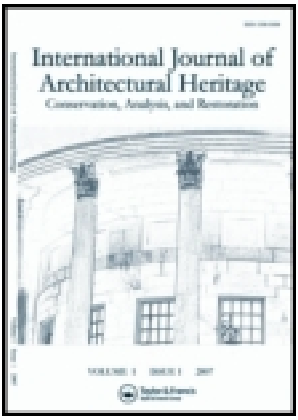

International Journal of Architectural Heritage: Conservation, Analysis, and Restoration
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/uarc20

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Accepted author version posted online: 12 Oct 2011. Version of record first published: 11 Jul 2012

International Journal of Architectural Heritage, 7: 207–224, 2013

ISSN: 1558-3058 print / 1558-3066 online
DOI: 10.1080/15583058.2011.626491

USING HANDHELD MOISTURE METERS ON LIMESTONE: FACTORS AFFECTING PERFORMANCE AND GUIDELINES FOR BEST PRACTICE

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Hand-held moisture meters are frequently used by conservators and conservation architects for the non-destructive investigation of dampness problems in stone and mixed building structures, despite such meters being primarily developed and calibrated for wood. Following extensive use of hand-held moisture meters on historic stone monuments under field conditions, we tested one resistance and two capacitance meters on Portland limestone in a laboratory setting. We found that each meter provided different readings on three types of limestone at the same moisture content. Readings from different meters were neither comparable nor predictable, as their relationship varied by substrate. Meter readings are therefore only of value when used relative to each other for any given surface/meter pairing, either by surveying several points over the same surface or monitoring the same points. Additionally, several factors were investigated for their contribution to variance in meter readings, and guidelines for best practice are presented. Despite the complexities observed when using moisture meters on stone, each moisture meter was found to produce reliable readings that could be related to absolute moisture contents for individual stone types. Thus, when used with care, hand-held moisture meters can provide good indications of the moisture contents of limestone.

KEY WORDS: hand-held moisture meters, limestone, non-destructive testing, moisture regimes, monitoring dampness, building conservation

1. INTRODUCTION

Traditionally, hand-held moisture meters have been calibrated for use on wood, although a few are also calibrated for some other building materials. Despite providing a reading typically expressed as *percent moisture content* or *% wood moisture equivalent* (%WME), hand-held moisture meters do not directly measure moisture content. They measure properties in wood that are affected by moisture, and these measurements are mathematically converted into an estimated moisture content using a calibration curve, which may take other properties of the specimen into account, such as wood species, density, or temperature. The majority of hand-held moisture meters currently available either

Received June 8, 2011; accepted September 20, 2011.
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measure the direct current resistance (or conductance) of a material and are referred to as resistance meters, or measure the dielectric constant of a material and are referred to as capacitance meters. Some meters, may include both types of sensors in a single instrument, which operate as independent modes (for example, the GE Surveymaster Protimeter [General Electric, Billerica, MA, USA]). Both resistance and capacitance meters are influenced by different material, environmental, and operator factors, such as temperature, density, moisture gradients, and the presence of contaminants, to name a few. Detailed descriptions about how moisture meters work can be found in James (1963) and Skaar (1988).

Considerable research has been conducted regarding the use of hand-held moisture meters on wood (James, 1963; Forsén and Tarvainen, 2000; Blakemore, 2003). However, relatively little systematic study has addressed the use of such meters on other building materials. A handful of studies have shown that readings from moisture meters used on brick must be interpreted with care. Research reported by Trotman et al. (2004) demonstrated that sand-faced Fletton bricks with an actual moisture content of 5% to 22% resulted in resistance meter readings of 80% to 90%. In another study, a saturated Staffordshire Blue engineering brick with 4% moisture content, produced a capacitance reading of 100% (Howell, 1995). Burkinshaw and Parrett (2003) reported Protimeter readings from samples of various materials kept in close proximity to timber at 75% relative humidity over 4 months, and found that as timber moisture content changed from 14.6% to 12.9%, brick changed from 0 to 9.7% WME, when in principle the readings should have been the same. This finding has prompted some researchers to avoid using any kind of percentage value when discussing hand-held moisture meter readings on materials other than wood, for example Burkinshaw and Parrett (2003) suggest using R/R for "relative readings" (p. 76). For the purposes of this study, meter-reading values will be referred to as *points*.

We have investigated the utility of hand-held moisture meters on limestone. We have explored some sources of error associated with using hand-held moisture meters on wood to determine if equivalent problems affect their use on limestone. Variables and issues investigated include: settings for meter sample thickness, taking readings on different faces of samples, placing samples on a non-conductive/capacitive layer during readings, orienting the sensor/bedding orientation, and drifting readings. The methodology used in this study varied considerably from that used in most timber research. The majority of studies assessing the performance of hand-held moisture meters on wood have used timber samples conditioned for several months at a specific temperature and relative humidity (see, for example: James, 1964; Forsén and Tarvainen, 2000; Simpson, 1994). However, as part of a larger study investigating moisture regimes and stone decay, we have been using hand-held moisture meters for the non-destructive monitoring of moisture patterns on headstones in several locations throughout Southern England. Therefore, we were particularly interested in the use of moisture meters on limestone monoliths in direct contact with the ground and exposed to an outdoor environment, where moisture gradients would be inevitable and the actual moisture content difficult to quantify without destructive sampling. Rather than conditioning stone samples through prolonged exposure to different relative humidity conditions, we have saturated stone samples and allowed them to dry slowly, while taking a series of moisture meter readings to examine how different moisture meters respond to changes in moisture content. No effort was made to control moisture gradients in the samples because we wished to investigate whether moisture meters could track the drying process with a natural moisture gradient present, similar to what would be encountered in the field.

The purpose of this experiment was not to approve certain meters for use, but rather to understand the significance of readings produced by different meters, how they compare with each other as well as to the actual moisture content as determined by the oven-dry method of different types of limestone, and what factors may influence the use of meters on limestone.

2. METHODS AND MATERIALS

2.1. Moisture Meters

Three hand-held moisture meters were selected for testing. The GE Surveymaster Protimeter includes a pin-type resistance meter with a sensor consisting of two 10 mm long stainless steel pins spaced approximately 14 mm apart. The Brookhuis FMW-T capacitance meter (Brookhuis Micro-Electronics BV, Enschede, The Netherlands) has a flat sensor plate measuring 25 mm by 90 mm. The CEM DT-128 capacitance meter (Shenzhen Everbest Machinery Industry Co., Ltd, Shenzhen, China) has a stainless steel spherical sensor 25 mm in diameter (see Figure 1 and Table 1 for specifications). Meters had fresh batteries installed at the beginning of the experiment, and their calibration was checked daily prior to taking measurements using the manufacturers' calibration instruments (Protimeter and FMW-T) or instructions (a mid-air reading taken with the CEM).

All meters were kept under the same environmental conditions as the stone samples, and the ambient temperature and relative humidity were recorded on a 30-minute basis throughout the experiment using iButton Hygrochron dataloggers (Maxim Integrated Products, Inc., Sunnyvale, CA, USA).

Figure 1. Photograph of each of the meters used in this experiment, from left to right: Protimeter, FMW-T and CEM.

Table 1. Specifications of hand-held moisture meters used. Information compiled from user manuals

Meter Make/Model	Meter type	Readings range	Accuracy resolution	Sample requirements	Calibration requirements
GE Surveymaster Protimeter	Resistance	6%–99% moisture content (%) of wood or % wood moisture equivalent (WME) of other material	Resolution: 1%	N/A	Temperature adjustment
Brookhuis FMW-T	Capacitance	2%–30% moisture content (%) for wood	Accuracy: 0.5%	At least 10 mm thick (measures an average moisture content up to 25 mm)	Calibration settings provided for range of materials (not limestone; set for 0 as per manual)
CEM DT-128	Capacitance	0%–60% moisture content (%) for other materials	Resolution: 0.1%	N/A	N/A

2.2. Limestone Samples

Portland limestone, a commonly used building stone within the UK and abroad, was selected as a test material. Three types of limestone were used: fresh Jordans Basebed, fresh Coombefield Whitbed and weathered Coombefield Whitbed (previously exposed as a Commonwealth War Graves Commission headstone, and weathered surfaces were maintained on the two main faces and one side of each sample, see Figure 2). Five replicate samples of each stone type were prepared, measuring 100 mm × 100 mm × 75 mm. Sample dimensions were based on those used in similar experiments carried out on wood (Forsén and Tarvainen, 2000; Garrahan, 1988) and the availability of areas that were uncarved on the weathered headstone. Samples were oven-dried at 70 ± 5°C until no more than 0.1% change in mass occurred over a 24-hour interval on a balance with readability of 0.01g, as set out in British Standard EN 1936: 2006 (British Standards Institute [BSI], 2007), and sample weights were recorded.

Standard open porosity and apparent density tests were done in accordance with the British Standard EN 1936:2006 (BSI, 2007) on the samples used in the experiment to investigate whether these properties affect readings. Although small differences were found in the open porosity and apparent density values of the three stone types tested (see Table 2), they are considered relatively minor. The differences between the weathered and fresh Coombefield Whitbed samples may be due to the dissolution and reprecipitation of endogenous minerals, as well as incorporation of exogenous material from the ground and air during exposure to the environment as a headstone.

The presence of salts (Simpson and TenWolde, 1999; James, 1963, 1980; Oliver, 1997; Burkinshaw and Parrett, 2003; Trotman et al. 2004; Pinchin, 2008), preservatives

Figure 2. Photograph of weathered Coombefield Whitbed Commonwealth War Graves Commission headstone sectioned into 100 mm × 100 mm samples for testing.

Table 2. Moisture content and meter reading ranges of limestone samples, with corresponding porosity and density data

Moisture content range	FJB	FCW	WCW
Sample 1	0–8.6%	0–7.4%	0–5.3%
Sample 2	0–8.0%	0–7.4%	0–5.5%
Sample 3	0–8.6%	0–7.4%	0–5.9%
Sample 4	0–7.7%	0–7.4%	0–6.0%
Sample 5	0–7.8%	0–7.3%	0–5.5%
Average maximum (saturated) moisture content	*8.1%*	*7.4%*	*5.6%*
Protimeter range	5*–27.1	5*–26.6	5*–36
FMW-T range	17.6–58.4	18.0–53.9	17.1–58.3
CEM range	24–42	24–41	25–49
Open porosity (%)	19.6 ($n = 3$)	17.3 ($n = 3$)	14.1 ($n = 6$)
Apparent density(kg/m^3)	2140.4(n=3)	2208.8 (n=3)	2293.2 (n=6)

Stone sample types are abbreviated as follows: fresh Jordan's Basebed (FJB), fresh Coombefield Whitbed (FCW) and weathered Coombefield Whitbed (WCW). * For the purposes of this research, Protimeter readings below the lowest value detectable by the meter (6), were given a nominal value of 5

(Ahmet et al. 1997; Division of Building Research, 1974; Smith and Jung, 1993; Trotman et al. 2004; Onysko et al. 2008), as well as adhesives, glues, and other coatings (Blakemore, 2003; Division of Building Research, 1974) are known to affect meter readings in wood. Although this effect is primarily known to influence resistance readings, in some cases similar effects have been observed using capacitance meters (James, 1963, 1980; Blakemore, 2003; Trotman et al. 2004; Pinchin, 2008). In a preliminary experiment, samples were saturated and moisture meter readings taken to investigate whether the presence of salts and other soluble contaminants may affect readings. Measurements of 100% were recorded using both the Protimeter and the CEM on the weathered Coombefield Whitbed, which was considerably higher than the maximum readings obtained following a desalination procedure (36% and 49%, respectively), in line with James (1980) observation that salts may cause readings to be two to three times higher due to a combination of increased hygroscopicity of salts as well as increased resistance/capacitance. Therefore, all samples used in the following experiment were desalinated by immersing each stone type in a bath of 8 L of deionized water (10.5 μs/cm at 25° C). Samples were slightly elevated from the bottom of the desalination container to facilitate maximum surface area exposure to water and to minimize the risk of creating a desalination gradient. The conductivity of the water was monitored and changed at 24-hour intervals until values stabilized for at least 3 days to less than 75 μs/cm at 25° C for the fresh limestone samples and less than 120 μs/cm at 25° C for the weathered limestone samples.

2.3. Experimental Protocol

Limestone sample weights were recorded immediately before taking meter readings and again after taking readings. Meter readings are affected by the amount of hand pressure applied to both resistance (Pinchin, 2008; Skaar, 1988; Trotman et al. 2004; Harriman, 2008) and capacitance meters (Division of Building Research, 1974; Mackay, 1981; Forrer and Funck, 1998; Forsén and Tarvainen, 2000; Onysko et al. 2008), as air gaps between the meter and the substrate being measured will lower readings. To ensure approximately 2 kg of hand pressure was consistently applied to meters when taking readings, as recommended by Blakemore (2003), all readings were taken with samples placed on a Sartorius CP4202S balance (Sartorius Limited Epsom, UK).

Some wood studies have suggested taking readings from more than one side of a sample (Division of Building Research, 1974; Shupe et al. 2002; Smith and Jung, 1993). Readings were taken on the front (A) and back (B) of each sample.

The depth of penetration of the signal for both the Protimeter and the CEM cannot be controlled. However, the FMW-T can perform a mathematical adjustment to reflect changes in moisture content in materials of different thicknesses, and the instrument can be set for samples between 10 and 20 mm thick (the 20-mm setting is recommended by the manufacturer for sample thicknesses exceeding 20 mm). Readings were taken twice with the FMW-T meter with the sample thickness set to both 10 mm and 20 mm to investigate changes in readings due to sample thickness settings.

The presence of conductive materials within or behind surfaces affecting hand-held moisture meter readings has been noted in the literature (Smith and Jung, 1993; Quarles et al. 1992; Blakemore, 2003). To test whether the metal balance weighing pan influenced meter readings, readings were taken twice: once with samples placed on a non-conductive/capacitive insulating layer and again with samples not placed on an insulating layer. The insulating layer consisted of two sheets of thick bubble-wrap sandwiched between two layers of 25-mm polystyrene, for a total thickness of 65 mm, large enough to cover the entire balance weighing pan. This arrangement was found to produce readings of ‘zero’ for all meters tested when placed on the balance-weighing pan without a stone sample present.

It is typically suggested that both resistance and capacitance hand-held moisture meter readings should be taken with the sensor oriented parallel to the grain of wood (Onysko et al. 2008; Simpson, 1991; Shupe et al. 2002; Blakemore et al. 2005; Dunlap, 1944; Dlugasch, 2004), as this orientation is how sensors are often calibrated by the manufacturers (James, 1963). Evidence of whether readings are affected by sensor orientation relative to the grain is somewhat contradictory, with one thorough study of several hand-held moisture meters suggesting no difference in readings taken parallel or perpendicular to the grain with either type of meter (Forsén and Tarvainen, 2000). To investigate whether stone bedding in sedimentary rocks could have a similar effect, meter readings were taken in the centre of the two 100 mm × 100 mm sample faces with the sensor both parallel as well as turned 90° and across the bedding (see Figure 3). The surface temperature of each sample was recorded with each set of readings using an infrared thermometer.

The problem of resistance moisture meter readings on wood "drifting" is well-documented in the literature, with several authors suggesting that the initial reading upon insertion of the pins is valid (Shupe et al. 2002; James, 1963; Ahmet et al. 1997; Simpson, 1999; Saïd, 2004) and others advocating a "3-second rule" to allow readings to stabilize briefly (Simpson, 1994; Blakemore, 2003). Readings were taken immediately on application of the sensor to the stone surface and again once the reading had stabilized, with less than 1 minute allowed for stabilization.

The first set of readings was taken immediately after desalination when samples were saturated with water, but excess surface moisture was removed using a damp cloth. Samples were then placed in a cabinet under room temperature conditions, and allowed to dry slowly over a period of approximately 3 weeks. Readings were taken daily initially, and then every 3 to 4 days as drying slowed until the weight of the samples was near the original oven-dry weight. Stones were oven dried again to quantify the remaining amount of water in samples and to account for the removal of salts and dust, or any minor damage to samples during the course of the experiment, and for a final set of oven-dry readings.

The moisture content of the limestone samples was calculated as a percentage of the oven-dry weight, following the convention used in reporting the moisture content of wood without an upper limit, as some wood can have a moisture content >200% (Espenas, 1951; Rasmussen, 1951; Delmhorst, 1956). The average was calculated of the weight of each stone sample before and after the meter measurements were taken, and from this

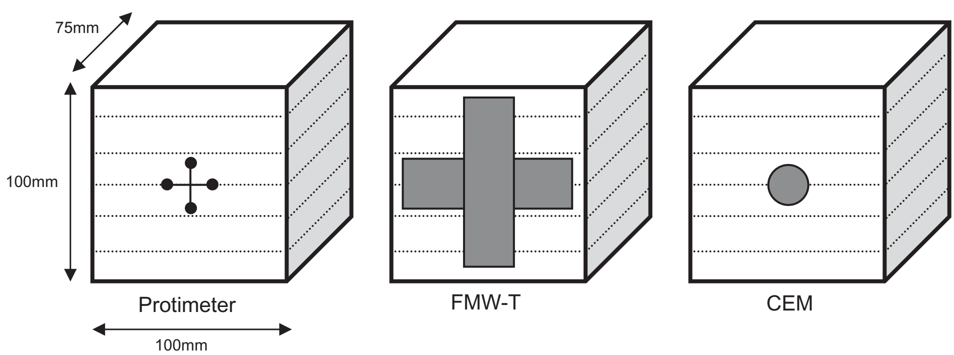

Figure 3. Diagram outlining sensor footprint in the location where meter readings were taken. A Perspex template was used to ensure Protimeter readings were taken in the same location each time.

value the oven-dry weight was subtracted to calculate the moisture content as shown in Equation 1:

$$MC = [((Initialwt + Finalwt/2) - ODwt)/ODwt] * 100 \qquad \text{(EQ1)}$$

where MC = moisture content, Initialwt = weight before readings taken, Finalwt = weight after readings taken, and ODwt = oven-dry weight.

2.4. Statistical Analysis

A series of paired t tests (t) were run to examine whether differences in readings resulting from changes in experimental variables were statistically significant ($p <$ .001 for all tests). Additionally, the effect size (Pearson's correlation coefficient, r) was calculated.

3. RESULTS AND DISCUSSION

The main objectives of this research were to determine the relationship between hand-held moisture meter readings with the actual moisture content of limestone samples and to understand the relationships between different meter readings, but first it was necessary to identify any sources of interference with the readings. Both on site and in the laboratory, it was noted that moisture meter readings suffered from a relatively high degree of variance, and we wanted to determine how to avoid possible sources of error in order to get the most consistent results. Factors investigated include both non-moisture-related factors, as mentioned previously, as well as the actual moisture content.

3.1. Non-Moisture-Related Factors Affecting Meter Readings

3.1.1. FMW-T sample thickness settings On average, readings were statistically significantly higher when the FMW-T was set for 10 mm (mean = 42.7, statistical error = 0.4) than when set for 20 mm (mean = 39.6, statistical error = 0.3), t (degrees of freedom = 1679) = 95.44, r = .92. This finding demonstrates the importance of using consistent settings when taking either a series of or repeated measurements. Only readings taken with the 20 mm setting are included below when assessing the relationship between moisture content and meter readings.

3.1.2. Readings on different faces For both the Protimeter and the CEM, the difference in measurements on the two faces of the samples was not statistically significant. However, on average, FMW-T readings were significantly higher on the back (mean = 40.0, standard error = 0.5) than the front (mean = 39.3, standard error = 0.5), t (degrees of freedom = 839) = −11.63, r = 0.4. This may be due to a higher sensitivity to slight differences in moisture gradient on the two faces, which may result from sample positioning in the drying cabinet. As the A side was consistently facing the door, it was potentially exposed to minor drafts resulting in a different moisture gradient than on the B side. For consistency, only the A side readings are included for assessing the relationship between moisture content and meter readings.

3.1.3. Insulating layer Readings taken using the two capacitance meters were found to be significantly affected by the metal balance weighing pan when samples were not placed on an insulating layer. It was observed that when the samples were damp, CEM readings taken without the insulating layer were approximately 12 points higher than those taken with the insulating layer under the sample. On average, when dry, readings were approximately 7 points higher. CEM readings were significantly higher without the insulating layer (mean = 42.0, standard error = 0.3) than with the insulating layer (mean = 32.7, standard error = 0.2), t (degrees of freedom = 839) = −115.75, r = .97. When using the FMW-T, the difference between readings without using the insulating layer was considerably less pronounced, with wet readings typically 1 point higher and, dry readings approximately 0.1 point higher. However, this difference was also found to be statistically significant, as readings without the insulating layer (mean = 40.1, standard error = 0.5) were significantly higher than with the insulating layer (mean = 39.2, standard error = 0.5), t (degrees of freedom = 839) = −37.83, r = .79. On site, we have observed interference from metal measuring tapes placed near meters when surveying large stone surfaces. It is clear that on small laboratory samples, it is essential to use a non-conductive/capacitive layer to prevent readings being influenced by worktops or other surfaces beneath or around the sample and to take care not to affect readings by keeping all metal objects, including jewelry away from the instrument when taking readings.

Readings taken using the Protimeter were found to be affected in an inverse way to those taken with capacitance meters, in that readings taken when using the insulating layer were higher (mean = 17.4, standard error = 0.3) than readings taken when not using the insulating layer (mean = 17.3, standard error = 0.3). However, this difference was not found to be statistically significant, and this observation is considered simply to be an artifact of the experiment due to the large number of readings (n = 840) used. However, for consistency with the results reported above for the capacitance meters, when assessing the relationship between moisture content and meter readings only data collected when using the insulating layer are included.

3.1.4. Bedding and sensor orientation The difference in readings taken with sensors parallel to or taken turned 90° and across the bedding was found not to be statistically significant for the Protimeter, but it was statistically significant for both capacitance meters. On average, for the FMW-T readings were slightly higher when taken parallel to the bedding (mean = 39.9, standard error = 0.5) than when taken across the bedding (mean = 39.3, standard error = 0.5), t (degrees of freedom = 839) = 22.65, r = .62. The difference in readings due to orientation was greater for the CEM, with readings being higher when taken parallel to the bedding (mean = 39.0, standard error = 0.3), than when taken across the bedding (mean = 35.7, standard error = 0.3), t (degrees of freedom = 839) = 64.27, r = .91.

It was observed towards the end of the experiment that changes in readings may have been due to how the capacitance meters were held, rather than simply the meters' orientation relative to the stone bedding. This finding may have been caused by rotating the instrument rather than rotating the sample to take readings across the bedding. Clear instructions are provided for holding the Protimeter in "search mode" (not tested in this study, as it only provides relative readings), suggesting that readings can be influenced by how the instrument is held. Although this issue is not mentioned in the manual for either the FMW-T or the CEM, it was observed when using the CEM that readings fluctuated depending on the position of one's hand on the instrument. Further testing of this issue is required and consistency in handling instruments when taking readings is important, as this issue may be a key source of repeated measurement as well as inter-operator error. For assessing the relationship between moisture content and meter readings, only those readings taken parallel to the bedding are included, as these readings were taken as would be expected by manufacturers for wood and ensures that the sensor was held in a standard way.

3.1.5. Drifting readings Although only very small fluctuations of 1 point were typically observed when using the CEM, considerable drift in readings were observed with the FMW-T and the Protimeter. Readings <6, the lowest limit for the Protimeter, were recorded in several cases initially. For both meters on all stone types tested, initial readings on limestone tended to be considerably lower than and somewhat erratic compared with the stable readings, as demonstrated using the fresh Coombefield Whitbed sample 1 in Figure 4. For assessing the relationship between moisture content and meter readings, only the stable readings were used.

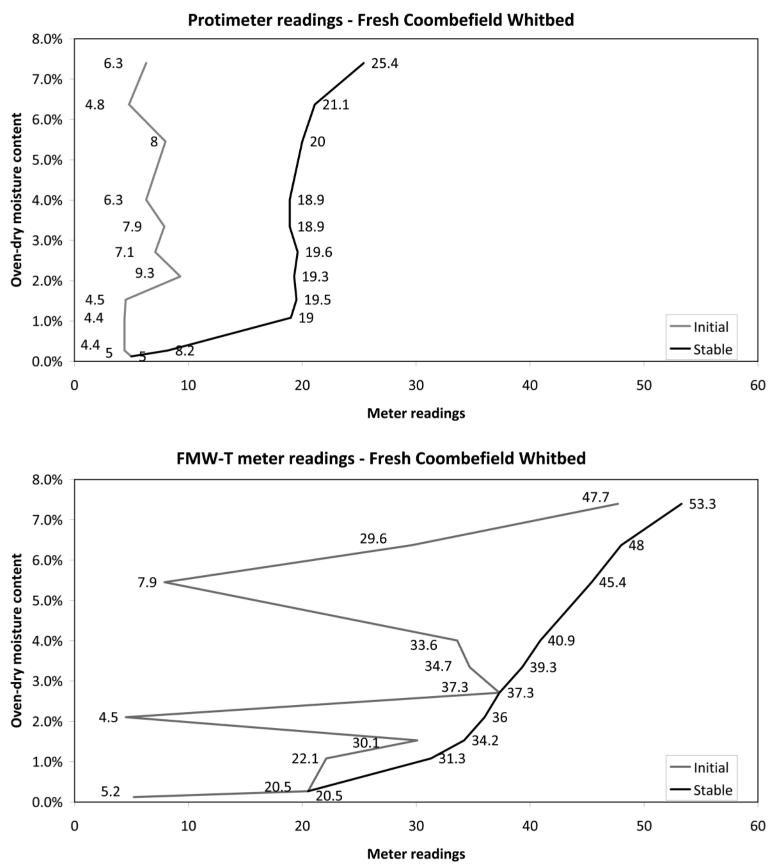

Figure 4. Graphs showing initial and stable readings from the Protimeter (top) and FMW-T (bottom) on fresh Coombefield Whitbed sample 1.

Optimised experimental protocol:

- Oven-dry samples
- Weigh samples
- Saturate samples by immersion in distilled water – monitor by checking weight periodically
- Remove surface moisture with a damp cloth
- Place sample on top of an insulating layer on top of a balance
- Record the weight of samples immediately before taking readings AND again after taking readings (use the average to calculate the moisture content)
- Record surface temperature of samples for all readings
- Ensure fresh batteries are installed in meters and check calibration of meters prior to each session of readings
- Take readings parallel to the bedding of samples (or in the same orientation if bedding is not obvious)
- Allow readings to stabilise for a few seconds (no longer than a minute)
- Hold meters in the same way and apply the same amount of pressure for each reading
- Allow samples to air dry, taking readings once a day in the centre of one face – record environmental conditions using a datalogger
- Oven-dry samples and calculate moisture content relative to the final oven-dry weight (to take into account any salts removed during initial saturation)

Figure 5. List of steps for an optimised variance introduced by factors found to adversely affect readings.

Based on the results of testing non-moisture-related factors affecting hand-held moisture meters on limestone, an optimized experimental protocol is suggested for determining the relationship between different moisture meters and stone types, as outlined in Figure 5. One factor not tested in this study, but that may be of importance, is whether temperature will affect meter readings on stone. During the laboratory study, sample surface temperatures varied little during each session of readings (never more than 2° C) and consistently remained within the range of 17.8° C to 25° C. No temperature adjustment was made for readings, based on guidance provided by the Protimeter user manual when used on wood. However, field conditions may vary considerably from the climate-controlled conditions of the laboratory, and further research into this issue is needed.

3.1.6. Moisture content and meter readings Samples of each stone type contained slightly different average moisture contents at saturation (see Table 2). Each meter provided readings that were relatively consistent for all five samples of each stone type tested. However, for each of the three types of limestone tested each meter provided readings over a different range from saturation to oven-dry conditions, and a slightly different relationship was observed when comparing the meter readings to the actual moisture contents (see Figure 6). None of the meter readings linearly correspond to the actual moisture contents or to the readings provided by one of the other meters.

4. CONCLUSION

4.1. Meter Sensitivity to Moisture Fluctuations in Stone

In testing three different types of hand-held moisture meters on three types of limestone, it was found that all three meters provided different readings for stone samples at the same moisture content. Although readings were similar for the two fresh

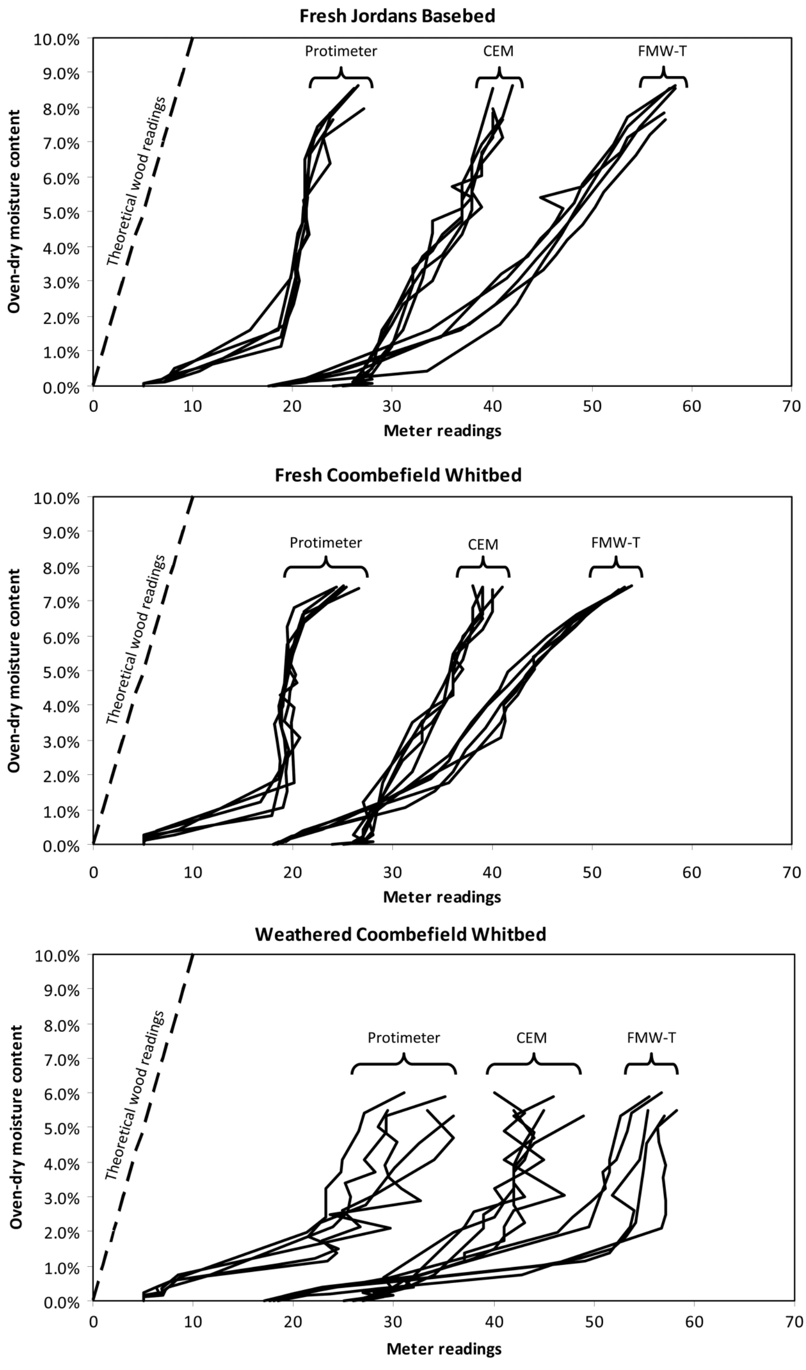

Figure 6. Graphs of meter readings for each of the three meters tested plotted against oven-dry moisture contents from saturation to dry for five samples of three different limestone types. Theoretical readings expected for wood is also plotted (acknowledging that many hand-held moisture meters do not give accurate results $<5\%$ to 7%).

limestones tested (Coombefield Whitbed and Jordans Basebed), readings were less comparable between the fresh and the weathered Coombefield Whitbed, possibly due to changes caused by weathering in internal variability, porosity and chemical content. It was also discovered that several factors may contribute to variance in readings (Table 3). To understand how a particular meter's readings correlate to a specific stone type's moisture content, a calibration test using the optimized experimental protocol presented above is recommended.

4.2. Best Practice for Using Hand-Held Moisture Meters on Stone

- Select a meter with a sensor geometry appropriate for the surface to be measured—good contact between the sensor and the substrate is essential. Large, flat sensors are unsuitable for rough surfaces, and pin-type sensors may not be the best option for soft stone or easily damaged surfaces, as holes may form with repeated measurements.
- Avoid conductive/capacitive entities, which may include anything metal, rust spots or even hands supporting the operator or structure being measured, as these may result in artificially high readings. Contamination with salts may also result in very high readings. By scanning the surface with a capacitance meter or similar device, sub-surface defects may be located and avoided in subsequent measurements.
- Avoid areas with irregular surfaces, such carvings, extremely weathered surfaces or other air pockets that may result in artificially low readings.
- Take readings in a consistent way. This includes alignment with bedding and/or how the equipment is held and the amount of pressure applied. In some cases, it may be preferable for the same person to carry out repeated surveys to ensure consistency in measurement taking.
- Meter depth settings should be checked prior to measurement, as adjustments afterwards may not be possible.
- Fluctuations in initial readings are to be expected. Allow readings to stabilize a few seconds after applying the sensor.
- Treat readings as relative readings or points, but not as an actual moisture content measurement.
- Compare meter readings taken on different types of stone or with different meters with caution. Each stone/meter pairing requires its own calibration to understand the relationship between them. Ionic, carbon and metal content of stone may affect readings. Do not assume that fresh and weathered samples of the same stone type will behave in a similar way. The same stone types exposed to different environments are likely to have taken up different amounts and types of contaminants from the environment, and are likely to exhibit differences in moisture readings, as well.
- Point readings are of minimal use without context. The best uses of moisture meter readings are to survey several points over a surface, measure the same point over time, or compare readings to a reference sample that is kept in a known state, either dry or at a particular moisture content.

In conclusion, hand-held moisture meters can be powerful tools for monitoring moisture regimes in stone monuments. The methodology described herein illustrates how sources of variation in moisture meter data can be investigated, and how for individual types of limestone calibration curves can be established to relate the values recorded by individual moisture meters to absolute water contents.

Table 3. Summary of factors affecting the use of hand-held moisture meters on wood as described in the literature, and on stone as found in this study

Factors	Wood	Stone
	Resistance Meters	
Moisture content	Accurate range is 6 or 7 to ~30% moisture content (depending on model), and over this range readings are thought to be largely qualitative.	Readings do not reflect actual moisture content and are not linearly related. Readings are relative values only, but are useful in monitoring wetting and/or drying.
Moisture gradients	It is recommended to drive pins into sample 1/3 to 1/6th of depth in order to get an "average" MC. However, surface wetness will cause readings to be too high, as will condensation, fog or rainy conditions. It is thought that meters read highest moisture content with which electrodes make contact.	Pins could not be driven into the sample, resulting in surface moisture content readings only. If surface is oversaturated, readings will be high. Use of meters in adverse weather conditions is not advisable, or when water is seen to pool on the surface. Allow meters to acclimate when changing environments.
Temperature	The temperature of the wood, not the ambient temperature is important, and as temperature increases, resistance decreases. Most meters are calibrated for 20° C (70° F) and temperature corrections should be available (some may automatically be calculated by the meter). As a general rule, add 1% to readings for every 10° C below the calibration temperature and subtract for temperatures below calibration temperature. Some evidence suggests extreme conditions (e.g., frozen and extremely hot) may affect the mechanical operation of meters. Under such conditions, meters requiring manual corrections rather than pre-programmed corrections would be advisable. Equipment should be acclimated prior to use. Also, apply temperature corrections before species corrections, as most species correction factors were calculated at or around the calibration temperature.	The effect of temperature was not investigated in this study, but requires investigation, as a different temperature correction factor may be necessary.
Species	Species affect readings, which is thought not to be due to density, but more to do with electrolytic qualities of the wood itself. Meters are typically calibrated for one specific species (often Douglas fir), with correction tables for other species.	Even similar stone types may give different meter readings at the same moisture content. Weathered stone and fresh stone may also give different readings due to changes in porosity and contaminants. In particular, differences in salt, carbon and metal content could affect readings.

Grain angle	Electrodes should be inserted so the current flows in the direction recommended by the manufacturer–typically parallel to the grain. Conductivity varies along the longitudinal, radial and tangential directions in the approximate ratio of: 1.0 : 0.55 : 0.50, respectively.	Readings should be taken in a consistent manner when bedding is apparent to minimize any potential effect.
Presence of contaminants	Preservatives, salts, adhesives, coatings and embedded fixings may all affect readings	Salts inherent to the stone, as well as those that have been deposited or have migrated into stone, will affect readings. Consolidants, adhesives, paints and other coatings could potentially also affect readings.
Drifting readings	Most sources advise taking the reading as soon as the electrode is inserted, or a couple of seconds after.	Take reading once contact with the stone is good and the reading is relatively stable.
Variations in material	Hardness, irregularities and inhomogeneous areas may affect readings	Avoid taking measurements over obvious defects.
User error	Contact pressure affects readings, with increasing pressure decreasing resistance up to a certain point beyond which little change is noted.	Ensure firm contact, especially as electrodes are not being driven into the stone.
	Capacitance Meters	
Moisture content	Most reliable between 4–6 and 30% MC, and thought to be qualitative above 30%	Readings do not reflect actual moisture content and are not linearly related. Readings are relative values only, but are useful in monitoring wetting and/or drying.
Moisture gradients	Designed to give an average MC over the area penetrated by electrode field. However, readings are strongly influenced by surface conditions, which may bias results.	If surface is oversaturated, readings will be high. Use of meters in adverse weather conditions is not advisable, or when water is seen to pool on the surface. Allow meters to acclimate when changing environments.
Temperature	Conflicting advice, but many capacitance meters do not include temperature correction factors as the effect is thought to be minimal, even at extremes (-10 to +70C)	The effect of temperature was not investigated in this study, but requires investigation.
Species	Species does not affect readings, but density does, with the dielectric constant increasing with increasing density. Also, presence of carbon or metals may affect readings.	Even similar stone types may give different meter readings at the same moisture content. Weathered stone and fresh stone may also give different readings due to changes in porosity and contaminants. In particular, differences in salt, carbon and metal content could affect readings.
Grain angle	Conflicting advice, possibly no effect because the electrode is symmetrical, OR 20–60% greater dielectric constant parallel to the grain v. perpendicular to the grain	Readings should be taken in a consistent manner when bedding is apparent to minimize any potential effect.

(Continued)

Table 3. (*Continued*)

Factors	Wood	Stone
Presence of contaminants	Salts may increase readings, particularly if hygroscopic. Adhesives, coatings and interior fixings may also affect readings.	Salts inherent to the stone, as well as those that have been deposited or have migrated into stone, will affect readings. Consolidants, adhesives, paints and other coatings could potentially also affect readings.
Instrument limitations	Effective depth of measurement varies with different designs. May be as little as 1–2 mm or up to 25 mm. Meters many mathematically adjust for depth rather than a sensor adjustment.	For the stones tested, depth of penetration is less than 5 mm. No change in reading was observed when a sample block was drilled and a copper wire inserted below the sensor at a depth of 5 mm below the surface.
Drifting readings	Not mentioned in the literature.	Drift was observed with the FMW-T, but readings typically stabilized in a few seconds.
Variations in material	Surface must be smooth (planed), and flat, as any air gaps reduce readings.	Rough surfaces where contact cannot be made with the entire sensor give lower readings.
User error	Light to moderate hand pressure should be applied.	Ensure firm contact with the stone.

ACKNOWLEDGEMENT

Many thanks to Dr. Mona Edwards, for providing her unpublished moisture meter test results and observations to us. We would also like to thank both the Commonwealth War Graves Commission and Albion Stone for providing the sample material tested in this study. A Leverhulme Trust Research Project Grant funded this project.

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