarse, angular consistency of the particles makes it difficult to work. (BS EN 12620, ‘Aggregates for concrete’)
- Soft sand is finer and contains rounded particles in a wider range of sizes, thus it results in a more workable mortar that is typically preferred for bricklaying and pointing. (BS EN 13139, ‘Aggregates for mortar’)

Limited historic information has been found relating to sand 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 would always have been favoured to provide the workability required for bricklaying*.

### 2.2.3 Summary

This section has discussed the various elements that contribute to the construction features of cavity walls since their popularity increased from the early 1900s. Table 5 summarises the findings. There are a range of consistent features, suggesting that all test walls should use:

1. Current standard size bricks
2. Machine made clay bricks

3. A stretcher bond
4. Weather struck or concave jointing
5. Modern stainless steel wall ties at a rate of at least 2.5 per $m^2$
6. Use of a cement/ lime blend mortar to class M4
7. Soft sand suitable for bricklaying

There are two particular variables that could be explored during laboratory testing, including:

1. Bricks with high and low water absorption respectively
2. Bricks with a smooth versus heavily textured finish

Table 5: Characteristics/ variables of cavity wall construction

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

## 2.3 As Designed Theoretical (ADT) versus As Built In Service (ABIS) conditions

The purpose of this section is to identify appropriate environmental conditions that should be used for the laboratory testing of water proofing treatments, and common ‘real world’ features that may reasonably be expected to be present in an otherwise seemingly good quality cavity wall, so as to make the testing realistic in practice.

A well constructed brick cavity wall should provide satisfactory resistance to moisture ingress.[34] Modern standards and guidance in brickwork ensure cavity walls, constructed with appropriate materials and incorporating a suitable cavity width for the expected environmental conditions, remain a barrier to moisture, even in areas of very high exposure.[3,35] These standards represent ‘As Designed Theoretical’ (ADT) conditions. However, during construction, workmanship could be sub-standard and after construction walls can settle and age, thus becoming subject to ‘As Built In Service’ (ABIS) conditions that can temper the efficacy of the ADT performance. ABIS is defined as the physical state of the wall at any given point in time post-construction, subjected to the environmental conditions found *in-situ*. Any number of these conditions will affect the ability of moisture to track through the wall, and indeed combinations of these conditions will exacerbate each individual issue.

For the purposes of this investigation, common conceivable ABIS conditions are collated and categorised according to their mechanism of influence on a wall. These are then compared with ‘real-world’ ABIS conditions identified in cavity walls in the UK. The two datasets are then analysed to determine the most representative cavity wall features and conditions that influence moisture movement, with the view that these are incorporated into subsequent laboratory testing samples to offer realistic conditions for the assessment of wall waterproofing treatments.

### 2.3.1 As Built In Service (ABIS) construction examples

In order to relate the work to understand the potential flaws and failures of walls to practical issues of construction, this section provides a correlation between the ABIS construction features/ defects or environmental conditions and their defined failure mechanisms or influencing factors, respectively. Each fundamental influencing factor or breaching mechanism can have more than one origin, though common causal factors are listed in Table 6, below.

Table 6: ABIS construction defects and breaching mechanisms

| As-Built In-Service Construction feature/ defect or Environmental Condition | Breaching Mechanism or External Influencing Factor |
|---|---|
| Exposed condition (wind) | Pressure differential |
| Exposed condition (rain) | Water volume |
| Exposed condition (solar) | Temperature |
| Internal relative humidity (RH) | Moisture available at inner leaf |
| Recessed or similar mortar joints retaining water<br>Moss or other vegetation on external face | Speed of run off |
| Recessed or similar mortar joints retaining water | Water penetrates through mortar |
| Recessed or similar mortar joints retaining water | Water penetrates cracks in mortar |
| Poorly sealed/ protected construction junctions to other elements | Water bypasses brickwork |
| No cavity trays installed | Moisture within cavity not directed out |
| Brick is poorly manufactured or wrongly specified for purpose | Water penetrates gaps in brick |
| Specified brick is too porous<br>Brick face has fractured off and brick has become more porous | Water penetrates through bricks |
| Missing perp-ends or similar workmanship gaps/holes in mortar[36] | Water penetrates gaps in mortar |
| Specified mortar is too porous | Water penetrates through mortar |
| Mortar too strong for brick type (bricks crack from lack of ability to expand) | Water penetrates through cracks in brickwork |
| Extended mortar joints jutting from outer leaf into cavity<br>Irregular brick courses jutting from outer leaf into cavity | Water splash deflection across cavity void |
| Mortar snots in cavities (on wall ties or otherwise)<br>Cavity wall ties sloping down to internal leaf | Water tracks over bridge in cavity |
| Timber lintels | Water penetrating into cavity due to timber shrinkage or rotting |
| High water content in walls (internal or external) | Water trapped in wall |
| Insulation moisture content/ absorption | Allows water penetration across insulation between layers |
| Insulation boards buckled[37] | Water splash deflection across cavity void |
| Incorrect insulation installation/ abutment | Water drawn through gaps in insulation |
| Impermeable external wall finish | Vapour unable to escape from wall |
| Cavity weep holes blocked | High moisture level in cavity (Water unable to escape cavity) |
| Earth banked up against wall surface above DPC | High moisture levels (Prevents moisture drying from external wall layer) |

| As-Built In-Service Construction feature/ defect or Environmental Condition | Breaching Mechanism or External Influencing Factor |
|---|---|
| Steel wall tie corrosion | Expansion (of rust) leads to spalling of brickwork, allowing water penetration through brick |
| Steel wall tie corrosion | Expansion (of rust) leads to cracks in mortar and subsequent water penetration |
| Salts or chemicals migrating into brickwork | Brick damage, allowing water penetration through brick |
| Damaged or weathered quoins | Brick damage, allowing water penetration into two wall planes |
| Partial wall reconstruction with similar or different bricks | Potential construction failure or weakness leading to water penetration |
| Erosion/ corrosion due to sea spray/ road salt | Water penetrates through brick and/or mortar |
| Erosion/ corrosion due to sea spray | Speed of run-off |
| Physical damage to wall | Water penetration directly into cavity |
| Saturated wall from broken rainwater pipe | Water penetrates through bricks and/or mortar |
| Poor or no site drainage from wall exterior | Water penetrates through bricks and/or mortar |
| Vegetation on external face of wall | Water penetrates through cracks in mortar |
| Weathered or damaged mortar courses | Water penetrates through mortar |
| Lack of deep sills and/or eaves | Speed of run-off |
| Cement pointing over lime mortar | Moisture trapped in wall |

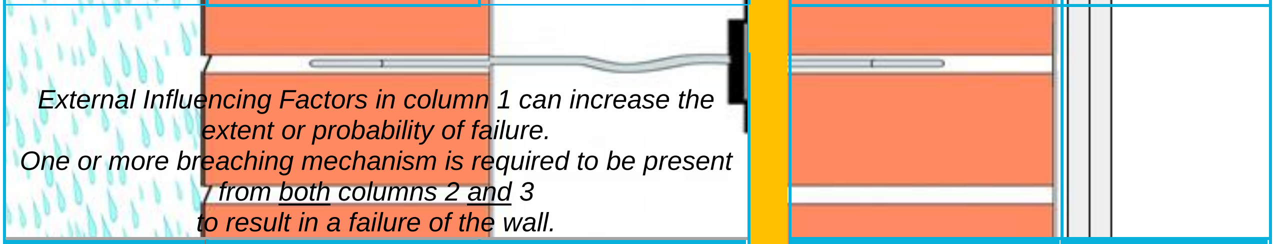
### 2.3.2 Mechanisms of cavity wall failure - fundamental

For a wall to fail from the outside as a result of moisture ingress, three actions must occur:

1. Water must be present externally;
2. Water must travel across the external brickwork leaf;
3. Water must travel across the internal cavity to arrive at the inner brickwork leaf.

The mechanisms for how the water breaches the brickwork leaf and the cavity can be different, but each must occur for an overall failure of the wall. Similarly, the water present externally can provide an influencing factor through water volume, pressure or other variables, but water must be present for the wall to fail. These influencing factors and mechanisms, identified in the previous section, are related to each part of the cavity wall in Table 7.

Table 7: Fundamental mechanisms of failures across all five zones of a cavity wall



*External Influencing Factors in column 1 can increase the extent or probability of failure. One or more breaching mechanism is required to be present from both columns 2 and 3 to result in a failure of the wall.*

| **Outside** | **External Leaf** | **Cavity** | **Internal Leaf** | **Inside** |
|---|---|---|---|---|
| Water volume | Water bypasses brickwork | Water splash deflection across cavity void | Water bypasses brickwork | Relative humidity |
| Speed of runoff | Water penetrates gaps in brick | Water tracks over bridge in cavity | Water penetrates gaps in brick | Pressure differential |
| Pressure differential | Water penetrates through bricks | Water penetrates through insulation | Water penetrates through bricks | Temperature |
| Temperature | Water penetrates gaps in mortar | Water penetrates gaps in insulation | Water penetrates gaps in mortar | |
| | Water penetrates through mortar | Water unable to escape cavity | Water penetrates through mortar | |

## 2.3.3 Mechanisms of cavity wall failure – quantification

The wall breaching mechanisms and influencing factors detailed above may have critical limits above or below which conditions for failure will occur. This section assesses available literature to identify these limits where previously established, or to otherwise consider variability ranges that may be considered for incorporation into laboratory test walls. For example, if we are to test how water breaches through a gap in a brick, we must define how big the gap is.

### 2.3.3.1 Relevance of existing testing standards

A range of test standards relating to exposure and water penetration of walls have been reviewed to consider whether their methodologies may be suitable for the testing of cavity walls or whether any testing parameters are of relevance and worthy of replicating. A summary of each standard and its potential to influence the quantification of testing parameters for this study are discussed below.

#### BS 8104:1992, ‘Code of practice for assessing exposure of walls to wind driven rain’[5]

This standard provides a methodology to determine the exposure of walls to wind driven rain, i.e. the quantity or rain that will fall on a vertical surface depending on localised weather conditions. The resulting ‘wall spell index’ is referenced in Building Regulations and used to set indicative exposure zones for the UK. While the method relies on weather data collected by the Met Office over time, including rain quantities associated with specific wind speeds, the data is effectively averaged out to reflect the worst spell likely to occur in any 3 year period; the wind speed or a rate of rainfall cannot readily be extrapolated from the Standard for the purposes of recreating equivalent conditions in laboratory testing. The resulting indicator therefore reflects a volume of water that may arrive at a wall surface in different locations, without a definitive associated wind speed or pressure, or an absolute timeframe given. (The Standard refers to a ‘spell’ as being the timeframe under consideration, but this could vary significantly, while still ultimately imparting the same volume of water.) The wind speed would need to be determined from elsewhere for the purposes of laboratory testing, although the metric of time can be normalised to that required to deliver the necessary water volume as if via a continuous ‘spell’.

### BS EN ISO 15927-3:2009, ‘Part 3: Calculation of a driving rain index for vertical surfaces from hourly wind driven rain data’[38]

This standard is very similar in principle to BS 8104:1992, however it allows for the calculation of a spell index from hourly observations of wind and rainfall at a given site, rather than utilising lookup tables of existing reference data for locations across the UK. Being based on actual collected site data, it may be expected that this method should provide a more accurate indication of likely wind driven rain quantities than BS 8104. However, unlike BS 8104, this standard is not referenced in UK building regulations. The standard offers a slightly more detailed description of the definition of a spell period; it is essentially a period of time where the water from driving rain exceeds the loss due to evaporation. It is stated that it can take as long as 96 hours with no rain before the evaporative loss exceeds the gain from the rain, hence a duration of 96 hours is taken to mark the end of any given spell. However, the rainfall itself may last only between 1 to 12 hours for example.

### Standards for assessing watertightness of curtain walling

There are a group of British Standards that may be used to assess the watertightness of curtain walling. These include laboratory tests under static and dynamic conditions (BS EN 12155:2000[39] and BS EN 13050:2011[40] respectively), a site test (BS EN 13051:2001[41]), and a performance classification against which the static test may be reported (BS EN 12154:2000[42]). The classification system reflects a pressure (in Pascal) that can be tolerated by the curtain walling without water leakage.

In each of these methods test samples are continually wetted to identify whether failure of the façade occurs (i.e. whether the façade allows water leakage). The site test requires that a wall must remain watertight for at least 30 minutes of wetting at a continual rate of 5 l/min. The laboratory tests use a wetting rate of 2 l/min and determine a pressure that may be tolerated by the construction without leakage occurring (total of 50 minutes up to 600 Pa).

The relative absorbency of the curtain walling materials is not considered since such systems would be assumed to be non-absorbent. The test focusses instead on the integrity of the construction (workmanship) and the quality of any seals. If absorbing materials were subjected to such conditions, external surfaces may become quickly saturated and therefore ‘blinded’ by high wetting rates, leading to water run off. If applied at a lower wetting rate, capillary action within absorbent materials such as bricks could have more opportunity to transfer moisture away from the surface layer and thus allow a higher rate of moisture uptake as water is renewed at the product surface. Consider that the ‘very severe’ spell index limit used in Building Regulations, based on the calculations in BS 8104, is 100 litres/m$^2$ per spell. The delivery of water in the curtain walling tests at 2 l/min would deliver 100 litres in 50 minutes. It is not known to what extent such wetting rates may truly affect the behaviour of absorbent materials.

The relative pressure to which the external surface is subjected would be expected to influence the rate of capillary transfer across absorbent materials. Arbitrary pressure ranges are applied to the curtain walling tests depending on the design wind pressure that the construction is intended to withstand. While this may ultimately link to the anticipated exposure conditions quoted in BR 262 and Building Regulations, this is separately determined by designers and not set out explicitly in the Standard(s). Pressure levels used in the static test for the purposes of the performance classification range from 50 to 600 Pa, with an ‘exceptional’ classification awarded for any product that can withstand more than 600 Pa without leakage. Unfortunately there is no direct link between these pressures and the spell indexes from BS 8104.

This group of test methods relating to curtain walling and their respective testing parameters is not obviously relevant for brick walls where a degree of absorbency is inevitable. It is also not clear how indicative the water application rates and pressure ranges are of real exposed conditions. This is explored further in the following sections.

### ASTM standards for assessing water penetration of masonry wall surfaces

American ASTM standards are available that specifically test for water penetration and leakage through masonry, both under laboratory and site conditions (ASTM E514-14[43] and C1601-14[44] respectively). During these test methods, water is set up to sheet down the exterior surface of a wall while a positive air pressure is imposed, intended to simulate a very severe storm with sustained winds of 60 mph over a 4 hour period (a pressure of approximately 480 Pa). A water flow rate equivalent to approximately 2.6 l/min is used. It has been acknowledged by practitioners that these conditions are extreme and are unlikely to occur under normal service conditions; in general they are certainly as severe, if not more severe, than the UK curtain walling tests described above. Test results are reported as absorbed litres per hour into the wall and no pass/fail criterion is given.

There is clear similarity between these testing methods and those for curtain walling, although in this case the method has explicitly been used for masonry walls. The following sections discuss the likely comparability between these parameters and weather conditions from severe exposed locations in the UK.

### BS EN 12865:2001, ‘Determination of the resistance of external wall systems to driving rain under pulsating air pressure’[45]

This standard sets out a method for assessing the driving rain resistance of wall systems by assessing the water tightness of the system under pulsating air pressure. The pulsating pressure regime is intended to simulate, in a simplified way, the dynamic nature of rain and wind pressure against a wall. The standard acknowledges the potential for water to be absorbed by the wall substrate.

Under this method, water is applied to wall surfaces in two ways; one to simulate driving rain evenly distributed over the external surface of the wall, and a second spray applied at the top of the wall to give a continuous film of water over the surface intended to simulate run off water. Water spray is applied at 1.5 $l/m^2$ per minute and 1.2 l/m per minute respectively.

Testing is carried out at a temperature of 23°C (± 5°C). Pressure is applied to the wall surface in pulses every 15 seconds, increasing from 150 to 600 Pa (or above, if the sample does not fail in this time and the actual failure pressure is sought). The test stops when water penetrates the sample. There are two test durations quoted; Procedure A tests increasing pulse pressures for time intervals of 10 minutes each, intended to qualitatively determine the pressure limit of water tightness of the construction (total of 1 hour up to 600 Pa). Procedure B tests increasing pulse pressures for time intervals of 60 minutes each, intended to assess the pressure limit of water tightness and the extent of water absorbed by the construction (total of 5 hours up to 600 Pa).

The primary difference between this test and the earlier described tests is the pulsed nature of the applied pressure, rather than a continual or cumulative pressure. Testing up to 1 hour for Procedure A is similar in principle to the static pressure curtain walling test in BS EN 12155, while testing up to 5 hours for Procedure B is closer in nature to the ASTM E514-14 test for masonry walls. The overall flow rate from the two spray sources proposed falls between that of both those methods. The pulsating pressure may recreate the gusting nature of wind, but its severity compared with continual or cumulatively building pressure cannot be predicted without direct practical comparison of each technique with equivalent test samples.

The following sections discuss the likely comparability between these parameters and weather conditions from severe exposed locations in the UK.

### BS 4315-2:1970, ‘Methods of test for resistance to air and water penetration – permeable walling constructions (water penetration)’[46]

This standard pre-dates the wind driven rain standard BS 8104, but is still a current British Standard. While this is a specific test for water penetration of permeable walls such as masonry, it is run over much longer periods than those previously described. Although it sets water flow rates and a pressure for testing purposes, it makes reference to BRE Digest 127, ‘An index of exposure to driving rain’[47], which is a predecessor of the current BS 8104 standard, suggesting that alternative spray rates and test pressures may be considered depending on expected local conditions. The Standard also makes specific reference to the testing of samples of cavity construction.

Three measurement options are described in the standard: the first is a visual assessment of water penetration creating staining on the reverse of test samples, the second is by weighing the samples periodically to determine the extent of water absorbed, and the third is by measuring the rate of water leakage through the sample by collecting liquid drained from the rear of the wall.

The second, sample weighing method would appear to offer most relevance to the present study, whereby the progressive water absorption (and thus water resistance) of samples could be determined without necessarily pushing test walls to the point of failure. Two wetting regimes are proposed; 1 minute of water applied at 0.5 $l/m^2$.min at half hourly intervals for a period of 48 hours at a constant pressure of 250 Pa (equivalent to approximately 45 mph), or 6 hours of water applied per day at the same rate and pressure for a number of consecutive days, although the latter is primarily intended for the third measurement method to determine the rate of water leakage.

This method, while apparently intended for the assessment of water penetration of permeable walling, still raises questions regarding the water flow rate and pressure that should be applied during testing so as to be suitably representative of real conditions. Relevant parameters from severe exposed locations in the UK are discussed in the following sections, which may be considered more suited for use with this standard. The methodology is relatively long, which may be restrictive, plus the weighing method ideally requires the use of specialist equipment to enable weighing of the entire test rig so the sample is not unduly disturbed to an extent that may influence the results.

#### 2.3.3.2 Comparison of weather data from very severe exposure locations across the UK

The map in Figure 4 indicates regions of the UK that are deemed to have very severe exposure to wind driven rain (WDR), i.e. >100 $l/m^2$ per spell. However, the actual WDR index in each area will inevitably vary. In order to understand whether the water flow rates and applied pressures for the previously discussed testing regimes are realistic in the UK context, a range of weather data was assessed for locations designated as very severe.

The Met Office provides summary data on their website for a number of weather stations across the UK[48]. Data includes average maximum temperature (°C), rainfall (mm) and wind speeds (knots, converted to mph below) per month and year between 1981 and 2010. Table 8 shows these parameters for locations across the UK within very severe WDR exposure areas. A WDR calculation to BS 8104 was also carried out for each location assuming worst case conditions for the effects of sheltering and wall factor etc. These values are also included in Table 8 to give context to the Met Office data. It can be seen that neither wind speed nor rainfall are necessarily the dominant factor in determining the WDR exposure rating; they are interrelated and if either parameter is high, the WDR spell index can be high.

It is acknowledged that some of these locations are not heavily populated, likely as a result of their historically severe exposure conditions. These are highlighted in grey in the table. It follows that these will not be significant potential markets for wall water proofing treatments where other measures (such as render) are likely to have already been employed to offer protection to buildings in such severe locations.

Of the remaining, more populated areas, the upper WDR index is 130 $l/m^2$ spell and lower index 104 $l/m^2$ spell. At 116 $l/m^2$ spell, Swansea and Valley in south and north Wales respectively offer a relative middle-ground across the range. Since Swansea is the second largest city in Wales, it represents both a highly populated and mid-range city in the very severe range.

More detailed weather data is collected by Swansea City Council at a number of monitoring stations across the city and is available via their website[49]. Their Swansea Bay station is evidently in relatively close proximity to the Met Office location, along the seafront of Swansea bay. The Council data is also more current than the summary data available via the Met Office website and covers hourly intervals between 2012 and 2017. Data includes temperature, rainfall, and wind speed. The additional granularity of this hourly data enables more detailed analysis than is possible with the summary monthly data available from the Met Office online. The implications of these weather conditions on testing regimes will be discussed in the relevant sections that follow.

Figure 4: Map of UK exposure zones from BR 262, with Met Office weather station locations

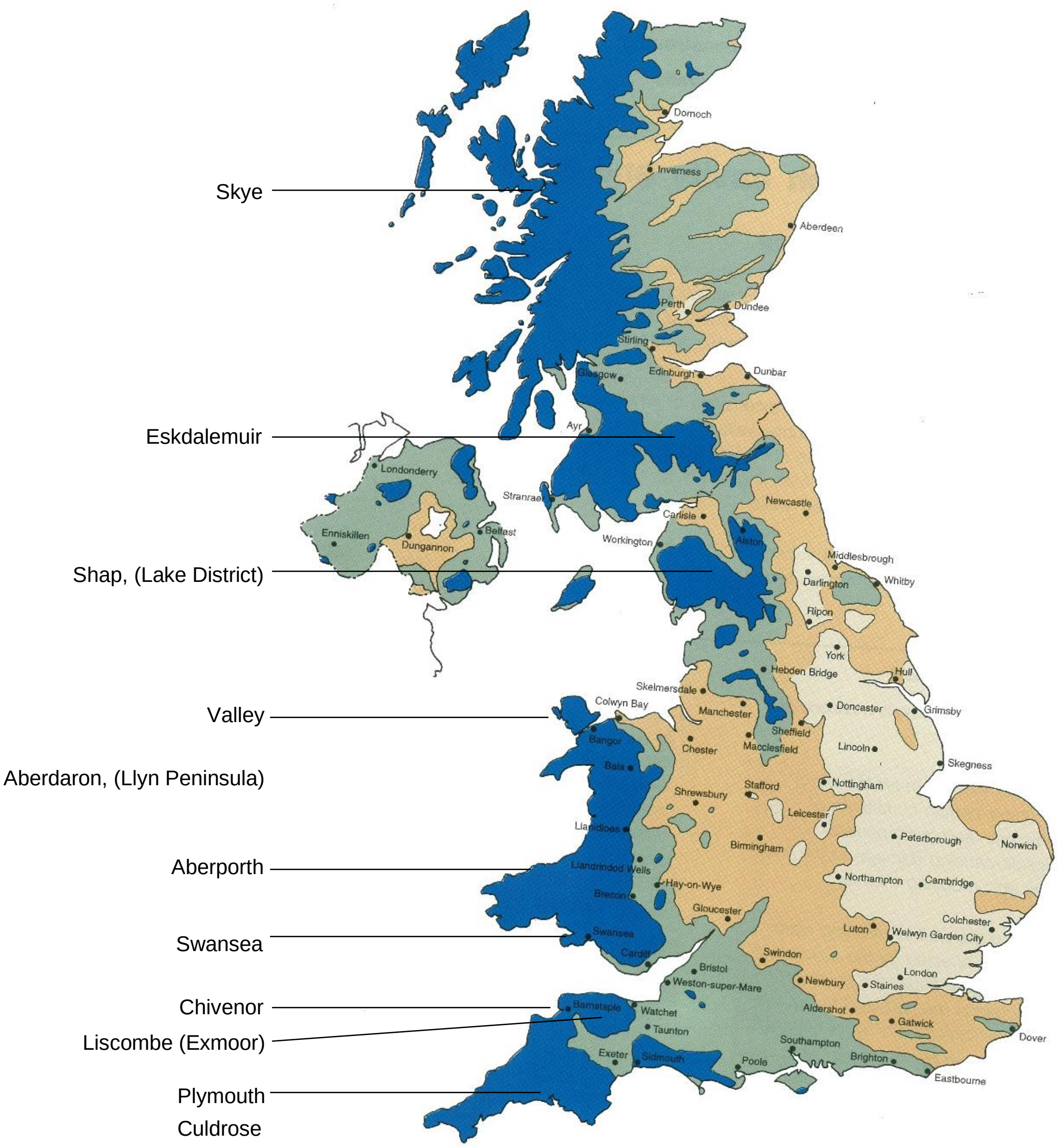


Table 8: Weather data from Met Office stations (1981-2010), plus BS 8104 wind driven rain exposure index approximation

| **Location** | Average maximum temperature, °C | Average annual rainfall, mm | Average annual wind speed, mph | WDR spell index, l/m$^2$ spell |
|---|---|---|---|---|
| Skye, Scotland | 11.9 | 2036.7 | 9.4 | 260 |
| Eskdalemuir, Scotland | 11.1 | 1742.0 | 8.3 | 113 |
| Shap, Lake District | 11.5 | 1779.3 | 9.0 | 160 |
| Valley, Wales | 13.2 | 841.1 | 14.0 | 116 |
| Aberdaron (Llyn Peninsula), Wales | 12.5 | 874.2 | 17.1 | 146 |
| Aberporth, Wales | 12.5 | 887.7 | 15.2 | 104 |
| Swansea, Wales | 13.4 | 999.2 | 15.4 | 116 |
| Chivenor, Devon | 14.4 | 910.1 | 11.9 | 104 |
| Liscombe (Exmoor), Somerset | 12.1 | 1445.2 | 11.0 | 184 |
| Plymouth, Devon | 14.0 | 1007.3 | 11.9 | 130 |
| Culdrose, Cornwall | 13.6 | 999.0 | 13.6 | 130 |

#### 2.3.3.3 External water volume

As defined in section 2.1, the typical volume of water to which a wall will be subjected externally is categorised by the relative exposure zone, according to BR 262.  For this study, we are concerned with exposure zone categories 3 and 4, i.e. severe or very severe. This reflects criteria of >56.5 litres/m$^2$ per spell and >100 litres/m$^2$ per spell respectively, calculated according to BS 8104. According to the standard, a spell may be of variable length with periods of up to 96 hours without appreciable wind-driven rain (i.e. a spell would be deemed to end after 96 hours without rain). For the purposes of testing, a spell may be deemed whatever duration is necessary to apply the required volume of water to the wall. (It should be noted that while 100 l/m$^2$ is the minimum volume of water considered for very severe exposure, worst case calculations could theoretically experience over 400 l/m$^2$, achieved by either higher rainfall, higher wind speeds, longer spell durations or a combination of these factors).

At a weather station operated by the Council in Swansea, the maximum hourly rainfall rate recorded over winter months (when there is most likelihood of coincident high winds) between 2012 and 2017 was 7.8 mm/hour (0.13 l/m$^2$.min). It would therefore take nearly 13 hours to deliver over 100 litres at this rate. This is lower than the lowest rate used in the test methods discussed earlier, of 0.5 l/min from BS 4315-2. That standard implies that the applied water flow rate for the test may be adapted according to known local conditions. However that test method imposed water spray for 1 minute at 30 minute intervals for 48 hours. Despite the flow rate being higher than the above weather conditions and the test period longer than 13 hours, only 48 litres of water would be applied to the wall overall via that test. Reducing the flow rate would correspondingly reduce the applied water volume, to 12.5 litres at 0.13 l/m$^2$.min. It follows that the intermittent application of water at this rate between extended periods of drying would impose impractically long test cycles for laboratory testing (in excess of 16 days) and would not truly be representative of very severe exposed spells in practice.

#### 2.3.3.4 Speed of runoff

Once water hits a wall, the speed of runoff will influence its absorption. In section 2.2.1.5, it is recognised that smooth surfaces may offer a different effect to textured surfaces. The surface finish may also influence the likelihood of materials being deposited and retained on the wall surface (e.g. minerals or biological components), which could themselves influence moisture behaviour; the presence of biological matter could itself retain water and hold it against the wall surface for an extended duration. It is not possible to propose actual rates of runoff for testing, as these will be dictated by the brick finish identified during wall selection. This will therefore be qualitatively assessed by comparison of both smooth and textured finished bricks.

#### 2.3.3.5 Pressure differential

The pressure exerted by wind striking a surface is a function of the wind speed and the density of the air.[50] The pressure of wind stagnating on a building facade may be determined from the following equation:

$$Pw=1/2 \times dV^2$$

where Pw=the stagnation pressure of wind, Pa.

d=density of air, kg/m$^3$, (about 1.2 kg/m$^3$),

V=velocity of the air, m/s.

At a weather station operated by the Council in Swansea, the maximum average *monthly* wind speed recorded between 2012 and 2017 was 11.9 mph, which would result in an exerted pressure on a wall surface of only approximately 17 Pa. The maximum *hourly* average within the same period was 39.2 mph, which would result in an exerted pressure of approximately 185 Pa. Clearly the averaging period has a significant effect on reducing the wind speed experienced during peak gusts. However, it also reflects that such gusts typically last for a limited time, perhaps only a few minutes within any hour. If higher pressures were to be used to simulate the effect of high speed gusts, it seems these would only be appropriate in pulsed bursts rather than being sustained for extended periods. Since there is no data available to support the derivation of the magnitude, but more importantly the duration and frequency of gusting in very severe weather locations, it has been decided to omit any gusting effects from the proposed testing regime and instead focus on replicable average longer term conditions.

185 Pa is towards the lower range of pressure values used in the test methods discussed earlier, although methods using lower pressure (150 Pa) do so as part of a stepped or cumulative pressure application that would typically reach much higher levels. The closest sustained pressure applied by the test methods discussed above is 250 Pa in BS 4315-2, which represents approximately 45 mph compared with 39 mph from the Swansea dataset. However, the standard does imply that the testing pressure may be adjusted according to known local conditions.

#### 2.3.3.6 External temperature

Temperature can have a significant effect on moisture movement in walls. In warmer environments with direct exposure to solar radiation, water is likely to be evaporated from wall surfaces, whereas at freezing temperatures moisture will expand and can cause damage to the structure. During construction, products should have been selected of sufficient quality to resist freezing in their proposed environment. Any damaged areas of wall with signs of frost damage would be expected to be repaired prior to the application of any water proofing treatments. Freezing effects are therefore outside the scope of this study.

The most challenging conditions for walls are expected to be during periods of elevated moisture exposure (i.e. wind driven rain) with little or no evaporative effects to help walls dry out, which could therefore facilitate the accumulation of moisture within walls. Water proofing products will need to perform effectively in these environmental conditions, which will be at modest temperatures where movement will be driven by diffusion gradients, not evaporative effects. When reviewing Swansea weather data recorded by the Council between 2012 and 2017, the average monthly temperature across the month that experienced the highest wind speeds (February 2014) was 7.6°C. While it may not be necessary to recreate such an exact temperature, it suggests that a consistent testing temperature of 10°C would not be unreasonable.

#### 2.3.3.7 Water bypassing brickwork

Walls should be appropriately sealed at junctions and openings and in a well maintained, quality construction it should not be possible for moisture to simply bypass the outer wall and enter the cavity. If such a fault is present within a building there is a high risk of failure and it should be repaired. It is not reasonable to assume that breathable water proofing treatments should be capable of overcoming such failings, hence such flaws should not need to be considered for replication during laboratory testing.

#### 2.3.3.8 Water penetrating through brick or mortar

The rate of water penetration through the brick and mortar (as opposed to through cracks within either of these) is a function of its porosity and will depend on the selected brick(s) and mortar(s) chosen for lab samples. No further quantification is therefore offered here.

#### 2.3.3.9 Gaps/ cracks in bricks or mortar

A known mechanism[51] for rain to track through the exterior of a cavity wall is through cracks in the outer leaf of the wall, through the bricks or the mortar. Cracks can appear due to multiple reasons (Table 6), but it is the size of cracks that dictate the extent of water ingress. Appendix A of BR 292, ‘Cracking in Buildings’[52] (originally published in DG 251[53]) classifies crack widths in walls. However, these are categorised according to damage and not clearly defined according to rain penetration, although Category 2 indicates the first breakdown in weather-tightness (Table 9). As to causes, up to Category 2 is difficult to define and most likely is a result of multiple causes (temperature or moisture induced size changes, chemical reactions, or poor construction techniques). Beyond Category 2, cracks are usually caused by ground movement.

Table 9: Categorisation of crack sizes in walls

| Category | Impact | Widths |
|---|---|---|
| **0** | Negligible hairline cracks | Up to 0.1mm |
| **1** | Cracks rarely visible | Up to 1mm |
| **2** | Cracks not necessarily visible, easily filled, can cause possible distortion to windows. Some repointing may be required to ensure weathertightness. | Up to 5mm |
| **3** | Doors and windows sticking, service pipes may fracture, weathertightness impaired. Repointing required. | 5-15mm or several, each up to 3mm |
| **4** | Walls leaning, service pipes disrupted, window distortion. Extensive repairs required, replacing sections of wall. | 15-25mm |
| **5** | Walls leaning badly, beams losing bearing, danger of instability. Partial or complete rebuilding of structure required. | Usually greater than 25mm. |

It is generally accepted that cracks up to 0.1mm in width (Category 0) do not contribute to rainwater ingress through a wall.[54] This is due to capillary action of water and hydrostatic pressure within cracks, whereby water is drawn back out of narrow cracks. In 1962, cracks between 0.1 and 4-5mm in width were found to be important to rain penetration. Interfacial cracks (between mortar and bricks) are generally 0.1mm to 1mm in width (Category 1).[55] Table 9 indicates these are rarely visible, but depending on the size of the crack, these can begin to be considered as contributory to water ingress as a whole. However, due to the sizes of aggregates in mortar, cracks up to 1mm wide (Category 1) are unlikely to be clear conduits for moisture. Capillary action, absorptivity of the mortar, and pressure differentials will determine the water’s progress through the crack. Multiple cracks of this width will be required to lead to significant water ingress into the cavity, but this could occur in practice.

Cracks of a size difficult to visually identify are likely to be of most concern with respect to the performance of water proofing treatments. Whereas cracks of Category 2 and above indicate a critical failure in the exterior wall and would require, at a minimum, repointing prior to any treatment to prevent significant amounts of moisture tracking through clear gaps and into the cavity, smaller cracks (up to Category 1) are likely to remain, thus offering a potential route to the passage of moisture.

Forcibly replicating such small crack widths in laboratory samples is practically impossible, but is likely to occur as a matter of course during the construction process and would reflect likely situations found in practice. Hence the presence of such cracks pose a realistic testing situation for water proofing treatments. It is therefore assumed that cracks smaller than 1mm will be present by default in all test samples; the extent may become apparent during the microscopic analysis of thin sections of samples during later work packages. As a means of quality control in the laboratory samples, if any cracks larger than 1mm are detected in the test specimens, these will be filled and repaired, as would be expected in good practice site situations.

#### 2.3.3.10 Internal relative humidity (RH)

Internal conditions within buildings can vary significantly. In dwellings, Building Regulations Part C[3] requires that internal RH should not exceed 65% for extended periods of time. However, ventilation in existing buildings is often inadequate, leading to higher RH commonly being experienced. Since the main concern is moisture penetration of cavity walls from outside, the internal humidity conditions are likely to play only a relatively minor role. Ensuring an RH of approximately 65% for the internal environment during testing should be reasonably representative of typical in-service conditions. Lower RH internally would promote a higher moisture gradient across the wall from outside to inside, which would be more conservative than a higher internal RH.

#### 2.3.3.11 Internal temperature

As stated above, temperature can have a significant effect on moisture movement in walls. With warmer internal environments, moisture will be evaporated from the inner wall surface. For regulatory purposes, standard temperature conditions are assumed within energy simulation modelling for dwellings of 21°C for the living room and 18°C for other parts of the dwelling. Other energy models (e.g. the Passivhaus standard) simplify this to 20°C throughout. In practice, some households will prefer warmer temperatures and some cooler, or buildings will be under-heated to save running costs. It is not realistic to assume that such a range of potential internal conditions could be replicated, and in any case external conditions would be expected to have a greater influencing effect. An internal temperature of 20°C should not be unreasonable.

#### 2.3.3.12 Transfer of moisture across the cavity

Table 7 identified a range of ways in which moisture can transfer across a cavity. Some of these relate to clear, unfilled cavities, others insulated cavities. Since the aim of this study is to investigate the potential for water proofing treatments to enable the insulation of cavities, mechanisms of most concern are those relevant to filled cavities. Causes of water splashing and ricocheting across an open cavity would not be relevant once insulated, hence should not need to be considered for laboratory testing. Other mechanisms relate to the quality of installation of insulation boards or batts (i.e. joints or gaps between units), whereas retrospective insulation would be injected and blown into place and hence would not experience such mechanisms.

The mechanisms most relevant for filled cavities are water tracking across a bridge in the cavity, such as a wall tie or rubble/ debris within the base of a cavity, or saturation of the insulation leading to penetration across the cavity. The latter is less likely with EPS bead insulation than blown mineral wool insulation for example, since EPS is non-absorptive. (It is assumed that EPS bead insulation would be favoured in areas of severe wind driven rain for this reason, and so has been proposed from the outset as the insulation choice for these investigations.)

Although some capillary action/ surface adhesion may occur, water arriving at the cavity would mostly run down the inside of the outer leaf into the base of the cavity where it should be able to drain away. It is not reasonable to assume that a water proofing treatment should be capable of overcoming the effects of blocked cavity drainage points, hence such a fault should not need to be considered for replication during laboratory testing. Similarly, the presence of rubble or debris within the base of a cavity, while likely to increase the risk of water tracking to the inner wall surface, should ideally be identified by initial property surveys. Hence, this fault should not be present in insulated cavity walls and thus not need to be considered for replication during testing.

It is however a point of note that the requirements of property surveys have been covered by the Government's Competent Person Scheme for the installation of cavity wall insulation since 2002[56]. All works should also comply with the requirements of PAS 2030, 'Specification for the installation of energy efficiency measures (EEM) in existing buildings'.[57] Additionally, guarantee schemes such as that administered by CIGA – the Cavity Insulation Guarantee Agency – require third party validation of property assessors under the BBA Cavity Assessment Surveillance Scheme (CASS).[58] Although such schemes have a requirement to identify any items that may affect the suitability for cavity wall insulation, no specific mention is made of inspecting the base of the cavity; the focus is instead on 'visible defects' and the condition of the inner and outer wall leaves. The withdrawn British Standard on which the survey guidance is based, BS 8208-1:1985,[2] includes a note about the risk of debris left in a cavity presenting problems with rain penetration. However, there is no mention of this risk or internal cavity inspection under the current requirements. The presence of debris that may bridge a cavity is considered an unreasonable risk of failure to be worthwhile testing under the current research study for water proofing treatments, i.e. it would be expected to cause failure and could not be mitigated by the proofing treatment. However, if such treatments were found to be beneficial in enabling cavity walls to be insulated in exposed areas, it may be necessary to make specific reference to the internal inspection of cavities, and indeed a number of specific items to be addressed at the survey stage, in the guidance accepted under Competent Persons and warranty schemes, to ensure such risks are identified and avoided prior to insulation.

Wall tie design has changed over time, including different materials, shapes, strengths, etc. BRE research[29] indicates that rust is the primary mechanism of failure of ties and that all ties installed prior to the 1980's may be at risk of failure. Rusting of ties can lead to spalling of surrounding mortar, which could create openings for moisture ingress. The mechanism of moisture ingress from gaps or cracking (section 2.3.3.9) will therefore be relevant in these cases.

Ties can also offer further potential mechanisms for the transfer of moisture across cavities if they become fouled with mortar droppings during construction. This increased surface area adjacent to the outer wall leaf can have the effect of collecting and concentrating moisture across the tie and deeper into the insulation layer if the cavity is filled. Such features can therefore accelerate moisture transfer at wall tie locations.

If water proofing treatments are shown to be effective in preventing water crossing a cavity in the ADT state, it may be worth considering testing compromised wall ties that may remain undetected during non-intrusive wall surveys, to assess the extent to which they may be a detriment to the insulated wall. Such potential failures cannot be quantified as such, other than to state the number of compromised wall ties present over a given wall area. Images may be obtained from site investigations showing typical wall tie mortar fouling and it would be recommended that an equivalent extent of fouling is visually replicated during laboratory testing. Such testing with ABIS conditions would of course be redundant if the walls failed under ADT conditions, hence the proposed ABIS testing will depend on the success of ADT testing.

### Cavity width

Aside from the features discussed above, the other key aspect that will influence the transfer of moisture will be the width of the cavity (i.e. the distance to be traversed). The greater the distance, the higher the likelihood that water quantities will not be sufficient to track across to the inner wall leaf.

Part C of the Building Regulations[3] indicates that for facing masonry walls with tooled joints there should be a minimum residual cavity of 50mm for walls in exposure zone 3 – severe, and a minimum of 75mm for walls in exposure zone 4 – very severe. If walls are fully filled the zone suitability reduces. For injected fill (excluding urea formaldehyde foam) a 50mm filled cavity would only be acceptable up to zone 2 – moderate, while 75-125mm filled cavities would be acceptable to zone 3 – severe. Only filled cavities of 150mm or greater are deemed acceptable in zone 4, very severe environments. On this basis, creating test walls with 75mm insulated cavities will assess whether the application of breathable water proofing treatments can improve the performance with regard to water penetration compared with the uninsulated state. If so, it may be argued that such walls may remain suitable in zone 4, i.e. offering the highest level of protection, rather than only zone 3. If this proved successful, it may subsequently be worthwhile to test insulated walls of 50mm cavity width to assess whether the performance may be suitable for zone 3, rather than only zone 2. However, clearly if the 75mm filled cavity is unsuccessful, it would be expected that the 50mm cavity would also be unsuccessful and therefore not worthwhile testing.

### Pre-existing dampness in walls

A fundamental reason why building owners may wish to use a wall water proofing treatment product is because they may know or suspect their walls to already be damp. Unfilled cavity walls may experience a degree of water absorption in their outer leaf during annual wetting and drying cycles. However, this would not be expected to pose a risk to the internal wall leaf when isolated via a clear cavity. It may therefore be anticipated that external wall surfaces could contain moisture as an ABIS condition prior to the installation of cavity fill. While many water proofing product suppliers insist that walls should be dry prior to application of the product, some water-based products state that they can be applied to damp walls.

*It would therefore be useful to test an appropriate product that claims to be applicable to both damp or wet walls to assess the extent to which the residual wall wetness at the point of treatment may influence its ultimate performance*.

The extent of moisture within existing walls could vary significantly. A study of brick samples for English Heritage[59] indicated moisture contents (to capillary saturation) over a range of brick densities from 5.1-31.1% (vol), with high density bricks (approx. 2200 kg/m$^3$) at the lower end of the scale and lower density bricks (approx. 1700 kg/m$^3$) at the high end. By comparison CIBSE Guide A, ‘Environmental design’,[60] considers a ‘standard’ moisture content for exposed masonry of 5% (vol). For consistency in testing approach across any substrate wall samples, all should be capable of taking on an additional moisture capacity of 5%, hence this value, consistent with the advice in CIBSE Guide A, should be targeted during laboratory testing of pre-wetted walls. When wetting samples, water should be applied via a single wall face (i.e. samples not entirely submerged) to represent moisture absorption from an exposed façade of a wall from rain wetting.

## 2.3.4 Summary

This section has identified and quantified where possible, the various moisture transfer mechanisms and environmental factors to which a cavity wall may be subjected. This includes a range of potential ABIS conditions that would in fact be deemed flaws when compared to the wall’s intended design (ADT conditions).

Investigations into existing standard test methodologies for wind driven rain has shown that no single current test would adequately deliver all the environmental conditions identified from this study, based on weather data for a known severely exposed location (Swansea, South Wales). BS 4315-2:1970 offered the closest conditions, though the requirement to only apply water for 1 minute every 30 minutes is not really representative of a very severe wind driven rain spell. (Even though technically it satisfies the criteria that a spell may not experience a single drying period greater than 96 hours, this timeframe would be exceeded overall in an attempt to deliver 100 litres of water, hence it is not felt to be representative of the principle of the spell, as defined by BS 8104 and BS EN ISO 15927-3.) Aside from this feature, the other key aspects of the BS 4315-2 sample weighing methodology, adaptable for known local weather conditions, appear reasonable and are therefore likely to form the basis of the WDR laboratory testing.

The conditions that should be replicated during laboratory testing of walls with water proofing treatments are summarised in Table 10. This also includes selected ABIS conditions that would be expected to pose additional risks of failure but may remain undetected during property surveys, which could subsequently be tested if the treatments prove successful on samples without such faults.

Environmental/ wall conditions to be used include:

1. Cavity width of 75mm, which uninsulated would be deemed acceptable in zone 4, very severe exposure conditions. (If shown to be successful, 50mm cavities could be tested, which would be relevant up to zone 3, severe exposure conditions.)

2. Water exposure volumes equivalent to very severe exposure conditions of 100 l/m$^2$.spell, i.e. 0.13 l/m$^2$.min for at least 13 hours to deliver 100 l/m$^2$. Extending the duration of wetting would have the effect of increasing exposure severity
3. External pressure applied to the outside of the wall of 185 Pa, equivalent to sustained average 39 mph winds
4. An external temperature of 10°C
5. An internal temperature of 20°C
6. An internal relative humidity (RH) of 65%

ABIS ‘faults’ that may be considered for replication include:

7. Cracking within the brickwork, or more likely mortar, of approximately Category 1 classification, i.e. up to 1mm. (These are assumed to be present by default within the construction)
8. Mortar accumulation on wall ties (visual replication of site observations)
9. Substrate walls already in a damp state (only tested with products claiming to be applicable in such conditions)

Table 10: Environmental conditions and ABIS features for cavity wall testing

| **Characteristics** | **Performance (variable extremes, where relevant)** | |
|---|---|---|
| Cavity width | 50mm | 75mm |
| Water exposure volume | 0.13 litres/m$^2$.min for >13h | |
| External pressure | 185 Pa | |
| External temperature | 10°C | |
| Internal temperature | 20°C | |
| Internal relative humidity | 65% | |
| **ABIS features** | | |
| Cracking | Up to 1mm (assumed built in) | |
| Mortar accumulation on wall ties | Visual replication of site observations | |
| Relative moisture state of wall | Dry | Damp |

### 2.3.5 Frequency of construction examples resulting in failure mechanisms

In order to understand the likelihood of a cavity wall failing as a result of the factors discussed in the previous section, results from investigations into known cavity wall failures have been reviewed. In 2015 BRE visited over 1300 dwellings whilst undertaking a cavity wall insulation review on behalf of Constructing Excellence Wales[61]. This is believed to be the most comprehensive independent investigation into failed cavity wall dwellings to date. A significant portion of the dwellings assessed had a render finish. Since this study is only concerned with exposed facing brick walls, rendered dwellings have been excluded from subsequent analysis, leaving 390 properties. Project surveyors determined the primary ABIS conditions that had led to failure in each dwelling, along with the associated sizes of defects in the observed walls where relevant. Table 11 correlates the observed dominant ABIS conditions in the houses surveyed with the breaching mechanisms defined earlier in Table 7.

Table 11: Observed ABIS conditions in house surveys (2015)

| Primary ABIS | Primary failure mechanism | Size of crack | Number of Occurrences |
|---|---|---|---|
| **Damaged brick face** | Water bypasses brickwork | 2-3 mm | 71 |
| | | 1-2 mm | 52 |
| **Rubble in base of cavity** | Water unable to escape cavity | N/A | 79 |
| **Saturation > 25% (common brick)** | Water penetrates through brick | 1.5-2 mm | 67 |
| **Wall tie failure** | Water penetrates gaps in mortar | 1-2 mm | 52 |
| **Pointing failure** | Water penetrates gaps in mortar | 0.5-1 mm | 21 |
| **Saturation of mortar behind new pointing/ cement pointing over lime: moisture trapped** | Water penetrates through mortar | N/A | 21 |
| **Subsidence** | Water penetrates gaps in mortar | 7-10 mm | 14 |
| **No cavity closer around windows** | Water bypasses brickwork | 1-2 mm | 13 |
| **Total number of properties** | | | **390** |

The relative proportion of the primary ABIS failure conditions is shown in Figure 5. Damaged brick faces alone represent almost a third of all cited primary ABIS conditions. Each of these ABIS conditions is associated with a breaching mechanism in Table 11. These have been grouped where they overlap, with the respective occurrences illustrated in Figure 6. Since damaged brick faces result in water bypassing brickwork, this is consequently the most frequent failure mechanism identified from the study. Other significant mechanisms are water penetrating gaps in mortar and water unable to escape the cavity. There were instances where existing lime mortar, which is more permeable to moisture transfer than cement mortar, had been at least partially saturated when new cement mortar pointing was applied on top of it. The new cement mortar effectively trapped moisture within the original mortar behind. Here this has been classified as ‘water penetrates through mortar’, though in practice this is essentially because re-evaporation has been impeded.

In addition, Table 11 includes the sizes of cracks associated with any of the primary or secondary ABIS conditions identified.

Figure 7 shows the frequency with which various crack sizes were recorded across the surveyed properties, with the vast majority (70%) up to 2mm. This demonstrates that a wall *in-situ* will have significant potential to develop cracks of some description over its lifetime, and these outputs quantify those cracks to be most often 1-2mm in width. Quantifying the size of gaps in mortar (and to a lesser extent, brick) through which water can track was reported in Table 9, where it was noted that cracks of less than 1mm in width are hardly visible, although they do have the ability to contribute to water penetrating through a wall. It is therefore possible that a higher proportion of very small cracks (<0.5mm) may have contributed to water penetration in the surveyed site examples but were not captured during the study.

Figure 5: Prevalence of observed ABIS failure causes in houses surveyed (2015)

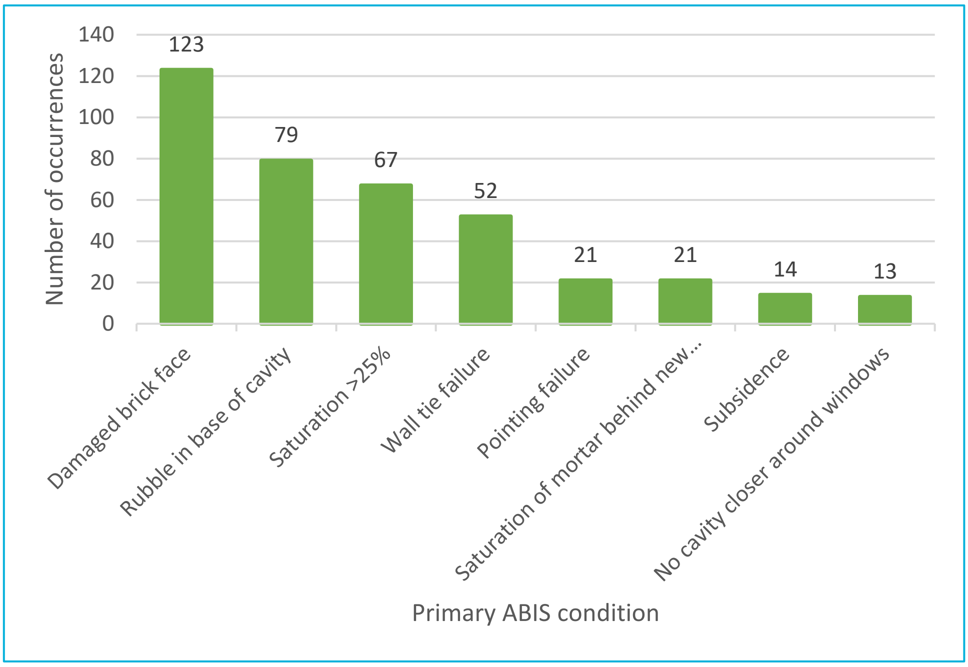


Figure 6: Breaching mechanisms in surveyed houses (2015)

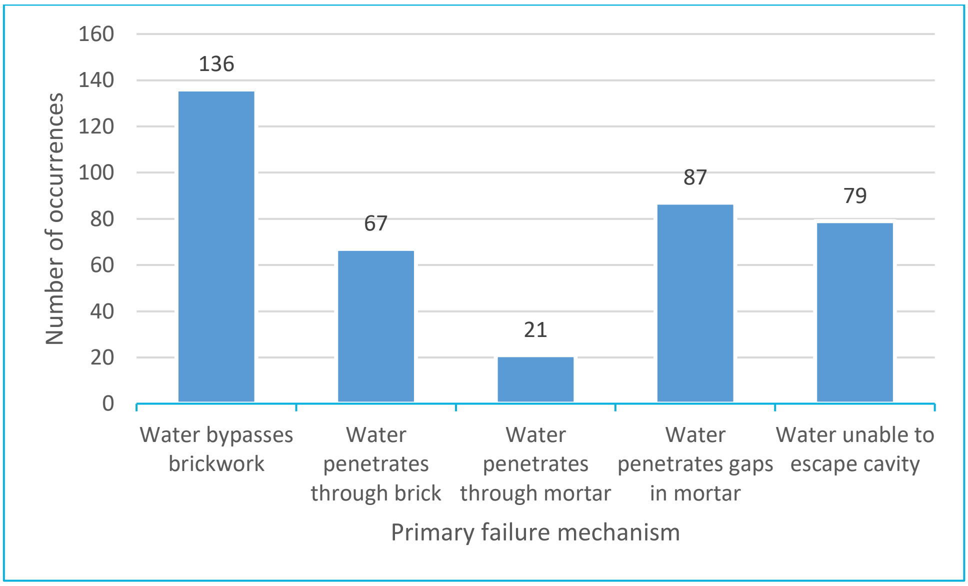
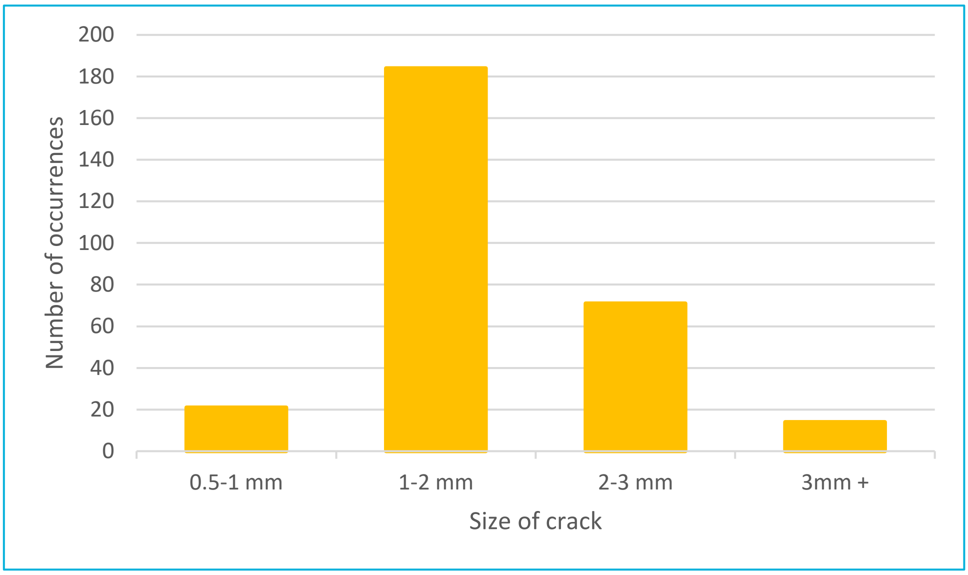


Figure 7: Prevalence of crack sizes observed in houses surveyed (2015)



### 2.3.5.1 Relevant conclusions from site investigations

Examination of a number of facing brickwork cavity wall failures shows that water bypassing brickwork as a result of either damaged bricks or a lack of closers around openings was the most frequent noted failure route. As discussed in section 2.3.3, when considering the waterproofing treatment of cavity walls there are a number of ABIS conditions that it would be necessary to rectify before a treatment may be expected to work effectively. While they may be shown as genuine failure mechanisms within building investigations, the inevitability of failure under such circumstances means there is no value in replicating such conditions in laboratory testing of products. Only those that may remain undetected during wall surveys and hence not receive any form of rectification are likely to carry continued risk and thus warrant further investigation during the present study.

Water penetrating through bricks or mortar collectively represent the next most significant breaching mechanism, resulting from saturation of either substrate. These aspects are the key focus of the waterproofing investigation – to assess whether this type of fault (saturation) can be reduced or eliminated through the use of waterproofing treatments to repel water from walls. It should however be noted that the mortar saturation mechanisms highlighted were a result of moisture being trapped behind new pointing where the new mortar must have been relatively impermeable, thus trapping existing moisture within the wall. Such practices should be avoided in practice, but in any case the use of breathable waterproofing treatments, which are the focus of this study, should not exacerbate or introduce such conditions.

22% of the observed wall failures were a consequence of water penetrating gaps/ cracks in mortar through various faults, including wall tie failure, pointing failure and subsidence; the latter resulting in the largest observed crack ranges but in a relatively small number of cases overall. The crack width analysis from Figure 7 also supports the conclusions in section 2.3.3.9 that it is smaller cracks that are most likely to be present in walls (sufficiently small to remain untreated and unrepaired) and hence contribute to moisture penetration.

The remaining failures include 20% of assessed dwellings where water is unable to escape the cavity and thus bridges the space as a result of rubble present in the base of the cavity. With the exception of water bypassing brickwork through large scale faults that would be expected to cause failures, the remaining ABIS conditions identified from the housing survey support the conclusions derived from earlier sections of this report to identify potential faults representative of real world conditions for the laboratory testing of waterproofing treatments.

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