Moisture properties of insulation materials and their applicability to traditional construction

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1 Introduction

The purpose of this guide is to provide a wide range of users, including industry practitioners, specifiers, installers and building owners, with the technical knowledge needed to make informed decisions about selecting and applying appropriate retrofit insulation materials and systems.

This guide introduces the moisture-related characteristics of insulation systems, examining main considerations, interactions between different materials and their applicability to the retrofit of traditionally constructed buildings. It also defines technical terminology related to the moisture performance of insulation materials, and provides an overview of key concepts, practical guidance, and current knowledge gaps. It outlines how heat and moisture move through insulated fabric, and why relying on a single material property when specifying systems can be misleading. Insulation materials do not perform in isolation; they interact with other materials in the building fabric as part of a wider system. It is their combined behaviour that influences the overall performance.

Moisture behaviour in buildings is complex and interconnected, so we recommend reading this guide as a whole. Selecting or interpreting information in isolation, without considering the wider context, can lead to inappropriate decisions and unintended consequences.

Think about it this way

Throughout the guide, this pop-up will appear to explain terms or principles in a simpler way.

2 Insulation materials and their moisture-related properties

The first part of this guide introduces insulation materials by focusing on their moisture-related properties and how these influence performance in retrofit applications. The definitions and the physical principles underpinning these properties are summarised in APPENDIX A , while this section provides a practical overview relevant to traditionally constructed buildings.

In this guide, various insulation materials are categorised based on their moisture-related properties, with a focus on hygrothermal (heat and moisture) behaviour. Since the hygrothermal performance of materials typically exists along a spectrum, we introduce two moisture-related scales for better clarity: a vapour permeability scale – describing the ease with which water vapour can move through a material via diffusion – and a capillarity scale, describing the tendency of a material to absorb and redistribute water by capillarity (Figure 1). Due to the complex behaviour of porous materials, vapour permeability, moisture storage and liquid transport are not directly linked; for example, mineral wool is vapour permeable but neither hygroscopic nor capillary active. Materials must therefore be evaluated across their different moisture-related properties, as performance in one aspect does not guarantee suitability in all conditions.

For this reason, simply labelling a material as ‘vapour permeable’ is not sufficient. Its behaviour must be appropriate to the specific context in which it is used, taking into account how it interacts with other materials and the overall moisture dynamics of the building fabric.

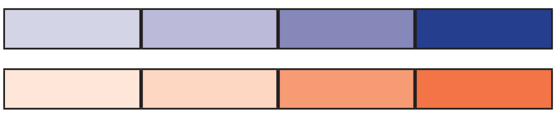
The table overleaf provides indicative typical values for both the λ-value (thermal conductivity) and μ-value (vapour diffusion resistance factor), and also illustrates where each material sits on the capillarity scale; a more detailed explanation of these properties is provided in APPENDIX A. Note that this table uses a colour-coding system: this approach is necessary because there are no absolute thresholds to categorise materials into clear-cut groups; the transition between the two extremes is gradual.

By examining the interaction of insulation materials with vapour and liquid moisture, we can better understand their functionality. Many insulation materials facilitate vapour diffusion – materials that permit vapour diffusion to a significant degree – are classified as ‘vapour open’, but since vapour permeability is a gradual scale, the binary terms ‘vapour open’ and ‘vapour impermeable’ oversimplify the more complex range of material behaviours. Vapour permeability can vary significantly from one material to another, and even within the same material depending on its moisture content and environmental conditions.

Material	Thermal conductivity λ-value [W/mK]	Vapour permeability μ-value [–]	Capillarity
Bio-based insulation			
High-density wood fibre (board)	0.038 – 0.050	5 – 10	
Low-density wood fibre (quilt)	0.035 – 0.040	1 – 2	
Cork	0.037 – 0.040	5 – 10	
Sheep's wool	0.035 – 0.040	1 – 2	
Hemp	0.040 – 0.045	1 – 5	
Straw	0.045 – 0.050	1 – 2	
Insulating lime plasters			
Hydraulic lime plaster	0.800 – 0.900	10 – 15	
Non-hydraulic lime plaster	0.700 – 0.800	5 – 10	
Mineral boards			
Calcium silicate	0.050 – 0.060	5 – 10	
Foam insulation			
Spray-foam (open cell)	0.035 – 0.040	3 – 5	
Expanded Polystyrene (EPS)	0.030 – 0.040	30 – 70	
Extruded Polystyrene (XPS)	0.025 – 0.035	80 – 200	
Spray-foam (closed cell)	0.023 – 0.026	30 – 60	
Polyisocyanurate (PIR)	0.023 – 0.025	50 – 100	
Phenolic Foam (PF)	0.020 – 0.025	50 – 100	
Other non-biobased			
Mineral wool	0.030 – 0.045	1 – 5	
Aerogel	0.013 – 0.018	5 – 10	

Table 1: Insulation materials and moisture-related properties

vapour permeable



vapour impermeable

capilary active

not capilary active

Figure 1: Scale for vapour permeability and capillarity

Some materials also exhibit hygroscopicity, meaning they can absorb and store moisture in vapour form.

In addition to vapour permeability and hygroscopicity, some materials can absorb and redistribute liquid water. These are referred to as *capillary active*[1] materials; the behaviour of these materials extends beyond what we strictly define as capillary flow, as it includes aspects of moisture storage within the material. Unlike vapour permeability, which can be expressed with a single numerical value, moisture storage and capillary transport are more complex phenomena that cannot be captured by a single parameter, as explained in Annex Section A.3. With the 'capillarity' colour scale in Table 1, we aim to illustrate a material's ability to redistribute moisture (and facilitate drying), whether in response to high vapour levels or liquid water.

Think about it this way

Think of a capillary active material like a sponge placed against a damp wall. It doesn't just block moisture or let it drift through — it absorbs and redistributes it, wicking it through the material and eventually drying out. This is how moisture moves through fine pores of the material, similar to how water travels across a paper towel.

But it's not just about visible water. For some materials, much of the action happens at high relative humidity. At this point, materials can still take up moisture even though there is no liquid water present. In this range, moisture exists partly as vapour and partly as liquid within the material, and its movement involves a complex interplay between vapour and liquid transport through the pores.

Capillary active materials help manage this by absorbing moisture during wet periods, redistributing it and releasing it again when conditions are drier. This ability to wick moisture – to absorb it, redistribute it, and let it dry out later – makes them especially valuable in insulation systems, where the goal is not to resist moisture, but to accommodate it safely.

Capillary active materials are often integrated into internal wall insulation (IWI) systems, to help mitigate moisture risks by redistributing moisture during wetting periods (autumn and winter). This process helps prevent excessive moisture build-up at the wall-insulation interface and facilitates drying. Such systems are particularly beneficial when outdoor moisture sources, such as rainwater, are moderately present within the wall and need to dry out, which happens regularly in the UK. However, for buildings with porous masonry walls highly exposed to wind-driven rain, measures to reduce the wind-driven rain exposure should be considered alongside IWI, if it is deemed an appropriate measure for the situation. Such

1 They are sometimes also called *hygroscopic capillary active materials* (e.g., BS EN 15026:2023, BS EN ISO 15148: 2002)

measures may include the application of vapour permeable external finishes, such as lime-based render, and improvements to rainwater management, including the repair or upgrade of gutters, downpipes and drainage systems. The suitability of these measures must be evaluated to ensure compatibility with the existing building fabric and to avoid increasing moisture risks. This guide does not recommend the use of hydrophobic surface treatments as a general approach. They are not reversible, and there are ongoing uncertainties about their long-term effects on building performance. While research is under way to better understand their impact, current evidence does not support their routine use; they may be appropriate only in specific, well-justified cases.

Other materials resist water absorption and are often more vapour impermeable. In some cases this can be beneficial in creating a highly controlled indoor environment, and even in traditional buildings these materials can sometimes be required in specific situations (e.g. basement insulation, where vapour permeable, capillary active materials are not appropriate). However, this approach also means that moisture trapped inside the building fabric has no easy escape route, potentially leading to failure if not properly managed.

Please note that even within a single insulation material category, significant differences exist between specific products. Variations in density, composition, and processing methods can lead to substantial differences in thermal and moisture-handling properties. For example, different densities of wood fibre insulation influence both vapour permeability and capillary action, while not all insulating lime plasters have the same porosity or hygroscopicity, which contributes to moisture storage (a description of these properties is also provided in APPENDIX A). These variations must be considered when selecting materials for a given application.

Furthermore, within buildings, materials never behave in isolation. When assessing the hygrothermal performance of a building element, such as a wall or roof, it is essential to consider the entire assembly of materials as a whole. The moisture and thermal behaviour of individual components – such as vapour diffusion, capillary transport, and heat transfer – interact within the system and can significantly influence the overall performance of both the insulation system and the building. Understanding both the differences within material types and how materials function together as part of a system is essential for ensuring robust moisture and thermal performance within the structure. This is why the rest of the guide focuses on insulation systems rather than materials in isolation, to reflect how they perform in practice and to support robust moisture and thermal performance in real buildings.

3 Traditional buildings and insulation: the challenges

This section outlines the practical challenges of retrofitting traditional buildings, focusing on how insulation can affect moisture behaviour and why a whole-building approach is needed.

Various retrofit failures[2] [3] highlight the challenges that can arise when insulation is installed without following an appropriate, whole building approach addressing the complexities of building retrofit. Moisture balance can be disrupted by factors such as lack of maintenance, poor building preparation, assessment and design, poor-quality installation and inadequate detailing, inadequate ventilation, and a general **lack of understanding**, resulting in sometimes serious unintended consequences for the building fabric and occupants' health.

Looking ahead, retrofit must not only address current risks but also remain effective under future climate conditions. The coming decades are likely to bring heavier winter rainfall, more frequent intense rain events and warmer summers. These changes will alter moisture loads and drying conditions across the UK. As such, retrofit strategies must be designed with future resilience in mind, not just to prevent overheating, but to maintain moisture balance under shifting patterns of rain, humidity and indoor use.

3.1 Retrofit: The need for moisture balance

Insulation systems influence energy efficiency, occupant health and the fabric integrity of buildings. Maintaining a moisture balance is necessary to prevent problems such as mould and wood rot, which are caused by excess moisture and can adversely affect both occupant health and the building fabric – see Chapter 5 for a detailed explanation of moisture balance, moisture sources and mechanisms as well as consequences on moisture imbalance. A well-designed and well-implemented retrofit strategy – including, but not limited to, insulation, airtightness and ventilation – can make spaces easier to heat, reduce the risk of fuel poverty and keep internal surfaces warmer, reducing indoor mould growth risk.

However, poorly-considered retrofit can also disrupt the moisture balance of a building, potentially leading to moisture problems. For example, upgrading windows improves airtightness but can significantly reduce natural ventilation if not combined with appropriate measures. Another example is the addition of insulation, which changes the moisture behaviour within the building fabric and, if discontinuous, can lead to localised cold spots on interior surfaces (see Section 5.2.4 on thermal bridges).

2 https://passivehouseplus.ie/news/health/disastrous-preston-retrofit-scheme-remains-unresolved
3 Action taken to protect households with poor-quality insulation – GOV.UK

A lack of moisture balance refers to the presence or build-up of excess moisture, whether visible or hidden, resulting from an imbalance between moisture ingress, transport mechanisms, and drying processes. Maintaining a moisture balance during retrofit begins with ensuring that the building is in a condition suitable for retrofit.

To achieve moisture balance after retrofit, it is essential to understand that this is influenced not only by the materials and systems used but also by the building as a whole. As described in BS 5250:2021, this 'Whole Building Approach' includes four key principles:[4 5]

1. **Context**, considering the age, location, exposure, and use of the building;
2. **Coherence**, ensuring that interventions work together rather than in isolation to avoid unintended moisture risks;
3. **Capacity**, designing systems with sufficient capacity to cope with expected and unexpected moisture loads, as well as changes in climate and other conditions, including occupancy patterns, without compromising performance; and
4. **Caution**, recognising uncertainties in moisture behaviour and monitoring the potential risks of retrofit measures.

This guide introduces the moisture-related properties of insulation materials and examines their application in solid masonry walls, roofs, and suspended timber floors. It focuses on traditionally constructed buildings but does not cover all building types, like for instance flat roofs or timber frame walls. **Insulation materials cannot be evaluated in isolation, and their performance must be understood within the context of the entire insulated system**.

3.2 Retrofit insulation approaches

Solid masonry walls can contribute considerably to heat loss in traditional buildings, although their performance is often better than assumed by energy models and U-value calculations, as evidenced by widespread monitoring of stone, brick and other traditional wall build-ups by numerous organisations[6]. As with any building, their performance depends on their geometry, materials, thickness, location, orientation and the condition of the wall, including its moisture content and maintenance history. From a technical perspective, therefore, the walls can often form an important part of a whole-building retrofit plan. However, while insulation may improve thermal performance – including warmer internal surfaces that help reduce the risk of surface mould – walls remain one of the riskiest elements to upgrade and must be addressed with thorough, holistic consideration to safeguard overall building health and durability.

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4 BS 5250:2021 *Management of moisture in buildings*

5 May N. and Sanders C. (2016) Moisture in buildings: an integrated approach to risk assessment and guidance, BSi

6 Field studies include: In-situ measurements of wall U-values in English housing (BRE, 2013); Solid-wall U-values: heat flux measurements compared with standard assumptions (Li et al, 2015); Technical Paper 10: U-values and Traditional Buildings (Historic Environment Scotland, 2010); The SPAB Research Report 1: U-value Report (SPAB, 2012).

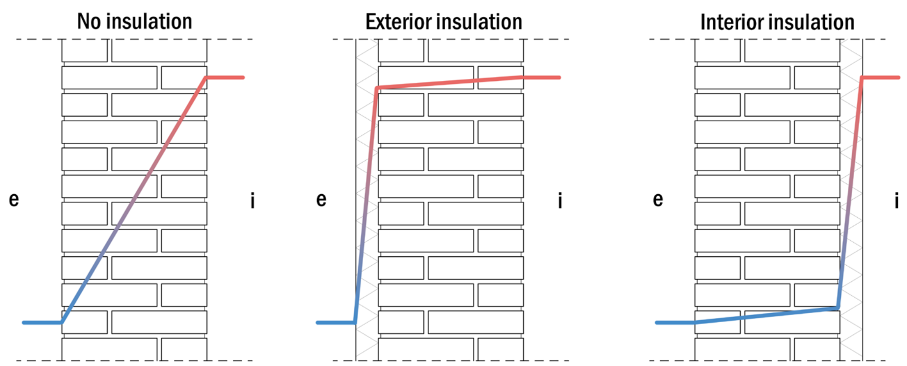
The decision on whether to insulate externally or internally is dependent on many factors, but both approaches bring their challenges (and not every wall is suitable for insulation). Key considerations for both external and internal insulation options are set out below (and further details on the different options for each are provided in Section 4), but it should be highlighted that solid wall insulation is one of the most technically complex retrofit measures particularly for traditional buildings, and careful preparation, design and installation in line with best-practice guidance are all essential. In many cases, and particularly for internal wall insulation, a detailed moisture risk assessment is important to inform detailed design decisions for this measure (more information on tools for risk assessment is given in Section 7). Solid wall insulation is also a measure that must be accompanied by other, related measures (often a combination of maintenance and enabling works, other insulation and airtightness measures and improved ventilation), to ensure a balanced approach and minimise the risk of unintended consequences.

Further guidance on the principles and detailing of wall insulation in traditional buildings should be read at an early stage to inform detailed design and installation works[7].

3.2.1 External wall insulation

External wall insulation (EWI), if designed and executed using appropriate materials and with robust design, thorough detailing and installation, could provide a thermally continuous and robust solution from a technical perspective. However, achieving continuity is often constrained by external features such as gas pipes, meter boxes, short eaves, and architectural details on the façade, as well as street elements like lamp posts, all of which complicate the detailing required to address thermal bridges and rainwater protection. Moreover, in historic settings, the impact on aesthetics and architectural or historic values means it is not often feasible.

Figure 2: Theoretical temperature gradient through typical wall assemblies.
Image © Kaat Jenssens



7 Examples of current guidance include: A Bristolian's Guide to Solid Wall Insulation: A guide to the responsible retrofit of traditional homes in Bristol (STBA, 2015); Historic England: Upgrading Thermal Elements: Installing Insulation (Historic England, 2024); Guide to energy retrofit of traditional buildings (Historic Environment Scotland, 2021); Retrofit internal wall insulation: Guide to best practice (BEIS, 2021); Sustainable Renovation: Improving homes for Energy, Health and Environment (2nd ed., SEDA, 2023); Thermal upgrade of traditional buildings (NI Department for Communities, Historic Environment Division, 2024)

Where full coverage is possible and appropriate for the existing building and detailing, EWI allows the thermal mass of the walls to be retained internally; it generally reduces rather than increases moisture levels in the masonry; it reduces overheating risk[8]; and, **if done properly**, it protects the wall fabric from external water ingress (e.g. wind-driven rain), which is becoming increasingly important as the climate continues to change. As described in Section 4, EWI systems vary considerably in properties and installation methods, resulting in different overall performance.

In the context of traditional buildings, EWI is considered where the existing building is already rendered or has been in the past. However, with changing climate conditions, additional external coatings may increasingly be considered to protect buildings from the weather regardless of the pre-existing finish. In some cases the requirement for a robust weatherproof coating may be deemed sufficient justification for covering currently-exposed masonry with a render coating that might include insulative aggregates. The effectiveness of EWI is also improved by building details such as deep eaves, roof overhangs or similar protective mechanisms – which provide greater protection to the wall than verge trims alone – along with robust rainwater goods and regular maintenance.

However, EWI often brings many challenges, particularly for more complex buildings. As well as aesthetic issues, technical challenges can include long-term prevention of rain ingress (a critical factor, requiring robust protection mechanisms and effective design and execution of interfaces with other building elements, particularly windows, doors and external ground levels); adaptation of rooflines, rainwater goods and gullies; and addressing certain thermal bridges. Many alterations can also be required, such as relocating gas pipes, meters, outdoor taps, sockets and bell boxes. As such, it is often best suited to simpler buildings, and buildings with inherent protection mechanisms such as deep roof overhangs.

For traditional buildings, it is important to differentiate between appropriate and inappropriate approaches to EWI. In most cases, appropriate EWI approaches are likely to focus on either an insulating render system or – where building details permit – an appropriate rigid board-based system (e.g. woodfibre) with robust weather protection such as a ventilated rainscreen. However, the prevalence of poor-quality installation has undermined confidence in EWI. Failures in large-scale EWI schemes[9] have tarnished its reputation. While these cases highlight the challenges of delivering effective EWI, the failures are caused by poor practice – including inadequate survey, design, detailing, preparation and installation – the use of inappropriate systems (e.g. impermeable systems, inadequate weatherproofing) and a single-measure approach that lacks integration with other insulation or airtightness measures, or with adequate ventilation. These issues are driven by a host of complicating factors which are beyond the remit of this guide. If an appropriate, holistic approach is planned and implemented properly, these issues are all avoidable, and on the right building EWI can be a successful and low-risk option.

8 Demonstration of Energy Efficiency Potential (DEEP) Case Studies Summary, 2016, GOV.UK

9 Disastrous Preston retrofit scheme remains unresolved (Passive house + , 2018); Action taken to protect households with poor-quality insulation (GOV.UK, 2025)

3.2.2 Internal wall insulation

Internal wall insulation (IWI), when designed and installed using appropriate materials and thorough detailing, can improve thermal performance and increase internal surface temperatures, reducing the risk of surface mould growth. It is particularly relevant where changes to the external appearance are not acceptable, or where internal refurbishment is already planned. As with EWI, IWI should be part of an integrated retrofit strategy that includes airtightness, ventilation, and maintenance.

Where appropriate and carefully detailed, IWI can be very effective, but meticulous care and attention are required at all stages. In particular, IWI leaves the masonry on the cold side of the insulation, which generally increases moisture profiles in the masonry, particularly where the external masonry is exposed and weatherproofing of the outer wall surface remains an ongoing challenge. Compared with external insulation, the overall moisture dynamics are more complex and less predictable.

IWI may also increase overheating risks, particularly where internal layers limit thermal mass. While it is often more disruptive than external insulation, it can be incorporated relatively easily into major refurbishment works. Achieving a coherent and continuous layer of insulation can also be challenging, particularly in buildings with irregular surfaces, services or retained internal features. The same applies to the airtightness layer: discontinuities or poor detailing can lead to air leakage, allowing warm, moisture-laden air to bypass the insulation and become trapped against cold masonry, increasing the risk of elevated moisture levels and hidden mould growth.

Appropriate systems and materials (generally vapour permeable **and** capillary active, as defined in Section 2) must be used in all cases. Many of the potential risks associated with internal insulation can be considerably reduced where the external façade is in good condition and protected, for example by appropriate render, and in some cases, both external and internal insulation may be combined. With the right materials a combined approach can be successful, providing weather protection in an increasingly unstable climate and reducing internal space impacts.

However, IWI also brings multiple challenges, and while some are similar to those for EWI others are more specific to IWI. These include:

- extensive preparatory work (often requiring stripping and parging the internal walls);
- addressing thermal bridges (often requiring highly invasive work);
- avoiding air leakage into the wall assembly (addressed via an appropriate approach);
- accessing and detailing around complex junctions, electrical and heating equipment, kitchen and bathroom fittings, tiled surfaces etc.;
- addressing window and door reveals effectively (which can require specialist materials);
- the need to limit insulation depth to moderate moisture risks;

- the need for multiple layers, tapes and membranes (depending on the system);
- and ensuring the long-term good maintenance of the external façade and rainwater management systems.

One of the key requirements when designing an IWI assembly is to maintain a balance between wetting and drying, which must be achieved through appropriate specification, as well as the above steps. Nonetheless, with appropriate materials, and guided by an appropriate moisture risk assessment, the risk of moisture accumulation within the wall assembly can usually be managed within acceptable bounds.

As described in Section 7, the perception of IWI as a 'risky' retrofit measure is in part driven by the 'Glaser paradigm' – a partial understanding of moisture risk based entirely on this simplified condensation risk assessment, now known to be inappropriate for solid masonry walls – which tends to lead the user towards the use of relatively vapour-closed layers on the inside of the IWI assembly. However, the moisture dynamics of IWI systems are considerably more complex than this simplified approach suggests, and dynamic hygrothermal simulation methods (rather than the Glaser method) can help give a more accurate picture of moisture risks – and generally lead the user towards IWI systems that are both more vapour permeable and capillary active. Where such simulations are undertaken to assess moisture risk in IWI, they must follow a full hygrothermal simulation approach (e.g. WUFI®), as described in Section 7.2 – indeed, such assessment is now explicitly recommended in numerous standards and guidance for moisture-safe retrofit of IWI on traditional masonry walls[10]. Nonetheless, while IWI remains a technically complex measure which often carries a degree of uncertainty, if an appropriate approach is planned and implemented properly then IWI can be a successful and robust option.

3.2.3 Insulating timber structures: roofs and suspended timber floors

Timber structures, such as roofs and suspended timber floors, can be insulated by placing insulation between structural timber elements and/or above or below them. To do this successfully, it is important to consider how the addition of insulation influences the moisture transport and storage.

In pitched roofs, insulation can be installed either at ceiling level (cold pitched roof, covered in Section 4.2.1) or at rafter level (warm pitched roof, see Section4.2.2). Traditional cold pitched roofs rely on airflow in the loft space to maintain moisture balance, while warm pitched roofs can maintain moisture balance with a combination of airtightness, vapour control, and ventilated voids.

The challenges with insulating at rafter level include the careful location of airtightness, vapour control, and insulation layers; ensuring that moisture is not

10 BS 5250:2021 Management of moisture in buildings – Code of Practice; May N. and Sanders C. (2016) Moisture in buildings: an integrated approach to risk assessment and guidance; S. Price et al. (2021).Retrofit Internal Wall Insulation: guide to best practice, BEIS; Historic England Research Report 44/2024: Air and Vapour Control Layers (AVCLs) in buildings of traditional construction. A literature review to understand appropriate use (Historic England, 2024)

trapped within the construction; avoiding air leakage paths that could lead to hidden moisture accumulation; and allowing for sufficient ventilation to promote drying towards the exterior. Although placing insulation above the rafters minimises thermal bridging and protects the timber rafters, it is typically only possible when the roof covering is being replaced.

Flat timber roofs, which lack natural ventilation pathways, require particular attention to vapour control, drainage, and airtightness to avoid excess moisture accumulation and material degradation (flat roofs are not covered in detail in this guide).

Suspended timber floors, commonly found in traditional buildings, incorporate an air void beneath them to provide ventilation and maintain moisture balance. Restricting airflow without appropriate moisture management can lead to excess moisture accumulation, which might affect the structural integrity of the floor. Insulating suspended timber floors can improve thermal performance but must be undertaken carefully to avoid disrupting this moisture balance (see 4.3). In many buildings, airflow is already compromised – for example, by extensions, blocked vents or raised external ground levels – and these issues must be identified and resolved before or as part of the retrofit. Without good design, the presence of insulation can affect this moisture balance: for example, measures such as EWI need appropriate design to avoid inadvertently blocking air vents. Other risks in insulated suspended timber floors include trapped moisture after a water leak[11], and increased moisture content in floor joists[12].

11 J. Godefroy and M. Baeli (2024). Retrofit Revisit : 10 Case Studies. CIBSE.

12 Roy, C., Bigtashi, A., Frenette, C., Derome, D. (2025). Modeling Hygrothermal Performance of Wood Assemblies Exposed to Serpula Lacrymans. In: Berardi, U. (eds) Multiphysics and Multiscale Building Physics. IABP 2024. Lecture Notes in Civil Engineering, vol 552. Springer, Singapore.

4 Insulation systems

Having previously considered material properties and challenges of insulation systems separately, this chapter brings them together by examining how different materials, each with their specific hygrothermal behaviour, are combined within complete building assemblies.

The performance of insulation does not depend solely on its inherent material properties but also on its placement and function within the structure, and the climate the structure is exposed to, inside and out. Each material interacts with adjacent layers, influencing the overall heat, air, vapour, and water balances within the assembly. Every moisture flow has a driving force (as described in APPENDIX A), for instance the vapour diffusion flow goes from high to low vapour pressure. An insulation system must be designed as a whole, ensuring that vapour permeability, capillary action, and thermal resistance work together to prevent moisture accumulation, heat loss, and potential degradation.

Approaches to the design of insulated building envelope systems differ in how they manage moisture movement. Some systems rely on porous materials that allow vapour diffusion and, in some cases, capillary transport, promoting drying potential. Others incorporate at least one vapour-closed material, which significantly reduces vapour permeability and liquid absorption, limiting moisture transfer through the system. However, the range of permeability within porous materials is vast, making it necessary to assess each material individually, in each context. To ensure effective moisture management, it is important to consider vapour permeability, air permeability, hygroscopicity, capillarity, and liquid transport properties within the context of the full insulated building component.

This chapter therefore explores different insulation system configurations, showing how materials can be combined to optimise hygrothermal performance in various building contexts.

Think about it this way

A cake isn't just flour, eggs, and sugar—it's how those ingredients work together that makes it rise, stay moist, or collapse. You could have the finest flour in the world, but if the oven's too hot or you forget the baking powder, the whole thing falls apart. Buildings are no different. You can't judge performance just by looking at materials in isolation. What really matters is how all the parts—insulation, structure, membranes, finishes—work as a system. It's the combination, not the components, that makes it robust, durable, and fit for purpose.

4.1 Wall insulation: placement and types

4.1.1 External wall insulation (EWI)

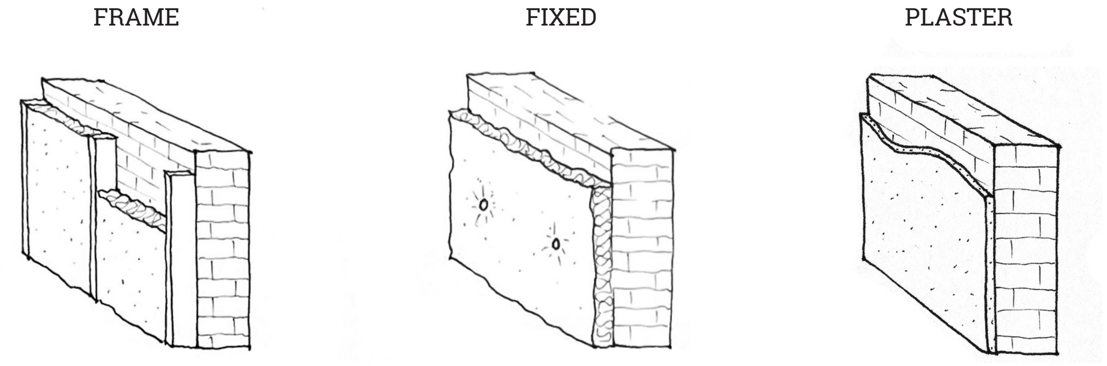


Figure 3: External wall insulation options. Image © Kaat Janssens

External wall insulation (EWI) (Figure 3) has the potential to be a robust option for insulating solid walls, provided it is carefully selected, detailed and properly installed. By placing the insulation on the outside, the structural elements are kept warmer, reducing thermal bridging from internal walls and floors and shielding the fabric from temperature fluctuations and external moisture sources such as rainwater. The performance of EWI also depends on the careful repositioning and detailing of rainwater goods, both to provide clearance for the insulation layer and to ensure the system remains well protected. Where possible, components should be upgraded or resized to accommodate increased rainfall under future climate scenarios. These combined measures can improve the overall hygrothermal performance of the building and lower the risk of moisture-related problems within the fabric, such as mould growth or material decay.

A range of finishes may be applied to the external face of EWI systems. Render is most common, but cladding systems (e.g. timber cladding) offers greater robustness in some contexts. While cladding is likely to remain a niche option in most traditional buildings, it can be a suitable choice in conversions or major retrofit projects where detailing allows. However, because EWI becomes the building's primary weatherproofing layer, any shortcomings in design, detailing, or installation can lead to significant failures. These risks depend on the type of EWI system, the building details, and how interfaces are handled. In most cases they can be designed out through careful detailing and the selection of an appropriate system. Where this is not achievable, EWI may not be the right option for that building.

Insulating render

An alternative approach involves the application of an insulating render directly onto the external surface of the wall. This can consist of a thick coat of insulating lime render, or similar permeable products incorporating lightweight aggregates such as expanded perlite, natural fibres (e.g. hemp-lime) or cork. In many cases a different specification of material is applied as a thin finishing coat. These systems can offer a lower-profile and flexible EWI solution, which can be more appropriate for previously rendered buildings with heritage significance or where retaining the building's external appearance is important. It can be graded into certain junctions where full-thickness insulation would be difficult to accommodate. When applied correctly, insulating renders can improve thermal performance while maintaining moisture balance and allowing moisture to dry out of the wall. They can be particularly effective in managing moisture and allowing drying, and are often preferable to fixed or framed EWI approaches where a rendered finish is required, offering lower risk of biological decay.

Key considerations

- While performance varies by product, insulating renders typically offer lower thermal performance per unit thickness than other EWI systems. Some renders marketed as insulating provide only marginal improvement over conventional render, but the best-performing products can approach the performance of certain board-based approaches. The choice of system depends on the existing wall construction, desired thermal targets, and available space. Thinner applications may offer smaller thermal improvements compared to thicker insulation systems but can significantly reduce moisture risks, making them particularly suitable where a more cautious approach is needed to maintain the building's moisture balance.
- Attention must be paid to consistent application thickness and quality of workmanship to avoid thermal inconsistencies. Given the reliance on on-site mixing and application, installer experience is critical. Junctions and transitions — especially around openings and where different substrates meet — should be detailed to prevent thermal bridging and to ensure continued vapour permeability and water shedding, and prevent cracking on junction lines. The climate and exposure of the building must also be considered; if insulating plasters are used externally, their resistance to freeze-thaw cycles should be assessed. Lime-based systems require appropriate curing conditions and protection during application and for a while after.
- Even if the render is not insulating, a suitable lime render can help reduce moisture risks, including in cases where insulation is applied internally. By limiting rainwater ingress and allowing outward drying, it supports a more balanced moisture profile within the wall.

Mechanically fixed

Insulation boards (such as dense wood fibre) can be mechanically fixed by pinning them to the load-bearing structure. In the UK, the most common finishing option is to apply render directly to the insulation, but a ventilated rainscreen arrangement (e.g. timber cladding on battens) can often be a more robust option with respect to protection against rain ingress.

Key considerations

- Mechanically fixed insulation systems can create a small air gap or allow for slight movement, which can influence moisture behaviour. Make sure that there is a seamless connection between the boards to avoid cold bridges and air movement, which, as well as undermining the thermal performance, can lead to moisture problems. Care should also be taken to prevent insects from entering the system by sealing all gaps and penetrations. A parge coat is recommended to level uneven substrates and support consistent board adhesion, helping to reduce air leakage behind the insulation layer.
- It is particularly important to ensure that the junctions with other elements such as the floor/ground, around windows and eaves, gables and parapets are adequately detailed to avoid thermal bridging. Any potential thermal bridges should be assessed for mould risk due to reduced internal surface temperature, as well as heat loss. All junctions must be robustly weatherproofed, including good roof overhangs and proper flashing arrangements, ideally with two 'lines of defence' neither of which rely on adhesives. Effective weatherproofing at these points is essential; failure to achieve it can undermine the entire EWI system.

Frame

A third approach is to install flexible or blown-in insulation materials, such as wood fibre or cellulose, between the studs of a timber frame, which is then finished with cladding or a rendered system. Although less common, this approach allows heavier finishes and drainage/ventilation cavities to be introduced which can result in a robust assembly. It is not recommended to fit rigid boards between studs, because it is hard to achieve the close fit required for thermal performance and moisture balance.

Key considerations

- The overall vapour permeability of the wall depends on the total behaviour of the system, including wooden boards, membranes and external finishes. Gaps or crevices between the frame and the insulation, and between the insulation and substrate should be avoided to prevent undesired air flow, which can undermine both thermal and moisture performance. Where flexible insulation is used on uneven masonry, a parge coat may help to achieve contact; if the wall is highly irregular, this approach may not be appropriate. Care should also be taken to prevent insects from entering the system by sealing all gaps and penetrations. Finally, as above, effective weatherproofing is essential.

4.1.2 Internal wall insulation (IWI)

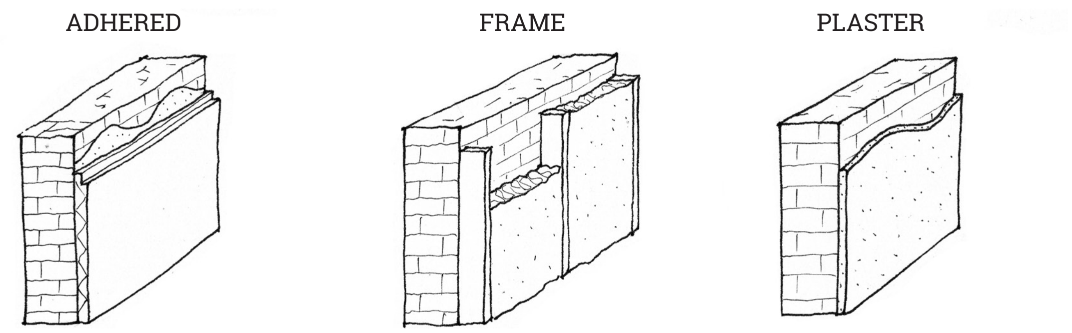


Figure 4: internal wall insulation options. Image © Kaat Janssens

Internal wall insulation (IWI) (Figure 8) can be an effective solution for improving the thermal performance of solid walls, particularly in cases where external wall insulation (EWI) is not appropriate. However, this approach places the structural elements on the cold side of the insulation, changing the moisture balance of the wall and making it more susceptible to temperature fluctuations and moisture-related issues[13]. The impact of this change is often uncertain, and needs to be carefully evaluated to ensure the long-term durability of the building fabric.

To ensure the long-term performance and durability of an IWI system, proper moisture management and maintaining the drying potential of the wall assembly to both sides are crucial. For example, to reduce rain loads, the external application of a lime-based render or other cladding can often be highly beneficial alongside IWI. It should also be recognised that in some cases (e.g. walls affected by excessive moisture ingress) no form of IWI may be appropriate.

Regardless of the chosen approach, it is essential that the façade itself is free of cracks or leaks and that rainwater goods and drainage are adequate, well maintained and properly sized, not only for current conditions but also with future climate projections in mind.

Well-installed vapour-permeable airtightness layers – such as membranes or lime plasters – can help control air movement and vapour diffusion in IWI assemblies, reducing moisture accumulation within the wall[14]. Typically placed on the warm

13 For further guidance on installation of IWI, please see: Retrofit Internal Wall Insulation: guide to best practice (BEIS, 2021) .

14 For further guidance on AVCLs, see: Historic England Research Report 44/2024: Air and Vapour Control Layers (AVCLs) in buildings of traditional construction. A literature review to understand appropriate use (Historic England, 2024)

side of the insulation, they limit excess moisture from reaching the colder interface between insulation and masonry. Even if vapour-permeable, these layers still provide some level of vapour control, helping to moderate the amount of moisture reaching colder parts of the wall build-up. They are often referred to in industry as vapour control layers (VCLs) or air and vapour control layers (AVCLs), though these terms are used inconsistently and are sometimes wrongly assumed to imply high vapour resistance. In traditional solid wall construction, highly vapour-resistant layers must not be used, as they can trap moisture and prevent necessary drying towards the interior. Overly vapour-permeable systems, on the other hand, can allow excessive vapour diffusion towards the cold wall-insulation interface, increasing too the risk of moisture accumulation and mould growth.

Think about it this way

Picture wearing a wind-proof jacket made from impermeable plastic: it blocks every gust but soon feels sweaty inside because the moisture your body produces cannot escape. Now imagine a 'breathable' wind proof jacket. It stops the wind yet allows water vapour to escape, so the inside stays dry and comfortable.

Air and vapour control layers (AVCLs) behave like the second jacket: positioned on the warm side of insulation, they stop air leakage while still allowing vapour diffusion. Although often wrongly assumed to have high resistance, an AVCL can have an s_d-value as low as 2 m, and versions with variable vapour diffusion resistance can drop to 0.05 m when conditions promote drying. In this guidance, we focus on layers with low to moderate vapour resistance, and refer to these as vapour-permeable airtightness layers. Other membranes act more like 'breathable' waterproof jackets instead: breather membranes ($s_d < 0.12$ m) for walls and flat roofs, and low resistance (LR) underlays ($s_d < 0.05$ m) for pitched roofs, focus on blocking rain and wind across the building fabric while remaining very open to vapour. These membranes do not necessarily need to provide airtightness.

A balanced approach combines an appropriate vapour-permeable airtightness layer (with low-to-moderate vapour resistance) and capillary active insulation[15]. This combination can improve vapour control while allowing drying when needed. The airtightness layer must be specified carefully: the s_d-value is critical (see Appendix A1 for definitions). In some cases, membranes with variable vapour diffusion resistance – which adjust their permeability depending on humidity levels and are also called 'intelligent membranes' – may offer benefits

15 As explained in Section 2, capillary active materials are those that can absorb, store and redistribute liquid moisture within their structure. This behaviour goes beyond simple capillary flow and includes moisture storage responses to moisture in both vapour and liquid phases.

by allowing greater drying to the inside under certain conditions. Overall, the effectiveness of airtightness layers varies depending on the specific wall build-up and moisture load. A good moisture risk assessment can help determine whether a layer improves or worsens performance in a given context.

The effectiveness of any airtightness layer depends heavily on proper sealing; air leaks can bypass the layer, rendering it ineffective and leading to moisture problems. Achieving a reliably airtight and continuous membrane can be difficult in practice, particularly around junctions and service penetrations. A wet plaster applied directly over the insulation provides an airtight surface that can act as an airtightness layer, and can offer a simpler, more robust and more durable solution in many cases, as it forms a continuous, gap-free layer without requiring mechanical fixing or taping at seams. Alternatively, some systems use a vapour control membrane behind a service void, allowing finishes such as plasterboard to be fixed without damaging the membrane. Each approach has advantages and disadvantages. Using a membrane and service void can protect the airtightness layer from mechanical damage and allow pipes and cables to remain accessible without penetrating the membrane. However, it also introduces the risk that moisture problems may develop hidden behind the membrane, particularly in the case of leaks or rainwater ingress, making detection and remediation more difficult.

Finally, full bonding between the insulation and the masonry substrate plays an important role in the performance of IWI systems. By eliminating air cavities, full bonding reduces the risk of thermal bypass and uncontrolled air movement, which would otherwise impair thermal performance. It also helps inhibit mould growth by removing air spaces that provide a surface and oxygen supply for mould to develop; in some cases, the adhesive or bonding mortar can also create an alkaline environment, which is unfavourable to mould growth.

Beyond applying the principles outlined above, a proper moisture risk assessment that considers wall construction, exposure, moisture load and installation quality, is essential for all IWI systems to ensure that the chosen insulation approach and thickness are appropriate and any risks are effectively addressed (see Section 7). Footnotes give further guidance on best practice installation of IWI and on AVCL.

Fully bonded

Internal wall insulation (IWI) can be applied in various ways, depending on the chosen system and existing wall conditions. One common and often most robust method – particularly when using rigid insulation boards such as wood fibre or calcium silicate – is to bond the boards directly to the interior surface of the wall. As well as mechanical fixings in most cases, it is also essential to provide a continuous coat of adhesive or plaster; the 'dot and dab' approach should be avoided as it leaves gaps which risk thermal bypass[16], the ingress of warm moist air, and mould growth.

16 Thermal bypass describes the loss of heat through routes that avoid or reduce the effectiveness of insulation. This can happen through unintended air movement, poorly sealed gaps, or materials that conduct heat across the insulation layer. Even if insulation is correctly installed, thermal bypass can lead to reduced energy efficiency and increase the risk of mould growth by allowing warm air to move into colder parts of the building fabric. More information: Thermal bypass risks: a technical review M. Siddal (2022)

Key considerations

Adhesives must be compatible with the substrate and insulation. Vapour-open and capillary active IWI systems are the most appropriate for bonding with the substrate – these materials allow moisture to diffuse and be redistributed, reducing the risk of trapped moisture and potential damp issues. Vapour-resistant rigid insulation boards can trap moisture behind the insulation, reducing drying potential and increasing moisture risks, and these are rarely appropriate for traditional buildings unless there is a specific reason for not adopting a capillary active approach. A perfect bond between the insulation and the wall surface is crucial to prevent air gaps, that might allow warm indoor air to leak behind the insulation and condense, leading to mould growth on the cold masonry. Additionally, proper detailing at junctions, floor slabs, partition walls, and window reveals is necessary to minimise thermal bridging and ensure long-term performance.

Insulating plaster

Another option is to use an insulating plaster, applied in layers directly onto the interior wall surface. These plasters are generally lime based and often incorporate materials such as aerated lime, cork, perlite, or silica-based compounds. They generally have good levels of hygroscopicity and capillary action and can be particularly effective in managing moisture and allowing drying. They are also less vulnerable to biological growth and decay than natural fibre insulation. Crucially, they are also airtight, and if well sealed to junctions such as joist ends, can limit air movement – a key source of moisture transport into vulnerable areas. This integration of levelling, insulation, and airtightness into a single material reduces reliance on tapes, membranes and multiple layers, simplifying installation and reducing potential points of failure.

In some cases, their insulating value can be lower than other IWI methods, but there are some systems available with a thermal performance comparable to a natural fibre insulation. They can be a practical solution when interior space is limited, as their thickness is easily adapted to suit the specific context, although and they are sometimes applied in relatively thick layers. However, as with any IWI approach, increasing the insulation depth may also increase moisture risk, so the design thickness should be based on both thermal targets and moisture performance. It is increasingly common to combine insulating plasters with wood fibre boards, which can improve the moisture safety and practicality of the natural fibre IWI system. However, insulated plasters alone can also be appropriate and a good compromise where higher moisture risks make the use of natural fibre insulation less suitable but the insulation system used needs to remain permeable in nature.

Key considerations

- There is a wide range of insulating plasters available in the UK, and both composition and performance vary significantly. Some products offer relatively modest thermal benefit, while others can approach or match the performance of natural fibre insulation. The formulation of insulating plasters varies, including differences in the type and strength of lime binders used, and this can affect the moisture balance. These factors should be assessed at an early stage.
- Most systems are generally sprayed onto the masonry in layers, with the final thickness determined by a combination of thermal performance target and moisture risk assessment results. As they are applied wet, they can require an extended drying period, with thicker assemblies taking longer to dry – this can present some risk to embedded timbers during the initial drying period. As such, it is essential that they are installed in appropriate conditions, i.e. with adequate temperatures and ventilation, and ideally on masonry that has been allowed to dry as needed – this makes them best suited to installation during the warmer months. Their relatively simple spray or trowel application reduces the need for tapes and membranes, and can make it easier to achieve full coverage and access awkward junctions.

Frame

Another method is to install insulation within a timber or metal frame, placing flexible or blown-in insulation material between the studs. These systems rely on a high standard of design and execution, which can be difficult to achieve consistently in practice. For this reason, framed IWI is not generally recommended for traditional buildings. Where it is considered, it should only be used with a clear rationale and robust detailing

Key considerations

- Unlike fully bonded insulation systems, the frame for the IWI will create a gap at the interface with the existing wall. It is essential to make sure there are no gaps and crevices at junctions with the insulation, as this can lead to air movement and increased moisture risks if not properly sealed. It is easier to achieve a tight fit with flexible rather than rigid insulation materials. Metal studs must be carefully packed with insulation to avoid air gaps, but they introduce significant thermal bridging unless somehow thermally separated on one or both sides; they can also be susceptible to rust where the galvanising is compromised at cut ends and screw penetrations. Timber studs introduce less dramatic thermal bridging than metal studs, but can be susceptible to mould and/or decay under sustained high moisture conditions.

- A carefully selected vapour-permeable airtightness layer[17] (or AVCL) is needed on the warm side of the insulation. This is usually provided in the form of a vapour control membrane, but where the internal finish can support it – for example, a rigid wood fibre insulation board installed over the top of the frame – a wet plaster layer can also serve as the AVCL.
- Meticulous detailing at all junctions (e.g. floor-wall junctions, window and door reveals) is essential to ensure airtightness and long-term hygrothermal performance. While framed IWI systems are sometimes used, they introduce greater complexity and more potential points of failure — including insulation gaps, air leakage paths, and poorly sealed junctions. Poor execution can undermine the performance of the entire retrofit.

4.2 Roof insulation: placement and types

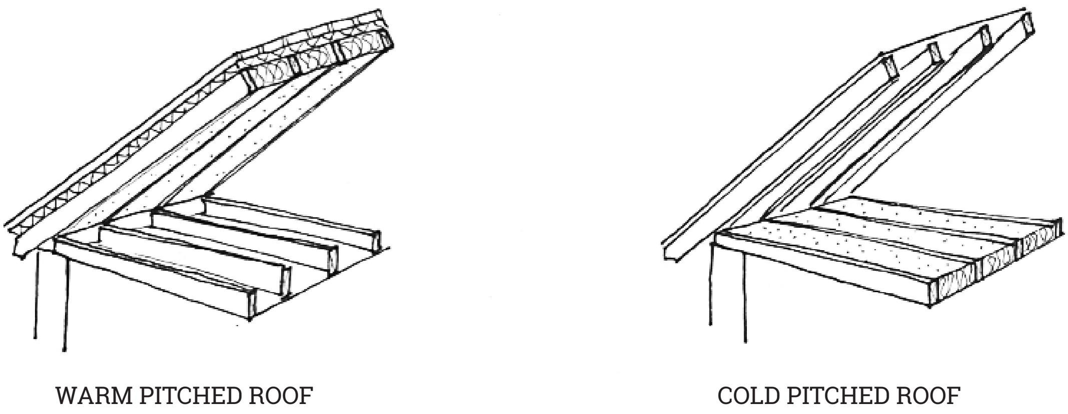


Figure 5: Types of insulated roofs. Image © Kaat Janssens

In timber frame roof constructions, insulation is typically placed between the structural elements. There are two main approaches to roof insulation: warm pitched roof, or cold pitched roof, each with distinct advantages depending on the building's design and intended use of the attic space.

4.2.1 Warm pitched roof

A warm pitched roof is a method used to bring the roof space within the heated volume of the building. Roof insulation was shown to play a role in reducing the risk of summertime overheating[18] , although the extent of its impact depends on the type of insulation used.

17 For further guidance on AVCLs, see: Historic England Research Report 44/2024: Air and Vapour Control Layers (AVCLs) in buildings of traditional construction. A literature review to understand appropriate use (Historic England, 2024)
18 Demonstration of Energy Efficiency Potential (DEEP) Case Studies Summary, 2016, GOV.UK

Key considerations

- The thermal performance of timber frame roofs is influenced by the rafter size and spacings. To reduce thermal bridging, insulation is typically installed between the rafters and, in many cases, supplemented with an additional layer above or below. Layers should be vapour permeable, particularly the external ones (e.g., wood fibre sarking boards). In retrofit projects, adding the extra layers above the rafters requires a roof strip and increases roof height, requiring adjustments to gutters, fascia boards, and other elements to maintain proper drainage and aesthetics; this approach can be very effective, but is only appropriate where such work can be accommodated.
- Best practice calls for a ventilated void to also be provided to the outside of the roof construction. This ventilation should be positioned either between the insulation and a high-resistance (HR) underlay or above a low-resistance (LR) underlay, allowing excess moisture to escape and maintaining the drying potential of the roof. HR underlays may be found beneath existing slate or tile finishes, where the underlay cannot easily be replaced. Where historic roofs retain a full or partial lime mortar 'torching' to the underside of the tiled finish (which predates underlay and forms the same function), its presence should form part of considerations as to appropriate approaches for roof insulation.
- A vapour-permeable airtightness layer (or AVCL) — provided either by a membrane or a continuous permeable plaster finish — must be used to prevent warm indoor air from reaching cold surfaces within the roof build-up, where condensation risks are highest. The AVCL must be specified carefully: the s_d-value is critical (see Appendix A.1 for definitions). Standard highly vapour-resistant vapour barriers can limit moisture ingress but also hinder drying if any moisture becomes trapped. In many cases, a vapour-permeable airtightness layer with variable vapour diffusion resistance can offer a more balanced approach, preventing vapour ingress during colder periods while allowing drying when conditions permit. The effectiveness of the AVCL also depends heavily on proper sealing and detailing at junctions, openings, and service penetrations. Air leaks can bypass the layer, rendering it ineffective and leading to moisture problems.
- The UK government report Moisture Risk of Spray Foam Insulation Applied to Timber Sloped Roofs[19] highlights concerns including the risk of timber decay as a result of spray foam insulation, particularly when the insulation is applied directly to high-resistance underlays or roof tiles. Foam can conceal defects, increasing the risk of hidden moisture accumulation and hidden damage within the roof structure, and potentially delaying necessary maintenance[20].

19 Moisture risk of spray foam insulation applied to timber sloped roofs – GOV.UK
20 Health and Safety Executive (HSE) (2024). Spray foam insulation applied to timber sloped roofs in dwellings.

There are many instances where spray foams have led to decay of timber roof members.

Some types of spray foam can significantly reduce the drying potential of timber elements, increasing the likelihood of prolonged high humidity and associated decay risks. Other formulations may permit vapour diffusion, but if applied over impermeable underlays without an appropriate vapour control strategy, they can lead to hidden moisture accumulation within the roof build-up.

Removal of spray foam without damaging the underlying structure is difficult, raising concerns about reversibility[21]. As such, this approach is not recommended, unless there is a clear reason why alternatives cannot be implemented and a robust moisture risk assessment has been carried out.

4.2.2 Cold pitched roof

A cold pitched roof (i.e. with loft insulation) is a common and cost-effective solution for improving thermal efficiency in buildings where the attic is not intended for regular use. Insulation is typically placed between and over the ceiling joists, creating a thermal barrier between the heated living space below and the unheated loft above. This method is relatively simple to install and minimises heat loss from the rooms beneath. However, since the loft remains cold – and often colder than it would be without insulation –precautions must be taken to prevent moisture build-up within the roof space and structure.

Key considerations

As with warm pitched roofs, thermal bridging through timber joists needs to be considered. Ensure insulation over wiring or recessed lighting follows safety guidelines, and, where parts of the loft are used for storage, solutions are available to accommodate rigid flooring above the insulation, which should not be crushed.

Vapour-permeable insulation materials are recommended to maintain a balanced moisture environment. In addition, adequate ventilation of the roof space is necessary to prevent moisture accumulation, and care must be taken to ensure that insulation does not block eaves vents.

21 RICS (2023). Consumer guide: Spray foam insulation. A clear, impartial guide.

4.3 Suspended floor insulation: placement and types

Suspended timber floors, commonly found in older buildings, are constructed with floorboards fixed to wooden joists, leaving a ventilated space underneath. If done properly, insulating these floors can reduce heat loss and air leakage, improve thermal comfort and lower energy bills – indeed, heat loss from suspended timber floors, and consequently the benefits of insulating them, are often under-estimated by energy modelling tools[22]. However, ensuring the long-term performance of suspended floor insulation requires attention to ventilation, moisture control, overheating risk and installation quality[23].

For suspended timber floors, a vapour-permeable airtightness layer (AVCL) is placed below the floorboards to reduce moisture transfer from the living space into the floor void and vice versa, improving airtightness and limiting moisture risks[24].

Flexible, vapour-permeable insulation is placed between the joists to maintain drying potential and provide thermal resistance. This can be achieved using materials such as cellulose, sheep's wool, or wood fibre, which conform to the spaces between joists and are preferable to rigid insulation boards (which must be fitted very tightly to be effective). Where a small increase in floor height can be accommodated, a thin layer of rigid insulation above the joists (with similar moisture properties to the rest of the insulation) is sometimes added.

The insulation must be well-supported to prevent sagging over time, which could create gaps and reduce effectiveness. It should be securely held in place using netting, battens, or a highly vapour-permeable breather membrane (with a very low s_d-value) installed below the insulation.

Installation quality is equally important, particularly in relation to airtightness and thermal bridging. Sealing skirting boards, service penetrations, and junctions helps maintain thermal continuity and prevents draughts. The floor perimeter – where the floor meets external walls – presents particular risk for thermal bridging and moisture accumulation and must be assessed and detailed with care. Also, maintaining effective subfloor ventilation remains essential to prevent moisture build-up and timber decay.

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22 S. Pelsmakers and C.A. Elwell (2017) Suspended timber ground floors: Heat loss reduction potential of insulation interventions. Energy and Buildings

23 Department for Business, Energy and Industrial Strategy (2020). Retrofit Floor Insulation – Suspended Timber Floors: Guide to Best Practice

24 Historic England Research Report 44/2024: Air and Vapour Control Layers (AVCLs) in buildings of traditional construction. A literature review to understand appropriate use (Historic England, 2024)

Key considerations

- Interactions with the ground mean that the hygrothermal behaviour of suspended floors is more complex than walls and roofs. For example, the vapour pressure can be higher in the void than in the occupied area; also, a floor with poor airtightness tends to allow air infiltration from the void upwards. In some locations, ground gases such as radon may also pose a risk, reinforcing the importance of airtightness and ventilation of the air void. It is essential to maintain clear and unobstructed subfloor ventilation, ensure airtight detailing at floor level, and check that retrofit measures such as external wall insulation do not impede airflow through existing vents. Where ventilation paths have been disrupted by previous alterations, such as extensions or raised ground levels, they should be reinstated as part of the retrofit.
- Insulating a suspended floor also alters how indoor moisture sources affect the construction. In uninsulated floors, the ventilated void often helped to dissipate minor leaks, but this drying capacity is reduced once insulation is added. In insulated timber floors, plumbing leaks, for instance, must be prevented from reaching timber joists. An airtightness layer above the insulation can help limit moisture ingress, and placing trays beneath appliances such as washing machines or dishwashers can reduce the risk of undetected leaks. If moisture does reach the floor, it is important that the system can dry effectively. Insulation build-ups that support drying and can be easily removed for inspection or remediation are strongly recommended. Moisture management must be carefully balanced, particularly in insulated suspended floors where traditional drying paths may be reduced. While insulation can help protect the internal environment from adverse void conditions, it also carries the risk of trapping moisture in hidden spaces if not properly detailed and specified. Vapour-permeable insulation materials should be used in moisture-sensitive buildings to support drying, preventing trapped moisture and potential damage. Also, systems that allow inspection, drying, and easy remediation in the event of water leaks or other failures are preferred.
- Spray-applied foam insulation products are not recommended for use in underfloor applications, due to the associated moisture, inspection and reversibility challenges. While sometimes promoted for their thermal performance, there are currently concerns around their long-term safety and moisture behaviour in suspended floor voids. The physics of underfloor spaces differs from that of roofs, but the same principles apply, and limited access can make both thorough installation and future remediation more difficult. As discussed in Section 4.2.1, these concerns are compounded by the difficulty of inspection.

- The increasing use of underfloor heating (UFH), particularly in combination with heat pumps, presents further considerations. While UFH can enhance thermal comfort and system efficiency, its installation may reduce the drying capacity of the floor depending on the system used, and particular care is needed in managing the risk of leaks.
- In some cases, replacing suspended timber floors with solid constructions – such as lime-based construction – may be considered. This approach can simplify airtightness detailing, support UFH installation, and avoid subfloor void risks. However, the installation is invasive and not reversible, and it can affect the moisture balance of adjacent walls depending on ground conditions. With solid floor insulation, the ability to dissipate ground moisture is reduced, and it's largely lost where vapour-closed materials such as concrete screeds are used. This can redirect moisture into adjacent wall areas, increasing the risk of salt efflorescence and surface degradation[25].

25 J. Godefroy and M. Baeli (2024). Retrofit Revisit : 10 Case Studies. CIBSE.

5 Moisture balance

This section highlights the importance of installing insulation properly by discussing failure mechanisms and associated risks. It explains the long-term consequences of moisture imbalance, highlighting common issues such as condensation, mould growth, and frost damage.

BS 5250:2021 *Management of moisture in buildings*[26 27] provides comprehensive guidance on managing moisture risks in buildings through a whole-building approach, and should be read and adhered to by all practitioners working on traditional buildings. A notable revision from the previous 2016 edition – which focused narrowly on condensation and was titled *Code of practice for control of condensation in buildings* – is the expanded scope and emphasis on managing moisture more broadly. The Standard moves beyond the 'Glaser paradigm' of vapour diffusion and interstitial condensation, and considers a wider range of moisture-related issues, including rainwater penetration, capillary rise, and systemic moisture risks.

The Standard recognises that moisture risks are influenced by complex interactions between building elements, environmental conditions, and occupant behaviour. It also introduces updated strategies for mitigating these risks, including robust hygrothermal simulations, prescriptive design approaches, and adaptive ventilation strategies.

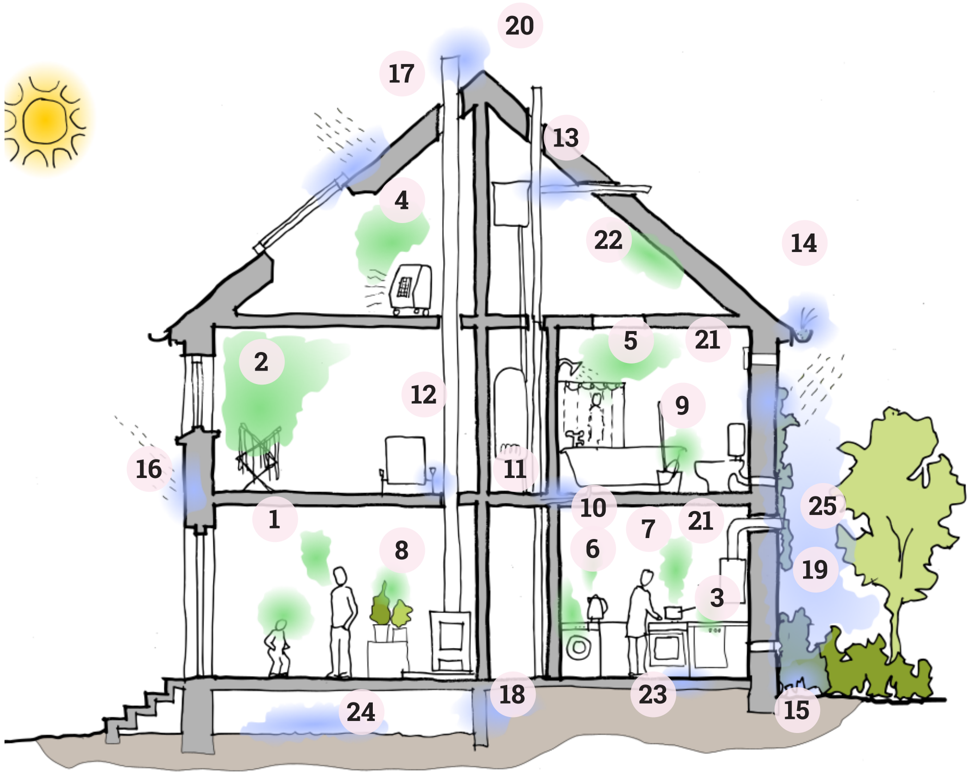
Another key revision is its emphasis on retrofit, particularly in relation to walls, floors, and roofs, where added insulation can alter moisture dynamics. By integrating the principles detailed in BS 5250:2021, this section identifies the main moisture-related issues and their primary causes, providing a foundation for effective moisture management in building design and renovation.

5.1 Achieving moisture balance

Moisture is a natural and essential part of our indoor environment, but excess moisture can lead to problems such as damp and mould. Figure 6[28] highlights the various sources of water vapour inside and outside the building. Everyday activities like cooking, washing, drying clothes indoors, and even breathing release moisture into the air, while external sources such as rain, leaking gutters, and broken pipes can introduce additional moisture.

26 BS 5250:2021 Management of moisture in buildings. Code of Practice.
27 May N. and Sanders C. (2016) Moisture in buildings: an integrated approach to risk assessment and guidance
28 Image adapted from: SUSTAINABLE RENOVATION: Improving Homes for Energy, Health and Environment.

The video ‘Moisture Guidance for Existing Homeowners’[29] by the UK Centre for Moisture in Buildings (UKCMB) explains in simple terms how air holds different amounts of water vapour depending on temperature. Warm air can hold more moisture, but when it cools its capacity decreases, leading to condensation, for example when warm air meets a cold surface like a window in winter. Even without visible condensation, this process can contribute to issues including mould, wood rot, corrosion and poor indoor air quality, particularly in spaces with limited ventilation.



1 breathing and perspiration
2 clothes drying
3 cooking
4 portable gas heating
5 bathing
6 kettles
7 dishwashing
8 plants and soil
9 floor/surface washing
10 washing maching/tumble dryer (depending on venting arrangement)
11 leaks in waste drainage (eg bath connection or toilet cistern) or overflowing bath/basin
12 plumbing leaks – water supplies or central heating
13 burst (frozen) pipes in uninsulated areas
14 gutters leaking/blocked/overflowing or downpipes leaking/blocked eg, at fixings
15 gullies blocked/ground nearby saturated
16 rain direct onto walls. in voa gaps/cracks in pointing or render
17 rain direct through roof, via missing slates/leaking flashings etc
18 groundwater via inadequately waterproofed or low level walls or floors
19 ‘rising damp’ driven up walls
20 rain via uncapped chimneys/flues/ flashings etc
21 condensation in wet rooms/cold surfaces/ poor ventilation
23 ‘built-in’ moisture from construction
24 flooding/high water tables
25 high mositure levels to shaded/ unventilated areas (overgrown to north)

Figure 6: Moisture sources in a building. Image © John Gilbert Architects

29 UKCMB (2018) Moisture guidance for existing homeowners

Maintaining a balanced indoor environment requires both controlling moisture sources and ensuring proper ventilation to prevent excessive humidity levels, which can encourage mould growth. The UKCMB video emphasises the importance of understanding how buildings manage moisture, how insulation and ventilation play a role, and how small lifestyle adjustments—such as drying clothes outside when possible or using lids while cooking—can help regulate moisture levels. By managing indoor humidity and ensuring good ventilation, it is possible to create a healthier and more comfortable living space.

5.1.1 The impact of climate change on moisture balance

The UK has a temperate maritime climate, with significant exposure to wind-driven rain. This exposure tends to be strongest in the west of Great Britain, affecting many western and southern façades, but high exposure and associated risk can be highly localised areas, depending on topography, orientation and sheltering. Climate change projections indicate that while annual totals of wind-driven rain may remain relatively stable, seasonal patterns will shift, with increases expected during winter and reductions in summer[30].

More intense wetting events are likely to subject building façades to greater moisture stress. Combined with warmer, wetter winters, these changes will increase the likelihood of rainwater penetration and moisture accumulation, leading to higher risk of biological growth, and accelerated material deterioration[31]. These shifts may challenge the assumptions underpinning current definitions of exposure zones in the Building Regulations, which are likely to become outdated as climate conditions continue to change.

Research indicates that solid masonry walls are vulnerable to increased moisture accumulation under future climate scenarios, particularly when insulated with low vapour permeability insulation systems. While the referenced study did not assess different thicknesses of solid walls, vulnerability to negative impacts of increased moisture accumulation is linked to the depth and porosity of masonry walls.The risk is more pronounced in thinner, highly porous brick walls than thicker rubble stone walls and less porous stone walls. To address these evolving risks, retrofit strategies must prioritise capacity and robust solutions, designing systems that not only perform under current conditions but can also accommodate future changes in climate. This also highlights the need for good maintenance before, during and after a retrofit.

5.2 The physical mechanisms causing moisture issues

This section examines the key physical mechanisms that can lead to moisture imbalance and failure associated with retrofit measures, focusing on moisture management and thermal performance.

30 Projected Wind-Driven Rain in the United Kingdom (DESNZ, 2024)
31 Resilience of Buildings to Challenges Associated with Climate Change (Hayles, 2021)

5.2.1 Moisture in air and phase change

Air can hold varying amounts of water vapour depending on its temperature. Warmer air can hold more moisture, also known as its ‘holding capacity.’ However, when the air reaches its maximum moisture-holding limit, it becomes saturated, and any extra moisture condenses into liquid water. This is the same process that forms rain. It occurs in a building when warm, moisture-laden air comes into contact with a cold surface. As the air cools quickly, its ability to hold moisture decreases, causing condensation to form.

We measure how much moisture is in the air through relative humidity (RH)[32]. While condensation occurs when RH reaches 100%, the point at which air becomes saturated, moisture-related problems can begin well before this, typically at around 80% RH, depending on the circumstances. Even at lower levels, high RH can create favourable conditions for mould growth and other forms of moisture damage[33]. The temperature at which saturation occurs is known as the dew point temperature[34].

Condensation is more pronounced on non-porous materials like glass or metal, where moisture forms visible droplets which in some cases can run and pool. In contrast, porous materials such as masonry, lime plaster or timber can absorb and redistribute moisture, reducing surface condensation but still being vulnerable if they reach a too high moisture content. Persistent high humidity or repeated condensation can contribute to issues such as mould growth, wood rot, and corrosion (more detail in Section 5.3), as well as affecting indoor air quality.

In retrofit applications, increasing airtightness without adequate ventilation can lead to prolonged periods of high humidity, making surfaces more prone to moisture-related problems, even in the absence of visible condensation. This is why ventilation is recognised as one of the most important aspects of responsible retrofit. Additionally, inappropriate retrofit measures can trap moisture within the building fabric, further increasing the likelihood of deterioration.

5.2.2 Outward vapour diffusion

Outward vapour diffusion occurs when internal vapour travels through the building envelope, passing through areas of changing temperature. If this process occurs in excess, moisture can accumulate in colder zones of the structure. This can happen, for example, in internally insulated walls or in warm roof assemblies with high-resistance (HR) underlays, where vapour can become trapped. This can lead to moisture imbalance if there is no ventilation of the cold area or enough capacity for redistributing excess moisture. A low to moderate degree of vapour control on the

32 Relative humidity (RH) is the ratio of the actual amount of water vapour in the air to the maximum amount the air could hold at the same temperature, expressed as a percentage. In other words, 100% RH means the air is saturated and cannot hold any more water vapour at that temperature, 50% RH means the air holds half the amount of moisture it could hold at that temperature.

33 The term ‘interstitial condensation’ is often used to describe moisture accumulation within building elements. However, focusing on moisture accumulation more broadly is more appropriate, as adverse consequences such as mould growth and wood rot can occur without visible condensation.

34 The dew point refers to the state where moist air becomes saturated with water vapour at a constant pressure, leading to the onset of condensation. This state is characterised by the air reaching 100% relative humidity. The dew point temperature is the specific temperature at which this saturation occurs for a given partial pressure of water vapour.

warm side of the construction is often enough to effectively reduce vapour diffusion. In addition, using appropriate insulation materials and systems that either promote redistribution of excess moisture and drying or provide effective ventilation on the outer layer can help mitigate this risk.

Outward vapour diffusion is a typical process in vapour permeable construction in the UK, driven by high internal moisture loads, especially in winter. However, it must be balanced against the risk of reverse vapour diffusion. Reducing vapour permeability alone is not an effective solution, as it can restrict necessary evaporation from porous materials and increase the risk of trapping moisture in case of inward vapour movement.

5.2.3 Reverse (solar-driven) vapour diffusion

Reverse vapour diffusion occurs when solar radiation heats the outer surface of walls or roofs, driving moisture stored within the external porous layer back into the building. In walls with a porous surface, such as unrendered masonry, the external leaf can act as a moisture reservoir: rainwater is absorbed and retained within the material. When the surface is exposed to sunshine, this moisture evaporates, generating vapour diffusion not only outward but also inward, towards the interior. The effect is more pronounced on sun-exposed and darker-coloured surfaces, which absorb more solar energy[35].

This process is particularly common where porous walls are exposed to high levels of wind-driven rain, as these conditions result in greater moisture stored near the surface. This can lead to excess moisture accumulation within the fabric and mould growth, particularly in some IWI systems applied to thin solid walls or inadequately ventilated roofs (especially flat roofs) where excessive vapour control on the inside prevents the inward movement of moisture. For IWI, while the likelihood of reverse diffusion is relatively low for thicker rubble stone walls and less porous stone types, the risk is more pronounced in thinner, highly porous brick walls, where absorbed moisture is stored relatively close to the internal surface and is more easily driven inwards. For these systems, a balanced approach is needed: one that considers both outward and reverse vapour diffusion (as well as air leakage), addressing not just the degree of vapour control but also additional moisture-handling properties of the entire build-up.

As climate change leads to higher rainfall intensity and warmer, drier summers, reverse vapour diffusion is likely to become more frequent. These changing conditions increase the amount of moisture entering the outer wall layer and the energy available to drive it inward, particularly in porous materials. This makes it even more important to design systems that can accommodate vapour movement in both directions.

5.2.4 Thermal bridges

Thermal bridges occur at junctions or penetrations where insulation is interrupted, resulting in heat loss and colder surfaces. These colder spots can lead to surface

35 Marincioni, V., and Altamirano-Medina, H. (2014). Effect of orientation on the hygrothermal behaviour of a capillary active internal wall insulation system.

condensation and mould growth. This issue is not related to the moisture properties of materials but rather to the continuity of insulation and proper detailing[36], which can be complex in retrofit.

5.2.5 Air leaks

Poor airtightness (particularly gaps in intended airtightness layers) can result in warm, humid air from the indoor environment moving to colder areas within the building fabric (e.g. behind insulation), elevating humidity or condensing as it cools. This movement introduces additional moisture into the fabric – moisture that is often not accounted for in the design and is therefore harder to manage – which can lead to material degradation and moisture-related damage over time. Common causes include improper detailing around openings, junctions, or other vulnerable areas. Gaps or poor sealing in the building envelope often exacerbate this issue; minimising air leakage is particularly important in IWI systems and roofs without external ventilation (e.g. flat roofs), where vapour ingress via air leaks can lead to excess moisture accumulation. Finally, some moisture leaks are closely linked to the concept of thermal bypass[37], where unintended air movement through or around insulation layers leads to unintended heat loss. As well as potentially increasing moisture risks, poor airtightness can also considerably undermine the beneficial impacts of insulation.

5.2.6 Freeze-thaw cycles

Freeze-thaw cycles occur when water trapped in the pores of porous building materials, such as brick or stone, freezes and expands, generating internal pressure. As temperatures rise, the ice thaws, releasing the pressure, but repeated cycles of expansion and contraction can gradually weaken the material. This process is particularly problematic in colder climates or areas where temperatures frequently fluctuate around freezing. When the material is saturated with water, the risk of frost damage increases, leading to cracks, chipping, or even loss of surface material (e.g. masonry spalling) over time.

Adding internal wall insulation exposes external masonry to greater temperature fluctuations, as it no longer benefits from a heated indoor environment. This can increase freeze-thaw cycles, where water in the masonry pores repeatedly freezes and expands, then thaws and contracts. Over time, this can lead to frost damage, especially in colder climates or areas with frequent temperature changes around freezing[38]. However, this risk is dependent on many variables including materials and their pore structure, exposure and orientation, thermal resistance of insulation, conditions, presence of salts and so on.

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36 For examples, please see S. Price et al. (2021).Retrofit Internal Wall Insulation: guide to best practice.

37 Thermal bypass describes the loss of heat through routes that avoid or reduce the effectiveness of insulation. This can happen through unintended air movement, poorly sealed gaps, or materials that conduct heat across the insulation layer. Even if insulation is correctly installed, thermal bypass can lead to reduced energy efficiency and increase the risk of condensation or damp by allowing warm air to move into colder parts of the building fabric. For more information, please see M. Siddal (2022) Thermal bypass risks: a technical review

38 K. Janssens et al. (2024). Comparison of different frost models with hygrothermal simulations to better understand frost damage in porous building materials. Building and Environment, 255 (111399).

Recent research on IWI suggests that inappropriate cement pointing presents more of a risk to external masonry than the thermal resistance (and thickness) of insulation[39]. This underlines the need for appropriate materials and adequate maintenance of the external envelope, especially the use of lime-based mortars for repointing and effective rainwater management to reduce the risk of freeze-thaw damage.

5.2.7 Salt crystallisation

Salt crystallisation is a physical process that occurs in porous building materials, where salts dissolved in moisture crystallise as the water evaporates. This can happen in two ways: efflorescence, where salts form on the surface, causing white, powdery deposits that are mostly cosmetic; and cryptoflorescence, where crystals grow inside the pores of the material. Cryptoflorescence is more serious because the expanding crystals create pressure that can crack, weaken, or break the material over time. This issue is more likely in areas exposed to salty water, such as coastal regions or where de-icing salts are used.

Retrofit measures such as solid floor insulation can lead to increased salt accumulation and crystallisation in walls, as a result of moisture from the ground. For example, this has been observed where a vapour-closed concrete screed was installed, inhibiting drying through the floor and pushing ground moisture into adjacent wall areas where evaporation could still occur[40]. Also, there is evidence that some hydrophobic masonry treatments, particularly earlier formulations, have increased this risk under certain circumstances[41].

5.3 Consequences of moisture imbalance

The term 'damp' is often used to describe moisture-related issues in buildings, but it is a vague concept that does not fully capture the range of potential problems. Dampness generally refers to materials having excessive moisture, whether due to the presence of liquid water or high levels of water vapour within the building fabric. It has been used as an indicator of underlying issues[42]. However, instead of relying on dampness as a catch-all term, it is more precise to consider the specific moisture-related issues outlined below.

5.3.1 Mould

Mould growth happens when certain conditions allow mould spores to thrive, usually in humid or poorly ventilated areas. It can appear on the interior surface of external walls, or even behind insulation if moisture gets trapped and the environment is warm and humid enough. Mould feeds on nutrients and spreads across surfaces, starting as microscopic growth that is hard to see and eventually

39 J. Godefroy and M. Baeli (2024). Retrofit Revisit : 10 Case Studies. CIBSE.
40 J. Godefroy and M. Baeli (2024). Retrofit Revisit : 10 Case Studies. CIBSE.
41 T. Cambray et al. (2024) Hydrophobic treatments and their application with internal wall insulation
42 BRE Expert Collection 7 Condensation and dampness – a collection of BRE expert guidance on assessing and treating dampness in buildings, BRE – Publication Index | NBS

becoming visible as patches of black, green, or other colours[43]. Inside the building fabric, this process is more likely in areas where building layers are not tightly sealed (e.g. in air voids behind insulation), creating hidden spaces where moisture can accumulate and mould develop.

Mould growth is influenced by several factors, including high relative humidity, the presence of organic nutrients such as dust, pH levels (inhibited at alkaline pH), and temperature (with growth broadly occurring within a typical range of 10°C to 35°C). Oxygen availability and the duration of exposure to favourable conditions are also important[44].

In retrofit, airtightness without well-considered ventilation can lead to an increase in mould growth on interior surfaces. Also, interstitial mould growth can be caused by inappropriate or poorly-detailed retrofit measures.

For a practical overview of mould in buildings, please see the UK Centre for Moisture in Buildings (UKCMB) resources[45].

5.3.2 Wood rot

Wood rot is an issue that can affect timber in buildings, especially when exposed to excess moisture levels. Timber embedded in masonry or in the construction can remain sound if surrounding materials stay dry. However, when masonry becomes persistently wet (for example due to a lack of maintenance or inappropriate interventions) conditions can allow fungi to grow and break down the timber. This can weaken the wood over time and even cause structural damage if left unchecked[46].

If they are not specified, detailed and installed appropriately, retrofit measures such as floor, roof or internal wall insulation can increase the risk of wood rot by reducing the ability of embedded timber or joist ends to dry out. These risks can often be mitigated by appropriate insulation approaches.

5.3.3 External surface deterioration

External surface deterioration includes cracking, spalling, chipping, and material loss, often caused by moisture-related physical processes. Two main mechanisms contributing to this are freeze-thaw cycles (see Section 5.2.6) and salt crystallisation (see Section 5.2.7).

If they are not specified, detailed and installed appropriately, retrofit measures such as internal wall insulation can exacerbate this issue; this can be compounded by other inappropriate interventions that can occur during retrofit such as repointing with cement mortar.

43 H. Viitanen, M. Krus, T. Ojanen, V. Eitner and D. Zirkelbach (2015). Mold Risk Classification Based on Comparative Evaluation of Two Established Growth Models.

44 E. Vereecken and S. Roels (2012), Review of mould prediction models and their influence on mould risk evaluation. Building and Environment, 51, 296–310.

45 A bit more about mould. UKCMB (2024)

46 C. Brischke and A. Rapp (2008). Dose-response relationships between wood moisture content, wood temperature and fungal decay determined for 23 European field test sites.

5.3.4 Corrosion

Corrosion is a common issue for metal components (e.g. steel reinforcements and fixings). It occurs when these metals are exposed to moisture and air, leading to rust and weakening over time. The process is particularly problematic when moisture accumulates and remains on metal surfaces for extended periods, acting as an electrolyte and creating conditions that accelerate corrosion; the rate of corrosion is further increased by the presence of salts and some pollutants[47]. Corrosion can reduce the strength of metal parts and surrounding structures, potentially compromising the structural integrity of a building. This is a particular concern in older structures where materials might not have been treated to resist corrosion.

If they are not specified, detailed and installed appropriately, retrofit measures such as internal wall insulation can increase the risk of corrosion by reducing the ability of metal components (if embedded in the system) to dry out.

5.3.5 Algae growth

Algae growth on exterior walls is a common issue caused by microorganisms settling and spreading on masonry surfaces, especially in damp areas. It often starts with fast-growing organisms, followed by slower ones over time. Algae can cause green or dark stains, impacting the appearance of the wall and potentially leading to surface degradation. This growth is more likely in environments with high humidity, moderate temperatures, and away from direct sunlight[48]. Rough or porous surfaces also make it easier for algae to adhere and spread.

If they are not specified, detailed and installed appropriately, retrofit measures such as external or internal wall insulation can exacerbate algae growth, as the exterior surface no longer benefits from a heated indoor environment.

47 F. Vidal et al. (2019) Review of environmental and air pollution impacts on built heritage: 10 questions on corrosion and soiling effects for urban intervention, Journal of Cultural Heritage, 37, 273 – 295.

48 M. Nakajima et al. (2020). Field survey of the relationship between environmental conditions and algal growth on exterior walls. Building and Environment, 169, 106575.

6 Principles and design considerations

This section provides retrofit design principles (grouped under the four principles for moisture balance[49]) based on the details of moisture transfer, material properties and failure mechanisms described in this guide. By implementing these design principles, together with understanding the appropriate use of materials as discussed in this guide, insulation systems can be specified to provide thermal resistance while effectively managing moisture[50], reducing the risk of structural damage, and promoting a comfortable and healthy indoor climate.

6.1 Context

Retrofit ready: preparation, and assessment – Before any retrofit measures are considered, it is essential that the building is 'Retrofit Ready'. This involves a detailed survey to understand the construction, existing defects, moisture ingress, and maintenance issues. Any necessary repair works or preparatory steps must be completed first, ensuring the building can support insulation without exacerbating existing risks. It is also important to address any past mistakes, such as the use of inappropriate materials or defective pointing, renders, or finishes, which could compromise the performance of new insulation systems. These issues must be identified and properly rectified before proceeding with retrofit.

Minimising or removing sources of excess moisture – Effective moisture management starts with reducing excess moisture generation within the building. Common sources include indoor drying of clothes, and inadequate extraction in bathrooms and kitchens. Moisture already present within the building fabric (e.g. wet walls due to building defects) must also be considered. Design strategies should incorporate internal and external moisture management solutions such as adequate heating and ventilation and effective rainwater management, and should comply with the relevant Building Regulations. These measures must be appropriate to the specific context of the building, taking into account its construction type, age, materials, and use.

Using the right systems – In the design and specification of insulation systems, it is important to consider how the system performs as a whole, rather than focusing solely on individual materials. Materials must be selected and combined to work

49 For more information on the four principles in retrofit, please see V. Gori, V. Marincioni, and H. Altamirano-Medina, (2021) Retrofitting traditional buildings: a risk-management framework integrating energy and moisture. Buildings and Cities , 2 (1) pp. 411-424. N. May and C. Sanders (2016) Moisture in buildings: an integrated approach to risk assessment and guidance, BSi

50 T. Cambray, S. Price and K. Megagiannis (2023) Moisture and EnerPHit.

with the natural moisture dynamics of the building fabric. While adequate ventilation plays an essential role in managing moisture, increasing ventilation is not a substitute for using appropriate insulation systems.

6.2 Coherence

Continuous thermal insulation layer – To ensure good thermal performance and prevent unintended heat loss, thermal bridging, and the associated risk of mould growth, a continuous insulation layer must be maintained across the building fabric.

Airtightness and ventilation strategy – Where insulation is being installed, a continuous airtightness layer must also be established to prevent unintended air movement through the fabric. This not only improves energy efficiency but also supports moisture control by reducing the likelihood of air leakage and moisture accumulation in hidden areas.

The ventilation strategy is often dictated by the level of retrofit undertaken, with higher levels of airtightness and insulation requiring higher levels of ventilation. Retrofit projects must include a well-thought-out ventilation strategy to prevent excess moisture build-up. Insulation systems improve energy efficiency but can also lead to indoor and interstitial moisture accumulation if not paired with sufficient ventilation. This applies to all insulation systems, whether vapour-impermeable, vapour-permeable, or capillary active: different approaches manage moisture differently, but none eliminates the need for effective ventilation.

Ventilation strategies should be incorporated to maintain indoor air quality and manage humidity levels effectively. While natural ventilation may be sufficient in some cases, particularly for less demanding levels of retrofit, mechanical ventilation (e.g., continuous mechanical extract ventilation (MEV), demand-controlled MEV, or mechanical ventilation with heat recovery (MVHR) is often required for more substantial retrofits. Centralised mechanical systems are the most effective option, but in some older buildings, it can be challenging to accommodate the ducting required for centralised systems; in these cases, decentralised systems will generally be required but care should be taken to ensure they are adequate.

The retrofit must balance airtightness with controlled ventilation to avoid unintended consequences such as mould growth on internal surfaces. If a robust ventilation strategy cannot be assured, insulation and airtightness targets may need to be reviewed to ensure there is no imbalance following the retrofit. Poorly designed or poorly installed ventilation can let down an otherwise good retrofit project, so it is often beneficial to get independent expert support unless you have adequate knowledge and experience.

Balancing thermal performance with moisture risk – Improving the thermal performance must be balanced against moisture risk, particularly in retrofit. In some cases, moderating the insulation thickness may be necessary to avoid increasing moisture retention within the structure and the associated risk of damage over time.

The multiple roles of insulation systems – Insulation does not only provide thermal resistance and regulate moisture, it can also improve acoustic performance and contribute to indoor comfort. For example, natural fibre (or bio-based) insulation systems can deliver multiple benefits, offering advantages such as having low embodied carbon, as well as being resource efficient, renewable, recyclable and non-hazardous materials, alongside their moisture-related properties[51].

6.3 Capacity

Specifying robust systems – Retrofit designs must prioritise robust, moisture-safe systems. Examples include designing systems to tolerate minor leaks or imperfections without leading to hidden moisture accumulation. Where cavities are used, ventilating them to the outside helps moisture to escape. Fully bonded insulation systems are often preferred for IWI because they reduce thermal bypass risks and inhibit interstitial mould growth. Placing the primary insulation layer on the exterior, where it is feasible to do so properly, can be another robust approach as it keeps structural elements warmer. However, in either case caution is needed, as different elements present different challenges, and correct installation is critical, as discussed in Sections 3 and 4. Robust systems are those that continue to perform safely even when actual moisture loads exceed design assumptions, for example, due to increased exposure, unexpected leaks or changes in occupancy patterns.

Allowing moisture to dry out – While AVCLs and insulation materials can help manage moisture ingress, it is equally important to provide a means for any moisture that does enter the structure to dry out. The ability to control moisture movement and drying varies depending on the properties of the different materials making up the system. The capillary pore structure of materials play a crucial role in allowing liquid water to move through and evaporate, helping to avoid moisture build-up and the risk of structural damage. What constitutes a vapour-permeable material must be understood in relative terms, as discussed earlier: materials vary widely in how easily they allow water vapour to move. Simply labelling a material as 'vapour permeable' is not sufficient – its hygrothermal properties must be appropriate to the specific conditions of the building and system.

6.4 Caution

Designing for inspection, maintenance, and hidden moisture risk – Even the best-designed retrofit systems can experience minor failures or moisture ingress over time. Good retrofit design must minimise the risk of hidden moisture accumulation by allowing moisture to escape where possible, and by enabling future inspection, maintenance, and repair. Systems that conceal critical components without access increase long-term risk and should be avoided.

Prioritising reversible or repairable solutions – Wherever possible, retrofit measures should avoid irreversible interventions. Systems should allow future inspection, maintenance, and repair while minimising damage to the original building fabric.

51 https://asbp.org.uk/group/natural-fibre-insulation

7 Quantitative tools for assessing moisture risk

Evaluation tools play a crucial role in assessing the moisture management ability of insulation systems. This section guides building professionals on selecting appropriate quantitative tools to assess moisture risks in retrofit projects. In practice, the key decision is between basic steady-state methods and more advanced hygrothermal simulations.

7.1 Glaser method

Condensation risk (or dew-point) analysis tools based on the Glaser method are commonly used to assess condensation risks in some building assemblies. Where it is appropriate to use it, the Glaser method helps determine if condensation is likely to form within a building component, by comparing the temperature and humidity levels at different points in the structure. If the relative humidity reaches 100% within the wall, condensation can occur, leading to potential damage or mould growth. The Glaser method allows building professionals to evaluate whether the design or insulation choices may cause condensation, helping them adjust building components to prevent moisture issues.

However, the Glaser method has limitations and is not appropriate for all building assemblies, particularly those found in many traditional buildings. Firstly, it assumes a steady-state condition, meaning it doesn't account for the dynamic nature of temperature and moisture levels that can fluctuate throughout the day or month; this brings inherent limitations. Secondly, it only considers internal water vapour – it doesn't consider the effects of wind, rain, building usage, or moisture-buffering materials, all of which can affect real-world moisture conditions (particularly in traditional buildings) and can often be the dominant moisture source for masonry walls in particular. The method doesn't fully account for the complex movement of moisture through building materials, not accounting for the movement of air or liquid water, nor hygroscopic buffering. BS EN ISO 13788:2012, titled 'Hygrothermal performance of building components and building elements — Internal surface temperature to avoid critical surface humidity and interstitial condensation — Calculation methods', provides calculation methods and clearly defines the limitations of the Glaser method. It states that this method 'does not take account of a number of important physical phenomena including:

- the variation of material properties with moisture content;
- capillary suction and liquid moisture transfer within materials;

- air movement from within the building into the component through gaps or within air spaces;
- the hygroscopic moisture capacity of materials.

Consequently, the method is applicable only where the effects of these phenomena can be considered to be negligible.'

The Glaser method only evaluates condensation risk, without considering other moisture-related phenomena like mould growth or material degradation (e.g. wood rot/corrosion), which can result from extended periods of high moisture levels (even without reaching condensation, i.e. 100% RH). Furthermore, it simplifies or completely ignores external conditions (like rain loads, orientation and drying behaviour) so it cannot accurately represent complex real-world environments, and it typically relies on a one-dimensional analysis which misses the multi-dimensional transport of vapour in building envelopes. In particular, it takes no account of rainwater ingress or other sources of liquid, or bulk air movement.

Therefore, while the Glaser method is useful for basic analysis in some construction types, it is often insufficient or even incorrect for many traditional building situations, and should only be used where it is appropriate. As noted in Historic Environment Scotland's Technical Paper 15[52], 'Construction guidance and practice are still heavily influenced by…a reductionist but deeply held view that vapour diffusion is the only relevant moisture transport mechanism in building fabric and the use of a vapour barrier to control it is always best practice.' It continues: 'The Glaser method… has little place in the evaluation of solid wall traditional buildings.'

7.2 Hygrothermal simulations

For a more accurate evaluation than the Glaser method, and for retrofit measures such as IWI in particular, hygrothermal simulations that incorporate dynamic material behaviour should be used. These simulations model heat, moisture, and air flow, providing a more realistic assessment of moisture risks in buildings, and are aligned with the international standard BS EN 15026:2023.

The most commonly used and industry-standard software for this purpose is WUFI®, a family of dynamic hygrothermal simulation tools developed by the Fraunhofer Institute for Building Physics[53]. The building component simulation tools, WUFI® Pro and WUFI® 2D, allow users to model the coupled transport of heat and moisture through building components under real, time-varying climate conditions. Simulations can include factors such as wind-driven rain, solar radiation, vapour diffusion, capillary suction, and moisture storage effects. WUFI® Pro has become the default tool for hygrothermal risk assessment in retrofit projects involving traditional and existing buildings. It is supported by guidance, training courses, and user forums, which make it more accessible to practitioners than many other simulation tools. However, WUFI® Pro is limited to one-dimensional

52 Little, J., Ferraro, C. and Arregi, B. (2015). Technical Paper 15: Assessing the hygrothermal performance of walls. Historic Environment Scotland.

53 https://wufi.de/en/software/what-is-wufi/

simulations and is therefore most suitable for assessing planar building elements such as walls or roofs. Where analysis of junctions or more complex geometries is required, two-dimensional simulations with WUFI® 2D or tools such as Delphin are needed[54].

Delphin is primarily used in academic and specialist research contexts and offers several advanced capabilities not currently available in standard WUFI® tools. These include the ability to simulate airflow paths within building components, making it suitable for assessing ventilated roof constructions and timber frame walls where convective moisture transport is relevant. Delphin also supports batch simulations and user scripting, which can be useful for sensitivity analyses or large parametric studies. Despite these features, Delphin is rarely used in UK practice and requires advanced technical expertise. At present, WUFI® Pro remains the only hygrothermal simulation tool in widespread professional use.

As with all hygrothermal simulation tools, a high level of expertise is not only required to interpret results correctly but also to define appropriate assumptions and input parameters. Without sufficient technical knowledge, there is a risk of input errors or misinterpretation that could lead to incorrect conclusions. Simulations can also be time-consuming, costly, and computationally intensive, especially when multiple design scenarios are to be assessed. Nonetheless, when used appropriately, these tools provide a far more robust basis for assessing moisture and thermal risk than the Glaser method, and should be considered essential in complex retrofit projects.

7.3 Future developments: emerging simplified tools

To address some of the limitations of full hygrothermal simulations, simplified tools are being developed to support early-stage assessment. These tools are currently in beta version and draw on pre-run simulations to reduce complexity.

The RIBuild[55] Insulation Calculation Tool (Figure 8), developed as part of a European project focused on internal wall insulation, focuses on the evaluation of energy performance and moisture risks for different IWI systems in Europe. It includes indicators such as mould growth risk behind insulation and algae growth on the exterior surface. However, the underlying simulations do not include UK locations, so the results are not directly applicable to the UK context.

The HAMalyser UK webtool Figure 9), launched in 2024, offers easy-to-understand moisture risk assessments for internal wall insulation. It focuses on IWI and climate change-related moisture impacts and is underpinned by pre-run Delphin simulations. Currently available for London, it is designed to inform both building owners and professionals[56].

54 https://bauklimatik-dresden.de/en/software/delphin/
55 https://www.ribuild.eu/
56 https://hamalyser.shinyapps.io/HAMalyserUK/

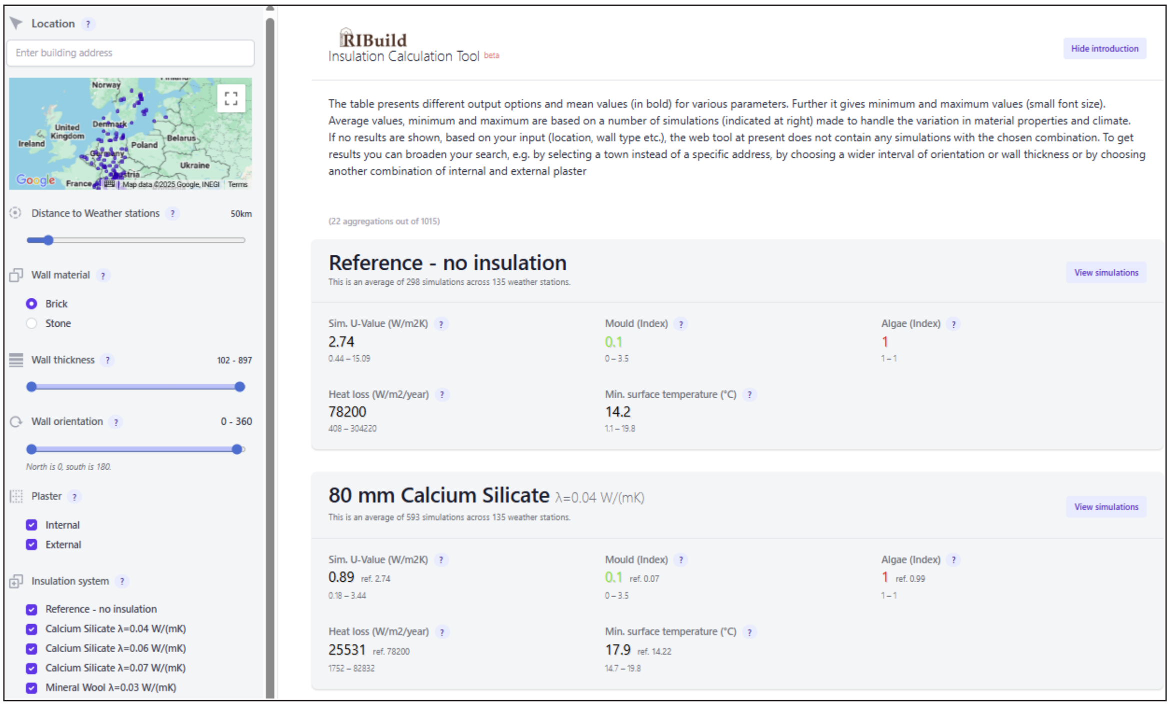

Figure 8: Interface of the RIBuild webtool

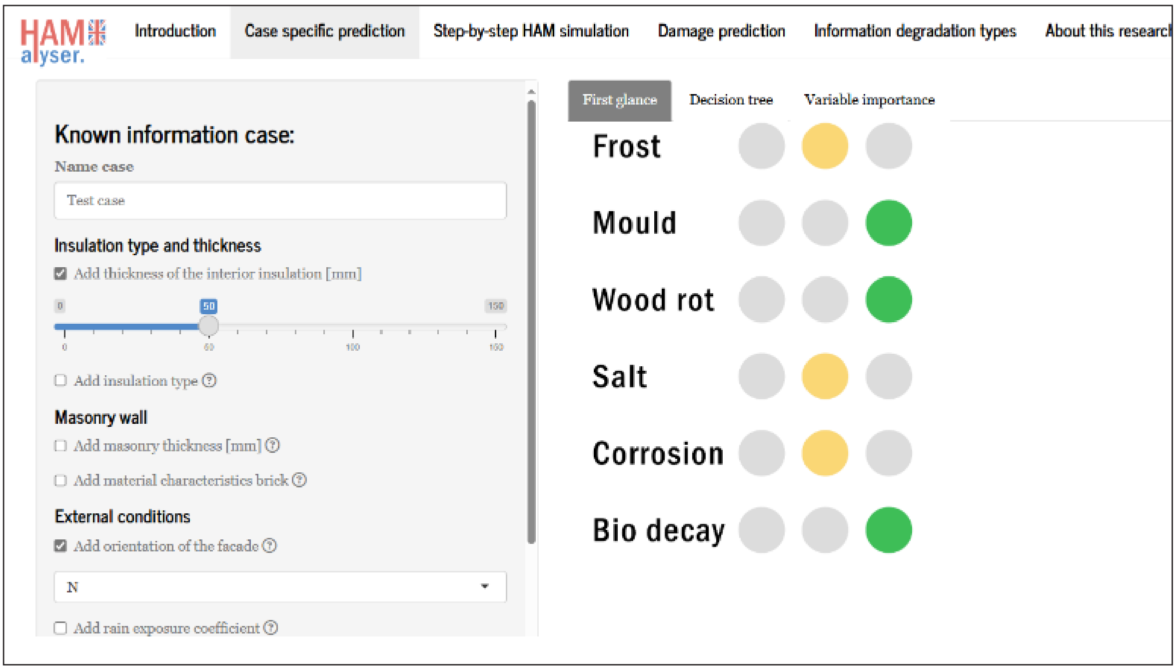

Figure 9: Interface of the HAMalyser UK webtool

8 Conclusions and recommendations

In conclusion, this guide highlights the importance of informed decision-making in achieving moisture-safe retrofit strategies for traditional buildings. By examining the moisture-related properties of insulation materials and systems, it reinforces the need for a holistic approach that considers building context, coherence between interventions, and the capacity to handle moisture loads effectively.

The guide emphasises that retrofit solutions should not be applied in isolation but must be carefully integrated to balance energy efficiency, occupant health, and building durability. Moisture performance must always be understood at the system level, not just through the characteristics of individual materials but through how these materials interact within a build-up and respond to internal and external conditions. Challenges such as thermal bridging, hidden moisture accumulation and unintended consequences of airtightness demonstrate the importance of proper consideration of risk verses benefit of installing insulation, of material selection, installation quality and ventilation strategies.

While significant advancements have been made in understanding hygrothermal performance, knowledge gaps remain, particularly in real-world performance validation, long-term material behaviour, and the impact of climate change on retrofit strategies. We have a good basis for decision making, but ongoing research is required to improve guidance, refine predictive models and develop accessible tools for industry professionals and building owners.

Ultimately, a well-considered approach to retrofit, based on evidence and best practice, will help ensure that traditional buildings remain both functional and resilient in a changing climate.

8.1 Next steps

While this guide provides an overview of the current evidence on moisture-safe retrofit strategies, several key knowledge gaps remain that require further research, monitoring and development to improve guidance and decision-making in the field. Addressing these gaps will help refine existing approaches, validate long-term performance, and enhance the accessibility of hygrothermal risk assessment for industry professionals and building owners.

Long-term performance and robustness of insulation systems – The theoretical performance of insulation systems has been evaluated extensively; however, installation and in-situ conditions are often less than ideal, highlighting the need for more monitoring of actual retrofits and research into robust and resilient systems. This should also include resilience to changing climate conditions, such as increased rainfall and temperature extremes. This analysis should also consider natural fibre (or bio-based) insulation systems, which offer advantages such as having low embodied carbon, as well as being resource efficient, renewable, recyclable and non-hazardous materials, alongside their moisture-related properties. Strengthening the evidence base on their durability, effectiveness, and moisture risk mitigation will support more reliable specification in retrofit applications.

Models for predicting and assessing material decay – The long-term impact of moisture exposure on building materials remains difficult to quantify. While some degradation models exist[57], they are not always validated with real-world case studies or long-term monitoring data. There is a need to refine and expand degradation models to better predict material aging, structural risks, and failure mechanisms under different retrofit scenarios. This includes integrating the effects of moisture cycling, freeze-thaw damage, salt crystallisation, and biological growth into predictive tools. Improving these models will support more accurate assessments of the durability and longevity of insulation systems.

Advancing hygrothermal risk assessment tools – While dynamic hygrothermal simulation tools such as WUFI® and Delphin provide detailed insights into moisture risks, they remain complex and require specialist knowledge, although they are slowly becoming more common. There is a need for simplified, yet scientifically robust, risk assessment tools that are accessible to a broader audience, including homeowners, installers, and general practitioners in the construction industry. Future developments should focus on making these tools more intuitive while maintaining accuracy, including the integration of climate change scenarios with more extreme moisture loads, improved selection of appropriate material data, and the ability to provide actionable insights for different retrofit contexts.

57 DESNZ Deterioration of retrofit insulation performance

APPENDIX A

Building physics – Moisture transport in building and insulation materials

Before discussing key material metrics, it is essential to understand the fundamental principles of moisture transport. Moisture exists in different forms, i.e. water vapour (gas), liquid water (liquid) and ice (solid). In building materials and structures, these forms often appear together and/or change over time, influencing how materials interact with moisture (Figure 10). Moisture transport is a type of mass transport, and its behaviour is sometimes described in analogy with heat transfer. While heat transfer follows the principle of energy conservation, moisture movement is governed by the conservation of mass. This means that the total mass of moisture within a system results from the balance between inflow, outflow, and any internal changes.

Think about it this way

Imagine filling a bathtub. The water level rises depending on how fast the taps are running (inflow), whether the drain is open (outflow), and if water is being splashed out or added from elsewhere (internal changes). You're not creating or destroying water—you're just moving it around. Moisture in a building works the same way. The total amount doesn't magically appear or vanish; it's all about how much comes in, how much leaves, and what's happening inside the materials themselves. Unlike heat, which is about energy, this is all about mass—the conservation of it.

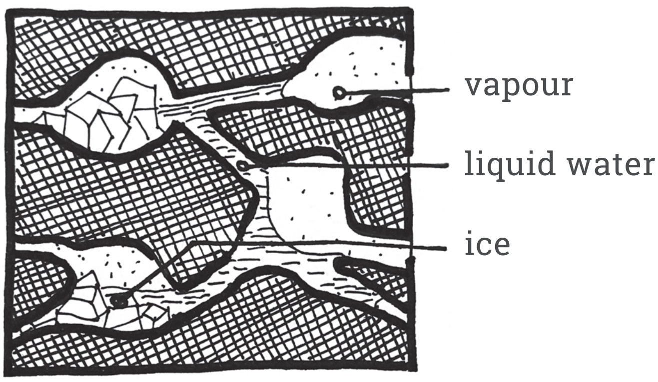

Figure 10: Different phases of moisture existing together within the pore structure of a material. Image © Kaat Janssens

How these different phases of moisture behave or are stored within a material or construction can take different forms:

- **Vapour Diffusion** – The movement of water vapour molecules due to differences in vapour concentration, either in the air or within the pores of a material. This process follows diffusion principles, meaning vapour moves from areas of higher concentration to lower concentration in an attempt to reach equilibrium, similar to how heat flows from warmer to cooler regions. The rate of diffusion depends on the vapour permeability of the materials involved.
- **Bulk Vapour Transport** (air movement) – The transport of water vapour caused by the movement of humid air due to air pressure differences. This can occur through ventilation, air leaks due to gaps in the insulation system, or other airflow mechanisms within a building, and depends on factors such as wind speed and direction, temperature gradients, the permeability of building materials, and the effectiveness and presence of air barriers.
- **Capillary Flow** – The movement of liquid water within porous materials due to intermolecular forces between the water and the pore walls. This depends on the capillary action of a material, which enables moisture to rise or spread within a material.
- **Gravity Flow** – Water can also flow downward due to gravity, a mechanism often used in cavity drainage systems. This depends on factors such as water pressure differentials, material permeability, structural vulnerabilities, and drainage efficiency.
- **Vapour sorption** – The process leading to moisture storage in the pores of a material. This depends on the hygroscopicity of a material and is linked to the concept of moisture buffering.

Think about it this way

Think of a pair of wet shoes after a rainy walk. If you leave them in a warm room, moisture evaporates and moves into the air— in case of still air, this evaporation is driven by vapour diffusion. If you put them near a fan, moving air speeds up the drying process, driven by convective transport. But if the shoes are soaked through, water may spread within the material before it evaporates, similar to capillary action. And if you step on them, water squeezes out under pressure—much like pressure-driven flow. Moisture doesn't just (dis) appear—it moves depending on the environment, just as it does in buildings.

This section covers the hygrothermal characteristics of building materials including insulation– how they handle and transfer heat and moisture – using key metrics to describe their behaviour.

As discussed earlier, moisture moves through materials in different ways, influenced by factors such as vapour diffusion and capillary action. The ability of a material to interact with moisture depends on its specific properties, such as vapour permeability, hygroscopicity, and moisture storage capacity. Understanding these characteristics is essential for evaluating how materials perform in traditional buildings and how they contribute to moisture management and overall building durability.

A.1 Vapour diffusion

As discussed above, the rate at which vapour diffuses through a material depends on the difference in vapour pressure, and the resistance a layer presents to that diffusion. The vapour resistance of a layer depends on the nature of the material, and on its thickness. For example, consider a particular rigid wood fibre board which is available in a variety of thicknesses. All the different boards have the same permeability (because that is a property of the material), but an 80mm board will have twice the resistance of a 40mm board because there is twice as much 'stuff' in the way of the water molecules. If we know the vapour permeability and the thickness of a layer, we can work out the vapour resistance.

Vapour permeability refers to how easily water vapour can pass through a material, and is quantified by the 'vapour diffusion resistance coefficient' (μ-value). This resistance is linked to the 'vapour diffusion equivalent air layer thickness' (s_d-value) [m] and is calculated by multiplying the vapour diffusion resistance coefficient (μ-value) times the thickness of the material (expressed in metres). A higher μ-value or s_d-value indicates greater vapour resistance, while a lower value allows more moisture movement[58]. The diffusion resistance factor (μ) expresses how much more resistant a material is to water vapour diffusion compared to still air. Still air is defined as the reference, with a μ-value of 1. By definition, the μ-value of any building material is greater than 1. Materials with a μ-value close to air (approximately 1 to 10) are generally considered towards the vapour-permeable or vapour-open end of the spectrum. Materials with higher μ-values (around 100) can be considered vapour-resistant (e.g., dense concrete, plastic foams), while very high μ-values (e.g., plastics, metals, glass) indicate vapour-closed or vapour-impermeable materials. Understanding μ-values helps in selecting materials to provide moisture balance within construction systems. However, it is important to recognise that materials vary across a spectrum, and that simple categories like 'vapour-open' or 'vapour-closed' are relative, not absolute. Furthermore, properties, such as vapour permeability and hygroscopicity, are distinct: a material can be vapour-permeable but not hygroscopic, as shown in Table 1.

58 https://www.builddesk.co.uk/wp-content/uploads/2013/01/vapourResistances.pdf

Think about it this way

Imagine wearing an impermeable rain jacket on a rainy day. While the jacket keeps the rain out, it doesn't allow your body's moisture (like sweat) to escape. After a while, you might feel hot and uncomfortable because the moisture gets trapped inside. In the same way, materials with low vapour permeability, like the fabric of that jacket, don't allow water vapour to pass through.

Drying of materials is closely linked to vapour transport but involves more than vapour diffusion alone[59]. It is a combination of evaporation at the surface of the material and diffusion of water vapour through the material and into the surrounding air. Drying can be enhanced by factors that promote evaporation, such as air movement (for example, from wind) or solar radiation. Therefore, drying rates depend both on the material properties and on external environmental conditions.

Think about it this way

Imagine drying a damp towel. If you hang it up so that air can reach both sides, it dries more quickly because moisture can escape in multiple directions. However, if you fold it or place it on a non-absorbent surface, the trapped moisture takes much longer to evaporate, and the towel may stay damp for an extended period.

Walls behave similarly. In their original state, moisture can usually move and dry out in more than one direction. However, when insulation is added, one side of the wall may become less permeable, and the drying pathways can be restricted. If drying remains possible through at least one side, moisture management can still be possible, though slower drying can cause issues. If insulation or finishes restrict drying from both sides, moisture can become trapped within the wall.

59 For more information on evaporation and drying, please see C. Hall, and W. D. Hoff (2021) Water Transport in Brick, Stone and Concrete (3rd ed.). CRC Press.

A.2 Moisture storage

Building materials can store moisture in both liquid and vapour form. In porous hygroscopic materials, water vapour accumulates on the surfaces of internal pores, while under higher humidity conditions, some pores begin to fill with liquid water through capillary condensation. This moisture storage behaviour depends on the pore structure of the material and ambient conditions, and can be expressed as a relationship between moisture content and either relative humidity (mainly focusing on the vapour phase) or capillary pressure.

Hygroscopicity refers to the ability of a material to absorb and release water vapour from the surrounding air, contributing to hygroscopic or moisture buffering. It is associated with vapour sorption and desorption, describing how materials take up and release moisture depending on ambient conditions. Rather than being a single parameter, hygroscopicity is described by a function that defines the relationship between a material's moisture content and the relative humidity of the air in its pores (at equilibrium). Every material has its own characteristic. When a dry, porous material is exposed to humid air, two main processes contribute to moisture uptake (Figure 11) until an equilibrium moisture content is reached, balancing the material's moisture content with the air's relative humidity. These two processes are molecular adsorption and capillary condensation:

1 **Molecular Adsorption** – At lower humidity levels, water vapour molecules are bound to pore surfaces, forming bound water. This process is influenced by the pore structure of the material and the surface polarity. Fine-pored materials, which have a larger total pore surface area, tend to adsorb more moisture than materials with larger pores.

2 **Capillary Condensation** – As humidity increases, the adsorbed water layers thicken, eventually leading to condensation within the smallest pores. When these thin water films connect, the smallest pores become completely filled with liquid water. The smaller the pore diameter, the greater the reduction in saturation vapour pressure, making fine-pored materials more effective at retaining moisture.

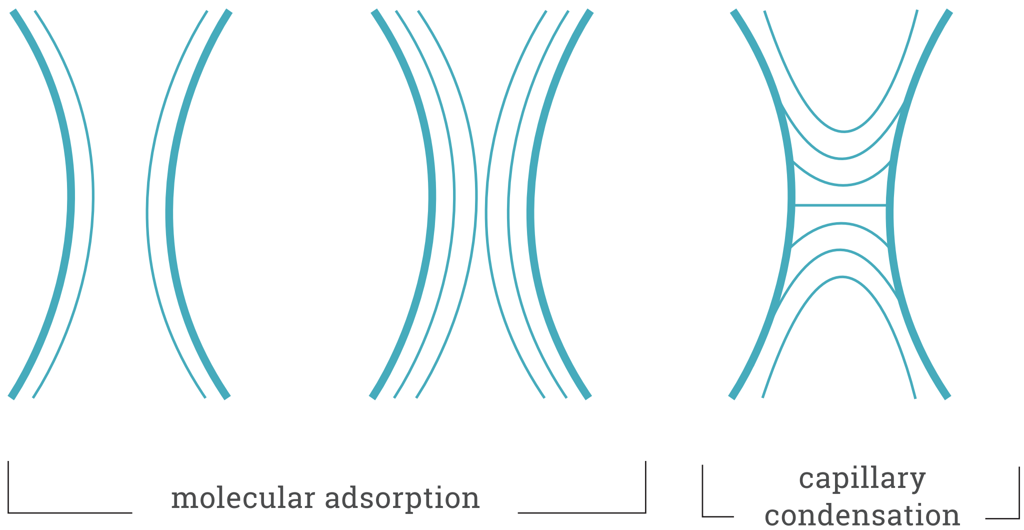

Figure 11: stages of hygroscopic buffering

Think about it this way

Ever dropped your phone in water and placed it in a bag of rice to dry it out? The rice absorbs moisture from the air inside the bag, pulling water away from the phone. This works because rice is hygroscopic—it attracts and holds water vapour from the air, just like some building materials do.

A.3 Liquid transport

Capillary flow (Figure 12) refers to the movement of liquid water through the pore structure of a material, driven by surface tension forces. When a porous material comes into contact with water, surface tension causes the liquid to be drawn into its pores. This process typically involves unsaturated flow, as pores are rarely fully saturated in real conditions[60].

Capillary flow is governed by capillary pressure, the pressure difference caused by surface tension acting across curved liquid surfaces within the pores. The magnitude of capillary pressure depends on the surface tension of the liquid, the contact angle with the pore walls, and the size of the pores — with smaller pores generating higher capillary pressures.

Capillary flow is complex and difficult to fully characterise with simple properties[61]. For example, in smaller pores, water uptake is initially fast due to high capillary forces, while in coarser pores uptake is slower. Over time, moisture may redistribute from finer to coarser pores, and dead-end pores can trap air, limiting full saturation.

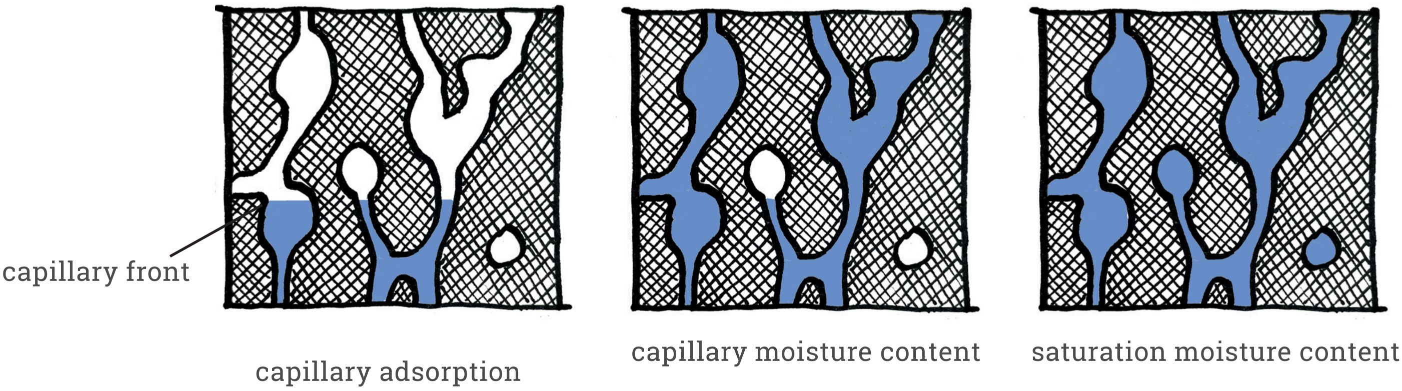

Figure 12: Graphical descriptions of capillary flow inside the pore network of a material, showing capillary absorption (left), the condition after moisture redistribution, with air trapped in pores (centre), and a fully saturated material, a rare phenomenon in buildings under real conditions (right). Image © Kaat Janssens

60 For more information on unsaturated flow, please see C. Hall, and W. D. Hoff (2021) *Water Transport in Brick, Stone and Concrete* (3rd ed.). CRC Press.

61 Also, at low humidity, vapour diffusion is usually the main mechanism and moisture behaviour can be simplified. However, at higher humidity, moisture storage within materials and liquid movement through pores both play a role, making moisture flow harder to characterise. Moreover, these processes can happen at the same time, further complicating how materials respond to changing conditions.

To provide practical information, the water absorption coefficient (A-value) [$kg/(m^2 \cdot s^{0.5})$] gives an empirical measure of the rate at which a dry material absorbs water over time. Although the A-value gives useful information about moisture uptake, it does not fully capture the material's ability to redistribute moisture, where capillary flow continues to play the main role. This ability to redistribute moisture is critical for maintaining material performance and supporting drying in traditional buildings. For the purposes of this guide, capillary action is considered more broadly as the material's ability to redistribute moisture, rather than being defined solely by the A-value.

Think about it this way

Imagine a sugar cube sitting in a puddle of coffee. Even though only the bottom touches the liquid, the coffee quickly rises through the sugar, reaching the top. This happens because the tiny pores in the sugar act like capillaries, pulling the liquid upwards against gravity. The same principle applies to porous building materials like bricks and plaster, where water can travel through small pores. This is known as capillary action.

A.4 Thermophysical properties

Porosity refers to the proportion of the volume of a material that consists of voids or air pockets, and is expressed as a percentage (%). It affects both moisture transport and thermal performance, influencing how well a material can store, absorb, and redistribute moisture. The total porosity of a material is determined by the volume of its pores relative to its overall volume. However, not all pores contribute equally to moisture movement: open pores are interconnected and allow water and air to pass through, while closed pores remain isolated and do not participate in transport processes.

In terms of thermal performance, porosity plays a crucial role in a material's ability to conduct or resist heat. Materials with high porosity tend to have lower thermal conductivity, because air or other gases trapped within the pores act as an insulator, as long as the gas remains still. Smaller pore sizes are particularly effective in minimising heat transfer, a principle exemplified by nanomaterials like aerogels. However, if moisture enters porous materials, this can increase thermal conductivity, as water conducts heat more effectively than air, leading to potential heat loss and reduced energy efficiency.

Since the diffusion of water vapour molecules primarily occurs through a material's pore network, the 'water vapour permeability coefficient' (δ) [s] is strongly influenced by porosity. In general, the higher the porosity, the greater the material's vapour permeability. This relationship establishes a theoretical upper limit: the vapour permeability of stationary air (where porosity = 100%) represents the maximum possible permeability for any material. As a result, highly porous materials tend to facilitate moisture transport through vapour diffusion, while denser materials with fewer interconnected pores exhibit lower vapour permeability.

Porosity also affects the capillary absorption (see Figure 4) and thermal conductivity of materials. Materials with a fine-pored, high-porosity structure can store more moisture and exhibit strong capillary action, drawing water through their network of tiny channels. Conversely, materials with larger, disconnected pores may have lower capillary uptake but higher vapour permeability, allowing moisture to evaporate more easily. Additionally, materials with a high proportion of air-filled voids tend to have lower thermal conductivity, improving their insulating properties. Understanding porosity is essential when evaluating building materials, as it directly influences their ability to manage moisture and regulate indoor climate conditions.

Lastly, **thermal conductivity** (λ-value) [W/mK] measures a material's ability to conduct heat through its structure. The lower the λ-value, the better the material acts as an insulator, slowing down heat flow and helping to maintain a stable internal temperature. Materials with low thermal conductivity are often used as insulation, as they reduce heat transfer, keeping spaces warmer in winter and cooler in summer. From a practical perspective, we are usually considering the material's thermal resistance, which depends on both its thermal conductivity and its thickness. Thermal resistance (R-value) increases with greater thickness and decreases with higher thermal conductivity.

The λ-value (thermal conductivity) of insulation materials is influenced not only by their intrinsic properties but also by their moisture content. When a material absorbs moisture, its thermal conductivity increases, as water has a much higher thermal conductivity than air. As a result, a material that performs well when dry may see a reduction in insulating performance when moisture levels rise. The degree of this change depends on the material. Laboratory testing has shown that all insulation products, including natural, mineral, and synthetic, are susceptible to thermal performance degradation over time when moisture is present. Mineral and glass wools can suffer binder breakdown under prolonged exposure to moisture, affecting both structure and performance. Foamed plastic products, such as polystyrene and polyurethane, are also vulnerable: they can degrade due to the loss of their original blowing agents as well as moisture accumulation. Even high-performance materials, such as aerogel-based insulations, although inherently low in thermal conductivity when dry, have been shown to experience an increase in thermal conductivity when exposed to moisture[62].

This interaction between moisture and thermal conductivity is crucial for understanding how materials perform in real-world environments, where changes in humidity and moisture content can impact both thermal and moisture-related performance. When selecting materials for building applications, it is essential to consider not only their thermal properties in dry conditions but also their behaviour in response to moisture, ensuring they continue to provide effective insulation and moisture management over time.

62 M. Fletcher et al. (2024) Deterioration of retrofit insulation performance (DRIP): Phase 1. Department for Energy Security and Net Zero.

APPENDIX B

Glossary

Traditional construction: Construction methods and materials typical of buildings built before 1919, often including solid wall construction.

Building envelope/building fabric: The physical parts of a building that separate the interior from the exterior environment, including walls, floors, roofs, windows, and doors. It regulates heat, air, and moisture flow and contributes to the thermal and environmental performance of the building.

Bulk vapour transport: Bulk vapour transport describes the movement of vapour with air flow, for example through leaks or openings, as vapour moves along with air across pressure gradients. It is associated with convective air flow and is also called vapour advection.

Capillary flow: Capillary flow is the movement of liquid water through open and interconnected pores in materials, driven by the attraction between the liquid molecules and the surface of the material (capillary action).

Equivalent air layer thickness (sd): The sd-value represents the vapour diffusion resistance of a layer, expressed in relation to the vapour diffusion resistance of still air. It is a common quantity to describe the vapour diffusion resistance of AVCLs and membranes. Units: m.

Vapour diffusion resistance coefficient (μ): The ratio of the resistance of a material to water vapour diffusion compared to that of still air at the same temperature and pressure. A higher μ-value indicates greater resistance to vapour diffusion. This property is material-specific and independent of thickness. Units: dimensionless (no units).

Vapour permeability (δ): A measure of the ease with which water vapour diffuses through a material. Units: g·m/(MN·s).

Vapour resistivity (1/δ): The inverse of vapour permeability, describing the resistance of a unit thickness of material to water vapour diffusion at unit vapour pressure difference. Higher vapour resistivity indicates greater resistance to vapour diffusion. Units: MN·s/(g·m).

Vapour barriers: Materials with very high vapour diffusion resistance. Vapour barriers are designed to prevent almost all vapour movement.

Vapour retarders: Materials with moderate resistance to water vapour diffusion. They are designed to allow some vapour diffusion through.

Air and Vapour Control Layer (AVCL): 'A continuous layer of low [air] permeability material used to control the movement of air and water vapour through building fabric', as defined in BS 6229:2018. AVCLs may take the form of membranes, wet plaster, or other integrated components. The AVCL serves a dual purpose acting as an airtightness layer and providing vapour control. Their vapour resistance varies widely, from less than 2m, providing limited vapour control, to over 1500m, acting as vapour barriers.

Vapour closed: Describes materials or systems that resist the passage of water vapour.

Vapour open: Describes materials or systems that allow water vapour to pass through relatively easily.

Drying season: Time period, typically during warmer months, when environmental conditions favour evaporation and drying of building materials and overall reduction of moisture content in the fabric.

Wetting season: Time period, typically during colder months, when environmental conditions favour moisture ingress into the building fabric and increase of overall moisture content.