Historic England

Assessing Damp in Historic Buildings

A Practical Guide to Investigation and Diagnosis

Summary

Excessive moisture – damp – is harmful to buildings. It damages their fabric, reduces energy efficiency and adversely affects the health and comfort of occupants. A variety of techniques and devices for assessing and monitoring moisture have been developed and are available to practitioners and building professionals. But what do these techniques and devices actually tell us? Are they accurate? And how should we interpret the data they provide?

This guidance answers these questions, discussing the use and limitations of various methods of assessing and monitoring moisture. It also provides practical advice on investigating and diagnosing damp in historic buildings. Although this guidance is intended primarily for conservation practitioners, building professionals and contractors, it will also be of interest to property managers, householders and other building users who wish to understand more about damp and its assessment.

The guidance is arranged in three parts. Chapter 1 deals with building physics: the processes that drive the movement of moisture between building fabric and its surroundings. It also considers how moisture behaves in permeable materials and how it affects those materials. Chapter 2 discusses approaches to investigation and assessment and looks at the potential sources and characteristic symptoms of damp in buildings. Chapter 3 reviews the use and limitations of moisture detection, measurement, and monitoring techniques and devices. Case studies provide some practical examples of damp investigations. Finally, guidance is given on further sources of advice and information.

Terms in bold text are defined in the glossary.

Front cover:
Damp stone parapet with visible mould and vegetation growth, concentrated around an outlet that may be blocked, leaking, or failing to discharge water effectively.

This document has been prepared by Dr Brian Ridout and Iain McCaig.
This edition published by Historic England June 2026.

Please refer to this document as:
Historic England 2026 *Assessing Damp in Historic Buildings: A Practical Guide to Investigation and Diagnosis*; Swindon; Historic England.
HistoricEngland.org.uk/advice/technical-advice/buildings/damp-in-historic-buildings

Contents

1 Moisture in buildings

Moisture is present in all buildings. It is in the materials they are made from and in the environment that surrounds them. This moisture, however, does not necessarily make a building damp. Nor is it always damaging. Moisture in buildings is only a problem when there is too much of it.

Excess moisture accumulates in building fabric for many reasons. Occupants' activities, building defects, faulty engineering services, and leaking utilities and drains are all common causes of damp. Groundwater and emergencies, such as flood and fire, may also play a role. Whatever the cause, too much moisture is harmful. Excess moisture reduces the thermal performance of the building envelope and may lead to poor indoor air quality, thus harming the health and comfort of building occupants. It is also the primary cause of deterioration and damage affecting construction materials, finishes, fittings and engineering services.

The ability to accurately assess and monitor moisture conditions in a building is key when diagnosing problems, appraising risks and devising solutions. It is also essential for evaluating the effectiveness of remedial measures.

The behaviour of moisture in buildings is complex and dynamic. There is a continual interchange of moisture between the building fabric and the environment, which is strongly influenced by air movement and heat. Other physical forces drive the movement of water within porous materials, both as a liquid and as a gas (vapour). These processes are described in the following section.

How do porous building materials interact with moisture in the air?

Water molecules exist in a dynamic gaseous phase in the atmosphere. They are energised by heat, and their motion produces a **partial vapour pressure**. (It is 'partial' because water vapour is only one of the gases contributing to atmospheric pressure.) As the temperature rises, there is a corresponding increase in **vapour pressure**.

A dynamic two-way exchange of water molecules occurs between a source of moisture and the air. There is a temperature-dependent point at which the rate of molecules leaving the moisture source (by **evaporation**) is balanced by molecules returning to it (by **condensation**). This is described as the

equilibrium vapour pressure (or saturation vapour pressure). If the actual vapour pressure in a space is divided by the equilibrium vapour pressure at that temperature, and multiplied by 100, the result is described as the **relative humidity**, expressed as a percentage (%). There is an inversely proportional relationship between relative humidity and temperature – relative humidity increases as temperature decreases. When relative humidity reaches 100%, condensation starts to exceed evaporation and droplets of liquid water form. This is known as the **dew point**.

All porous building materials are **hygroscopic** to some degree due to their composition or the **salts** they contain. This means they gradually gain or lose moisture depending on the relative humidity of the surrounding air. When the vapour pressure of water held within a material equals the vapour pressure of the surrounding air, the **moisture content** of the material is said to be its **equilibrium moisture content**.

When is a building damp?

No building is completely dry. All are built from a variety of hygroscopic materials that draw moisture from the surrounding air. However, this does not mean they are damp. If the environment within a building is acceptably dry, it is reasonable to conclude that the materials that enclose it will also be dry. Relative humidity between 40 and 65% at around 20°C is generally considered to be healthy and comfortable for most occupants. In these conditions, the equilibrium moisture content of timber would range from 8 to 12%. In porous masonry, it might be less than 1%, depending on density and pore structure. At these levels, moisture is not harmful. Although equilibrium moisture contents vary between different materials, relating them to an 'air dry' environment gives a helpful baseline for comparison.

A building might be considered 'damp' when the moisture content of its materials rises to levels that would harm either the environment they enclose (causing poor indoor air quality or mould growth, for example) or the materials themselves (causing deterioration, decay or corrosion, for example). For moisture content to rise from 'air dry' to 'damp', a source (or sources) of liquid water would normally be responsible. This is discussed in Chapter 2.

Moisture in timber

The moisture content of timber exposed to external air changes with the seasons. It tends to increase during the winter, when temperatures drop and relative humidity rises, and decrease during the summer, when relative humidity is normally lower. In fact, it is not uncommon for the surface moisture content of timber in a cold roof to exceed 20% in winter when the relative humidity of the attic may approach 90%.

The moisture content of timber is of practical significance because it can be related directly to risks from wood-boring insect infestations and fungal decay. Furniture beetles and deathwatch beetles will not thrive if the moisture content of timber remains below about 15%. Such conditions might, therefore, be considered 'acceptably dry'. Decay fungi will not develop and thrive until the timber moisture content approaches the **fibre saturation point** (nominally 26 - 30%). However, some fungi have been shown to grow feebly in laboratory conditions at moisture contents as low as 22%. This has led to the widely accepted conclusion that decay is inevitable if wood moisture contents exceed 20%. As a result, some moisture meters display red warning lights and produce audible alarm signals when this level is reached.

In general, elevated equilibrium moisture contents of timber caused by high relative humidity of the surrounding air are not a reason for concern. However, timber may be susceptible to deterioration and damage if moisture contents ranging from about 17 to 28% are sustained at depth by continual water ingress from leaks or other sources.

Moisture in masonry

Researchers differ on how much moisture porous masonry should contain in order to be considered 'dry' or 'damp'. Masari and Masari (1993) concluded that a moisture content of 3% in the brick and 6% in the stone they investigated would be 'dry'. However, Burkinshaw and Parrett (2003) concluded that a 'dry' brick would have a moisture content of between 0.5 and 1.5%. Therefore, a brick with a moisture content of 3% would be classified as 'damp'. Hola (2017) reviewed published data and proposed a categorisation scheme (Scheme 1). The authors suggest alternative categories based on several decades of practical monitoring (Scheme 2). The two schemes are compared in Table 1. The differences are largely in the terminology.

Table 1:
Masonry (brick) moisture contents (mc).

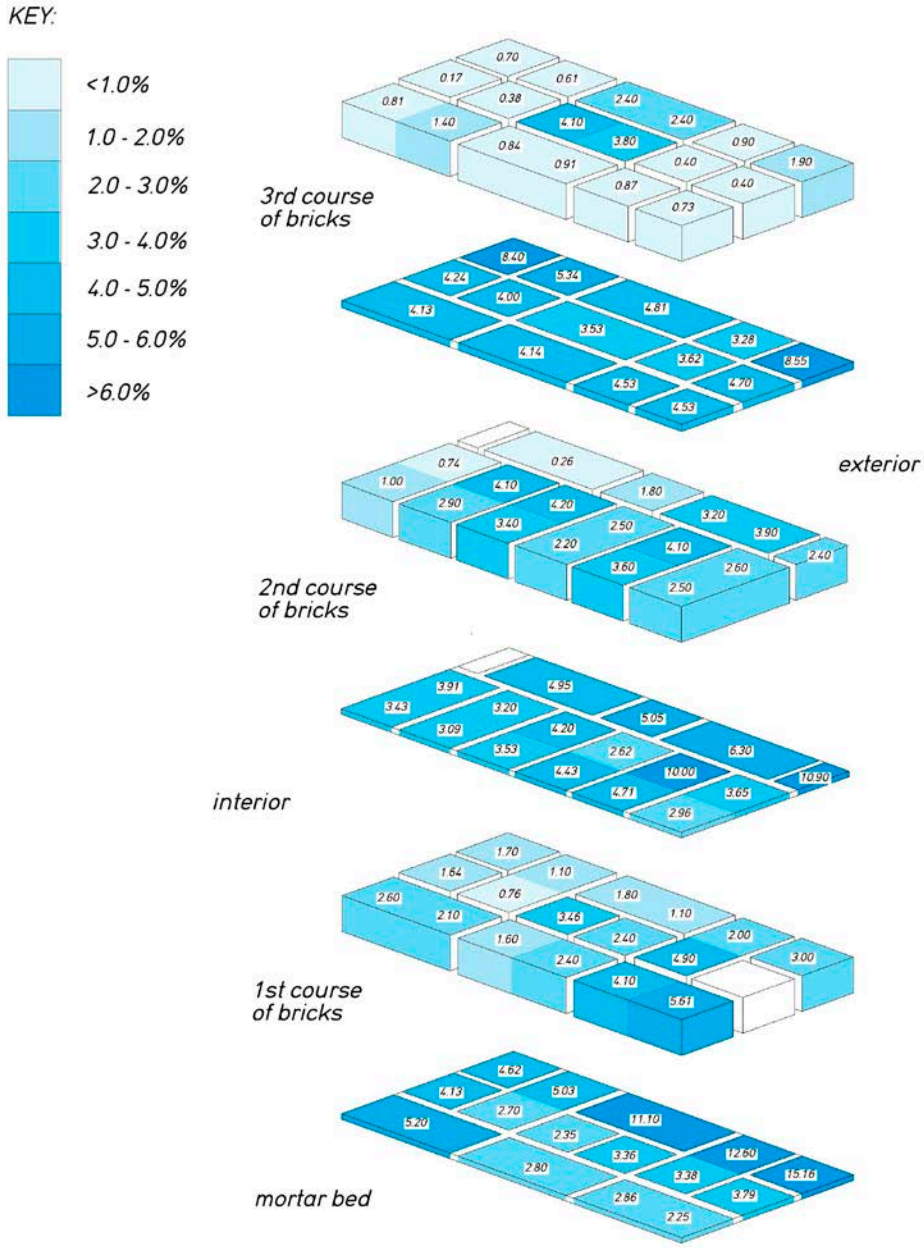
Scheme 1 Hola (2017)	Moisture range (%mc dry weight)	Scheme 2	Moisture range (%mc dry weight)
Permissible	0–3	Dry	0–3
Elevated moisture content	3–5	Damp	3.1–6
Medium damp	5–8	Wet	6.1–10
Very damp	8–12	Saturated	>10
Wet	>12		

Moisture variability in walls

The moisture content of a wall can vary considerably because of differences in the **permeability** of the materials used in its construction. An investigation of moisture distribution in a section of brick walling from a Victorian house showed that the moisture contents of its mortar and bricks were largely random and independent of one another (Figure 1). Both a 'dry' brick with a moisture content less than 1% and a 'damp' one with a moisture content between 4 and 5% could be adjacent to mortar with a moisture content between 2 and 4%.

Figure 1:
Moisture content of bricks and mortar from a carefully dismantled portion of walling taken from the ground floor of a Victorian house. The moisture content of each half brick and the section of the mortar bed directly below was determined gravimetrically.

A detailed account of this investigation can be obtained here.



Most of the higher readings were obtained from the external face of the wall. They revealed differences in moisture uptake between bricks and mortar but little relationship between them. Even a large uptake of moisture by a mortar joint had little effect on the moisture content of an adjacent brick.

This small study demonstrates the difficulty of describing a wall as either ‘dry’ or ‘damp’. It also shows that a limited number of samples or meter readings (which might be all that is possible during a single site visit) could lead to erroneous conclusions if taken in isolation, without considering the wall’s construction and surroundings.

Moisture movement in porous materials

The speed and direction of moisture movement in porous materials are influenced by many factors. These include the shape and size of the pores of the material, as well as their connections with one another and with the surfaces where moisture ingress and egress may occur. When combined with ambient environmental conditions, these properties influence the wetting and drying behaviour of materials and their susceptibility to deterioration and decay.

The form in which moisture is present also has an effect. Although the vapour permeability of materials receives a lot of attention in building conservation and product literature, the movement of water as a liquid is of greater significance. The diffusion of water vapour through porous and permeable materials due to vapour pressure gradients is relatively slow. In comparison, liquid water moves quickly through the pores of a material towards an evaporative surface. Capillary forces also drive the movement of liquid water and can be strong enough to raise it against gravity. However, gravity influences the movement of water in larger pores and voids, causing it to move downwards.

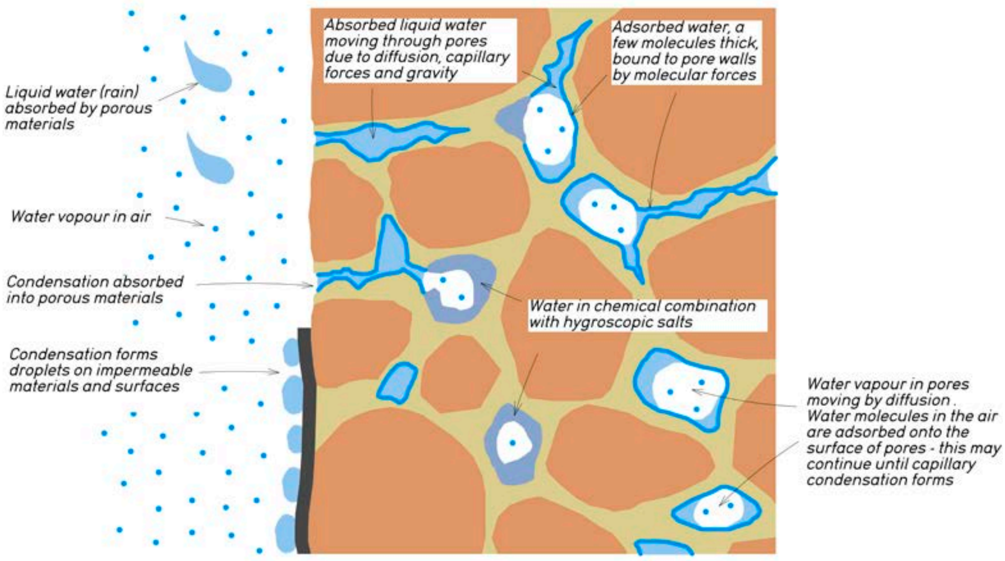


Figure 2:
How water may be present in porous masonry.

Where does the moisture come from?

Liquid water absorbed by porous materials comes from a variety of sources. The most common is blocked or faulty rainwater goods. Other potential sources include wind-driven rain, ineffective surface water drainage, leaking water supply pipes (above or below ground), blocked or defective drains, and groundwater. Liquid water can also come from the condensation of water vapour when the temperature of a material falls below the dew point. Moisture sources and the phenomena associated with them are discussed in more detail in Chapter 2.

What are the effects of damp in buildings?

Excess moisture in buildings can be harmful in many ways. Since much information has already been published on this topic (see Further reading and sources of information), only the primary effects are summarised here.

Certain moulds may colonise damp surfaces. It is difficult to be precise about the relative humidity at which mould growth might occur because it depends on several parameters. These include the type of material, temperature and species of mould. In general, mould growth is unlikely if the relative humidity remains below 65% and likely if it persists above 75%. Moulds can cause staining and discoloration and may, eventually, become a health hazard if allergens and toxic substances are produced.

Different materials respond to moisture differently. Liquid water can cause superficial deterioration in porous masonry, where it is the catalyst for salt crystallisation and freeze/thaw damage. Walls made of earthen materials can be weakened and may even collapse if subjected to excess moisture. Metalwork is susceptible to corrosion when exposed to high levels of relative humidity. Persistently high moisture contents in timber can result in decay and damage caused by wood-destroying fungi and wood-boring insects. In addition, fluctuations in humidity can cause cracking, splitting and the detachment of finishes.

Because water is a good conductor of heat, it reduces the thermal resistance of porous materials, thereby diminishing the energy efficiency of buildings. Damp walls are also less thermally efficient because of the cooling effect of moisture evaporating from them.

Figure 3:
Deterioration and damage caused by excess moisture:
a. Mould growth on internal surfaces.
b. Freeze/thaw damage to brickwork saturated by blocked rainwater pipe.
c. Collapse of earthen walling caused by water trapped by impermeable surface finishes.
d. Warping and buckling of floor boards saturated by flooding.
e. Timber decay and infestation.
f. Spalling of masonry caused by corrosion of embedded iron cramps.
g. Salt crystallisation damage to brickwork.
h. Colonisation of surface by algae, moss and plants.
i. Damp patches – internal finishes disfigured and damaged.

2 Assessing and monitoring damp

Investigating damp in a historic building can be difficult. Repairs, extensions and changes of use may have modified its construction and performance. Furthermore, important evidence may be concealed behind finishes that the surveyor is not allowed to disturb.

Electronic moisture meters are often used to assist in surveys. However, it is frequently unclear what the readings obtained actually mean, especially when they come from walls where materials and methods of construction are unknown or concealed by finishes. A few high meter readings will not necessarily reveal the cause, magnitude and extent of a damp problem. Nor will they justify costly and invasive remedial measures.

Careful and methodical observation combined with a comprehensive approach that takes account of the environment, construction and history of the building remains the best survey aid. This chapter provides some background information and ideas to support this approach.

Why assess and monitor moisture in buildings?

In practical terms, the main reasons for assessing and monitoring moisture in buildings are to:

- diagnose causes of damp
- identify sources of moisture ingress
- assess the level of threat to vulnerable fabric from moisture
- assess the health risks to building occupants
- assess the impact of damp on energy performance
- appraise the effectiveness of measures to remedy damp
- manage the drying of buildings after flood or fire.

How to approach assessment

Investigations and assessments should always aim to answer clear and specific questions. They should be proportionate to the nature and complexity of the building's problems and its heritage significance. Assessment is an iterative process and investigations may need to be scaled up or down depending on the results obtained at each stage and the resources available. The aim should always be to strike an optimal balance between precision, timescale and cost.

In some cases, a single site visit may be sufficient to assess the situation and identify the extent and causes of damp. In others, a more detailed assessment over a longer time period may be needed if the sources of moisture are unclear. Sometimes, complementary investigations, such as drainage or hydrology surveys, may be required to aid accurate diagnosis. Periodic inspections and measurements have to be made over many months when monitoring drying after remedial measures, flooding or fire.

When assessing damp in historic buildings and monuments, it is important to keep in mind that invasive (destructive) moisture measurement techniques may not be permitted. Investigations may, therefore, be limited to non-destructive methods. The use and limitations of such methods, including a range of commonly used techniques and devices, are discussed in Chapter 3.

Investigation of moisture and its effects on traditional buildings: Principles and competencies. Joint position statement, 1st edition, September 2022

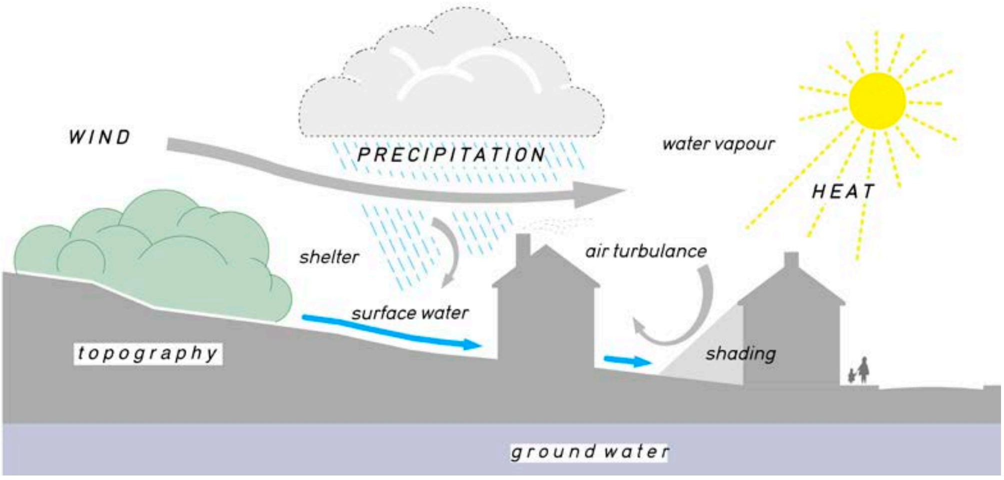
This document sets out the principles to be followed and the competencies required when assessing moisture in buildings of traditional construction. The document has been produced jointly by the Royal Institute of Chartered Surveyors, Historic England and the Property Care Association. It is also supported by Historic Environment Scotland, Cadw, Historic Environment Division Northern Ireland, the Society for the Protection of Ancient Buildings (SPAB) and the Institute for Historic Buildings Conservation (IHBC) (SPAB). The joint position statement can be downloaded here.

Carrying out assessments and monitoring

Understanding the building in context

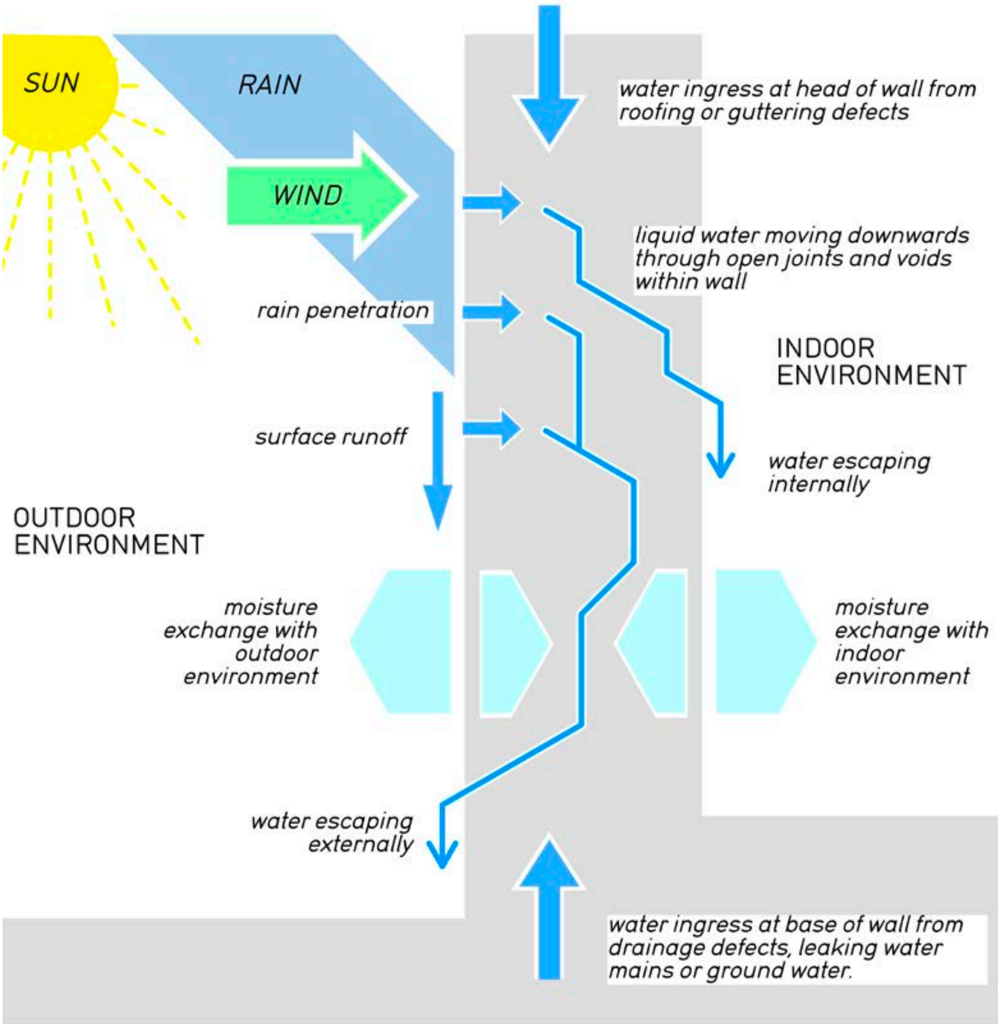
Every historic building is unique, and diagnosis can be complicated, especially when there is more than one source of moisture. Location, orientation, design, construction, engineering services, maintenance history and the way the building has been used and managed should all be considered. Historical information can be invaluable, particularly if it sheds light on past alterations or interventions.

Figure 4:
Many aspects of a building's location and setting have a bearing on its vulnerability to damp.



In general, buildings were designed and built to avoid damp. Therefore, when undertaking an assessment, it is important to think about how the building was intended to cope with moisture, and what might have changed. In addition, the consequences of any proposed alterations should be considered. These might include adding insulation, changing the way the building is used or modifying the heating and ventilation. For example, damp might not be a problem in a cellar until the owner wants to use it for storing moisture-sensitive materials or as a living space. Increased ventilation and intermittent heating could destabilise a previously benign environment and lead to the rapid deterioration of masonry surfaces.

Figure 5:
Typical moisture pathways in masonry walls of traditional construction.



In some cases, the symptoms may appear a long way from the place where moisture enters the building. This can be misleading and result in an incorrect diagnosis. Therefore, symptoms should always be viewed in their wider context.

Deterioration and the presence of moisture should be considered together, because one might be the key to understanding the other. For example, an active dry rot outbreak indicates a significant and sustained source of water, whereas dead dry rot shows that the water source has been eliminated. Similarly, an active furniture beetle infestation will be evidence of an environment that is locally or comprehensively damp.

Practical limitations

Surveys should usually start at the roof and work downwards. The best approach is to 'follow the water'. Symptoms of water percolating downwards from a blocked or defective parapet gutter may be more apparent in the roof space than in the accommodation below, where they might be hidden behind panelling or window shutters. However, if a building is in poor condition, this approach can be hazardous. Before climbing to the attic, the condition of the ceilings on each floor should be assessed. They are often the first elements to show moisture damage in the form of fungal decay, which may, in turn, have made the floors unsound. This is particularly important when the floors are carpeted and their condition is not obvious.

A building that appears to be in reasonable condition can present a greater challenge because the consequences of damp may not be evident. It then becomes necessary to look for less obvious signs of damp, such as mould growing on walls behind pictures or furniture. Monitoring air temperature and relative humidity can be helpful in understanding the environment, but a whole year's monitoring might be needed to fully achieve this. Unfortunately, this is of no help to the surveyor who has to complete an inspection in a few hours.

It is important to remember that a less than perfect survey method can still produce useful results and be valid provided that it is fully documented and the limitations are highlighted. Leaving data loggers against a wall and in the centre of a room for half an hour to compare air moisture contents in each location will give only a snapshot of conditions on that particular day. It will not tell you what would happen at a different time of year or in different weather conditions. Nevertheless, a snapshot may provide enough information to indicate a problem.

Is the building damp?

When symptoms of moisture-related deterioration or decay are observed in a building, the first two questions to address are:

- Is the problem active and ongoing?
- Is the damage historical – that is, the result of past moisture ingress from defects that have long since been remedied?

Moisture content of air

The moisture content of air within a building is influenced by the moisture content of building fabric (and vice versa. Environmental data can therefore help in identifying active sources of moisture. Many instruments that measure air temperature and relative humidity - thermohygrometers - are available. They can be used to assess the moisture content of air in a room and the contribution of moisture coming from the walls and floor.

Readings taken from the centre of a room are used as a basic control. These can be compared with readings taken against walls (and in corners to locate surfaces that are contributing moisture to the air in the room. The thermohygrometer should be left undisturbed in each location until readings have stabilised. This means avoiding air movement as far as is practical. If there are time constraints, a fixed time (for example, 10 minutes should be allowed in each monitoring position. The normally inverse relationship between temperature and relative humidity means that a higher humidity against the wall might simply be caused by a lower temperature. Therefore, the paired readings should be converted to air moisture contents (**absolute humidity** in g/m^3. Free online calculators are available to do this.

Where possible, temperature/relative humidity data loggers should be used because they give a more representative picture of environmental conditions over time than the snapshot provided by point measurements. If practicable, they should be left in place overnight, when windows and doors can be closed to reduce environmental disturbance. This also allows time for moisture in the air to equilibrate with moisture in the building fabric. Even if the monitoring time is insufficient for conditions to equilibrate fully, the rate at which humidity readings increase can be informative. If the initial rise in absolute humidity is rapid, it is likely that the moisture content of the fabric is high.

Another method for assessing damp migration through walls and solid floors is to determine the humidity of air trapped beneath a sheet of polythene. Ideally, the polythene sheet should be about $1m^2$ and sealed around the edges with tape (Figure 6). However, this will not always be practical, and the surveyor may have to improvise. On floors where it is not possible to use tape, the edges of the polythene sheet can be weighted down with sand or a wooden frame (Figure 7). Alternatively, a shallow polythene box might be used. This would also have to be weighted down and sealed around the edges with adhesive foam tape to reduce vapour loss. On walls, if adhesive tape is not suitable because of delicate surfaces or finishes, then polythene on a wooden frame or a polythene box can be supported by careful propping. The moisture content of the small volume of trapped air will equilibrate with the building fabric quite rapidly and can be calculated using data from a thermohygrometer or logger. Loggers placed elsewhere in the room are used to provide data for comparison.

Figure 6:
The surveyor was asked if moisture was rising through a basement floor slab. Moisture meters produced erratic readings, so squares of polythene were taped down in a grid pattern and left overnight. In the morning, a small slit was cut in the centre of each, and the probe of a thermohygrometer was inserted. Readings from each square (converted into absolute air moisture content) were compared with readings obtained from the room.

Figure 7:
In this case, because space was limited and adhesive tape was not practical, a wooden frame was used to produce an enclosed environment. The assemblage was left for several days, after which logger readings within and outside the enclosure were compared.

Although the ‘trapped air’ method provides an **equilibrium relative humidity** for sections of a wall or floor, it will not give precise results overall. In most cases, though, precision is not necessary. If the wall or floor is not contributing moisture, then the moisture contents of the trapped air and the air in the room will be similar. Relative humidity close to the wall and floor may be higher because surface temperatures may be lower. Therefore, the paired readings should be converted to absolute humidity (g/m³), as mentioned previously.

Moisture content of timber

Timber equilibrates with relative humidity. Temperature has only a very small effect over the normal range of moisture content found in building timbers. The relationship between relative humidity and wood moisture content is shown in Figure 8.

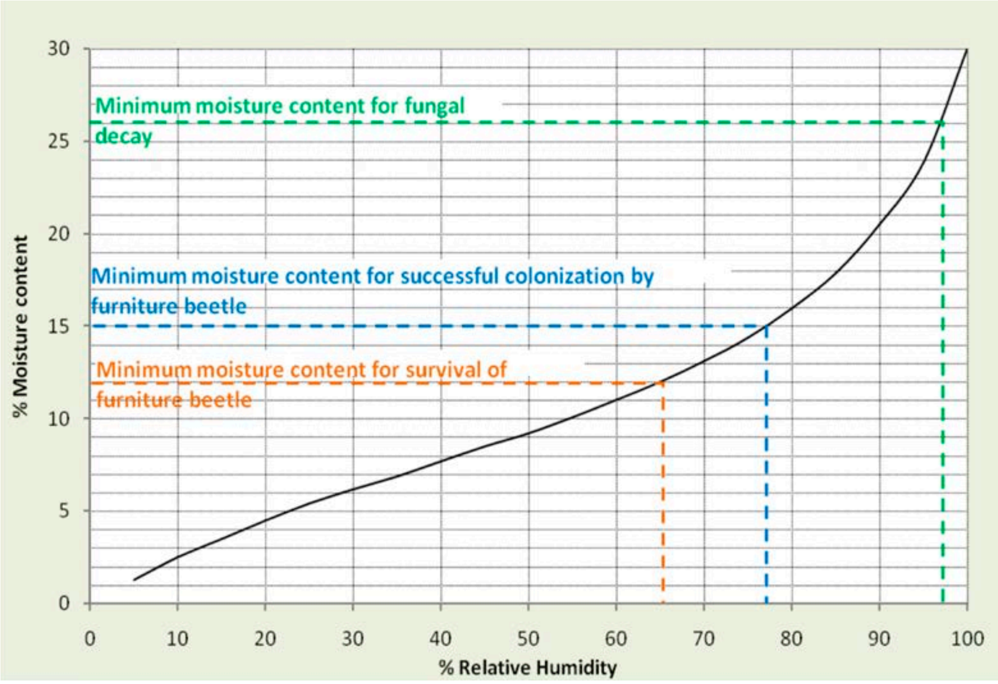


Figure 8:
The relationship between wood moisture content and relative humidity at equilibrium.

Relative humidity can be very high in roofs in winter, when temperatures drop. It can also be high under suspended ground floors in summer, when the building structure heats up and draws moisture from the ground and construction materials.

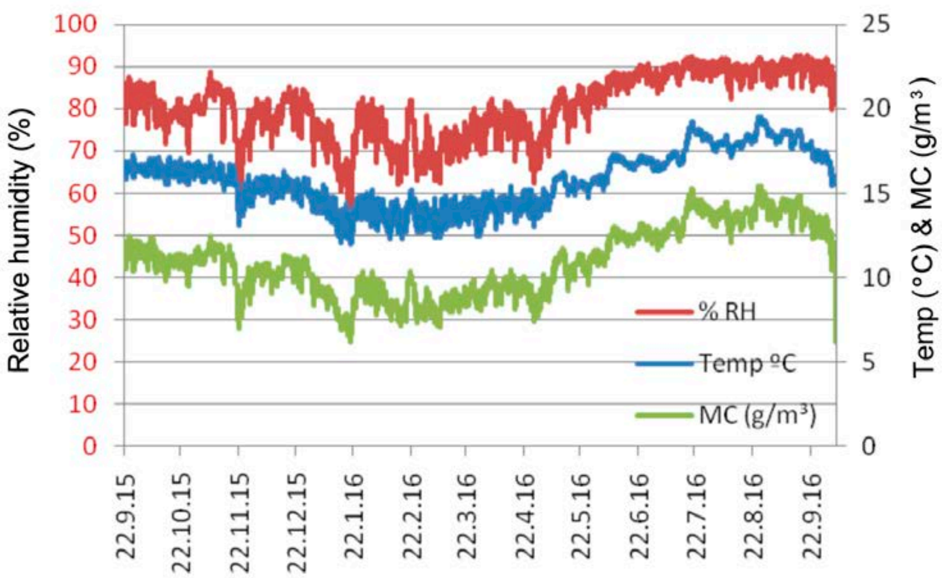


Figure 9:
A year's monitoring of temperature and relative humidity in the dry subfloor void of a house in Hampshire. The temperature rises during the summer months (blue trace) because of thermal gain by the entire building. This draws more moisture from the ground (green trace), thus increasing the relative humidity to more than 90% (red trace).

If the relative humidities shown in Figure 9 are translated into wood moisture contents (using Figure 8), then the results illustrate an interesting problem. A surveyor inspecting the floor in January, when the relative humidity was about 70%, would obtain moisture meter readings of around 15% and conclude that the floor structure was dry. However, if the floor was inspected in July, when the relative humidity was 90%, then the moisture content reading would be about 20%, and the floor structure would be deemed to be wet and at risk from decay. In fact, there is no increase in the amount of water. The subfloor environment is simply cycling moisture between the ground, air and timber, as it has since the building was constructed. A direct (as opposed to inverse) relationship between temperature and relative humidity exists because of a consistent reservoir of moisture in a confined space. (Note: The floor void was monitored with sensitive air movement sensors, and there were no indications that subfloor ventilation occurred in this or any of the other eight buildings studied. See the report here.

The same sort of results might be anticipated in a roof space. However, the substantially greater volume of a roof void means that the normal inverse relationship between temperature and relative humidity does, in fact, exist. A 90% relative humidity reading and a correspondingly high timber moisture content would be obtained in winter when the air temperature was low. In summer, the <70% relative humidity, and correspondingly lower timber moisture content readings, might be obtained when the roof space air temperature was high.

To conclude:

- If moisture meter readings indicate that timber is dry then it probably is.

- If meter readings indicate damp, this might only be a transitory surface effect caused by seasonal fluctuations in ambient relative humidity.(Elevated surface readings may also be the result of timber treatments or chemical contamination. Sub-surface readings should be taken using insulated probes).

Figure 10 demonstrates the latter, with timber moisture monitoring data gathered over 12 months from mid-20th-century pine roof timbers at Lincoln Cathedral. These data were obtained by the electrical resistance method (see Chapter 3), using paired screws as electrodes for surface readings and insulated nails with exposed tips for 100 mm-deep readings. Surface readings fluctuate from 16% in summer to 20% in winter, while readings at depth remain between 11 and 13% – a range that is safely dry.

Old timbers may be more problematic because the electrical properties of surfaces can change as timber ages, thus affecting moisture meter readings. Figure 11 shows moisture readings from a similar timber in the same roof as Figure 10. The difference is that this is an old repair timber, probably dating from the 19th century. In this case, the surface and depth readings are similar and acceptably dry in summer. However, surface readings become very erratic and confusing in winter, when the roof is cold and relative humidity is high.

Figure 10:
Surface and depth (100 mm) moisture contents based on electrical resistance in 1960s Scots pine in the Consistory Court roof at Lincoln Cathedral.

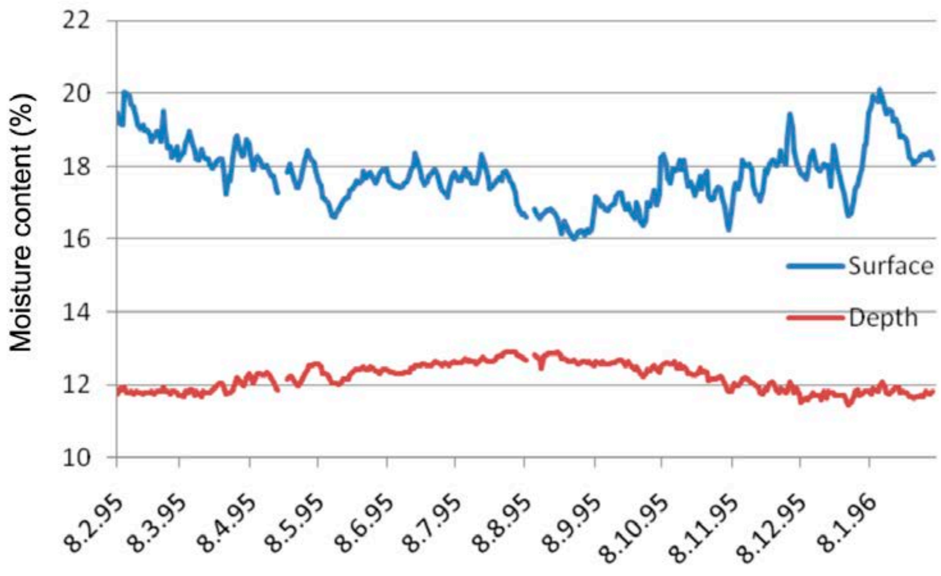
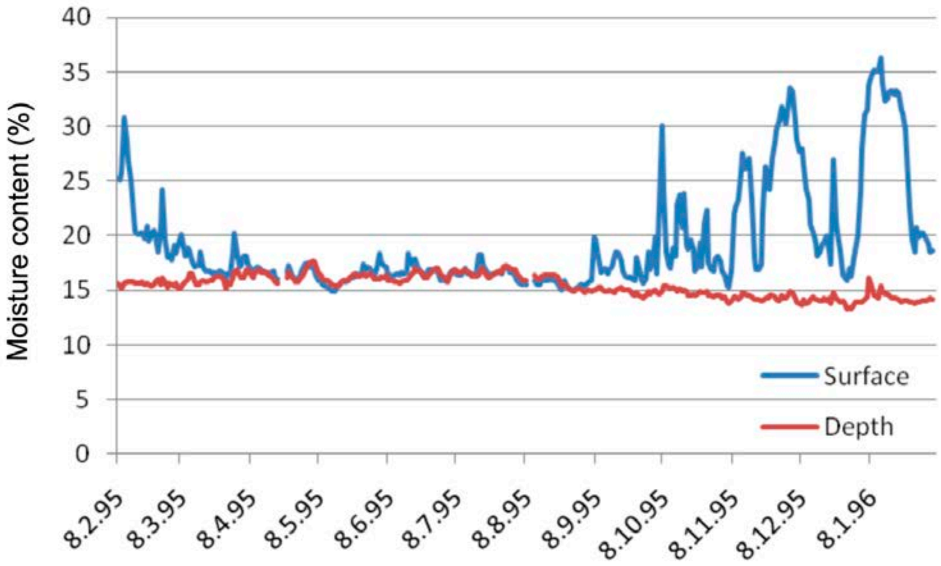
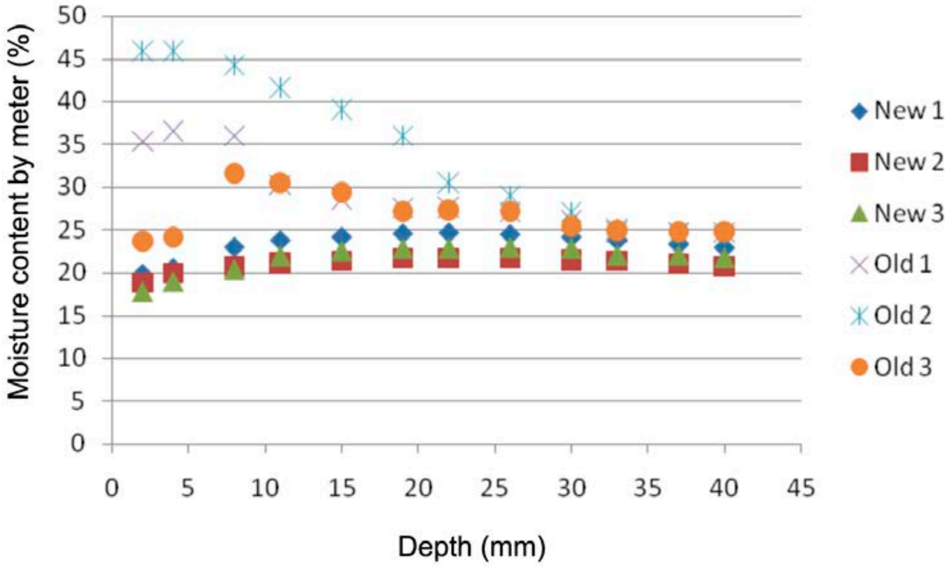


Figure 11:
Surface and depth (100 mm) moisture contents based on electrical resistance in 19th-century Scots pine in the Consistory Court roof at Lincoln Cathedral.



Seasonal moisture fluctuations in sound dry timber extend to a depth of only a few millimetres. However, this may vary with both age and moisture content in a damp roof. Figure 12 shows data obtained from a February survey of a softwood roof in Lincolnshire. The old timbers date from the 19th century; the new from the late 20th century. The new timbers achieved a stable moisture content at a depth of about 15mm. The moisture content of the old timbers was far more erratic. This problem is discussed further in Chapter 3.

Figure 12: Equilibrium moisture contents at different depths in a softwood roof in Lincolnshire as measured in February 2019. Readings were obtained from three new and three old timbers using a resistance type moisture meter with a hammer electrode (see Figure 36).



Moisture content of masonry

If signs of surface deterioration and damp are observed in a wall, it is common to assume there must be a current source of moisture. However, this is not always the case. The moisture problem may, in fact, have been resolved, leaving staining and other evidence behind. Where there is damp damage to a wall with no obvious source of moisture, two possibilities should be considered:

- The damage is old and the wall is dry. This conclusion may sometimes be supported when papers or books near the damage are in good condition (Figure 13). It is advisable to enquire into the history of the problem.
- Hygroscopic salts may have been brought to the surface by a previous moisture source. These salts absorb moisture from the air and may appear as damp patches when the atmosphere becomes humid.

Handheld meters are often used to assess moisture in walls, but surface readings can be confusing because of variables such as localised salt migration, variations in material density and uneven surfaces (see Chapter 3). Readings ranging from apparently dry to saturated can sometimes be obtained within a small area of wall.

If time is not a constraint, moisture levels in a wall can be assessed more reliably by using a data logger to record the temperature and relative humidity of air trapped behind a polythene sheet, as described previously (see Figures 6 and 7).

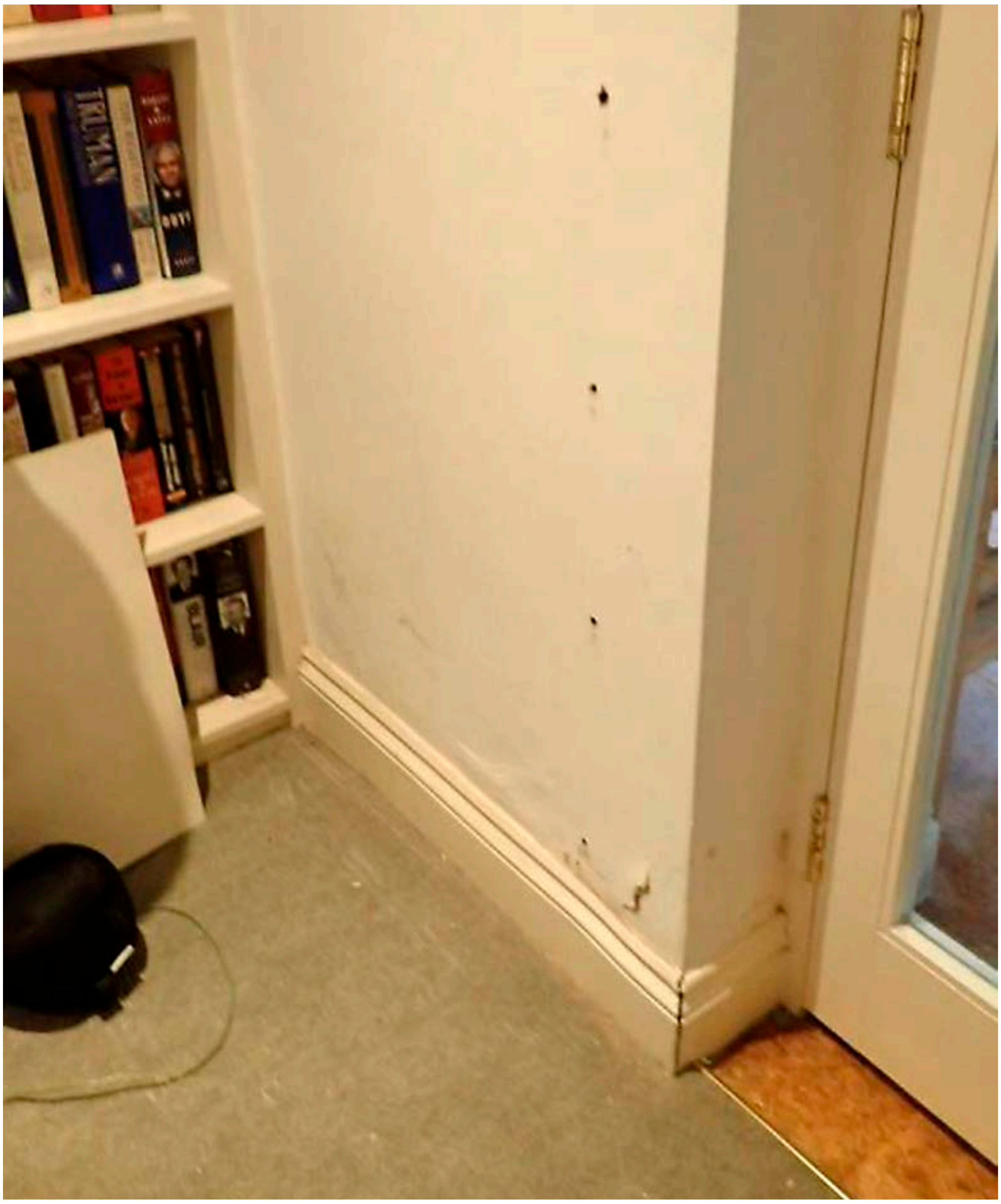


Figure 13:
Damage at the base of the wall was thought to be caused by rising damp, but nearby books and carpet were not damaged or mouldy, and a resistance moisture meter gave dry readings from the top of the skirting (where it was in contact with the wall). Subsequent sampling confirmed that the wall was dry. Originally an external wall, it had dried out when an extension to the house was added. As the moisture evaporated, salts were brought to the surface, resulting in superficial damage.

Identifying sources and symptoms of moisture

Plotting moisture sources and areas of damp damage and decay on floor plans and elevations provides a spatial overview that can give a basic understanding of the problems. It also helps to identify areas that require further investigation and to select the most suitable methods to use for this.

This publication is not intended to be a manual on building surveying. The faults that might allow water into buildings are too numerous to describe fully here. Sources of more detailed information are listed in Further reading and sources of information.

Some basic problems commonly found in historic buildings are discussed below.

Condensation

Condensation occurs when the temperature of a surface drops below the dew point. Typically, this happens on visible surfaces such as windows, plaster adjacent to windows and cold-water pipework but may also occur within the thickness of building elements ('interstitial condensation') Condensation may also occur in locations where differences in thermal resistance of materials result in one construction element being colder than its surroundings. This effect is described as a **thermal bridge**. It may also occur where there are gaps in insulation.

Condensation appears as droplets on impermeable surfaces, but will be absorbed by porous materials, thus raising their moisture content. One useful way of distinguishing between moisture transmission and condensation is to attach a piece of metal foil to the suspect area. If the problem is condensation, moisture droplets should form on top of the foil. If it is transmitted moisture, then the dampness will remain beneath it and no surface droplets will form.

An assessment with an infrared thermometer or thermal imaging camera (see Chapter 3) can also help to identify areas where damp is likely to be caused by condensation.

Leaking services

Water leaking from pipework or plumbing fittings can result in significant damp. Plumbing is often concealed, so leaks may not be discovered until damage or decay becomes evident. Condensation dripping from air conditioning units can also cause substantial accumulations of moisture in building fabric if not suitably drained.

Figure 14:
Water from a leaking cistern has resulted in fungal decay in a timber pattress.

Gutters and rainwater pipes

Among the most common causes of moisture ingress in buildings are blocked or leaking rainwater goods. Experience indicates that most rainwater disposal systems cope with the majority of storms if adequately maintained, although they might overflow under extreme conditions. Gutter and rainwater pipe sizes can be checked against current standards (Building Regulations Approved Document H; BS EN 12056) and if they are too small, they should be upgraded. Since current estimates of future weather conditions indicate that storms will become more frequent, it might also be necessary to upgrade rainwater goods if they are merely adequate for current conditions.

Gutters, especially valley and parapet gutters and outlets, should be inspected regularly to ensure they are free from blockages. In addition, rainwater pipes should be checked regularly to make sure they are draining freely. Damp staining on walls behind pipes might indicate blocked **hoppers**, leaking joints or perhaps rust damage at the back of a cast iron pipe. If vegetation is visible, it is usually a sign that the gutter is blocked; rainwater will be finding pathways down the walls and into open joints. Inspection and clearance are often fairly straightforward (Figure 15) but can be difficult where there is restricted access (Figure 16).

Figure 15:
Rainwater overflowing from a partially blocked gutter and hopper head was indicated by the algae staining the wall. In addition, the back of the hopper had corroded and water was leaking into the wall through open joints.

Figure 16:
Height and restricted access can make gutter inspection and clearing difficult and expensive. However, if vegetation is visible from ground level), it is likely that rainwater will be finding its own way down through the building.

Occasionally, architects do not want rainwater pipes to be visible on the principal elevations. In such cases, concealed and often complex drainage routes are devised. For example, a parapet gutter might drain into a lead-lined wooden trough within the roof space, before discharging into a rainwater pipe on the rear elevation. Rainwater pipes might also be routed inside the building. These are often boxed in or concealed within the thickness of walls (Figure 17), and only visible in the basement. If these internal rainwater pipes become blocked, they can cause considerable decay and damage (Figure 18). Surveyors should look for hatches or access points at intermediate levels in order to reach the source of damage.

Figure 17:
An old lead internal rainwater pipe revealed when wall linings were removed.

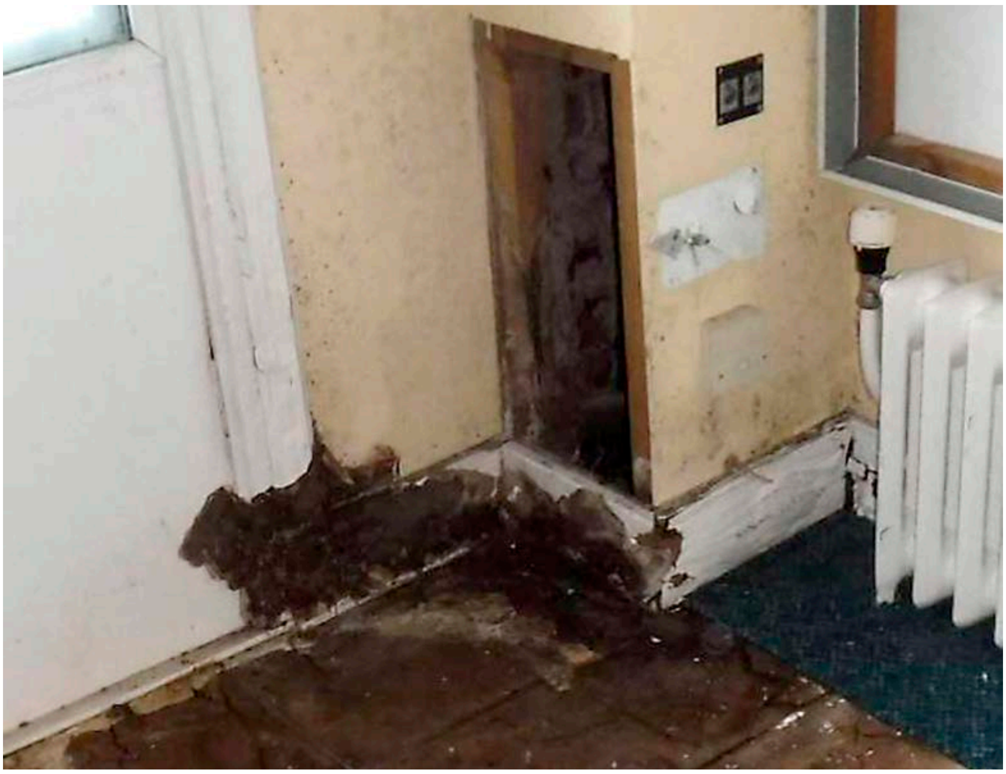


Figure 18:
Fungal decay (discoloured by spray treatment) caused by a leaking joint near the bottom of a boxed-in lead rainwater pipe.

When undertaking a damp and decay survey in a large building, it is always good practice to identify drainage routes and plot them on a floor plan, along with any signs of interior damp and damage. Note that gravity strongly affects the movement of liquid water. Therefore, water entering the top of a wall from roof or guttering defects will track downwards through cracks and voids within the thickness of the wall. Sometimes, it will accumulate at the base of the wall, where it can be mistaken for moisture coming from the soil.

Rainwater gullies

Rainwater goods may be carrying water away from the roof effectively, but this will not fully protect the building unless the water is safely disposed of when it reaches the ground. A moisture assessment should, therefore, include an inspection of all drainage gullies. It is often helpful to pour a bucket of water into a **gully** if blockages are suspected. Problems with gullies and gully surrounds often occur because they have not been routinely cleaned, or because defects appeared gradually and were either not noticed or not addressed.

Figure 19:
The ground floor in this building is at the same level as the external ground level, so it is essential that the external area is well drained. Unfortunately, water discharging from the rainwater pipe does not reach the gulley because of the unevenness of the paving. Instead, it soaks into the joints between the slabs, allowing vegetation to grow and saturating the ground beneath. Moisture then rises within the wall.

It is important to note that, unlike lateral moisture penetration, drainage faults allow substantial volumes of water to accumulate in the base of a wall. If the external walls have a damp-proof course, and the ground floors have been replaced with concrete incorporating a damp-proof membrane, then this water may percolate beneath the floor slab and wick up an interior wall. If damp damage is observed on an internal wall with no obvious cause, then the surveyor should always check for an external fault. However, understanding the construction of a building can often be difficult, particularly if there have been alterations, extensions and interventions.

Below-ground drains

The underground drainage systems of old buildings should always be investigated. Soakaways are particularly suspect if they are a few decades old because they silt up easily and often collapse. Inspection is particularly important if pipes are in close proximity to large woody perennial plants. If the rainwater pipe is surrounded by a tangle of dense vegetation, then the below ground drainage will be suspect.

A drainage survey may be needed to trace drain runs, assess their condition and ensure that they discharge in suitable locations away from the building.

Vegetation

Vegetation may be both a symptom and a cause of moisture problems. The presence of algae, lichen and moss signifies damp, but the growths themselves are not necessarily harmful to building fabric. However, moss, higher plants, and leaves from nearby trees and shrubs can block gutters, thereby creating conditions in which woody perennials, such as buddleia, can flourish. Their expanding roots and stems can significantly disrupt brick and stone masonry. Climbing plants can also cause moisture ingress if they are allowed to grow above gutter level, where they can disrupt rainwater goods and force their way between roof tiles.

Below ground, tree roots will not usually harm gullies and drains that are in good condition, unless they are particularly close to the trunk. However, if leaks have developed in the past – perhaps because of moisture movements in clay soils, or because there is seepage through joints caused by blockages – then roots will follow the moisture gradients. Fine roots may penetrate a drain and proliferate within, thus enlarging the crack through which they entered.

Figure 20:
The roots of a shrub growing in a chimney stack cause structural damage and allows water penetration. These problems will get worse as the plant grows.

Impermeable walling materials and finishes

During the first half of the 20th century, hard cement-based mortars and renders were thought to be an ideal barrier against wind-driven rain (Blake 1923). Unfortunately, this has proved not to be the case. In fact, they can exacerbate moisture accumulation. However carefully these materials are applied, there will always be shrinkage cracks, gaps or joints where water can penetrate. Because many cement-based mortars lack the capillary pathways to allow absorbed moisture to return freely to the surface and evaporate, water becomes trapped and can build up over time. If the full thickness of the wall becomes saturated, pathways will develop that transfer liquid water quickly from the exterior to the interior.

Even where impermeable materials are used on only part of a wall, there can still be problems. For example, repointing a brick wall with an impermeable mortar will reduce the area from which moisture can evaporate freely by almost a fifth.

Cementitious renders have proved to be particularly harmful when applied to timber-framed buildings. Renders crack, allowing water penetration, but they also produce an impermeable cold internal surface within the thickness of the wall on which condensation forms (Figure 21). Cement-rendered infill panels produce similar problems. Original daub panels expanded when wet, forming a seal with the surrounding timber framing, but the cementitious material shrinks away, leaving fine cracks that allow water ingress. Trapped moisture can then cause significant decay. It also allows deathwatch beetles to thrive. In earthen constructions, water trapped by cementitious renders may weaken walls to the extent they become unstable and collapse.

Figure 21:
This timber frame was covered by an impermeable cementitious render on metal mesh. Fine shrinkage cracks allowed moisture to penetrate. In addition, condensation occurred on the cold interior surface of the render. Trapped moisture at the interface between the frame and the render caused the timber to decay.

Moisture from the ground: ‘rising damp’

Rising damp caused by ground water is fairly uncommon. In fact, when the Building Research Establishment (BRE) analysed results from 1,500 damp investigations, it found that rising damp accounted for only 4% of cases (Trotman et al 2004). Trotman makes the following observation:

‘In the 1970’s BRE carried out an exercise with a major damp-proofing contractor to evaluate their system. Great difficulty was experienced in locating sufficient properties that had a rising damp problem’ (Trotman et al 2004 154).

More commonly, damp at the base of a wall is the symptom of a fault or blockage in the drainage system or a leaking water supply pipe. it may also be caused by inadequate arrangements for surface water disposal or splashing from hard surfaces at the base of the wall. In some situations, condensation may occur at the base of a wall due to thermal bridging between the masonry and the ground. In such cases, invasive treatment of the wall is not necessary; instead, the water source should be eliminated.

Lateral moisture penetration can occur where external ground levels have built up against the base of a wall. This is a common accidental problem, particularly with raised patios and flower beds. The consequent interior damage is frequently mistaken for rising damp. (Damp that had, in fact, risen from the **water table** would normally have a more widespread effect.) Measuring the difference between the soil level and that of the floor (for example, at a window) and plotting it on a floor plan against the damp damage will provide a basic understanding of the problem and indicate if further investigation is required.

Water will rise by **capillary action** in a wall built of porous materials if it is in direct contact with a source of moisture in the soil. When this occurs, water will rise until the evaporative loss from the wall surfaces equals the moisture gain. The rate of evaporative loss depends on the environment around the wall, because the surrounding air must be able to accept water. Therefore, water is likely to rise higher in a cool north-facing wall than in a sunny south-facing one of similar construction. It will also rise higher if wall surfaces are covered by materials that impede evaporation, such as impermeable renders or coatings. The surface area to volume ratio of the wall is important. Damp will tend to rise higher in a thick wall than it would in a thin wall of similar construction because there is a greater reservoir of water.

Walling materials and construction make a difference. Water will move further in a fine-pored material than in a coarse-pored one. Therefore, masonry units or mortar joints with coarse pores may resist the movement of moisture from one unit to another. The movement of water may also be impeded in the rubble core of a thick composite masonry wall because of a lack of uninterrupted capillary pathways.

Soil type is also relevant. It has been calculated that water might rise 3m from a water table in clay/lime soil but only 0.3m in medium sandy soil (Masari and Masari 1993). However, in non-saturated soil, the upward capillary force in a wall will be opposed by suction pressure from the ground. The greater the distance between the wall base and the water table, the greater the suction. Correspondingly, the risk of rising damp will be reduced.

The transfer of moisture depends on the geology and hydrology of the soil and the material properties and construction of the wall. It is not inevitable, therefore, that an unprotected wall will suffer from rising damp. However, when groundwater wicks up a wall, it will usually leave an irregular horizontal band of salts transported from the soil. Most of these salts are hygroscopic: that is, they absorb moisture from the atmosphere. The presence (or absence) and distribution of these salts can provide valuable clues to the cause of a damp problem.

Firefighting and floods

Although fire services try to minimise water damage when firefighting, large volumes of water will inevitably be discharged into a building during a serious incident. Because fires are often fought from above, rooms at lower levels in the building may be reasonably dry when initially inspected. However, water will gradually migrate downwards though the building fabric under the force of gravity. As a result, moisture at lower levels may be found to increase over time while upper levels become drier.

Significant damp may also be caused by flooding from natural causes. Its effects can vary widely and depend on many factors. These include: the construction of the building, the existence of protection measures, the type of flooding and its duration, speed of flow, and depth. In some situations, floodwater may also become contaminated with untreated sewage and present health risks.

In both cases, the underlying cause will be obvious, but periodic inspections and monitoring will be needed to ensure that building fabric is drying satisfactorily.

Hygroscopicity and salts as indicators of damp

Contamination of building materials with soluble salts is often associated with damp. Soluble salts come from various sources, including groundwater, decayed biological matter, pollution, road de-icers and sea spray. Some are inherent in the building materials themselves. Liquid water travels rapidly through porous materials, carrying salts in solution and depositing them wherever the liquid flow is broken by evaporation.

When porous materials are contaminated with salts, their equilibrium moisture content will be higher than in similar but uncontaminated materials. Certain salts are highly hygroscopic and will change to a liquid state at an equilibrium relative humidity that occurs during normal building usage. In such cases, damp areas may appear even after the source of moisture that carried the salts into the wall has been removed.

Fortunately, salt contamination is usually localised and may be detected by moisture meters even when the salt is not visible.

Salts from groundwater

Groundwater salts in the UK are usually chlorides and nitrates of sodium and calcium in concentrations of about 20 and 50mg/l (parts per million), respectively. If groundwater rises in a wall, the salts carried in solution will slowly concentrate in a band at a height where evaporation halts moisture rise. This process is gradual, and it can take many years for the band to appear as the salts accumulate.

Groundwater salts have a low equilibrium relative humidity and will readily absorb moisture from a damp atmosphere. They do not occur naturally to any great extent in building materials. Therefore, the presence of hygroscopic salts in a band across a wall may indicate water that has travelled some distance through the soil. The detection of hygroscopic salt bands is discussed in Chapter 3.

Salts from building usage

Potassium salts are not common in groundwater. However, potassium nitrate may be plentiful in walls in stables and some agricultural buildings because of soil contamination from animal urine. This may become a problem when such buildings are converted to other uses. Sometimes, potassium nitrate occurs in church walls because of the proximity of burials. Potassium nitrate is not hygroscopic and does not go into solution until a relative humidity of 94% is reached. It is, therefore, likely to persist as a white **efflorescence** on a wall. If the wall is dry, or even damp, this efflorescence can be brushed off and should not reappear. However, if the wall is wet or the salts have been washed off, more salts will be mobilised from the reservoir within the wall, and the problem will recur.

The combustion products of wood and coal are also a source of salts. In 2013, the purchaser of an old farmhouse in Clitheroe, Lancashire, was alarmed to find a blood-like fluid dripping through the ceiling and into the bath. An inspection of the roof space above found that the gable wall, which contained a flue, was discoloured with red water run marks (Figure 22). Analysis of the fluid showed that it contained predominantly calcium chloride with potassium, magnesium and ammonium salts. The red material was a water-soluble combustion product from lignin. Wood and coal had been used as a domestic fuel for many years, and water penetration at the back of the chimney stack was mobilising contaminating salts from the unlined flue.

Figure 22:
The 'blood in the bath mystery'.

Patches of plaster with hygroscopic discoloration are sometimes found on walls containing old flues. They indicate moisture movement and the consequential migration of contaminants. The abnormally high chloride level in the Clitheroe example may have been partially due to hydrogen chloride emissions from lime kilns further down the valley.

Salts from construction materials

Salts from building materials are usually sulphates of calcium, sodium and magnesium. Sodium sulphate is plentiful in clay-based materials such as brick, which will frequently produce initial sulphate efflorescence. Magnesium sulphate is occasionally found emerging from roof timbers, sometimes in large quantities. This salt is the product of atmospheric pollution acting on stone slates with a high magnesium carbonate content. In most cases, the problem is likely to be historical, first appearing at a period when atmospheric pollution was severe. Where existing roof coverings do not seem to be the source of salts, consider whether earlier roof coverings may have been replaced.

Unlike salts from groundwater, salts that come from building materials are not being continually replenished. Eventually, they will be depleted. The equilibrium relative humidity of these sulphates is 90% and above, so they are not hygroscopic and, therefore, appear as efflorescence on surfaces. In many cases, if the surface is dry, this efflorescence can be brushed off and will not return. (Note that the equilibrium relative humidity of salt mixtures tends to be different to that of individual salts; salts with a high equilibrium relative humidity tend to be fairly pure.)

A potentially damaging source of sulphates is Portland cement, particularly in conjunction with atmospheric pollution. However, the appearance of salts may not necessarily represent an active and ongoing damp problem, but a temporary migration phase that will end once the structure is dry.

Ongoing sulphate damage is usually the result of fluctuating temperature and humidity, rather than moisture migration. Although sodium sulphate will remain in the form of crystals throughout most of the normal humidity range, this does not mean it will remain stable. Changes in the salt's hydration state will result in high crystallisation pressures within the pores of contaminated materials. This can cause surfaces to spall (Price and Brimblecombe 1994; Rodríguez-Navarro 2000).

This damaging process will continue indefinitely unless salts are removed or the environment is stabilised. Internally, damage is often found in basement boiler rooms, where the periodic heating can cause rapid relative humidity changes.

It can also occur when attempts are made to ventilate damp cellar rooms because the temperature and humidity of external air are unstable. Maintaining high humidity in a cellar might make the room less useable, but it will keep the salt in a stable hydrated state, thereby avoiding further crystallisation damage to masonry.

3 Moisture measurement techniques and devices

As discussed in Chapter 2, a preliminary assessment of damp problems can be based on the environment they produce and the symptoms presented. However, a more detailed assessment may be needed to make a firm diagnosis and to identify solutions. Water penetration is obvious if it is dripping through a ceiling or if there are large dry rot fruiting bodies. Locating and assessing more elusive sources of damp may require special measurement techniques and devices.

This section looks at the methods most likely to be used on site by surveyors and other practitioners. Sophisticated techniques that are more applicable to scientific research and typically used in a laboratory are not covered.

Direct measurements of moisture content are made by extracting material samples and measuring the amount of water they contain. However, extracting samples is destructive and may not be desirable or permissible in some situations (for example, where sensitive historic fabric is of high heritage value). Indirect methods rely on measuring a property of the material that is influenced by the presence of moisture, such as its ability to conduct electricity or hold an electrical charge. Because indirect methods are non-destructive, they can be used repeatedly without harming building fabric. The advantages and disadvantages of direct and indirect measurements are summarised below.

Table 2:
Direct and indirect measurements compared

	Advantages	Disadvantages
Direct measurement	Provides accurate absolute moisture content data Provides moisture content data at known depths	Invasive: samples need to be extracted from a structure, resulting in potential harm to significance Information about the distribution of moisture limited by the number of samples extracted Periodic measurement requires the removal of further samples
Indirect measurement	Non-invasive: samples do not need to be extracted Measurements can be taken rapidly over large areas Can easily provide information about the superficial distribution of moisture Periodic measurements can be taken easily	Indicates relative moisture content only; does not provide absolute moisture content data Not suitable if calibration is required Readings affected by salts and material properties Difficult to compare readings from different materials Uncertainty about depth of measurement

Direct measurement of moisture content

Oven/balance method

The absolute moisture content of a material can be obtained gravimetrically by the oven/balance method. In this, the **percentage moisture content** (%mc) of each sample of the material is determined by weighing it to obtain a **wet weight** (wt^1), then drying it to obtain a **dry weight** (wt^2). This is the simplest way to obtain data to calibrate indirect measurement techniques.

Since moisture content in a wall varies, surveyors should obtain an array of samples in order to understand the scope of the problem. Samples are extracted as dust using a sharp drill bit and sealed into pots with airtight lids. Ideally, the samples should be obtained from materials of the same type (for example, mortar, stone or brick), although this may not be possible where the material is concealed behind plaster. The colour and material type of each sample should be recorded. This can be helpful where large variations in moisture content are found that may be related to differing materials. Plaster dust should be stored separately or discarded.

The samples should be weighed as soon as possible after extraction to determine their wet weight. Small wood samples are best weighed on site using a sensitive portable balance (readable to 0.005g) because they lose moisture rapidly. If this is not practical, they should be sealed into vapour-impermeable containers and weighed as soon as possible.

Samples are then dried in a ventilated oven. The temperature used to dry the samples is important because any plaster or salts within them may contain bound water (water of crystallisation) and this could produce an erroneously high moisture content. Drying samples at a low temperature of 20–30°C, until a constant weight is obtained, can reduce this problem. If a sample comprises uncontaminated brick or mortar, then a temperature of 80–90°C could be used. It is generally convenient to dry the samples overnight at the lower temperature. For timber, ASTM standard D 4442 – 92 (2003) states that a forced convection oven should be maintained at 103°C ± 2°C until the weight loss in a three-hour period is less than twice the sensitivity of the balance used.

The sample moisture content is calculated using the following formula, where wt^0 is the weight of the pot, wt^1 is the wet weight of the sample and wt^2 is its dry weight:

Formula 1

$$\%mc = \frac{wt^1 - wt^2}{wt^2 - wt^0} \times 100$$

Some references (BRE DG 245, for example) modify the equation when using it for wall materials by subtracting the dry weight from the wet weight and dividing the result by the wet weight (that is, wt^1 rather than wt^2). This is supposed to express the water content as a percentage of the mass of the extracted sample. However, because the mass of the sample also contains moisture, the calculation will become increasingly inaccurate the more water there is in the sample. Differences are small up to a moisture content of about 10%, when there is about a 1% inaccuracy. This increases steadily to about 3% inaccuracy at a moisture content of 16%. Division by the wet weight progressively underestimates the actual moisture content.

Measurements of absolute moisture content are usually determined off site, because a drying oven and an accurate balance scale are required. However, on-site gravimetric measurements can be made with a 'moisture analyser'.

Gravimetric moisture analyser

This automated device allows the absolute moisture content of powdered samples of masonry and mortar extracted by drilling to be determined quickly on site. It measures the weight of the wet sample before drying it with a built-in heater and reweighing it. The analyser then calculates and displays the moisture content of the sample as a percentage of its dry weight.

Figure 23: Gravimetric moisture analyser.

Determining hygroscopic moisture contents of salts from groundwater

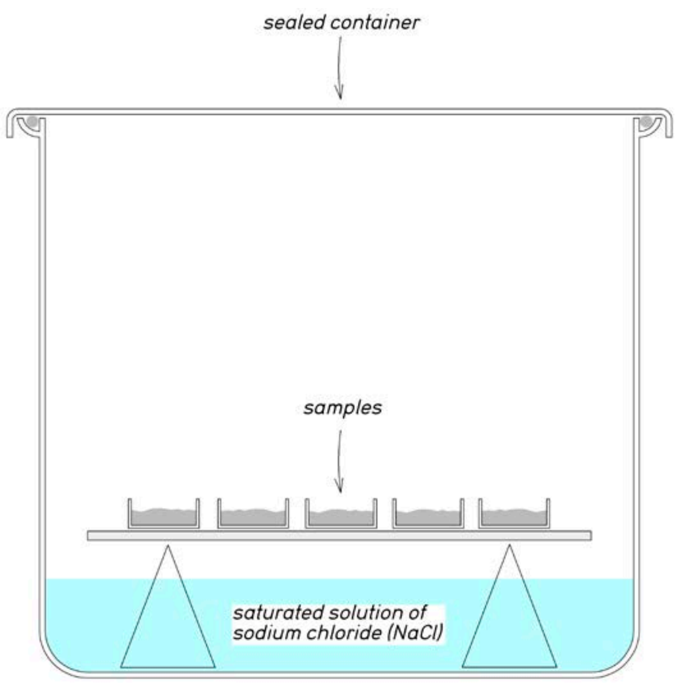
Long-term migration of moisture from the ground to a wall will transport hygroscopic salts that concentrate in a horizontal band where the upward rise of moisture is balanced by evaporative loss. The presence of a band of hygroscopic salts will, therefore, indicate rising damp that might be ongoing or have occurred in the past. Determining the **hygroscopic moisture content** of samples extracted from the wall can help differentiate between these two possibilities.

Random extraction of samples from a wall may miss the salt band and result in a mistaken diagnosis. This problem can be overcome by taking samples at regular intervals up the wall. Samples should be taken internally at 250mm intervals, from floor level up to a height of 1.5m. An additional sample should be taken at a height of 2m to serve as a control. Samples should then be sealed in pots with tightly fitting lids, and weighed as quickly as possible. (The sampling process is described in the previous section.

Each sample is weighed to determine the wet weight (wt^1). Samples are then oven-dried at a temperature not exceeding 35°C to obtain the dry weight (wt^2), then stored at a constant humidity. Their moisture content will either remain constant or increase, according to their hygroscopic salt content. A third weighing provides a hygroscopic weight (wt^3).

In general, the most practical way of providing a constant humidity is to store the samples in a sealed container over a saturated solution of sodium chloride. This salt maintains an equilibrium relative humidity of 75%. Most of the salts commonly found in soil will be in solution at this humidity, and 75% relative humidity would not be uncommon in a damp room. Care must be taken to ensure that the salt solution is fully saturated so that no more salt will dissolve. If this is not achieved, the humidity within the container may not be sufficiently depressed.

Figure 24:
Set-up for determining the hygroscopic moisture content of samples.



The length of time that it takes for a sample to equilibrate with the humidity in the chamber will depend on its size. The BRE proposes that a thin layer of dust extracted from a wall should take a few hours. However, practical experience suggests it is better to leave the sample for about three days to ensure that equilibration is complete.

The absolute moisture content of the sample is calculated as a percentage of the dry weight using Formula 1. (The BRE states that a moisture content of less than 5% at the floor/wall junction means that rising damp is unlikely (Trotman et al 2004). However, it is often difficult to obtain samples in this location because most walls have skirting boards).

The hygroscopic moisture content (%hmc) is calculated using Formula 2, where wt^0 is the weight of the pot, wt^1 is the wet weight of the sample and (wt^3) is the hygroscopic weight:

Formula 2

$$\%hmc = \frac{wt^1 - wt3}{wt^3 - wt^0} \times 100$$

Example

Table 3 shows some data from a house in London. The **free water** moisture content is obtained by subtracting the hygroscopic moisture content from the absolute moisture content. BRE Digest 245 states that some materials have a natural hygroscopicity of up to about 5% and remedial measures are not necessary unless it is higher.

Table 3:
Absolute moisture contents (%mc), hygroscopic moisture contents (%hmc) and free water moisture content of samples extracted from brick walls on the ground floor of a house in London.

Height above floor (mm)	Sample location 1	%mc	%hmc	Free water %	Sample location 2	%mc	%hmc	Free water %
2000	1.6	27.7	1.7	26.0	2.6	4.3	1.9	2.4
1500	1.5	29.3	1.7	27.5	2.5	4.4	1.7	2.7
1000	1.4	30.2	1.9	28.4	2.4	6.6	2.2	4.4
750	1.3	33.8	2.2	31.6	2.3	8.2	2.2	6.0
500	1.2	20.0	1.6	18.4	2.2	10.4	2.3	8.0
250	1.1	31.1	3.0	28.1	2.1	13.2	2.0	11.3
Height above floor (mm)	**Sample location 3**	**%mc**	**%hmc**	**Free water %**	**Sample location 4**	**% mc**	**%hmc**	**Free water %**
2000	3.6	28.2	1.6	26.6	4.6	2.4	2.4	0
1500	3.5	29.0	5.4	13.7	4.5	2.6	2.7	0
1000	3.4	29.8	1.8	28.0	4.4	1.0	1.2	0
750	3.3	24.6	3.8	20.9	4.3	0.5	0.7	0
500	3.2	18.7	0.3	18.4	4.2	3.2	2.4	0.8
250	3.1	21.2	0.4	20.8	4.1	4.5	0.5	4.0

Moisture contents are categorised according to the following colour scheme:

Dry	<3%
Damp	3.1–6.0%
Wet	6.1–10.0%
Saturated	>10%

Samples from locations 1 and 3 were taken from walls behind faulty rainwater pipes and were found to be saturated. Samples 3.3 and 3.5, however, had an elevated hygroscopicity that suggested there might have been an older background problem, such as a faulty drain, which led to the deposition of salts. This was localised and did not occur in any other samples. Therefore, a general rising damp problem was not indicated. An elevated hygroscopicity of 5.4% might, theoretically, cause a damp patch in a humid environment if the salt migrated through new plaster, or if the old plaster was similarly contaminated. However, contamination was slight and infrequent in the data, so it was not a cause for concern.

Location 2 was an area where external ground levels had been allowed to build up considerably above interior floor levels. This accounted for the higher moisture contents at the base of the wall.

Location 4 was mostly dry, although patio slabs had built up the ground level a little with a corresponding increase in moisture content at the base of the wall.

Gas carbide meters

On-site measurements can also be obtained with a gas **carbide meter**. This device measures the pressure generated by the acetylene gas produced when moisture in the sample reacts with calcium carbide (BRE Digest 245). Commercially available meters work by mixing a fixed weight of powdered test material with a fixed volume of calcium carbide in a pressure cylinder. The cylinder is fitted with a manometer calibrated as percentage moisture content (%mc). Carbide meters indicate free water and are not, therefore, largely influenced by the type or properties of the test material, provided it can be powdered. These meters require a fixed weight of sample, commonly 6g. If hygroscopicity is to be assessed, a further quantity will be needed for a separate laboratory test.

Figure 25:
Gas carbide meter.

In comparison, the size of samples required for the oven/balance method can be smaller: typically 2 – 3g. Sample materials can, therefore, be extracted from smaller holes. The same samples may be used for assessing both moisture content and hygroscopicity.

Whichever method is used to determine moisture content, remember that the result will only be accurate for the sample obtained. In a damp wall, differing sample sizes may give slightly different results because of variations in the moisture content of the material. For example, if the moisture content of a whole brick is calculated, the result will be an average of its wetter and drier parts (see Figure 1). This is a minor problem if the material is air dry, but increases if the moisture content is higher.

Using equilibrium humidity to assess moisture content

Measuring the humidity of air in holes drilled into walls has become a popular method for monitoring drying after flooding. Unfortunately, there is a tendency to rely on relative humidity readings alone, without taking account of temperature. Therefore, the results obtained can be very misleading because of the inverse relationship between temperature and relative humidity: air that is quite dry can have a high relative humidity if the temperature is low. The way to avoid this mistake is to convert the temperature and relative humidity readings into absolute air moisture contents.

Keep in mind that any amount of free water within the building fabric surrounding the hole will raise the relative humidity of air in a hole to 100%. Therefore, the humidity reading will not reflect a reducing free water content, so the actual drying progress of the wall may not be detected.

Using proxy materials to assess moisture content

Moisture can be assessed in masonry by inserting a proxy material with known characteristics into a hole drilled into the wall and allowing it to equilibrate with the host material. Wood has proved to be useful for this purpose. In addition, using wood will indicate the likely moisture content of adjacent building timbers embedded in the wall. Dill (2000) describes a sensor consisting of a wooden plug sleeved with polythene, which was inserted into a hole drilled into the material to be assessed. The hole was then sealed to prevent air exchange. The sleeve isolated the sensor from the sides of the hole, thereby avoiding moisture and salt migration from the wall, so it equilibrated with the relative humidity of air within the hole. The moisture content of the sensor was subsequently measured with a **resistance moisture meter**.

A simpler but equally effective approach is to insert bare timber dowels into holes drilled into the wall to the required depth. The diameter of the holes should be large enough to allow for the expansion of the dowels as their moisture content increases; otherwise, they will be impossible to remove. A 10 to 15mm-diameter dowel will take about three weeks to equilibrate fully, although it will absorb a large proportion of its eventual moisture content within the first few days.

The moisture content of the dowels can be measured using the oven/balance method. Alternatively, a moisture meter may be used, but the results will be less accurate if the wall is very damp and the moisture content of the dowels exceeds the resolution of the meter. If the rods are cut up into sections before being measured, a moisture profile through the thickness of the wall can be obtained.

In a wet wall, dowels will start to degrade if left in place for more than a few weeks. This will invalidate any measurements but may sometimes be useful for detecting fungal activity. Therefore, if readings need to be taken over a long period of time, dowels should be replaced with new ones inserted into the same holes, after each monitoring cycle. This method is particularly useful for assessing the rates of drying in walls following firefighting. It has the advantage of simplicity and avoids the potential loss or damage of more sophisticated and expensive sensors on building sites or in places where there is public access. No claim is made for the precision of this method, but the results obtained are consistent.

Sometimes, long-term readings are required but dowels cannot be replaced regularly, for example where access is difficult. In such cases, electrodes can be embedded in the dowels and wired to a remote location where resistance moisture meter readings can be taken (Figure 29). Alternatively, they can be connected to a suitably programmed data logger. Dowels should be pre-treated with preservative to stop decay. (Solvent-based formulations will not make a significance difference to readings, which in any case are wanted to indicate changes rather than precise moisture contents). However, in damp conditions, corrosion of the electrodes may eventually cause the sensor to fail, even if the rods are pre-treated. Sleeved rods might then be preferable, or a more durable proxy material might be used. Historic England has experimented with ceramic dowels. These have been found to perform satisfactorily in comparison to wooden dowels.

In very wet walls, the dowels may end up with a moisture content beyond the resolution of a resistance meter. In this case, the oven/balance method would have to be used.

Figure 26:
Diagram of a segmented timber dowel with embedded electrodes. Dividing the rod into segments allows a moisture profile through the thickness of a wall to be obtained.

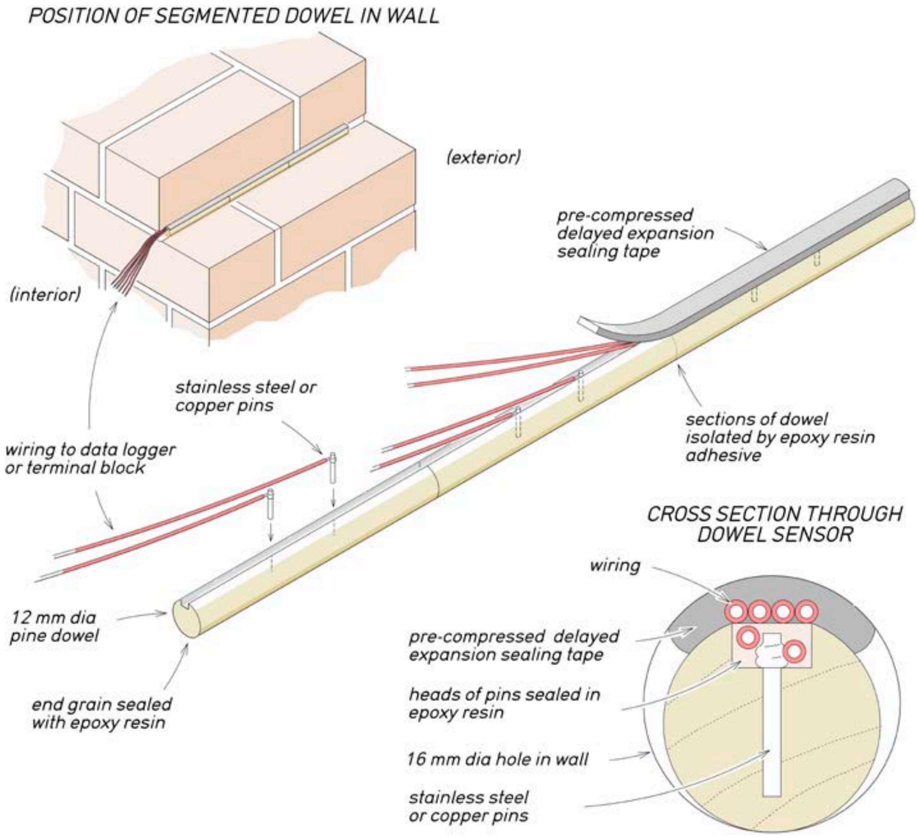


Figure 27:
A timber dowel in three segments.

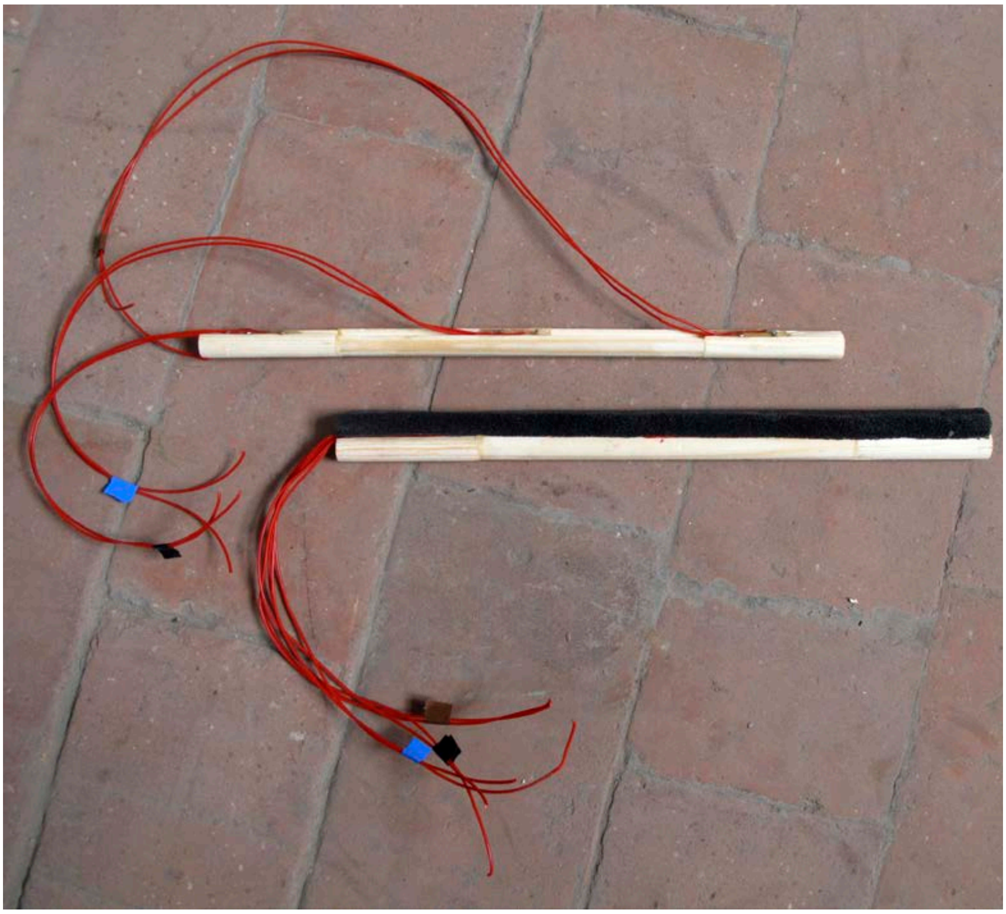


Figure 28:
Inserting segmented timber dowel into a hole drilled in wall.

Figure 29:
Remote measurement of moisture content of timber dowel using a resistance moisture meter.

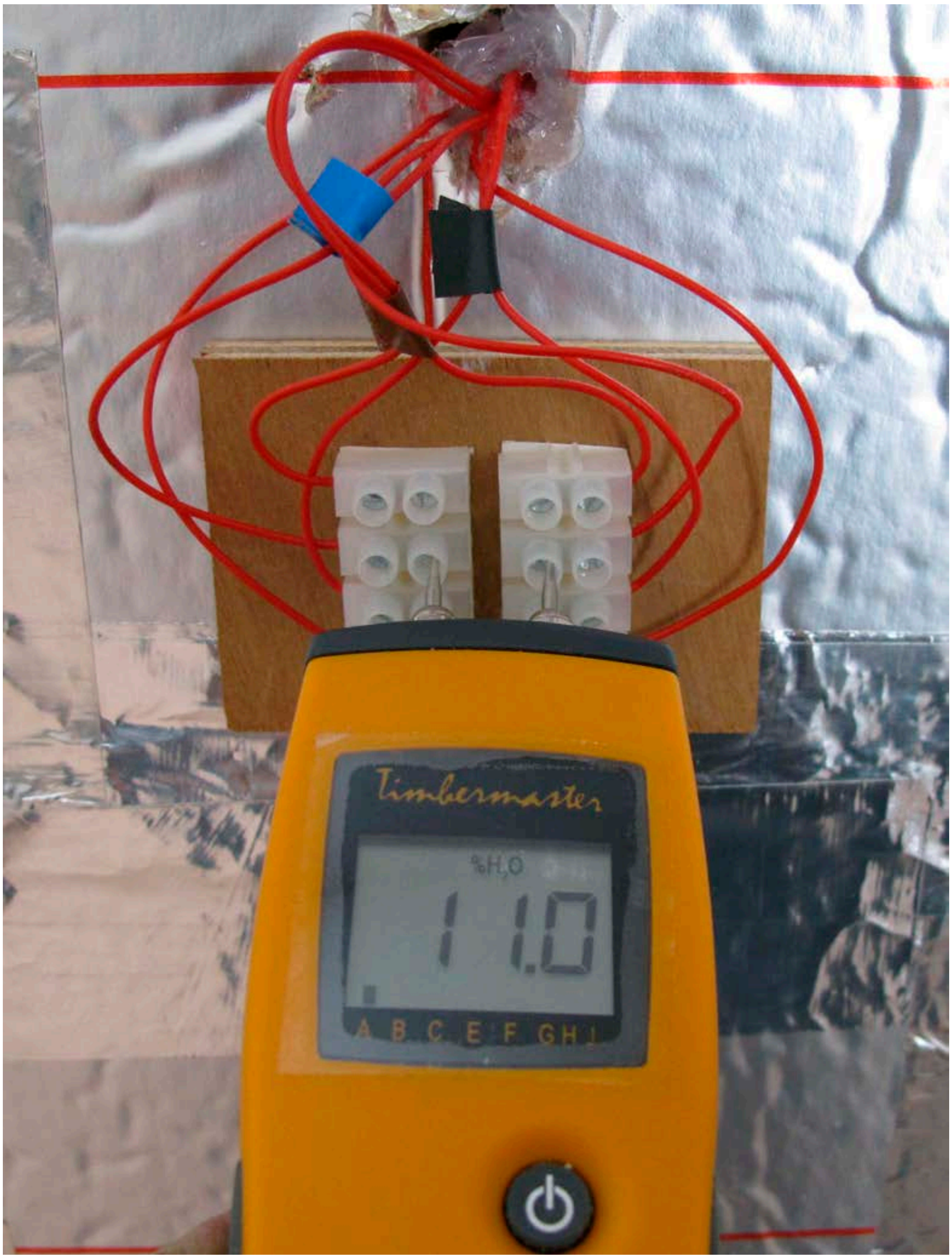


Figure 30 shows data obtained by inserting softwood dowels, each 400mm long and 15mm diameter, into 18mm diameter drilled holes in a church tower. They were left for six weeks to equilibrate, then withdrawn and cut into three equal sections. A moisture meter reading was taken half-way along each section. The dowels were also weighed on site and their moisture contents ascertained using the oven/balance method. The graph includes a line of best fit with an **R2 value** (a perfect fit would be 1.0 and 0.4 is poor). It is clear that the meter considerably underestimates the total moisture content.

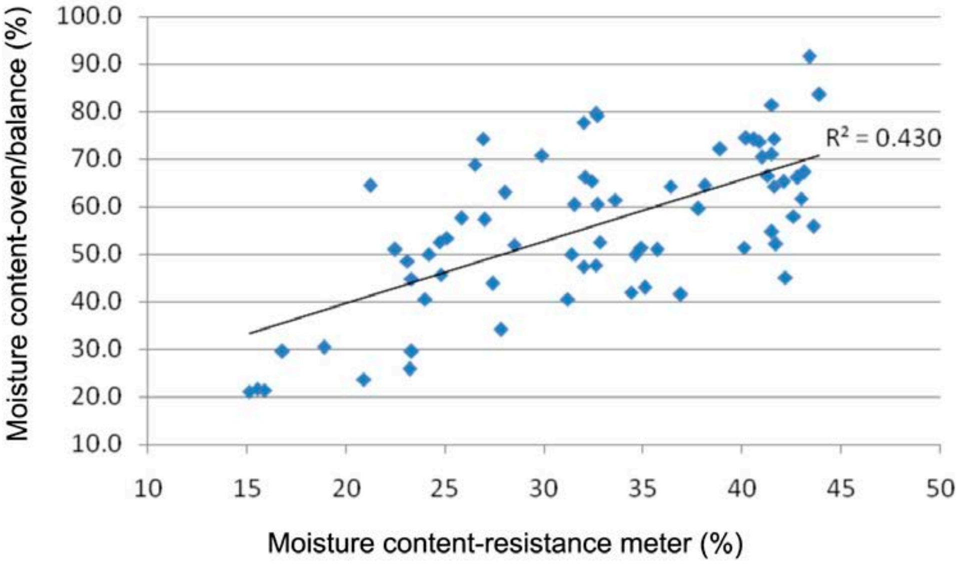


Figure 30:
A comparison between total moisture contents and resistance moisture meter readings for dowel rods above the dry-to-damp meter range.

Dowels can only give an indication of the moisture content of a wall. This is because the porosities of timber and masonry are different, and no direct relationship between them can be established. Furthermore, as has already been noted, the moisture distribution in a damp/wet wall is erratic (see Figure 1). However, the dowel method will, at least, allow for comparisons to be made over time.

Indirect measurement of moisture content

Although it is natural to assume that an instrument described as a 'moisture meter' measures moisture, this (with the arguable exception of the gas carbide meter) is a misconception. The device actually measures a property of the test material that is influenced by moisture, such as its electrical resistance or **dielectric** properties. This measurement is then converted into a moisture content or numerical reference scale by the instrument. Unfortunately, if something other than moisture affects the measured parameter, a false reading will be obtained.

The first handheld moisture meters exploited electrical resistance. They were developed in the 1920s, initially to monitor the moisture contents of the fresh timber output from drying kilns. The move to a survey instrument was a marketing afterthought: if the instrument measures moisture, why not use it in a building?

But, are the electrical properties of freshly sawn timber in a wood yard the same as, say, the roof timbers of a 200-year-old house in an industrial town with a history of atmospheric pollution? The extent of this problem can be assessed by looking at the factors that affect the accuracy of moisture meters in the environment for which they were initially developed, then considering how those factors would apply in a historic building.

In the 1990s, the Technical Research Centre of Finland (VTT) tested the accuracy of 22 different resistance moisture meters and six different **capacitance moisture meters** on 3,000 sections of timber. This was part of an EU project on timber drying (VTT Publications 420 2000). The results of this study and their relevance to historic buildings are referred to in the sections which follow.

Figure 31:
Commonly used types of hand-held moisture meter:
a. Resistance meters. These all have pins that have to be pushed firmly into the materials under investigation. Longer pins, which are insulated except for their tips, can be connected to some devices to obtain readings at depth.
b. Capacitance ('pinless') meters. Devices usually have sensor heads in the form of a pad or ball.
c. Microwave meters. Some devices have interchangeable non-invasive sensor heads for differing depths of penetration.
d. An invasive microwave probe designed to be inserted into a drilled hole. This allows a moisture profile through the thickness of a wall to be obtained.
e. Multi-function meters. Some meters have both resistance and capacitance modes. In addition, they may incorporate surface and air temperature and relative humidity sensors as well as software for calculating dew point temperatures.

Resistance moisture meters

Assessing timber

As the moisture content of wood decreases, its electrical resistance increases. Therefore, if the resistance between electrodes inserted into a timber is measured, its moisture content can be deduced. (Above the fibre saturation point – about 30% moisture content by dry weight – the electrical resistance changes erratically, but by only a small amount, depending on the electrical properties of the free water within the cells.)

Unfortunately, wood is not a homogeneous material, so moisture and other factors affecting electrical resistance are unlikely to be evenly distributed. This means that the moisture content of a sample will be represented by a range of resistance readings. This problem has been addressed by plotting the data and constructing a **calibration** curve that minimises variation (Figure 32).

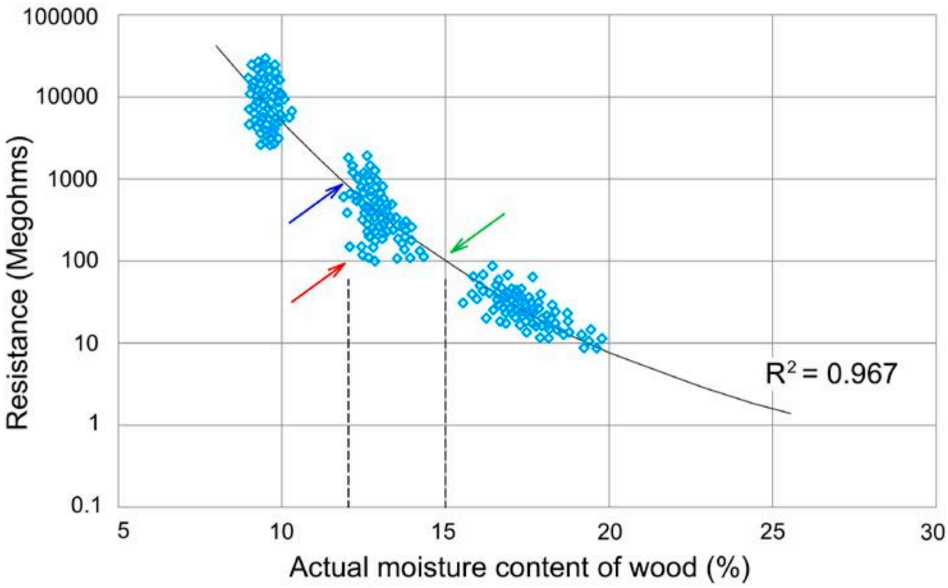


Figure 32:
A resistance calibration curve for pine (source: VTT Publication 420, 2000).

The curve illustrated in Figure 32 was carefully prepared by the VTT from its laboratory data. The scatter variation is minimised by a calibration curve. For example, electrical resistance readings of 1000 megohms (blue arrow) or 100 megohms (red arrow) were obtained when the actual moisture content of the specimen was about 12%. If a moisture meter interprets these resistance readings using the calibration curve, then 100 megohms gives a moisture reading of 15% (green arrow). In practical terms, the difference between 12% and 15% does not matter, because it is within the dry range for timber. However, it demonstrates that it is probably impossible to make an 'accurate' resistance moisture meter, and results expressed to decimal points are meaningless.

The VTT study concluded that results from resistance moisture meters are acceptably accurate within a moisture content range of 8 to 24%. This range makes the instruments very useful for comparative readings. However, there are limitations that must be considered.

How are readings affected by variations in timber?
Wood is a non-isotropic material; in other words, its properties vary up and across the tree trunk. This variability increases as the timber becomes damp. The meter and its various correction factors may be able to assess the moisture content to a reasonable level of accuracy at the position where its electrodes are inserted. However, this does not mean that a similar reading will be obtained elsewhere in the same timber or an adjacent timber. This problem is negligible in dry timbers but becomes serious as moisture contents approach and exceed 20%. Furthermore, as wood becomes damp, natural variation in moisture distribution means that meter calibration is even less reliable. The larger and damper the sample, the less likely it is that the meter reading will reflect its entire moisture content.

The problem is illustrated in Figure 33 using data from 200 sections of timber dowel (each 100mm long x 12mm diameter), which were left to equilibrate in the brick walls of Shrewsbury Flaxmill Maltings. The moisture content of each section was assessed halfway along the dowel with a resistance moisture meter. Its absolute moisture content was determined by the oven/balance method. The line of 'best fit' has a high R2 value (1.0 would be perfect), which means that the resistance moisture meter data provide a good assessment of the situation. But it can be seen that the meter readings become less representative of the sample as moisture content increases. This is because the moisture in the dowel is not evenly distributed.

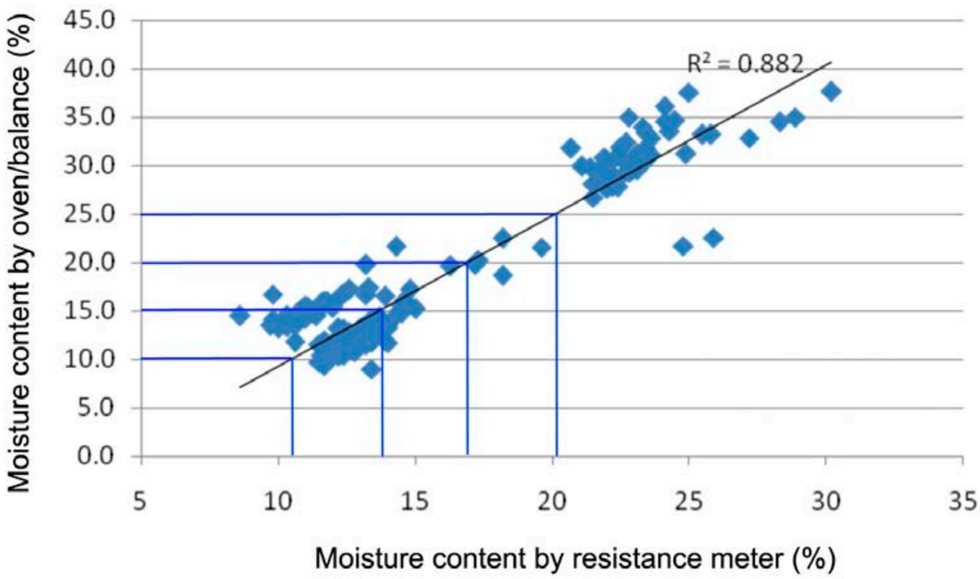


Figure 33:
A comparison between the moisture content of 200 timber dowel sections determined by oven/balance method and readings above the dry-to-damp range obtained with a resistance moisture meter.

How are readings affected by timber species?
The electrical properties of timber vary from species to species, and even from sample to sample in the same species. Therefore, some level of inaccuracy must be accepted. Meter manufacturers generally provide calibration for different types of timber, but this does not overcome variations within the sample.

Species calibration may also have limited practical application for the surveyor crawling through an old dusty roof where the species of timber is unclear. In the UK, structural timbers from buildings dating from the mid-

18th to the 19th century are most likely to be Scots pine. In older buildings, structural timbers are most likely oak or occasionally elm. However, inevitably, there are many exceptions and surprises. Oak was heavy and difficult to transport on deeply rutted and muddy roads, so other local timbers may have been used for repair.

Joinery in historic buildings may be made from an even wider range of species, and accurate identification on site is often impossible. If individual structural members or joinery components consistently give different readings to other timbers in the vicinity, this may be because they are different species.

How are readings affected by electrode orientation, profile and spacing?

Electrical resistance in timber has been found to be two to eight times greater across the grain than along the grain. Meter readings parallel to the grain have been shown to produce the most accurate assessment of moisture content. However, the effect is generally negligible below about 15% moisture content. The VTT study did not find any meaningful difference between measurements made in either orientation. This will be reassuring to a surveyor assessing a dirty historic roof where the slope of grain may be indistinguishable. Nevertheless, where practicable, consistency in electrode orientation is preferable when comparing readings.

The profile of the electrode ends seems to make some difference to the readings. Therefore, the probes used should always be those provided by the meter manufacturer.

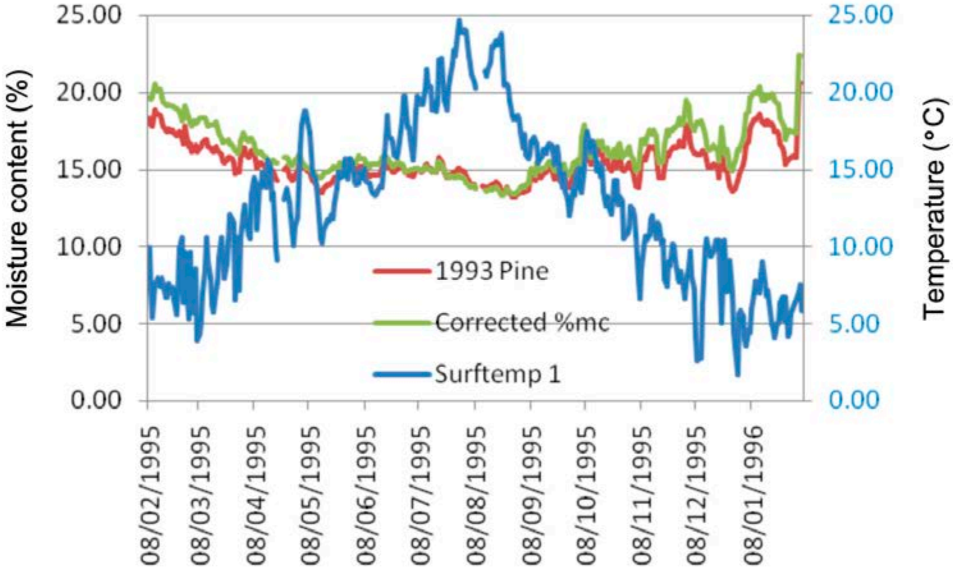
The VTT study tested electrode spacing from 20 to 120mm and found that distance between electrodes had no effect on moisture content values obtained.

How are readings affected by temperature?

The electrical resistance of wood decreases as its temperature increases. The effect is small, however. The average value for the temperature effect has been calculated to be 0.15% per degree Celsius (°C) change. The temperature effect has little practical significance in summer, but may be more important during cold winter months.

Protimeter states that its meter readings may be approximately corrected by adding 0.5% for every 5°C below 20°C (the temperature at which meters have usually been calibrated) and subtracting the same amount above 20°C. If a more accurate correction is required, then the Pfaff and Garrahan equation (Box 1) can be used. In general, this will only be necessary for scientific research. Figure 34 illustrates the effect of temperature correction on data from a softwood component in the roof of Lincoln Cathedral.

Figure 34:
The red trace shows the moisture content of a pine bearer in the roof of Lincoln Cathedral. Electrical resistance measurements were logged remotely at hourly intervals over a period of a year. These were converted to moisture contents using a calibration curve obtained from a moisture meter manufacturer. The green trace is the moisture content reading corrected for temperature. The blue trace is the surface temperature of the timber.



Box 1

The Pfaff and Garrahan equation for the temperature effect on resistance readings, as modified by Samuelsson (1992) to set the calibration point at +20°C.

$$u_k = \frac{u + 0.567 - 0.0260x + 0.000051x^2}{0.881\,(1.0056)^x}$$

u = moisture meter reading

u_k = temperature corrected %mc

x = surface temperature + 2.8°C

How are readings affected by surface treatments, contamination and degradation?

Surface treatments can affect meter readings. Inorganic salts in water-based preservatives or fire retardants decrease electrical resistance and raise meter readings. Conversely, organic coatings such as creosote increase the resistance, leading to lower readings. Organic solvents have little effect either way.

Similar problems may occur because of surface contamination. A surveyor might find an apparently damp-stained timber in a roof and think that it needs to be assessed with a moisture meter (Figure 35). However, the staining may, in fact, be a surface modification and might even contain salts carried from adjacent walls or roof coverings. This can lead to inaccurate and misleading moisture meter readings. If a meter gives a low reading, then the timber is most likely to be dry. But dry timbers may also give high readings if there is surface contamination.

Figure 35:
Damp staining on roof timbers might suggest the need for assessment with a moisture meter, but superficial chemical changes in the timber or contamination in the stained areas may result in erroneous readings.

Similarly, partially decayed timber or timber that has been significantly damaged by wood-boring insects must be evaluated with caution. Meters are not calibrated for wood that has undergone changes in its chemistry or density. Nevertheless, a meter could still be useful, because a comparison with adjacent timbers might suggest that the damaged timber is wet and that decay is likely to be ongoing. The exact meter readings will, however, be meaningless, and comparative differences should be considered in the context of the wider environment.

Assessing moisture gradients within timber

Figures 10 to 12 and 35 show how the surface of timber responds to environmental fluctuations and physical and chemical alterations wrought by time. Moisture content readings obtained from the surface of a component could be high, especially during the colder months. These readings, however, might not reflect the actual moisture content of the rest of the timber. Some part of a high surface reading might well represent extra moisture. However, because the calibration curve against which it is being tested is based on sound wood, this is by no means a certainty.

If surface readings are high, it is important to distinguish between some form of superficial phenomenon and actual elevated moisture content in the timber. Hammer probes that allow measurements to be taken at depth are useful for this (Figure 36). The electrodes have insulated shanks and exposed tips so that a moisture content gradient can be determined by driving them to progressively greater depths. In practice, the maximum depth may be limited. For example, electrodes driven 15mm into old dry oak might be very difficult to extract without snapping them. To avoid this, small diameter holes may be drilled to enable measurements to be made at depth.

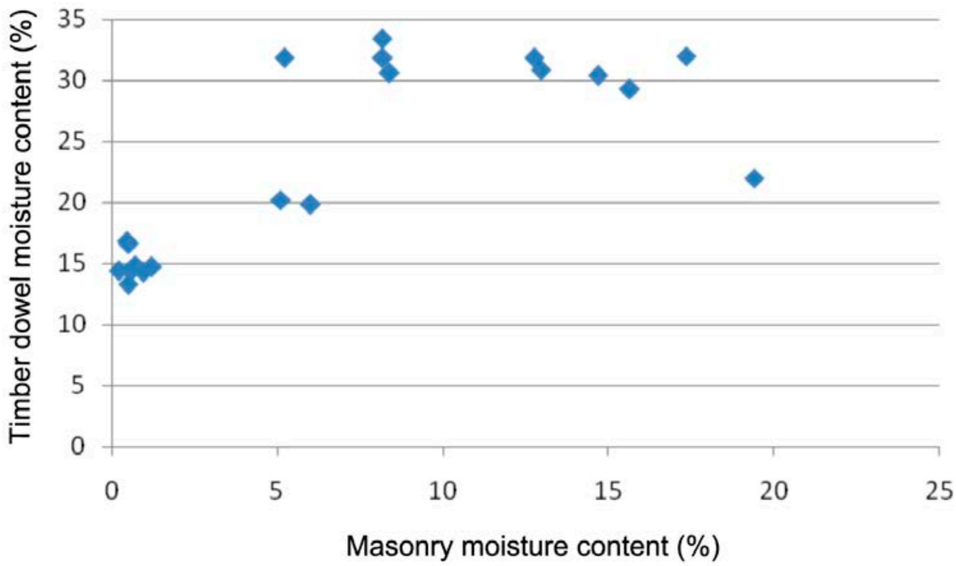
Figure 36:
A hammer probe has electrodes that are insulated, except at the tip. These can be driven into the timber to various depths to provide a moisture gradient.

Assessing masonry

Resistance meters for the non-destructive measurement of moisture contents in porous masonry have proved difficult to devise. Unlike timber, there is no easily exploitable relationship between moisture content and electrical resistance in masonry.

Some manufacturers have addressed this problem by producing meters that give readings in the form of an arbitrary reference scale, such as 1 to 100. Others show 'wood moisture equivalent'. This is claimed to be the moisture content that wood would attain if it was in contact with the material being measured. However, since the actual moisture content of the test material is unclear, its relationship with wood is dubious. In reality, the exchange of moisture between different construction materials is complex. There is rarely a simple relationship (Figure 37).

Figure 37:
A comparison between the moisture content of dust obtained by drilling 100mm-deep holes in the mortar joints of a Victorian brick wall and that of timber dowels inserted in the same holes and left to equilibrate for six weeks. All moisture contents were obtained by the oven/balance method.



Deeper readings in walls may be obtained if small holes are drilled. Several resistance meter manufacturers produce long insulated probes with uninsulated tips that can be inserted into pairs of pre-drilled holes. However, as with surface use, the contact between the probes and the wall is strongly influenced by the pressure applied (Trotman et al 2004). Consistent and meaningful readings can, therefore, be difficult to obtain. A second significant problem is that walls are rarely homogenous, making results difficult to interpret. A further shortcoming is that readings from resistance meters are greatly influenced by soluble salts, which will often be present in masonry affected by moisture.

Electromagnetic (pinless) devices

Pinless moisture meters use the influence of electromagnetic energy on the dielectric properties of materials to assess moisture content. The three main types suitable for site use are based on capacitance, microwave and ground penetrating radar technologies.

These devices allow easy and non-destructive investigation of large areas of wall surfaces. However, the reasons for any variations in meter readings will not necessarily be clear. Translating results into actual moisture content requires careful calibration, by referring to the moisture content of material samples determined by the oven/balance method. This might not be possible in a historic building where extracting samples is not permitted.

A further problem is that readings are influenced not only by the presence of moisture but also by material properties, including density and **porosity**. In traditional construction, these properties can vary considerably, even between masonry units within the same wall. For example, the porosity of bricks may vary because of inconsistent firing conditions in different parts of the kiln or clamp. If the meter indicates a 'damp' brick is next to a 'dry' brick, it is not always clear how much of the difference is due to moisture. A reading of, say, '42' on one brick would not necessarily indicate the same degree of saturation as a value of '42' obtained from another. Moreover, the deeper the generated signal penetrates, the more likely it is that there will be material variation or mixed materials. Therefore, the moisture content reading obtained will be an average not an exact amount.

In most cases, determining the absolute moisture content of materials (other than timber) is not necessary for practical purposes. Comparative readings between areas that are dry and those where damp is detected will generally be sufficient. Readings or scans should be taken on apparently dry surfaces similar to those being investigated. This will give 'dry' reference values against which other readings may be compared.

Differences between resistance meters and the three dielectric methods are summarised in Table 4.

Table 4:
A comparison between resistance meters and the three methods based on dielectric properties

Method	Measuring depth	Advantages	Disadvantages
Resistance meter	Surface, or up to depth of probe	Minimally destructive, unless deep wall probe used Acceptably accurate in timber at moisture contents below about 20% if surface effects are excluded and readings are adjusted for timber species Not affected by material density	Limited use in masonry because of difficulty in ensuring consistent contact with electrodes, resulting in variable readings and problems in interpretation Readings affected by salts Readings affected by temperature
Capacitance meter	Up to 50mm, but significantly less if there is a moisture gradient from a damp surface	Non-destructive Easy to use for comparative readings if surfaces allow for good contact with sensor head Readings not affected by temperature Readings less affected by salts than those from resistance meters	Readings significantly affected by material density Readings affected by surface texture of materials; readings from some meters are affected by the pressure with which they are applied to the surface Material sampling needed for calibration
Microwave (>10 GHz)	Up to 300mm, but less if there is a moisture gradient from a damp surface	Non-destructive Potentially greater depth of assessment than capacitance meters Readings not influenced by salts Readings not influenced by temperature Some devices allow large surface areas to be investigated on a grid pattern	Readings affected by material density, construction anomalies and voids Readings affected by surface texture Readings will be an average from surface to depth of signal penetration Material sampling needed for calibration
Ground penetrating radar	<1.5m in dry masonry, decreasing to <1m in damp masonry	Non-destructive Allows large surface areas to be investigated, usually on a grid pattern	Mixed construction and voids have effects that are hard to quantify, making it difficult to interpret results Need to produce a calibration curve by material sampling, so only really suitable for homogeneous construction

Capacitance moisture meters

Capacitance meters measure the ability of a material to hold an electrical charge. This ability is controlled by the insulating (dielectric) properties of the material concerned. Each material has a dielectric constant, which is the measure of its ability to store electrical energy in an electromagnetic field. The dielectric constant of water is high (approximately 80.1 at 20°C), but that of dry construction materials it is generally far lower (<5.0 at 20°C). This means that the capacitance of a wall material in situ is proportional to the amount of water it contains.

Capacitance meters use radio frequency waves to generate an electromagnetic field to a depth of perhaps 50mm in the material. They then measure the variations in dielectric constant. Their readings are unaffected by temperature and less influenced by salts than those produced by resistance meters. Their main disadvantage is that readings are influenced greatly by the density of the material under investigation. There are other drawbacks, too. Capacitance meters are significantly more sensitive to moisture at or near the surface than they are to moisture at depth. This can result in inflated readings caused by the presence of hygroscopic moisture or condensation. Misleading readings may also be obtained if the sensor is not in good contact with the surface or not held at the correct angle. With some devices, readings may be affected by how much pressure is applied to the surface. It is always important to follow manufacturers' instructions closely and to be consistent.

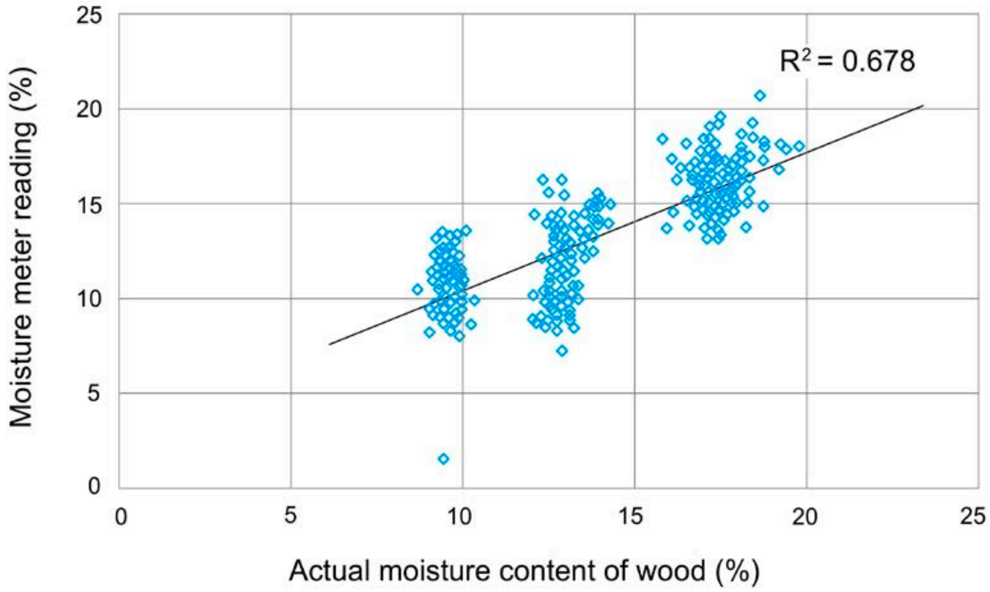
Assessing timber

The sensitivity of capacitance meters to variations in material density and surface roughness limits their usefulness in assessing timbers in historic buildings. Good results might be obtained with a carefully calibrated instrument from a sample of planed timber of known density, but unidentified timbers in historic buildings are a different proposition.

The density of timber varies between different tree species, between trees of the same species, and even within a single tree. Age is also a factor. Timber from a 200-year-old pine from the forests of northern Russia will generally be denser than timber from one grown on a modern plantation.

The VTT investigation provides a graph of wood moisture content readings, obtained gravimetrically, against capacitance meter readings that have not been corrected for density (Figure 38).

Figure 38:
Actual moisture content and capacitance meter readings for pine wood when the meter has not been corrected for density (source: VTT Publication 420, 2000). This shows a poor correlation between the two sets of measurements.



Assessing masonry

The University of Oxford carried out a laboratory-based evaluation of a range of moisture meters for Historic England (Viles et al 2022). Meter readings obtained from samples of limestone and brick were compared with their absolute moisture content at intervals during periods of wetting and drying. Capacitance meters all gave different readings from the same samples of known moisture content. However, some provided a reasonable correlation between meter readings and moisture content over at least a portion of the moisture range from dry to saturated. This may be useful for qualitative comparisons.

Meter readings obtained on site can be greatly affected by the surface roughness of walls or floors and variations in material density. Wall plaster might seem to be a good surface to scan, but it is difficult to be sure what lies beneath. Sudden high readings could reflect elevated moisture content, but they might also indicate a different type of brick or some other concealed anomaly. Similarly, stones in a damp wall may well be dry if water is percolating primarily through the mortar joints.

Microwave moisture meters

Microwave moisture meters transmit high frequency radio waves into a material and measure the attenuation of reflected signals. As with other electromagnetic techniques (capacitance, radar), the measurement relies on the contrasting dielectric properties of water and dry construction materials. A higher moisture content results in a greater amount of reflected energy and a correspondingly higher reading. While microwave moisture readings are not greatly affected by salts, they are strongly influenced by construction anomalies, including voids and the interfaces between different materials. Embedded metalwork, such as meshes, cramps and reinforcement, can also have a significant effect on readings.

Microwave devices produce electromagnetic fields that can penetrate up to 300mm in masonry. In general, they are sensitive to moisture within a radius equal to the depth of penetration. Some devices have interchangeable heads for different depths of penetration (see Case study 4), but they are significantly more sensitive to moisture near the surface. Like capacitance meters, microwave devices can give artificially high readings due to hygroscopic moisture or condensation.

Microwave meters usually display readings as an arbitrary numerical reference scale or as moisture contents calibrated for a particular type of material. Calibration tables are sometimes provided by manufacturers. However, their validity is questionable because of the variability of historic materials and the effects of ageing and weathering. Some devices incorporate software that allows a grid of readings to be displayed graphically as colours or grey-scale tones (see Case study 4). These can be an effective way of conveying measurements, but care is needed when choosing the colour/tone palette and scale. Some colour/tone schemes may lead to biased interpretation if they exaggerate or understate differences between wet and dry areas (Orr 2021, 32).

Like capacitance meters, readings from microwave meters are influenced by surface roughness. This can interfere with the transmission and reflection of the signal. Therefore, care should be taken when interpreting readings from materials with uneven or irregular surfaces. The angle of operation can also significantly affect the readings. It is important that the sensor head is positioned so the electromagnetic field is at right angles to the surface.

Radar

Ground-penetrating radar is an electromagnetic technique most commonly employed in structural investigations to locate hidden features and defects. It can also be used to indicate the presence of moisture. Radar signals are emitted by transmitter, potentially to a depth of 1.2m. The signals are scattered and reflected when they encounter interfaces between materials with differing dielectric properties. A receiver detects the reflected signals and measures their amplitude and travel time. In this way, moisture can be detected across the thickness of a construction as it will affect the travel time and amplitude of the reflected signal.

Readings are generally displayed as an x-y plot or a grid of measurements in which moisture levels are represented by colour, hue or grey-scale tone. In common with other electromagnetic techniques, radar does not measure absolute moisture content, so calibration is needed to obtain this information.

Radar moisture measurement requires specialised equipment and software to collect and analyse data. Data are usually collected along transects and grids, which can make using the device on rough surfaces or in difficult-to-reach places a challenge. Furthermore, the results can be hard to interpret, as outputs are influenced by anomalies in construction and voids as well as moisture. The validity and usefulness of the results will depend to a large extent on the knowledge, skill and experience of the operator.

Figure 39:
A schematic diagram of a radar antenna configuration showing the two main signal components used for measuring moisture and the way they travel through a wall. The surface wave amplitude provides information about surface moisture, and the travel time indicates the average level of moisture across the thickness of the construction.

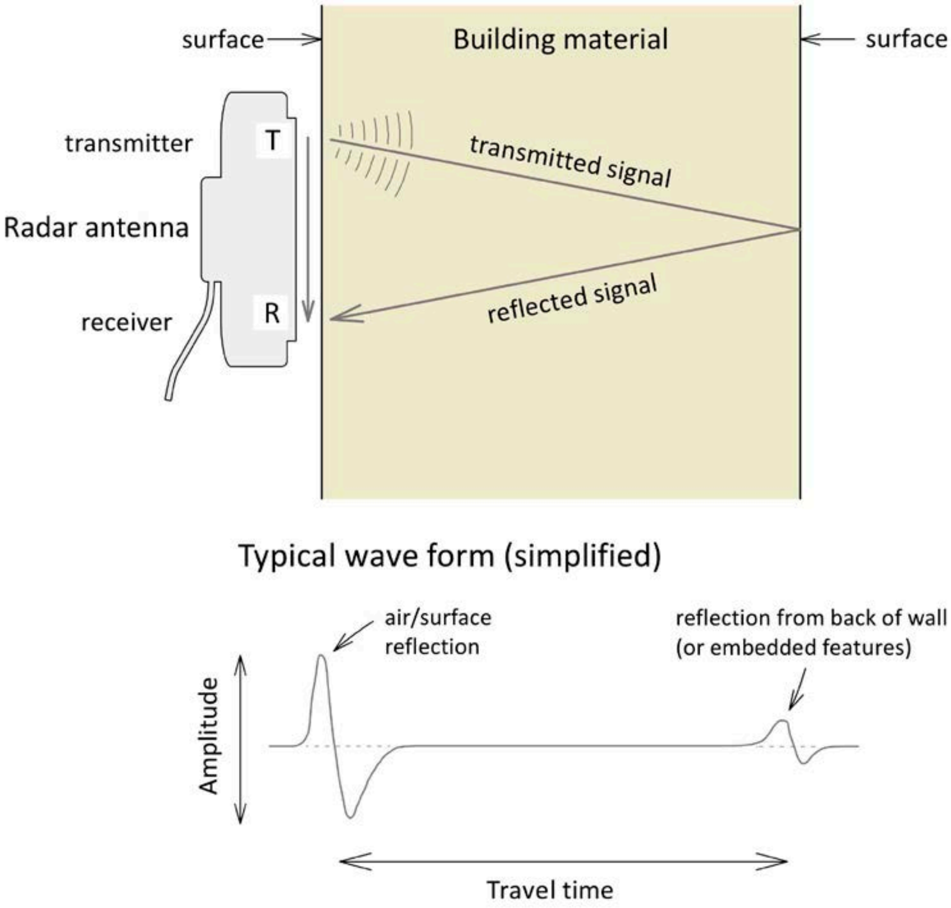


Figure 40:
A high resolution radar device in use. The antenna is placed on the surface of the wall, while the receiving unit (in the beige case) records the signal that is being reflected by the wall.

Infrared thermography

Infrared thermography (thermal imaging) uses a type of digital camera to produce images of **infrared radiation** emitted by objects or building surfaces. Since moisture evaporating from a surface has a cooling effect, the resulting reduction in temperature may be visible on a thermal image. Temperature differences between moist and dry areas may also exist because of increased thermal conductivity or capacitance, Thermal imaging can also be used to locate areas where condensation might occur because surface temperatures are below the dew point. Some cameras are capable of being programmed to calculate the dew point temperature in a particular environment and display the areas at risk of condensation.

Thermal imaging cameras convert the intensity of radiation at each image pixel to a surface temperature. Built-in software then displays temperature ranges as different tones or colours, which allow variations to be seen. Thermal imaging is useful because it is non-destructive, provides immediate results and enables large areas to be covered quickly. However, it does have some drawbacks. Interpreting images can be difficult, as variations in surface temperature are influenced by many factors unrelated to moisture. These include variations in the **emissivity** of surfaces and anomalies in construction.

Results are also affected by ambient environmental conditions and solar gain before and during the survey. For example, if air temperatures are low and relative humidity is high, there will be little evaporative cooling of surfaces, and temperature variations due to damp will not be visible. In certain conditions, moisture at depth within a wall may be warmer than surrounding materials because its thermal capacity is higher. In this situation, the presence of moisture would be indicated by the warmer area, rather than the cooler one.

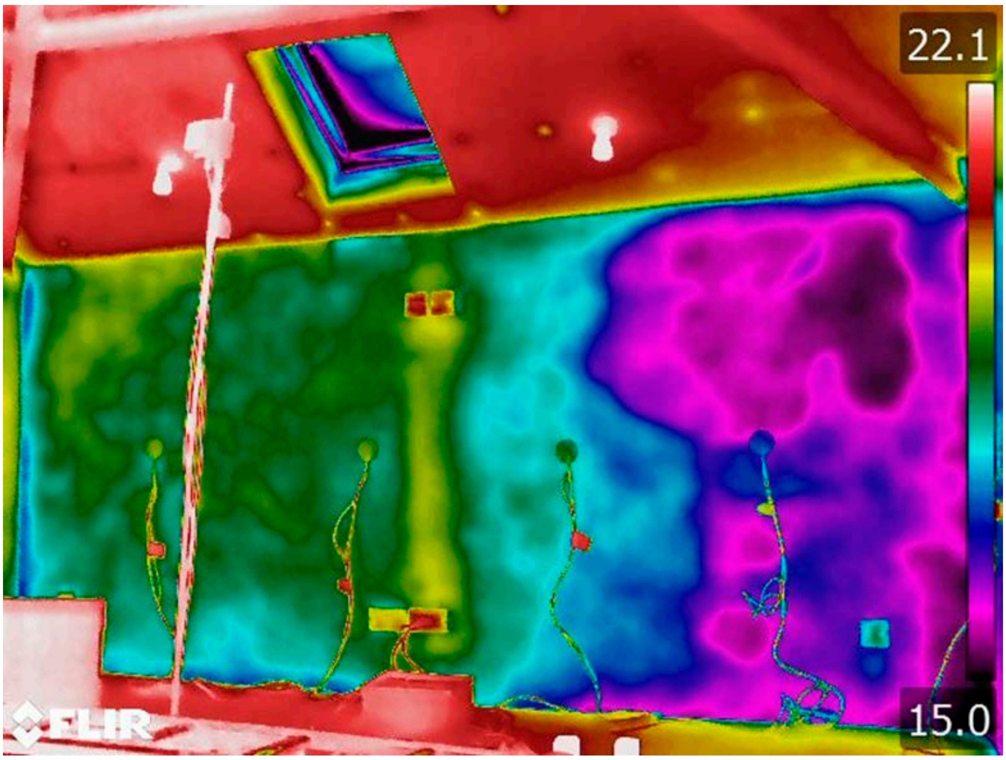


Figure 41: Thermographic image of the interior of an external wall. The colder (blue) areas on the right of the image correspond to damp caused by defective flashings to a chimney stack.

While thermal imaging is a useful investigative technique, it cannot distinguish between sources of moisture or 'see' beneath the surface. Therefore, it is best used in conjunction with other techniques. Ultimately, the quality and usefulness of the information obtained depend on the sensitivity and resolution of the camera and the skill and experience of the surveyor operating it and interpreting the outputs.

4 Conclusions

Investigating damp in historic buildings can be challenging. Although a building owner might allow a strip of plaster to be removed so that mortar joints can be sampled, this might not be allowed in a listed building or ancient monument. Investigations may also be hampered by time and financial constraints. Only limited conclusions can be drawn from limited data, but sometimes these are all that can be obtained. Then surveyors must rely on background information, appraisal of context, and their most effective and versatile tools: observation, experience and judgement.

In general, buildings have been designed and built to manage moisture and not become damp. Therefore, when investigating damp, there are two important questions to answer:

- How was the building intended to cope with moisture?
- What has changed?

Carefully annotated floor plans of each storey can help in providing a focus for observations and are indispensable if large areas or whole buildings are to be surveyed. They can be compared with one another to give a profile of problems in three dimensions, and to highlight gaps in the information obtained. Questions such as 'Where does that drain discharge to?' can sometimes explain a puzzling outbreak of decay.

If the limitations of specific measurement techniques are understood, then the most appropriate ones can be selected. It should always be remembered that moisture meters are not accurate instruments, and that different types and models will often give different readings.

If high resistance moisture meter readings are obtained from the surfaces of roof timbers in winter, a hammer-type probe should be used to determine the moisture content at depth in the bulk of the timber. Modern timbers in an old roof (such as repairs or added walkways) should be included in the survey, because they will have equilibrated in the same environment as the historic timbers. Hammer probes are also useful for assessing the risk of active decay at the backs of embedded components, such as wall plates and bonding timbers, because the moisture readings will increase with depth.

Moisture in materials other than timber is so variable that observing the adjacent environment gives a useful preliminary assessment. For example, a stack of dry magazines next to a moisture-damaged wall suggests that the wall is no longer damp; otherwise, the magazines would be damp too. Conversely, the presence of mould on wall surfaces behind furniture indicates a damp problem that should be investigated. Confirmatory tests should always be made where possible. Bear in mind that readings obtained from pinless moisture meters are influenced by the density of the materials under investigation as well as by moisture. These properties can vary considerably, even within the same wall. This problem can often be overcome by taking as many readings as time permits in both dry and damp areas. In this way, a range of readings from 'dry' to 'saturated' can be deduced.

Overall, the aim of investigation and treatment should be to trace the water back to its source, then eliminate it. But there may be several sources of moisture, some of which may not be immediately obvious. In such cases, periodic reappraisals over time will be needed to locate other sources of moisture, once more obvious problems have been eliminated.

The principles to be followed and the competencies required when assessing moisture in buildings of traditional construction are set out in a joint position statement issued by the Royal Institute of Chartered Surveyors. This was produced in collaboration with Historic England and the Property Care Association and can be downloaded here.

5 Case studies

Case study 1: Basement of a terraced house in London

The basement of a late Victorian end-of-terrace house in London was in poor condition when it was refurbished and extended in the 1990s. Twelve years later, the householder built a new bathroom. Then patches of damp staining started to appear. The wall between the study and the bedroom was the worst affected, and it was treated by a remedial company. There were concerns that a culvert beneath the road might be leaking, causing water to seep under the basement. Damp patches continued to appear on other walls, and comprehensive remedial plastering of the walls was recommended.

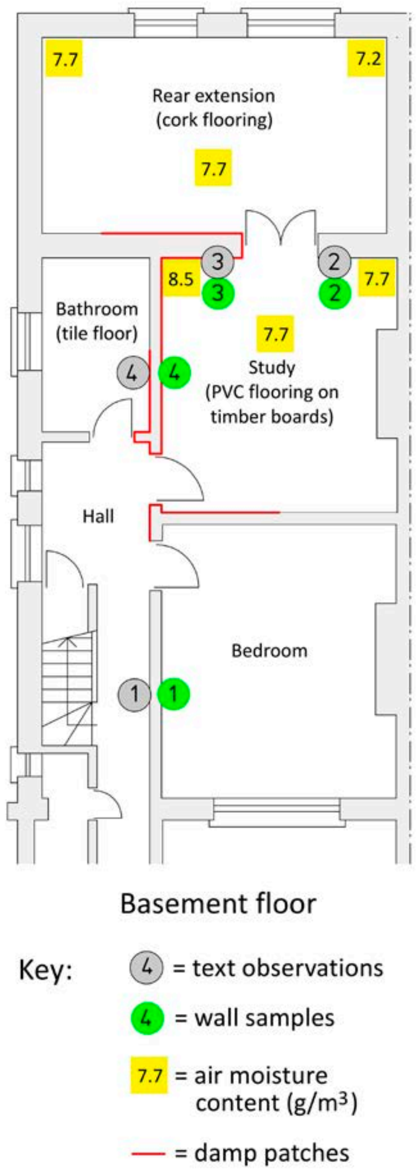


Figure 42:
Basement floor plan showing locations of observations (referred to in the text), extracted samples and air moisture content measurements.

Observations

See Figure 42 for locations.

Location 1: The plaster on the hall side of the wall was detached, although this was only apparent when it was tapped.

Location 2: Paint was flaking on the study side of the wall and the skirting board was damaged. Resistance moisture meter readings at the base of the door frame and skirting were 8 to 10%. (A dry reading would be less than about 16%.)

Location 3: Paint was flaking and skirting was damaged on both sides of the wall. Resistance moisture meter readings of the skirting board were 27 to 33%.

Location 4: Paint was flaking on both sides of the wall.

Wall moisture assessment

Method

A masonry bit was used to extract samples of plaster and brick from the walls. The samples, each about 3.0g, were extracted sequentially – first the plaster, then the brick – and sealed into separate glass vials for moisture content assessment by the oven/balance method. The samples were weighed, then dried for five hours at 35°C. Next, the dry samples were stored at a relative humidity of 75% for four days to determine their hygroscopic moisture content. This is a measure of hygroscopic salt contamination that could signify damp caused by water percolating through the ground.

Results

The results are presented in Table 5:

Table 5:
Absolute moisture contents (%mc), hygroscopic moisture contents (%hmc) and free water moisture content.

Height above floor (mm)	Sample location 1	%mc	%hmc	Free water %	Sample location 2	%mc	%hmc	Free water %
1000	1.4 brick	0.5	1.2	0	2.4 brick	0.3	1.2	0
1000	1.4 plaster	0.2	0.7	0	2.4 plaster	0.6	2.2	0
750	1.3 brick	0.1	0.8	0	2.3 brick	0.0	0.4	0
750	1.3 plaster	0.0	3.0	0	2.3 plaster	0.2	0.8	0
500	1.2 brick	0.3	0.6	0	2.2 brick	0.4	1.1	0
500	1.2 plaster	0.1	3.2	0	2.2 plaster	1.0	3.0	0
200	1.1 brick	3.6	3.7	0	2.1 brick	0.5	0.5	0
200	1.1 plaster	1.2	3.0	0	2.1 plaster	3.5	1.5	2.0
Height above floor (mm)	Sample location 3	%mc	%hmc	Free water %	Sample location 4	% mc	%hmc	Free water %
1000	3.4 brick	0.2	0.7	0	4.4 brick	2.2	1.7	0.5
1000	3.4 plaster	1.0	2.9	0	4.4 plaster	1.5	3.1	0
750	3.3 brick	0.4	0.8	0	4.3 brick	8.1	5.8	2.3
750	3.3 plaster	0.3	0.9	0	4.3 plaster	1.7	2.5	0
500	3.2 brick	0.4	0.8	0	4.2 brick	15.0	1.2	13.8
500	3.2 plaster	1.4	3.3	0	4.2 plaster	7.6	3.7	3.9
200	3.1 brick	3.4	0.7	2.7	4.1 brick	2.0	1.3	0.7
200	3.1 plaster	3.2	1.0	2.2	4.1 plaster	2.3	2.0	0.3

Moisture contents are categorised according to the following colour scheme:

	Dry	<3%
	Damp	3.1–6.0%
	Wet	6.1–10.0%
	Saturated	>10%

The amount of free water present (that is, water not bound to hygroscopic salts) is calculated by subtracting the hygroscopic moisture content from the moisture content and obtaining a positive result. For example, the moisture of 1.4 brick was 0.5%, but its hygroscopic moisture content was 1.2%. Therefore, no free water was present.

Location 1 was dry, but the slightly elevated hygroscopic moisture content in the plaster at 750mm (1.3 plaster = 3.0%hmc) and brick to at least 200mm (1.1 brick = 3.7%hmc) shows that there had been moisture rising in the internal walls. However, the brick moisture content (%mc = 3.6) was the same as the brick hygroscopic moisture content (%hmc = 3.7). This indicates that the damp in the wall base was moisture absorption by hygroscopic salts. There was no free water in the brick or the plaster and, therefore, no indication that water was coming from the road or the front wall of the building.

In Location 2, there was slightly damp plaster at about 200mm (2.1 plaster = 3.5%mc). The evaporation of rising moisture had produced a minor salt band at about 500mm (2.2 plaster = 3.0%hmc), but the brickwork behind was dry. This salt band might have been a remnant of an old problem, because the free water at the base of the wall was only 2%.

Location 3 was also slightly damp at 200mm. However, in this case, the plaster and the brick behind had similar moisture contents (3.1 plaster = 3.2%mc; 3.1 brick = 3.4%mc). Both were higher than their hygroscopic moisture content, thus indicating 2 to 3% free water. The hygroscopic band in the plaster at 500mm (3.2 plaster = 3.3%hmc) suggests that there was an old damp problem that carried salts into the plaster at the highest point of evaporation. However, the moisture problem at 200mm with no hygroscopicity indicates an additional fairly recent source of damp.

Location 4 was wet from below 500mm to above 750mm above the floor (4.2 plaster = 7.6%mc; 4.2 brick = 15.0%mc; 4.3 brick = 8.1%mc). Samples at 200mm were dry (4.1 brick = 2.0%mc). This suggests that the water was coming from the bathroom wash hand basin on the other side of the wall. Elevated hygroscopic moisture content readings from about 750mm to 1m in the bricks and plaster (4.3 brick = 5.8%hmc; 4.4 plaster = 3.1%hmc) indicate a historic damp problem with this wall. Bands of hygroscopicity take many decades to develop.

Environmental assessment

Air moisture contents (g/m^3) were calculated from temperature/relative humidity readings obtained using a thermohygrometer, which was allowed to equilibrate in each location. Results are provided in Figure 42. Readings were taken in the corners (in a cupboard and under a piano in the extension) for comparison with the centre of the rooms. Results show that the external walls are not contributing moisture to the room environment, except in the corner of the study between wall locations 3 and 4. This result was supported by dry resistance moisture meter readings (8–10%) obtained from the top edges of skirting boards (the part definitely in contact with the wall) around most of the walls wherever measurements were practical.

Significantly, books and papers within the rooms had not been affected by damp, despite prolonged wet weather prior to the survey.

Conclusions

The basement did not have a severe damp problem, and there were no indications that water might be leaking in from a culverted river. The building was in poor condition prior to renovation, and there was a history of damp at the bases of the walls, which had left a residue of hygroscopic salts in the brickwork and plaster. Occupancy raises humidity and moisture absorption by hygroscopicity, and was probably the cause of the earlier treated damp damage.

There was a little free water at skirting level either side of the door to the extension (Locations 2 and 3). However, the percentage was low, which suggests that either residual moisture was still being lost from what had been an external wall (but the hygroscopicity was low) or that there is some small current source.

The localised wet area in the wall between the study and the bathroom suggests a fault associated with the wash hand basin. Water from the bathroom might also have been the cause of the other two damp areas if it had percolated down within the wall to below the floor slab.

The external drainage system was modern and had been surveyed a few years prior to the damp survey. The rainwater pipes on the side and back wall were too far away from the bathroom/study partition wall to be implicated in localised damp at the base of the old external wall. There was a narrow channel adjacent to the old external wall, but this seemed intended only to lower the ground level. It appeared unlikely that general ground moisture from the exterior would have penetrated so far under the floor as to reach the old external wall. The bathroom plumbing required investigation, but there did not seem to be any need for plaster removal or other large-scale interventions.

Case study 2: Damp staining and condensation

This case study concerns the west wing of a mid-18th-century Palladian house that was surveyed in 2010, a few weeks before it was severely damaged by fire. Case study 3 considers the consequences of the fire.

The roof of the house had been replaced in two phases between 2003 and 2006. A condition survey in January 2010 reported extensive damp staining on first-floor ceilings and some wall areas, together with severe condensation. The surveyor's instructions were to locate the sources of moisture causing the condensation and to ascertain if the damp staining was progressing, or whether it predated the roof replacement. The winter weather had been warm and wet, followed by a long cold period. There was no heating or ventilation in the building.

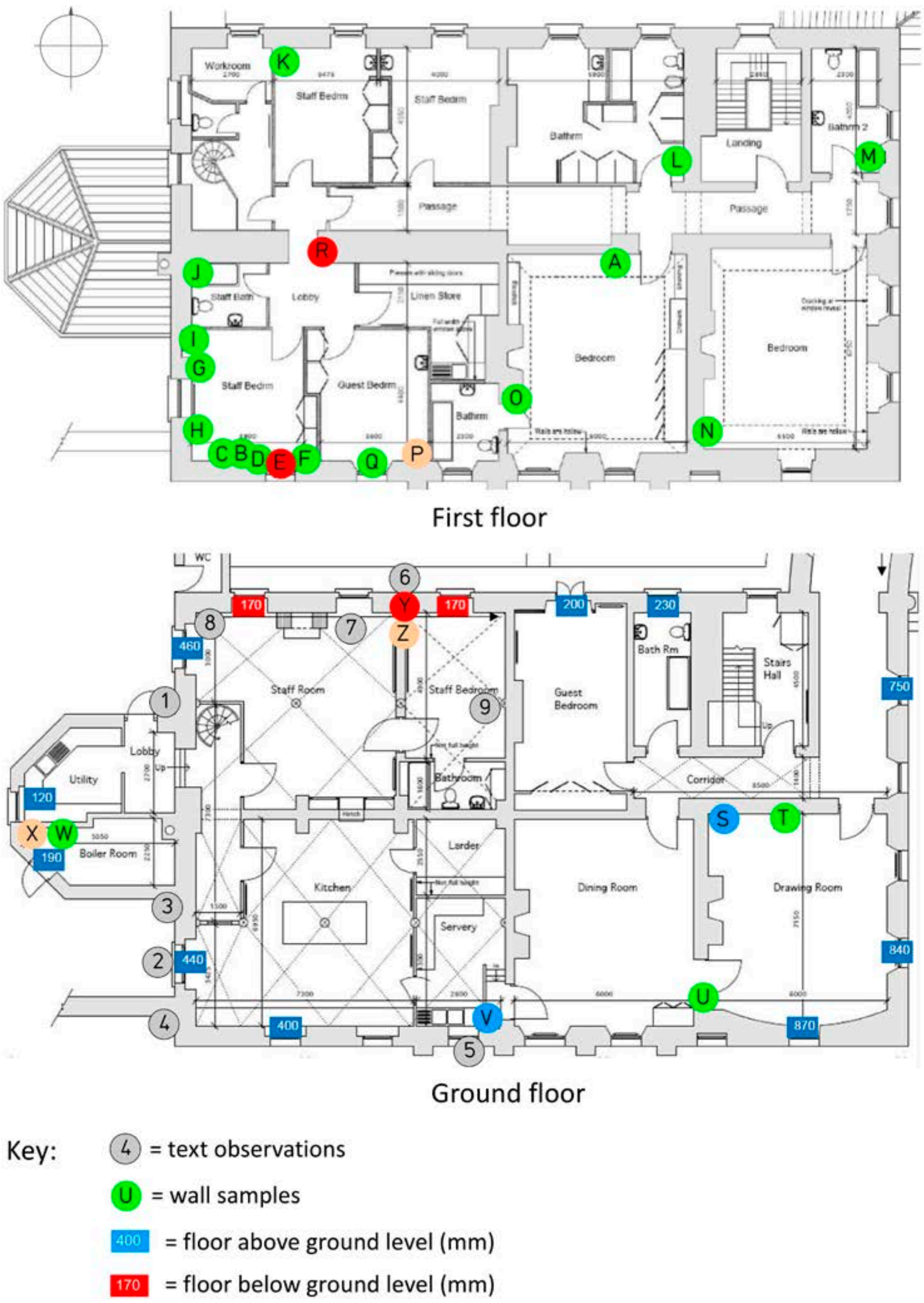


Figure 43:
Ground and first-floor plans showing locations of observations (referred to in the text), extracted samples and the relationship between ground-floor and exterior levels.

Observations

Locations are shown in Figure 43.

Location 1: Standing water was visible in the drain. Gutters above had moss and run-off stains down the wall, suggesting a blockage.

Location 2: Render was cut out around a large crack above the window.

Location 3: Drain was blocked.

Location 4: From the last joint downwards, the lead downpipe was badly split. There was no connection with the plastic section, and the drain was blocked.

Location 5: Drain was blocked.

Location 6: Drain was blocked

Location 7: There was damp at low level (skirting board 18–20%mc).

Location 8: There was severe damp damage at low level; the wall was saturated. Patches of damp damage were seen over the full height of the wall. A small asphalt roof had failed completely, revealing a water tank.

Location 9: There was damp damage at the base of the wall and a wet skirting board (>29%mc).

Method

Discrete sampling of wall materials from damaged areas was permitted. It was not practicable to use data loggers in the time available because the damp staining was too extensive. A total of 26 masonry samples were removed from the walls: 18 from the first floor, in areas where the walls were not lined, and 8 from the ground floor. The samples could not be extracted solely from mortar joints, because this would have involved removing unacceptably large areas of plaster. However, a dry result would be similar in any of the walling materials. Absolute and hygroscopic moisture contents were obtained gravimetrically, using the methods described in Chapter 3.

Potential sources of damp were identified by inspecting the drainage and comparing ground levels with floor levels at a ground-floor window.

Results

Results are shown in Tables 6 and 7.

Table 6:
First floor.

Sample	Position	Sampling observations	%mc	%hmc	Free water%
A	1.5 m from floor level	Area of damp staining	0.2	0.1	0.1
B	1.5 m from floor level	Area of damp staining	0.9	0.8	0
C	0.5 m from floor level	Area of damp staining	1.3	1.8	0
D	1.25 m from floor level	Area of damp staining in window reveal	2.3	1.9	0.4
E	Centre of arch	Area of damp staining in soffit of window reveal	17.8	0.8	17.0
F	1.25 m from floor level	Window reveal – undamaged area (control)	0.4	0.2	0.2
G	1.5 m from floor level	Undamaged area (control)	0.3	0.3	0
H	1.25 m from floor level	Area of damp staining	2.2	2.6	0
I	Centre of arch	Area of damp staining. Centre of reveal arch	1.2	1.0	0.2
J	1.25 m from floor level	Area of damp staining	2.9	2.8	0.1
K	1.25 m from floor level	Taken from area of exposed masonry	1.6	1.3	0.3
L	2.1 m from floor level	Taken as 'test' from area of damaged paintwork that is attributed to condensation	1.3	1.3	0
M	2 m from floor level	Slight damp damage	2.4	1.3	1.1
N	1.25 m from floor level	Undamaged, below structural crack and above damp damage at ground level	0.5	0.6	0
O	1.25 m from floor level	Taken as 'test' from area of damaged paintwork that is attributed to condensation	0.3	0.4	0
P	1.75 m from floor level	Area of damp staining	6.6	3.1	3.5
Q	Centre of arch	Area of damp staining. Centre of reveal arch	1.7	1.0	0.7
R	High level	Area of damp staining on chimney. At roof level, a flue is open (photograph 2) and several cladding slates are missing	14.7	0.9	13.8

Moisture contents are categorised according to the following colour scheme:

Dry	<3%
Damp	3.1–6.0%
Wet	6.1–10.0%
Saturated	>10%

Table 7:
Ground floor.

Sample	Position	Sampling observations	%mc	%hmc	Free water%
S	1.15 m from floor level	Masonry removed from behind the wet wallpaper	4.7	5.6	0
T	1.25 m from floor level	Masonry removed from behind the wet wallpaper	2.0	2.5	0
U	0.4m from floor level	Internal wall. Wall behind damp wallpaper on south wall is dry lined	0.7	0.8	0
V	1.25 m from floor level	Exposed masonry in area from which sinks etc have been removed	6.3	4.8	1.5
W	1.25 m from floor level	Exposed masonry	1.0	0.7	0.3
X	0.15 m from floor level	Exposed masonry below sample W	9.7	0.9	8.8
Y	0.15 m from floor level	Exposed masonry at low level. Sample visibly saturated	25.8	2.9	22.9
Z	1.1 m from floor level	Exposed masonry above sample Y	7.0	2.2	4.8

Moisture contents are categorised according to the following colour scheme:

Dry	<3%
Damp	3.1–6.0%
Wet	6.1–10.0%
Saturated	>10%

Free water is present only where the absolute moisture content exceeds the hygroscopic moisture content and is significant only when the samples fall into the ‘damp’, ‘wet’ or ‘saturated’ categories. This is only found in samples E, P and R on the first floor and V, X, Y and Z on the ground floor, and it is associated with external faults. Sample S was damp, but this was attributed to hygroscopic salts from a flue (%mc = 4.7; %hmc = 5.6).

Conclusions

The walls were mostly dry, and the damp staining predated the re-roofing. The water contributing to the excess condensation came from a variety of sources: two flues (Sample R on the first floor, Observations: Location 9 on the ground floor); high ground levels along the west half of the north wall; a faulty flat roof over an attached external WC in the northwest corner (Observations: Location 8), and faulty below-ground drainage all around the building.

Case study 3: Drying following fire damage

The damp investigations discussed in Case study 2 were undertaken at the end of January 2010. A few weeks later, there was a serious fire caused by an electrical fault, which destroyed about 80 per cent of the roof as well as first-floor ceilings and partitions.

The external walls of the building were built of stone rubble and the interior walls of brick. The ground floor in the fire-damaged area had originally accommodated stables and was built as a series of brick groin vaults supported on granite columns. This construction prevented the fire from spreading to the ground floor. However, it acted as a sponge for the water used to fight the fire. It is this section of the building that is the subject of this case study.

The fire occurred during a refurbishment contract, and the project team was able to react rapidly with 'first aid' protection measures in the immediate aftermath. This was critical, because long delays often occur after fires while forensic investigations and insurance assessments are dealt with. A prolonged lack of weatherproofing combined with wet debris can result in serious decay.

By the time the first damp survey was carried out in March 2010, a temporary roof, designed to maximise ventilation, was in place (Figure 44) and most of the debris had been cleared.

The surveyor's instructions were to:

- Establish the levels of moisture in the core fabric now that the structure was protected from weather
- Advise on a regime and measures for drying out the building (for example, removing hard or impervious coatings).

Figure 44: Temporary roof and weatherproofing designed to maximise ventilation.

Method

The fire-damaged wing of the building was inspected, as far as safe access permitted. Mould growth was noted, and resistance moisture meter readings were taken from timber wherever appropriate. Mortar samples were collected from the walls using a 9 mm masonry bit to a depth of 200 mm. The dust collected from each hole was mixed to minimise 'within sample' variation, and enough was retained to fill a glass vial (about 3 g). Moisture contents and hygroscopic moisture contents were determined gravimetrically, using the methods described in Chapter 3 to ascertain the pattern of moisture distribution.

Results

The moisture content (%mc) and hygroscopic moisture content (%hmc) results for different sample locations are shown in the floor plans in Figure 45.

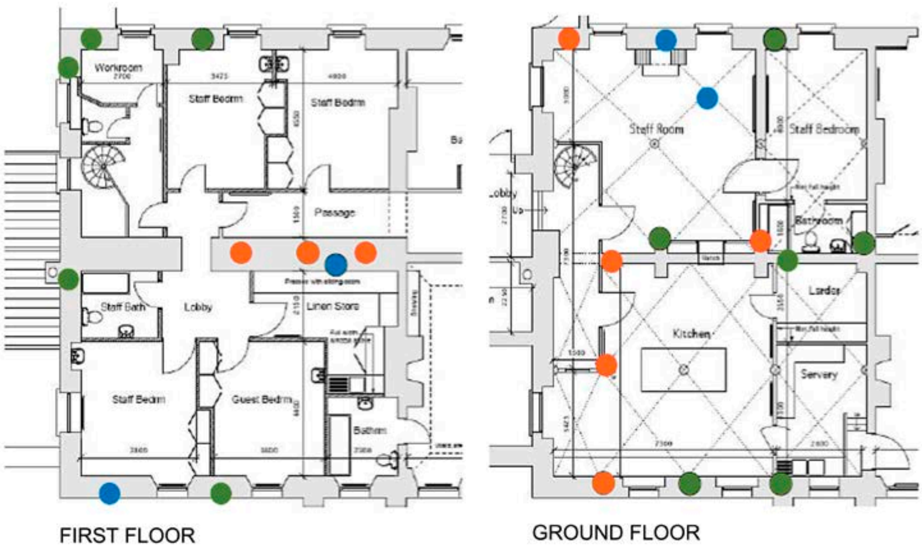


Figure 45:
Ground and first-floor plans showing moisture distribution as indicated by samples removed from the fire damaged area in March and August 2010, after removal of hard, cementitious render. The results obtained in August are ringed in black.

Moisture contents are categorised according to the following colour scheme:

Dry	<3%
Damp	3.1–6.0%
Wet	6.1–10.0%
Saturated	>10%

The water used to fight the fire had mostly soaked the internal central wall, but the external walls were largely unaffected. The fire had destroyed the central portion of the roof, but the rafter ends above the external walls were mostly undamaged. This suggested that the roof had remained largely intact in this location during firefighting, which prevented water ingress at the head of the walls (Figure 46). The damp area in the top left corner of the ground-floor plan in Figure 45 predated the fire (see Case study 2). The brick vaulting, which still retained its lime plaster, was visibly wet, with mould growth developing.

Figure 46:
Although the central portion of the roof was destroyed by the fire, it remained intact above the external walls. The rafter ends were mostly undamaged, as can be seen in the lower left of this image. This protected the wall heads from saturation by water used in fighting the fire.

Radiant panel heaters were installed, providing background heating to assist drying. Blowers were used to maintain good air circulation. (Quadrupling the air flow across a surface doubles the rate of evaporation). One heater was placed next to the central wall on the first floor, and two blowers were angled to provide air flow across the wall surface. Eleven heaters were positioned around the walls on the ground floor, with the same number of blowers directed upwards to the vaulting (Figure 47).

Figure 47:
Heaters and air blowers (pointing upwards in a wooden frame) in use after the hard cementitious finishes had been removed from the external walls to aid drying. The original lime plaster on the vaulting was not removed.

The building was revisited a year later, in March 2011. The old radiator system was now working (replacing the radiant panel heaters) and the blowers were still in use. Timber moisture contents were dry, except where they were in contact with recently applied plaster on the first floor. Mortar samples were taken from accessible areas. Results are shown in Figure 48.

Figure 48: Ground and first floor plans showing locations of samples taken in March 2011. A drying environment was maintained by the heating system and blowers. Thermo-hygrometer readings taken around the rooms were 45% relative humidity at 13 to 15° (in three locations) on the ground floor and 45 to 54% relative humidity at 12 to 15°C (in four locations) on the first floor.

Moisture contents are categorised according to the following colour scheme:

Dry	<3%
Damp	3.1–6.0%
Wet	6.1–10.0%
Saturated	>10%

Conclusions

The building had been dried using background heating and forced air circulation. Key stages of reinstatement works could then commence.

A final visit was made during November 2012, when works were complete. Mortar samples could not be removed, but moisture meter readings were taken from the tops of skirting boards and joinery elements all around the rooms. Enough time had passed for the timber to be in equilibrium with the walls behind. All readings were below 12%mc in the fire-damaged zone. The environment was dry, and there were no signs of residual damp.

Case study 4: Damp patches on walls in an 18th-century orangery

This case study describes investigations carried out to identify the cause of damp affecting walls in the northwest corner of a former 18th-century orangery, now used as an events venue. The walls were built of 450 mm-thick brickwork, finished externally with oil-painted render and internally with painted plaster. The building has a pitched slate roof, which drains into lead-lined parapet gutters on its north and south sides. Each gutter terminates at the west end in a shallow lead-lined sump with an outlet. This discharges into a lead pipe that passes through the brick parapet and thence into a lead hopper head and rainwater pipe on the west elevation of the building.

Figure 49:
Northwest exterior of the orangery.

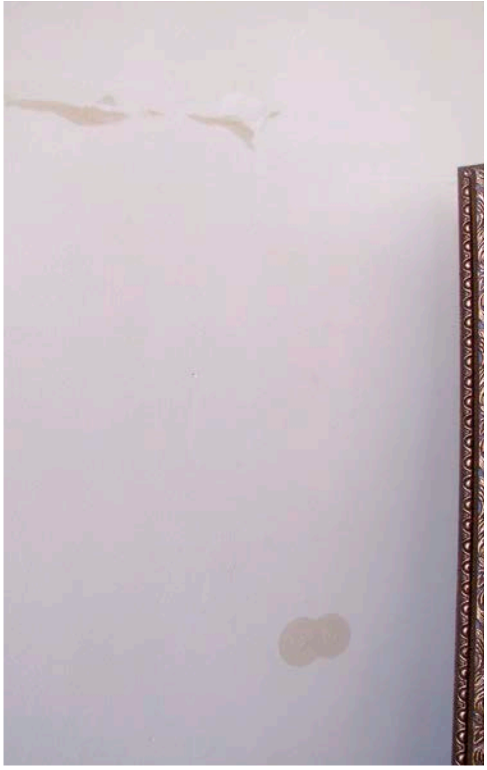
Initial observations

Internally, there were numerous irregularly shaped damp patches covering an area of approximately 6m^2 at the western end of the north wall. The affected area extended to a height of approximately 3 m above floor level. On the west wall, there were two smaller damp patches, about 1.2 to 1.5 m above floor level (Figures 50 and 51). Soluble salts were evident on surfaces within the damp areas, and some localised detachment and flaking of paint finishes had occurred. On the west wall, one of the damp patches was circular and centred around a screw or other fastening; the other was linear and corresponded to a crack in the plaster substrate.

Externally, there were some localised areas of flaking paintwork at high level on the north elevation; otherwise, the render and paintwork appeared to be in good condition. The lead parapet gutters also seemed to be in sound condition, although some leaves, twigs and moss were partially obstructing the outlets at the west end of the roof (Figure 52). It was noted that the lightning protection down-conductors (which had been routed through the

Figure 50 (left):
Detail of damp patches on the interior of the north wall. Detachment of loose and flaking modern coatings revealed blue lime wash.

Figure 51 (right):
Two small damp patches on interior of west wall. The upper one appeared to reflect a crack in the substrate; the lower one surrounded a fastening. This suggested that an impermeable render/plaster finish had been applied to this wall, but that moisture had penetrated where this was cracked or pierced.



outlet pipe passing through the parapet for aesthetic reasons) increased the risk of blockages by trapping leaves and debris. Inspection of the roof space revealed no evidence of recent rain penetration. However, the gullies at the base of the rainwater pipes were partially blocked.

The building manager reported that guttering defects at the west end of the roof had caused significant water penetration through the ceiling, and that water had been seen running down the north wall. These defects had been remedied 12 months prior to the surveyor's initial inspection. The building manager also observed that the damp patches appeared to become more conspicuous during damp and wet weather.

Figure 52:
Rainwater outlet from the parapet gutter on the north side of the building. The outlet was relatively small, and a lightning protection down-conductor routed through it increased the risk of blockages.

Figure 53:
Hopper head and rainwater pipe from parapet gutter on north side of building.

Initial diagnosis and recommendations

It was thought that the damp patches were a remnant of the rain penetration that occurred before the remedial works to the parapet gutters were carried out. Large volumes of water penetrating wall heads would have tended to flow downwards and spread laterally through open joints within the thickness of the wall. The thickness of brickwork, coupled with relatively impermeable internal and external finishes, meant that drying would have been a slow process. It would be quite possible for the walls to still be damp after 12 months. The fact that the damp patches seemed more conspicuous during periods of high humidity could be explained by the hygroscopicity of soluble salts that had migrated to the surface as drying proceeded. Recommendations included clearing the blocked gullies, investigating the adequacy of below ground drainage arrangements, using fans to aid drying and providing leaf guards to prevent rainwater outlets becoming blocked.

Subsequent investigations

Four months later, the building manager reported water oozing from the damp patches during a long spell of heavy rain. It was clear that further investigations were needed to pinpoint the source of moisture ingress. In addition, the investigations provided an opportunity to compare the results obtained from a variety of moisture assessment techniques and devices. These included a capacitance moisture meter, timber dowels, a microwave moisture meter and infrared thermography.

In addition, a closed-circuit television inspection was made of the above ground rainwater drainage arrangements.

Assessment with capacitance moisture meter

Method

Surface readings were taken with a capacitance moisture meter (CEM DT 128) on a 300 mm grid over the affected area. This moisture meter displays readings as a numerical reference scale from 1 to 100. To obtain a 'dry' value for comparison, multiple readings were taken from adjacent wall surfaces where there were no signs of damp.

Results

The results were plotted on a drawing to indicate moisture distribution (Figure 54). This corresponded with the visible patterns of dampness.

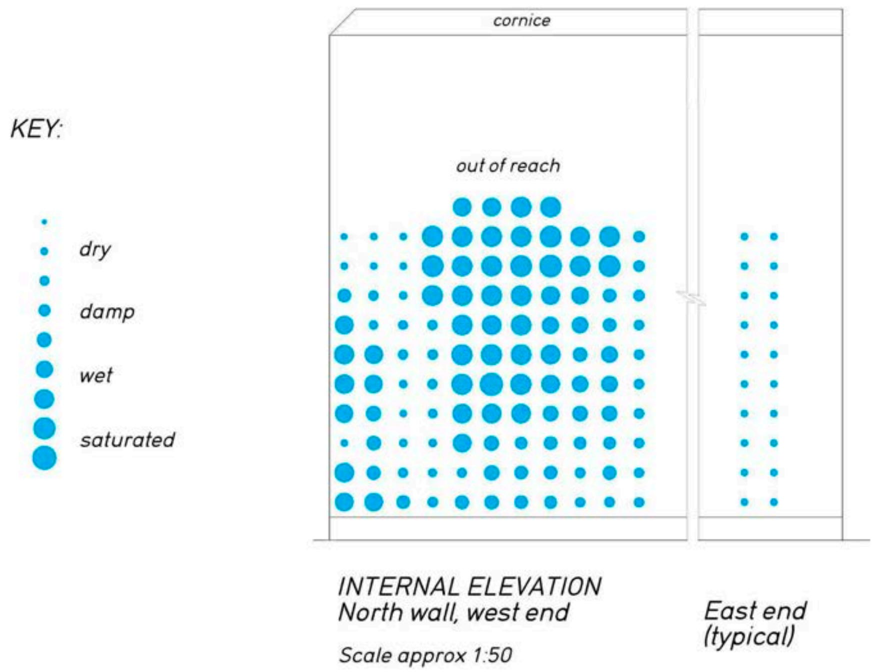


Figure 54:
Interior of north wall: superficial moisture mapping using a capacitance moisture meter.

Assessment with timber dowels

Method

Permission was obtained to drill an array of 12 mm-diameter holes, 300 mm deep, in the damp-affected area. Pine dowels (8 mm diameter) were inserted and the open ends of the holes were plugged with an acrylic sealant. The dowels were left for six weeks to equilibrate. They were then removed and cut into three 100mm-long sections. The moisture content of each section was determined by the oven/balance method.

Results

The results were plotted on a drawing to indicate moisture distribution and profiles through the wall (Figure 55). They showed that the masonry in the northwest corner was wetter than indicated by the surface capacitance meter readings and the visible patterns of damp.

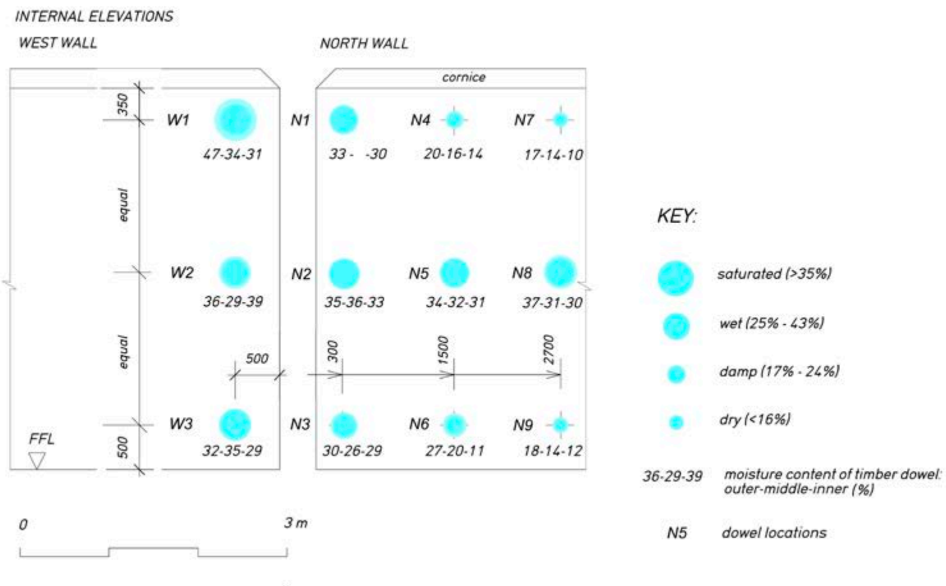


Figure 55:
Moisture content of timber dowels.

Assessment with microwave moisture meter

Method

Surface readings were made using a microwave moisture meter (MOIST 350B) on a 500 mm grid. This device has three interchangeable non-invasive sensor heads, producing electromagnetic fields that penetrate masonry incrementally up to a depth of about 300 mm. Readings are displayed as a numerical reference scale from 1 to 5,000. The instrument also allows outputs to be displayed graphically as grey-scale tones or colours. Readings within the thickness of the wall were taken, at 50mm increments up to a depth of 350 mm, using a probe-type sensor head inserted into the holes drilled for the timber dowels.

Results

The results are shown in Figures 56 and 57. The outputs from the surface sensors corresponded closely to the results obtained using the capacitance meter and from the visible patterns of damp. The results from the probe sensor corresponded with those obtained from the timber dowels and indicated higher moisture contents in the northwest corner at depth than were evident on the surface.

Figure 56:
North wall: moisture mapping using a microwave moisture meter.

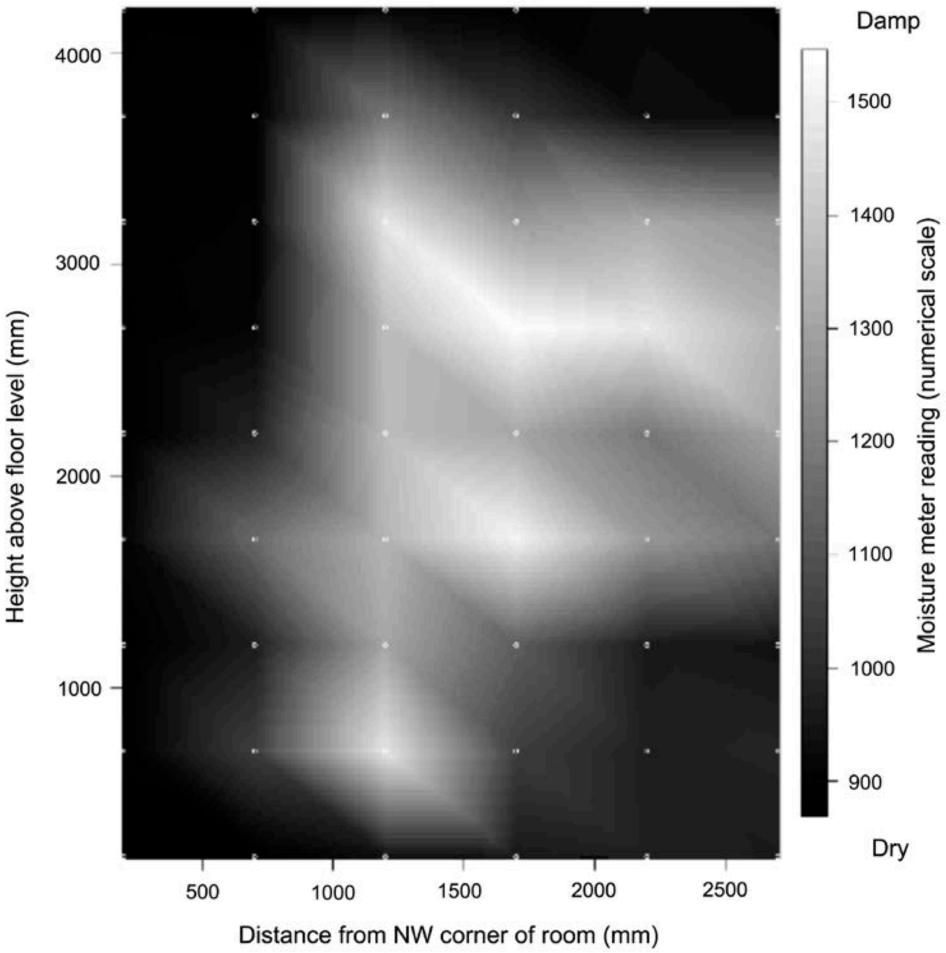
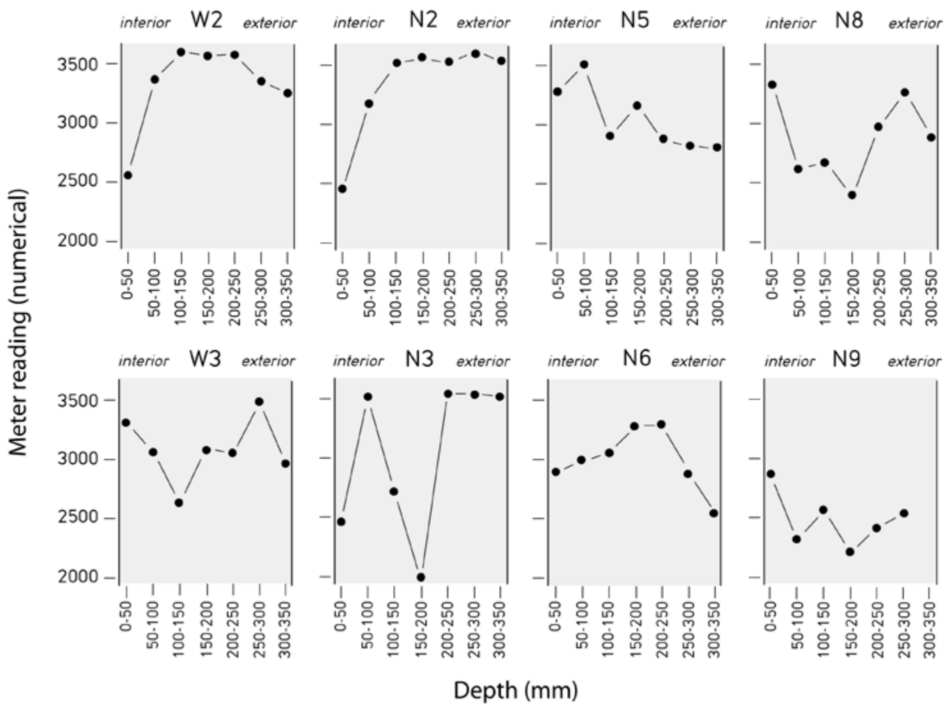


Figure 57:
Moisture profiles through thickness of north and west walls using microwave probe sensor inserted into the holes previously drilled for timber dowels (positions shown in Figure 55).



Assessment with infrared thermography

Method

Infrared thermographic images of the internal surfaces of the wall were obtained from a thermal imaging camera (FLIR Model B335).

Results

The thermal images revealed variations in surface temperature corresponding to the differing thermal properties of construction elements and materials, as well as differences in moisture content. In particular, rectangular features in the northwest corner suggested that the original plaster in this area had been replaced. The thermal images also indicated a cooler area on the north wall, which corresponded with the visible patterns of damp and the results obtained from the non-invasive assessment techniques (Figures 58 and 59).

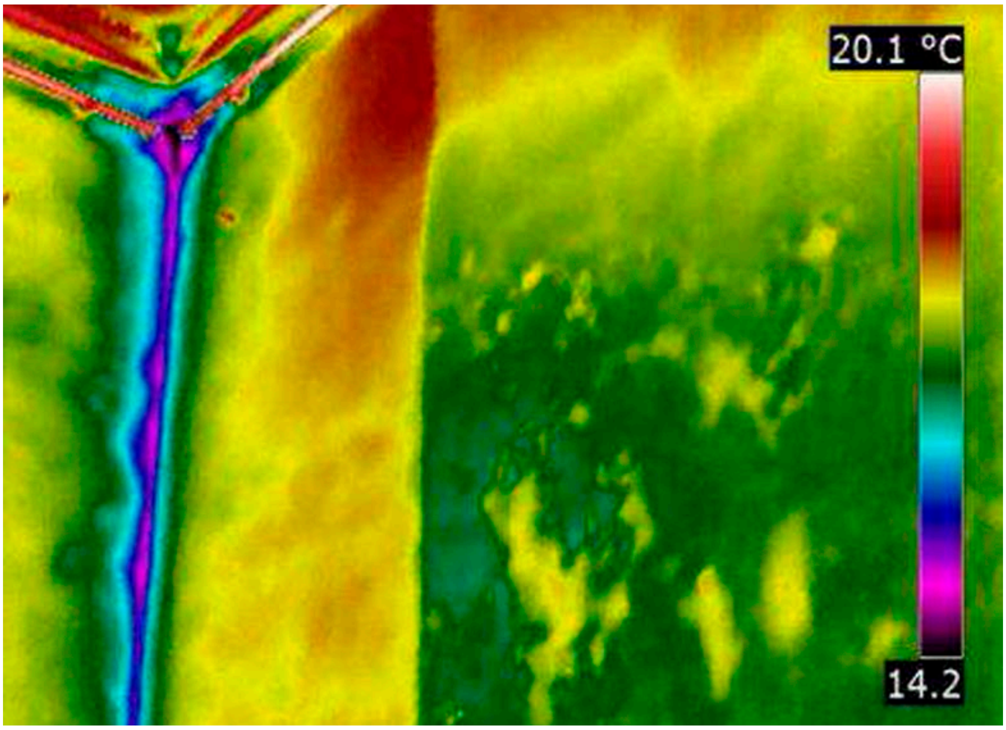


Figure 58:
North wall internal elevation: thermal image.

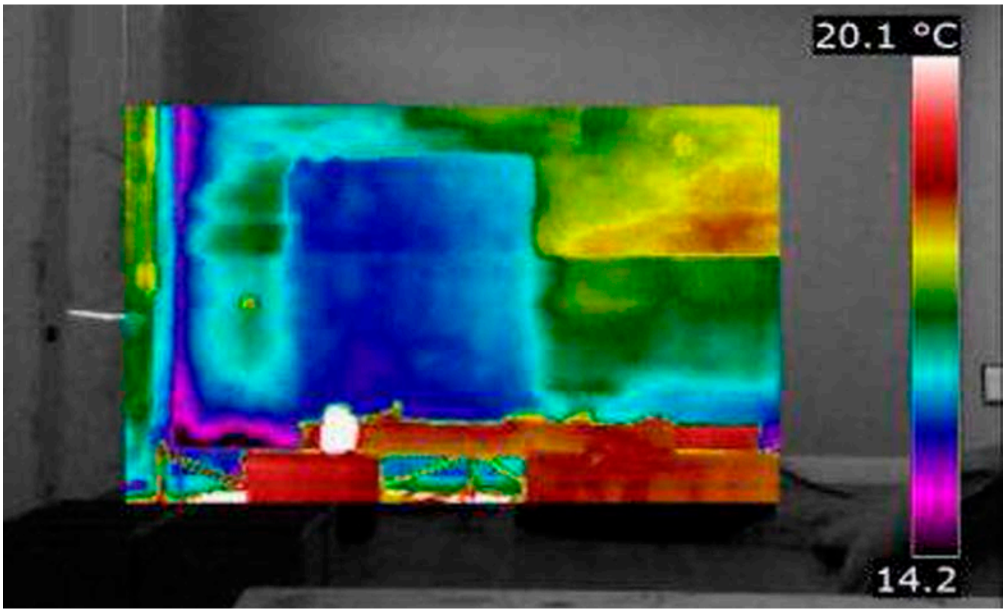


Figure 59:
West wall internal elevation: thermal image.

Discussion

The thermal images suggested that walls in the northwest corner had been replastered. In this area, there were very few signs of superficial damp. However, invasive assessments using timber dowels and a microwave probe showed that the brickwork behind the replacement plaster was wet. This implied that the replacement plaster system was relatively impermeable, and might well have been applied in conjunction with a chemical damp-proof course (as indicated by a row of filled holes at low level in the exterior of the west wall).

The results of the investigations pointed towards moisture ingress at the head of the walls in the northwest corner of the orangery. As noted previously, the outlet sump in the parapet gutter was shallow, and the outlet opening was small and vulnerable to blockage. A further complication was that a lightning protection down-conductor passed through the outlet. The CCTV survey showed that the pipe connecting the outlet to the rainwater hopper head was blocked by leaves, moss and twigs caught up on the lightning conductor lead.

Water entering the top of the wall was trapped within by impermeable external and internal finishes. Moisture migrated downward and laterally to areas where the internal finishes were more permeable. This allowed it to reach the surface and evaporate, resulting in damp patches and salt efflorescence. Liquid water appeared rapidly in these areas during heavy rain because the brickwork was saturated.

Conclusions

Outputs from non-invasive capacitance and microwave moisture meters gave similar results. They also showed how both techniques are strongly influenced by differences in material properties. There were few indications of damp in the northwest corner of the room, either visually or from results obtained using non-invasive devices. However, invasive assessments – timber dowels and the microwave probe – revealed that the underlying brickwork was wet. A relatively thin layer of cementitious plaster was sufficient to interfere with the outputs of the non-invasive devices to the extent that moisture behind it was not detected. The results highlighted the limitations of non-invasive techniques and showed the value of using a variety of complementary moisture assessment techniques. The thermal images clearly indicated anomalies in construction that helped interpret both the visual evidence and data obtained from other assessment techniques.

6 Glossary

Absolute humidity

The actual number of water molecules in the air at a given time, expressed in terms of the ratio of the mass of water vapour to the volume of air (grams of water per cubic metre of air, g/m^3).

Calibration

The process of determining absolute values corresponding to the graduations on an instrumental scale, setting the relationship between the output of the instrument and the absolute values of the parameter being measured.

Capacitance moisture meter

A non-invasive electronic device that measures changes in the capacitance of a material (its ability to store an electric charge) due to variations in moisture content. In environmental monitoring, capacitance sensors are used to record the dielectric properties of permeable materials such as earth, mortar, brick and stone, and thus, indirectly, the moisture content. Handheld devices obtain a shallow moisture content reading from the attenuation of an electric field applied at the surface.

Capillary action

The spontaneous flow of a liquid in a confined space, such as a narrow tube, or between two flat surfaces laid close together. Essentially, capillarity is a consequence of the intermolecular forces that occur within a liquid and between a liquid and walls. It can cause liquids such as water to rise against gravity: the narrower the space, the higher the rise. Also known as 'wicking'.

Carbide meter

Device for measuring free moisture content of drilled masonry or soil samples. The powder sample is weighed, then placed in a sealed flask with a measured amount of calcium carbide powder. The flask is shaken vigorously, and the moisture in the sample reacts with the calcium carbide to produce acetylene gas, which exerts a pressure within the flask. The pressure is proportionate to the moisture content of the sample, which can be read on an external gauge.

Condensation

The process of forming a liquid from its vapour. When moist air is cooled below its dew point, water vapour condenses and forms a film of liquid water or a cloud of mist. Water vapour can condense on surfaces (superficial condensation), inside pores or on the internal interfaces between materials within building elements (interstitial condensation).

Dew point

The temperature at which air at a given pressure becomes saturated with water vapour (the gaseous state of water). At dew point, water vapour and liquid water in the air are in equilibrium because water vapour is condensing at the same rate as liquid water is evaporating. When air is cooled below the dew point, the rate of condensation exceeds the rate of evaporation, forming droplets of liquid water.

Dielectric

A substance – solid, liquid or gas – of very low electrical conductivity that can sustain a static electric field.

Dry weight

The measured weight of a material after it has been exposed to a controlled temperature until its weight is no longer decreasing because all the free water it contained has evaporated.

Efflorescence

Crystalline deposits (ranging from loose and powdery to hard and compact) resulting from the evaporation of water from a salt solution, which can form on the surface of a porous material exposed to air.

Emissivity

The ratio of emissive power of a surface at a given temperature to that of a black body at the same temperature. In other words, the ability of the surface to emit radiation (governed by the type of material and especially by its surface texture and reflectivity).

Equilibrium moisture content

The percentage moisture content of a hygroscopic material at a particular ambient relative humidity. It may take several weeks for materials to reach equilibrium with the surrounding environment. At a given relative humidity, different materials will exhibit different equilibrium moisture contents (that is, they will be holding different amounts of water).

Equilibrium relative humidity

The relative humidity of air when in equilibrium with an adjacent hygroscopic material. In soluble **salts**, it is the relative humidity needed for a given species of salt crystal to become liquid (deliquesce).

Equilibrium vapour pressure

The pressure exerted by a vapour in equilibrium with its solid or liquid form at a given temperature in a closed system. In building environment terms, the point at which the rate of molecules leaving a moisture source (by evaporation) is equalised by molecules returning to it (by condensation). See also Partial vapour pressure.

Evaporation

The conversion of a liquid into a vapour. The rate of evaporation increases with a rise in temperature because it depends on the saturated vapour pressure of the liquid. It also depends on air movement: moving air has a much greater capacity for evaporation than still air of the same absolute humidity and temperature.

Fibre saturation point

In timber, the point at which moisture chemically bound in its cell walls is at its maximum limit. It is normally taken to be between 26 - 30% moisture content in most species of building timber. Above that level, cell cavities are occupied by free water.

Free water

Water that is not chemically bound to another substance.

Ground-penetrating radar

Non-destructive analytical technique, using pulsed radio energy transmitted from an antenna held against the wall surface and reflected back to another antenna. Different materials absorb and reflect differently, so ground penetrating radar can be useful for locating cracks, voids and embedded materials. Also known as 'impulse radar'.

Gully

An inlet to transfer surface water and waste water from downpipes into the drainage system.

Hopper

In rainwater disposal, a top-loading collector at the head of a downpipe to collect rainwater from a gutter.

Hygroscopic

Able to take up moisture from the atmosphere. Permeable materials tend to be hygroscopic because of the reduction in vapour pressure in the pores that occurs as a result of condensation, capillarity and salt action.

Hygroscopic moisture content

The amount of moisture a material would normally take up from the air when in a state of equilibrium (so, excluding any moisture taken up from other sources, such as the capillary uptake of liquid water).

Infrared radiation

Radiation in wavelengths longer than that of visible light (between 760 nm and 1 mm).

Infrared thermography

Specialised non-invasive analytical technique using cameras with infrared detectors and filters to record variations in the infrared radiation emitted by building materials and features.

Microwave moisture meter

A non-invasive electronic device that measures changes in the electromagnetic energy absorbed by a material due to variations in moisture content.

Moisture content

The quantity of water contained in a porous material. Usually defined as the mass of water expressed as a percentage of the dry mass of the material.

Partial vapour pressure

The vapour pressure that a single component in a mixture contributes to the total pressure in the system (for example, water vapour in the atmosphere).

Percentage moisture content

The amount of moisture held by a hygroscopic material at a given time under certain conditions, as determined by gravimetry or other methods. Can be used in conjunction with knowledge about the material and its behaviour to evaluate moisture levels and risks to materials and components.

Permeability

The ability of a material to transmit fluids (especially water or gases), notably through its pores.

Porosity

The ratio of voids to solid matter in a material, expressed as a percentage of total bulk volume. Transfer of liquid water and water vapour in porous materials – permeability – depends not so much on pore ratios (or ‘absolute porosity’) as on how the pores connect to one another and to the exterior, and on their shape, size and chemical characteristics (that is, the ‘effective porosity’).

R2 value

The correlation coefficient that measures the strength and direction of a linear relationship between two variables on a scatterplot. The R2 value ranges from +1.0 to -1.0. The closer it is to 1.0, the more closely the two variables are related. An R2 value of 0 means there is no relation between the variables. Also known as 'coefficient of determination'.

Relative humidity

The ratio of vapour pressure of water in the air to vapour pressure of water in saturated air at the same temperature. In other words, the percentage of saturation at a given temperature.

Resistance moisture meter

An electronic device for measuring changes in the electrical resistance of a material due to variations in moisture content. Handheld devices measure the resistance to an electric current flowing between electrodes (pins) inserted into the sample material.

Salt

A compound resulting from the reaction of an acid and a base, in which a hydrogen atom in the acid is replaced by a positively charged atom, such as a metal ion. Salts are typically neutral, ionic (electrically charged) and crystalline at ordinary temperatures.

Thermal bridge

Heat loss or transfer through a building envelope from warm to cold areas by way of building elements made of materials with low thermal inertias (typically, very conductive materials such as metal or glass), or through relatively less well-insulated areas of the envelope. Also known as thermal bridge.

Vapour pressure

See Equilibrium vapour pressure and Partial vapour pressure.

Water table

The highest point or level of water in an aquifer (a body of porous sediment or rock saturated with groundwater).

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8 Further reading and sources of information

Historic England's Technical Conservation Guidance Brochure lists all its current free-to-download technical conservation guidance, webinars and research reports.

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9 Acknowledgements

Figures

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HEAG0311
Publication date: June 2026 v1.0 © Historic England
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