A Review of Rising Damp in Masonry Buildings

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1: Introduction

Rising damp is the upward movement of ground water through a permeable masonry wall. The water rises through the pores in the masonry via a process called capillarity. Capillarity is a process whereby water molecules are electrochemically attracted to mineral surfaces, enabling water to move vertically through pores of a certain size despite the counteractive force of gravity. The phenomenon of rising damp has been observed over the centuries. It is a perennial and ubiquitous problem.

Rising damp was identified and reported from both the heritage and ordinary masonry buildings all over the world. Dampness tends to cause many problems to a building with dire health, environmental, social and economic implications. The unwanted moisture enables the growth of various fungi in wood, causing rot. Plaster and paint deteriorate and wallpaper loosens. Stains from the water, salts and mould would ruin surfaces. Externally, mortar may crumble and salt stains may appear on the walls. Steel & iron fasteners rust. It may also cause respiratory illness in occupants. In extreme cases, mortar or plaster may fall away from the affected wall and the building can become completely inhabitable.

The purpose of this paper is to review the work published on the subject of rising damp or capillary rise. The review has been done by searching scientific papers from online databases for reported work and assessing them based upon author's experience and expertise developed in his R&D activities in this area. This paper covers the mechanisms of water movement in masonry in an attempt to develop a good understanding of rising damp phenomenon and to review the research, development activities and common practices on combating against rising damp all over the world.

2: Phenomenon and mechanism of rising damp

A number of published papers are dedicated to defining rising damp phenomenon and developing good understandings of mechanisms involved in rising damp. Alfano et al wrote that rising damp occurred when groundwater flowed into the base of a construction and was allowed to rise through the pore structure. It was defined here as the upward vertical flow of water through a permeable wall structure (1).

In the BRE Digest 'Understanding Dampness', rising damp is described as the result of porous masonry sucking up water from the ground. It rises up the wall, often to a height of a metre or more, and usually leaves a characteristic horizontal tide mark. Below it, the wall is discoloured with general darkening and patchiness, and there may be mould growth and loose wall paper (2).

The materials used conventionally in the construction of masonry walls are all porous to some extent so they contain a certain volume of air. The porosity is defined as the ratio of volume or air divided by the total volume, which is always less than unity. The air pockets are often connected to one another through a network of pores so liquid can pass through the material. Some values or porosity are given in Table 1. It should be noted that these values will vary depending on the particular material origin.

Table 1: Porosity values of common building materials (3) (4)

	Porosity (f)		Porosity (f)
Softwood	0.65	Extruded brick	0.07-0.28
Hardwood	0.50	Sandstone	0.05-0.20
Chipboard	0.40	Cement render	0.20
General purpose brick	0.35	Cement mortar (3:1 s:c)	0.17
Sand-lime brick	0.30	Granite	0.02
Lime render	0.30		

For example, the porosity of softwood is 0.65 which means that there is 65% of the volume taken up by air and 35% by solid material.

Water has a strong affinity to the pores and small capillaries present which brings about the rise of water into the internal structure. Water is drawn up into the material by the force of capillarity. The capillary suction or capillarity is greatest for small capillaries and inversely proportional to the pore radius as Jurin's law describes (1). The height of rise of water in a capillary (h) is governed by the following equation:

$$h = \frac{2\gamma \cos\theta}{r\rho g}$$ ....Equation 1

Where;

γ = surface tension,

θ = contact angle,

r = capillary radius,

ρ = liquid density,

g = gravity.

The equation describes the relationship of pore size and rising height. In the case of water, it has been found that when the pore size is 0.1 mm then the rise is 14 cm but when the size is 0.01 mm the rise can be 1.4 m. The pore size in bricks and mortar can be as small as 0.001 mm so there is a significant potential for rising damp.

The potential for capillary rise is governed by the above equation but there are further factors for being taken into consideration.

When liquid flows through a tube, there are fictional factors which slow down the flow. The Hagen-Poiseuille law describes the behaviour and the determining equation shows the flow rate to be inversely proportional to the square of the pore radius (5). This means that as pores become smaller, the flow rate is increasingly reduced. The importance of this is that frictional factors counteract the capillary suction effect. As pores become smaller, there is a greater tendency for the water to rise but the processes becomes slower because of frictional contributions. Hence there are two competing influences.

The general term for describing the difficulty or ease of flow of a liquid through a porous substrate is the permeability and some examples of permeability values are given in Table 2.

Table 2: **Permeability of Water through some Materials** (3)

Material	Permeability (mS-1) x10^9
Brick (porosity 0.40)	32
Brick (porosity 0.31)	3.8
Cement paste w/c 0.5	0.00038
Cement paste w/c 0.8	0.046
Cement mortar (3:1 s:c)	0.046

This data show there are big differences in the permeability rates of water though these different materials. Although a well made cement paste has very fine capillaries and hence great potential for capillary rise, the process of movement becomes very slow because of the low permeability and flow rates.

A further factor to consider is that when the surface of a wall becomes wet, water can be removed from the surface by the process of evaporation. The evaporation of water from a surface depends on the temperature of the wet surface, the humidity in the air and the velocity of air above the surface. In the situation where the surrounding air is particularly humid, the evaporation is slowed down as the driving force for evaporation is reduced. As wind speed increases so does evaporation rate but not in a particularly strong relationship as evaporation rate is proportional to the square root of wind velocity (3). In the case of a partly wet wall surface, the controlling factor can then be how quickly this is replenished by internal moisture in the wall as the moisture is removed from the surface.

It should also be noted that evaporation of water is accompanied by heat loss and intensified cooling effect due to the latent heat of water evaporation. Techniques and products being employed for combating against rising damp will synergistically contribute to energy saving on household heating and cooling.

To bring all these factors together, in the case of rising damp we have on one hand, capillary rise increasing the height of the rising damp front and, on the other, gravity, frictional forces and evaporation in counter balance as described by the equation below.

$$Capillary\ Forces = Gravity + Frictional\ Forces + Evaporation \qquad \text{....Equation 2}$$

More recently, Hall & Hoff have developed the Sharp Front model for rising damp; it is so named because in the model the boundary between wet and dry parts of the wall is discrete or sharp (6). This builds on the concept of balance between capillarity and evaporation. The equation which describes the height of rise is;

$$H = S\left[\frac{b}{2\ e\alpha}\right]^{1/2} \qquad \text{....Equation 3}$$

Where:

H = height of the rising damp front

S = Sorptivity (the suction of water into the mortar)

b = wall thickness

e = rate of evaporation per unit area of the wetted surface

α = moisture content of the wetted region i.e. the volume of water per unit volume material.

The sorptivity is a measure of the suction or absorption of water into the material and has a strong influence on the height of the rising damp front. In terms of earlier model it combines the effects of capillary rise and frictional flow. It can be measured by partial immersion of the test material in water and recording the weight increase with time. Some examples of different sorptivity are given in Table 3.

Materials with lower sorptivity will show less potential for rising damp, for example, engineering bricks.

From the model it is possible to calculate some interesting quantities. For a solid masonry wall constructed of stone with a sorptivity of 1.0 mm $min^{-0.5}$, at a wall thickness of 150 mm the steady-state height of rise is 0.61 metres. If the wall thickness is increased to 300 mm, the height of rise increases to 0.87 m. This is because there is proportionally less evaporation to capillary suction in a thicker wall.

Table 3: Sorptivity Values of Building Materials (3)

	Porosity	Sorptivity mm $min^{-0.5}$
Clay brick – pressed semi-dry	0.36	1.32
Clay brick – hand moulded	0.33	2.21
Clay brick – engineering	0.07	0.09
Portland limestone	0.19	0.30
Sandstone	0.14-0.23	0.03-2.33
Gypsum plaster	0.42	1.62
Cement-lime mortar	0.27-0.36	0.56-1.94
Concrete w/c 0.55	0.10	0.19
Concrete w/c 0.75	0.13	0.29

It has been noted that the long timescale of rising damp equilibrium can impede laboratory experiments (3). The analysis of absorption into different layer composites showed that it was helpful to select an appropriately sorptive mortar. Cement mortars tended to be of low sorptivity and could impede capillary rise. The authors commented that lime mortars were better for use in capillary rise experiments.

In 20th Century, Mason was one of the key researchers to develop a model for rising damp where capillary rise and evaporation coexist in balance. A series of equations describe the flow processes through the capillary structure which are then balanced with evaporation (7). With evaporation introduced, the height of rise is governed by the constants relating to capillary pores, wall thickness and evaporation rate. In principle, evaporation equilibrium is an n-shaped profile of water distribution. The equilibrium between capillarity and surface evaporation is schematically shown in Figure 1.

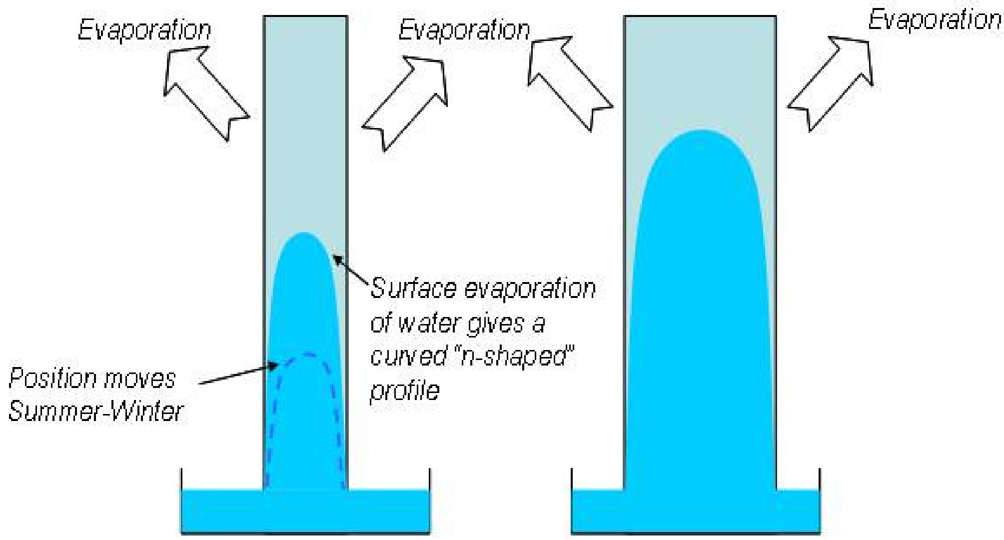

Figure 1: Schematic of equilibrium between capillarity and surface evaporation

In a thin wall, there is proportionally more evaporation than capillary rise. It means that the height of the rising damp front is reduced. An increase in the evaporation rate, as may happen from greater surface temperatures in the summer months, will also result in a drop in the height of rise. Similarly a reduction in the ground water level will also bring about a reduction in height of the rising damp front.

One problem highlighted by Mason is that the height of rise "increases by a factor of about seven between the first and perhaps the hundredth year of the lifetime of the wall". A tentative explanation is offered where slightly acidic water washes out free lime from the mortar to increase the flow process. Therefore, it is difficult to implement a test for rising damp with new mortars as these are not representative of the true situation in an older wall.

A further important paper is the publication by Massari and Massari which reports on "humidity rising" (rising damp) from the subsoil of buildings. A number of historic buildings in Rome were examined by the authors to determine the extent of rising damp. The height of rise was observed to be 5.3 metres in the extreme case of a 4 m thick wall (8).

The authors went on to describe the relationship between wall thickness and height of rise through a “climb index” which depended on thickness and ventilation. A 3 metre rise at Sapienza in Rome was shown in pictures.   In the extreme case of a San Bernardo church, the moisture reached a height of 5.3 metres (17 ft) with an unusually thick wall of 4 metres.

3. Published work on rising damp

Rising damp has been recognised as a perennial and ubiquitous problem in masonry buildings. Different aspects associated with rising damp including health and safety hazards, economic implications, fundamental research on its nature, experimental investigation, techniques and product development for combating against rising damp and case study of ordinary and heritage buildings have been well reported.

Health and safety implications resulted from rising damp have been identified and widely reported. According to the World Health Organisation publication ‘Damp and Mould’, in Europe between 10 and 50% of the indoor environments where people live, work and play are damp. Humid walls create coldness that makes more heating necessary and increases energy bills due to the higher thermal conductivity and heat capacity of water and moisture vapour. Rising damp is given in this report as one of the main causes of excessive moisture (9).

Looking specifically at the UK, the self-reported problems of damp is given as 15% in a further World Health Organisation document published in 2007. Occupants of damp and mouldy buildings are at increased risk of respiratory symptoms, respiratory infection and the exacerbation of asthma (10).

There are several historic references to rising damp which were published in the 19th Century. An early UK patent describes a flat slab made from a water resistant clay compound which can be placed at the foundation of walls to prevent damp from rising (11). An article in The Building News in 1862 refers to a method of making walls damp-resistant (12) and an entry in the British Medical Journal in 1872 discusses arresting rising damp with an impervious damp-proof course (13).

The architect, Thomas Worthington, described rising damp in his 1892 essay, and recommended that the damp course should disconnect the whole of the foundations from the superstructure. This preventative may consist of a double layer of thick slates bedded in cement, or of patent perforated stone-ware blocks or of three-quarters of an inch of best asphalt (14). It can therefore be seen that the subjects of rising damp and public health were becoming of importance in the latter part of the 19th century.

In a 16th Century building Farnesian in Rome, the damp was found to rise to 1.5 metres on the south side and 3.1 m on the north side. As there was no other difference between the two situations the sun exposure was deduced to reduce the rise by 1.6 m through increased evaporation consistent with Equation 2.

Detailed moisture content measurements were made by the BRE on a total of ninety four 100-year old properties in the Cardiff Bay area (15). Rising damp was said to occur if the moisture content was above 5%. These were taken in the basement of buildings but included studies on internal walls where no penetrating damp was possible. It was found that 54% of the properties were suffering from rising damp at a height of 0.3 m above floor level.

A useful text on the subject of rising damp is the BRE book "Understanding Dampness" (2). This gives a description of rising damp consistent with the balance equation above and points out the importance of the water table. If the water table falls the height of rise drops and a new equilibrium position is established.

It is noted that soluble salts are drawn up into the structure and become deposited in the wall. When water evaporates, the salt solution becomes more concentrated at the surface and the salts crystallise out of solution. This blocks the pores, reduces evaporation and raises the height of level of dampness. It should be noted that many of the salts are hygroscopic and can absorb moisture from the humid air causing damp patches in the wall. Photographs are given of cases where external render and interior plaster has bridged the damp proof course causing water to rise though the new pathway.

A detailed study of salt damage on a 16th-17th century church has been reported by the University of Minho in a Portuguese study (16). Samples were taken from many heights and locations for analysis to build up a full picture of salt damage. The main conclusions were that salts had been introduced by rising damp and were present at heights of over 2 metres. The construction of the church was a granitic stone with lime mortar joints; the mortar joints were considered to be salt-pollution reservoirs which needed to be addressed in any future conservation work.

Frossel in his book on masonry drying discussed the importance of covering the wall surface (17). Tiles, linings, paint systems and plasters are impermeable to vapour diffusion so they can increase the height of water to metres. The comments made by Frossel on the mechanism are generally in good agreement with experimental findings. He stated that fine capillaries absorbed water slower than coarse –pored materials but the maximum rise could eventually be greater.

I 'Anson and Hoff discussed the water movement in walls in their 1986 paper (18). Some interesting results on evaporation rate were reported shown which had then an impact on rising damp height. At a temperature of 5 ^{0}C and a humidity of 80% RH, the height of capillary rise at equilibrium was found to be 0.8 metres for an unrendered wall and 1.3 metres for the rendered case. The characteristic time (time taken to reach 95% equilibrium moisture content) was 2.9 years for the unrendered wall and 7.7 years for the rendered case. In the situation where the RH is 90%, the rendered wall took 18.3 years to reach equilibrium. This work demonstrated that the long time scales were involved in rising damp.

In a study in Copenhagen, the Danish Technological Institute found rising damp was at heights of over one metre when using Danish yellow soft mud bricks and different mortars (19). It was observed that rising damp was more severe with lime mortar compared to walls with lime plus cement as the binder in the mortar. In the walls with lime mortar, the water was observed to pass freely from bricks to mortar whereas in the lime plus cement case the transport only appeared to occur in the mortar joints.

In a study in Netherlands, Lubelli reported that a series of investigations and monitoring of a restoration plaster applied on heavy salt loaded masonry were performed (20). The investigation was made during a period of more than three years on an ancient church flooded by the sea 50 years ago. This building was representative for many other masonry monuments in the flooded areas in Netherlands. The church was restored several times in the past 50 years, showed a serious decay, mainly affecting the restoration plaster applied in the interior. In this study, better understandings of the mechanisms were developed in order to find out the reasons of the unsuccessful repairs performed in the past and possible solutions were proposed to stop or slow down the decay process.

Lubelli also reported that sea salt damage to porous building materials was not only in regions located near the sea but also in continental areas (21). In walls, sea salts might stem from different sources and would penetrate from the ground by rising damp. Salt could be carried by the wind in the form of salt spray, occasional or recurrent flooding, and the use of sea water in the preparation of the mortar. He commented that although accelerated crystallization tests performed in laboratory on building materials usually showed that sea salts were less harmful to masonry than sodium sulphate, in reality they might cause serious damage. Different decay patterns of sea salt weathering were found for different sources and conditions. It was reported that various sources of sea salts were present in the same masonry wall in the church of Domburg which located in a coastal area of Netherlands. A 'rising damp zone' showing brick blistering and a 'sea spray zone' affected by powdering of the brick were identified at different height from the ground level.

In a study in Greece, the characterization of historical mortars from a Venetian Villa in Chania, Crete and the new synthesized mortars for its restoration were presented as case study by Maravelaki-Kalaitzaki etc. (22). The villa was built during the 15th century and was representative for Venetian architecture in rural areas. The main reasons of deterioration of the construction materials were identified to salt crystallization, water and salt solutions movement through walls by capillarity. The use of cement mortars in the villa during previous treatments induced severe damage to the adjacent stone blocks. The most common decay patterns were extensive voids and loss of material of the binding mortar.

In a study in Australia, Lopez-Arce reported that building in Adelaide suffered from rapid damage to historic building materials due to salts, rising damp and damp-proof course failures (23). 24 historic buildings in Adelaide were examined with a focus on the building materials, historic interventions and current treatments applied to treat rising damp and salt decay. Analysis of 90 samples found high levels of sodium sulphate, sodium chloride and sodium nitrate in cellars, ground water and building materials, suggesting typical example of rising damp. Different treatments of salt-laden masonry, with hundreds of treated buildings of the same age in the same environment were experimentally compared and analysed.

In a study in Malaysia, Rahman reported that salt attack and rising damp were considered the most challenging, particularly for building conservation (24). Both problems of salt attack and rising damp were closely associated. Moisture from the rising damp made the building's existing salts soluble, or ground water that contained salt found its way through the building wall. High salt concentrations in masonry walls caused extensive fretting and crumbling of the lower parts of walls. Sodium chloride and calcium sulphate were commonly found in masonry walls, apart from other forms of salts. In a case study, the author investigated five buildings in Penang and the research findings showed that these buildings suffered several common building defects, including salt attack and rising damp. Treatment guidelines for salt attack and rising damp were proposed in the context of Malaysian architectural heritage and climatic conditions.

Some differences in the behaviour of different mortars were also recently published by Rirsch and Zhang (25). Walls of 0.5 metre height were built from Fletton bricks with high and low permeability mortars representative of historic and modern compositions. Over a 12 month timescale, a considerable difference in behaviour was observed with damp rising to over 0.5 metres in the high permeability case and only 80 mm in the low permeability mortar. There was a notable difference in the moisture contents of the bricks in the two situations as shown in the figure below.

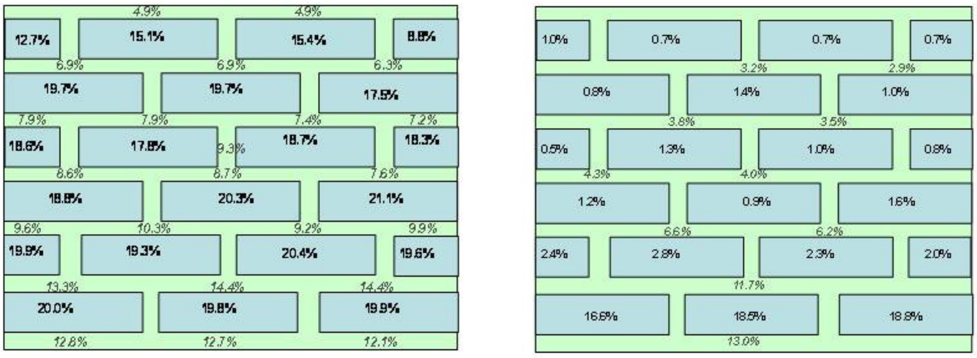

Figure 2: The influence of mortar on the water distribution of two walls made with the same brick type

Measurements of the sorptivity of the mortar showed the results to fit well with the Sharp Front model. Using this model it was possible to calculate that the with the high sorptivity mortar the amount of water passing through one metre length of a single skin wall is of the order of 250 litres per year, which is a significantly high volume.

A further interesting point was that where rising damp was occurring, a data logger inserted in the wall showed that evaporative cooling reduced the wall temperature by 0.5 ^{0}C.

In a follow-up paper Rirsch and Zhang (26) described the properties of mortar samples obtained from a range of older properties in the UK, some of which were suffering from rising damp problems. An analysis of the samples showed that the pH of the mortars reduced with time consistent with carbonation, the amount of soluble salt generally increased with the age of the wall. A wide range of sorptivity values were found, suggesting that there be a significant difference in the rising damp potential of mortars found in the field.

It was also observed that the mock-up historic mortar used in the first study was quite representative of the real case.

Table 4: Examples of observed mortar properties (26)

Sample	Sorptivity	pH	Water absorption
	mm min(-1/2)		wt% 24 hours
6 months old - Modern mortar	0.3	12.1	9.0
110 years old - brick wall terraced house	1.3	9.2	19.1
160 years old - lime mortar stone wall	4.6	9.0	22.8
15 yrs old - pointing	0.2	11.9	2.5
160 yrs - solid stone wall	14.0	8.5	25.0
140 yrs old - brick wall	4.1	9.0	19.2
400 yrs old - stone wall (Warsaw)	0.5	8.7	10.0

Finally, the rising damp in a brick pillar constructed from Ibstock Arundel multi stock bricks with a 1:3 natural hydraulic lime to sand mortar has recently been reported by Burkinshaw (27). After 45 days, the moisture level had reached approximately 600 mm. The author commented that the moisture would have risen yet higher if longer time was given to the test.

Some comments were also made on the observed speed of rise. In the early stages of the test, the rate of rise was 6.5 mm/hour which gradually slowed to 0.3 mm/hour.

4. Conclusions

The following conclusions can be drawn based upon a systematic search and review of published papers on rising damp.

1. Rising damp is an age-old and ubiquitous problem. It has been causing many problems to masonry buildings with dire health, environmental, social and economic implications.
2. Records on observation and descriptions on this phenomenon date back to early times. It was identified as a public health issue in the second half of the 19th Century.
3. Today rising damp is well understood. Mason and more recently Hall and Hoff have developed the models which describes the balance between rising capillary forces with gravity and evaporation.
4. The key controlling material property is the sorptivity (rate of suction) of water into the mortar. Modern mortars have lower sorptivity than those found in older buildings and therefore differ significantly in their rising damp behaviour.
5. Thicker walls show more rising damp. This is because as wall thickness increases the relative amount of evaporation is reduced. Any addition to the wall surface (rendering or painting) has a tendency to increase rising damp by reducing evaporation.
6. A fact stressed by some workers is the long time scales that it can take before rising damp reaches a steady-state level. There is evidence that processes occur which increases the sorptivity of the mortar with time and therefore drives the damp front higher.
7. Lime mortar and bricks construction walls quickly show rising damp of 0.5 to 1 metre.
8. Rising damp leads to poor building insulation, which causes poor household energy consumption efficiency with economic loss and environmental damage.
9. Significant efforts have been made to establish good understandings of raising damp, to develop products and techniques and to provide services for combating this problem.

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