How traditional lime coatings work

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Further to a presentation on the subject at the Building Limes Forum Gathering in Stirling in 2019, this article examines the functional behaviour of traditional lime coatings. First, some physical principles relating to moisture movement in porous building materials are explained; next, these principles are applied to interpret the behaviour of lime surface coatings in practice; thereafter, modern alternatives are critically appraised against the historic example; and finally, the practical implications for buildings are summarised.

Traditional lime coatings to masonry buildings include plaster and limewash internally, and harling/render and limewash externally. Although such coatings undoubtedly serve an aesthetic purpose, their primary function has always been to keep buildings dry and habitable.[1,2,3]

In grappling with the moisture load on buildings, which is at the heart of building conservation, lime coatings not only improve the drying performance of the walling fabric but also sacrificially protect the masonry substrate. For repairs on traditional masonry buildings to be compatible, they need to complement the functional behaviour of the original fabric. The importance of technical compatibility has been widely established,[4] exemplified by the failure in the past century of incompatible cement mortars to protect historic building fabric by sacrificial decay. In recent years, the practice of altering so-called ‘lime’ mortars with chemical additives has created a new threat to the historic fabric being conserved. The UK climate is becoming wetter, and the obvious knee-jerk reaction is to ‘protect’ old buildings with modern treatments, such as waterproofing agents and modified mortars, to keep them dry. However, a thorough understanding of how traditional lime coatings work reveals that it is rarely necessary to modify their complex functional behaviour with such additives.

Fig. 1 Lime harling to the chancel of the Church of St Oswald, Warton, Lancashire, following significant structural repairs to the three-centred arch and gable peak. Note the contrast with the cement roughcast through the nave, aisles and belfry tower.

Physical principles

Moisture is the engine of decay in traditional buildings: it mobilises the agents of decay, affects habitability and degrades structural integrity.[5] The principal agent of decay in UK traditional masonry buildings is soluble salt, mobilised by wetting and drying cycles.[6] Buildings get wet from the outside (wind-driven rain striking the walls), the inside (internally generated water vapour) and from below (rising damp). The walling fabric acts as a buffer between the internal and external environments.

Examination of the response of the walling fabric to this moisture load looks to the science of porous materials.[7] It is well known that old buildings need to 'breathe'.[8] However, it is a widely held misconception that this 'breathing' concerns the vapour permeability of the walling fabric. Before examining how moisture actually moves through a masonry wall, it is helpful to consider first the spontaneous natural water distribution in porous materials, in which there is no external force encouraging water to move in any particular direction. Figure 2 presents an idealised random cross-section through such a material.

Water molecules are attracted to the walls of hydrophilic (wettable) solids and stick to them (adhesion); they are also attracted to one another and stick together (cohesion).[9] A wetted porous solid is a three-phase (gas/liquid/solid) molecular system, which naturally strives to reach a state of minimum energy. This is achieved by minimising the solid/gas interface and maximising the solid/liquid interface.[10]

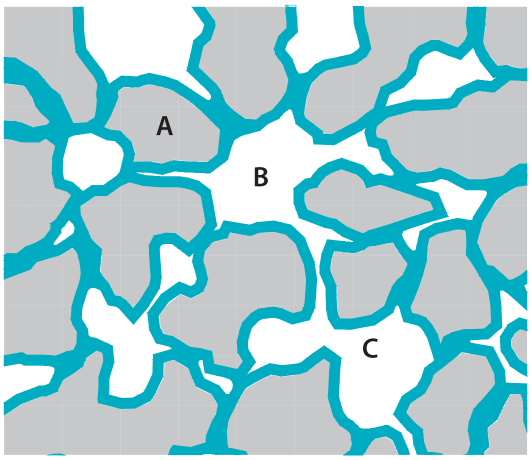


Fig. 2 Cross-section through porous material showing spontaneous water distribution without movement. A) Solid phase; B) pores; C) water adhering to pore walls.

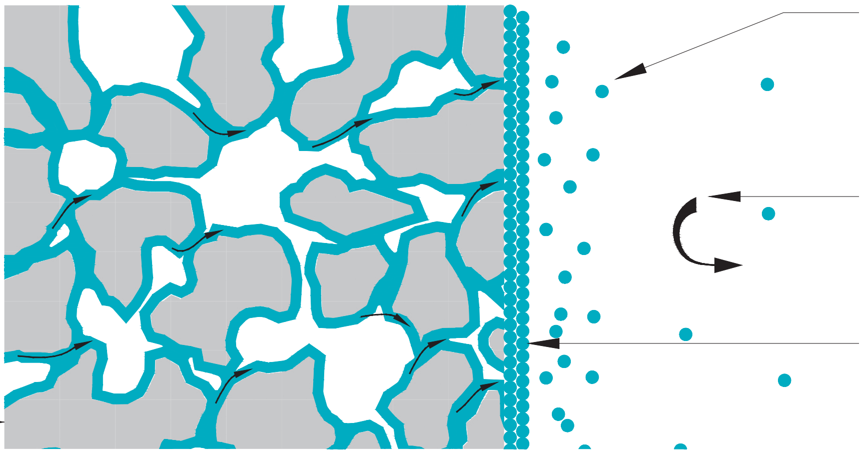
This quest to maximise the solid/liquid interface is the driver behind the phenomenon of capillarity, whereby the meniscus climbs against gravity pulling the body of water upwards to stick to the surface of the solid phase.[11] The result of this molecular interaction is a film of water that lines the pore walls, forming an interconnected three-dimensional web or network of water throughout the porous material. At high moisture contents, it is a thick film; at low moisture contents, it is a thin film.[12,13]

Suppose the arrangement in Figure 2 has an exposed surface that is subject to drying. The principal driver behind the drying of porous materials is air movement across the surface; the faster it moves, the more rapid the rate of drying.[14] This is known as convective drying. This is why clothes dry outside on a washing line even when it is cold, and why it takes a long time to dry washing indoors. Figure 3 shows the wetted porous material with a drying front now introduced.

As water evaporates from the surface of the material, a dynamic thinning of the film occurs near the surface. This is compensated by a flow of water molecules along the film network within the material, which progressively transports water towards the surface and reduces the thickness of the film of water lining the pore walls at depth. This process of moisture movement sustaining the drying flux is known as stage 1 drying. The mode of moisture transport through the material is the liquid phase.[15]

Towards the end of drying, as the layer of adsorbed water lining the pores becomes thinner, the coherent bonds of the water film eventually break, leaving a series of isolated clusters of water within the material. It is only at this point that the mode of moisture transport changes to the vapour phase: that is, a diffusion-based process of gradual equalisation of gas concentration over time, known as stage 2 drying. This is an inefficient and very protracted process,[16] bluntly characterised as 'vanishingly slow'.[17]

Porous masonry responds to water vapour in much the same manner: internally generated water vapour in traditional buildings is absorbed by the walling



'Evaporation layer': not-quite-liquid, not-quite-gas (stagnant)

Wind blows away evaporation layer, maximising stage 1 drying

Water film accessing drying front supplied by capillary flow through material

Porous material (non-saturated flow)

Fig. 3 Cross-section through porous material showing capillary flow towards drying front.

fabric, but there is a phase change from vapour to liquid at or close to the internal surface (interstitial condensation).[18] Although there is potential for water vapour to diffuse from the humid interior of a building to a drier exterior separated by a porous wall, this is overcome by the local forces within the porous solid: with relative humidity within the pores of damp porous materials at almost 100 per cent, the condensed water vapour molecules adhere to the pore walls. They then traverse the porous material as part of the network of liquid water, rather than in vapour form.[19] Wind cannot freely blow through porous materials like masonry fabric because the microstructure is tortuous. When water vapour enters a porous material, the molecules bump into the walls of the pores and lose energy until they condense, sticking to the liquid film lining the pores. This usually happens within the first few pores, essentially at the surface of the material.[20] Movement through the material then occurs in the liquid phase.

So, the absorption of water in either liquid or vapour form, the transportation through the walling fabric, and ultimately the drying of a single-layer porous material constitute, principally, a liquid phase process. This is determined by material microstructure (porosity, pore size distribution and interconnectivity) and the surface chemistry of the pore walls, which drive the molecular adhesion force behind capillarity.

Lime surface coatings on masonry substrates form multi-layered systems. In the drying of multi-layered porous media, the same physical principles apply as for single-layered porous materials. However, the relative predominant pore size of each layer induces capillary flow between the materials: the material with fine pores will draw the water out of the material with coarse pores because of its higher capillary affinity.[21] In essence, the three-phase molecular system tries to replace as much solid/gas interface with liquid/solid interface, and can find proportionately far more internal surface area in the pores of the fine-pored material than it can in the coarse-pored material, therefore spontaneously moving water into the finer pored material.

This suction of water from coarse-pored material into fine-pored material underpins the behaviour of a desalination poultice: the moving water transports with it the soluble salt ions in a process known as advection.[22] The coarse-pored material dries first because its bound water is pulled out by the finer pored poultice. The fine-pored material holds onto the water for longer while it sustains the drying front, but is ultimately where the salt precipitates in the final stage of the drying process, thus damaging the fine-pored material (Figure 4). This is the root of the sacrificial behaviour of traditional lime mortar.[23]

It is important to note that a coarse-pored material cannot draw water – and by extension, salts – out of a fine-pored material.[24] In such an arrangement, the drying front is located at the surface of the fine-pored material, where salt deposition then takes place.[25] Similarly, a fine-pored material that has a hydrophobic (water-repellent) surface chemistry cannot draw water out of a coarse-pored material. Instead, the drying front is repelled into the coarse-pored material,[26] and with it go the salts, where they then cause damage (Figure 5).

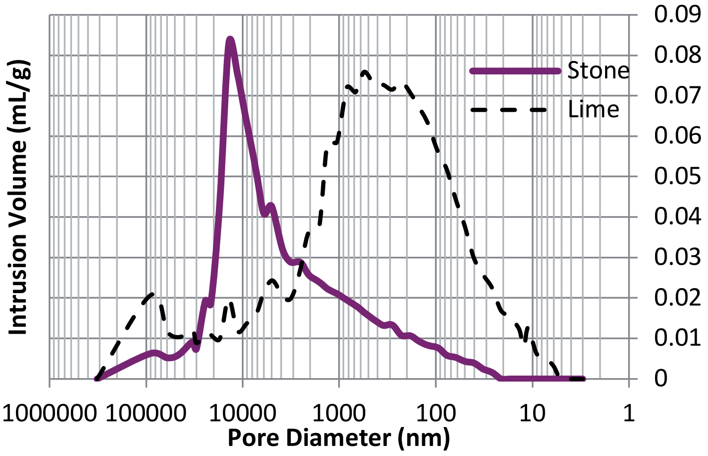
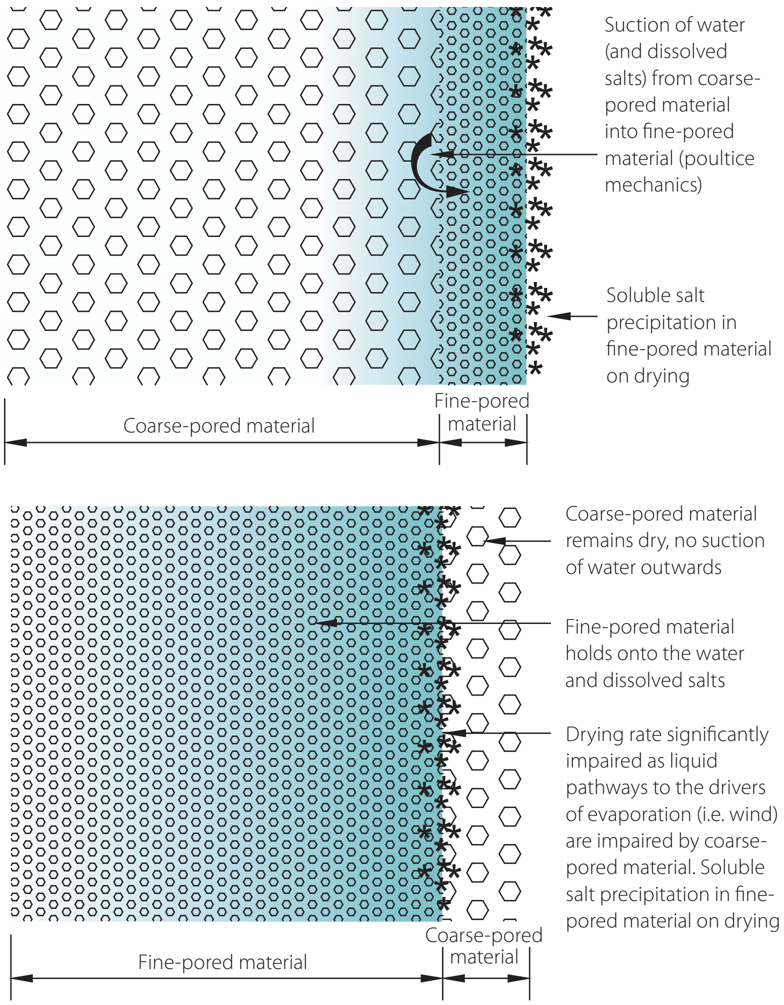


Fig. 4 (Above) Relative pore size distributions of sandstone and traditional lime mortar at Bothwell Castle, Glasgow. The distinct difference in predominant pore size (approximately an order of magnitude) creates a marked poulticing effect.

Fig. 5 (Below) Idealised cross-section through fine-pored coating on coarse-pored substrate, and vice-versa, showing capillary flow direction.

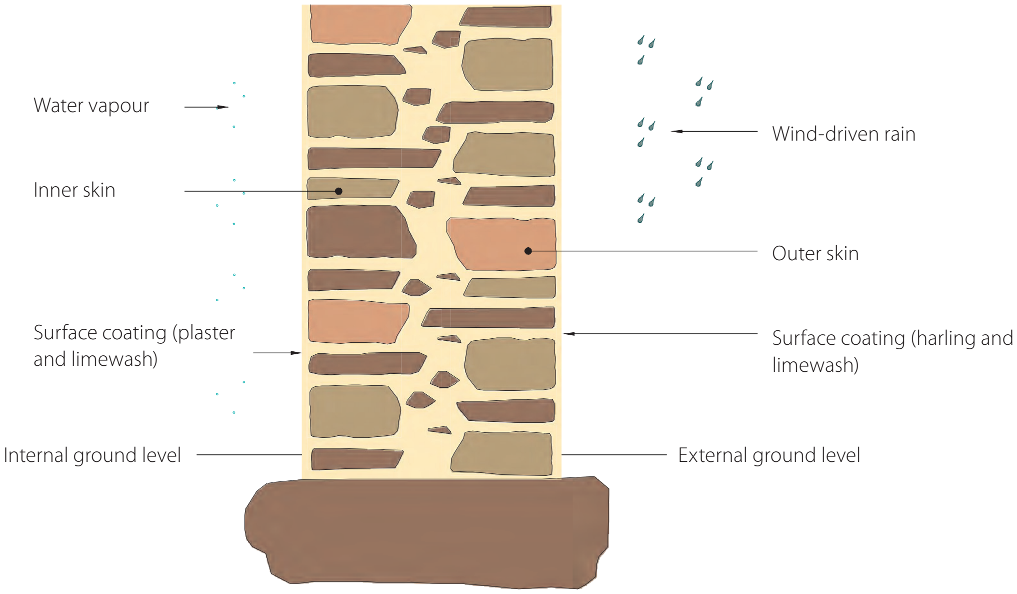


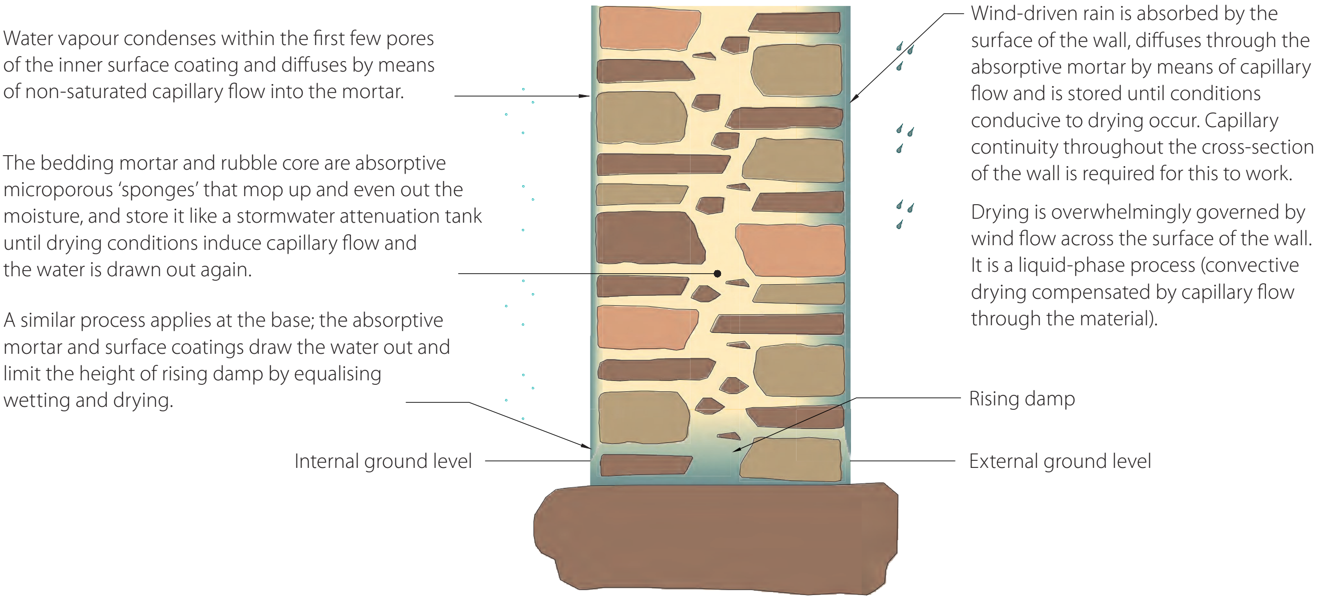
Applying the physical principles

Traditionally built and finished walls 'breathe' by the convective drying described above to both the inner and outer surfaces. The thickness of the porous walling fabric is simply a storage tank to mop up and hold the moisture until conditions conducive to evaporation arrive. When they do, the internal and external coatings (plaster, harl or limewash) recharge the stored moisture into the environment (Figure 6).

The functional element in a traditional lime coating is primarily the mineral binder. Traditional lime as a binder (specifically, calcium carbonate) is highly microporous. Its microstructure is optimally

Fig. 6 Behaviour of traditional masonry walls in response to moisture.


Cross-section through a traditional stone masonry solid wall


Behaviour of a traditional stone masonry wall in response to moisture

Water vapour condenses within the first few pores of the inner surface coating and diffuses by means of non-saturated capillary flow into the mortar.

The bedding mortar and rubble core are absorptive microporous 'sponges' that mop up and even out the moisture, and store it like a stormwater attenuation tank until drying conditions induce capillary flow and the water is drawn out again.

A similar process applies at the base; the absorptive mortar and surface coatings draw the water out and limit the height of rising damp by equalising wetting and drying.

Wind-driven rain is absorbed by the surface of the wall, diffuses through the absorptive mortar by means of capillary flow and is stored until conditions conducive to drying occur. Capillary continuity throughout the cross-section of the wall is required for this to work.

Drying is overwhelmingly governed by wind flow across the surface of the wall. It is a liquid-phase process (convective drying compensated by capillary flow through the material).

suited to capillary activity, characterised by an open, interconnected matrix of pores – with a predominant size of approximately 1 µm – of wettable surface chemistry.[27] This microstructure is an outworking of its mineralogical composition: the causal agent responsible is free or uncombined lime in the fresh mortar, which subsequently carbonates.[28,29,30] Through a microscope, it looks like a sponge (Figure 7).

Thanks to this binder, the mortar joints are highly microporous: they are the primary pathway for moisture in traditional masonry construction.[31,32] The surface coatings intimately engage with the bedding mortar,[33] maintaining capillary continuity. The behaviour of each coating is examined below.

Internal lime coatings

In an average domestic dwelling, housing four occupants, around 3½ tonnes of water vapour are generated internally every year.[34] In a well-cared-for building, much of this would be ventilated through the windows, fireplaces and so on, but inevitably some of it will condense within the building fabric. Absorbent traditional lime finishes draw internally generated water vapour into the porous fabric, where interstitial condensation then occurs, eliminating surface condensation and mitigating mould propagation – the latter further enhanced by the antiseptic, antibacterial and antifungal properties of lime finishes.[35,36] This natural hygroscopicity helps to buffer changes in relative humidity of the air inside buildings throughout seasonal changes in environment.

Rising damp is a high-volume, long-term water load on traditional masonry buildings. In their seminal work on the subject, Christopher Hall and William Hoff showed that even for a relatively thin (15 cm) solid limestone wall in typical environmental conditions, a total volume flow through the wall of some 320 litres per linear metre occurs every year.[37] For a typical dwelling, this water load is markedly larger than that absorbed from internally generated vapour. For a traditionally thick masonry wall, it is considerably more.

Clearly, all this water needs to go somewhere. Lime plaster, finished with limewash, provides a large, capillary-active drying front to evaporate the water drawn into the wall by rising damp and interstitial condensation.[38] A lime plaster coating on a fine-pored masonry substrate will slightly increase the drying rate of the wall compared with bare masonry.[39] But for coarse-pored masonry substrates, a lime plaster coating will cause a marked acceleration of the drying rate compared with bare masonry.[40] In the latter case, the lime plaster pulls the body of water out of the wall through poultice mechanics; the plaster remains wet while the coarse pores of the substrate become drier as water is drawn out to the evaporation front.[41]

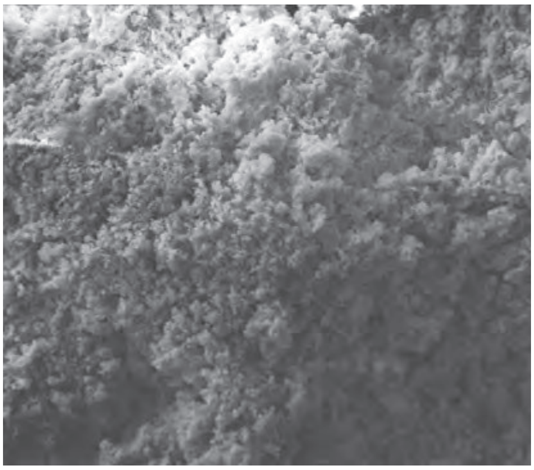


Fig. 7 Scanning electron micrograph of traditional lime mortar from Kilmahew Castle, Argyll and Bute. 10,000x magnification.

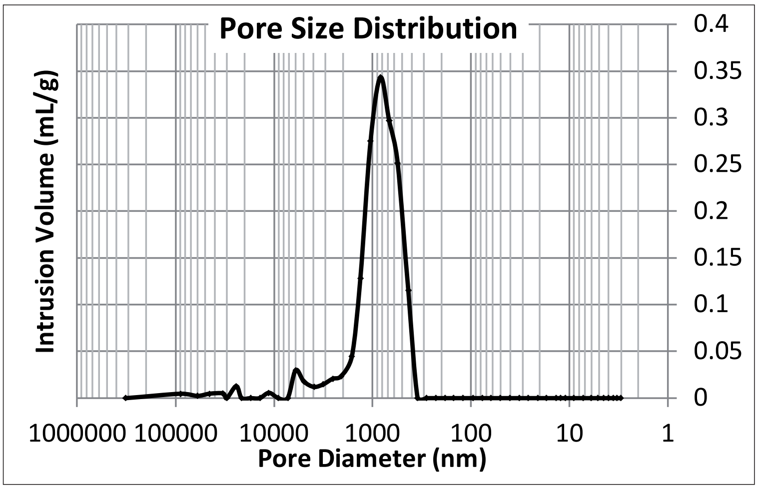


Fig. 8 Pore size distribution of traditional lime plaster from Cleeve Abbey, Somerset. Note the predominant pore size is approximately 1 µm, commensurate with calcite binder (an air lime mortar) – optimally tuned for capillary activity.

The plaster absorbs and stores moisture, and then either re-evaporates it internally or transports it in liquid form through the bedding mortar to the outer surface coating, where it evaporates externally. When things work well, they tend to go unnoticed. However, when traditional internal lime surface coatings are replaced or smothered by incompatible materials, such as impermeable paint, cement mortar or gypsum plaster,[42] the moisture content in the porous fabric steadily builds up and leads to problems that are well known.

External lime coatings

Wind-driven rain (WDR) is the main source of moisture for building facades.[43] The WDR load varies according to the exposure zone and the orientation of the particular wall.[44] For walls in 'sheltered' exposure zones, the approximate WDR load is up to 33 l/m^2 per WDR spell; for walls in 'very severe' exposure zones, the approximate WDR load is in excess of 100 l/m^2 per spell.[45]

Over a period of some 30 years, the average total water load from WDR was measured across the UK. Western coastal sites received more than 380 l/m^2 per year of WDR averaged across all facades and wall

Fig. 9 Traditional lime harling, limewashed, becomes waterlogged during heavy rainfall and forms a film of water on the outer surface to minimise water ingress.

orientations. Tiree – the most westerly island in the Inner Hebrides, Scotland – received some 540 l/m^2 per year. Inland areas averaged less than 240 l/m^2 per year.[46] For a typical building, this puts the WDR load on the walls of buildings in the region of tens of tonnes, every year. This is a lot of water, and it needs to go somewhere.

Traditional lime surface coatings minimise water ingress into masonry walls. Compared with bare masonry, a wall covered in a traditional lime surface coating remains drier for longer during spells of WDR. As observed in the 'Physical principles' section (Figure 4), a coarse-pored material cannot draw water out of a fine-pored material: the fine-pored surface coating material holds onto the water as long as it can, and the coarse-pored substrate material can only become wet when the fine-pored coating has become saturated – and even then only through diffusion-based movement (a slow process), not by capillary flow. Therefore, the majority of water entering the wall is held at or just below the surface, exploiting the 'overcoat' behaviour of traditional buildings.[47] This means that WDR in excess of what the surface coating can readily absorb is deflected: it either splashes back off the wall or forms a film on the surface of the waterlogged region and flows down the wall (Figure 9).

Fig. 10 Church of St Oswald, Warton, Lancashire. Traditional lime harling, limewashed, drying after wind-driven rain. The darkened side on the left is orientated towards the prevailing wind.

When the rain stops but the wind keeps blowing, the film on the surface quickly vanishes, either through evaporation or by being absorbed into the surface coating. The lime coating then reverts to the non-saturated convective drying process, maintaining the liquid film pathways throughout the material that are essential for effective drying at depth and that often give traditionally finished masonry buildings the ability to dry out during the same storm.[48] It is also the reason why lime-coated materials darken in colour during storms, appear soaking wet on the outside, but remain dry on the inside (Figure 10).

For a bare masonry wall (bedded and pointed with lime mortar), the primary drying front is the surface of the mortar joints.[49,50] This is broadly true for masonry units of porous composition, but it is especially pronounced for those that are non-porous.[51] For a typical wall, this surface area is a relatively small (but not insignificant) proportion of the wall as a whole. The entire wall gets wet though, according to its shape, orientation and exposure, and so the mortar has to work hard to recharge this moisture back into the external environment. Applying a traditional lime coating across the full surface of the wall increases the size of the drying front, thus significantly enhancing its drying efficiency.

Applying limewash also improves the drying rate. A study by Vânia Brito and Teresa Gonçalves demonstrates that the drying performance of a wide variety of substrates is enhanced by applying even a relatively thin coating of limewash.[52] For coarse-pored substrates, the drying rate is increased by 50 per cent. Even the drying efficiency of the lime mortar control specimen in the study was enhanced by coating with limewash. The reason that the drying behaviour of lime mortar is enhanced by limewashing can be explained by the fact that limewash is neat binder, whereas mortar comprises binder and aggregate. In a mortar, it is the microporous sponge-like binder rather than the aggregate that is responsible for functional behaviour (unless, of course, the aggregate is microporous and then it, too, contributes). Limewashing increases the surface area of the lime mortar by coating the aggregate (Figure 11).

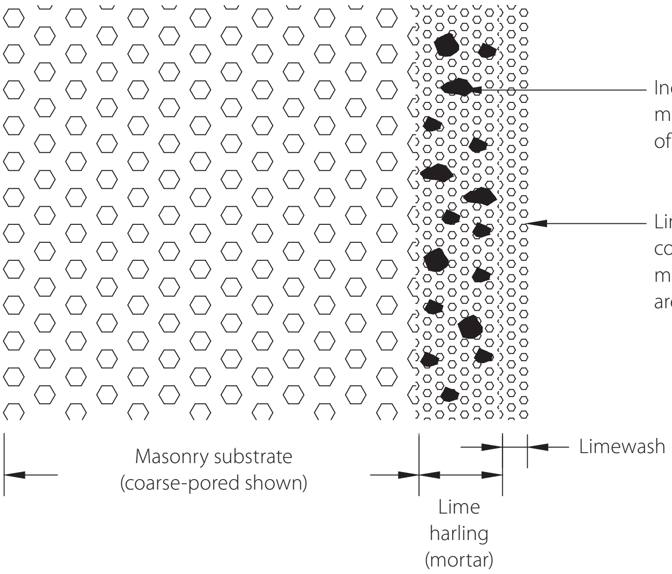


Fig. 11 Idealised cross-section through lime render/harling, finished with limewash.

Paradoxically, limewash dries even quicker than an open body of water under the same environmental conditions.[53,54] The surface of a body of water is smooth, so the size of the drying front of such a body is the plan area. The surface of limewash, on the other hand, is microscopically rough, which markedly increases its surface area and thus the drying front, compared to the plan area. As it is highly capillary-active, limewash can sustain the higher evaporation rate through capillary flow.

Sacrificial protection

Traditional internal and external lime coatings, including limewash, are both decorative and functional. As a result of the way they handle the water load on the walling fabric, they sacrificially protect the masonry substrate. This subject has been examined in a previous article by the author published in the 2017 edition of this journal.[55]

Broadly, this sacrificial protection is due to the poulticing principle: where the water goes, the salt goes. The last element to dry in multi-layered porous materials is the fine-pored material with the highest capillary affinity, and in the context of lime coatings on masonry walls this is almost always the lime coating itself. A study by Jelena Petković et al demonstrates that for lime plaster on a coarse-pored masonry substrate, salts entirely accumulate in the plaster, leaving the substrate clean.[56] This shows the marked efficiency of lime coatings in preserving historic masonry fabric. Put simply, lime coatings desalinate masonry.[57, 58]

Fig. 12 Pronounced manifestation of sacrificial protection at work at Hurst Castle, Hampshire. The highly soluble salt load is being poulticed out of the coarse-pored brick substrate by the fine-pored traditional lime mortar (Credit: Kim Collins, Historic England).

Modified mortars and coatings

At face value, covering traditional buildings in waterproof coatings to keep them dry seems to make sense. Inevitably, however, such an intervention will result in a wet building and accelerated decay of the masonry fabric. Commercial admixtures such as oleates, stearates, silanes and oils (linseed, olive and so on) have all been shown to impair or inhibit capillary activity, coarsen microstructure and impair the bond between mortar and substrate.[59, 60, 61]

Studies by Cristiana Nunes et al demonstrate that lime plasters modified with water repellents significantly hinder the drying rate of masonry substrates.[62] This is attributed to the disruption of capillary flow, starving the wet substrate of liquid phase access to favourable evaporation conditions at the outer surface. This forces evaporation at depth, where the moisture then has to diffuse through the plaster – which is an incredibly slow and inefficient process, regardless of how vapour-permeable the plaster is.

Imagine hanging your damp washing on a clothes line inside a GORE-TEX tent: although the fabric of the tent is highly vapour-permeable, it is also windproof, and so starves the damp washing of the air flow that is vital to its efficient drying. Figure 13 presents this principle in an idealised cross-section through such a coating on a masonry substrate.

This disruption to the drying behaviour ruins the sacrificial behaviour of the lime coatings by displacing the evaporation front away from the surface of the coating and into the substrate. The harmful salt precipitation stage is also displaced and forced into the substrate, leading to decay of the masonry. Precisely this arrangement has been demonstrated by Gonçalves et al.[63]

On the basis that modified lime mortars do not breathe, and do not provide sacrificial protection, they defeat the purpose of the lime coating in the first place. The evidence now exists to demonstrate that these materials are objectively incompatible with traditional buildings. Presented with the temptation to 'waterproof' old buildings, it is imperative to go back to basics, learn lessons from history and use traditional skills, otherwise historic buildings will inevitably pay the price.

Summary

How traditional lime coatings work can be explained scientifically and measured experimentally; however, the best evidence testifying to their behaviour is found in the thousands of years of empiricism and experience.[64, 65] By comparing cement mortars and traditional lime coatings, the effectiveness of the latter can be starkly clarified. This was demonstrated at the Haa of Sand, a traditional solid-walled building in Shetland, spectacularly exposed to WDR. Once chronically wet under a cement roughcast, the interior is now dry and habitable following the removal of the cement and its replacement with hot-mixed lime harling.[66]

So, to summarise:

- Traditional buildings do not 'breathe' by vapour permeability of the walling fabric.
- Traditional buildings 'breathe' by convective drying, the flux of which is compensated by capillary flow through the porous walling fabric – primarily through the mortar joints.
- Traditional lime coatings perform a vital role in drying masonry walls, actively drawing out the water from the substrate and increasing the size of the evaporation front.
- The consequence of this drying behaviour is the sacrificial protection of the masonry substrate.
- Modified mortars significantly impair the drying behaviour of traditional masonry walls and accelerate fabric decay: they are objectively incompatible with traditional buildings.

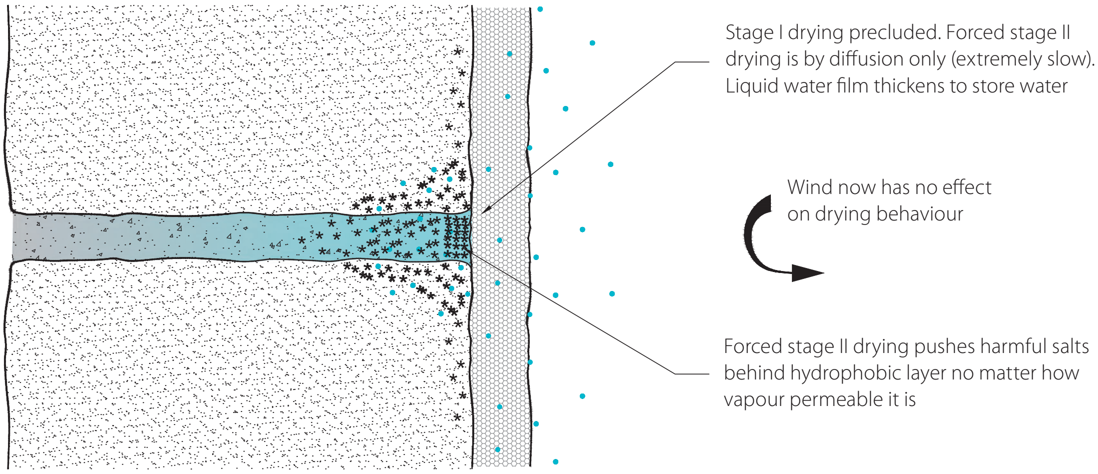


Fig. 13 Idealised cross-section through a lime mortar joint in a porous masonry wall showing disruption to drying and sacrificial protection by a modified lime mortar coating.

Endnotes

1 J. C. Loudon, *Encyclopaedia of Cottage, Farm and Villa Architecture*, 1st ed, 1833.

2 B. Bennett, 'Awash with colour: The decorative and protective roles of limewash', *The Building Conservation Directory*, 1997.

3 C. Frew, 'Lime harling', *The Journal of the Building Limes Forum*, 22, 2015, pp. 25–31.

4 A. Henry and J. Stewart, *Mortars, Plaster & Renders*, 2012.

5 I. Maxwell, 'Introduction to lime in Scotland', in J. Dorrington-Ward and I. Maxwell (eds) *The Historic Scotland International Lime Conference, Edinburgh,* 1995, p. 5.

6 C. Price, 'The decay and preservation of natural building stone', *Chemistry in Britain*, 11(10), 1975, pp. 350–53.

7 G. Torraca, *Porous Building Materials: Materials Science for Architectural Conservation*, 2nd ed, 1982.

8 P. Hughes, *The Need for Old Buildings to 'Breathe'*, 1986.

9 E. K. Chapin, 'Two contrasting theories of capillary action', *American Journal of Physics*, 27(9), 1959, pp. 617–19.

10 H. Stone, 'Interfaces: In fluid mechanics and across disciplines', *Journal of Fluid Mechanics*, 645, 2010, pp. 1–25.

11 M. Sophocleous, 'Understanding and explaining surface tension and capillarity: An introduction to fundamental physics for water professionals', *Hydrogeology Journal*, 18(4), 2010, pp. 811–21.

12 D. Tabor, *Gases, Liquids and Solids and Other States of Matter*, 3rd ed, 1991.

13 Torraca, 1982, op cit.

14 C. Hall and W. D. Hoff, *Water Transport in Brick, Stone and Concrete*, 1st ed, 2002.

15 P. Coussot, 'Scaling approach of the convective drying of a porous medium', *The European Physical Journal B: Condensed Matter and Complex Systems,* 15(3), 2000, pp. 557–66.

16 Hall and Hoff, 2002, op cit.

17 R. Pender, *A Common-Sense Approach to Damp*, 2020. historicengland.adobeconnect.com/plbf7ucly2lj/ (accessed August 2021)

18 R. Pender, 'Water in permeable building materials', *The Building Conservation Directory*, 2016.

19 Torraca, 1982, op cit.

20 Pender, 2020, op cit.

21 L. Pel, 'Moisture transport in porous building materials', PhD thesis, Technische Universiteit Eindhoven, 1995.

22 L. Pel, A. Sawdy and V. Voronina, 'Physical principles and efficiency of salt extraction by poulticing', *Journal of Cultural Heritage*, 11, 2010, pp. 59–67.

23 D. E. Wiggins, 'Lime mortar and sacrificial protection of heritage masonry', PhD thesis, Glasgow Caledonian University, 2015.

24 L. Pel, A. Sawdy and V. Voronina, 2010, op cit.

25 J. Petković et al, 'Salt transport in plaster/substrate layers', *Materials and Structures*, 40, 2007, pp. 475–90.

26 T. Gonçalves, L. Pel and J. Rodrigues, 'Worsening of dampness and salt damage after restoration interventions: Use of water repellent additives in plasters and renders', *Historical Mortars Conference: Characterization, Diagnosis, Conservation, Repair and Compatibility*, 2008.

27 Wiggins, 2015, op cit.

28 J. Alvarez, J. Lanas and A. Izaguirre, 'Ageing of lime mortars with admixtures: Durability and strength assessment', *Cement and Concrete Research*, 40, 2010, pp. 1081–95.

29 M. Bart et al, 'Porous structure and water vapour sorption of hemp-based materials', *Construction and Building Materials*, 22, 2008, pp. 1271–80.

30 R. J. Lawrence, T. Mays, S. Rigby, P. Walker and D. D'Ayala, 'Effects of carbonation on the pore structure of non-hydraulic lime mortars', *Cement and Concrete Research*, 37, 2007, pp. 1059–69.

31 E. Vereecken and S. Roels, 'Hygric performance of a massive masonry wall: How do the mortar joints influence the moisture flux?', *Construction and Building Materials*, 41, 2013, pp. 697–707.

32 L. Fusade et al, 'Drying response of lime-mortar joints in granite masonry after an intense rainfall and after repointing', *Heritage Science,* 7(38), 2019.

33 T. Addyman and T. Meek, *Technical Paper 31*: *Historic External Lime Finishes in Scotland*, 2019.

34 H. Hens, *Applied Building Physics: Boundary Conditions, Building Performance and Material Properties*, 1st ed, 2011.

35 Bennet, 1997, op cit.

36 N. Ashurst, A. Thomas and G. Williams, *Control of Damp in Old Buildings*, 1992.

37 C. Hall and W. D. Hoff, 'Rising damp: Capillary rise dynamics in walls', *Proceedings of the Royal Society*, 463, 2007, pp. 1871–84.

38 Ashurst, 1992, op cit.

39 C. Nunes and Z. Slizkova, 'Effect of application of lime plasters to salt-laden bricks', *Proceedings of the International RILEM Conference Materials, Systems and Structures in Civil Engineering Segment on Historical Masonry*, 2016.

40 W. Brachaczek, 'Study of the impact of microstructure and sorption properties of the renovation plasters on the wall drying rate', *Periodica Polytechnica Civil Engineering*, 2018, pp. 1–8.

41 Petković, 2007, op cit.

42 M. Seck et al, 'The mechanisms of plaster drying', *Journal of Materials Science,* 50, 2015, pp. 2491–501.

43 D. D'Ayala, A. Erkal and L. Sequeira, 'Assessment of wind-driven rain impact, related surface erosion and surface strength reduction of historic building materials', *Building and Environment*, 57, 2012, pp. 336–48.

44 S. Orr and H. Viles, 'Characterisation of building exposure to wind-driven rain in the UK and evaluation of current standards', *Journal of Wind Engineering & Industrial Aerodynamics*, 180, 2018, pp. 88–97.

45 C. Stirling, *Thermal Insulation: Avoiding Risks*, 2002.

46 S. Orr et al, 'Wind-driven rain and future risk to built heritage in the United Kingdom: Novel metrics for characterising rain spells', *Science of the Total Environment,* 640–641C, 2018, pp. 1098–111.

47 M. Hall and Y. Djerbib, 'Moisture ingress in rammed earth: Part 2 – The effect of soil particle-size distribution on the absorption of static pressure-driven water', *Construction and Building Materials*, 20, 2006, pp. 374–83.

48 Pender, 2020, op cit.

49 SPAB, *Repointing Stone and Brick Walling*, 2002.

50 L. Fusade and H. Viles, 'A comparison of standard and realistic curing conditions of natural hydraulic lime repointing mortar for damp masonry: Impact on laboratory evaluation', *Journal of Cultural Heritage*, 37, 2019, pp. 82–93.

51 Fusade et al, 2019, op cit.

52 V. Brito and T. Gonçalves, 'Artisanal lime coatings and their influence on moisture transport during drying', J. Hughes (ed), *Proceedings of the 3rd Historic Mortars Conference*, 2013.

53 Ibid.

54 T. Gonçalves, V. Brito and J. Musacchi, 'The whole and the parts: Can lime coatings enhance the drying of salt laden materials?', *Construction and Building Materials*, 57, 2014, pp. 179–89.

55 D. E. Wiggins, 'Traditional lime mortars and masonry preservation', *The Journal of the Building Limes Forum*, 24, 2017, pp. 28–37.

56 Petković, 2007, op cit.

57 Gonçalves, 2014, op cit.

58 T. Gonçalves, L. Pel and J. Rodrigues, 'Drying of salt-contaminated masonry: MRI laboratory monitoring', *Environmental Geology*, 52, 2007, pp. 293–302.

59 A. Izaguirre, J. Lanas and J. Álvarez, 'Effect of water-repellent admixtures on the behaviour of aerial lime-based mortars', *Cement and Concrete Research*, 39, 2009, pp. 1095–104.

60 E. Vejmelková et al, 'Effect of hydrophobization on the properties of lime–metakaolin plasters', *Construction and Building Materials,* 37, 2012, pp. 556–61.

61 F. Falchi et al, 'Influence and effectiveness of water-repellent admixtures on pozzolana–lime mortars for restoration application', *Construction and Building Materials*, 49, 2013, pp. 272–80.

62 C. Nunes et al, 'The influence of the pore structure on the moisture transport in lime plaster-brick systems as studied by NMR', *Construction and Building Materials*, 142, 2017, pp. 395–409.

63 Gonçalves, 2008, op cit.

64 Copsey, 2019, op cit.

65 P. Mcafee, *Lime Works,* 2009.

66 J. Hunnisett, *Historic Environment Scotland Refurbishment Case Study 25. Haa of Sand, Shetland: Hot-mixed Mortar Re-harling and Adapting a Gable End Wall*, 2016.