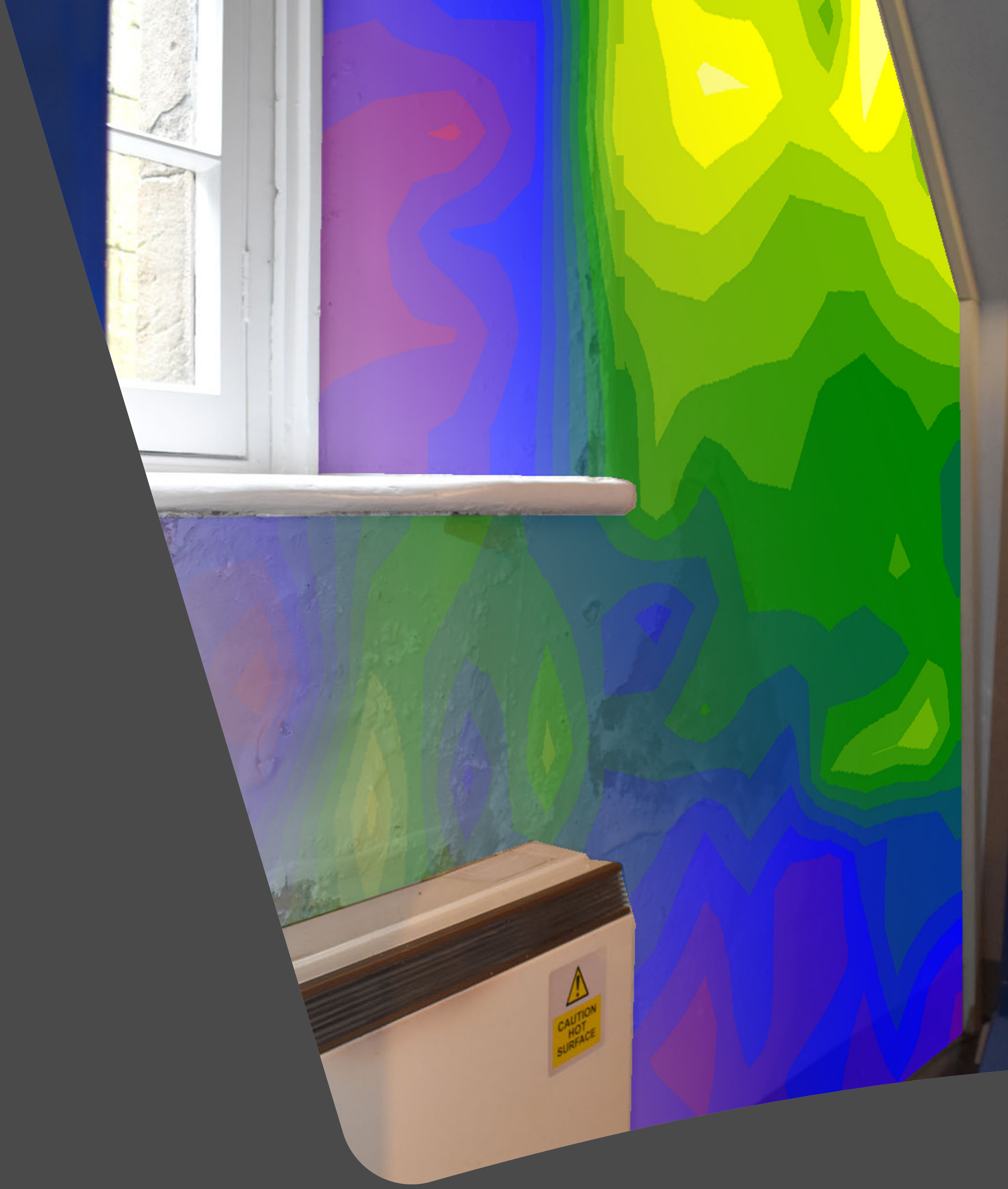

TECHNICAL PAPER 35

MOISTURE MEASUREMENT IN THE HISTORIC ENVIRONMENT

HISTORIC
ENVIRONMENT
SCOTLAND

ÀRAINNEACHD
EACHDRAIDHEIL
ALBA

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PREFACE

Moisture is ubiquitously present in a variety of forms in building materials. The amount that is present varies depending on the substrate, adjacent materials and environmental conditions. It only becomes a problem in excessive amounts (or, rarely, in too small an amount). The ability to use technology to determine when excessive moisture is present and to investigate its source, distribution and change over time is highly valuable in diagnosing problems in buildings, in protecting the building fabric from deterioration and in maintaining a healthy and comfortable environment for the building occupants.

This Technical Paper is intended as a guide to the wide variety of methods used to investigate and quantify sub-surface moisture in building materials. The methods covered range from commonly used building surveying tools, such as conductivity meters, to specialist and micro-scale techniques more suited to research projects.

The choice of an appropriate tool, or a combination of tools, depends on understanding something of the principles and limitations that underlie the various moisture measurement technologies. This allows the user to choose methods appropriate to the substrate and the investigation.

A basic understanding is vital to the correct interpretation of moisture and, therefore, this Paper begins with a general introduction to moisture in buildings and the variety of forms it can take. It introduces the reader to the important concepts, such as saturation and equilibrium, using ‘technical boxes’ to provide more detail where users may want to delve deeper into particular principles.

Advance planning for the survey is necessary, so that appropriate data is obtained to address an issue. Can the method be ‘destructive’, perhaps including sampling or drilling into a wall, or does it have to be non-destructive? Is a one-off survey sufficient or will the question only be answered by repeated surveys over time to monitor changes in moisture content and distribution? Do you need a baseline survey before undertaking an intervention to the building fabric? Some techniques require physical access to surfaces, others work remotely. Choices may also be limited by cost (both time and money) and by the skills required of the operative. Consider in advance how the data need to be processed, what data can be extracted and how best to display results – e.g. overlaid on architectural plans or photos, as charts or tables. Don’t neglect the need to store the data (and metadata) in formats that can be usefully retrieved, should an issue recur in the future.

This Technical Paper also provides background on whether data from particular methods are qualitative (i.e. data will provide indications of relative differences in moisture level) or quantitative (i.e. calibrations are used to put a value on the moisture content). It concludes with a substantial section covering commonly used and widely available moisture measurement methods in detail, as well as dealing with their suitability or unsuitability for specific situations.

ACKNOWLEDGEMENTS

This Technical Paper is based on the doctoral studies of Dr Scott Allan Orr, University of Oxford. We are grateful for the contributions and guidance provided by the Oxford Resilient Buildings and Landscapes (OxRBL) Lab. Historic Environment Scotland's Conservation Science team contributed significant intellectual input and effort to the Short Guide, and the improvements suggested by three technical reviewers have greatly improved its quality and rigour. Several others have contributed visual material, content and structural recommendations and these have been acknowledged, where relevant, in the text.

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I INTRODUCTION

Moisture is a normal occurrence in a building. The nature of materials and construction techniques commonly used in the historic built environment make the free movement of moisture vapour essential to their operation. Excessive or uncontrolled moisture causes several problems in buildings, including impacts on human health and comfort, damage to or loss of materials, and decreased energy efficiency and thermal performance.

Moisture measurement provides evidence that can be used to understand how a building functions. Different types of measurements are suited to particular kinds of problems and understanding the physical principles that underpin commercial moisture measurement devices is essential to interpreting their results. Results from moisture measurement devices can be especially difficult to interpret in the historic environment, due to complex combinations of materials, construction methods and past repairs that do not adhere to contemporary building standards (Fig. 1).

Figure 1 *- Buildings in the historic environment may contain complex combinations of materials, methods of construction and past repair interventions, making the interpretation of moisture data complex.*

This Technical Paper is an introduction to moisture measurement within the historic environment. It emphasises techniques that are commonly applied when surveying buildings. It provides a general outline of how and why moisture is present in buildings, explains common methods and principles used in measurement and provides guidance on how to acknowledge the limitations of these techniques while undertaking, interpreting and presenting measurements of moisture.

Moisture can come from external sources such as groundwater and wind-driven rain, as well as internal sources such as cooking (Fig. 2). Moisture is also often introduced through the built context, including roof leakage, defective flashing, uncapped chimneys and under-performing rainwater goods (e.g. gutters and drainpipes). These elements are part of what is considered the building envelope.

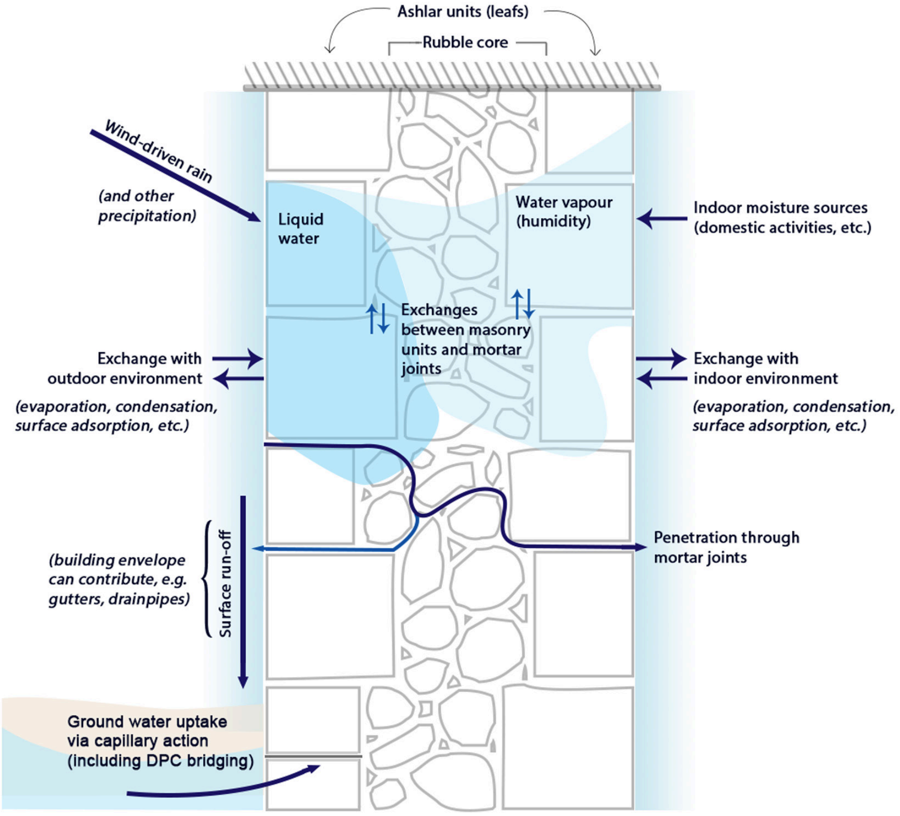


Figure 2 *- Common moisture ingress pathways for traditional structures, such as this rubble core stone masonry wall.*

1.1 IMPACTS OF MOISTURE ON BUILDINGS

Moisture can have several detrimental effects on historic buildings and structures, including reducing the strength and longevity of its materials, negatively impacting occupants' comfort and health and decreasing energy efficiency.

Materials that are exposed to the environment are subjected to processes of physical change that decrease their strength and longevity. For porous building materials, these include chemical attack, stress from freeze-thaw cycles, salt crystallisation and biodegradation. These processes are underpinned by the presence and movement of moisture.

The ingress of moisture through historic building fabric can introduce moisture to reservoirs, worsen existing moisture problems and support mould growth (Fig. 3).

Figure 3 *- Moulds and other microorganisms will colonise damp internal walls.*

Managing moisture within the historic environment is linked to the energy efficiency and thermal performance of a building. Higher moisture levels within solid walls increases the rate of heat loss through the wall. Adding insulation or draught proofing improves a building envelope's thermal performance, but also alters its moisture performance and can create or increase the risks of moisture related deterioration.

According to the UK Climate Projections 2018 (UKCP18), the UK is predicted to be warmer and wetter during the 21st century, with more extreme precipitation events. The resilience of the historic environment to these changes is uncertain. Water is involved in most building decay processes, so predicted climate change scenarios (where buildings may be exposed to wetter conditions for longer periods) imply long-term damage due to more frequent physical, chemical and biological attack on materials. Specifically, a predicted increase in the magnitude and wider variation of cycles of moisture movement, as well as more frequent intense events, will challenge the capacity of current rainwater goods.

1.2 HOW WATER IS PRESENT IN BUILDING MATERIALS

Water, referred to as 'moisture' in the built environment context, is a normal occurrence within all building materials, but it may become a problem where it is present in excessive amounts. Moisture is normally present in a relatively small quantity as a vapour (humidity) or as a liquid within solids (capillary moisture). It may also condense on a surface (e.g. as hygroscopic moisture) and it can be attached through chemical crystallisation or hydration of salts within masonry components, such as mortar. Moisture present in hydrated salts is not easily transferred or exchanged with the environment and is, therefore, not normally problematic.

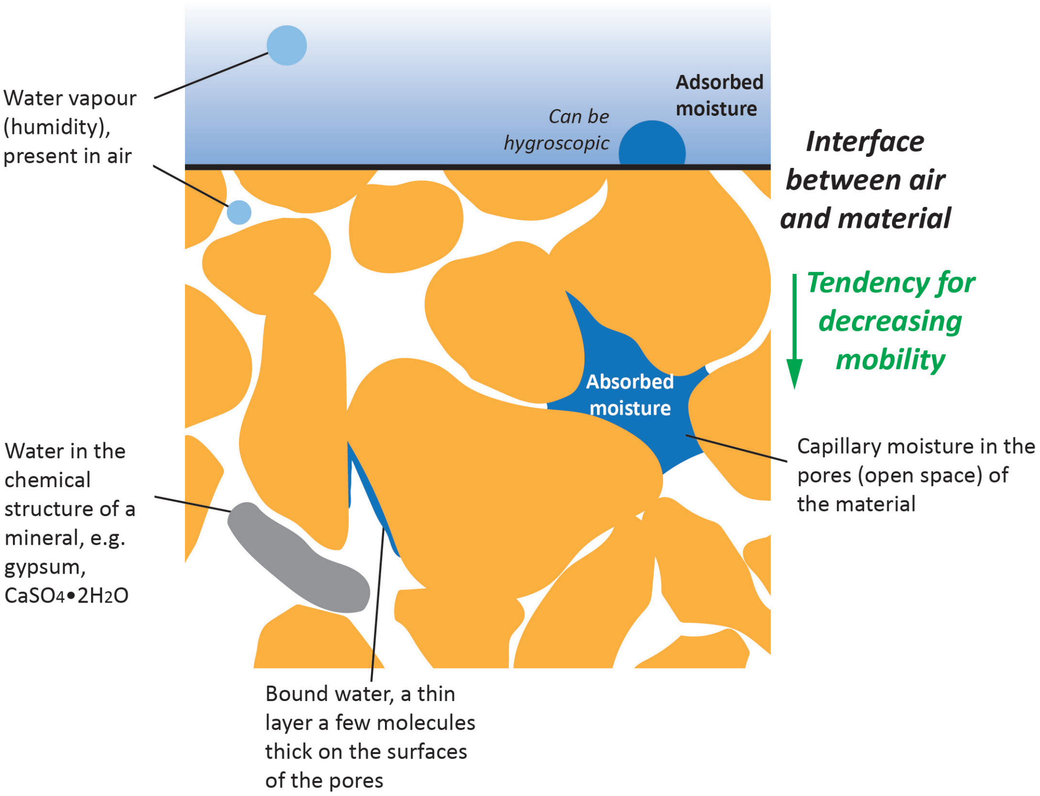


Figure 4 *- Various ways in which water can be present in and around a building material.*

Moisture is constantly moving through materials in response to changes in the external and internal environments of a building (Fig. 4). Two important properties that will have a significant influence on the dynamics of moisture movement and the moisture content are:

- saturated moisture content: the maximum amount of moisture a material can hold in its pores
- equilibrium moisture content: the moisture content that a material tends toward in its ambient environment.

In summary, a damp building is one in which the levels or thresholds of moisture have exceeded the point beyond which they begin to detrimentally impact - or have the potential to impact - the fabric of the building and its use. It should be noted that this point is not always known and varies with material and context.

TECHNICAL BOX 1: Defining and understanding moisture content

The quantity of moisture present in a building material can be represented in several ways. They are all technically correct and easily converted to one another. The most important thing is to identify which representation is being used when a moisture content value is reported.

Moisture content, MCd (%), dry basis

The mass of water relative to the dry mass of the building material:

$$MC_d = \frac{(m_t - m_d)}{m_d} \times 100\% = \frac{m_w}{m_d} \times 100\%$$

Moisture content, MCw (%), wet basis

The mass of water relative to the total mass of the building material and any mobile water it contains:

$$MC_w = \frac{(m_t - m_d)}{m_t} \times 100\% = \frac{m_w}{m_t} \times 100\%$$

To convert from a dry basis (MCd) to wet basis (MCw), you can multiply it by the ratio of dry mass to total mass (and vice versa):

$$MC_w = MC_d \times \frac{m_d}{m_t}$$

$$MC_d = MC_w \times \frac{m_t}{m_d}$$

Volumetric water content, WCv (%)

The volume of water relative to the total volume of the building material, including pore space:

$$WC_V = \frac{V_w}{V_t} \times 100\% = \frac{m_w \times \rho_w}{V_t} \times 100\%$$

This can also be converted to a degree of saturation, S (generally expressed as a %), by dividing it by the porosity Φ of the material:

$$S = \frac{WC_v}{\Phi}$$

The degree of saturation ranges from 0% (fully dry), to 100% (holding as much water as it can, i.e. saturated).

Symbols

m_d	mass of the dry sample
m_w	mass of the water in the sample
m_t	total mass of the sample (i.e. material and water)
V_w	volume of water in the sample
V_p	volume of the pores within the sample
V_t	total volume of sample, including pores and solid material
ρ_w	density of water
Φ	porosity, the fraction of void space in a material

TECHNICAL BOX 2: Equilibrium moisture content

To understand moisture measurement, we must consider the natural response of materials to changes of relative humidity (RH) in the environment. This is called the equilibrium moisture content (EMC) — the moisture content that would be reached if a material is exposed to a constant relative humidity. At 100% RH, maintained for a sufficient period of time, a material will attain its saturation moisture content. Different types of material exhibit very different behaviour due to their microscopic qualities. For example, wood will consistently and rapidly gain moisture as RH increases, whilst most other porous building materials tend to absorb relatively little of their full capacity, until the RH is greater than roughly 90%.

Understanding equilibrium moisture content is important for comparing moisture levels in materials. Although timber elements may have higher levels of moisture relative to materials such as brick and stone, this may not indicate greater moisture ingress in the timber. Rather, it may be a result of the higher equilibrium moisture content of the timber at a given relative humidity (Fig. 5).

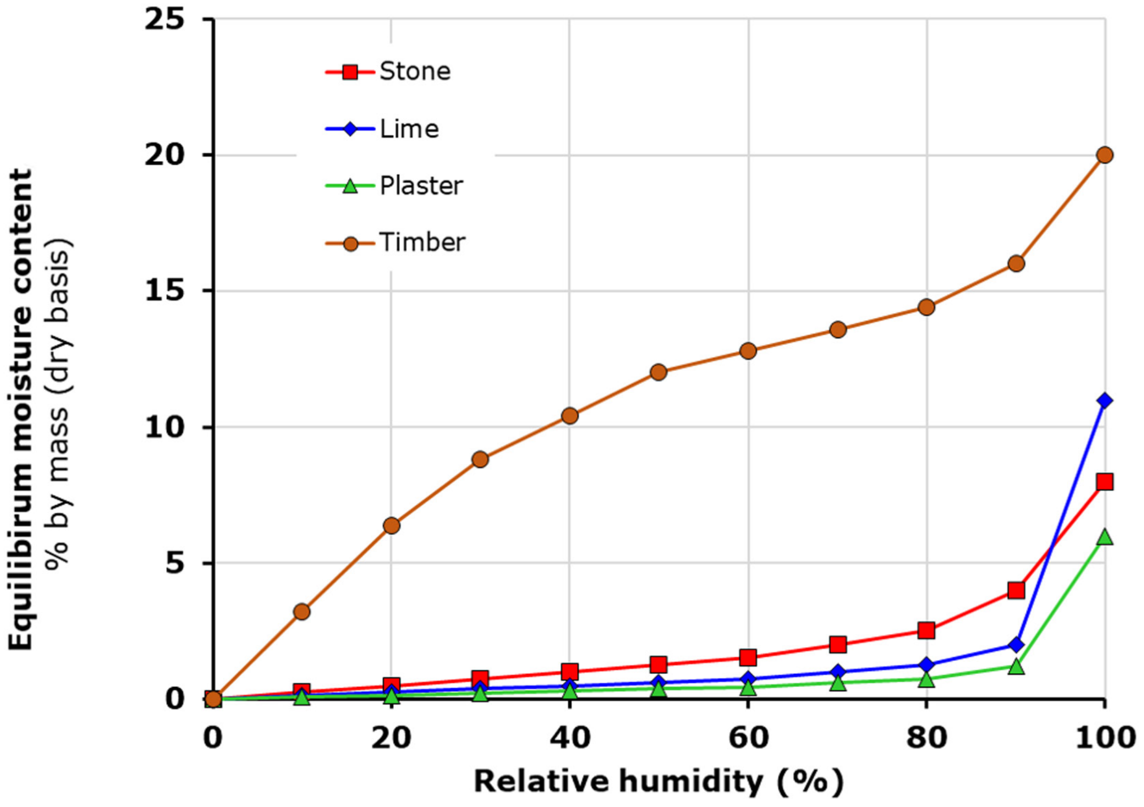


Figure 5 *- Equilibrium moisture contents during absorption for types of building materials common in the historic environment.*

1.3 WHEN AND WHY SHOULD MOISTURE BE MEASURED

There are several scenarios in which moisture measurement can provide useful quantitative evidence. Measurement of moisture content can:

- monitor the efficacy of an intervention, such as the installation of new drainage or insulation;
- monitor the drying of a building following a flooding or flood-like event;
- provide a baseline evaluation of moisture levels that can be compared to seasonal or long-term variation;
- locate areas of a building which receive higher environmental exposure and are therefore at greater risk of deterioration and/or failure;
- identify specific building defects or failures.

Different information is needed for each of these scenarios, but they all generally require a knowledge of where moisture is, in what quantity and how this is changing over time.

An ideal technique for moisture measurement in the historic environment would non-invasively scan large areas of the surface and determine changes in moisture in specific locations and at different depths. The measurements would be repeatable, accurate, independent of the material and unaffected by its inhomogeneity or irregular texture. The device would also be portable, safe to operate, efficient and affordable enough for regular and prolonged use. Unfortunately, no existing measurement technique fits this ideal, but when used correctly, currently available techniques can be useful tools when integrated with more general approaches to understanding buildings and building surveying.

2 MOISTURE INVESTIGATIONS

There are several important considerations when planning and undertaking a moisture measurement survey. The approach determines whether a survey is invasive or non-invasive. The strategy determines how a device is implemented and how frequently measurements are taken. The measurement method is the physical principle on which a measurement is based. Together, these three aspects determine the kind of information that is gained from a moisture measurement survey (Fig. 6) and an effective survey will address all three.

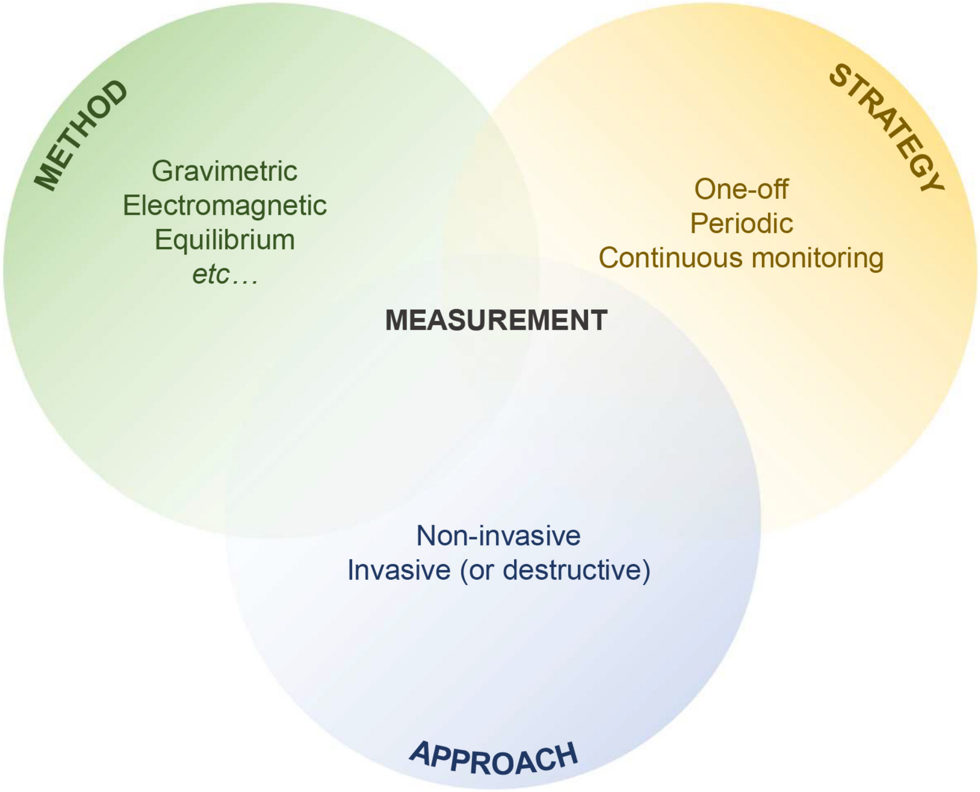


Figure 6 *- The method, strategy and approach used in a measurement campaign determine what kind of information will be collected.*

An effective methodology should minimise the time, materials and effort needed without compromising the investigation. Investigations may be one-off activities, but should be designed, implemented and documented to allow them to be repeatable and robust.

The strategy, method and approach are often closely related. In some cases, the selection of one can determine another. For example, the gravimetric method is inherently invasive and destructive (requiring samples to be extracted), unless it is implemented into the design of purpose-built structures for testing. The design of commercial devices often dictates which strategy, method and approach will be used. However, it is useful to distinguish these aspects, especially in the consideration and design of new or bespoke equipment.

2.1 APPROACH

When designing a moisture measurement survey, the approach should be considered separately from the strategy and determined before the measurement method.

Non-invasive techniques do not require any modification to a structure. They are primarily used to identify relative levels of moisture content.

In contrast, invasive techniques involve destructive sampling or drilling so that probes can be inserted at depth. These permanently change the fabric of a building. Consequently, a moisture measurement scheme should be carefully designed to minimise impact on both the aesthetics and the function of the building. The Ethical Sampling Guidance produced by the Institute of Conservation (ICON) Heritage Science Group introduces a decision-making framework for appropriate survey design, considering the ethics of invasive or destructive testing.

Table 1 *- Advantages and disadvantages of non-invasive and invasive moisture measurement.*

	Advantages	**Disadvantages**
Non-invasive measurement	Does not require changes (e.g. invasive drilling) to the structure.	Generally indicates relative moisture levels, not absolute moisture contents.
	Quick to take measurements.	Difficult to compare between different materials.
	Can easily provide information about the distribution of moisture.	Higher uncertainty about the depths to which these devices are measuring.
	Allows for periodic measurements without altering potential ingress.	
Invasive measurement	Can provide accurate information about absolute moisture contents.	Destructive methods that involve permanent modification to a structure, resulting in a loss of material.
	Provides information about moisture at unequivocal depths.	Provides information about the distribution of moisture only to the extent of the invasive sampling.

2.2 STRATEGY

The objective of the moisture survey will determine whether it involves one-off and periodic measurements or continuous monitoring.

2.2.1 One-off and periodic measurements

One-off measurements are primarily used to identify relative levels of moisture (Fig. 7). This is because they provide readings indicating moisture levels based on proxy measurements or in arbitrary units. This can be done using a scanning approach (e.g. thermal imaging) or with more localised spot measurements. Spot measurements can be taken quickly and easily with handheld meters. Since they do not change the structure of the material or surface under investigation, one-off measurements using non-invasive tools can be repeated periodically, providing information about how moisture levels change over time.

In general, non-invasive tools are applied as part of a building pathology approach. They are particularly suited to identifying how moisture enters a structure (e.g. uptake of groundwater, a leaking pipe, or poorly functioning rainwater goods). However, these methods are susceptible to external influences, such as fluctuations in temperature and humidity, so they may be supplemented with long-term monitoring.

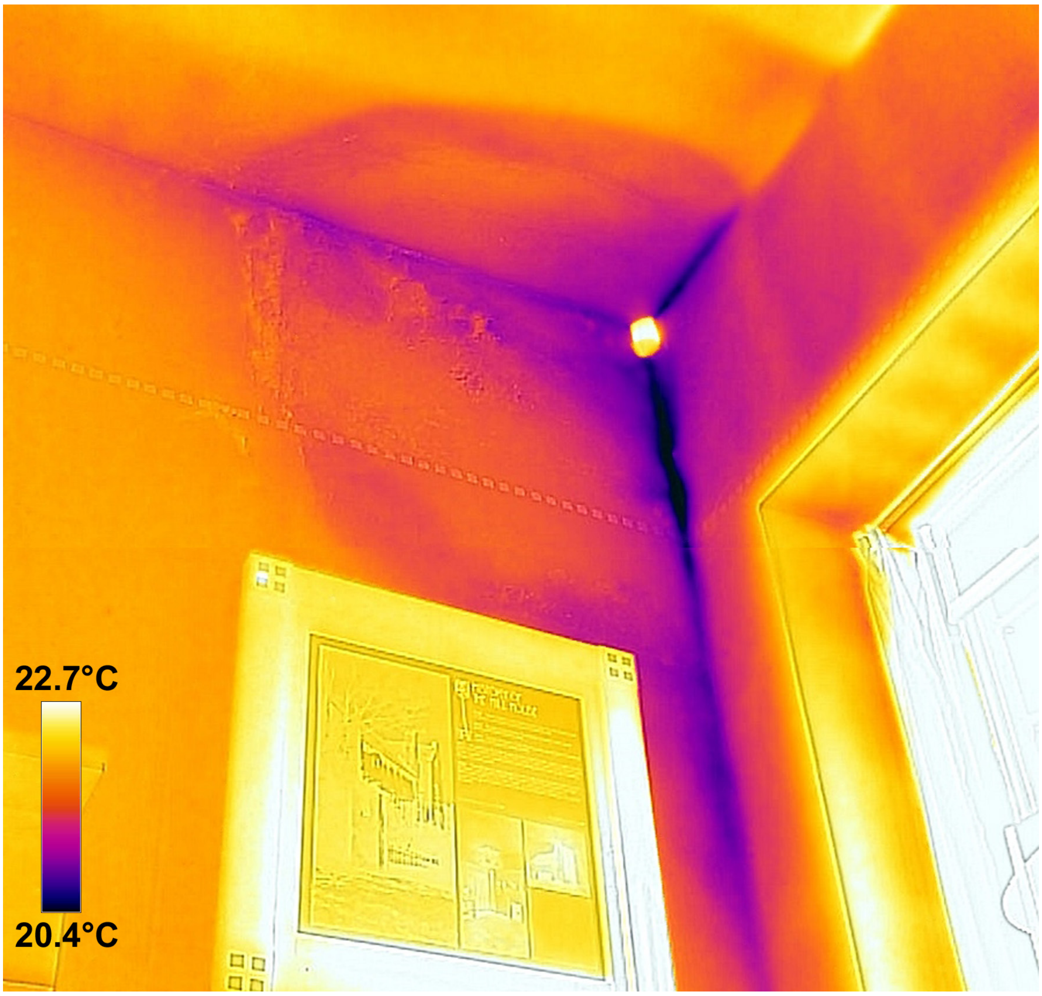


Figure 7 *- This thermal image of a water ingress problem is an example of a 'one-off' or 'periodic' measurement.*

2.2.2 Continuous monitoring

Continuous monitoring typically involves installing monitoring devices and can be long-term or used for relatively short periods of fixed duration.

This strategy is best suited to addressing several types of problems:

- To track the efficacy of a maintenance or mitigation activity. For example, the installation of new drainage, removal of an inappropriate render or mortar, or post-flood conditions.
- To understand the dynamics of moisture transfer within complex constructions. (Although laboratory testing and modelling can provide similar information, these do not easily represent the complexities of historic constructions such as cracks and heterogeneous material properties, which often influence the rate and pattern of moisture movement).
- To relate moisture levels and dynamics within the building envelope to external environmental conditions. Most commonly, temperature and humidity are monitored. In some circumstances,

changes in atmospheric pressure can also influence moisture dynamics.

In most instances, continuous monitoring involves the use of invasive probes (Fig. 8). The probes are connected to a data logger that takes measurements at specified intervals.

As with all invasive processes, it is necessary to consider whether the value of the resulting information warrants the consequent irreversible changes to components of the building fabric. Very thin probes are now commercially available which can minimise the destructive impact of some invasive procedures.

Figure 8 *- Invasive electrical probes being built into the bedding mortar of a purpose-built test wall. Probes can also be installed by drilling holes into the masonry units and mortar joints of an existing construction. © Dr Evy Vereecken*

2.3 MEASUREMENT METHOD

Methods to identify moisture levels in a building material take advantage of several principles. These methods can be classified as:

- Direct methods, which quantify the amount of moisture present.
- Indirect methods, which measure proxies (qualities that indicate the presence of moisture) to identify relative differences in levels of moisture. The measurement indicates the levels of moisture present by converting the proxy value via an appropriate calibration. Indirect techniques can provide useful information about relative levels and localised variation of moisture. To create a relationship between the measured readings and absolute moisture contents, gravimetric calibration may be used (see Technical Box 3).

Table 2 *- Moisture measurement methods for on-site surveying.*

Methods	**Strategy**	**Approach**	**Typical depth of penetration**	**Skill level to operate**	**Skill level to interpret**	**Cost**	**Influence of salts present***
Gravimetry	One-off	Invasive	Depends on implementation	General user	General user	£	None
Calcium carbite	One-off	Invasive	Depends on implementation	General user	General user	££	None
Electrical conductivity/ resistivity	One-off, periodic or long-term monitoring	Non-invasive	Surface and near-surface	General user	General user	£-££	Strong
Capacitance	One-off, periodic or long-term monitoring	Non-invasive	Surface and near-surface	General user	General user	£	Some
Microwave	One-off, periodic or long-term monitoring	Non-invasive	Surface, near-surface, and depth	General or technical user	General or technical user	£-£££	None
Radar	One-off or periodic; non-invasive	Non-invasive	Near-surface and depth	Technical user	Specialist	££££	None
Thermal imaging	One-off or periodic (although long-term monitoring is possible)	Non-invasive	Surface	General or technical user	Technical user	£-£££	None
Equilibrium methods	Periodic or long-term monitoring	Invasive	Depends on implementation	Technical user	General user	£-££	None
Time domain reflectometry	Long-term monitoring	Invasive	Generally, surface to mid-depth; Depends on implementation	Specialist	Technical user	££££	Some

**All methods can be influenced by salts if they are hygroscopic. Like building materials, the hygroscopic behaviour of salts can cause water to be absorbed and desorbed in response to environmental conditions.*

TECHNICAL BOX 3: Using multiple measurement methods

While one moisture measurement device or method can produce useful and effective measurements, using more than one has several potential benefits:

- It reduces the likelihood of false interpretation.
- It capitalises on the effective depth of different devices. It is common to use a combination of moisture measurement techniques to compare hygroscopic surface moisture (< 1mm), subsurface moisture (up to 3 or 4cm deep) and the internal moisture content (e.g. 30 to 40cm deep). This is part of 'building pathology', which compares surface and subsurface conditions with moisture at depth.
- It enables identifying an area of interest or high risk requiring a more thorough investigation. For instance, a scanning technique (such as thermal imaging) can reveal an area needing a more thorough investigation using other methods.
- The technical requirements of one method can provide an opportunity for another. For example, invasive drilling of holes for embedded probes could provide material that can be tested gravimetrically.

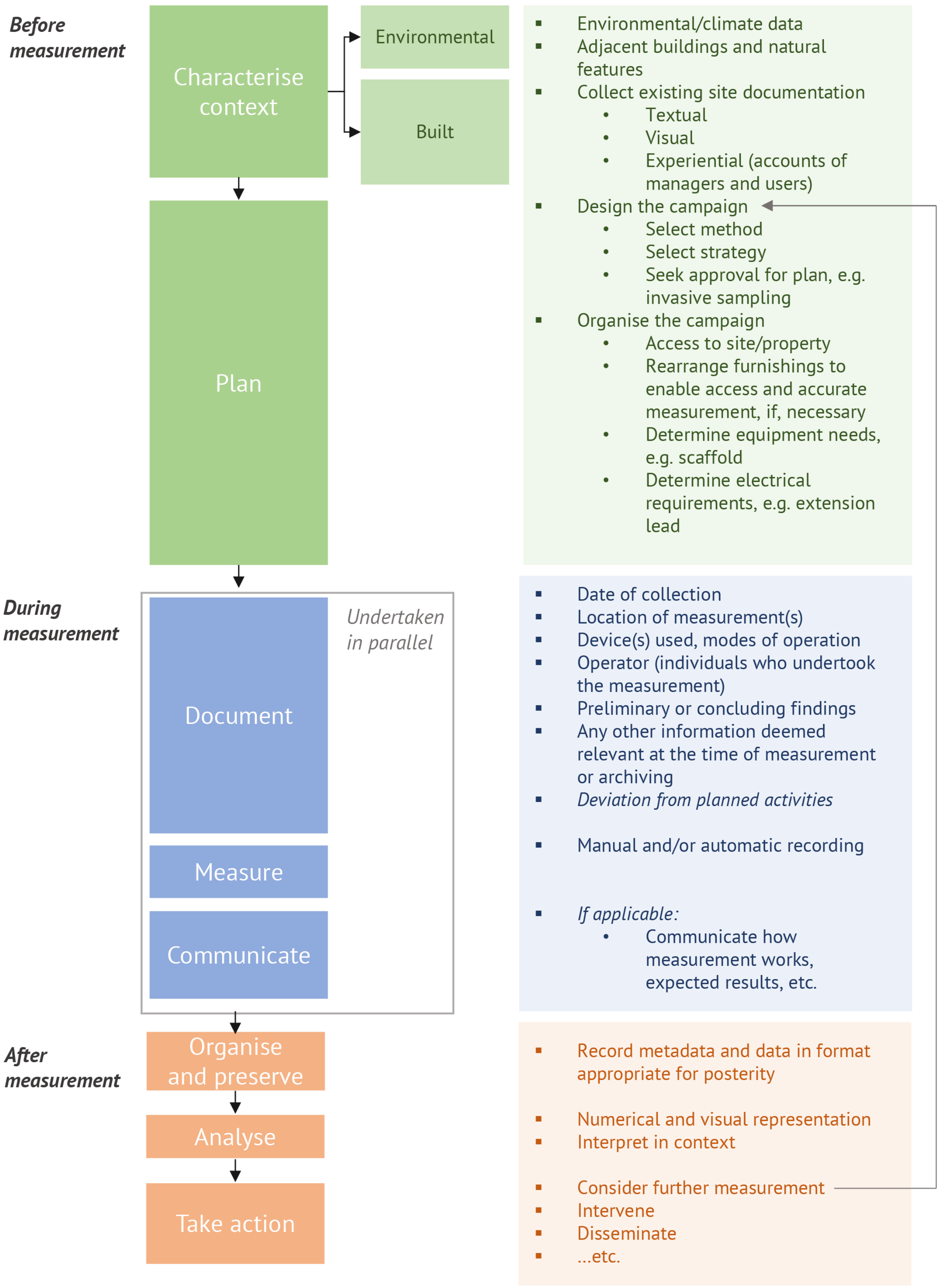
It is methodologically incorrect to determine moisture distributions by comparing readings produced by two devices, which are based on different measurement methods. If both instruments provide absolute or relative readings in arbitrary units, it is not possible to compare independent readings, even if manufacturers have expressed both in percentages (or a similar scale), implicitly suggesting that they are comparable. Depending on the measurement ranges of interest, caution is also advised when comparing readings produced by using the same measurement method, but with devices that are different in terms of resolution and accuracy.

2.4 UNDERTAKING MOISTURE MEASUREMENTS

An efficient moisture measurement survey requires careful planning and recognition of the need to retain records and related documentation for future reference (Fig. 9). This process is summarised in Fig. 10 and each stage is covered in more detail in subsequent sections.

Existing documentation about the building and its setting should be collected. This can help us to understand the built context and, having access to this information on site, can aid in survey design and recording details of the measurement.

Figure 9 *- An efficient moisture measurement survey requires careful planning and documentation.*



- Environmental/climate data
- Adjacent buildings and natural features
- Collect existing site documentation
    - Textual
    - Visual
    - Experiential (accounts of managers and users)
- Design the campaign
    - Select method
    - Select strategy
    - Seek approval for plan, e.g. invasive sampling
- Organise the campaign
    - Access to site/property
    - Rearrange furnishings to enable access and accurate measurement, if, necessary
    - Determine equipment needs, e.g. scaffold
    - Determine electrical requirements, e.g. extension lead

- Date of collection
- Location of measurement(s)
- Device(s) used, modes of operation
- Operator (individuals who undertook the measurement)
- Preliminary or concluding findings
- Any other information deemed relevant at the time of measurement or archiving
- *Deviation from planned activities*

- Manual and/or automatic recording

- *If applicable:*
    - Communicate how measurement works, expected results, etc.

- Record metadata and data in format appropriate for posterity

- Numerical and visual representation
- Interpret in context

- Consider further measurement
- Intervene
- Disseminate
- ...etc.

Figure 10 *- General procedure for planning, undertaking and concluding a moisture measurement.*

2.4.1 Built context

Moisture measurements require an awareness of the built context. Historical records, maintenance archives, architectural drawings, building surveys and scientific investigations among other sources, all contribute to this understanding. Similarly, moisture measurement should be part of a wider set of activities around building management and surveys.

The nature of the building fabric influences moisture measurements and, as such, it is important to characterise the structure and components of a wall. This means identifying the types of material used, the presence of any voids within the walls, support beams, internal wall insulation, metal ties and other features that might affect measurements. It is also important to have a good understanding of the original nature of the building fabric and how past interventions may have increased the complexity and heterogeneous nature of the construction.

Moisture measurement can also impact the fabric of a building; for example, invasive analysis (e.g. drill cores) might have unintended consequences for its structural integrity or cause the loss of valued material. We must understand and characterise the built context before undertaking invasive analysis, in order to ensure ethical sampling and secure administrative approvals.

We must also understand how a building functions and how it is used, in order to interpret moisture measurements. These aspects of a building determine how moisture and heat are introduced and transferred across the interior and the exterior skins of the building. While characterising the building fabric is an important part of understanding how a building functions, it is also important to understand the impact of human use and environmental management systems, such as air conditioning. For example, interpreting thermal images requires a knowledge of the recent history of heating.

2.4.2 Environmental context

The environment - the climate and natural components of a building's surroundings - can both cause undesirable excess moisture and complicate diagnostics. Local and regional characteristics, climate, extreme weather events and sheltering due to adjacent buildings or natural features are all important aspects of the interpretation of moisture surveys.

Table 3 identifies several components of the external environment and suggests potential measuring tools. This is not an exhaustive list, but one that reflects the potential complexity of the external environment.

Table 3 *- Important components of the environment to consider when assessing moisture measurements.*

Environmental component	**Variability**	**Potential measuring tools**	**Implications for moisture measurement**
Soil moisture and groundwater	Seasonal	Resistivity probes, visual inspection	Varying moisture levels within the structure near to the ground
Surrounding buildings	Stochastic	Visual inspection	Impact on exposure, including amount of rain, wind and sunlight
Winds (prevailing direction, speed)	Highly variable on short time scales, negligible in the long-term	Anemometers, regional climate information	Varying rates of evaporation from structure; impact on exposure (especially rain)
Proximity to coast and other water bodies	Negligible	Cartography and GPS	Introduction of hygroscopic salts into structure, influencing moisture levels; varying moisture levels within the structure near to the ground
Heating due to solar radiation	Seasonal, long-term	Visual inspection, regional climate information	Impact on evaporation and drying rates
Temperature	Diurnal, seasonal/annual, long-term	Thermometer, temperature loggers, regional climate information	Impact on evaporation and drying rates; influence on occurrence of physical and chemical weathering mechanisms, especially those related to relative humidity
Pressure	Diurnal, seasonal/annual, long-term	Barometer	Impact on evaporation and drying rates; influence on occurrence of physical and chemical weathering mechanisms, especially those related to relative humidity
Humidity	Diurnal, seasonal/annual, long-term	Relative humidity measurement (often built into handheld meters),	Impact on evaporation and drying rates; influence on occurrence of physical and chemical weathering mechanisms
Solar irradiance	Diurnal, seasonal/annual	Solarimeter, but difficult to assess	Impact on evaporation and drying rates
Precipitation	Stochastic but generally seasonally or annually classified	Regional climate information, rain gauge/bucket	Influence on localised moisture levels within a structure - often depending on geometry and context of the structure
Topography and altitude	Negligible	Cartography, GPS	Influence on localised moisture levels within a structure; further implications due to changes in pressure (see above)

2.4.3 Before measurement

Preparing and planning is a significant component of any survey. Notebooks, tablets and photography can provide further useful methods of documentation before, during and after a survey.

It is also important to consider how data collection might disrupt activity within the building. Moisture measurements can inconvenience regularly scheduled activities, but they can also provide an opportunity for stakeholders and users, including members of the public, to engage with building conservation and heritage science.

Physical access must be considered in advance. For example, furniture may need to be moved away from any surfaces of interest well in advance of measurements. This allows the walls to equilibrate with their surroundings (Fig. 11) and minimises the time needed on site. Assuming the objective or object of study is known in advance, the type of access needed, along with any additional equipment required, should be determined and arranged. Establish whether the necessary equipment (especially for physical access, e.g. ladders and scaffolding) is available on site, as well as access to electricity. Communicate with the relevant individuals (managers, owners, occupants) to determine if the surveyor needs to be aware of any security protocols or logistics of access. On-site health and safety protocols should be strictly adhered to and normal precautions taken when working in risky areas.

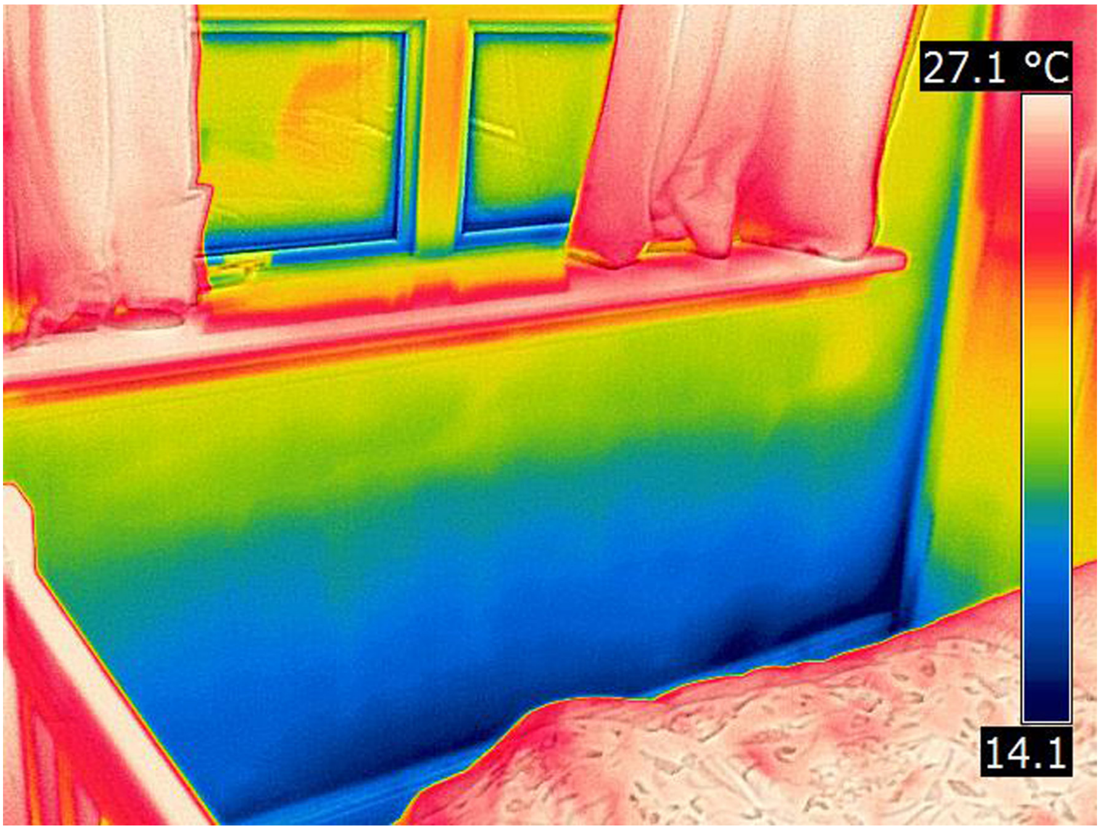


Figure 11 *- The blue area does not show dampness at the bottom of the wall. The bed was moved away from the wall shortly before the thermal survey, which did not allow sufficient time for the temperature of the wall to equilibrate with its surroundings.*

2.4.4 During measurement

Moisture measurement data can be acquired in several ways.

Measurements can be compared to a ‘dry reference’. The dry reference value is obtained in a location which is unaffected by moisture ingress. It can be measured in raw values or arbitrary units. Similarly, a ‘wet reference’ can be collected by taking a measurement in an area that has been sprayed with water until it is believed to be saturated. In some circumstances a more accurate dry reference can be acquired through gravimetric calibration. This also provides the opportunity to have a ‘saturated reference’ (see Technical Box 4 and Technical Box 5).

TECHNICAL BOX 4: Moisture reference samples

A ‘dry reference’ is data obtained from a sample or area presumed to be unaffected by moisture ingress or other damp problems. NB. The substrate will not have zero moisture content - it will be assumed for the purposes of the survey to have equilibrated to ‘normal’ environmental conditions.

A ‘saturated reference’ is data obtained from a sample or area which is known to be saturated with moisture – saturation having been confirmed by another method.

A ‘wet reference’ is data obtained from a sample or area presumed to be saturated with moisture, but where the degree of saturation has not been confirmed.

Measuring on a consistent two-dimensional grid is a repeatable method of measurement that is easy to document. Alternatively, a horizontal or vertical transect can be used. The exact positioning of the grid can be documented in written notes, visual images and on architectural drawings. The resolution of the grid (i.e. the spacing of the measurement points) must consider several factors, including:

- The spatial capture of the technique. Invasive drill coring with long-term monitoring is a localised technique that provides information within a well-defined area. The grid spacing for non-invasive devices can be determined from the radius within which the device captures moisture data.
- How the grid maps onto different materials and surfaces. Measurements might not be directly comparable if the grid overlaps masonry units, mortar or different internal materials. In some cases, it is preferable to design and overlay a measurement grid onto a single material or region of construction to ensure comparability.
- Whether measurements need to be repeated. Do they need to be on the same spot in the future? If so, documentation of this becomes important.

A high density of measurements can be taken with non-invasive devices. This should be balanced with making an effective use of time. Replicating measurements at a smaller number of individual points might be better than taking several individual measurements across a grid. This is especially useful for heterogeneous constructions or when characterising how different materials behave within the building. For each area of interest, a sufficient number of measurements is taken to allow for robust statistics to be calculated (see Section 3.3.1). This method accounts for the natural variability of the measurements due to material heterogeneity and can be a powerful approach to periodic monitoring with non-invasive tools.

2.4.5 After measurement

One of the greatest challenges to making data available for posterity is its format. Moisture measurement data comes in several formats. All relevant data need to be stored in a way that is accessible and sustainable. This ensures that, in the future, it is not just data that are available, but information that can help us to understand the past states and behaviour of a building. Many moisture-measurement tools store data in formats which require specific software to access them. These formats should be avoided for long-term storage. Instead, data should be exported to text-based formats (e.g. text, or .TXT) or comma-separated values (CSV), which have longevity in the digital world. Image-based formats (e.g. JPEG and GIF) are useful for reference and quick evaluations but are limited in their archival use since they cannot be easily adapted or modified.

Data alone are insufficient to provide information for archival purposes and future assessment. Several aspects of the provenance or metadata should be documented and accompany any stored data pertaining to moisture measurement. These include:

- Date of collection
- Site
- Built and environmental context
- Location of measurements (word description, visual images, etc.)
- Device(s) used, modes of operation (if applicable)
- Operator (individuals who undertook the measurement)
- Methods of data analysis employed
- Preliminary or concluding findings
- Any other information deemed relevant at the time of measurement or archiving.

Data should preferably be stored in more than one electronic location. This can also be accomplished by ensuring that they are archived on institution servers and/or the cloud (if applicable), which often have robust mechanisms in place for ensuring that data is stored in a way that minimises the chance of loss. While hard copy back-ups can also be useful, these have their own sets of challenges and issues of sustainability.

3 INTERPRETING MOISTURE MEASUREMENTS

The choice of an appropriate moisture measurement method is influenced by the form in which data is gathered, how it will be evaluated and considerations regarding further processing for reporting and presentation.

3.1 UNDERSTANDING THE MEASUREMENT VALUES

Equipment used to assess moisture has three independent factors that should be considered:

- Method: direct or indirect, based on a variety of physical phenomena.
- Approach: invasive (destructive) versus non-invasive (non-destructive).
- Internal data processing (if applicable): raw measurement values or arbitrary units, qualitative or quantitative.

These factors determine the applications for which they would be appropriate and how their output is interpreted.

Direct methods (e.g. gravimetry) provide readings of absolute moisture contents. These come in several forms and can easily be converted to be equivalent to each other. Measurements can be easily understood in physical terms in relation to pore space and the volume of a sample. In contrast, indirect methods (e.g. electrical resistivity) can provide a range of values, including the raw physical measurements (e.g. resistivity), a reading in arbitrary units or internal calibrations. Each of these has different requirements for understanding their meaning.

Indirect methods do not measure moisture directly – they quantify measurable properties of materials which are indicative of moisture, such as resistivity. However, in some cases, they can be converted into moisture content estimates, if they are calibrated using an appropriate method. Importantly, a physical measurement may not relate linearly to moisture content. For example, electrical resistivity measurements relate to moisture content exponentially, meaning that a 10% increase in moisture content results in a ten-fold increase in conductivity.

A commercial device will often convert physical measurement into a specific range of values expressed as arbitrary units, sometimes referred to as a moisture digit or index. These are challenging to evaluate because it is not always clear how these units relate to the raw values produced by the measurement principle. If a device has been designed for use on a particular material, the arbitrary units might be scaled accordingly, but these would not be applicable for other materials. The index might not increase linearly with respect to changes in moisture content. Put another way, a reading of 50 cannot be assumed to represent twice as much moisture as a reading of 25. Similarly, a reading of 50 on one material does not necessarily mean the same as a reading of 50 on a different material. Since most measurements are also influenced by material properties, they cannot necessarily be compared between different types of materials, although manufacturers will often report general ranges of values that represent different levels of moisture.

3.1.1 Internal calibrations

Some devices include built-in calibrations for types of materials. These can be very useful, since they should be based on robust procedures. However, they must be carefully interpreted, as these will be based on particular examples of a material that might not represent the diversity of its type found in the historic environment - typically modified by the natural heterogeneity of traditional building materials and changes in their physical properties over time due to weathering. The decision to use the closest material type setting or a default setting must be taken based on operator experience and device characteristics.

TECHNICAL BOX 5: Gravimetric calibration

Gravimetric calibration creates a relationship between the readings (physical property or arbitrary units) and the moisture content on a mass or volume basis. The typical procedure monitors the absolute moisture content of a sample while it dries in controlled conditions and records the device measurement to characterise the relationship between them. Calibrations can then be made for invasive methods (e.g. dowels) and non-invasive devices.

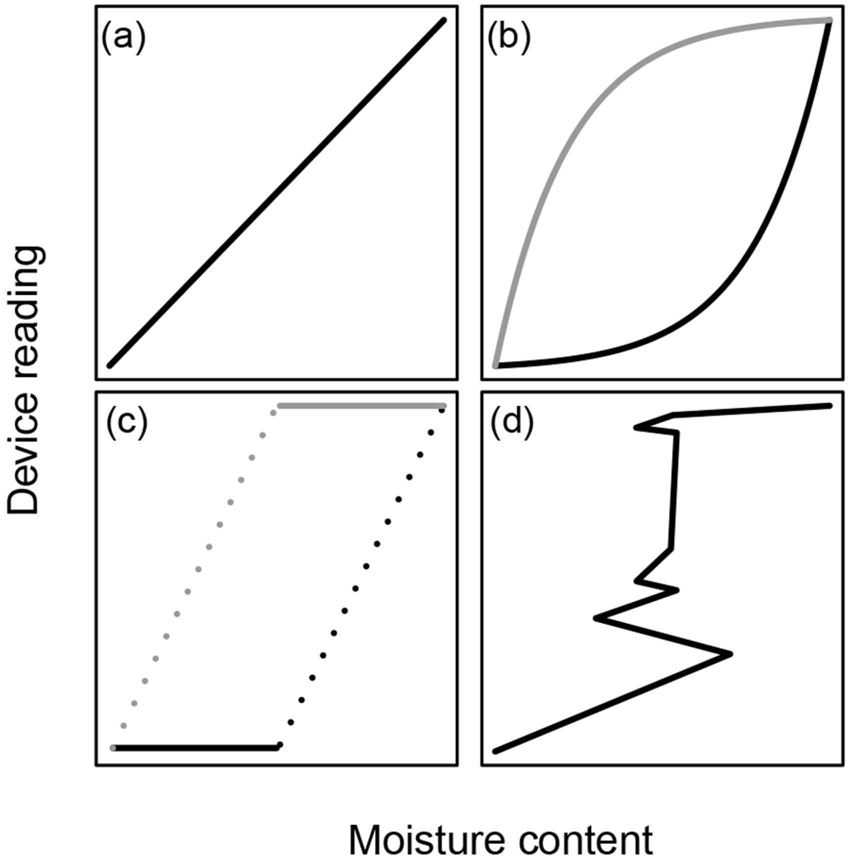


Figure 12 *- Generalised shapes that calibration curves can have when produced for moisture measurement devices.*
(a) Represents the ideal behaviour in which there is a proportional, linear relationship.
(b) Shows non-linear relationships in which there is greater sensitivity at high moisture content (black) and low moisture content (grey).
(c) Demonstrates a device that is not sensitive to the range of possible moisture content (black: lower, grey: upper).
(d) A scenario in which, although the device readings generally indicate moisture levels, the relationship is inconsistent.

Many factors can influence gravimetric calibration results, including material properties, sample size and shape, environmental conditions, frequency of measurements and range of moisture content. An uneven distribution of moisture within a sample might result in a false relationship between the measurement and the moisture content, since gravimetry calculations assume a homogeneous distribution. This is of particular concern for calibrations produced from ambient drying on larger samples. The sample size required for calibration is, in part, determined from the depth of penetration and spatial capture of a device.

3.2 EVALUATING MEASUREMENT VALUES

Determining how moisture measurement readings are evaluated depends on the form of moisture ingress being characterised. This can be broadly classified as absolute values (with and without thresholds) and rates (or levels) of change over time.

3.2.1 Absolute values

Evaluating absolute values can include comparing them to ranges of 'acceptable' readings/measurements and thresholds or reference values. This method primarily applies to identifying spatial variation within a façade or evaluating the entire façade against a standard.

However, it is difficult to determine which measurements or readings are 'acceptable'. Most moisture-related processes that affect building materials do not occur above or below thresholds but are rather related to the movement and dynamics of water. In some scenarios, it is possible to set guidelines; For example, each material has a critical degree of saturation that determines whether freeze-thaw weathering will cause change with lasting effects. Although this degree of saturation is also difficult to determine, it can be evaluated through direct invasive methods or calibrated indirect methods. Similarly, if a threshold is set for a building which is expected to be drying out, it is important to remember that a 'dry' threshold should not be set below the equilibrium moisture content, since the material would not be expected to have a moisture content lower than that value in normal circumstances (see Technical Box 1).

If a 'dry reference' is being determined experimentally based on a part of the facade, it is important to ensure that this has not been impacted by severe weather events in the preceding days and acknowledge that these values might also vary seasonally.

3.2.2 Rates of change over time

Evaluating how moisture levels change over time is a powerful method of evaluation for the following scenarios:

- Monitoring change following an intervention.
- Monitoring moisture levels following a flooding or other wetting event.
- Assessing seasonal variation of moisture levels.

3.3 PRESENTATION AND VISUALISATION

Moisture readings are most commonly presented as a numerical summary (Section 3.3.1) or a visual representation (Section 3.3.2).

3.3.1 Numerical representation

It is common practice to represent each grid, area or time period with an average value, standard deviation and, if appropriate, the value range showing the maximum and minimum points.

A standard deviation should be calculated on at least three measurements, but ideally five or more. If values of the mean plus or minus the standard deviation overlap, it creates problems differentiating between moisture levels. If there are individual readings which are significantly outside the range of the other values (a large value when subtracted from the mean, i.e. an outlier), these can be omitted if the signal is suspected to have been influenced by factors besides the presence of moisture. If many readings are significantly different to the mean, consideration needs to be given as to whether they are clustered in a particular area or time period and should be analysed in a separate group. Otherwise, we might refer to the data as being 'non-normally distributed' and the readings would be better presented as a range from minimum to maximum.

3.3.2 Visual representation

The distribution of moisture across a façade is often presented as a two-dimensional plot in which colour is used to show different readings. This is especially true for 'scanning' techniques (such as thermal imaging), but a similar approach can be used to present any measurement made on a grid.

It is important to create a visual presentation that represents data accurately. Gradient maps mainly use interpolation techniques to produce a continuous visual image using a change in colour, saturation, and/or hue. In some cases, these can introduce misleading characteristics into the colour map. Colour maps should be produced carefully to ensure they do not mislead or prompt misdiagnosis.

TECHNICAL BOX 6: Principles of wetting and drying

Two-stage drying

As a building dries out naturally (after a significant wetting event, such as a flood), most moisture transfer to the surrounding environment will occur at surfaces. This can result in a sustained period in which the surface remains at a constant moisture level near saturation while moisture levels at depth decrease. This is followed by a second period of time in which surface levels of moisture will decrease, since there is no longer significant transfer of moisture occurring through the surface.

If a device is only sensitive to surface conditions, or the measurement is dominated by surface and near-surface conditions, periodic measurements and continuous monitoring will not reveal any change. No change in measurements does not always mean there is no moisture present or no drying occurring; rather, it might be that moisture is transferring from depth to surface at a constant rate. For thicker walls with deep-set moisture, this initial period can last for up to several weeks if not months.

The hysteresis effect

Hysteresis is a well-characterised phenomenon that occurs naturally in many materials. Depending on the pore structure, a building material will absorb different amounts of water during wetting than it will potentially lose during drying at the same relative humidity. Thus, the equilibrium moisture content (EMC) during wetting and drying is not the same.

To an extent, this partially explains why it is difficult to ‘dry out’ a building material after significant water ingress. As it dries, it will not return to the moisture content it had in previous prevailing environmental conditions (Fig. 13).

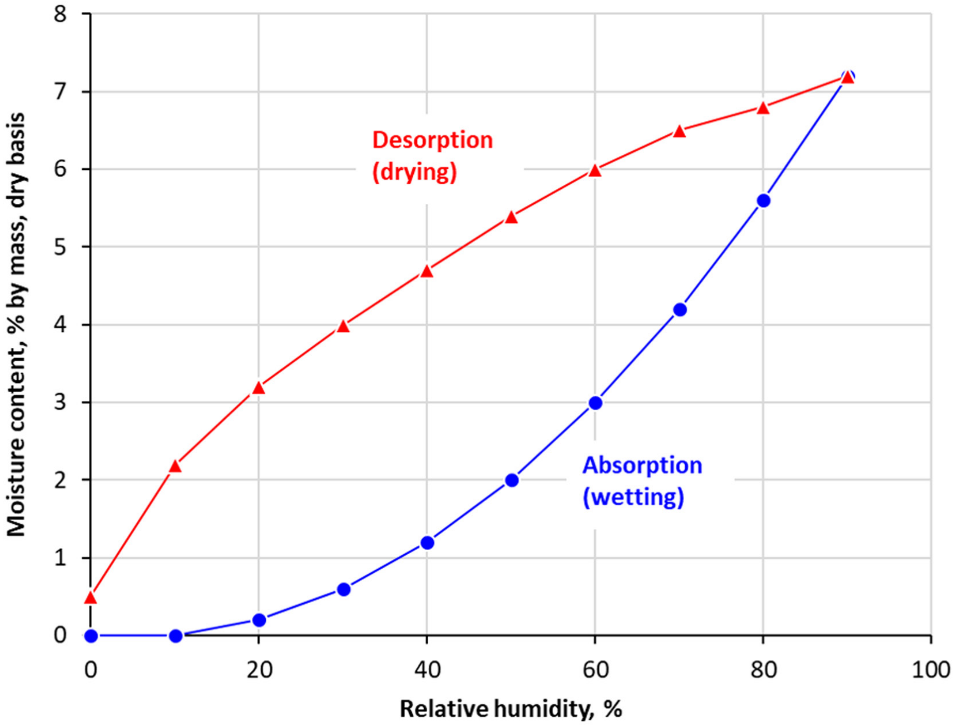
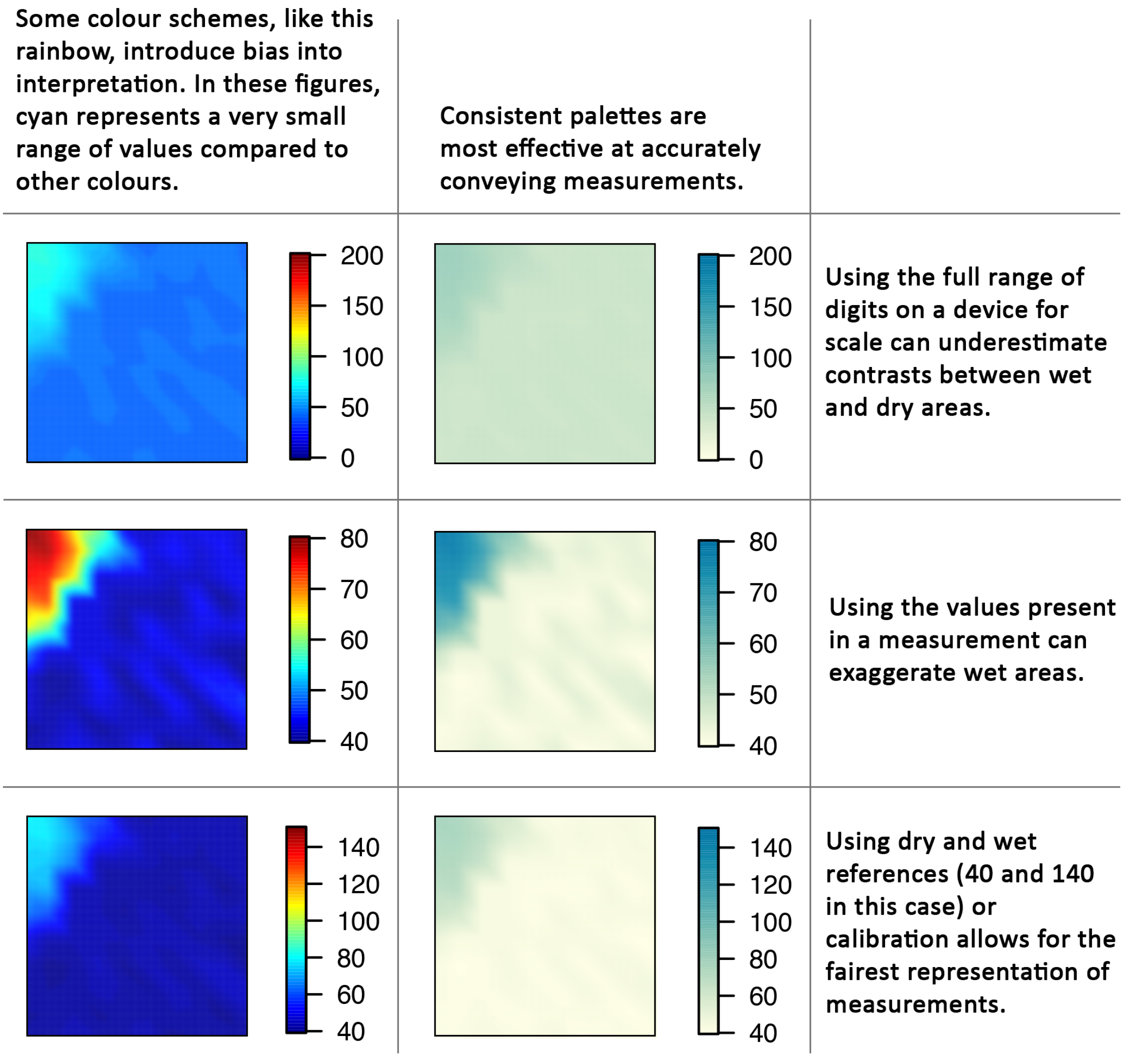


Figure 13 *- A demonstrative plot of a building material absorbing and desorbing moisture in response to changes in relative humidity.*

Colour mapping should include a legend describing what the colours represent. How and which types of values are presented will be determined by the intended audience and nature of the investigation. For example, the results of a direct gravimetric measurement might be presented as absolute moisture contents, while measurements from an indirect reading can be presented in their arbitrary units, normalised between 0 and 1, or indicated with descriptions of 'wetter' and 'drier'. It can be advantageous to present a combination of these for indirect readings to communicate with several audiences simultaneously: a general reader will understand the relative measures, while someone familiar with the device can contextualise the arbitrary units based on their experience.

The range of the colour palette should be determined by context (Fig. 14). Ideally, the most extreme colours should represent the expected minimum and maximum, which can be determined from a priori information (a calibration that indicates values for dry and saturated readings) or based on manufacturer's specifications (if appropriate to the material(s) and context). Without a priori information, the colour palette can be scaled to the range of values present within the grid or a set of measurements to ensure that comparisons are being made on equivalent scales.



Some colour schemes, like this rainbow, introduce bias into interpretation. In these figures, cyan represents a very small range of values compared to other colours.

Consistent palettes are most effective at accurately conveying measurements.

Using the full range of digits on a device for scale can underestimate contrasts between wet and dry areas.

Using the values present in a measurement can exaggerate wet areas.

Using dry and wet references (40 and 140 in this case) or calibration allows for the fairest representation of measurements.

Figure 14 - *The choice of colour palette and scale can greatly influence how a grid of moisture measurements is interpreted. Some colour schemes, like the rainbow used on the left, introduce bias into interpretation. In these figures, cyan represents a very small range of values compared to other colours. Consistent palettes are most effective at accurately conveying measurements.*

Overlaying colour maps onto visual imagery is a powerful technique for understanding the measurements in context (Fig. 15). Integrating these colour maps with digital documentation, especially 3D models, can also be helpful (see Technical Box 7 - Fig. 16, 17).

Colour schemes used to represent moisture distributions should be appropriate for readers with visual impairments. The lightness variations in the rainbow colour are difficult to interpret for many forms of colour blindness. It is also worth noting that colour schemes with a continuous gradation in lightness (with or without colour contrast) reproduce well in grayscale or black and white printing and are easily interpreted.

Figure 15 *- Visual representation of moisture can be overlaid onto images, so that their context can be better understood.*

TECHNICAL BOX 7: Integration with 3D models

Several technologies that enable accurate 3D models of buildings are becoming quick and affordable to use. Two prominent examples include photogrammetry and laser scanning.

When combined with moisture measurement devices, this can be a powerful way to analyse moisture measurements in context. This is especially true for building facades or surfaces with complex geometry or where moisture problems span different rooms or levels. By overlaying these models with moisture measurement data, a deeper understanding of the distribution of moisture in relation to the structure can be achieved.

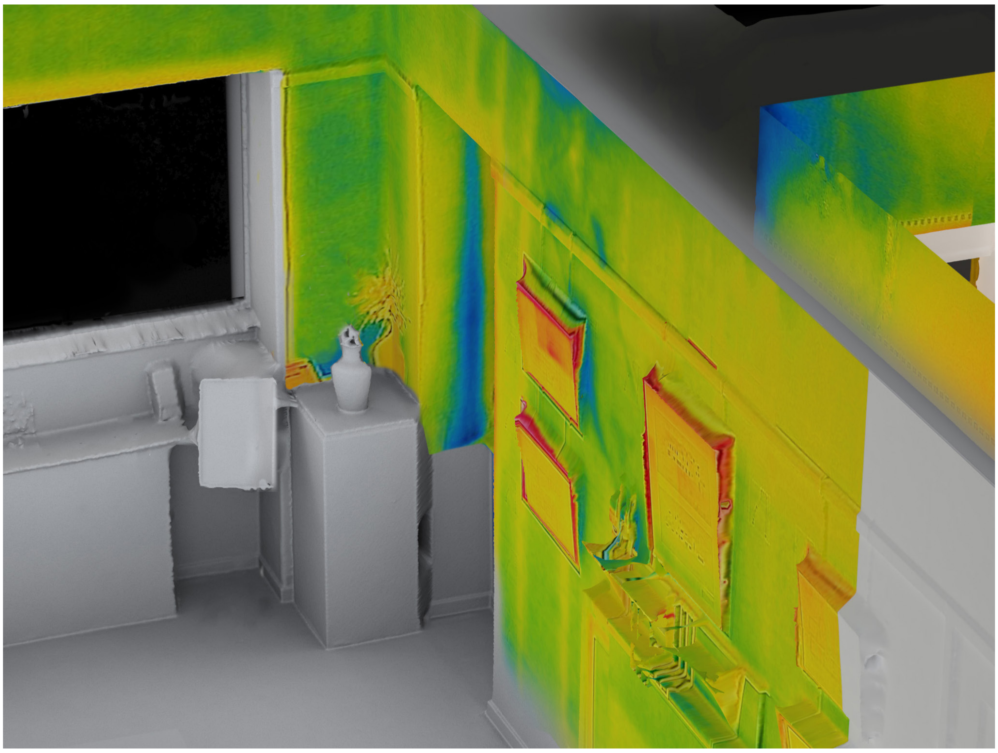


Figure 16 *- Thermal imaging overlaid onto a 3D laser scanning model.*

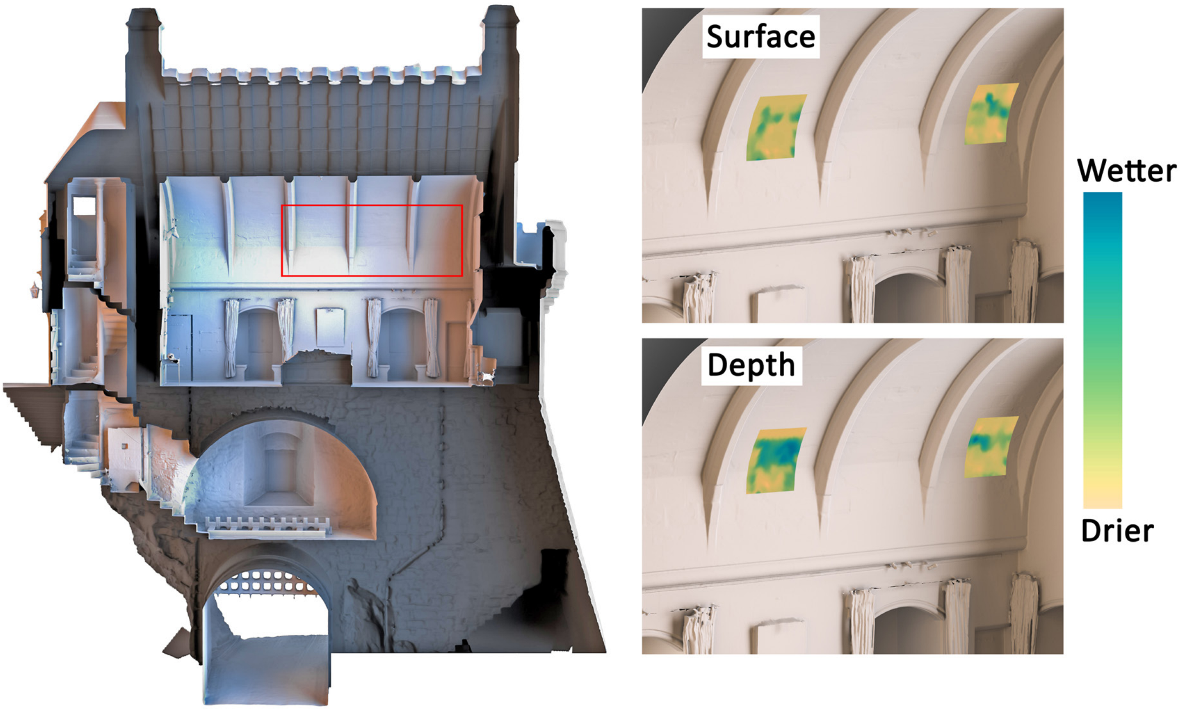


Figure 17 *- Four grids of moisture measurements overlaid onto a 3D laser scan of Argyle Tower in Edinburgh Castle. The unique stone-vaulted roof and ceiling construction has potentially introduced unexpected ingress pathways.*

4 OVERVIEW OF MEASUREMENT METHODS

Several techniques that can be used to measure moisture are not included here, because they are not commonly used or have not been developed as commercial tools for this purpose. These include near-infrared spectroscopy (NIR), evanescent-field dielectrometry (EFD) and self-potential (SP), among others. The following sections provide an overview of the more commonly used and more widely available measurement methods.

4.1 GRAVIMETRY

APPROACH **INVASIVE** | OPERATION **GENERAL USER** | INTERPRETATION **GENERAL USER** | COST **£**

Gravimetric methods determine moisture content by measuring the mass of water present in a sample. The sample is typically collected invasively, using a specialised drill bit to extract a core that is a few centimetres in diameter (Fig. 18). Drilling should be undertaken slowly to reduce the potential for evaporation due to heating of the bit (and therefore, an underestimation of moisture content). Drilling that uses water for cooling is also problematic, as it introduces water into the samples. The core can be weighed on site after drilling to determine the total mass (of the building material and the moisture present within it). Generally, this needs to be accurate to 0.1g or better to precisely determine the moisture content at the time of extraction. It must then be tightly sealed to reduce the possibility of evaporative moisture loss, before being transported for further measurement. The core can be weighed again upon arrival to determine if any moisture has been lost during transport.

The core is then heated in an oven at 70 ± 5°C for at least 24 hours with the mass recorded once a day, until it exhibits change of less than 0.1% between sequential measurements (i.e. in a 24-hour period). The mass of the core is at that point recorded; this represents the dry mass of the building material. Moisture content at the time of extraction can then be determined.

NB. Oven heating of the sample will probably result in an 'over-dry' material, which will subsequently behave differently when exposed to moisture. Consequently, its moisture content will not reflect the equilibrium moisture content described in Technical Box 1.

Alternatively, a halogen moisture analyser can be used. The same principle is applied to a core or powder material sample (Fig. 19), except that the analyser automates the process of recording the relevant mass values. A halogen source rapidly heats the sample until it reaches a constant mass, giving the moisture content.

Obtaining accurate measurements requires a balance sensitive enough to register a 0.1% change in mass. A typical masonry drill core with a diameter of 2cm and a length of 5cm might have a dry mass of approximately 50g, so a balance capable of measuring mass to the nearest 0.5g would be needed.

For an automated approach, there are several commercial halogen moisture analyser devices available with appropriate precision.

Gravimetry can cover a range of depths and spatial resolutions but is limited by practical considerations and ethical guidelines on invasive sampling. Invasive sampling by drilling is limited by the diameter and length of appropriate drill bits. Drill cores allow targeted analysis of a particular area and can be collected using vertical transect sampling (e.g. a few holes at the same point on a wall but at different heights) or a grid pattern. Cores can be divided into slices and analysed separately to assess moisture content at different depths. If the core is not divided up prior to analysis, the calculation of moisture content is limited by an assumption that the water is evenly distributed through the core.

Figure 18 *- Drill core being extracted from a rendered masonry wall.*

Figure 19 *- Powder being collected in a sample bag for gravimetric analysis.*

Gravimetry is one of the only in situ methods that can provide accurate information about moisture content at specific depths. The main drawback of this method is that extracting drill cores causes permanent change to the fabric of a building. Consequently, a moisture measurement scheme using this approach must be designed to minimise impact on both the aesthetics and the function of the building. *Ethical Sampling Guidance* has been produced by the ICON Heritage Science Group to address this.

4.2 CALCIUM CARBIDE

APPROACH **INVASIVE** | OPERATION **GENERAL USER** | INTERPRETATION **GENERAL USER** | COST **££**

This method determines the moisture content of a powder sample of building material via a chemical reaction. Moisture measurements are made by mixing a sample of material with known mass of calcium carbide reagent in a sealed pressure vessel. The reagent reacts chemically with water to produce acetylene gas, changing the pressure within the vessel. The pressure change is determined by the quantity of water present in the sample, which can be read directly from a calibrated pressure gauge mounted on the vessel.

In addition to the calcium carbide vessel, a balance is needed that can precisely record the mass of the sample - ideally to within 0.1% of its weight.

The calcium carbide method can cover samples from a range of depths of penetration and spatial resolutions across a wall or facade but is limited by the practical considerations of drilling holes and by ethical guidelines regarding invasive sampling (as mentioned above). Invasive sample collection by drilling is limited by the diameter and length of appropriate drill bits, but drilling can be targeted to a particular area of interest using a vertical transect (e.g. a few holes at the same point on a wall but at different heights) or a grid pattern.

The calcium carbide method provides an accurate measurement of moisture content. Most importantly, it is one of the few in situ methods that can provide accurate information about moisture contents at specific depths. However, drilling causes permanent changes to the fabric of a building, therefore a moisture measurement scheme using this approach must be sensitive to both the aesthetics and the function of the building.

4.3 ELECTRICAL CONDUCTIVITY/RESISTIVITY

APPROACH **NON-INVASIVE** | OPERATION **GENERAL USER** | INTERPRETATION **GENERAL USER** | COST **£**

Commercial electrical devices are quick to use and the measurements can be taken in several locations. Electrical readings are mainly non-invasive, except for small indents that can result from the pins (Fig. 20) - especially when there are several repeated measurements in the same location.

Electrical conductivity/resistivity techniques are based on measuring the resistance of a material to the passage of an electric current. This can also be expressed as the inverse property, ‘conductance’. This technique is particularly effective for monitoring moisture because most building materials are poor electrical conductors; the higher the moisture content, the less resistance it will exhibit to the passage of an electrical current.

However, resistance is also strongly dependent on the presence of salts and influenced by porosity. Interpreting a series of readings can be difficult if there are heterogeneous material properties or differences in temperature. Temperature affects the amount of salt in solution and, consequently, the conductivity/resistivity of the substrate. This is especially important if measurements are taken during periods when any salts present might be near their deliquescence point (the relative humidity at which they dissolve into solution). Although the deliquescence point of common soluble salts is typically above 80% RH at most ambient temperatures, it can change drastically with temperature and vary widely for other salts and salt mixtures.

In addition to the influence of salt, it is important to recognise that the reliability of readings from electrical devices can be undermined by the presence of other electrically conductive materials, such as metals, conductive wallpaper paste and the use of industrial waste products.

Electrical techniques are most effective when the probes have consistent contact with the surface, since this influences the resistivity. These meters typically operate in reflectance mode (i.e. the transmitter and detector are on the same side of the structure). Therefore, the quality of contact with a surface will profoundly influence the accuracy of the data. To ensure good contact, it is recommended practice to temporarily remove a pin from the surface, using the other as a hinge, then make surface contact again, to ensure that the reading is not being significantly influenced by poor contact, especially on rougher surfaces. The device will not produce a reading if insufficient pressure is applied. Alternatively, in more bespoke applications, electrodes can be temporarily fastened to a surface with an adhesive that will not leave a permanent residue, or electrodes may be fixed into the wall.

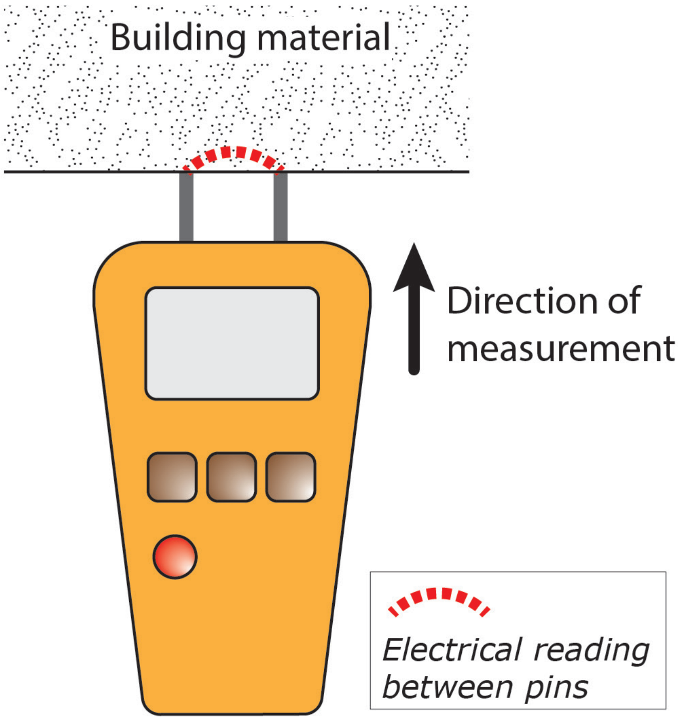


Figure 20 *- A resistance pin moisture meter. The presence of moisture is assessed based on the electrical resistance between the two pins.*

The depth to which electrical readings will penetrate is primarily determined by the distance separating the pins. A rough guide is that the depth of penetration is 1/6th of the maximum pin spacing. For most handheld meter devices this means that the readings represent conditions within the first few millimetres below the surface. The readings are an average representation of moisture for the entire depth of the signal. Some instruments have multiple probes that can be used, which have different pin spacings. Thus, several probes can be used to infer the general moisture levels to different depths.

Table 4 *- Approximate ranges of depth of penetration of electrical techniques depending on the pin (electrode) spacing.*

Pin spacing (mm)	**Approximate maximum depth of penetration (mm)**
10	1.5 to 2
20	3 to 4
40	6 to 7
150	20 to 30
200	25 to 35

4.4 CAPACITANCE

APPROACH **NON-INVASIVE** | OPERATION **GENERAL USER** | INTERPRETATION **GENERAL USER** | COST **£**

Capacitance techniques produce an electrical field and measure the response of a material. A higher reflection (measurement) indicates a higher moisture level. The measurement might also be expressed as an impedance - the inverse of capacitance. The dielectric constant (see Technical Box 9) is an important property that influences capacitance readings, but neither it nor the readings are strongly affected by soluble salts. Commercial capacitance devices, which do not require specialised technical knowledge or training, are quick to use and measurements can be taken in several locations, often working in reflectance mode. Since capacitance techniques do not require consistent and good contact with the surface, they are especially suitable for more fragile surfaces, although they still need to make direct surface contact.

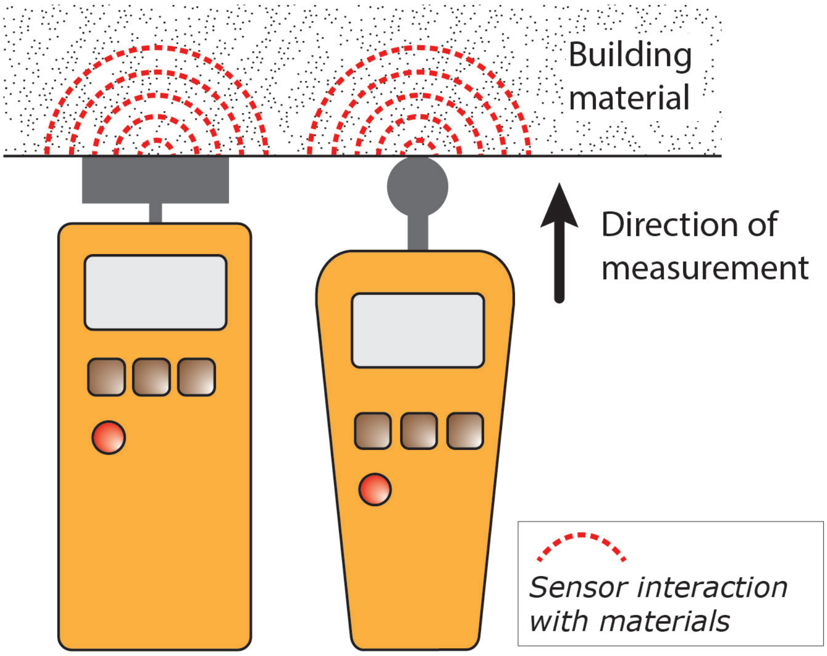


Figure 21 *- Different types of capacitance meter heads. These devices assess moisture levels by measuring how the building material interacts with an applied electrical field.*

Handheld meters are most commonly used to measure capacitance (Fig. 21). The raw measurement is converted by the meter into an arbitrary scale of values for relative comparison. In most cases, these scales do not represent an absolute moisture content or degree of saturation. The range of values will be influenced by the dielectric constant; a material with a higher dielectric constant will have a higher value of capacitance (and likely a converted reading) for the same moisture contents. For example, based on values of the dielectric constant presented in Table 5, a dry-stone façade would yield a lower reading than a dry brick wall.

Although the meters are easy to use, the operator must understand that because of the nature of electrical fields, the angle of operation can significantly impact the readings. Therefore, measurements should be consistently angled - with the field oriented 90° to the surface - but this can mean that reliable measurements can be difficult to acquire on rough or uneven surfaces.

Most commercial devices will have a capacitance field that penetrates to a few centimetres in depth and most devices are one-sided applications that work in a reflection mode (Technical Box 8). Capacitance techniques are therefore more sensitive to moisture present nearer to the surface, with a typical device being 16 times more sensitive to moisture present within the first 2.5mm below the surface, than moisture at 10mm depth. Hence, capacitance devices are susceptible to inflated readings due to hygroscopic moisture and condensation present on a surface.

TECHNICAL BOX 8: Transmittance and reflectance

Most commercial tools are designed to operate in a reflectance or one-sided configuration. This means that the component that produces the signal (transmitter) and the part that measures the response (receiver) are in the same piece of kit.

Some devices separate these so that they can be placed on opposites sides of a wall. These operate in a transmittance or two-sided configuration. The main advantage of transmittance is that it is much clearer that the measurements represent the distance/area between the transmitter and the receiver, so there is less ambiguity about what volume the measurement represents. Devices that operate in transmittance mode often require specialised equipment intended for research and are not commonly used in commercial settings.

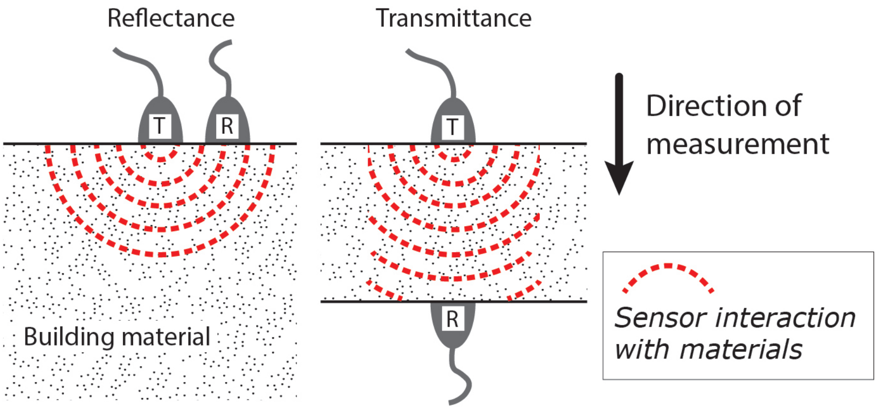


Figure 22 *- Comparison of the configuration of reflectance and transmittance measurements in moisture measurement devices. Reflectance is more common in devices designed for general use (T = transmitter, R = receiver).*

TECHNICAL BOX 9: Dielectric constant

The dielectric constant is an important material property of building materials and represents the capacity of a material to store electromagnetic energy. This common name is a misnomer – the dielectric constant is not constant, as it varies significantly with frequency. It depends on several intrinsic material properties, such as density, porosity and mineralogy, which vary considerably between different types of building material. Finding measured values of the dielectric constant at a frequency relevant to a specific device is difficult and is made more complicated by the natural heterogeneity of historical building materials and changes to their properties over time.

***Table 5** - Dielectric constant values for samples of building materials. (Cuiñas and Sánchez, 2002).*

Material	**Dielectric constant (at 5.8 GHz)**
Plywood	2.88
Brick wall	3.58
Glass	6.06
Plasterboard	2.02
Stone facade	2.00

4.5 MICROWAVE

APPROACH **NON-INVASIVE**	OPERATION **GENERAL USER/TECHNICAL USER**	INTERPRETATION **GENERAL USER/TECHNICAL USER**	COST **£-££££**

Microwaves are a form of electromagnetic energy with frequencies between 300MHz and 300GHz. Like other electromagnetic techniques, microwave devices capitalise on the contrast between the dielectric properties of water and most porous building materials. They typically operate at frequencies available for open use, such as 2.45GHz. Within most of the microwave region (at frequencies greater than 1GHz), the influence of salts on the device readings are negligible, but microwave moisture readings are strongly influenced by structure and interfaces between different materials, including voids.

***Figure 23** - A microwave sensor being used to determine variations in sub-surface moisture.*

Most one-sided microwave sensors measure the ratio of energy that is reflected by the material. A higher moisture level results in a higher amount of reflected energy. A dry material will not usually give a reading of zero, since a fraction of energy will naturally be reflected by the dry building material. Similarly, the upper limit of the realistic range of reflection coefficients will depend on the dielectric properties of the material and the maximum fraction of water it can hold.

Rough surfaces can influence microwave device readings, since they can interfere with how the signal is transmitted and reflected. Care should be taken when interpreting readings from materials with these types of surfaces. Due to the nature of electrical fields, the angle of operation can significantly impact the readings. Measurements should be consistently angled, with the field oriented 90° to the surface (Fig. 23), but this operational requirement can place limits in the contexts in which these devices might be used.

Operating frequency is a dominant factor in determining the depth of penetration of a microwave device. However, the generated field can be manipulated to increase or decrease the volume in which a sensor is sensitive to changes in moisture. In general, most commercial microwave devices are sensitive to moisture within a radius equal to the depth. For example, a device that can detect moisture up to depths of 10-15cm will indicate the moisture levels within a 10-15cm radius around that device beneath the surface. However, this sensitivity - both parallel to the surface and with depth - can be much greater for materials such as metals. Metal has the potential to influence the measurements based on electromagnetic energy. This interference is likely to be greater than the sensitivity of the instrument to differences in moisture levels. Consequently, no useful data can be obtained in areas immediately adjacent to or containing embedded metal.

Microwave techniques are more sensitive to moisture that is present closer to the surface, with a typical device being 16 times more sensitive to moisture present within the first 2.5mm, than moisture at 10mm depth. This makes microwave devices very susceptible to the influence of hygroscopic moisture and/or condensation on the surface of a building material.

4.6 RADAR

APPROACH **NON-INVASIVE** | OPERATION **TECHNICAL USER** | INTERPRETATION **SPECIALIST** | COST **£££**

Radar, frequently called ‘ground penetrating radar’ (GPR), is an electromagnetic technique that is most commonly used to investigate structural aspects of constructions. A transmitter emits electromagnetic waves (radar signals) and a receiver records the response. When the electromagnetic waves make contact with an interface between two materials with different dielectric properties, they are usually reflected or scattered in many directions. However, some of the electromagnetic energy will be absorbed and penetrate beyond the interface.

The detection of radar signals is reported as a wave that has an amplitude recorded over a travel time (Fig. 24). Since multiple aspects of radar signals can be used to infer moisture, the technique can be used to indicate moisture levels at various depths. For example, the amplitude of the direct (surface) wave can indicate surface moisture conditions, whilst the travel time or average velocity to the back-wall reflection represents the average condition across the thickness of a construction.

Both surface wave amplitude and travel time can be used to indicate relative levels of moisture in a construction and are generally represented on an x-y plot or as a grid of measurements, in which colour, hue or saturation represent the moisture level.

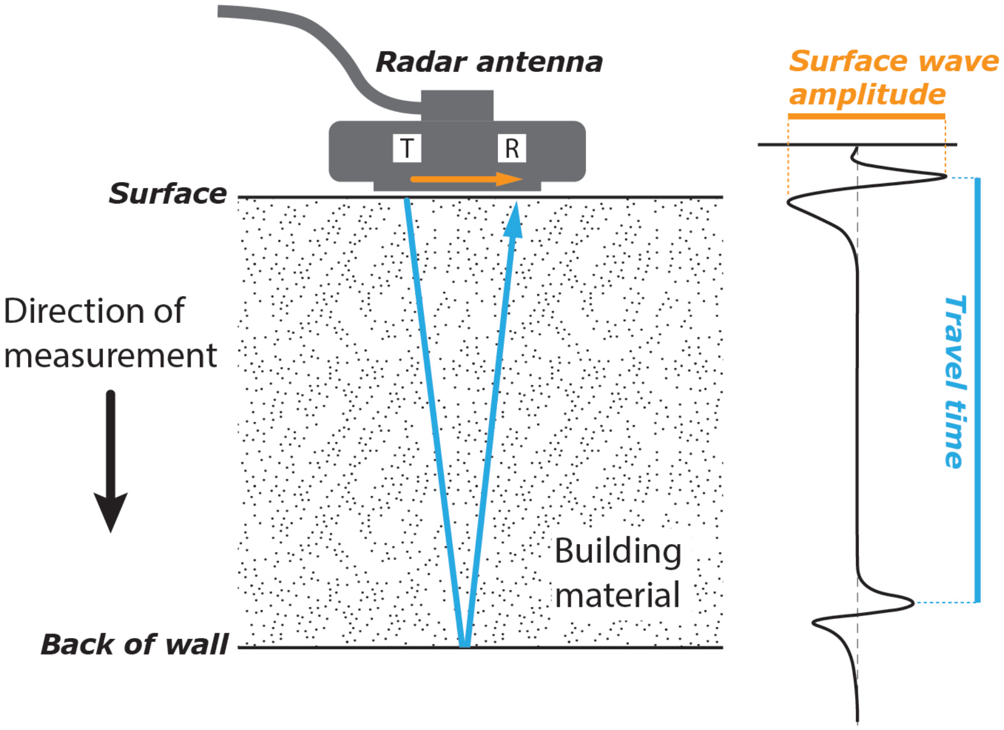


Figure 24 *- A radar antenna configuration, showing the two main signal components used for moisture measurement and how they travel through a wall (T = transmitter, R = receiver).*

It is possible to assess these aspects of the radar signal visually (qualitatively) and analytically (quantitatively). Visual inspection of a radargram - a common method for presenting radar signals - shows that a higher moisture level will produce a lower amplitude of the direct wave. A longer travel time through the same material also indicates a higher moisture content and represents the mean moisture content across the entire depth of wall. This assumes that the construction or material has a consistent physical thickness, unless this is accounted for in the calculations.

Radar measurements require specialised equipment and software to collect and analyse data. Data is usually collected along transects and grids, which can make it difficult to use the device on rough surfaces or in hard-to-reach places.

TECHNICAL BOX 10: Calculating the total travel time

Quantitative assessment of the signal travel time is based on a simple calculation of the velocity of the signal within the building material. This can be calculated using the following equation, in which v is the average velocity, z is the thickness and t the travel time.

$$v = \frac{2z}{t}$$

If the signal takes longer to travel the same physical distance, it will have a slower average velocity.

TECHNICAL BOX 11: Fundamentals of electromagnetic principles

Several indirect moisture measurement methods are based on electric or electromagnetic properties (i.e. representations of how energy interacts with solid objects). These are particularly useful for identifying moisture levels, as the properties of building materials are often substantially different than those of water. This means that a small change in the amount of moisture results in a large change in the overall electric and electromagnetic properties.

The contrast in properties between water and most building materials is significant but varies across most of the electromagnetic spectrum. Indirect methods operate within certain frequency ranges to balance the trade-off between spatial resolution and depth of penetration. For example, most commercial electromagnetic devices operate within the FM radio and microwave range, which can detect moisture from a few centimetres to a few metres in depth. By contrast, high energy techniques, such as X-rays and gamma-rays (γ), provide the high resolution required to study how liquids travel through the pore spaces of porous building materials. However, the higher energy required to produce this radiation restricts their use to specialised laboratory-based methods, applicable only to very small volumes, not to buildings in the field.

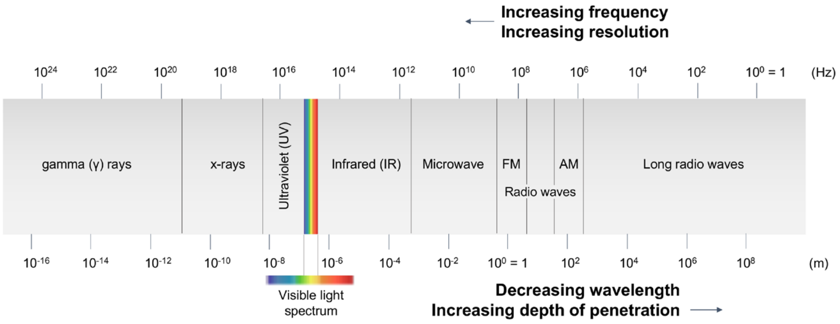


Figure 25 *- The electromagnetic spectrum.*

Figure 26 *- A high-resolution radar being used. The antenna is placed on the surface of the wall, while the control unit (in the case) records the signals reflected by the wall surface and from components of the sub-surface.*

Commercial radar antennae use a wide range of frequencies. Geological studies, for example, operate at frequencies much less than 1GHz, since they are interested in measuring properties of the subsurface up to several metres in depth. In contrast, civil engineering antennae can operate at higher frequencies (e.g. 1.6GHz, 2.3GHz) to provide higher resolution measurements, while still ensuring the signal can penetrate to the back-wall (Fig. 26). If the signal does not show a sufficiently strong reflection wave, a metal plate can be placed on the back-wall to increase its strength (since the stone-metal interface has more strongly contrasting dielectric properties then the stone-air interface).

4.7 THERMAL IMAGING

APPROACH **NON-INVASIVE**	OPERATION **GENERAL USER/TECHNICAL USER**	INTERPRETATION **GENERAL USER/TECHNICAL USER**	COST **£-££££**

Thermal imaging, also known as infrared thermography, is a type of non-invasive technique that can rapidly image temperature variation across a surface. This variation has several causes, including the distribution of moisture. Thermography can be used in areas that are difficult to survey at close range without the use of ladders or scaffolding. Thermal imaging only shows the temperature of surfaces. Its ability to provide information about sub-surface moisture distribution is dependent on conditions being such that sub-surface properties influence surface temperature in a known way. Although thermal imaging devices can be very costly, handheld devices - similar in cost to moisture meters - are becoming more readily available and provide new opportunities to explore the use of this technology.

Surface and near-surface moisture concentrations can be observed in thermal images, where environmental conditions allow moisture to evaporate, chilling moist surfaces relative to drier areas (Fig. 27). Under appropriate conditions, it is also possible to observe sub-surface moisture concentrations where the contrast between the thermal capacity of water and building materials affects surface temperature (Fig. 28).

Moisture levels can be evaluated by visually (qualitatively) and quantitatively assessing thermal images. Each pixel on the thermogram has a temperature value represented by a colour. This data can be extracted to a spreadsheet for further analysis. The resultant temperature distribution patterns can reveal variations in moisture content across a surface that are not obvious to the naked eye.

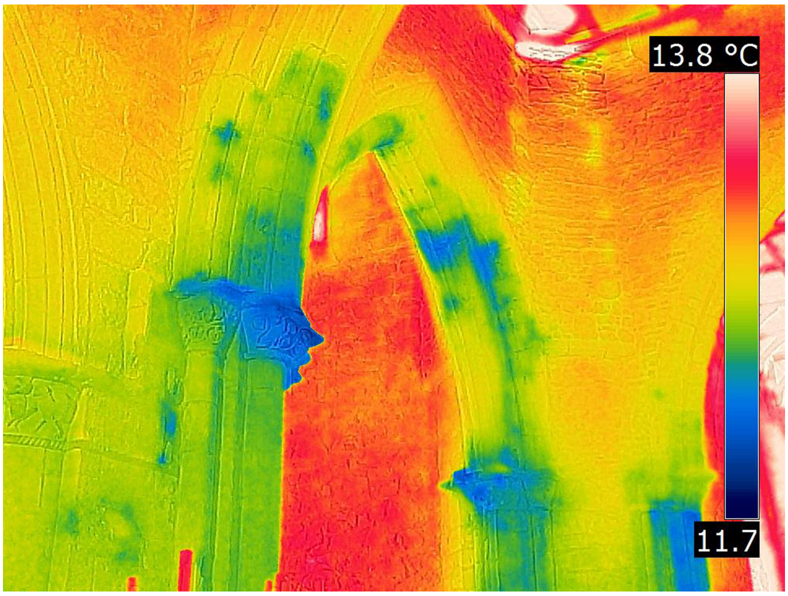


Figure 27 *- A thermal image showing the distribution of damp stonework by relatively colder surfaces.*

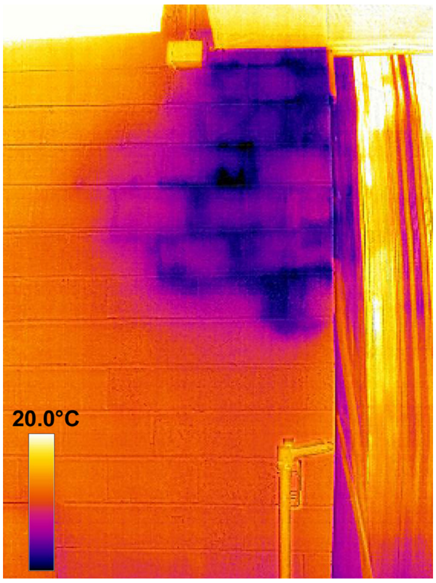


Figure 28 *- A thermal image of a cinder block masonry wall showing the distribution of dampness from a leaking pipe, revealed by the colder patch of wall.*

Thermal imaging can also be used to detect the risk of condensation on a surface by comparing surface temperature to the dew point. Many commercial devices and associated software can make this calculation.

Thermal images are collected in a similar way to visual images. When imaging with a specific focus on moisture, thermal imaging can be undertaken passively or actively. In passive imaging, images are taken at an appropriate time to take advantage of natural changes in temperature. Active thermography applies heat using specialised devices or by heating an indoor space using systems already in place.

TECHNICAL BOX 12: Principles of thermal imaging

Thermal cameras detect infrared radiation (IR) related to the temperature of an object. Thermal images, or ‘thermograms’, are images in which every pixel records a temperature.

A thermal imaging camera will measure the infrared radiation from a surface and convert this into a temperature based on a material property called emissivity. Emissivity is a value ranging between 0 and 1 that represents the ratio of energy radiated by a material compared to a blackbody – a theoretical object that perfectly emits energy. While differences in emissivity between most building materials has a minimal impact on the calculated temperature, some are notably different (including metals and glass).

Other parameters (such as the reflected apparent temperature, air temperature and humidity) are also important components of the accurate calculation of surface temperature and should be appropriately recorded. However, to observe differences in surface moisture concentrations, highly accurate analysis of surface temperature is likely to be unnecessary. Relative differences in temperature may be sufficient to provide a visual representation of spatial differences in surface and near-surface moisture levels.

Note that it is not possible to calculate the moisture content of materials from thermal data.

4.8 EQUILIBRIUM METHODS

APPROACH **INVASIVE** | OPERATION **TECHNICAL USER** | INTERPRETATION **GENERAL USER** | COST **£-££**

Materials that are in contact with one another transfer liquid moisture between them and exchange water vapour (humidity). The extent to which these processes occur is based on the materials' natural response to reach an equilibrium state with their environment and surroundings.

The dowel method is a reliable technique that provides long-term and reliable measurements. Additionally, it has the potential to operate on more than one measurement principle (e.g. electrical methods and gravimetry), providing a greater range of information and alternative data sources, should technological difficulties be encountered with indirect methods. Most commonly, equilibrium methods introduce wooden or ceramic dowels into drill holes within a construction (Fig. 29). The method requires suitable holes to be drilled into the masonry units and/or mortar joints, in which the dowels are inserted. The dowels respond to changes in moisture within the surrounding structure. These dowels can be monitored continuously, if they include electrical sensors (e.g. resistance pins), or periodically based on the same principle and/or gravimetry. These dowels must be in good contact with the surrounding materials to be effective and should be left in the structure for several weeks to equilibrate.

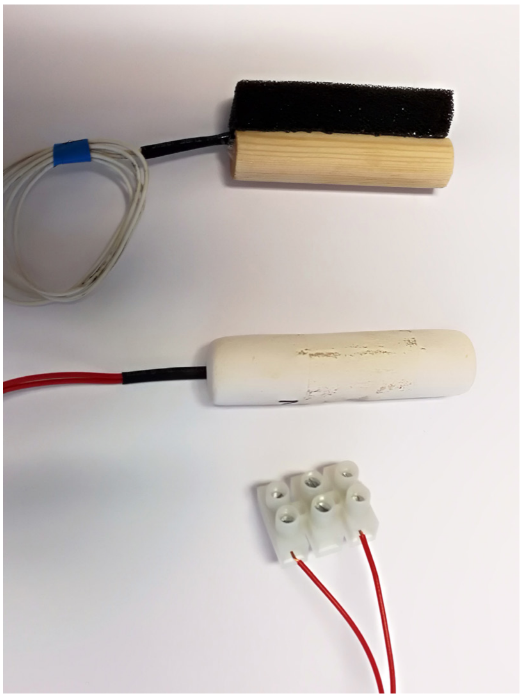


Figure 29 *- Examples of bespoke wooden (above) and ceramic (below) dowels, which use embedded electrical resistivity sensors to monitor moisture contents of the walls.*

Dowels can be used in several types of investigations. For example, an indirect method (such as electrical resistivity) can be built into them and this can be monitored automatically or periodically recorded by manual measurement. Alternatively, a periodic direct measurement by on-site gravimetry can also provide useful information.

The dowels will swell if they absorb a significant amount of water. To this end, a drill hole must be sufficiently sized to accommodate changes in dowel dimension, while also ensuring that there is good contact between the dowel and the surrounding material. The expansion of wood due to saturation varies, but can be up to 8%, depending on the cut of the wood relative to the grain. Due to reliance on equilibrium and exchange between dowels and their surroundings, it is possible that the dowels might not always reflect the conditions of the adjacent material. For example, a dowel will not respond immediately to a marked change in the amount of liquid water in the surrounding material, since the rate of change will be limited by the laws of diffusion. Similarly, a dowel reading may not reflect very high moisture content, if the dowel material has reached saturation before reaching equilibrium with a higher moisture concentration in the surrounding material.

Dowels can cover a range of depths of penetration and spatial resolutions, but these are limited by practical considerations of drill coring and ethical guidelines regarding invasive sampling. Invasive sample collection by drilling is limited by the diameter and length of appropriate drill bits. Dowels can be installed in a particular area of interest, a vertical transect or in a grid pattern. Dowels can also incorporate multiple sensors to assess conditions at different depths.

Drilling causes permanent change to the fabric of a building; a moisture measurement scheme should therefore be designed carefully to minimise impact on both the aesthetics and the function of the building.

4.9 TIME DOMAIN REFLECTOMETRY

APPROACH **INVASIVE**	OPERATION **SPECIALIST**	INTERPRETATION **TECHNICAL USER**	COST **£££**

Time domain reflectometry (TDR) is an electromagnetic technique that can be applied to measure the water content of materials (Fig. 30). It works on the principle of measuring the time between transmission and reception of a radio signal. The dielectric constant can be calculated from this travel time. This allows the moisture content of a substrate to be quantified due to the high contrast in dielectric constants between water and dry substrate.

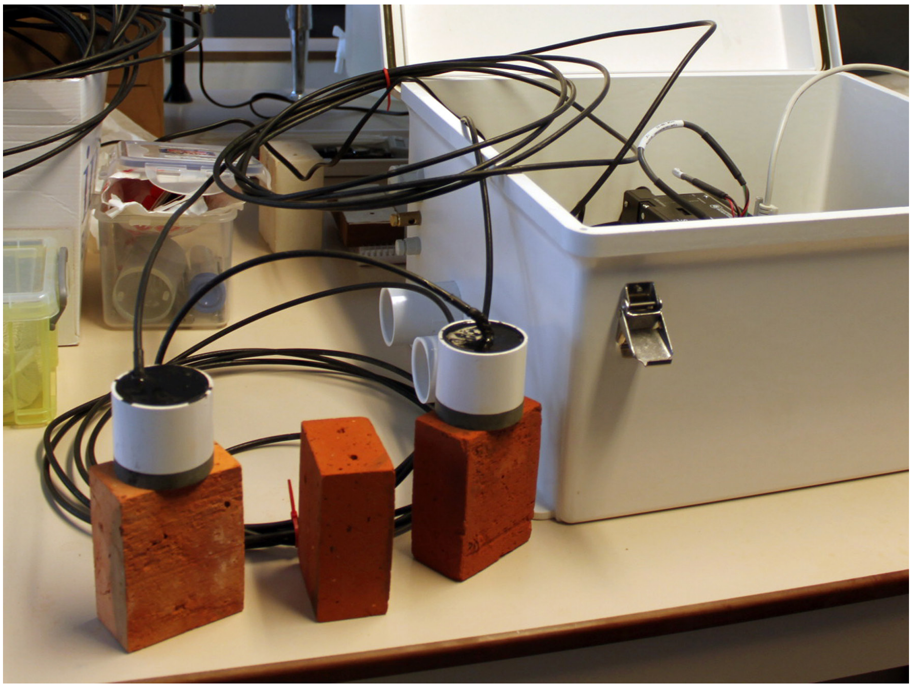


Figure 30 *- A demonstrative set-up for calibrating a TDR device. The probes pictured here are inserted into brick samples, while the computer components and data logger are inside the weather-tight box.*

Any gap between the probes and the internal extent of the drill holes has been known to significantly influence the readings. Therefore, drill holes should be made that allow for a tight fit and good contact between the probes and the surrounding material.

TDR probes can cover a range of depths and spatial resolutions, but like most invasive techniques, they are limited by practical and ethical considerations. TDR probes can be installed in a particular area of interest, a vertical transect (e.g. a few holes at the same point on a wall but at different heights) or in a grid pattern.

TDR is especially useful for providing long-term and reliable moisture monitoring. Due to its operating frequency, it is negligibly impacted by the presence of salts. It is especially useful for providing information about moisture at a specific depth and within a specific range, since the measurement is taken over a small electromagnetic field between the two probes.

TECHNICAL BOX 13: Time domain reflectometry

Time domain reflectometry (TDR) is an electromagnetic method that measures an ‘apparent’ dielectric constant by sending an electromagnetic pulse along a cable, terminating with waveguides that measure the reflection of the signal. Two metal probes are embedded into the material being examined. The frequency of TDR signals is set to minimise the impact of the imaginary component - and thus the effect of conductivity on the measurement - by being set to ensure minimal relaxation losses. As such, TDR does not measure the dielectric constant of a material, which has led to a confusing variety of terms used to describe it.

The travel time of the energy between the two probes is used to determine the dielectric constant by comparing an ‘apparent’ length of the inter-probe distance (based on the signal velocity) and the actual length of travel (distance between the probes). Any of these values can be used as an indicator of moisture.

The TDR requires a specialised receiving unit to process the waveguides that are measured by the probes. This receiving unit can be linked with several sets of probes, meaning that multiple nearby locations can be monitored simultaneously.

4.10 MICROSCALE METHODS

APPROACH **INVASIVE** | OPERATION **SPECIALIST** | INTERPRETATION **SPECIALIST** | COST **££££**

Methods that provide high-resolution measurements (under 1mm, but usually smaller) are rarely applicable to on-site evaluation. They use electromagnetic energy at high frequencies and intensities, and typically require specialised facilities such the Diamond Light Source in Harwell, UK. This class of techniques includes X-rays, gamma rays (γ-rays), neutron investigations and nuclear magnetic resonance (Fig. 31). While these facilities are often accessible to anyone with a viable course of investigation, there are only a few such sources in the UK and their use requires discussion with their scientific staff.

Neutron-based investigations are particularly suited to identifying water due to a high sensitivity to the presence of hydrogen.

Nuclear magnetic resonance (NMR) is a method that can identify the nucleus (centre) of a specific type of atom (e.g. hydrogen). To this end, it can be tailored toward identifying moisture in building materials. NMR has been implemented in a portable tool (e.g. the NMR-MOUSE) which can be used in on-site investigations of moisture. While it can be used without the need for specialist facilities, the logistics of using it on vertical surfaces such as walls means that collecting measurements can be time-consuming.

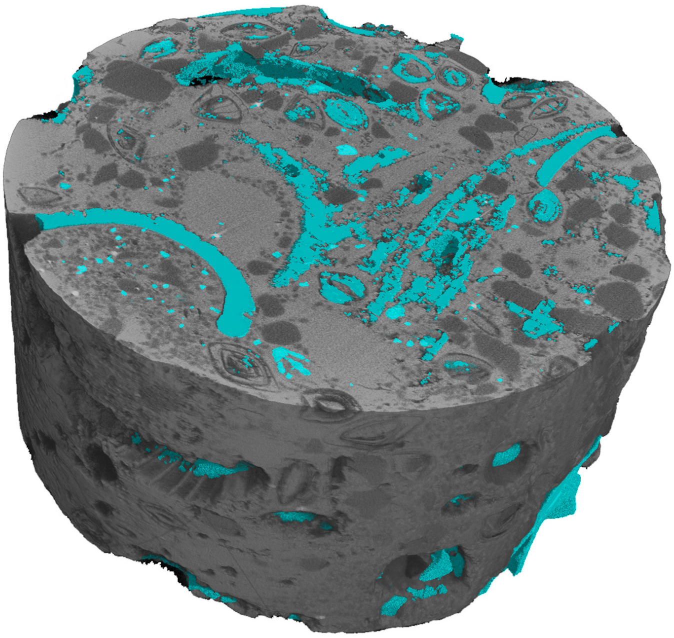


Figure 31 *- A micro-CT scan of a porous stone, with minerals shown in various shades of grey and water in blue. Used with permission of the Ghent University Centre for X-ray Tomography (UGCT).*

5 CONCLUSION

Moisture measurement is useful for investigating a wide range of moisture-related problems in the historic environment. Moisture is a normal occurrence within all building materials, but it may become a problem in excessive amounts.

A well-conducted moisture investigation considers the suspected issue(s) and identifies an appropriate method, strategy and approach. While there are several considerations before, during and after measurement, the most important thing is diligence and documentation. Moisture measurement should be undertaken as part of a wider building survey and diagnostic actions.

Interpreting moisture measurements should consider whether a device is providing raw readings of material properties, arbitrary units, or values calibrated for specific types of materials. These device readings should be contextualised within the dynamics of how moisture moves within building materials and how it responds to the surrounding environment.

The numerical and visual presentation of moisture measurements should accurately reflect the variation and measurement error, while being contextualised within an understanding of building materials, how a building functions and the aims of the investigation.

The limitations of each method and strategy need to be considered in order to provide an accurate assessment of moisture. A range of approaches is available, which may be generally classified as invasive (those which physically impact on the building fabric) or non-invasive (those which have no impact on the building fabric). The choice of methodology and analytical equipment will depend on the investigation aims, as well as ethical and administrative procedures. Currently available techniques span a range of costs and operator requirements to collect and interpret data, which will further inform the selection.

When carried out correctly, moisture measurement and analysis can be an effective, useful and efficient tool, used to inform the management of historic assets and in adaptations to the historic environment.

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7 REFERENCES

AASHTO (2014). *Standard Method of Test for Determination of Moisture in Soils by Means of a Calcium Carbide Gas Pressure Moisture Tester.* AASHTO T217. American Association of State Highway and Transportation Officials.

ASTM International (2013). *Standard Practice for Field Calibration and Application of Hand-Held Moisture Meters*. ASTM Standard 7438–13. West Conshohocken, PA, USA: ASTM International.

ASTM International (2013). *Standard Test Method for Laboratory Standardization and Calibration of Hand-Held Moisture Meters*. ASTM Standard D4444–13. West Conshohocken, PA, USA: ASTM International.

ASTM International (2016). *Standard Test Methods for Direct Moisture Content Measurement of Wood and Wood-Based Materials*. ASTM Standard D4442–16. West Conshohocken, PA, USA: ASTM International.

ASTM International (2018). *Standard Test Method for Field Determination of Water (Moisture) Content of Soil by the Calcium Carbide Gas Pressure Tester.* ASTM Standard D4944–18. West Conshohocken, PA, USA: ASTM International.

Brimblecombe, P. (2014). 'Refining climate change threats to heritage'. *Journal of the Institute of Conservation,* 37(2), pp. 85–93. doi:10.1080/19455224.2014.916226.

Brundrett, G. W. (1990). *Criteria for moisture control*. Butterworths.

BSI (2002). *Moisture content of a piece of sawn timber. Estimation by electrical resistance method*. EN 13183-2:2002. BSI Group.

BSI (2009). *Hygrothermal performance of buildings - Calculation and presentation of climatic data - Part 3: Calculation of a driving rain index for vertical surfaces from hourly wind and rain data*. EN ISO 15927-3: 2009. BSI Group.

BSI (2017). *Conservation of cultural heritage. Methods of measurement of moisture content, or water content, in materials constituting immovable cultural heritage.* BS EN 16682:2017. BSI Group.

Bureau of Indian Standards (1987). *Rapid moisture meter for rapid determination of water content for soil.* IS-12175:1987. Bureau of Indian Standards.

Camuffo, D. and Bertolin, C. (2012). Towards standardisation of moisture content measurement in cultural heritage materials. *E-Preserv. Sci*, 9, pp. 23-35.

Dill, M.J. (2000). *A review of testing for moisture in building elements*. CIRIA.

Cuiñas I. and Sánchez M.G. (2002). Permittivity and conductivity measurements of building materials at 5.8 GHz and 41.5 GHz. *Wireless Personal Communications*, 20(1), pp. 93-100.

Hall, C. and Hoff, W. D. (2012). *Water Transport in Brick, Stone and Concrete*. London, New York: Spon Press, Taylor & Francis Group.

Historic England (2016). Measuring Moisture Content in Historic Building Materials. In: *Research Report Series no. 43*. Historic England.

HES (2013). *Short Guide 1: Fabric Improvements for Energy Efficiency*. Historic Environment Scotland.

HES (2015). *Short Guide 10: Thermal Imaging in the Historic Environment*. Historic Environment Scotland.

HES (2017). *Short Guide 11: Climate Change Adaptation for Traditional Buildings*. Historic Environment Scotland.

HES (2017). *Scotland's Traditional Building Materials: A consideration of current provision, challenges and opportunities*. Historic Environment Scotland.

HES (2018). *Short Guide 13: Applied Digital Documentation in the Historic Environment*. Historic Environment Scotland.

Kotova, L., Jacob, D., Leissner, J., Mathis, M. and Mikolajewicz, U. (2018). Climate Information for the Preservation of Cultural Heritage: Needs and Challenges. In: I*nternational Conference on Transdisciplinary Multispectral Modeling and Cooperation for the Preservation of Cultural Heritage*. Springer, Cham, pp. 353-359.

Lacy, R. E. (1977). *Climate and building in Britain*. HMSO.

McCaig, I., ed. (2013). *Practical building conservation: Conservation basics*. London, Farnham: English Heritage, Ashgate.

Nilsson, L.O (2018). *Methods of Measuring Moisture in Building Materials and Structures*. Springer International Publishing.

Odgers, D. and Henry, A., Eds. (2012). *Practical building conservation: Stone. London*, Farnham: English Heritage, Ashgate.

Oliver, A. C. (1997). *Dampness in Buildings*. Ed. by J. Douglas and S. Stirling. Chichester, UK: Wiley.

Orr, S.A. (2018). *Methodologies for evaluating exposure and response of stone masonry to wind-driven rain*. PhD Thesis, University of Oxford.

Pinchin, S.E. (2008). Techniques for monitoring moisture in walls. *Studies in Conservation*, 53(sup2), pp. 33-45.

Phillipson, M.C., Baker, P.H., Davies, M., Ye, Z., McNaughtan, A., Galbraith, G.H. and McLean, R.C. (2007). Moisture measurement in building materials: an overview of current methods and new approaches. *Building Services Engineering Research and Technology*, 28(4), pp. 303-316.

Pender, R., Ridout, B., and Curteis, T., eds. (2014). *Practical Building Conservation: Building Environment*. London, Farnham: English Heritage, Ashgate.

Quye, A. and Strlič, M. (2019). *ICON Heritage Science Group, Ethical Sampling Guidance*.

Roels, S., Carmeliet, J., Hens, H., Adan, O., Brocken, H., Cerny, R., Pavlik, Z., Ellis, A.T., Hall, C., Kumaran, K. and Pel, L. (2004). A comparison of different techniques to quantify moisture content profiles in porous building materials. *Journal of Thermal Envelope and Building Science*, 27(4), pp. 261-276.

Saïd, M.N.A. (2007). Measurement methods of moisture in building envelopes–a literature review. *International Journal of Architectural Heritage*, 1(3), pp. 293-310.

Little, J., Ferraro, C. and Arregi, B. (2015). *Technical Paper 15: Assessing risks in insulation retrofits using hygrothermal software tools*. 2nd ed. Historic Environment Scotland.

UNE (2000). *Thermal performance of buildings. Qualitative detection of thermal irregularities in building envelopes. Infrared method.* EN 13187: 1998 / ISO 6781: 1983 modified.

8 HES TECHNICAL CONSERVATION PUBLICATION SERIES

The following publications are all free to download and are available from the publications page on our website: https://www.historicenvironment.scot/archives-and-research/publications/

Technical Papers
Our Technical Papers series disseminates the results of research carried out or commissioned by Historic Environment Scotland, mostly related to improving energy efficiency in traditional buildings. This series covers topics such as thermal performance of traditional windows, U-values and traditional buildings, keeping warm in a cool house and slim-profile double-glazing.

Refurbishment Case Studies
This series details practical applications concerning the repair and upgrade of traditional structures to improve thermal performance. The Refurbishment Case Studies are projects sponsored by Historic Environment Scotland and the results are part of the evidence base that informs our technical guidance. This series covers measures such as upgrades to windows, walls and roof spaces in a range of traditional building types such as tenements, cottages and public buildings.

INFORM Guides
Our INFORM Guides provide short introductions to a range of topics relating to traditional skills and materials, building defects and the conservation and repair of traditional buildings. This series covers topics such as: ventilation in traditional houses, maintaining sash and case windows, domestic chimneys and flues, damp causes and solutions improving energy efficiency in traditional buildings and biological growth on masonry.

Short Guides
Our Short Guides are more in-depth guides, aimed at practitioners and professionals, but may also be of interest to contractors, home owners and students. The series provides advice on a range of topics relating to traditional buildings and skills.

9 GLOSSARY

Absolute humidity	The quantity of water vapour present in the air.
Absorption	A process in which a solid holds a gas or liquid within its open volume.
Adsorption	A process in which a solid holds a gas or liquid on its surface as a thin film.
Atmospheric pressure	The air pressure at any given time for a specific location, which varies according to latitude and global weather patterns.
Bound water	A type of water which is not easily mobilised, since it is an intrinsic component of a molecule such as a mineral.
Building pathology	A holistic approach to studying and understanding buildings, with an emphasis on defects and remedying problems.
Calcium carbide	A chemical compound with formula CaC2, used to measure moisture as a result of chemical reaction.
Capacitance	A measure of the ability of a system to store electrical charge. Inverse of impedance.
Capillarity	The tendency of a liquid in an absorbent material to move as a result of surface tension.
Capillary rise	Controlled by capillarity - the rise of a liquid in an absorbent material above the level that would be influenced solely by atmospheric pressure.
Condensation	Water which collects as droplets on a surface whose temperature is below the dew point.
Conductance	A measurement of the ability for electrical charge to flow in a material; the reciprocal of resistance.
Conductivity	A material property representing the degree to which it conducts electricity; the reciprocal of resistivity.
Data logger	An electronic device that records data over time or in relation to location either with a built-in instrument or sensor or via external instruments and sensors.
Deliquescence point	The relative humidity at which crystalline materials begin adsorbing large quantities of water from the atmosphere.
Desorption	The release of an adsorbed substance from a surface.
Deterioration	A physical change that implies an impairment in value or usefulness.
Dew point (temperature)	The temperature at which water droplets begin to condense and dew can form; also dependent on atmospheric pressure.
Dielectric constant	A quantity related to the ability of a substance to store electrical energy, which represents how the material interacts with electromagnetic energy and is strongly dependent on moisture content.
Direct measurement	Moisture measurement that uses a physical or chemical technique to determine the moisture content.
Direct wave	A component of a radar measurement that represents the part of the signal that travels just beneath the surface of a material.
Diurnal	Daily, or during the day
Dry reference	Data obtained from a sample or area presumed to be unaffected by moisture ingress or other damp problems. NB. The substrate will not have zero moisture content. It will be assumed to have equilibrated to 'normal' environmental conditions.

Electrical resistance	A measurement of the impedance of an electrical charge to flow in a certain material; the reciprocal of conductance.
Electrical resistivity	A material property representing the degree to which a material impedes the transfer of electricity; the reciprocal of conductivity.
Electromagnetic energy	A natural phenomenon in which radiant energy exists at a range of wavelengths. Several forms of electromagnetic energy can be used as an indirect measurement method for moisture.
Emissivity	In infrared thermography—a representation of the extent to which a material reflects radiant energy, ranging from 0 (entirely reflected) to 1 (entirely absorbed).
Equilibrium moisture content	The moisture content at which a material is neither gaining nor losing moisture through exchanges with the ambient environment.
Frequency	The number of waves that pass a fixed point in a given amount of time, i.e. the number of cycles or oscillations of electromagnetic energy; the inverse of wavelength.
Gamma rays	A form of electromagnetic energy with the highest frequency (i.e. the highest level of energy) and arising from the radioactive decay of atomic nuclei.
GHz	A common unit of frequency, representing a billion cycles per second.
Gravimetric calibration	A procedure to relate a measurement to the absolute amount of water present in a sample, based on its mass.
Gravimetry	The measurement of weight–usually to determine the mass of an object.
Hygroscopic	The tendency of a material to absorb moisture from air.
Hygroscopic moisture	Moisture that is adsorbed or absorbed onto the surface of a material due to exchanges with the environment, relating to the equilibrium moisture content.
Hysteresis	A phenomenon in which a material absorbs and desorbs water differently at the same relative humidity.
Impedance	The effective resistance of a material to an alternating current. Inverse of capacitance.
Indirect measurement	A moisture measurement technique that uses a physical property or measurement as an indicative representation of the moisture content.
Infrared radiation	A region of the electromagnetic energy spectrum (used in infrared thermography) where wavelengths are longer than those of visible light, but shorter than those of radio waves.
MHz	A common unit of frequency, representing a million cycles per second.
Microwaves	A form of electromagnetic energy with wavelengths ranging approximately from 1 to 300 GHz.
Moisture	Water that is freely mobile as a liquid, gas (vapour), and solid (ice). All moisture is water, but not all water is moisture, as it is not necessarily freely mobile.
Moisture content	The quantity of moisture present within a material.
Neutrons	A subatomic particle that can be used to investigate properties of materials at a small-scale.
nm	Nanometres, a unit of measurement of which there are 1 billion in a metre.
One-sided application	An implementation of an electromagnetic principle in which the transmitter and receiver are on the same side of a construction, operating on the principle of reflectance.

Porosity	A measure of the total amount of void space in a material, usually expressed as a percentage (%).
Radar	A system for detecting the presence and distance of sub-surface features based on electromagnetic waves reflected from boundaries between materials with different physical properties.
Rainwater goods	An all-encompassing term for components installed on the exterior of a building to direct rainwater away from the building.
Receiver	The component of a device that measures the response in a signal.
Reflectance mode	See 'one-sided' application
Relative humidity	A measure of the amount of moisture relative to the total amount air can hold at a given temperature, usually expressed as a percentage.
Relaxation losses	A measure of coherence loss within a magnetic field with increasing distance from the source.
Saturated reference	Data obtained from a sample or area which is known to be saturated with moisture.
Saturation	The state attained by a material when the addition of further water does not result in any further absorption.
Scanning techniques	A technique for moisture measurement that can rapidly measure across large areas, such as thermal imaging.
Stochastic	Data which has a random distribution and cannot be precisely predicted.
Transmittance	See 'two-sided' application
Transmitter	The component of a device that produces the signal.
Two-sided application	An implementation of an electromagnetic principle in which the transmitter and receiver are on opposite sides of a construction, operating on the principle of reflectance.
Two-stage drying	A well-established theory of how materials dry. Stage 1 is characterised by a level of moisture at the surface of evaporation that is near saturation, as moisture flows through from greater depths. Stage 2 occurs when there is no longer a sufficient level of water to maintain high rates of evaporation. It is characterised by a decrease in liquid water transport and an increase in vapour diffusion, resulting in slower rates of drying relative to Stage 1.
Water vapour	Water that is present a gas in air.
Waveguide	A structure that guides waves.
Wavelength	The distance between successive crests of an electromagnetic wave; the inverse of frequency.
Weathering	The natural breakdown of materials due to interactions of the atmosphere, water, and biological organisms.
Wet reference	Data obtained from a sample or area presumed to be saturated with moisture, but where the degree of saturation has not been confirmed.
X-rays	A high-energy form of electromagnetic energy.

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