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A Comparative Evaluation of Methods to Monitor Moisture in Historic Porous Masonry Materials

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SUMMARY

The project aimed to develop a methodology to compare the performance of a range of invasive and non-invasive moisture measurement methods used to assess moisture in porous masonry. This methodology was laboratory-based and used test blocks of common traditional building materials (limestone, sandstone, brick and lime mortar) under controlled conditions of drying and wetting. The performance of each method tested was compared against weight measurements, which give absolute measurements of moisture content – often called the *gravimetric* method. Experiments were also carried out to evaluate the influence of drying conditions and block size on the test results.

A variety of non-invasive handheld moisture measurement devices were tested, including commonly available resistance, capacitance and microwave moisture meters. Also tested was a range of invasive methods, including wooden and ceramic dowels, relative humidity sensors and time domain reflectometry (TDR) probes. For some of the non-invasive methods, further experiments were designed and carried out to evaluate the depths to which they could measure saturated parts of otherwise dry blocks of sandstone and limestone. A simple experiment was also designed to measure the depth to which some of the non-invasive methods could sense metal objects in otherwise dry materials. This was used to evaluate whether the presence of metal in historic walls could affect the moisture measurements obtained. Finally, a short field monitoring exercise was carried out to explore the usefulness of both non-invasive and invasive microwave moisture measurements in comparison with conventional wooden dowel surveys.

The results indicate, at least under controlled laboratory conditions and on test blocks, that most of the measurement techniques can give good semi-quantitative estimates of moisture levels in traditional porous building materials. Some devices performed better than others in the laboratory tests. A number gave reliable estimates of moisture contents over a range that extended from near-dry to near-saturated, while others were only reliable over part of that range. Some worked better on certain types of materials than on others. Also, the numerical values displayed by many of the devices were influenced by differences in the properties of the material tested. Thus, a measurement of, for example, 42 on a sandstone block would not indicate the same degree of saturation as a value of 42 obtained from a limestone block. This means that readings obtained from different materials cannot be directly compared.

Both drying and wetting experiments generated broadly similar datasets, but data from the wetting experiments were generally more variable and harder to interpret. The drying experiments provided a good simulation of recovery of historic masonry from flood, and the wetting experiments provided an effective simulation of the impact of driving rain on dry walls. The sensing depth of the non-invasive measurement methods tested was found to vary depending on material type and experimental conditions, and manufacturers' datasheets should be used to give a general indication of the likely depth of penetration.

The ceramic dowels developed recently by Historic England were found to perform well in comparison to wooden dowels. Also, using dowels in conjunction with

non-invasive microwave measurements was found to provide particularly useful information on short and longer term drying behaviour, both in the laboratory and within a historic building.

CONTRIBUTORS

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ARCHIVE LOCATION

Historic England Archive
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DATE OF RESEARCH

Phase 1 2015
Phase 2 2018

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FOREWORD

Excess moisture is responsible for many problems in buildings. It can adversely affect the health and comfort of occupants, lead to poor indoor air quality, and decrease the thermal performance and energy efficiency of the building envelope. Also, it is the primary cause of the deterioration and decay of many construction materials. The ability to assess and monitor moisture conditions in a building is key to identifying sources of moisture, assessing risks of decay and deterioration, finding solutions and evaluating the effectiveness of remedial works.
Historic England is often asked for advice on damp problems in historic and traditional buildings. Numerous techniques and devices for assessing moisture are available to the conservation practitioner. But what do they actually tell us, how accurate are they, and what factors affect the data they provide? The research presented in this report was carried out to help answer these questions.

Important note

The experiments described in this report aimed to evaluate the performance of different moisture measurement devices when applied to a range of historic building materials under laboratory conditions. Any comments made in this report about the performance of devices apply only to their application in these unusual circumstances. They do not represent any critical judgement about the performance of the devices when used in the applications for which they are designed.

BACKGROUND

Although there are many different methods commonly used to investigate and assess damp problems in walls, all have some drawbacks. Also, there is a lack of agreement over how they should best be used, and little information about how they compare one with another (Pinchin 2008). This project aimed to develop and test a common methodology for comparing the performance of different moisture measurement methods, based on laboratory testing. The overall goal of the research was to provide an inter-comparison of the performance of different methods of monitoring moisture within key porous materials likely to be found in historic buildings. The project was carried out in two phases: one for initial testing and the other for wider laboratory tests and a field evaluation.

1. PHASE 1

1.1 Objectives

The objectives of the drying tests in Phase 1 were to:

- test the performance of different moisture measurement methods (invasive and non-invasive) on fresh specimens of brick, mortar and limestone under controlled laboratory conditions
- investigate the influence of sample size and evaporation conditions (sealed vs unsealed sides) on the performance of different non-invasive methods
- test the influence of salinity on the performance of different non-invasive methods
- provide some guidelines for choosing a technique and following best practice

1.2 Materials and methods

Phase 1 of the project used a total of eight non-invasive and five invasive moisture measurement methods. It compared the values collected from each one with the absolute moisture contents (expressed as % dry weight) obtained by gravimetry.

Table 1 gives the details of each of the methods tested. The invasive methods are illustrated in Figure 1. Phase 1 focused on Portland limestone (Coombefield Whitbed), lime mortar and brick (largely, new handmade bricks manufactured by H G Matthews, with some pilot study tests on a machine-made brick and two old bricks). Table 2 lists the materials and sample sizes used for this phase and Figure 2 illustrates them. A good introduction to these and other methods of measuring moisture in porous building materials is provided by Historic Environment Scotland's *Technical Paper 35: Moisture Measurement in the Historic Environment* (2021).

Table 1: Moisture measurement methods used in Phase 1

Method	Name	Model/Mode	Manufacturer	Range of readings	Manufacturer's stated depth of penetration (mm)
Non-invasive methods	Pinless Moisture Meter (CEM)	DT-128 (capacitance)	Shenzhen Everbest Machinery Industry Co Ltd (China)	0–100 digits	20–40
	FMW	FMW-T (capacitance) (10 and 20mm settings)	Brookhuis Micro-Electronics B V (Netherlands)	0–60%	20–25
	M50 (Probe)	(capacitance)	JR Technology Ltd (UK)	0–50%	Up to 40
	GE Protimeter Surveymaster Dual-Function Moisture Meter	'Measure' mode (resistance)	Protimeter (USA)	6–90% WME (readings above 30% are relative)	12.7
		'Search' mode (capacitance)		60–999 digits	19
	Resipod	Surface Resistivity Meter (resistance)	Proceq (Switzerland)	0–1000 kΩcm	25 (based on pin spacing)
	Trotec	T610 (microwave)	Trotec GmbH & Co KG (Germany)	0–200 digits	200–300
		T660 (capacitance)	Trotec GmbH & Co KG (Germany)	0–200 digits	20–40
Invasive methods	GE Protimeter Surveymaster Dual-Function Moisture Meter	With deep wall probes 'Measure' mode (resistance)	Protimeter (USA)	6–90% WME (readings above 30% are relative)	Depends on length of probes (75, 150 or 360mm available)
	Tinytag	TGP-4505 (Air temperature/relative humidity)	Gemini Data Loggers (UK)	-20–+85°C 0–100% RH	Depends on hole depth
	Wooden dowel	Made by Historic England, but connected to Protimeter (resistance)	Historic England	6–90% wood moisture equivalent	Depends on hole depth
	HygroLog	HygroLog NT3 + HygroClip SC05 (Air temperature/relative humidity)	Rotronic (Switzerland)	-40-+100°C 0–100% RH	Depends on hole depth
	TDR	TDR100 (Time domain reflectometry)	Bespoke TDR kit	Assumed relative permittivity, recorded as εr	Length of probes c30

Figure 1 shows the non-invasive and invasive moisture measurement methods used in Phase 1.

Protimeter

CEM

FMW

Trotec T660

Trotec T610

M50

Resipod

TDR

Tinytag relative humidity probe and data logger

Protimeter with deep wall probe

Protimeter with Historic England probe wooden dowel

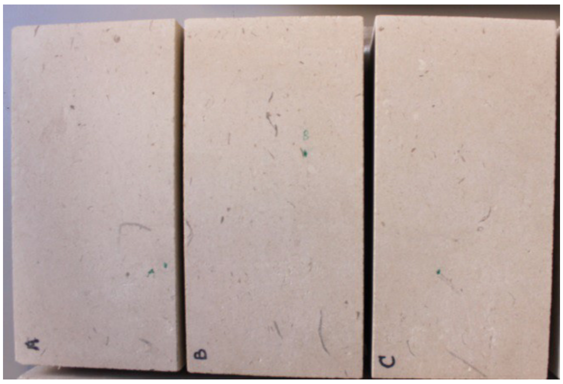
Rotronic relative humidity and data logger

Fig 1: Non-invasive and invasive moisture measurement methods used in Phase 1.

Table 2: Materials and sample sizes used in Phase 1

Material	Dimensions in mm (large samples)	Dimensions in mm (small samples)	Notes
Portland limestone (Coombefield Whitbed)	200 x 100 x 75	100 x 75 x 50	
New machine-made brick	200 x 100 x 50	N/A	Used in pilot study only Pavement brick
Old brick	220 x 110 x 60	N/A	Used in pilot study only Obtained from demolished garden wall
Handmade brick (H G Matthews)	220 x 105 x 65	100 x 75 x 45	Fired at 900°C in a wood-fuelled kiln
Lime mortar	Cylinder (300 x 105 diameter)	N/A	Made in 2007; 1 part NHL 3.5; 2.5 parts sand + porous aggregate

Figure 2 shows the materials used in Phase 1.



A) Portland limestone (Coombefield Whitbed)

B) New machine-made brick (left), old bricks obtained from demolished garden wall (right)

C) New handmade bricks from H G Matthews

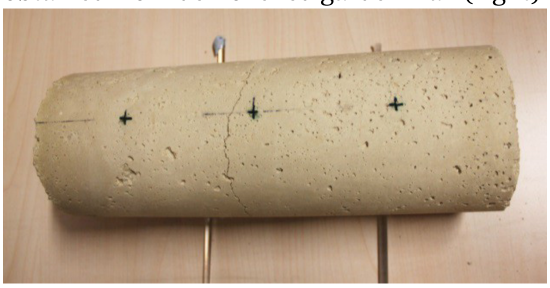

D) Lime mortar cylinder

Fig 2: Materials used in Phase 1.

Phase 1 of the project was divided into four main stages:

- **Pilot study:** Using four non-invasive moisture measurement methods to develop a robust methodology using blocks of Portland limestone, old brick and new brick (machine-made and handmade)
- **Stage 1:** Testing eight non-invasive moisture measurement devices on a range of blocks (large and small, with evaporation from all faces [unsealed) vs evaporation from one face only [sealed] to simulate the condition of masonry in a wall of handmade brick and Portland limestone (with some additional testing on lime mortar cylinders)
- **Stage 2:** Testing five invasive moisture measurement devices on blocks of Portland limestone and handmade brick
- **Stage 3:** Testing four non-invasive moisture measurement devices on blocks of Portland limestone and handmade brick treated with saline water (NaCl) to assess the effect of salts on the measurements

The materials used in the different stages are shown in Table 3.

Table 3: Materials tested in each of the stages

Project phase	Material type	Sample size (mm) and details	No. of replicates/ (sample names)
Pilot study	Portland limestone (Coombefield Whitbed)	200 x 100 x 75	3 (LPA, LPB, LPC)
	Old brick (Oxford)	220 x 110 x 60	2 (BA, BB)
	New machine-made brick	200 x 100 x 50	1 (BC)
Stage 1 (non-invasive methods)	Portland limestone (Coombefield Whitbed)	200 x 100 x 75 (sealed and unsealed)	3 (LPA, LPB, LPC)
	Portland limestone (Coombefield Whitbed)	100 x 75 x 50 (unsealed)	3 (LP1, LP2, LP3)
	Handmade brick (H G Matthews)	220 x 105 x 65 (sealed and unsealed)	3 (NBA, NBB, NBC)
	Handmade brick (H G Matthews)	100 x 75 x 45 (unsealed)	3 (NB1, NB2, NB3)
	Lime mortar (made in 2007; 1 part NHL 3.5: 2.5 parts sand + porous aggregate)	Cylinder of 300 x 105	3 (M1, M2, M3)
Stage 2 (invasive methods)	Portland limestone (Coombefield Whitbed)	100 x 75 x 50 (drilled with 1 or 2 holes depending on probe used)	3 (LP1, LP2, LP3)
	Handmade brick (H G Matthews)	100 x 75 x 50 (drilled with 1 or 2 holes depending on probe used)	3 (NB1, NB2, NB3)
Stage 3 (non-invasive methods with salinity)	Portland limestone (Coombefield Whitbed)	200 x 100 x 75	3 (LPA, LPB, LPC)
	Handmade brick (H G Matthews)	220 x 105 x 65	3 (NBA, NBB, NBC)

The moisture measurement methods tested in each stage are shown in Table 4.

Table 4: Moisture measurement methods used in each of the stages

Project phase	Moisture measurement method	Notes/operating principle
Pilot study	Protimeter	In resistance mode only
	Resipod	Resistance
	CEM	Capacitance
	FMW	Capacitance (set to read to depth of 10mm)
Stage 1a (non-invasive methods, unsealed Portland limestone and brick samples – both large and small)	Protimeter	In both resistance and capacitance mode
	Resipod	Resistance, usable only on larger samples
	CEM	Capacitance
	FMW	Capacitance (set to read to 20mm depth)
	T660	Capacitance
	M50	Capacitance
	T610	Microwave
Stage 1b (non-invasive methods, Portland limestone and brick sealed samples – large only)	Protimeter	In both resistance and capacitance mode
	Resipod	Resistance
	CEM	Capacitance
	FMW	Capacitance (set to read to 20mm depth)
	T660	Capacitance
Stage 1c (non-invasive methods, lime mortar cylinders)	Protimeter	In both resistance and capacitance mode
	Resipod	Resistance
	CEM	Capacitance
	T660	Capacitance
Stage 2 (invasive methods)	TDR	Bespoke TDR kit
	Protimeter	Two-pronged deep wall probe (6cm deep) Resistance
	Wooden dowel with embedded electrodes	Read using Protimeter, 5cm deep Resistance
	Tinytag probe	RH probe, 6cm deep
	Rotronic HygroLog NT3 probe	RH probe, 5cm deep
Stage 3 (non-invasive methods, Portland and brick samples, saline water)	Protimeter	In both resistance and capacitance mode
	Resipod	Resistance
	CEM	Capacitance
	FMW	Capacitance (set to read to 20mm depth) – limestone only

1.3 Testing protocols

The experimental methodology in each stage of the project is summarised below. Each of the methods was compared against gravimetric measurements of water contents at a number of time points as the samples dried out from the saturated state. The data were graphed to demonstrate the shape and strength of the relationship between the moisture measurement technique and the gravimetric measurements.

1.3.1 Pilot study

Figure 3 illustrates the experimental protocol followed in the pilot study, modified from that used by Eklund *et al* (2013).

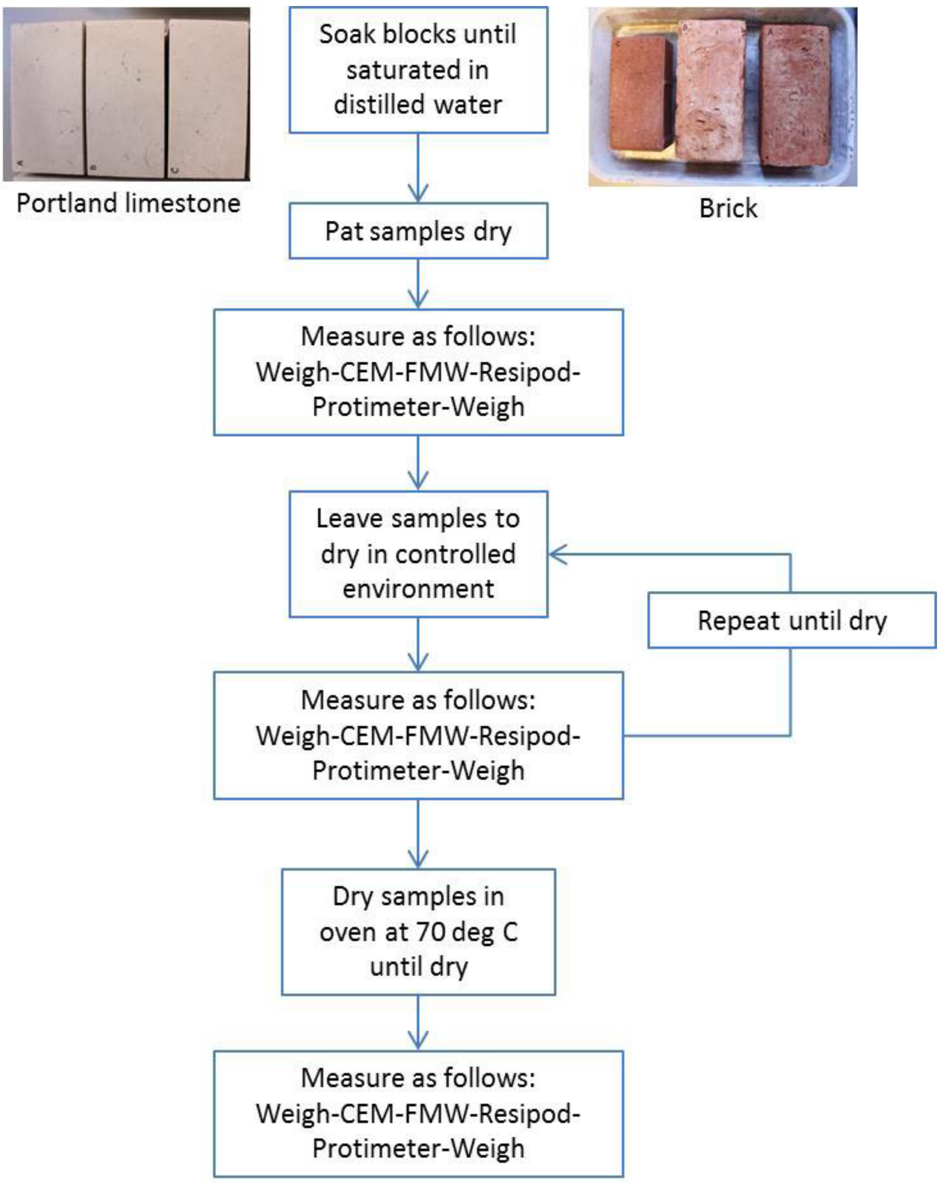


Fig 3: Methods flow chart.

1.3.3 Stage 1a

The pilot study testing protocol (Figure 3) was followed, but with more measurement methods used. All measurements were taken on each of three replicates of Portland limestone and handmade brick (large and small). The Resipod could not be used on small samples as the four measurement pins require a larger surface area.

1.3.4 Stage 1b

The pilot study testing protocol (Figure 3) was followed, but all surfaces except the top face were sealed with waterproof duct tape to prevent evaporation from everywhere except the top face. This represents real life conditions when bricks are embedded in a wall. All measurements were taken on each of three replicates of Portland limestone and handmade brick (large only).

1.3.5 Stage 1c

The pilot study testing protocol (Figure 3) was followed, but using only one cylinder of lime mortar (the second one broke after two measurements). Three measurement points were used for all but the Resipod, for which only one measurement point was used because of the wide spacing of the Resipod sensor pins.

1.3.6 Stage 2

The pilot study testing protocol (Figure 3) was followed, but three replicates were used for TDR probes and only one sample was tested for the other methods. This was because each method required a slightly different arrays of holes.

1.3.7 Stage 3

The pilot study testing protocol (Figure 3) was followed, but samples were saturated in a sodium chloride solution (1.46g NaCl per litre of water).

1.4 Results

1.4.1 Pilot study

The pilot study demonstrated that the method produced repeatable results. These results were highly comparable to those collected by Eklund *et al* (2013), and they are shown in Figures 4 and 5, where the readings from each moisture meter (with Protimeter used in resistance [‘Measure’] mode) are plotted against % moisture contents by weight obtained by gravimetry.

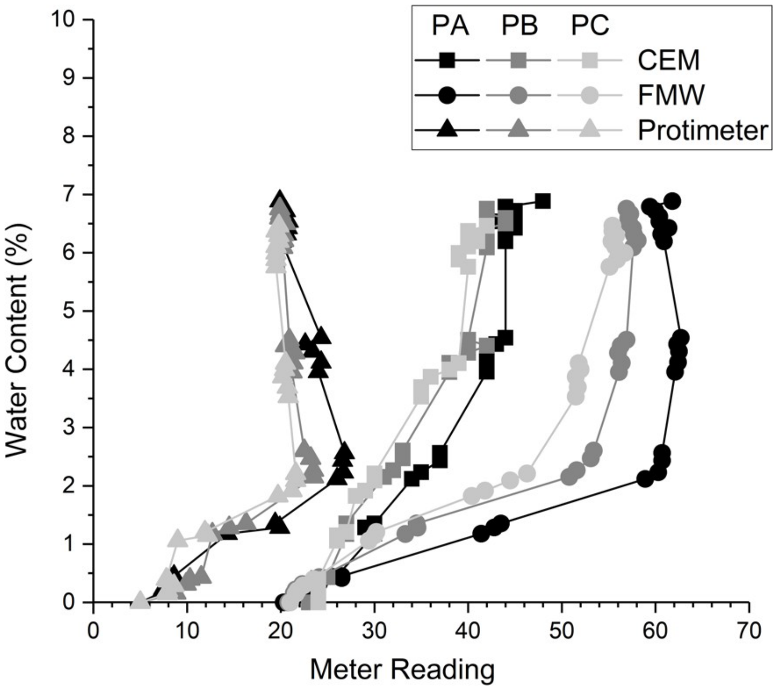


Fig 4: Pilot study results. CEM, FMW (10mm setting) and Protimeter (resistance ['Measure'] mode) readings plotted against gravimetric measurements of water contents for large samples of Portland limestone (Coombefield Whitbed) (PA, PB, PC).

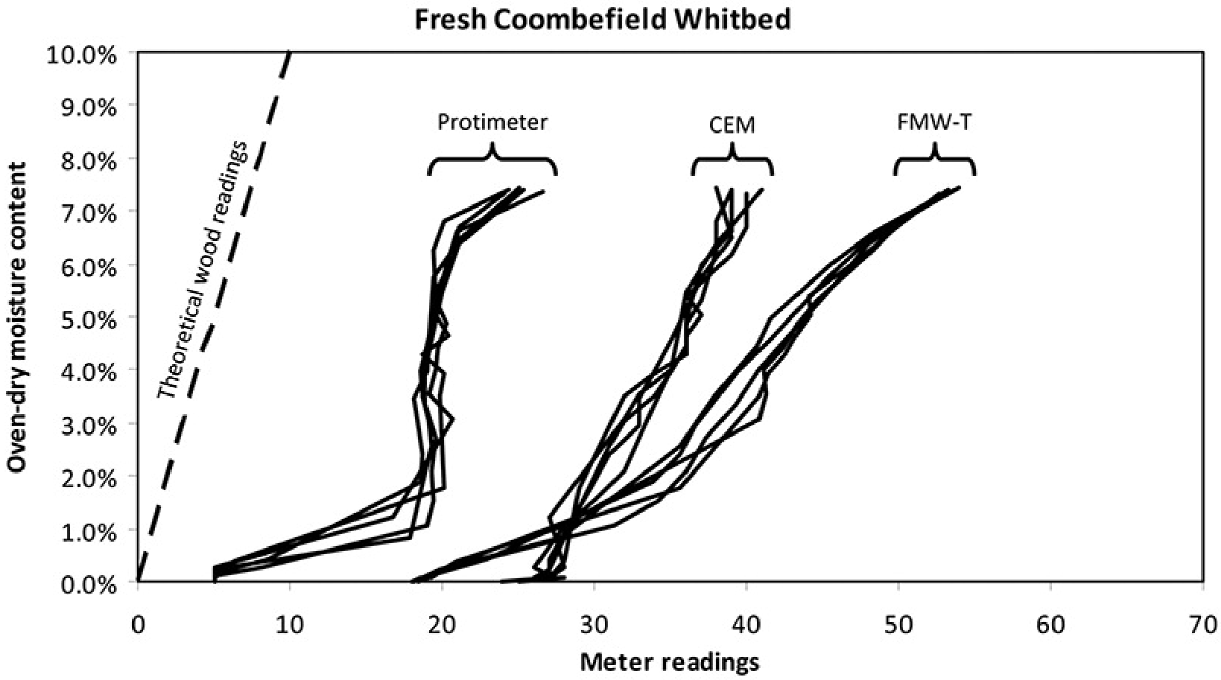


Fig 5: Results obtained by Eklund et al (2013) from Portland limestone (Coombefield Whitbed).

Figure 6 shows comparable data from the Protimeter, FMW and CEM on old and new brick specimens. It illustrates the very different saturated % moisture contents by weight of the two brick types. Comparing Figures 4 and 6 also illustrates the different behaviour of the three moisture meters on brick vs Portland limestone.

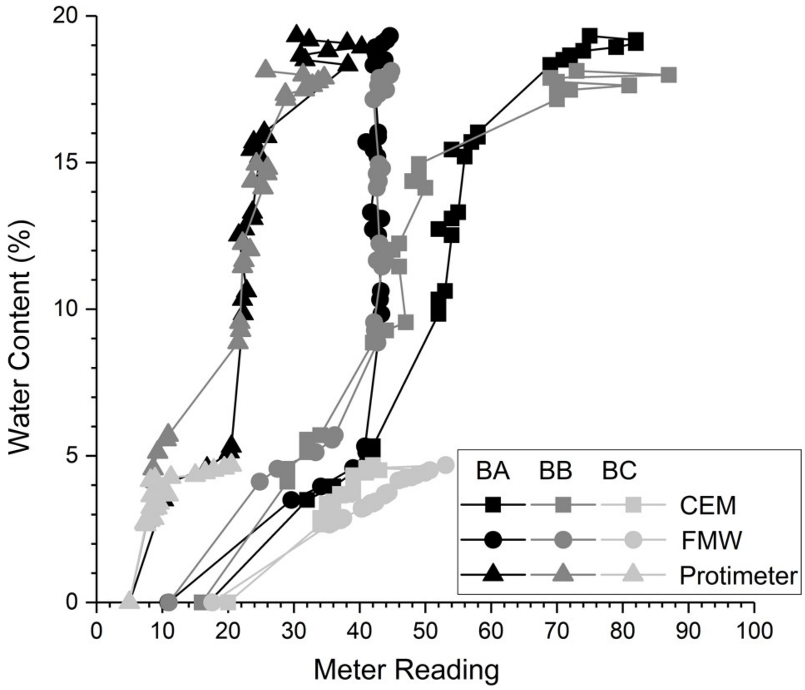


Fig 6: Pilot study results. CEM, FMW (10mm setting) and Protimeter (resistance ['Measure'] mode) readings plotted against gravimetric measurements of water contents for large samples of old brick (BA, BB) and new brick (BC).

The pilot study also used a further handheld device, the Resipod (Fig 7). Unlike the other resistance-based moisture meters, which give converted readings (using the inverse of resistance), the Resipod outputs resistance data directly. This means that the curves produced are the inverse of those in Figures 4, 5 and 6.

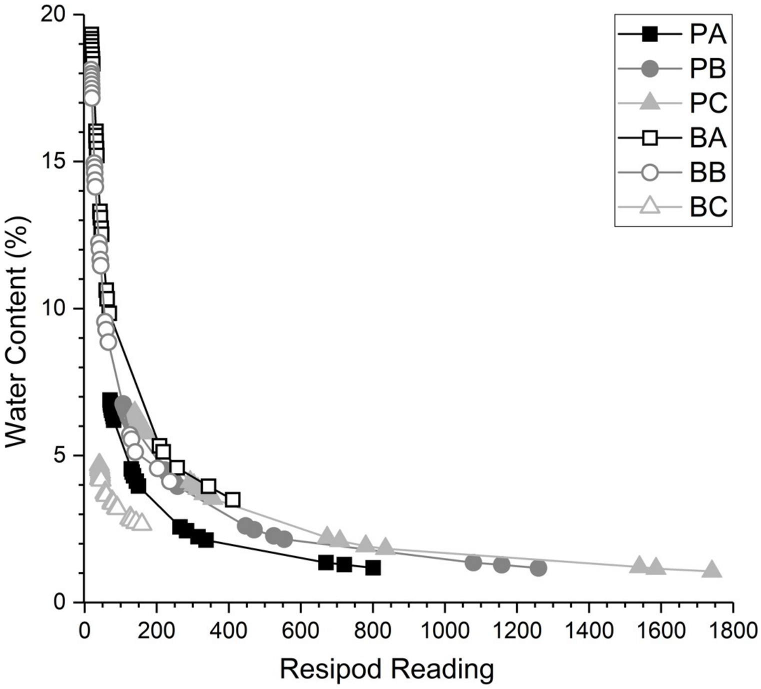


Fig 7: Pilot study results. Resipod readings plotted against gravimetric measurements of water contents for large samples of Portland limestone (Coombefield Whitbed) (PA, PB, PC), old brick (BA, BB) and new brick (BC).

1.4.2 Interpreting the results – what makes an effective moisture measurement method?

A simple way of assessing the effectiveness of the different moisture measurement methods is to look at the shape of the curves on the graphs of meter reading against % moisture contents by gravimetry. The straighter the curve, and the closer it is to 45 degrees from the horizontal, the better. This is because such a curve implies a simple 1:1 relationship between the meter reading and the real % moisture contents. Thus, Figure 8a illustrates a highly effective moisture measurement method, whereas Figures 8b and 8c illustrate less effective methods. However, simple curves, such as that presented in Figure 8d, can also produce effective measurements of moisture, even though there is a non-linear relationship between the measurement and real % moisture contents. In reality, the data collected are usually more complex. Figure 8e, for example, illustrates a dataset where the bottom part of the curve (below the dotted line threshold) is effective, whereas the upper part is not. Figure 8f shows how sometimes the upper part of the dataset can be particularly variable and unreliable. A further factor to consider, when looking at the effectiveness of different measurement methods, is how similar the curves are in different replicates of the same material. Figures 8g and 8h show some plausible scenarios. Finally, some methods are not able to capture data from very dry or very wet specimens, and thus may only be effective across some parts of the spectrum of moisture conditions.

In this report, graphs of data are presented in the Appendices to illustrate the nature of the curves obtained from the different measurement methods, usually for three replicate samples of each material. Given the exploratory nature of this report, instead of trying to produce calibration curves (which would involve pooling data from the replicates and producing a 'best fit curve' using correlation and regression analysis), the approach taken has been to inspect the graphs and summarise the range of moisture contents over which the method provides meaningful measurements. To use the idealised plots in Figure 8 as examples, all of the lines in Figures 8a to 8d would be classed as meaningful measurements, whereas only the range up to the threshold in Figure 8e and the lower, straighter section of Figure 8f would be seen as meaningful. Because of the high spread in data in Figure 8g, and the spread in data and complexity of the lines in Figure 8h, these would be deemed to be unreliable. Table 5 provides a summary of the reliable data extracted using this method.

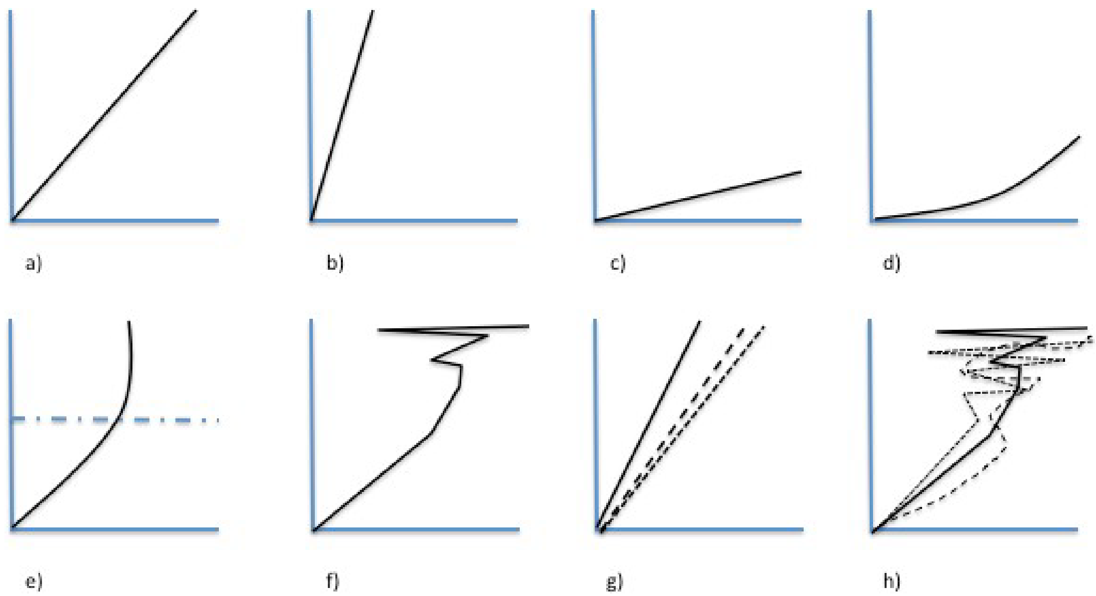


Fig 8: Idealised graphs of the relationship between data from a moisture measurement method (x axis) and moisture contents as % of dry weight (y axis) .

The following sections describe the major features of the data collected. Graphs of moisture measurement method readings against gravimetric data for each phase are shown in Appendix A and referred to as appropriate in the text below. Table 5 summarises the important aspects of the data.

1.4.3 Stage 1a: How do the non-invasive methods perform on limestone and brick, and does size matter?

The datasets collected for the large blocks in Stage 1a are depicted in Figures A.5, A.7, A.9, A.11, A.13 and A.15 in Appendix A and summarised in Table 5. Looking at the shape of the curves in comparison with those shown in Figure 8 provides a simple visual guide to the effectiveness of different measurement methods over different moisture ranges. As in the pilot study, the Protimeter in resistance mode is only effective for c 0–2% moisture contents on Portland limestone and c 0–10% on the handmade brick (*see* Fig A.11), whereas the CEM (*see* Fig A.5) and Resipod (*see* Fig A.17) show much greater effectiveness over almost the entire range of moisture contents, except at very low levels. The T660, which is a capacitance-based device (*see* Fig A.7), performs similarly well to the Protimeter in resistance mode. Using the Protimeter in capacitance mode (*see* Fig A.13) gives effective measurements for large blocks over the range 0–3% for Portland limestone and 0–10% for the handmade brick. The FMW (data graphed for the pilot study in Figure A.2, and summarised for both pilot study and Stage 1a in Table 5) shows comparable performance to the Protimeter in resistance mode, giving effective measurements for large blocks over the range 0–3% for Portland limestone and 0–6% for the handmade brick. The M50 is another capacitance-based moisture meter and it has a large, cylindrical measurement head. The curves depicted in Figure A.15 illustrate that the M50 is effective over a very narrow moisture range for both Portland limestone and the handmade brick (c 0–1% for Portland and c 0–2% for handmade brick). The T610 is a microwave-based moisture meter and it gave erratic readings (*see* Fig A.16), likely because the samples used were too small for this kind of device. In summary, for large samples, CEM and Resipod provide good measurements over most of the range of moisture contents for both handmade brick and Portland limestone. The Protimeter (in both resistance and capacitance modes), FMW and T660 provide useful data for samples with low moisture contents.

In order to evaluate whether size of block matters, we can compare data from large and small blocks for the CEM (cf Figs A.5 and A.6), T660 (cf Figs A.7 and A.8), T610 (cf Figs A.9 and A.10), Protimeter in resistance and capacitance modes (cf Figs A.11 and A.12, and A.13 and A.14), M50 (cf Figs A.15 and A.16) and FMW (cf Figs A.2 and A.18). Table 5 summarises the relevant data. For the methods shown to be reliable for large blocks, the Protimeter in resistance mode, FMW and M50 do not appear to be affected by block size, whereas the CEM and Protimeter in capacitance mode are affected in the upper parts of the moisture curves for both material types, and the T660 is affected for Portland limestone only. Where block size matters, it appears that the smaller the block the less well the devices perform at higher levels of saturation. The Resipod cannot be used on small blocks because of the geometry of the measurement head.

1.4.4 Stage 1b: Does limiting evaporation to the top face matter?

By using duct tape to seal off all sides but the top face, we are simulating the more natural conditions found in most building materials, where evaporation proceeds mainly from the front exposed surface. For this part of the project, we compared the performance of CEM (cf Figs A.5 and A.19), Protimeter (resistance and capacitance modes – cf Figs A.11 and 21, and A.13 and A.22), T660 (cf Figs A.7 and A.20), Resipod (cf Figs A.17 and A.23) and FMW (*see* Fig A.24). The FMW was used on Portland limestone samples only. Comparing the data collected from large samples before and after sealing the sides, all tested devices show very minor impacts. The Protimeter in capacitance mode, for example, shows virtually identical performance (*see* Figs A.13 and A.22), and the other devices only show differences in performance at the drier parts of their effective ranges.

1.4.5 Stage 1c: Do the non-invasive measurement methods perform well on mortar also?

The cylinder shape of the mortar sample precluded the use of the FMW, but the Protimeter (resistance and capacitance modes), Resipod, CEM and T660 were all tested (*see* Figs A.25 to A.29 and data summary in Table 5). All were found to perform comparably well on mortar. The Resipod again proved to be versatile and effective over the whole range of moisture contents, whereas the CEM, Protimeter in resistance and capacitance modes and T660 were found to perform especially well in the <8% (CEM), <6% (Protimeter resistance and T660) and <5% (Protimeter capacitance) ranges.

1.4.6 Stage 2: How do the invasive methods perform?

Results from the five invasive methods (TDR, Tinytag, Rotronic, Protimeter with deep wall probe and wooden dowel) are summarised in Table 5 and shown graphically in Appendix A (*see* Figs A.30 and A.31). Results for the Tinytag are not shown in Figure A.31 because the device failed to perform effectively. The invasive methods were tested on Portland limestone, and the TDR was additionally tested on the H G Matthews bricks. One key issue with using these invasive methods is getting holes drilled to exactly the right diameter to allow snug fit of the measurement probes. The two relative humidity probes (Tinytag and Rotronic HygroLog) both performed poorly, producing only very low or very high readings, with nothing in-between (*see* Fig A.31). The Protimeter with the deep wall probes performed well, giving reliable readings over the 0–6% moisture contents range. It also proved to give more stable results (that is, it was quicker to settle on a stable measurement) than the Protimeter in resistance and capacitance modes.

Once the set-up conditions for the Historic England wooden dowel with built-in electrodes to measure resistance had been optimised, this method worked well. To set up the wooden dowel effectively, it was dried, placed into a saturated block and then left to equilibrate to the surrounding conditions before any measurements were taken. The TDR provided the most accurate measurement method, especially for brick. For Portland limestone, the three replicate curves were offset from each other but otherwise the results were very good.

1.4.7 Stage 3: How does salinity affect the performance of selected non-invasive measurement methods?

Using the large unsealed brick and limestone samples, the experiments were run again using the CEM, Protimeter (in both resistance and capacitance modes), Resipod and FMW (with the FMW only used on stone samples). Samples were soaked in a medium-strength sodium chloride solution (1.46g NaCl per litre of water). The data are summarised in Table 5 and presented graphically in Appendix A (*see* Figs A.32 to A.40). All the measurement methods showed a strong effect of salinity on the relationship between readings and real moisture content (% dry weight). Thus, readings on samples with the same level of moisture in them differed greatly depending on whether or not the water was saline. Furthermore, the shape of the curves altered with the added salt, meaning that the effective range of the different devices changed. For example, the Protimeter in capacitance mode, the FMW and the Resipod became less effective at higher saline moisture contents than on samples treated with distilled water on both brick and limestone, whereas, in resistance mode, the Protimeter became more effective at the upper end of the range (although the curves showed some complexity and variability). The CEM was still effective at measuring most of the range of % moisture contents, although the data collected became more variable at higher % moisture contents, especially for brick samples.

1.4.8 Which method works best on brick, limestone and mortar?

Table 5 summarises the effective range of the different moisture measurement methods for the three types of materials under the different experimental stages in Phase 1. Two columns illustrate the efficacy of the different methods. The column labelled 'Range % MC' shows the range of moisture contents for which each method gives reliable results. The column labelled 'Range % Sat' shows the percentage of the total range of moisture contents covered by the different methods. Thus, if the method is accurate across the entire range, from bone dry to saturated, the figure given in this column would be 100%. As a summary, the ranked performance (from high to low) of the different methods is:

Handmade brick from H G Matthews:
TDR > CEM > Resipod > Protimeter (capacitance mode) > FMW and T660 > Protimeter (resistance mode) > T610 and M50

Lime mortar:
Resipod > CEM > Protimeter (resistance mode) > T660 > Protimeter (capacitance mode)

Portland limestone:
TDR > Wooden dowel and Protimeter (probe) > Resipod > CEM > FMW > Protimeter (capacitance and resistance modes) and T660 > M50 > T610

Table 5: Summary of the effective range of each moisture measurement method on each material

Material	Stage	Block characteristics	Saturation % MC	Method	Range % MC	Max % MC	Min % MC	Max % Sat	Min % Sat	Range % Sat
Handmade brick	1	L	16	CEM	0–12	12	0	75	0	75
	2	L/Sealed	16	CEM	0–9	9	0	56	0	56
	1	S	16	CEM	0–16	16	0	100	0	100
	3	L/Salted	16	CEM	0–8	8	0	50	0	50
	1	S	16	FMW (20)	0–6	6	0	38	0	38
	1	L	16	M50	0	0	0	0	0	0
	1	S	16	M50	0	0	0	0	0	0
	1	L	16	Protimeter (M)	0–5	5	0	31	0	31
	1	L/Sealed	16	Protimeter (M)	2–5	5	2	31	13	19
	1	S	16	Protimeter (M)	0–9	9	0	56	0	56
	3	L/Salted	16	Protimeter (M)	0–2	2	0	13	0	13
	1	L	16	Protimeter (S)	0–9	9	0	56	0	56
	1	L/Sealed	16	Protimeter (S)	0–8	8	0	50	0	50
	1	S	16	Protimeter (S)	0–11	11	0	69	0	69
	3	L/Salted	16	Protimeter (S)	0–4	4	0	25	0	25
	1	L	16	Resipod	4–16	16	4	100	25	75
	1	L/Sealed	16	Resipod	5–16	16	5	100	31	69
	3	L/Salted	16	Resipod	0.5–7	7	0.5	44	3	41
	1	L	16	T610	1–2	2	1	13	6	6
	1	S	16	T610	0	0	0	0	0	0
	1	L	16	T660	0–5	5	0	31	0	31
	1	L/Sealed	16	T660	0–5	5	0	31	0	31
	1	S	16	T660	0–6	6	0	38	0	38
	2	S	16	TDR	0–16	16	0	100	0	100
New brick	P	L	5	CEM	0–4	4	0	80	0	80
	P	L	5	FMW (10)	0–4	4	0	80	0	80
	P	L	5	Protimeter (M)	0–4	4	0	80	0	80
	P	L	5	Resipod	2.5–4	4	2.5	80	50	30
Old brick	P	L	20	CEM	0–18	18	0	90	0	90
	P	L	20	Protimeter (M)	0–17	17	0	85	0	85
	P	L	20	Resipod	2–10	10	2	50	10	40
	P	L	20	FMW (10mm setting)	0–10	10	0	50	0	50
Mortar	1	C	14	CEM	0–8	8	0	57	0	57
	1	C	14	Protimeter (M)	0–6	6	0	43	0	43
	1	C	14	Protimeter (S)	0–5	5	0	36	0	36
	1	C	14	Resipod	2–14	14	2	100	14	86
	1	C	14	T660	0–6	6	0	43	0	43

Material	Stage	Block characteristics	Saturation % MC	Method	Range % MC	Max % MC	Min % MC	Max % Sat	Min % Sat	Range % Sat
Portland limestone	P	L	7	CEM	0–4.5	4.5	0	64	0	64
	1	L	7	CEM	0–5	5	0	71	0	71
	1	L/Sealed	7	CEM	0–4	4	0	57	0	57
	1	S	7	CEM	0–5	5	0	71	0	71
	3	L/Salted	7	CEM	0–2	2	0	29	0	29
	P	L	7	FMW (10mm setting)	0–3	3	0	43	0	43
	1	L	7	FMW (20mm setting)	0–3	3	0	43	0	43
	1	L/Sealed	7	FMW (20mm setting)	0–3	3	0	43	0	43
	1	S	7	FMW (20mm setting)	0–4	4	0	57	0	57
	3	L/Salted	7	FMW (20mm setting)	0–1	1	0	14	0	14
	1	L	7	M50	0–1	1	0	14	0	14
	1	S	7	M50	0–1	1	0	14	0	14
	P	L	7	Protimeter (M)	0–2	2	0	29	0	29
	1	L	7	Protimeter (M)	0–3	3	0	43	0	43
	1	L/Sealed	7	Protimeter (M)	2–2.5	2.5	2	36	29	7
	1	S	7	Protimeter (M)	0–2	2	0	29	0	29
	3	L/Salted	7	Protimeter (M)	0–2	2	0	29	0	29
	1	L	7	Protimeter (S)	0–2	2	0	29	0	29
	1	L/Sealed	7	Protimeter (S)	0–2	2	0	29	0	29
	1	S	7	Protimeter (S)	0–3	3	0	43	0	43
	3	L/Salted	7	Protimeter (S)	0–1	1	0	14	0	14
	P	L	7	Resipod	2–7	7	2	100	29	71
	1	L	7	Resipod	1–7	7	1	100	14	86
	1	L/Sealed	7	Resipod	2–7	7	2	100	29	71
	3	L/Salted	7	Resipod	1–3	3	1	43	14	29
	1	L	7	T610	0	0	0	0	0	0
	1	S	7	T610	0	0	0	0	0	0
	1	L	7	T660	0–2	2	0	29	0	29
	1	L/Sealed	7	T660	0–2	2	0	29	0	29
	1	S	7	T660	0–1	1	0	14	0	14
	2	S	7	TDR	0–7	7	0	100	0	100
	2	S	7	Rotronic	0–0.25	0.25	0	4	0	4

Material	Stage	Block characteristics	Saturation % MC	Method	Range % MC	Max % MC	Min % MC	Max % Sat	Min % Sat	Range % Sat
Portland limestone	2	S	7	Tinytag	0	0	0	0	0	0
	2	S	7	Protimeter (P)	0–6	6	0	86	0	86
	2	S	7	Wood dowel	0–7	7	0	100	0	100

Key to Table 5:
Stage: Stage of Phase 1; P = pilot
Block characteristics: L = large block; S = small block; C = cylinder
Condition: Sealed = evaporation from top face only; Salted = saturated with saline water
Saturation MC: Moisture content at saturation, expressed as % dry weight and determined by gravimetry
Method: Measurement device tested (see text for explanation)
Measurement mode (Protimeter only):
(M): 'Measure' (resistance)
(S): 'Search' (capacitance)
(P): 'Deep-wall probe' (resistance)
Range % MC: Range of moisture content over which the device gives reliable results for the material tested, expressed as % dry weight and determined by gravimetry
Max % MC: Maximum moisture content for which the device gives reliable results
Min % MC: Minimum moisture content for which the device gives reliable results
Max % Sat: Maximum reliable value obtainable from the device, expressed as % of total saturation level
Min % Sat: Minimum reliable value obtainable from the device, expressed as % of total saturation level
Range % Sat: Range of moisture content over which the device gives reliable results for the material tested, expressed as % of total saturation level

Table 6 summarises the reduction in the effective measurement range when using saline vs distilled water on the different non-invasive methods tested on brick and Portland limestone.

Table 6: Comparison of the effective measurement range (as a % of the total range) of selected moisture measurement methods when distilled water vs saline water (in brackets) is used

Material	Range % sat measured in distilled (saline) water				
	CEM	Protimeter (r/m)	Protimeter (c/s)	Resipod	FMW
Brick (HG Matthews)	75 (50)	31 (13)	56 (25)	75 (41)	ND
Portland limestone	71 (29)	43 (29)	29 (14)	86 (29)	43 (14)

Table 7 gives an indication of the likely values recorded by a range of the more effective moisture measurement methods on brick, mortar and limestone, using a four-fold categorisation of wetness values: 0–25% saturated moisture contents = dry/damp; 25–50% = damp; 50–75% = moist; >75% = wet/saturated.

Table 7: Measurement ranges for different moisture categories on handmade brick, lime mortar and Portland limestone samples using selected methods

Handmade Brick (H G Matthews)									
% saturation	Wetness class	TDR	CEM	CEM (salt-affected)	Resipod	Resipod (salt-affected)	FMW	Protimeter (c/s)	Protimeter (c/s) – salt affected
0-25	Dry/damp	2-5	8-20	5-40	n/a	1200-250	10-40	200-750	200-850
25-50	Damp	5-7	20-27	40-70	1400-600	250-150	40-50	>750	>850
50-75	Moist	7-8	27-30	>70	600-400	n/a	n/a		
>75	Wet/ saturated	8-11	>30		400-300	n/a	n/a		

Lime mortar									
% saturation	Wetness class	TDR	CEM	CEM (salt-affected)	Resipod	Resipod (salt-affected)	FMW	Proti-meter (r/m)	T660
0-25	Dry/damp		20-40		450-200			7-12	30-80
25-50	Damp		40-50		200-100			12-20	80-150
50-75	Moist		>50		100-50			>20	>150
>75	Wet/ saturated				<50				

Portland limestone (Coombefield Whitbed)										
% saturation	Wetness class	TDR	CEM	CEM (salt-affected)	Resipod	Resipod (salt-affected)	FMW	FMW (salt-affected)	Wooden dowel	Proti-meter (probe)
0-25	Dry/damp	6-7	17-22	20-40	n/a	2000-250	20-35	25-60	10-45	7-25
25-50	Damp	7-8	22-30	40-50	1500-500	250-150	35-50	n/a	45-50	25-30
50-75	Moist	8-9	30-35	>50	500-300	n/a	>50	n/a	50-60	30-35
>75	Wet/ saturated	>9	>35		<300	n/a	>50	n/a	60-65	35-37

As shown in Table 7, knowledge of material types is very important for interpreting the output from different moisture measurement techniques.

1.5 Conclusions (Phase 1)

The methodology designed for this project, as evaluated in Phase 1 of the research, has enabled robust comparisons of the effectiveness of different moisture measurement techniques against absolute moisture contents (as monitored by gravimetry). Several non-invasive techniques were found to be highly effective on handmade brick, mortar and Portland limestone samples – notably CEM and Resipod, which provided reliable data across most of the range of moisture contents from dry to saturated. Some invasive techniques, notably TDR, the Historic England wooden dowel and the Protimeter with deep wall probe, were found to be very effective, too, as long as care was taken to install the probes correctly. Salinity was confirmed to have an important and predictable influence on selected non-invasive measurement methods (Resipod, Protimeter, CEM and FMW). Material characteristics were also found to be important. Each type of brick showed a slightly different relationship between moisture measurement technique readings and gravimetric moisture contents. These also differed from the relationships found for Portland limestone and lime mortar samples. Porosity played a big role in influencing the results, but mineralogy and other characteristics may also have affected them. The clear conclusion is that it is not advisable to directly compare meter readings from different building materials.

2. PHASE 2

2.1 Objectives
Further to the work undertaken in Phase 1, the objectives of Phase 2 were to:

- test the performance of a variety of non-invasive methods on a wider range of fresh and aged building materials during drying and wetting phases
- compare the performance of timber and ceramic dowels during drying tests
- explore the penetration depth of non-invasive methods on sandstone and limestone and the influence of metals during drying tests
- explore the use of microwave and radar techniques in a case study of moisture ingress in a brick historic house managed by English Heritage Trust

2.2 Materials and methods
Phase 2 of the project used seven non-invasive measurement devices and two types of dowels inserted into drilled holes in the laboratory, as well as ground-penetrating radar and a MOIST 350 B moisture meter with Endo probe (microwave) in the field. In the laboratory experiments, the values collected from each device were compared with the absolute moisture contents (expressed as % dry weight) obtained by gravimetry, following the same procedure used in Phase 1. Table 8 gives the details of each of the methods tested. The materials used are described in Table 9.

Table 8: Moisture measurement methods used in Phase 2

Mode	Name	Model/Mode	Manufacturer	Range of readings	Manufacturer's stated depth of penetration mm
Non-invasive methods	Pinless Moisture Meter (CEM)	DT-128 (capacitance)	Shenzen Everbest Machinery Industry Co. Ltd (China)	0–100 digits	20–40
	FMW	FMW-T (capacitance)	Brookhuis Micro-Electronics B.V (Netherlands)	0–60%	20–25
	GE Protimeter Surveymaster, Dual-Function Moisture Meter	'Measure' (M) mode (resistance)	Protimeter (USA)	6–90% WME (readings above 30% are relative)	12.7
		'Search' (S) mode (capacitance)		60–999 digits	19
	Resipod	(resistance)	Proceq (Switzerland)	0–1000 kΩcm	25 (based on pin spacing)
	MOIST350B Microwave Sensor	R1M	hf sensor (Germany)	0–4000 digits	20 – 30
		PM			90 – 110
		DM			200 – 300
	Tramex MRH III	Pin (Resistance)	Tramex (Ireland)	7–40% (Readings above 27% indicative)	Not stated
		Pinless (capacitance)		0–99 digits	25
	Extech MO297	Pin (resistance)	Extech by FLIR (USA)	13–99 %	Not stated
		Pinless (capacitance)		0–99.9 digits	19
	CX Concrete Explorer Radar with 1.6 antenna	High-resolution radar	Malå (Sweden)	-30000–30000, raw radar amplitudes	Near-surface with certain data handling/800 total
Invasive probes	Timber dowel with embedded electrodes	Made by Historic England, read using Tramex MRH III (resistance)	Historic England	7–40% (using TRAMEX MRH III)	N/A
	Ceramic dowel with embedded electrodes				N/A
	MOIST350B	Endo depth probe (microwave)	hf sensor, Germany	0–4000 digits	Incremental; probe marked with 50mm gradations up to 350mm

Table 9: Materials used in the laboratory tests

Material	Sample reference	Small samples, dimensions in mm
Portland Limestone (Coombefield Whitbed)	LPA	200 x 100 x 75
	LPB	201 x 10 x 75
	LPC	201 x 10 x 75
	LPD	84 x 70 x 124
	LPE	84 x 70 x 124
New handmade bricks (manufactured by H. G. Matthews)	NBA	220 x 105 x 67
	NBB	220 x 107 x 65
	NBC	220 x 107 x 65
Stoke Hall sandstone, see BRE (2000) for material data	SSA	200 x 100 x 75
	SSB	200 x 100 x 75
	SSC	200 x 102 x 73
	SSD	246 x 238 x 16
	SSE	246 x 238 x 16
	SSF	246 x 238 x 16
	SSG	246 x 238 x 18
Brick from Shrewsbury Flaxmill Maltings, Shropshire, *c* 1797 (supplied by Historic England)	DBA	235 x 100 x 98
	DBB	235 x 112 x 100
	DBC	235 x 115 x 95
Elm Park Limestone, see BRE (2000) for material data	EP	400 x 200 x 200
Clipsham Limestone, see BRE (2000) for material data	CL1–CL39	300 x 300 x 10
	CL 40	300 x 300 x 5

Phase 2 was divided into four main stages:

- Stage 1: Assessment of seven non-invasive moisture measurement devices on wetting and drying of four materials: Portland limestone, Stoke Hall sandstone, fresh bricks and weathered bricks
- Stage 2: Evaluation of timber and ceramic dowels: pilot study monitoring the drying of Portland limestone samples and a larger sample of Elm Park limestone, the latter simulating performance in a larger construction
- Stage 3: Quantification of the depth of penetration of non-invasive moisture measurement devices for Stoke Hall sandstone and Clipsham limestone
- Stage 4: Comparison of data from microwave sensors (surface contact and depth probes) with a high-resolution radar in a field study at the Orangery, Kenwood House, London.

Details of the samples and equipment used in each stage are presented in Table 10.

Table 10: The materials, samples and equipment used for each stage of Phase 2

Stage	Materials		Samples (replicates)	Moisture measurement equipment
Stage 1	Portland limestone		LPA LPB LPC	CEM FMW (10/20mm settings) Protimeter (resistance ['Measure'] and capacitance ['Search'] modes) MOIST 350 B (RM1 and DM sensors) (when available) Resipod Tramex (resistance [pin] and capacitance [pinless] modes) Extech MO297 (resistance [pin] and capacitance [pinless] modes)
	New brick		NBA NBB NBC	
	Stoke Hall sandstone		SSA SSB SSC	
	Shrewsbury Flaxmill Maltings brick		DBA DBB DBC	
Stage 2	Pilot study	Portland limestone	LPD LPE	Timber dowel Ceramic dowel
	Large block, to represent a masonry context	Elm Park limestone	EP	Timber dowel Ceramic dowel MOIST 350 B (R1M and DM sensors)
Stage 3	Stoke Hall sandstone		SSD SSE SSF SSG	Tramex (resistance [pin] and capacitance [pinless] modes) Extech MO297 (resistance [pin] and capacitance [pinless] modes)
	Clipsham limestone		CL1–40	MOIST 350 B (R1M and DM sensors) Tramex (resistance [pin] and capacitance [pinless] modes) Extech MO297 (resistance [pin] and capacitance [pinless] modes) Protimeter (resistance ['Measure'] and capacitance ['Search'] modes) CEM FMW (10 and 20mm settings)
Stage 4	18th-century brick walls		N/A	MOIST 350 B (R1M, PM, DM, and Endo sensors) High-resolution radar Timber dowels

2.3 Testing protocols

The experimental methodology in each stage is summarised below.

2.3.1 Stage 1: Assessment of seven non-invasive surface measurement devices on the drying of four materials

Drying tests

The experimental protocol developed in Phase 1 (as summarised in Fig 3) was followed in Stage 1 for the drying tests, with measurements being taken using all devices on three replicates of each material (Fig 9). Data for some devices on Portland limestone and the handmade new bricks had already been collected in Phase 1 and the measurements were not repeated here. Two experimental runs were carried out in order to provide some replication of results. The MOIST 350 B was only available for the second experimental run, and the FMW could not be used on the Shrewsbury Flaxmill Maltings brick because the surface was too rough.

Figure 9: Blocks in place for drying tests (four material types, three replicates).

Wetting tests

To investigate whether the moisture measurement devices behave differently under wetting and drying conditions, a method was developed to incrementally wet samples and compare data from each method with gravimetric measurements of water contents after each addition of water (Fig 10). The method involved applying a known amount of water to the top face of a block (10ml each application), then wrapping the block in cling film and leaving it in an environmental cabinet (Binder KBF 115) under constant conditions until the water diffused equally through the block. After that time, the block was weighed, and each moisture measurement device used. A similar protocol was developed by Orr *et al* (2018).

The test procedure involved the following steps:

1. Dry the samples in the oven at 70°C until constant weight is reached.
2. Use each moisture measurement device on the samples while they are still hot.
3. Use each moisture measurement device on the samples when the samples have cooled down to room temperature.
4. Add 10ml (or more, if the sample is very porous) of distilled water to the top of each sample surface (test surface) using a small hand-operated spray bottle. Allow water to spread across the whole surface and slowly penetrate the samples.
5. Wrap the samples in cling film and leave them in the environmental cabinet at 20°C, 75% relative humidity to allow the water to diffuse evenly throughout the samples.
6. After one to two days (depending on the quantity of water added), remove the samples from the environmental cabinet and take measurements on the samples in the following order: balance, CEM, FMW (10mm/20mm), Protimeter, MOIST 350 B, Resipod.
7. Repeat steps 4, 5 and 6 until water is unable to penetrate into the saturated samples and the test ends.

Fig 10: The surface 'wetting up' process in action on the sandstone samples. Measurements were taken on the top wetted surface.

2.3.2 Stage 2: Comparative assessment of timber (pine) and ceramic dowels

Two methods were used to compare the performance of timber (pine) and handmade ceramic dowels, both provided by Historic England. The use of timber dowels has an established history (English Heritage 2014, 301), and recently a ceramic alternative has been developed in-house. Both dowels have embedded electrodes that can be read using a handheld resistance-type moisture meter (in this case, the Tramex MRH III in pin mode). Initially, the tests were run on small blocks of Portland limestone to simulate drying from saturation, and then on a large block of Elm Park limestone to simulate drying after an episode of driving rain. Both dowels were placed in 7cm deep holes drilled into the samples, so that their tops were slightly recessed below the surface of the block.

Drying tests on Portland limestone

The test procedure involved the following steps:

1. Drill a hole in each sample for the dowels; blow the dust out of the holes using compressed air.
2. Insert the dowels and connect to the Tramex device.
3. Soak each sample in distilled water, leaving the top surfaces exposed above the water to avoid water getting into the holes (Fig 11).
4. Check the Tramex readings from time to time until the readings do not change and the samples are saturated.
5. Take the samples out of the water and wipe off water from all surfaces using a damp cloth.
6. Take a Tramex reading; weigh the sample with the dowel inside; remove the dowel and reweigh the sample; reinsert the dowel.
7. Leave the blocks to dry in the laboratory under ambient temperature and humidity conditions. Repeat steps 5 and 6 periodically until the readings reach a stable value.

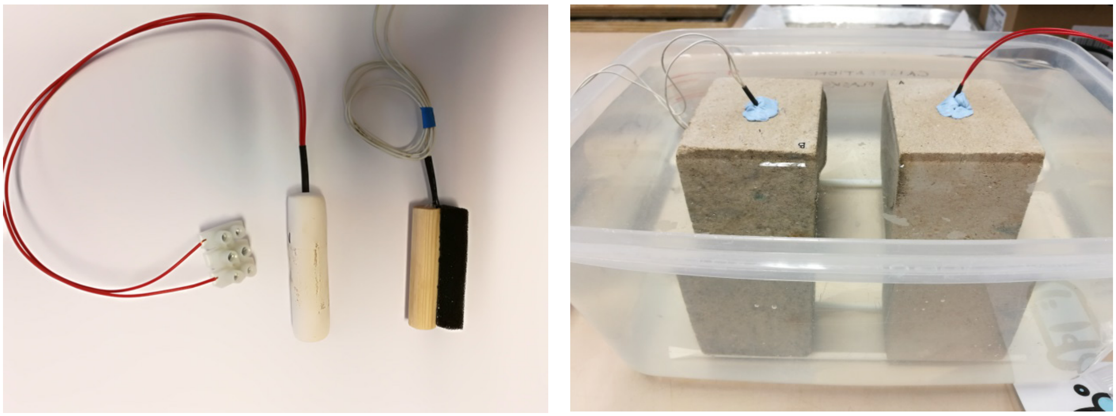


Fig 11: The ceramic and timber dowels (left) and the set-up for the pilot study of the performance of dowels on Portland limestone samples, during the saturation process (right).

Drying tests on larger Elm Park limestone block

In order to compare the response of the ceramic and wooden dowels to wetting through driving rain, a large block of Elm Park limestone (400 x 200 x 200mm) was mounted on a table. The block was sealed with cling film on all sides except the front vertical face, in which the dowels had been inserted. This face was then exposed to simulated driving rain (Fig 12). The block was sprayed with water twice: first using a hand-operated device, and second, intermittently over a three-hour period, using a portable pressurised spraying device (capable of producing 2–5 bar pressure). The first spray led to 250g of water being absorbed by the block (roughly simulating a medium driving rain event). This was followed by 12 days of drying. The second spray led to 410g of water being absorbed by the block (roughly simulating a higher intensity driving rain event), after which the drying of the block was monitored for 14 days. After each spray, the block (still mounted on the table) was dried with a damp cloth, to remove any surface moisture. It was then placed on a high capacity, high accuracy balance (Sartorius, capacity 600kg, minimum display 10g) and dried under ambient laboratory conditions. Sample drying was monitored over six weeks. Initially, measurements were taken every 30 minutes, then every hour, followed by increasingly long intervals as the drying rate slowed until constant weight was achieved.

At each measurement point, the protocol involved the following steps:

1. Take a weight measurement.
2. Use the Tramex to read each dowel.
3. Use the MOIST 350 B (using both R1M [near surface] and DM [11cm depth] sensor heads) to provide independent measurements of near-surface and deeper moisture contents at three points across the surface (*see* Fig 13).

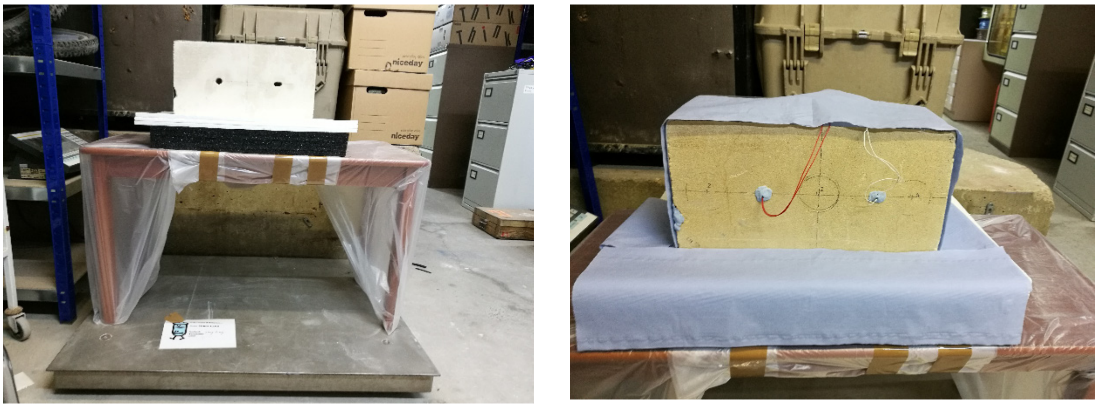


Fig 12: The set-up for the evaluation of the dowels in a larger limestone block (left). The block is lifted off the balance for two reasons: a) to enable ease of access to the dowels, and b) to reduce the potential effect of the metal sheet on the microwave meter readings (right).

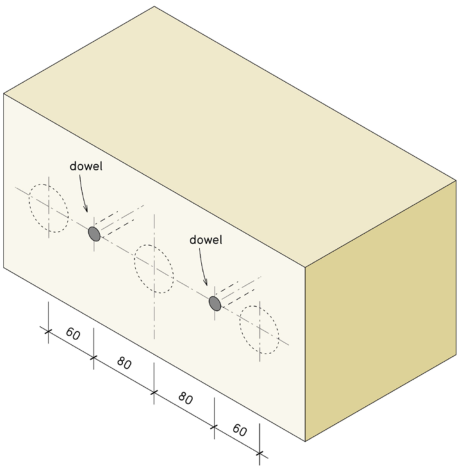


Fig 13: Location of microwave measurements (large dotted circles) in relation to the dowel locations within the Elm Park sample.

2.3.3 Stage 3: Quantification of the depth of penetration of devices

Pilot study on Stoke Hall sandstone

While manufacturers of many of the moisture measurement devices specify approximate penetration depths, these are likely to be dependent on material type and measurement conditions. In order to provide information about penetration depths on the porous building materials under study, a simple experiment was designed and trialled on Stoke Hall sandstone. Three 'slices' of Stoke Hall were cut to 246 x 238 x 16mm dimensions (SSD, SSE and SSF) and one was cut to 246 x 238 x 18mm (SSG). Three of the slices (16mm thick) were dried and the fourth (18mm thick) was saturated. The slices were then piled up in different combinations to see at what depths the moisture measurement devices could 'sense' the saturated slice.

In detail, the measurement protocol involved the following steps:

1. Soak block SSG in distilled water until saturated.
2. Leave blocks SSD, SSE and SSF to dry under ambient conditions.
3. Use Tramex and Extech (in pin and pinless modes) to measure blocks SSD, SSE and SSF. Take measurements parallel and perpendicular to bedding.
4. Dry SSD, SSE and SSF in the oven at 70°C, then remove and cool them to room temperature.
5. Use Tramex and Extech on all slices individually.
6. Assemble stacks of two, three and four slices with and without the saturated block (SSG). When using the saturated block, place it at the base of the stack.

Fig 14: The Stoke Hall sandstone samples used to investigate the depth penetration of the Tramex and the Extech, showing a stack of stone slices (left) and the templates for the meters (right).

Larger experiment with Clipsham limestone slices

The pilot experiments were designed to quantify the depth of detection of handheld moisture meters. The depth of detection is defined as the 'practical' detection limit of a meter: that is, the maximum depth from the surface of the area being surveyed at which the meter is sensitive to changes in moisture contents. Manufacturers typically provide guidelines on the depth of detection, but these values will be influenced by many factors, including material properties and moisture content. To contextualise these values, simple scenarios have been created incorporating layers of oven-dried and saturated samples.

The depth of detection for six non-invasive moisture meters was investigated: MOIST 350 B (with R1M and DM sensors); Tramex, Extech and Protimeter (all three using pin and pinless modes); FMW (10 and 20mm settings) and CEM.

A suite of 40 Clipsham limestone slices (39 slices at 300 x 300 x 10mm, and 1 slice at 300 x 300 x 5mm) was used for this experiment. Pilot experiments demonstrated that clamping the samples together (to reduce air spaces between them) was impractical and unnecessary once the pile contained more than two or three slices because the combined weight effectively removed air gaps. In order to evaluate the depth to which different moisture meters can sense moisture, four sets of data were collected (Fig 15):

Scenario A 'Dry individual': A reading on each 10mm thick slice of limestone (slices 1 to 39) was measured after drying.

Scenario B 'Dry set': Starting with the 5mm thick slice of limestone (slice 40), a stack of dried slices was created. Measurements were taken using each moisture meter.

Scenario C 'Wet 10mm': Starting with a wet 10mm thick slice of limestone, a stack was created by adding dry 10mm slices sequentially on top. Measurements were taken using each moisture meter.

Scenario D 'Wet 20mm': Starting with a wet 10mm thick slice of limestone, a stack was created by first adding a second wet 10mm slice and then adding dry 5mm and/or 10mm slices sequentially on top. Measurements were taken using each moisture meter.

The point of taking the 'dry individual' measurements was to look at any inter-slice variability in moisture meter readings. The 'dry set' measurements were designed to investigate if block thickness has an impact on the measurements (in the absence of added water). The 'wet 10mm' and 'wet 20mm' sets were used to monitor how deep the moisture meters could sense moisture – with one or two 10mm thick blocks saturated at the bottom of the stack designed to reproduce a thinner or thicker layer of deep-seated moisture within a stone block or masonry unit.

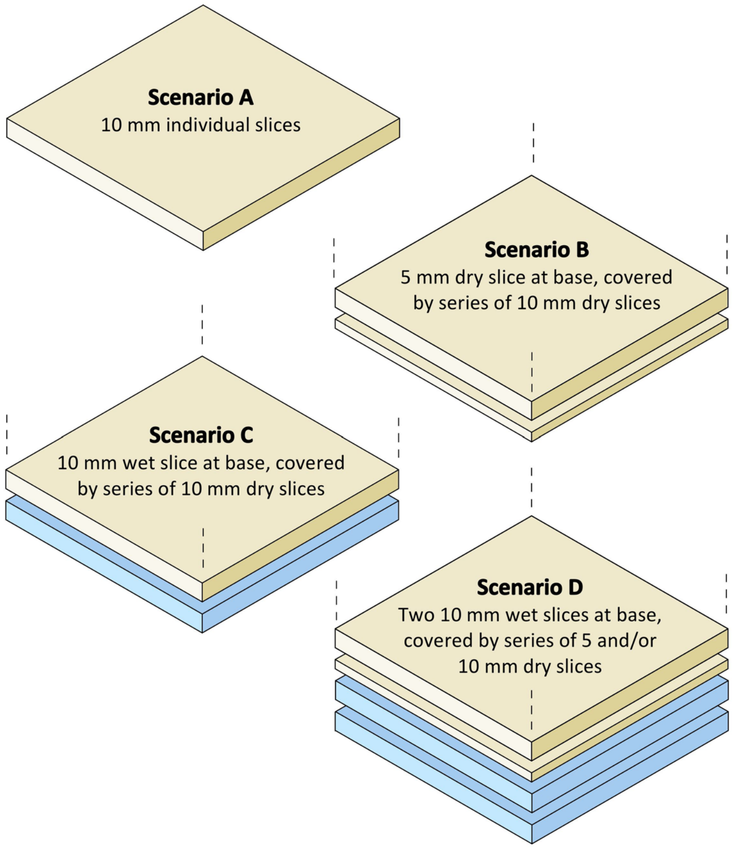


Fig 15: Illustrating the experimental design for collecting data on the 'moisture sensing' depths of handheld moisture meters on Clipsham limestone. Blue squares represent saturated slices; yellow squares represent oven-dried (but cooled). slices.

General protocol

1. A work area was prepared for the experiment, with a thick foam layer on the surface to minimise any interference. All meters were zeroed and calibrated prior to the test.
2. Measurement positions were marked at the centre of the slices with various templates so that non-circular probe heads could record moisture levels in two orientations perpendicular to one another (Fig 16).
3. The slices were numbered 1 to 40. Slices 1 to 39 were approximately 10mm thick and slice 40 was approximately 5mm thick. All slices were oven-dried at 70°C to constant mass, then the oven was turned off. When the internal temperature of the oven reached ambient conditions, the slices were reweighed. Additionally, slice 1 was painted with bitumen on all but one face. This was to limit moisture loss from all but the face on which measurements were taken or the face in contact with the adjacent slice.

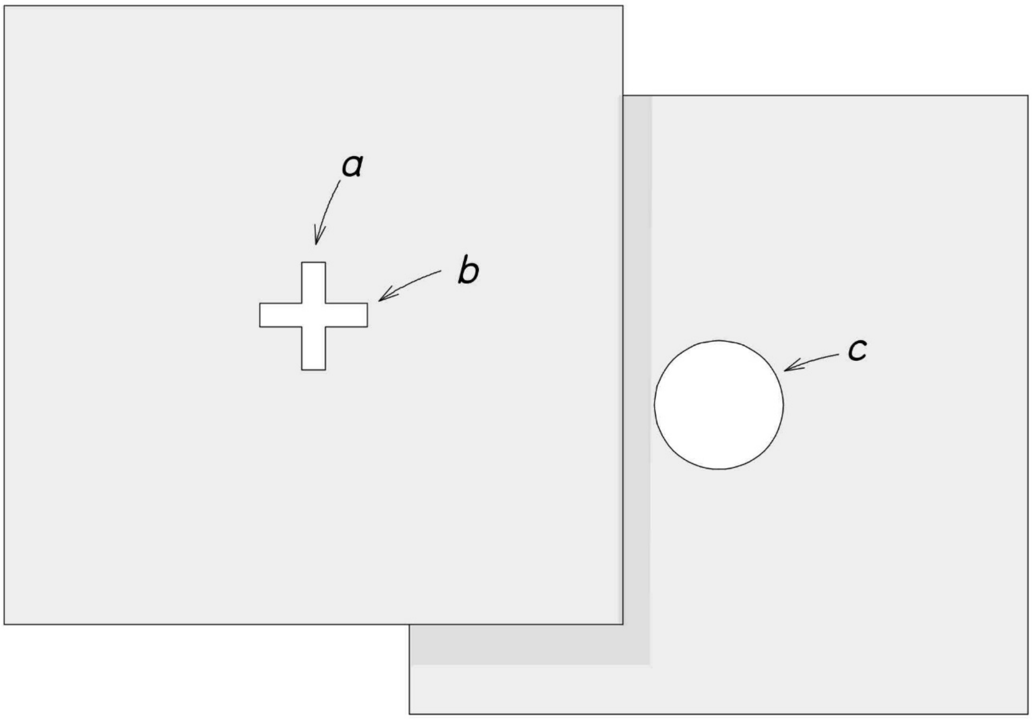


Fig 16: Measurement location on the Clipsham limestone samples. Two readings were taken for each meter, except the MOIST 350 B, in each scenario (in the centre in different orientations, 'a' and 'b'). For the MOIST 350 B, the reading was taken on the central circle ('c') but read three times per sensor head.

Protocol for Scenario A

1. Moisture level readings were taken with each device at the measurement locations specified in the general protocol for individual dry slices.

Protocol for Scenario B

1. Moisture level readings were taken with each device at the measurement locations specified in the general protocol for slice 1.
2. The slices were then stacked in numerical sequence on top of slice 1. The moisture levels were recorded with each device before the addition of each sequential slice. [1]
3. Step 2 was repeated until the thickness of the stack was equivalent to the maximum reported depth of detection of the device.
4. Moisture level readings were taken for each dry slice individually at the measurement locations specified in the general protocol.

[1] 1 Slice 40 is 5mm thick and was primarily used to evaluate surface/very shallow moisture meters, particularly for the Protimeter in 'measure' (resistance) mode. Therefore, when used, it was laid above slice 2 but under slice 3.

Protocol for Scenario C

1. Slice 1 was immersed in distilled water under ambient conditions until saturation.
2. Slice 1 was removed from immersion and its surface was dried gently using a damp cloth.
3. Moisture level readings were taken with each device at the measurement locations specified in the general protocol for slice 1.
4. Slice 2 was placed on top of slice 1.
5. Moisture level readings were recorded at the measurement locations specified in the general protocol with each device applied in turn to the top of the combined configuration of slices.
6. Step 5 was repeated while sequentially adding slices until the thickness of the stack was equivalent to the maximum reported depth of detection of the device.
7. For some devices, steps 4 to 6 were repeated, but with slice 40 (5mm thickness) in place of slice 2.

Note: If any slices within the stack had visibly absorbed water from slice 1, they were removed from the stack before repeating step 4.

Protocol for Scenario D

1. Slices 1 and 2 were immersed in distilled water under ambient conditions until saturation.
2. Slice 1 was removed from immersion and its surface was dried gently using a damp cloth.
3. Moisture level readings were taken with each device at the measurement locations specified in the general protocol for slice 1.
4. Slice 2 was removed from immersion and its surface was dried gently using a damp cloth.
5. Slice 2 was placed on top of slice 1.
6. Moisture level readings were recorded at the measurement locations specified in the general protocol with each device applied in turn to the top of the combined configuration of slices.
7. Step 6 was repeated while sequentially adding slices until the thickness of the stack was equivalent to the maximum reported depth of detection of the device.
8. For some devices, steps 5 to 7 were repeated, but with slice 40 (5mm thickness) in place of slice 2.

Note: If any slices within the stack had visibly absorbed water from slice 2, they were removed from the stack before repeating step 6.

Exploring the effect of the presence of metals on moisture meter readings

Metal will likely interfere with many moisture detection methods and give anomalously high readings. To investigate the effect of metal on the measurements of moisture meters, a modified form of the general protocol above was followed:

1. Moisture level readings were taken at the measurement locations specified in the general protocol on a 3mm thick steel plate.

2. Slice 1 was placed on top of the metal plate.
3. Moisture level readings were recorded at the measurement locations specified in the general protocol with each device applied in turn to the top of the combined configuration of slices.
4. Step 3 was repeated while sequentially adding slices until the thickness of the stack was equivalent to the maximum reported depth of detection of the device.
5. For some devices, steps 2 to 4 were repeated, but with slice 40 (5mm thickness) in place of slice 2.

2.3.4 Stage 4: The Orangery, Kenwood House field study

As part of the ongoing efforts to understand the ingress of moisture in the Orangery at Kenwood House, London, a short field measurement campaign was undertaken to assess the usefulness of non-invasive and invasive moisture measurements using a microwave device. Historic England had initiated timber dowel monitoring in 2016, using a grid of drill holes in the north-west corner. These holes provided a convenient place to test the microwave sensors.

Two measurement methods were used for eight existing drill holes (two on the west wall and six on the north wall): a microwave moisture device (MOIST 350 B with Endo probe) and timber dowels at three depths. (Data from the latter was collected by Historic England). The MOIST 350 B was also used across the same grid (500mm spacing) with three non-invasive sensor heads (R1M [near surface], DM [11cm depth] and PM [20–30cm depth]). A 4m linear transect was taken towards the base of the wall with a high-resolution radar device (Malå CX, 1.6 GHz antenna) to provide additional information on moisture contents and materials within the walls.

2.4 Results

2.4.1 Stage 1: Assessment of handheld meters

Drying tests

Seven non-invasive devices were used in the drying tests in Phase 2. The FMW, CEM, Protimeter (in resistance ['Measure'] and capacitance ['Search'] modes) and the Resipod had already been used on Portland limestone and new brick in Phase 1. They were only used in Phase 2 to monitor the drying of sandstone and aged brick samples. The Tramex and Extech MO297 devices were evaluated in this phase to monitor the drying of all four building materials, using both resistance (pin) and capacitance (pinless) modes. Capacitance mode data for both devices were only collected for Stoke Hall sandstone and Portland limestone. The MOIST 350 B with R1M head was only used on Stoke Hall sandstone and Shrewsbury Flaxmill Maltings brick. Results are summarised in Table 11 and presented graphically in Appendix B (with references to individual graphs given in the text below). The major findings are summarised as follows:

- The CEM (*see* Figs B.1 and B.6) and Resipod (*see* Figs B.4 and B.9) provided the best representation of moisture contents (in comparison with absolute measurements of moisture contents taken gravimetrically) over the widest range of moisture contents on both Stoke Hall sandstone and the old brick. As in Phase 1, the CEM performed less well for higher moisture contents, and the Resipod was unable to read very low moisture contents.

- The FMW (10) (*see* Figs B.5 and B.10) and MOIST 350 B (R1M, surface sensor, *see* Fig B.11) were both effective over part of the moisture range (lower moisture contents for FMW and higher moisture contents for MOIST 350 B).
- The Protimeter data were noisier than all other methods, in both resistance (*see* Figs B.2 and B.7) and capacitance (see Figs B.3 and B.8) modes. The device performed much less well than on the Portland limestone and new brick in Phase 1 (producing more variable data).
- The data from all devices were generally more variable for the old Shrewsbury Flaxmill Maltings bricks than for the new handmade bricks studied in Phase 1.
- The Tramex and Extech MO297 devices in resistance mode performed very similarly to the Protimeter in resistance mode on all four tested materials (cf Figs B.12 to B.15 with Figs B.2 and B.7). In capacitance mode, they appeared to perform less well than the Protimeter in capacitance mode (cf Figs B.16 and B.17 with Figs B.3 and B.8). The Extech data were particularly poor, reading only dry or wet.

From the results collected in both Phase 1 and Phase 2, we can rank the performance of the tested non-invasive moisture measurement methods under drying conditions on brick, Portland limestone and Stoke Hall sandstone, based on data in Tables 5 and 11.

Drying conditions – ranked performance

New brick (handmade by H G Matthews):
CEM > Resipod > Protimeter (capacitance mode) > FMW and T660 > Protimeter (resistance mode) > Extech MO297 (resistance mode) and Tramex (resistance mode) >> T610 and M50

Portland limestone:
Resipod > CEM > FMW > Tramex (resistance and capacitance modes) > Protimeter (resistance and capacitance modes) and T660 > Extech MO297 resistance and capacitance modes) > M50 >> T610

Stoke Hall sandstone:
Resipod > CEM and Protimeter (resistance and capacitance modes) > FMW and Tramex (resistance and capacitance modes) > Extech MO297 (resistance mode)

Old brick (Shrewsbury Flaxmill Maltings):
Resipod, CEM and Protimeter (capacitance mode) > Protimeter (resistance mode) > Tramex (resistance mode) and Extech MO297 (resistance mode)

Surface wetting tests

Five non-invasive devices that had performed well in the drying tests (FMW, CEM, Protimeter [resistance and capacitance modes], Resipod and MOIST 350 B [R1M]) were used to monitor the uptake of moisture by repeated surface wetting. The detailed datasets are presented graphically in Appendix B and the main findings are summarised in Table 11.

Where comparative data are available for drying and wetting, the devices generally performed in a similar way (the curves are similar shapes, showing similar effectiveness ranges). However, the datasets are quite different in detail, meaning that the devices gave different readings for the same absolute moisture contents under wetting and drying experimental conditions. Most devices gave more variable (noisier) results under the wetting experiment conditions in comparison to the drying experiment.

The CEM used on Portland limestone and new brick in the wetting experiment (see Fig B.18) gave quite good data, with many results similar to those obtained during the drying experiment (*see* Figs B.1 and B.6). However, the second run of the wetting experiment, using the CEM (*see* Fig B.24) on the same materials, gave rather different data. Similarly, the Resipod wetting experiments on Portland limestone and new brick (*see* Figs B.21 and B.27) gave variable results, and neither clearly followed the trends in the graph from drying experiments on the same materials (see Fig A.17, for example). Clear differences also emerged between wetting and drying experiment results for the Stoke Hall sandstone and Shrewsbury Flaxmill Maltings brick using the Resipod (cf Fig B.32 with Figs B.4 and B.9). The Protimeter (capacitance mode) provided some good data from the wetting experiment on Stoke Hall sandstone and Shrewsbury Flaxmill Maltings brick (see Fig B.31), which compares well with the drying experiment data from the same materials (*see* Figs B.3 and B.8).

Table 11: A summary of the regions of effective MC % and saturation % ranges for different devices

Material	Process	Device	Total MC % range	Effective MC % range of device	Effective saturation % range of Device
Portland limestone	Wetting up	FMW	0–6	0.5–5.5	8–92
		CEM		0–0.5, 4.5–6	0–8, 75–100
		Protimeter (resistance ['Measure'] mode)		4.5–6	75–100
		Protimeter (capacitance ['Search' mode)		3–6	50–100
		MOIST 350 B (R1M)		0–4	0–66
		Resipod		0.5–6	8–100
	Drying out	Tramex (resistance [pin] mode)		0–2	0–33
		Tramex (capacitance [pinless] mode)		0–3	0–50
		Extech MO297 (resistance)		0–1.5	0–25
		Extech MO297 (capacitance [pinless] mode)		0–1.5	0–25

Material	Process	Device	Total MC % range	Effective MC % range of device	Effective saturation % range of Device
New handmade bricks	Wetting up	FMW	0–12	No data	N/A
		CEM		0–3	0–25
		Protimeter (resistance [‘Measure’] mode)		8–10	66–83
		Protimeter (capacitance [‘Search’] mode)		8–11	66–92
		MOIST 350 B (R1M)		0–12	0–100
		Resipod		0–12	0–100
	Drying out	Tramex (resistance [pin] mode)		0–2	0–17
		Tramex (capacitance [pinless] mode)		No data	N/A
		Extech MO297 (resistance [pin] mode)		0–2	0–17
		Extech MO297 (capacitance [pinless] mode)		No data	N/A
Shrewsbury Flaxmill Maltings (old) brick	Wetting up	FMW	0–5	No data	N/A
		CEM		0–0.5	0–10
		Protimeter (resistance [‘Measure’] mode)		0–0.5	0–10
		Protimeter (capacitance [‘Search’] mode)		0–1	0–20
		Resipod		0–5	0–100
	Drying out	FMW		No data	N/A
		CEM		0–12	0–100
		Protimeter (resistance [‘Measure’] mode)		0–3, 4–12	0–25, 33–100
		Protimeter (capacitance [‘Search’] mode)		0–12	0–100
		MOIST 350 B (R1M)		No data	N/A
		Resipod		0–12	0–100
		Tramex (resistance [pin] mode)		2–7	17–58
		Tramex (capacitance [pinless] mode)		No data	N/A
		Extech MO297 (resistance [pin] mode)		2–7	17–58
		Extech MO297 (capacitance [pinless] mode)		No data	N/A

Material	Process	Device	Total MC % range	Effective MC % range of device	Effective saturation % range of Device
Stoke Hall sandstone	Wetting up	FMW	0–3	0–0.3	0–10
		CEM		0–0.5	0–16
		Protimeter (resistance [‘Measure’] mode)		0–1	0–33
		Protimeter (capacitance [‘Search’] mode)		0–1	0–33
		MOIST 350 B (R1M)		No data	N/A
		Resipod		0–1.5	0–50
	Drying out	FMW (10mm)		0–2	0–67
		CEM		0–2.5	0–83
		Protimeter (resistance [‘Measure’] mode)		0–2.5	0–83
		Protimeter (capacitance [‘Search’] mode)		0.5–3	17–100
		MOIST 350 B (R1M)		No data	N/A
		Resipod		0–3	0–100
		Tramex (resistance [pin] mode)		1–2.5	33–83
		Tramex (capacitance [pinless] mode)		1–2.5	33–83
		Extech MO297 (resistance [pin] mode)		1.5–2	50–67
		Extech MO297 (capacitance [pinless] mode)		None	N/A

The performance of each tested device that gave meaningful data is ranked from high to low for the wetting experiment, using data in Table 11.

Wetting conditions – ranked performance

New brick (handmade by H G Matthews):
Resipod and MOIST 350 B > CEM, Protimeter (capacitance and resistance modes)

Portland limestone:
Resipod > FMW and MOIST 350 B > Protimeter (capacitance mode) > Protimeter (resistance mode) and CEM

Stoke Hall sandstone:
Resipod > Protimeter (capacitance and resistance modes) > CEM > FMW

Old brick (Shrewsbury Flaxmill Maltings):
Resipod >> Protimeter (capacitance mode) > CEM and Protimeter (resistance mode)

2.4.2 Stage 2: Comparative evaluation of timber and ceramic dowels

Drying experiment using small Portland limestone blocks

The ceramic and timber dowels with embedded electrodes were used to monitor the drying out of two small Portland limestone samples, using the Tramex resistance mode to read the data from the embedded sensors. The datasets are graphed in Appendix B (*see* Fig B.33) and summarised in Table 12. The ceramic dowel was more sensitive to higher moisture contents, while the timber dowel was not able to strongly differentiate moisture contents greater than 2%.

Table 12: A summary of the regions of effective MC % and saturation % ranges of the timber and ceramic dowels in Portland limestone during drying tests

Material	Process	Device	Total MC % range	Effective MC % range of device	Effective saturation % range of device
Portland limestone	Drying out	Timber dowel with Tramex	0–6	0–1.5	0–25
		Ceramic dowel with Tramex	0–6	1.5–6	21–100

Drying experiment using larger Elm Park limestone block

During this drying experiment, both dowels were embedded in the same large Elm Park limestone block. Their measurements were compared with both the gravimetric readings and the R1M and DM sensors of the MOIST 350 B microwave moisture measurement device. The datasets are graphed in Figures 17 and 18.

The block experienced a two-phase drying curve, with more than 40% of the moisture within the block lost during the first four days, followed by a slower loss rate over the subsequent 38 days. Initially, both dowels responded slowly to this moisture loss, only sensing it 24 hours after the wetting event, and reaching the highest values after one week (just after the drying rate slowed). Figure 17 illustrates the comparative performance of the two dowels. Both show apparently puzzling results, with an approximately linear increase in values (as recorded by the Tramex) as the moisture contents (measured by weight) decline from 1 to 0.4%, followed by a quasi-linear decline in Tramex values between 0.4 and 0.2% moisture (gravimetric). The shapes of the curves are similar, but the wooden dowel appears to have greater sensitivity (that is, it reads over a wider range of values as recorded using the Tramex).

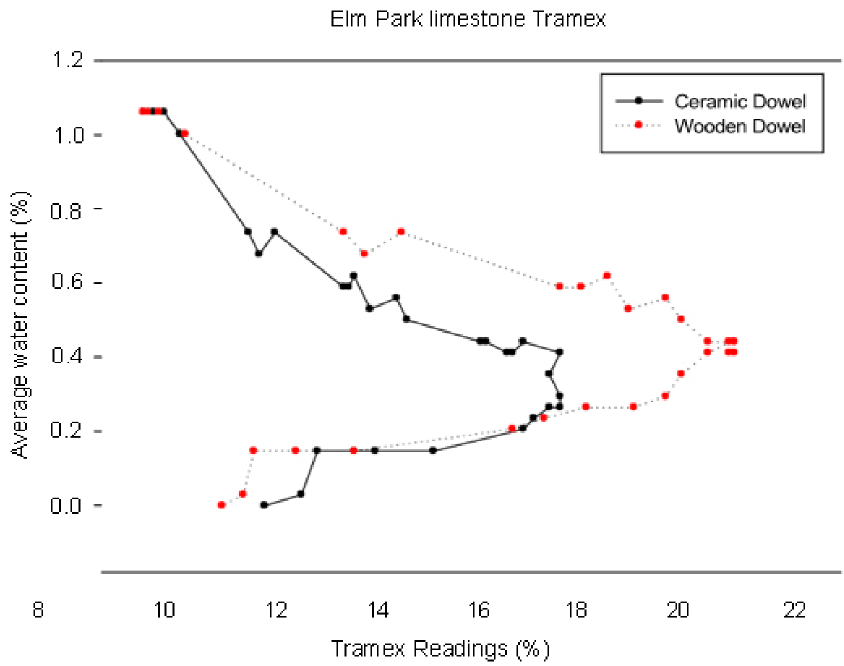


Fig 17: Readings (taken with the Tramex in resistance mode) from two types of embedded dowels in a large Elm Park sample exposed to an initial period of heavy wetting, compared with moisture content calculated from gravimetry. It should be noted that the gravimetric water contents are averaged over the entire sample, but that higher water contents would be expected near to the surface that was wetted at the start of the experiment. It is difficult, therefore, to provide meaningful absolute measurements of the water contents in the zone of the stone that the dowels are sensing.

The dowel readings show no clear relationship with the absolute moisture contents of the whole block (measured gravimetrically). This is perhaps unsurprising as dowels are generally used over relatively long periods (four weeks or so) to monitor equilibrium wall moisture levels, rather than to measure short-term responses to rainfall events. Similar lags have been noted by Baker *et al* (2007) and Ridout and McCaig (2016).

In contrast, both the near-surface (R1M) and deeper (DM) sensor heads on the MOIST 350 B show good congruence with the gravimetric data, peaking just after the simulated rainfall events and drying back to initial values after 5 to >14 days (depending on the initial volume of water applied). Replicate readings taken at three different measurement points for the R1M sensor head are very similar. Comparison of the R1M and DM sensor head values shows a more notable surface response in the hours after wetting than at depth, with no significant differences later in the drying cycles.

In contrast to the embedded dowels, both MOIST 350 B sensor heads reacted immediately to the water applied to the surface (Fig 18). When the sample was sprayed, both R1M and DM sensor heads, with depths of detection approximately 3cm and 11cm respectively, showed elevated readings with no difference between the two. Twenty-four hours after initial wetting, approximately 30% of the absorbed water had evaporated, and the two microwave meters responded accordingly. During this rapid evaporation phase, both sensor heads gave closely comparable readings, diverging slightly over the remainder of the drying cycle (with, as expected, the one that senses to 11cm depth recording higher values than the one that reads to 3cm depth). This might be attributed to the type of applicator used in the DM sensor, which is more sensitive to variation in the distribution of water within its field and immediate surroundings. Microwave meter readings can fluctuate in unexpected ways if there is 'layering' of moisture: that is, greater moisture at depth and a relatively dry surface.

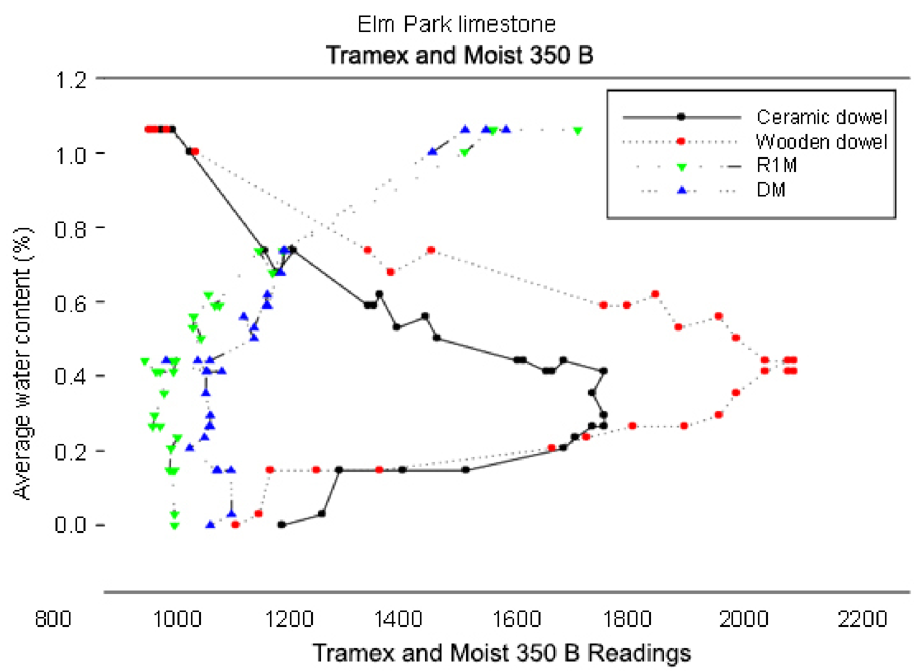


Fig 18: Readings from the dowels (measured with the Tramex) and microwave meter readings (R1M: surface, DM: mid-depth) compared to an average water content (%) calculated from gravimetry. The dowel readings have been multiplied by 100 to present them on the same plot as the microwave meter readings.

The results presented imply that both dowel types, read using the Tramex meter in resistance mode, gave a good picture of moisture levels in a stone block similar in dimensions to a masonry unit, once they had time to equilibrate with the surrounding material. The wooden dowel had slightly higher sensitivity, but the ceramic dowel gave well-correlated measurements. Use of non-invasive microwave sensor heads to monitor the initial phase of rapid drying is recommended from this experiment, as they provide reliable information during the first few days. The combination of the two techniques seems very promising. Further experiments on other materials would help evaluate the use of dowels and microwave sensors in tandem.

2.4.3 Stage 3: Depth penetration of handheld moisture meters

Experiment on Stoke Hall slices

The experiment to evaluate the depth penetration of handheld moisture meters was carried out on a set of slices of Stoke Hall sandstone, using the Extech MO927 and Tramex MRH III devices in resistance and capacitance modes. The main findings are summarised in Table 13 and reviewed in more detail below.

Table 13: Results of depth penetration experiment on Stoke Hall sandstone slices

Samples used	Condition	Stack depth (mm)	Extech M0297				Tramex MRH III			
			Resistance (0°)	Resistance (90°)	Capacitance (0°)	Capacitance (90°)	Resistance (0°)	Resistance (90°)	Capacitance (0°)	Capacitance (90°)
SSD	Naturally dried	16	N/A	N/A	53.7	63.1	N/A	N/A	38	37
SSE	Naturally dried	16	N/A	N/A	76.6	79.5	N/A	N/A	44	43
SSD +SSE	SSD on top, naturally dried	32	N/A	N/A	55.3	76.5	N/A	N/A	47	47
SSF	Naturally dried	16	N/A	N/A	71.6	71.2	N/A	N/A	39	38
SSD +SSE +SSF	SSD on top, naturally dried	48	N/A	N/A	68	72.1	N/A	N/A	50	48
SSD	Oven-dried	16	14.1	15.3	N/A	N/A	N/A	N/A	0	0
SSE	Oven-dried	16	14.5	14.5	N/A	N/A	8.6	No data	0	0
SSF	Oven-dried	16	16.1	16.3	N/A	N/A	7.6	7.8	0	0
SSG	Saturated	18	21.9	23.6	99.9	99.9	23.1	23.0	91	88
SSD +SSE	SSD on top, oven-dried	32	15.8	16.9	N/A	N/A	7.6	7.8	0	0
SSD +SSE +SSF	SSD on top, oven-dried	48	16.0	17.7	N/A	N/A	7.5	7.5	0	0
SS+SSE +SSF +SSG	SSD on top, oven-dried	66	17.1	18.3	N/A	N/A	N/A	N/A	0	0
SSD +SSE +SSG	SSD on top, oven-dried	50	17.6	18.9	N/A	N/A	N/A	N/A	0	0
SSD +SSG	SSD on top, oven-dried	34	17.6	20.6	N/A	N/A	N/A	N/A	0	0

Neither device was able to take measurements on the blocks dried under ambient conditions (singly or when stacked on top of each other) in resistance mode because the blocks were too dry. In capacitance mode, both devices could successfully measure the dry blocks (singly and in a stack), giving values of c 54–80 (Extech) and 37–50 (Tramex). When the blocks had been dried naturally, the Tramex in capacitance mode gave higher values for the two- and three-slice stacks in comparison with the single blocks. Both devices behaved very differently in capacitance mode when used on the oven-dried and saturated blocks. The Extech gave much lower values (14–18) for oven-dried versus naturally dried blocks, while the Tramex in capacitance mode read 0 for all oven-dried slices. For the two- and three-slice stacks of oven-dried sandstone, the Extech recorded very slightly higher values than on the same slices measured singly. For the oven-dried stacks and the two-, three- and four-slice stacks with oven-dried slices on top and the saturated one at the bottom, the Tramex gave 0 values (thus, it cannot sense the saturated slice). The Extech, however, gave slightly higher readings for the two- and three-slice stacks that included the saturated slice than for the stacks entirely composed of oven-dried slices. This provides some limited evidence that the Extech in capacitance mode can sense moisture >16mm below the surface of Stoke Hall sandstone under the conditions used in the experiment. According to the manufacturers' data sheets, penetration depths of 19mm for Extech MO297 and 30mm for Tramex MRH III are possible (but the results of this research suggest that these are likely to be very material-specific).

The tests in resistance mode on Stoke Hall sandstone were inconclusive, but there is no evidence that either device can sense deeper than 16mm in this stone type.

Experiment on Clipsham limestone slices

Detailed results from the four scenarios are presented in Appendix B in graphical form (*see* Figs B.34 to B.44). Table 14 summarises depth of detection of moisture in Clipsham limestone (grey-shaded column). The dominant factor in the depth of detection of a handheld meter is the method of measurement used, and this set of experiments has confirmed differences between capacitance, resistance and microwave-based methods.

Capacitance devices, that is the CEM and the FMW as well as the Protimeter, Extech and Tramex in capacitance mode, are shown in Table 14 to sense moisture to at least 20 mm beneath the surface of Clipsham limestone. Indeed, the Tramex in capacitance mode senses to 50mm. In contrast, the devices and modes based on resistivity (Protimeter, Extech and Tramex in resistance mode) are only sensitive to moisture contents in Clipsham limestone near the surface (<5mm). When readings were taken with 10mm of dry stone on top of two saturated slices, the readings of the meters in resistance mode were the same as for the individual dry and stacked dry slices. This means that the saturated layers were not affecting the meter readings. In some samples that had one saturated slice beneath one 10mm slice, no reading was produced. This supports the theory that these devices are not able to detect moisture beyond 5mm.

The evaluation of the MOIST 350 B microwave moisture measurement system demonstrates that the R1M (surface) sensor head detected moisture in Clipsham limestone comparably to the capacitance methods, that is to 20mm deep. This is close to the 30mmm depth penetration reported by the manufacturers. In contrast, the DM (mid-depth) sensor head is reported by the manufacturers to detect moisture up to 11cm deep. As the total thickness of the stack increased, the meter readings oscillated around a mean value (with decreasing amplitude) that was lower than the reading taken on a single saturated slice. Such behaviour is expected of microwave reflections (with unfocused applicators). For this reason, it is difficult to specify a depth of dry layer at which this sensor is no longer capable of detecting a saturated slice, as this must consider the frequency of oscillation. To determine a 'practical' depth of detection, a threshold of changes in the meter readings would need to be set.

There were no obvious differences in the depth-sensing ability of any of the devices between two perpendicular measurement directions (parallel and perpendicular to any bedding) on the stone slices.

Table 14: Depths to which the saturated slice could be detected within a stack of Clipsham limestone slices

Method	Meter	Operating mode	Measuring range	Meter head	Depth of detection		Condition of surface measured
					Reported by manufacturer	Measured in Clipsham Limestone	
Dielectric (capacitance)	CEM	N/A	0–100 digit	Ball head	20–40mm	20mm	Clean
	FMW-T	10mm 20 mm	0–60%*	8cm*25cm	25mm	20mm	Clean, flat and smooth
	Protimeter	Capacitance	0–999 digit	0.5cm* 4cm* 5cm of isosceles triangle	19mm	20mm	Clean and flat
	Tramex (MRH III)	Capacitance	0–99	30mm	Not provided	50mm	Clean and flat
	Extech (M0297)	Capacitance	0–99.9	19mm	Not provided	20mm	Clean and flat
Electrical resistivity	Protimeter	Resistance	6–99% WME	2 pins, 1.5cm apart	12.7mm	Surface	Clean
	Tramex (MRH III)	Resistance	7–40%*	Uncertain	Not provided	Surface	Clean
	Extech (M0297)	Resistance	13–99%	Uncertain	Not provided	Surface	Clean
Microwave	MOIST 350 B	R1M (surface sensor)	0–4000 digit	55mm diameter circle, Strayfield linear applicator (lines)	10–30mm (measuring volume some mm^3)	20mm	Clean and flat (surface roughness is important)
		DM (mid-depth sensor)		55mm diameter circle, Strayfield round applicator (symmetrical)	≤ 110mm (measuring volume up to $100cm^3$)	Uncertain	

Effect of the presence of metals on moisture meter readings
Appendix B contains graphical presentations of results (*see* Figs B.45 to B.47), obtained from Clipsham limestone. The data are summarised below.

For all devices, the measurements taken on the metal plate itself were at or very near to the maximum values, thus illustrating the important influence that metal bodies within walls can potentially have on moisture meter measurements. However, results indicated that the depth at which the metal object is found is crucial to the strength of its influence.

The capacitance meters (CEM, FWM 10/20, and the Extech, Tramex and Protimeter in capacitance mode) were all influenced by the presence of metal (which caused inflated readings) within the stacks up until the depths of detection identified in Table 14 (*see* Fig B.45). After the depth of detection, there was only slight variation in the meter readings, consistent across all meters. This suggests that this is caused by minor variations in the dielectric measurement due to the particular slice added to the stack for that measurement. In capacitance mode, the Tramex readings decreased linearly until 20mm, when they became constant at 0 (consistent with the meter readings on dry Clipsham limestone, *see* Fig B.46).

There was no observable influence on the readings from the resistance mode measurements (Extech, Protimeter and Tramex – data not graphed). Either a consistent reading was produced, with increasing thickness over a metal plate, or no reading was produced. This supports the very thin depths of detection discussed in Section 2.4.3.

The microwave-based readings demonstrated similar behaviour to the dielectric meters, in that they had high values when there was only a thin stack (or a single slice) above the metal plate. This was especially true of the R1M surface sensor, which had a similar depth of detection to the dielectric meters studied. In contrast, the DM mid-depth readings oscillated strongly up to 110mm (its reported depth of detection) and afterwards (see Fig B.47). These oscillations roughly correspond to the device's operating wavelength/4, which is approximately 3cm. This demonstrates that the DM readings can be heavily influenced by the presence of metal at depths beyond its reported depth of detection, which could result in artificially high values of reported moisture content if not placed in context.

2.4.4 Stage 4: Orangery, Kenwood House, field study
Stage 4 investigated the use of microwave moisture sensors and radar in the context of a historical construction, as part of the ongoing efforts to understand the ingress of moisture at the Orangery, Kenwood House. Water was thought to be coming into the building from the upper north-west corner, probably as a result of problems with drainage from the roof. On the advice of Historic England, holes had been drilled and timber dowel monitoring undertaken since 2016. The microwave data were collected on 4 October 2017 in humid conditions, with no rainfall.

Moisture at depth in drill holes
The MOIST 350 B was used with the Endo probe to record moisture contents at 50mm depth intervals down to 350mm, using the holes drilled for the dowel monitoring. Figure 19 shows the position of the dowel holes, and Figure 20 illustrates the depth profiles obtained (MI = moisture index value recorded on a scale of 0–4000). Holes W2 and N2, closest to the top of the NW corner of the building, indicate a significant build-up of moisture (near-saturation) in these regions, with saturation at depth also in N3. Hole N9, being the furthest from the presumed point of water ingress, shows lower MI values, especially at depth. This is in general agreement with the observations from the timber dowel measurements.

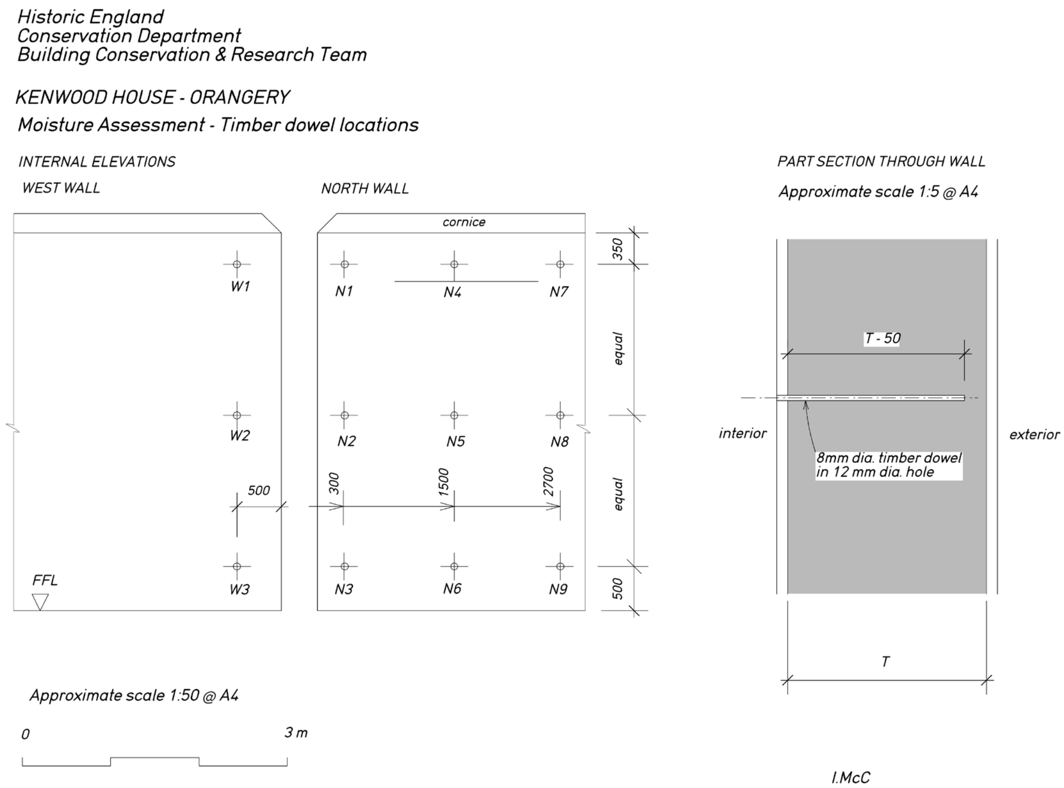


Fig 19: Guide to location and specifications for the drill holes created for moisture assessment in the Orangery, Kenwood House, which were also used for the microwave surveys (credit: Iain McCaig, Historic England).

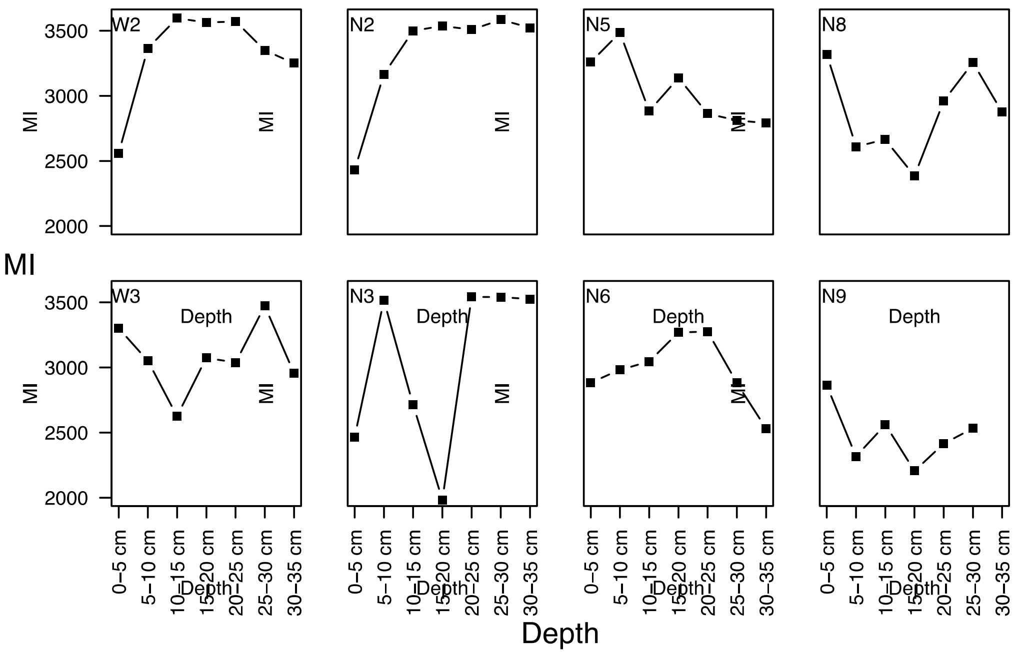


Fig 20: Moisture indices (MI) from the eight accessible drilled holes, showing variation with depth.

Surface sensor measurements

Grids of moisture measurements were also taken on the north wall at a spacing of 500mm using R1M, DM and PM non-invasive sensor heads, which should record moisture at 20 – 30mm, c 110mm and 200–300mm depths, respectively. The surface sensor (R1M) showed good agreement with the visible patterns of wetting (Fig 21).

The data from the non-invasive sensors showed drier conditions at the west end of the north wall than expected, based on the invasive measurements (Figs 22 and 23). It is suggested that a discrete area of impermeable plaster, which was found to have been applied to the west end of the wall, interfered with the sensors, because the values recorded were significantly lower than those obtained from similar building materials in the past. They were also lower than values taken from another part of the Orangery that was considered to be dry.

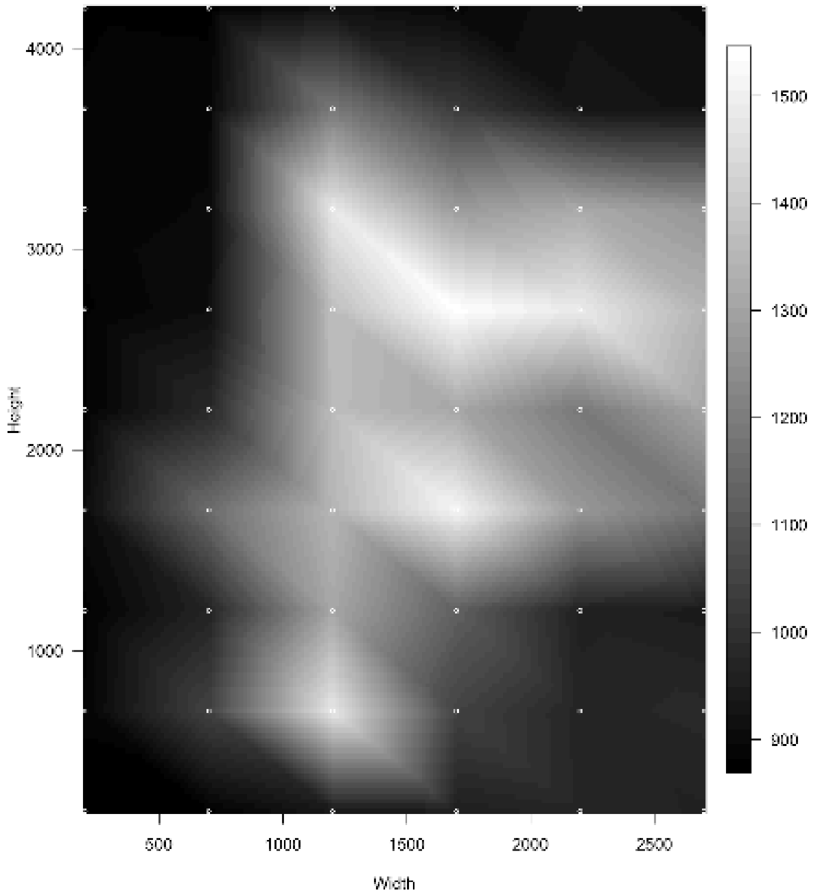


Fig 21: Moisture indices recorded with the R1M sensor, which should penetrate 0–2cm. Darker coloration = drier conditions. Measurements taken on another part of the Orangery suggest that dry values are likely to be approximately 880–900 for this sensor.

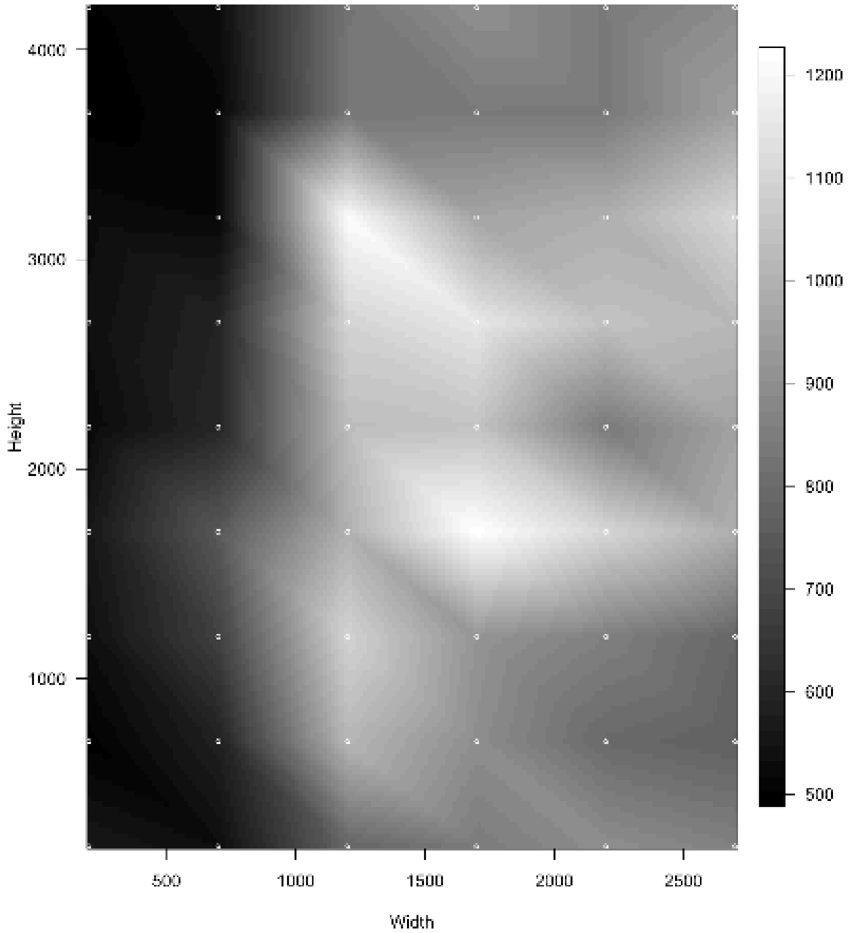


Fig 22: Moisture indices recorded with the DM sensor, which should penetrate 10cm. Darker coloration = drier conditions. Measurements taken on another part of the Orangery suggest that dry values are likely to be approximately 870 for this sensor.

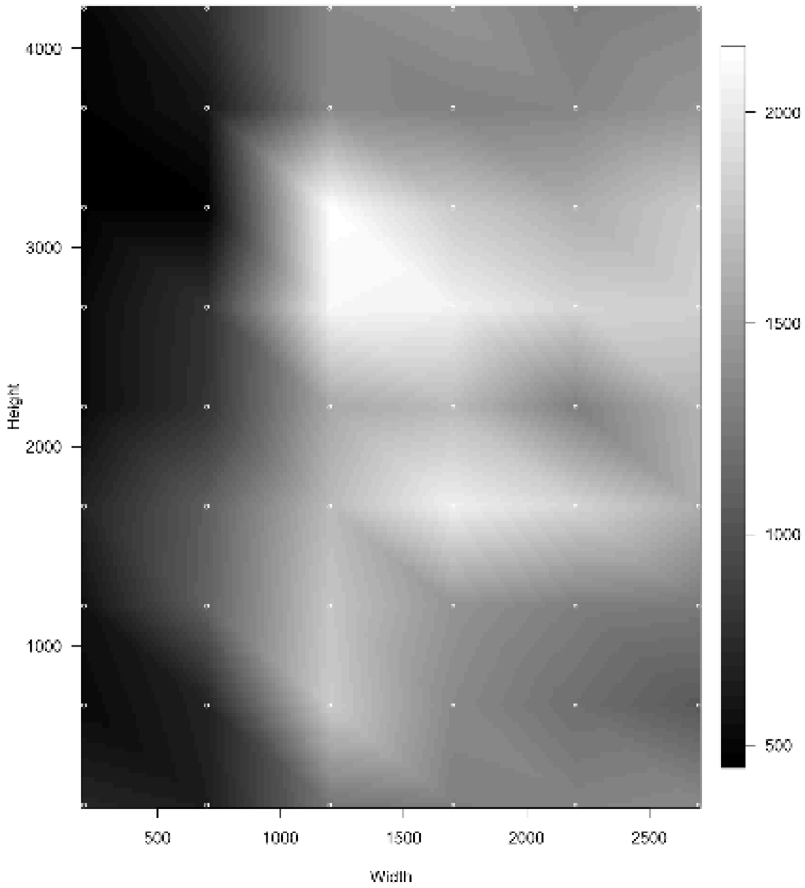


Fig 23: Moisture indices recorded with PM sensor, which generally penetrates 20–30cm. Darker coloration = drier conditions. Measurements taken on another part of the Orangery suggest that dry values are likely to be approximately 1300 for this sensor. The left portion of the grid has values significantly below likely dry values, suggesting interference from an unknown source.

Radar analysis

A high-frequency radar (Malå CX, 1.6 GHz antenna) was used to investigate both materials and moisture on the north wall. The radar analysis works by assessing various parameters of the 'first arrival', which is a complex combination of various reflections. A linear transect a few centimetres above the skirting showed a significant difference in the first metre of the transect relative to the north-west corner, further supporting the argument for the existence of a discrete area of impermeable plaster (Figs 24 and 25).

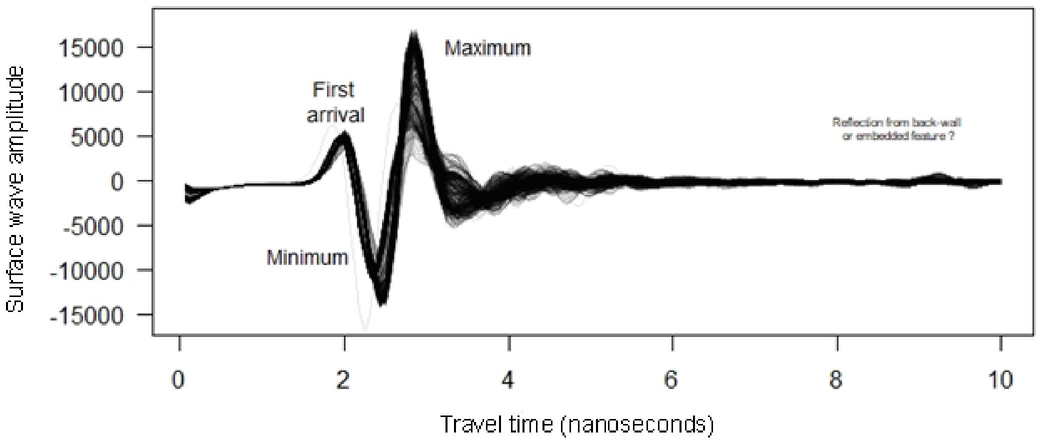


Fig 24: Travel time signals (measured at 5mm increments along the transect) for the Kenwood transect, showing the different features of the first arrival reflection. The travel time is indicative of depth, but has not been converted into distance (depth) units.

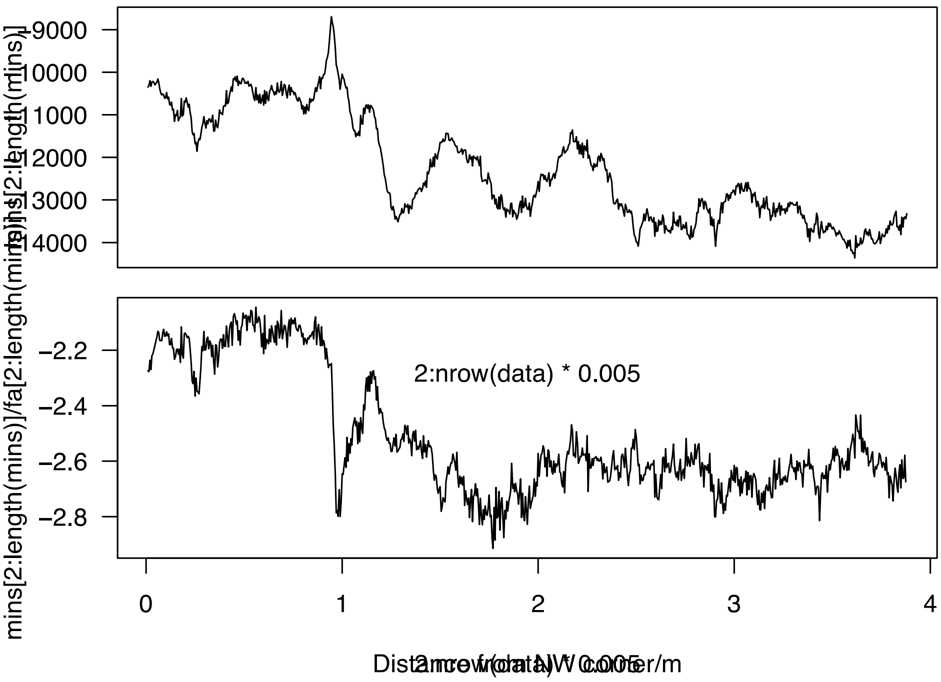


Fig 25: (Top) The intensity of the minimum of the surface reflection, showing a significant spike at the interface between the proposed location of the interface, between an impermeable and permeable render. (Bottom) The ratio of the minimum intensity of the surface reflection to the intensity of the first arrival of the surface reflection, showing a more pronounced difference in material characteristics between the first meter and the remaining length of the transect.

Relationship between the drill hole and surface sensor measurements
No significant relationship was found between the measurements at various depths of the drill holes and co-located measurements with the surface sensors. One important factor was that the mid-range (DM) and depth (PM) sensor readings (*see* Figs 22 and 23) were very highly correlated. This is because measurements were taken by both sensors cumulatively from the surface, and thus were influenced by the same moisture distributions. It is not, therefore, possible to compare the Endo probe readings with those taken by non-invasive sensors.

The microwave measurements taken with the Endo probe (*see* Fig 20) supported the theory that ingress was occurring through the upper corner and was likely due to drainage problems from the roof system. The surface reflections of radar further supported a significant difference of moisture and/or materials in the first metre of the north wall from the north-west corner. There was a notable difference in surface reflections of radar within the horizontal transect (*see* Fig 25) between the leftmost meter and the rest. This supports the hypothesis that there are different moisture levels and/or materials in the first metre of the north wall from the north- west corner.

2.5 Discussion of Phase 2 results

Questions posed by specific components of each stage of data collection are addressed in turn.

2.5.1 Stage 1: How does the performance of the non-invasive moisture measurement devices compare when used on fresh and aged materials?

Material characteristics, such as heterogeneity and surface roughness, were shown to affect the use of some non-invasive moisture measurement devices. All devices worked most effectively on flat clean surfaces and this was particularly important for those with large flat heads, such as the FMW. Surface roughness and friability were shown to be particularly influential on the performance of resistance (pin)-type meters (as seen in the variable data from aged Shrewsbury Flaxmill Maltings brick and Stoke Hall sandstone). In general, data collected from old weathered bricks were more variable than those obtained from new handmade bricks.

2.5.2 Stage 1: How does the performance of the non-invasive devices tested compare in the drying and surface wetting tests?

In some ways, the drying tests carried out in this research project provided analogous conditions to the drying of building materials after a period of flooding. In the test protocol, the samples were saturated to the extent they would be in ambient conditions in a relatively short time period. They were then monitored. The applicability of these results to post-flood conditions could be further enhanced by developing a test protocol that only allowed one-sided drying from saturation.

This would more closely resemble the post-flood drying of in situ building materials. Initial tests in Phase 1 where all faces but the top face were sealed showed little variation with the drying patterns from blocks with all unsealed faces.

In contrast, the wetting tests were designed to simulate the response of building materials to driving rain. More complex results were obtained from these tests, and clear differences were shown between how the non-invasive moisture measurement devices responded. The Resipod performed reasonably well on all materials, the Protimeter in capacitance mode gave comparable results between wetting and drying experiments for Stoke Hall sandstone and Shrewsbury Flaxmill Maltings brick over a narrower effective range, and the CEM generally performed less well under the wetting experiment conditions than during the drying experiments.

2.5.3 Stage 1: How does the performance of comparable devices vary?

Three similar resistance and capacitance mode moisture measurement devices were evaluated in this project (GE Protimeter Surveymaster, Tramex MRH III and Extech MO297). Differences were found in how they respond to drying and wetting under experimental conditions, with the Protimeter generally providing better results than the other two devices. All provided reliable data at lower levels of saturation, with higher 'noise' in the data as the blocks approached saturation.

2.5.4 Stage 2: How do ceramic dowels perform in comparison to wooden dowels when monitoring post flood-like drying conditions?

The ceramic dowel was found to have a larger effective measurement range than its timber counterpart for the tests in small Portland limestone blocks. It also gave a comparable performance under a more realistic simulation regime on a larger Elm Park limestone block. In carrying out these experiments, the following points were noted:

- There is a considerable lag in the response of dowels to changes in the moisture content of the surrounding material (not noticed using non-invasive microwave devices).
- The size of the interface between the dowel and the material, for example the ratio of the size of the drill hole to dowel diameter, can strongly influence the results.
- The results can be more accurate if readings are recorded when the dowels are left inside, rather than removed from the drill holes.

2.5.5 Stage 2: How do the dowels compare to non-destructive microwave moisture measurements in monitoring moisture contents of stone following a rain spell?

When used together on a large block under experimental conditions to simulate moisture dynamics after a rain spell, the MOIST 350 B sensors responded more quickly to applied simulated rainfall than either ceramic or wooden dowels, more effectively mirroring gravimetric readings. The two methods were found to be complementary. The microwave kit (MOIST 350 B with R1M and DM sensor heads) performed well over the rapid first phase of near-surface drying, whereas the dowels were more useful at recording the later slower phase of drying. It would be interesting to carry out further testing of the combined use of the two sets of equipment.

This test simulated the behaviour of dowels in the context of a larger construction, where most of the evaporation of near-surface moisture would be from the surface where the water first penetrated. This test highlighted the difficulty of using gravimetry to contextualise non-saturated moisture uptake within large blocks, as the moisture contents near the exposure surface are most likely much higher than the overall average of the entire block. Future work could attempt to use building simulation software, such as WUFI, to create an additional reference for moisture measurement tools.

2.5.6 Stage 3: How accurate are the reported penetration depths of moisture measurement devices?

An initial study using stacks of Stoke Hall sandstone slices illustrated the discrepancy between manufacturer-reported penetration depths and the reality of devices' capabilities on traditional building materials. It is likely that the maximum potential depth of penetration will be less than stated by device manufacturers for many traditional building materials that have lower densities than their contemporary counterparts. As the experiments in this report demonstrated, different materials with differing density, porosity and mineralogy give different readings with the same moisture device at the same level of saturation. Results can be compared within samples from the same material types, but not between different types of material without some sort of cross-calibration/standardisation exercise. Furthermore, many techniques (such as microwave and capacitance-based devices) experience a reduction in penetration depth with increasing moisture content, as the signal is more drastically attenuated (Orr *et al* 2020).

A larger evaluation, using Clipsham limestone slices assembled into stacks with one or two wet slices at the base, confirmed the depths at which different moisture meters can sense moisture to be <5mm for resistivity-based, two-pin meters and c 20 mm for most capacitance/dielectric method meters (except for the Tramex, which senses as far as 50mm inside the limestone stack). The MOIST 350 B with R1M sensor head detected moisture up to 20mm within the limestone stack, whereas the DM sensor head gave complex results. The experimental design used here appears to give reliable information about depth penetration, and we recommend that similar studies are done with other materials to confirm how applicable manufacturers' guidelines are to those materials.

2.5.7 Stage 3: What recommendations can be made about minimum sample thickness?

Our experience suggests that there are minimum sample thicknesses for consistent readings with these devices. In general, the minimum thickness should be at least the same or greater than the measured depth of detection. Thus, for most of the devices used here, the minimum thickness is 20mm (or 50mm, in the case of the Tramex in capacitance mode). More specifically, the data collected from the Clipsham limestone slices in Scenario B (stacked dry layers) can be used to propose minimum sample thicknesses. In Scenario B, when the readings become constant (lines on the graphs become flat) without notable fluctuations, it can be concluded that the sample is thick enough to provide a true measurement. For the CEM, this occurs around 40–60mm (*see* Fig B.34); for the Protimeter in capacitance mode, it is closer to 20mm (*see* Fig B.38).

2.5.8 Stage 3: How does the presence of metal affect various types of handheld moisture meters?

The experiment confirmed that metal influences all the handheld moisture meters tested. However, it can only influence readings significantly within the 'moisture sensing' depth range. Metal objects located deeper than the defined sensing depths presented in Table 13 should not interfere with moisture readings.

2.5.9 Stage 4: How do the results of dowel monitoring compare to using non-invasive and invasive microwave moisture sensors and high-resolution radar?

At the Orangery, Kenwood House, invasive and non-invasive microwave moisture monitoring methods were employed to identify the regions of higher moisture contents in an area already monitored using a grid of wooden dowels. Most importantly, this demonstrated the need to combine moisture measurement devices with surveying techniques, and to contextualise the readings within the building environment. Without the capability for gravimetric comparison, this stage of the project demonstrated the value of using a different part of the building of similar construction to create 'dry reference values' for moisture measurement devices. It also demonstrated the superiority of the invasive (Endo probe) microwave sensor.

The Endo probe, which gives localised measurements at 50mm increments into a drill hole, provided more reliable data than the non-invasive sensor heads. The latter were affected by the uneven dependence of microwave measurements on moisture through their entire field of penetration.

The use of high-resolution radar gave some evidence that treatments designed to reduce moisture ingress have caused problems. It is interesting, in this respect, that radar could detect different moisture and material properties between two adjacent plasters that were similar in appearance and thickness.

2.6 Conclusions (Phase 2)

Phase 2 of the project provided additional information on the performance of a range of non-invasive moisture measurement devices assessed in Phase 1 applied to materials exposed to wetting and drying conditions. In addition, two further non-invasive devices were assessed (Tramex MRH III and Extech MO297), along with two additional invasive devices (the ceramic dowel and MOIST 350 B Endo probe). Stoke Hall sandstone and old bricks from Shrewsbury Flaxmill Maltings were added to the range of materials studied.

As in Phase 1, the Resipod and CEM devices were found to be highly reliable for all material types tested under drying conditions. The Resipod also performed reasonably well under the experimental wetting conditions. In addition, information was collected on the effective measurement depth of the non-invasive measurement devices in Stoke Hall sandstone and Portland limestone. These results confirmed the influence of material properties on the depths to which moisture can be sensed. The ceramic dowel was found to perform comparably well against a wooden dowel of similar size. In a field test at the Orangery, Kenwood House, the MOIST 350 B with Endo probe was found to be a useful invasive method to sense moisture at different depths within pre-existing drill holes.

3. REFERENCES

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APPENDIX A: PHASE 1 RESULTS

Sample code	Sample dimensions (cm)	Material type	Notes
LPA	20 x 10 x 7.5	Portland limestone (Coombefield Whitbed)	Used in Stage 1
LPB	20 x 10 x 7.5	Portland limestone (Coombefield Whitbed)	Used in Stage 1
LPC	20 x 10 x 7.5	Portland limestone (Coombefield Whitbed)	Used in Stage 1
NBA	22 x 10.5 x 6.7	Handmade brick (H G Matthews)	Used in Stage 1
NBB	22 x 10.7 x 6.5	Handmade brick (H G Matthews)	Used in Stage 1
NBC	22 x 10.7 x 6.5	Handmade brick (H G Matthews)	Used in Stage 1
SSA	20 x 10 x 7.5	Stoke Hall sandstone	Used in Stage 1
SSB	20 x 10 x 7.5	Stoke Hall sandstone	Used in Stage 1
SSC	20 x 10.2 x 7.3	Stoke Hall sandstone	Used in Stage 1
DBA	23.5 x 10 x 9.8	Old brick from Shrewsbury Flaxmill Maltings	Used in Stage 1
DBB	23.5 x 11.2 x 10	Old brick from Shrewsbury Flaxmill Maltings	Used in Stage 1
DBC	23.5 x 11.5 x 9.5	Old brick from Shrewsbury Flaxmill Maltings	Used in Stage 1
LPD	12.4 x 8.4 x 7	Portland limestone (Coombefield Whitbed)	Used in Stage 2
LPE	12.3 x 8.4 x 7	Portland limestone (Coombefield Whitbed)	Used in Stage 2
EP	40 x 20 x 20	Elm Park limestone	Used in Stage 2
SSD	24.6 x 23.8 x 1.6	Stoke Hall sandstone	Used in Stage 3
SSE	24.6 x 23.8 x 1.6	Stoke Hall sandstone	Used in Stage 3
SSF	24.6 x 23.8 x 1.6	Stoke Hall sandstone	Used in Stage 3
SSG	24.6 x 23.8 x 1.8	Stoke Hall sandstone	Used in Stage 3
CL1-39	30 x 30 x 1	Clipsham limestone	39 identical samples Used in Stage 3
CL40	30 x 30 x 0.5	Clipsham limestone	Used in Stage 3

Pilot study results

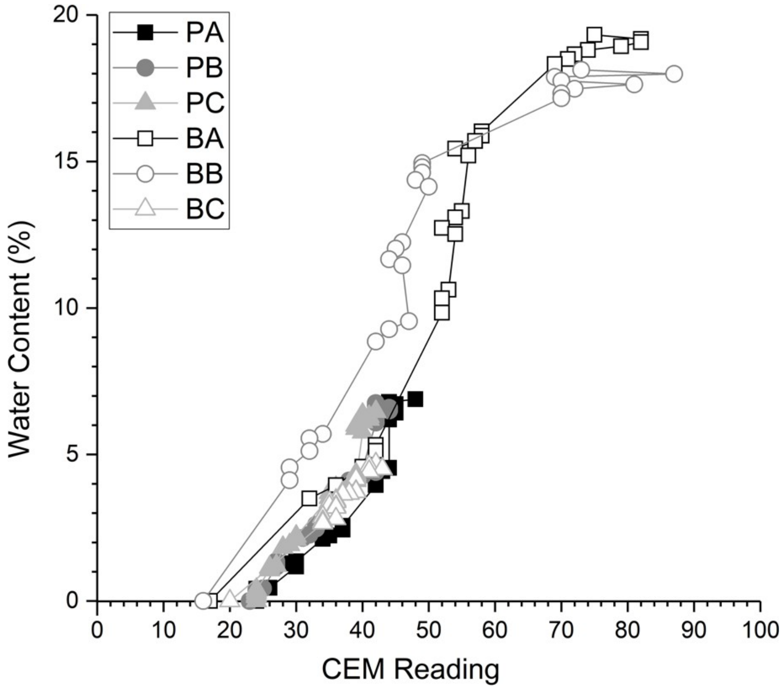


Fig A.1: CEM readings vs gravimetric measurements of water contents for large Portland limestone (PA, PB, PC) and large old (BA, BB) and new (BC) brick samples (drying test).

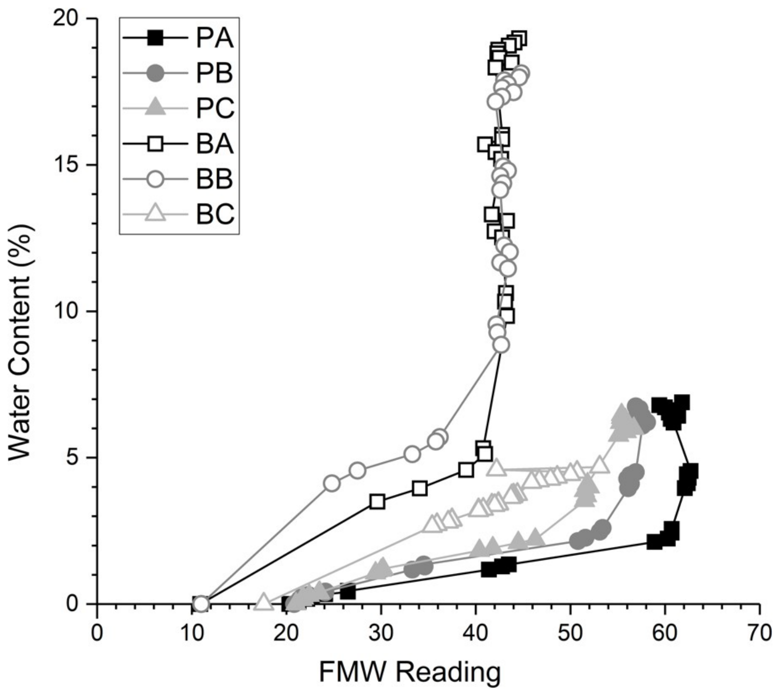


Fig A.2: FMW (10mm mode) readings vs gravimetric measurements of water contents for large Portland limestone (PA, PB, PC) and large old (BA, BB) and new (BC) brick samples (drying test).

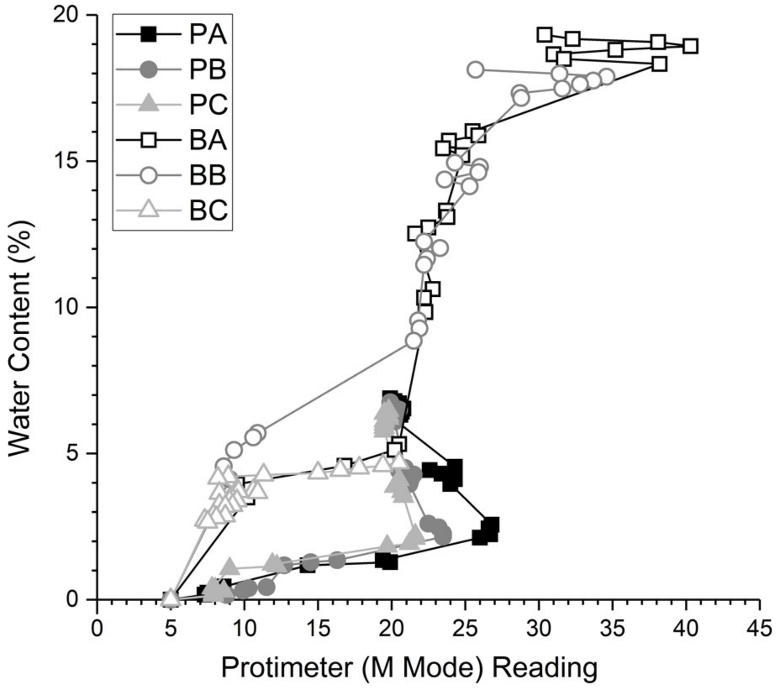


Fig A.3: Protimeter (resistance ['Measure'] mode) readings vs gravimetric measurements of water contents for large Portland limestone (PA, PB, PC) and large old (BA, BB) and new (BC) brick samples (drying test).

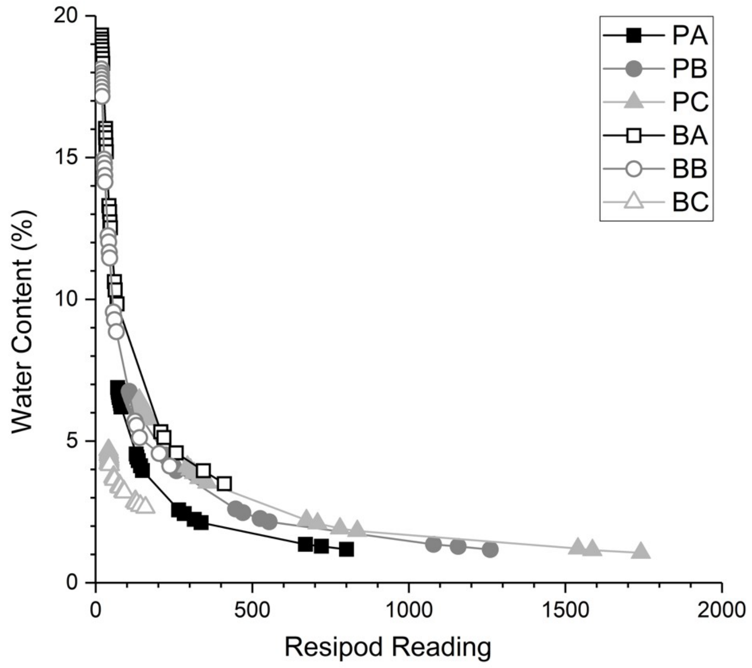


Fig A.4: Resipod readings vs gravimetric measurements of water contents for large Portland limestone (PA, PB, PC) and large old (BA, BB) and new (BC) brick samples (drying test).

Stage 1a results: large and small samples with evaporation from all faces

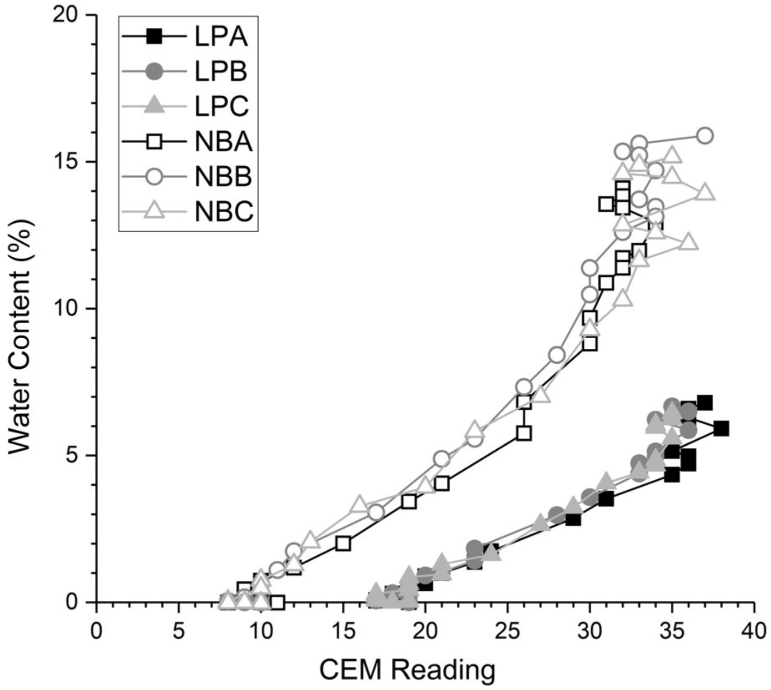


Fig A.5: CEM readings vs gravimetric measurements of water contents for large Portland limestone (LPA, LPB, LPC) and large handmade brick (NBA, NBB, NBC) samples (drying test).

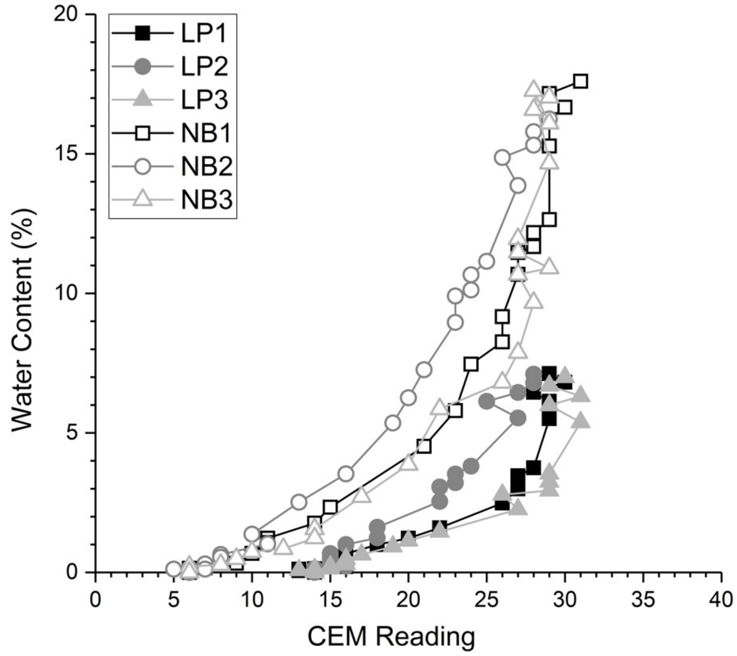


Fig A.6: CEM readings vs gravimetric measurements of water contents for small Portland limestone (LP1, LP2, LP3) and small handmade brick (NB1, NB2, NB3) samples (drying test).

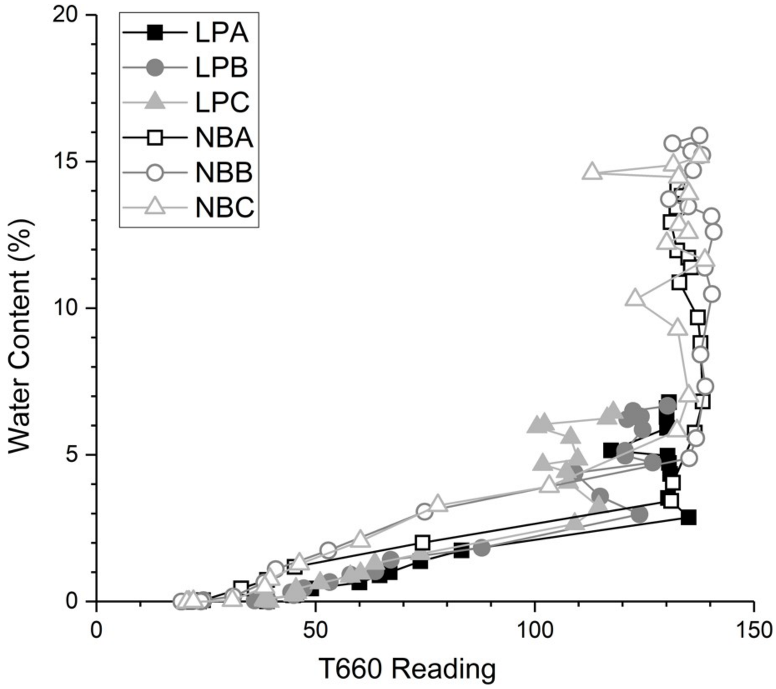


Fig A.7: T660 readings vs gravimetric measurements of water contents for large Portland limestone (LPA, LPB, LPC) and large handmade brick (NBA, NBB, NBC) samples (drying test).

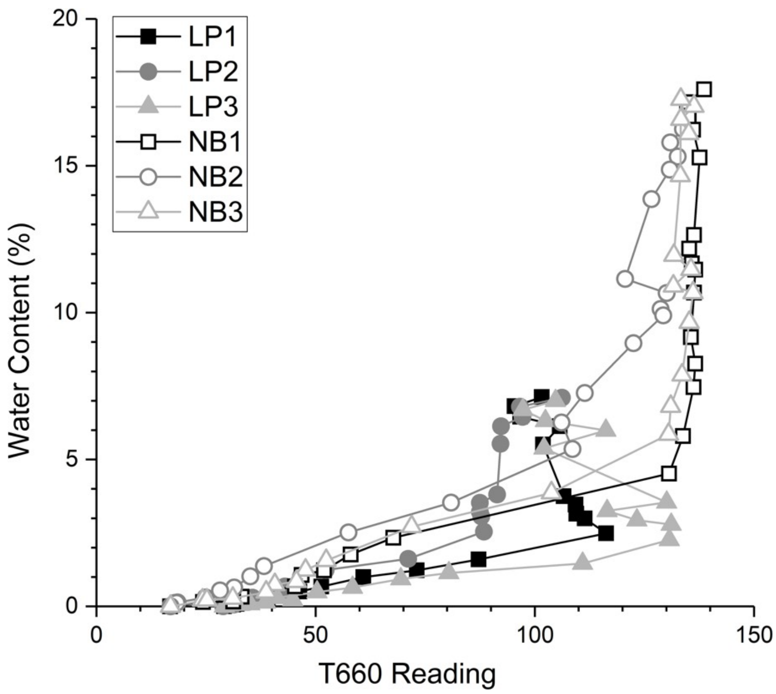


Fig A.8: T660 readings vs gravimetric measurements of water contents for small Portland limestone (LP1, LP2, LP3) and small handmade brick (NB1, NB2, NB3) samples (drying test).

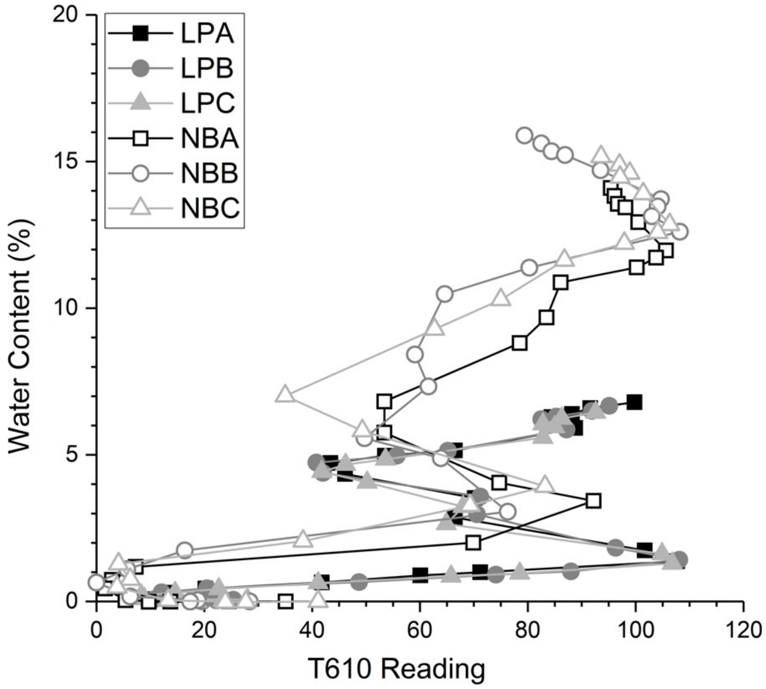


Fig A.9: T610 readings vs gravimetric measurements of water contents for large Portland limestone (LPA, LPB, LPC) and large handmade brick (NBA, NBB, NBC) samples (drying test).

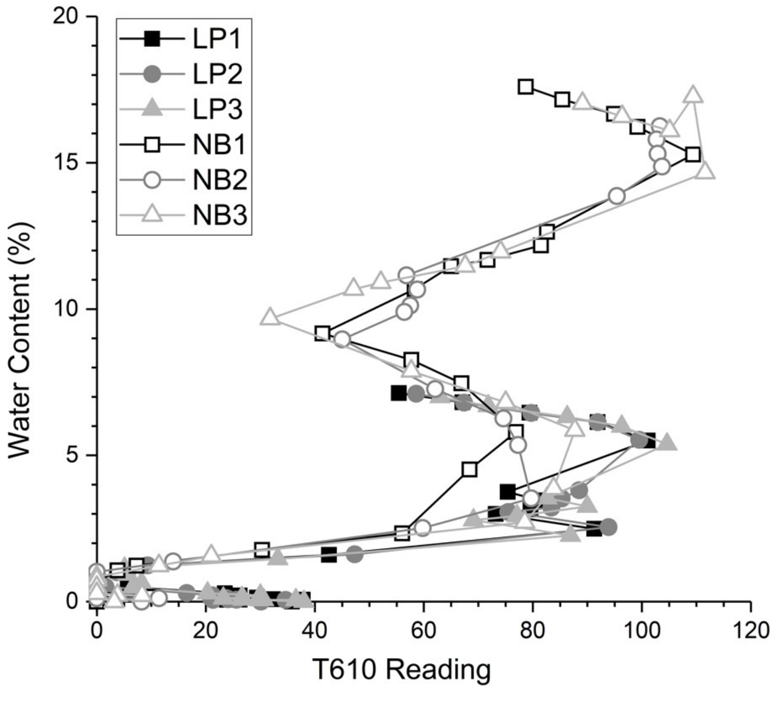


Fig A.10: T610 readings vs gravimetric measurements of water contents for small Portland limestone (LP1, LP2, LP3) and small handmade brick (NB1, NB2, NB3) samples (drying test).

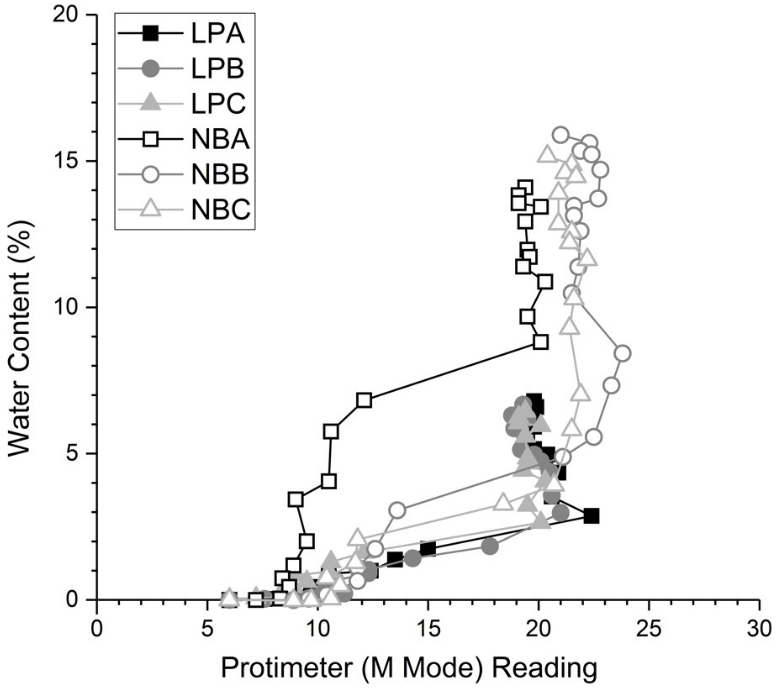


Fig A.11: Protimeter (resistance ['Measure'] mode) readings vs gravimetric measurements of water contents for large Portland limestone (LPA, LPB, LPC) and large handmade brick (NBA, NBB, NBC) samples (drying test).

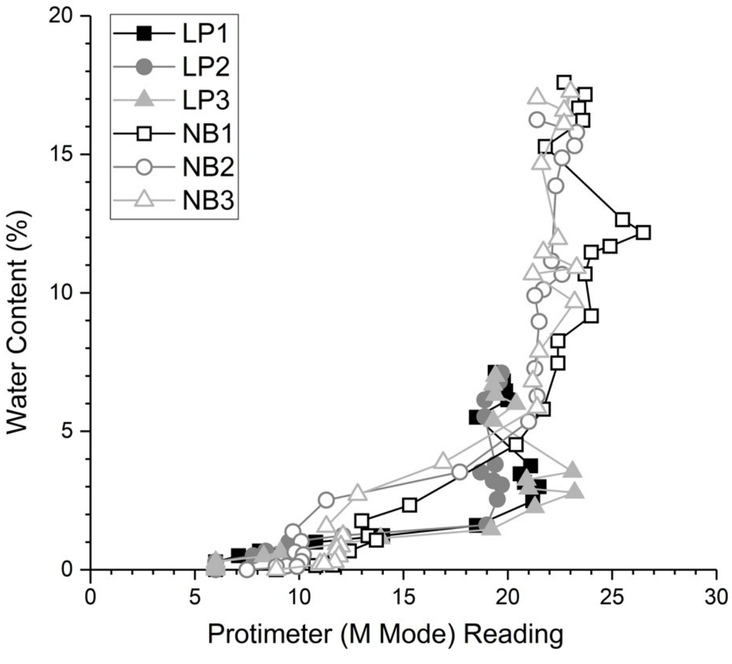


Fig A.12: Protimeter (resistance ['Measure'] mode) readings vs gravimetric measurements of water contents for small Portland limestone (LP1, LP2, LP3) and small handmade brick (NB1, NB2, NB3) samples (drying test).

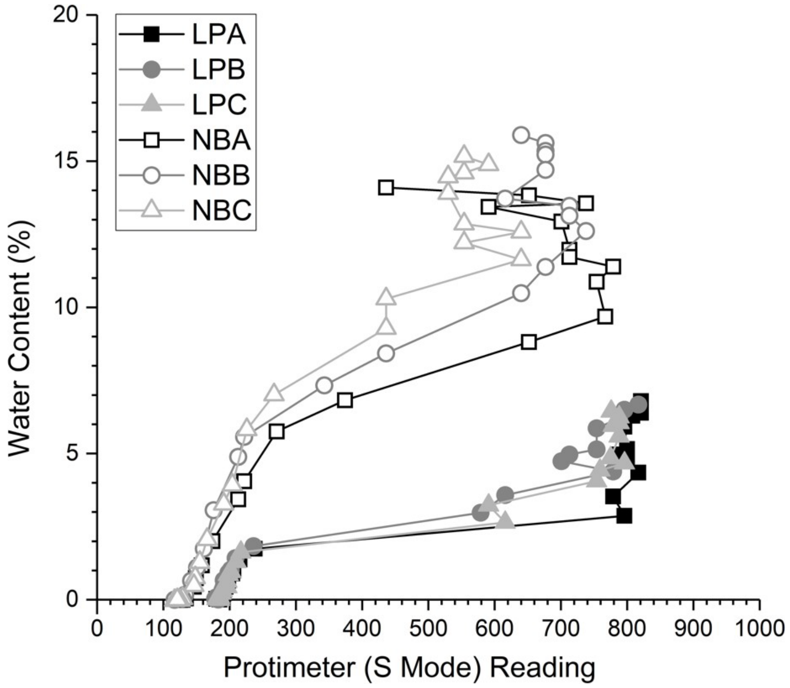


Fig A.13: Protimeter (capacitance ['Search'] mode) readings vs gravimetric measurements of water contents for large Portland limestone (LPA, LPB, LPC) and large handmade brick (NBA, NBB, NBC) samples (drying test).

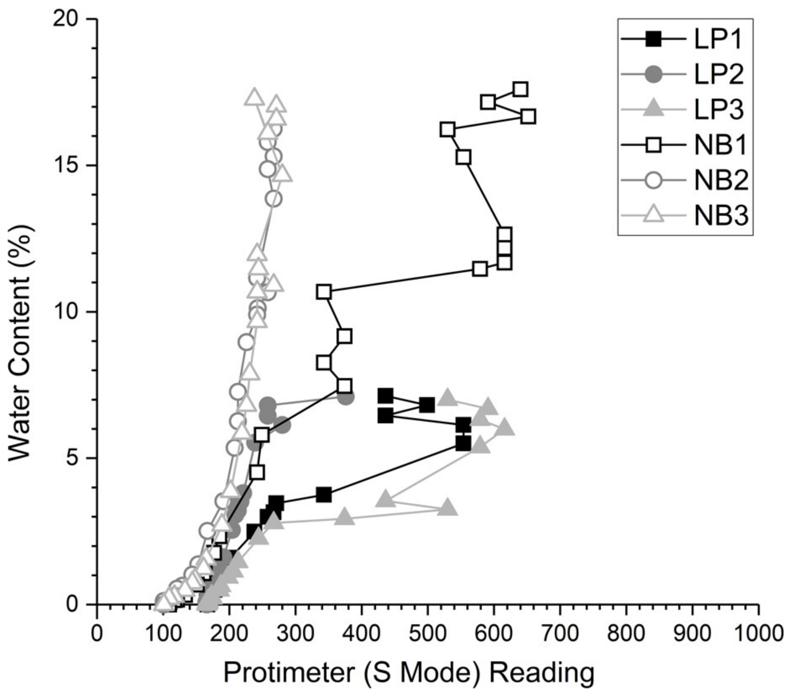


Fig A.14: Protimeter (capacitance ['Search'] mode) readings vs gravimetric measurements of water contents for small Portland limestone (LP1, LP2, LP3) and small handmade brick (NB1, NB2, NB3) samples (drying test).

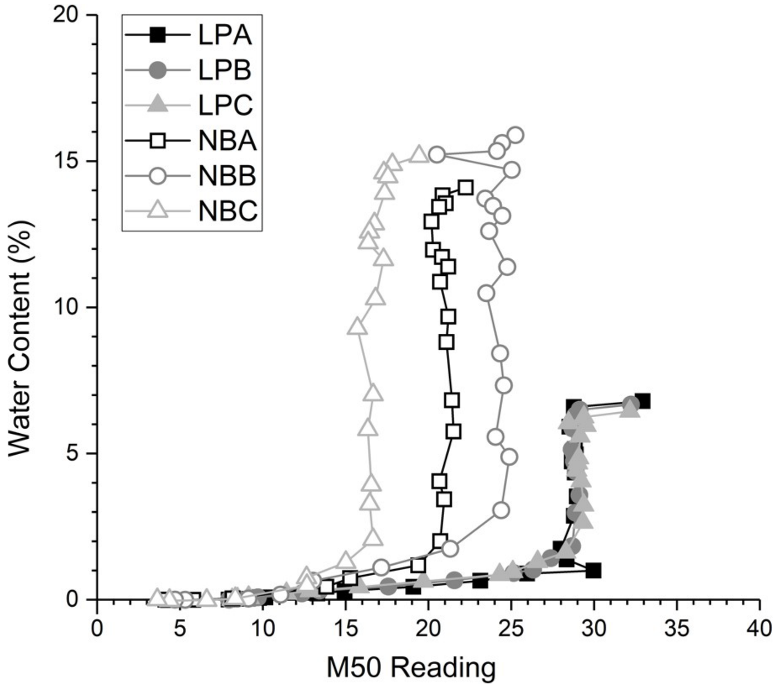


Fig A.15: M50 readings vs gravimetric measurements of water contents for large Portland limestone (LPA, LPB, LPC) and large handmade brick (NBA, NBB, NBC) samples (drying test).

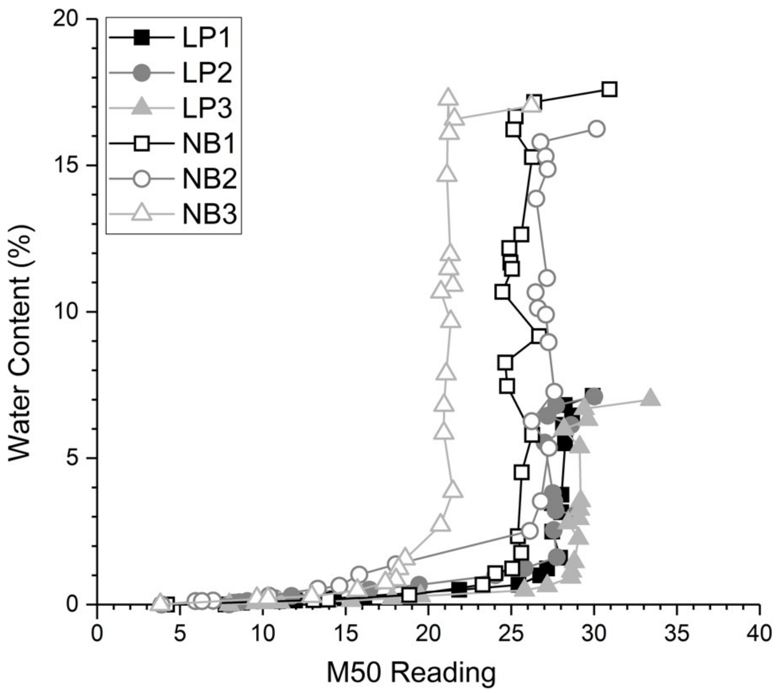


Fig A.16: M50 readings vs gravimetric measurements of water contents for small Portland limestone (LP1, LP2, LP3) and small handmade brick (NB1, NB2, NB3) samples (drying test).

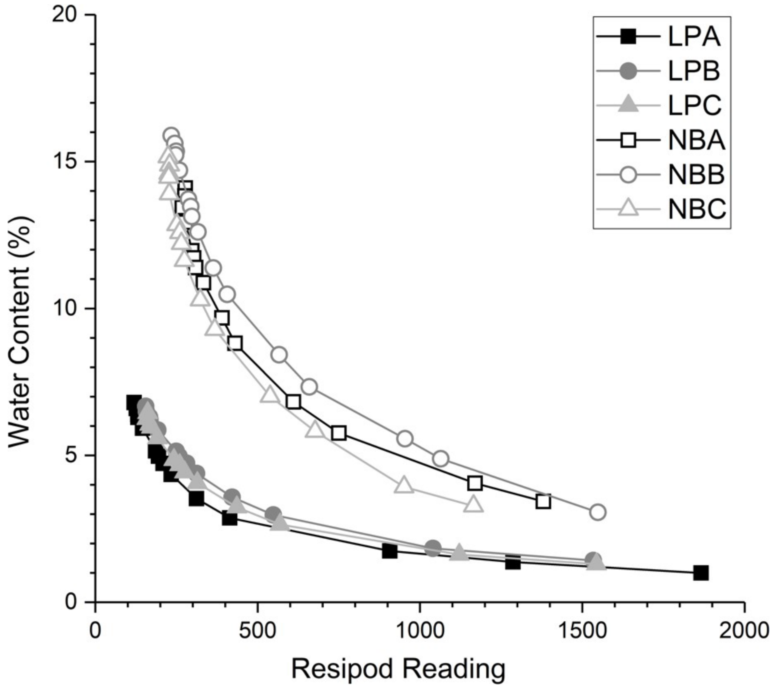


Fig A.17: Resipod vs gravimetric measurements of water contents for large Portland limestone (LPA, LPB, LPC) and large handmade brick (NBA, NBB, NBC) samples (drying test).

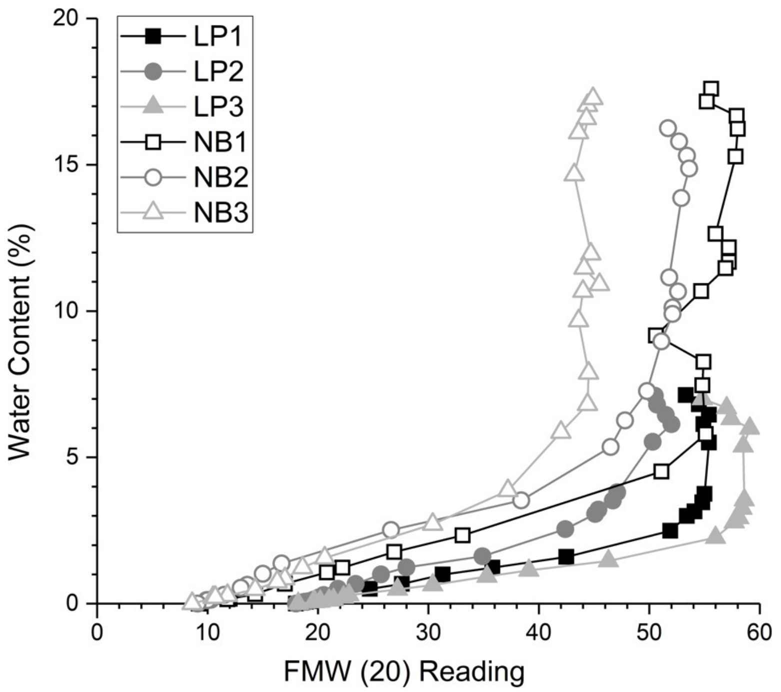


Fig A.18: FMW (20mm mode) readings vs gravimetric measurements of water contents for small Portland limestone (LP1, LP2, LP3) and small handmade brick (NB1, NB2, NB3) samples (drying test).

Stage 1b results: Samples with only one face exposed (others sealed)

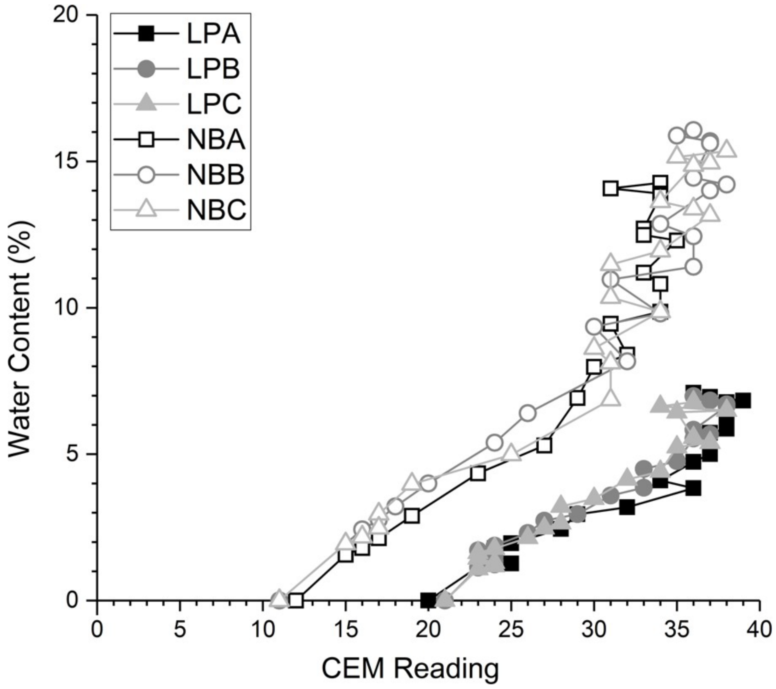


Fig A.19: CEM readings vs gravimetric measurements of water contents for large Portland limestone (LPA, LPB, LPC) and large handmade brick (NBA, NBB, NBC) sample with all but one face sealed (drying test).

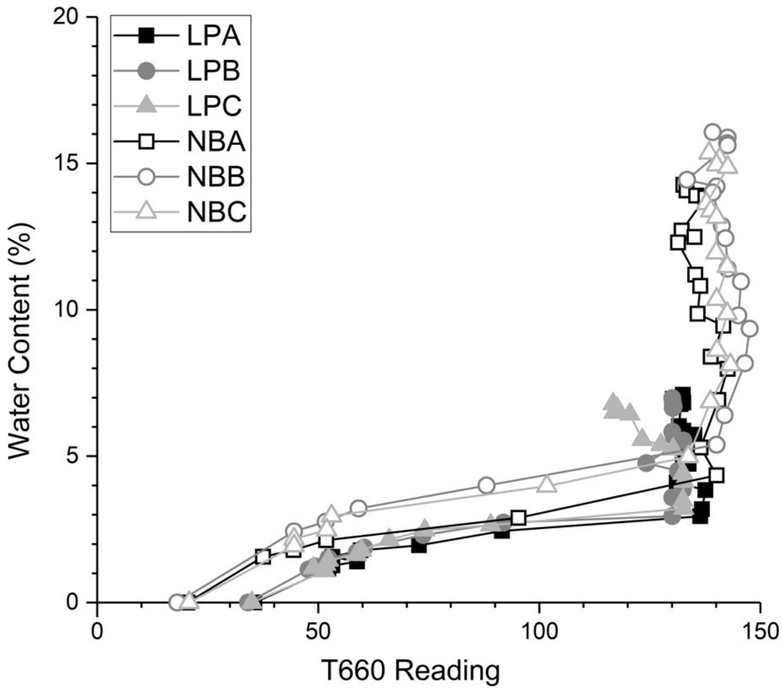


Fig A.20: T660 readings vs gravimetric measurements of water contents for large Portland limestone (LPA, LPB, LPC) and large handmade brick (NBA, NBB, NBC) sample with all but one face sealed (drying test).

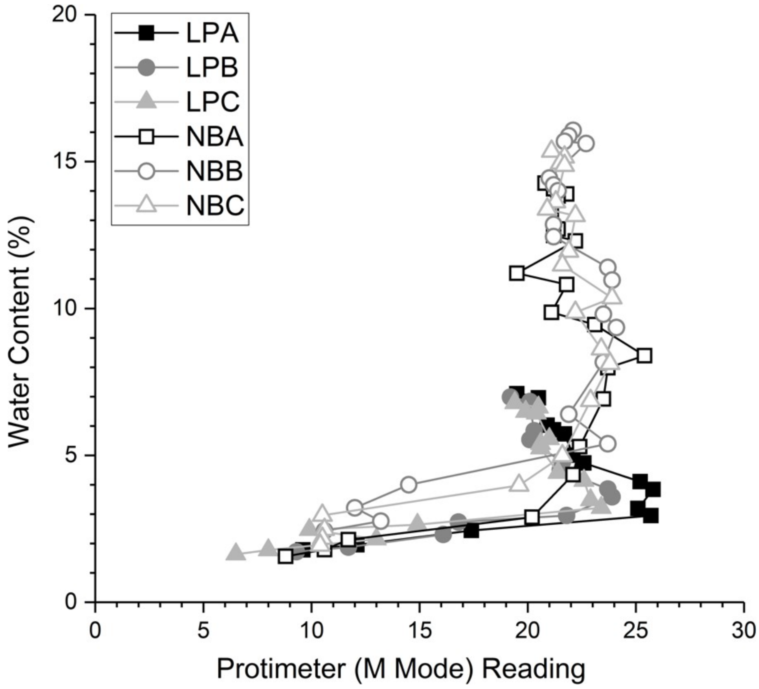


Fig A.21: Protimeter (resistance ['Measure'] mode) readings vs gravimetric measurements of water contents for large Portland limestone (LPA, LPB, LPC) and large handmade brick (NBA, NBB, NBC) sample with all but one face sealed (drying test).

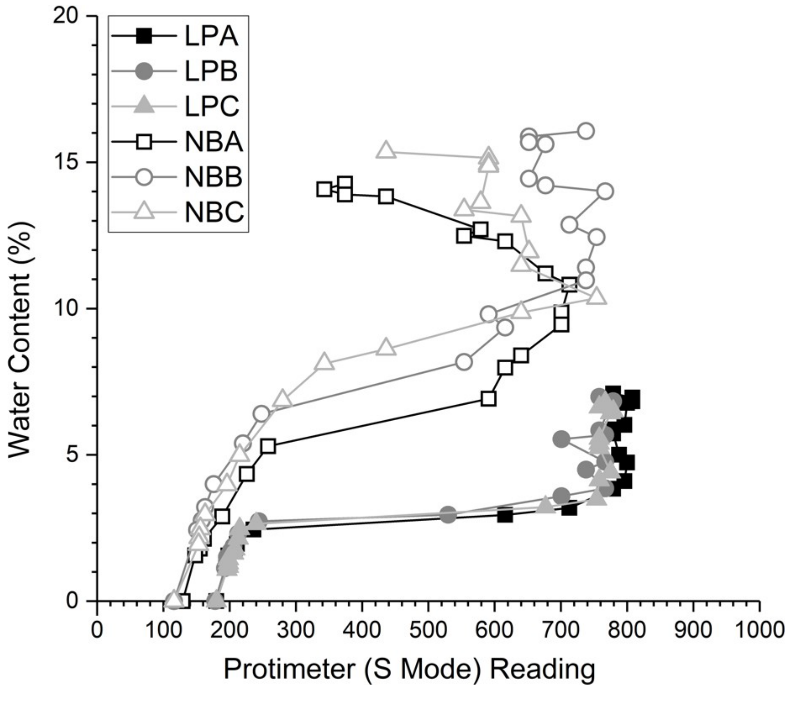


Fig A.22: Protimeter (capacitance ['Search'] mode) readings vs gravimetric measurements of water contents for large Portland limestone (LPA, LPB, LPC) and large handmade brick (NBA, NBB, NBC) sample with all but one face sealed (drying test).

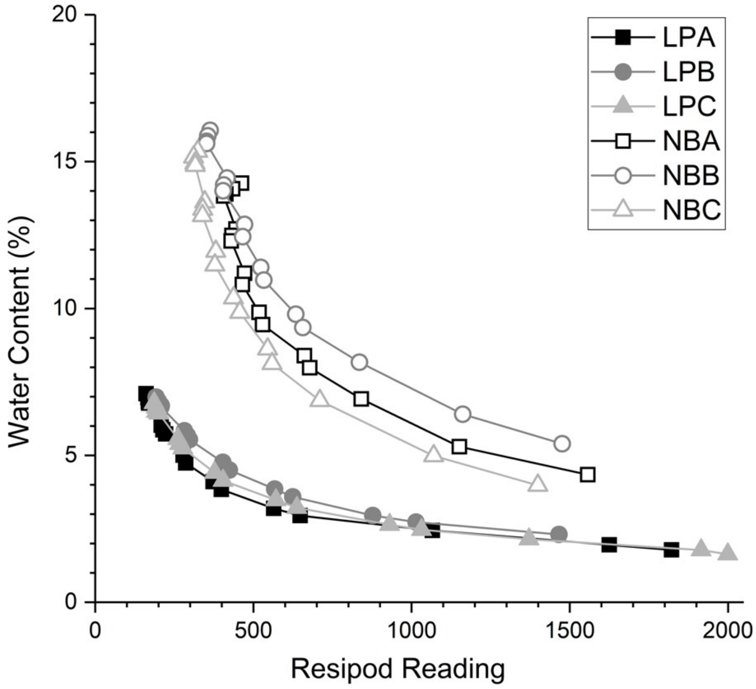


Fig A.23: Resipod readings vs gravimetric measurements of water contents for large Portland limestone (LPA, LPB, LPC) and large handmade brick (NBA, NBB, NBC) sample with all but one face sealed (drying test).

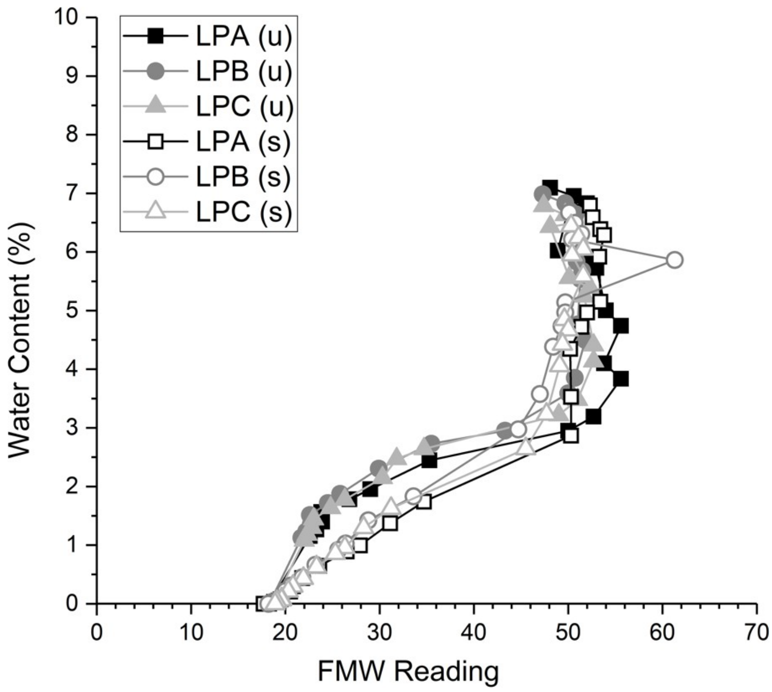


Fig A.24: FMW (20mm mode) readings vs gravimetric measurements of water contents for large Portland limestone (LPA, LPB, LPC) with all but one face sealed (s) in comparison with unsealed (u) (drying test).

Stage 1c results: Mortar cylinders

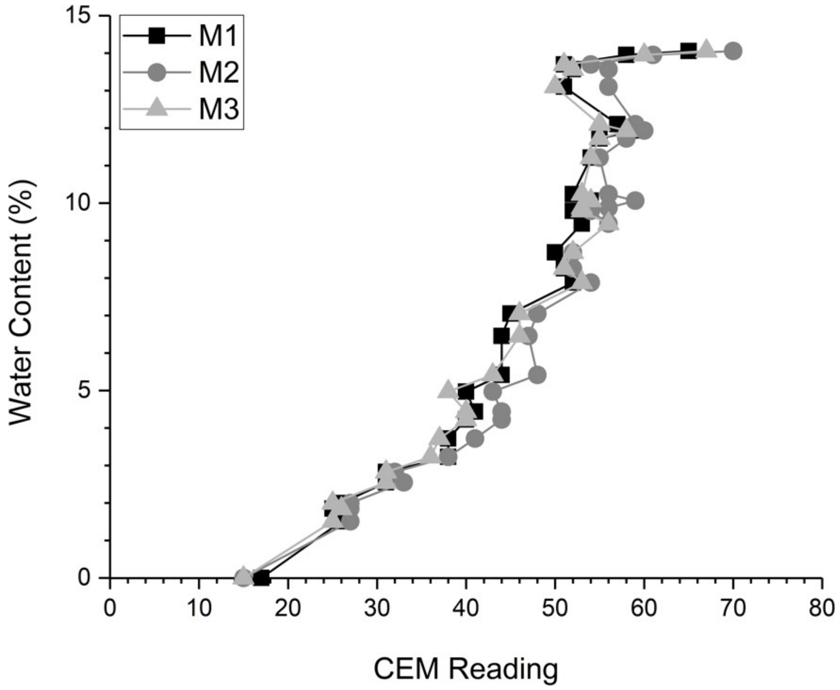


Fig A.25: CEM readings vs gravimetric measurements of water contents for cylindrical mortar (M1, M2, M3) samples (drying test).

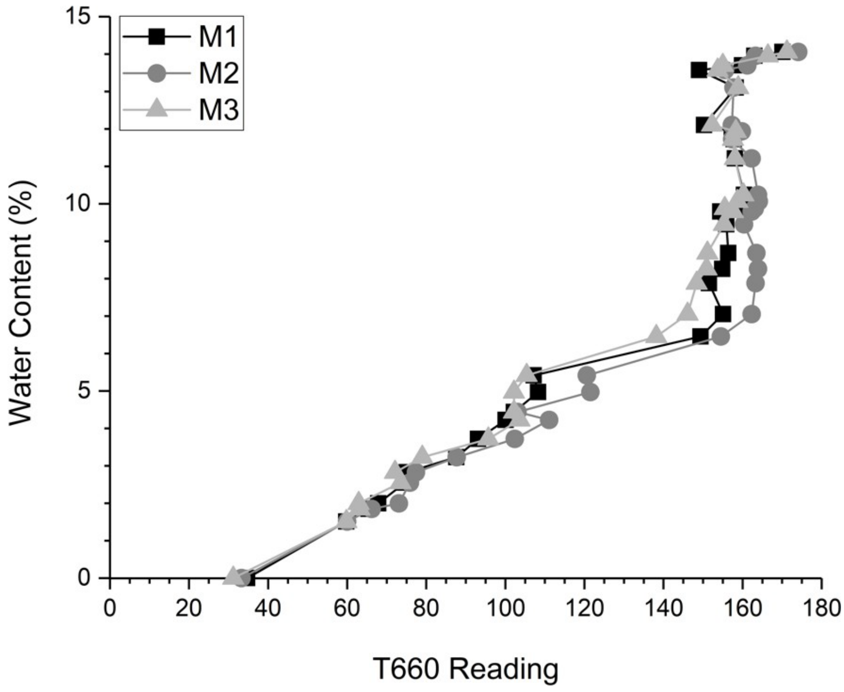


Fig A.26: T660 readings vs gravimetric measurements of water contents for cylindrical mortar (M1, M2, M3) samples (drying test).

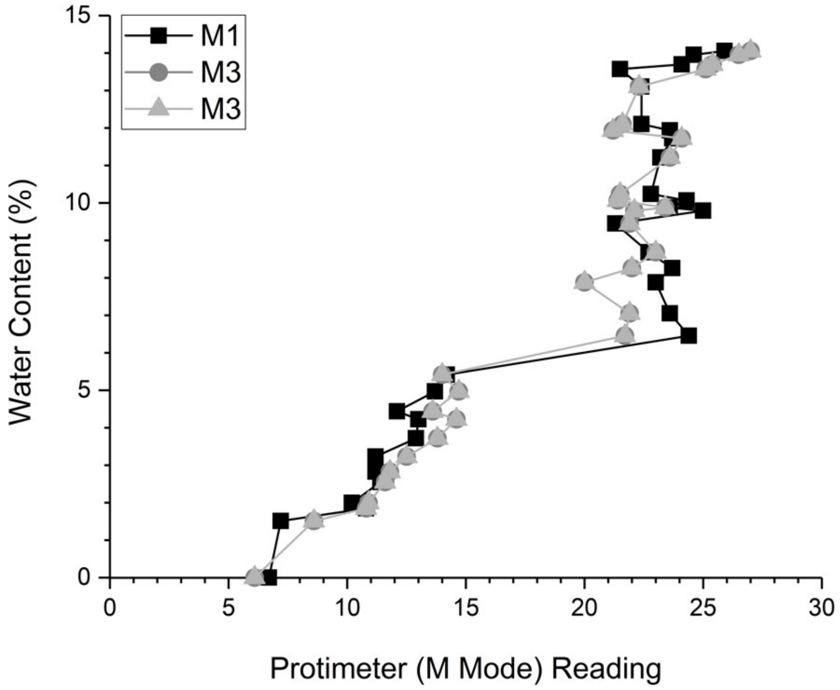


Fig A.27: Protimeter (resistance ['Measure'] mode) readings vs gravimetric measurements of water contents for cylindrical mortar (M1, M2, M3) samples (drying test).

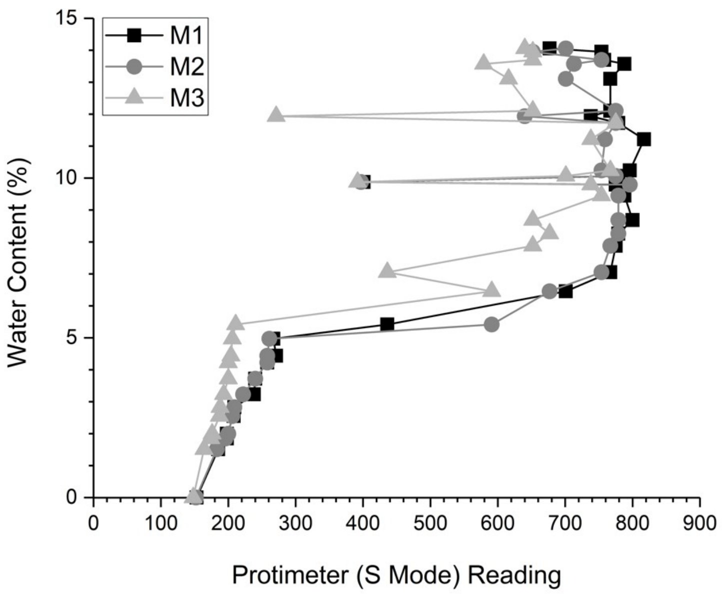


Fig A.28: Protimeter (capacitance ['Search'] mode) readings vs gravimetric measurements of water contents for cylindrical mortar (M1, M2, M3) samples (drying test).

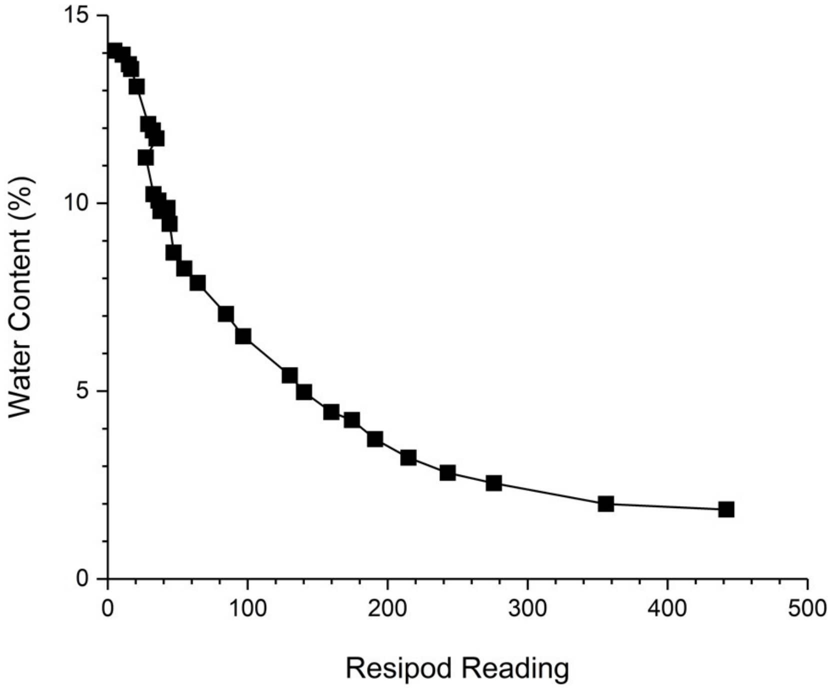


Fig A.29: Resipod readings vs gravimetric measurements of water contents for cylindrical mortar (M1) sample (drying test).

Stage 2 Results: Invasive measurement methods

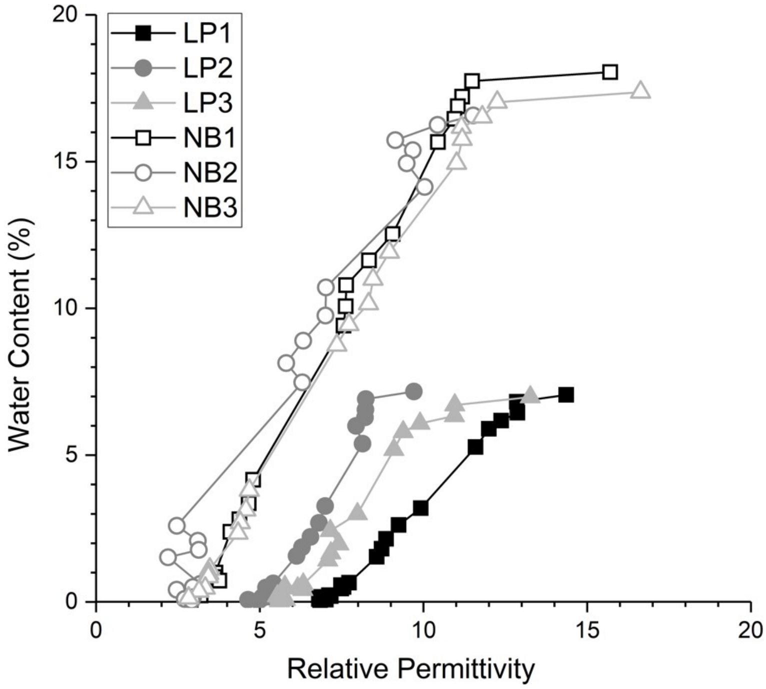


Fig A.30: Scaled TDR measurements vs gravimetric measurements of water contents for small Portland limestone (LP1, LP2, LP3) and small handmade brick (NB1, NB2, NB3) samples (drying test).

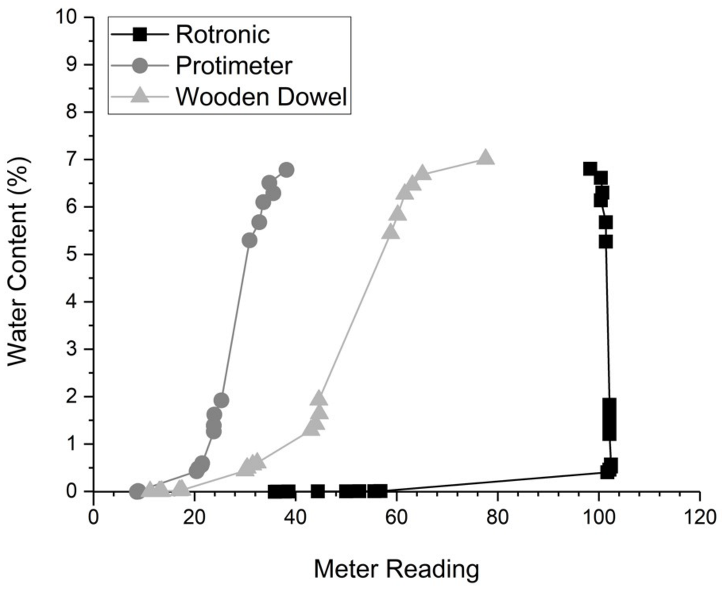


Fig A.31: Rotronic, Protimeter (resistance ['Deep Wall Probe'] mode) and wooden dowel measurements vs gravimetric measurements of water contents using a small sample of Portland limestone (drying test).

Stage 3 results: Comparisons between samples wetted with clean vs saline water

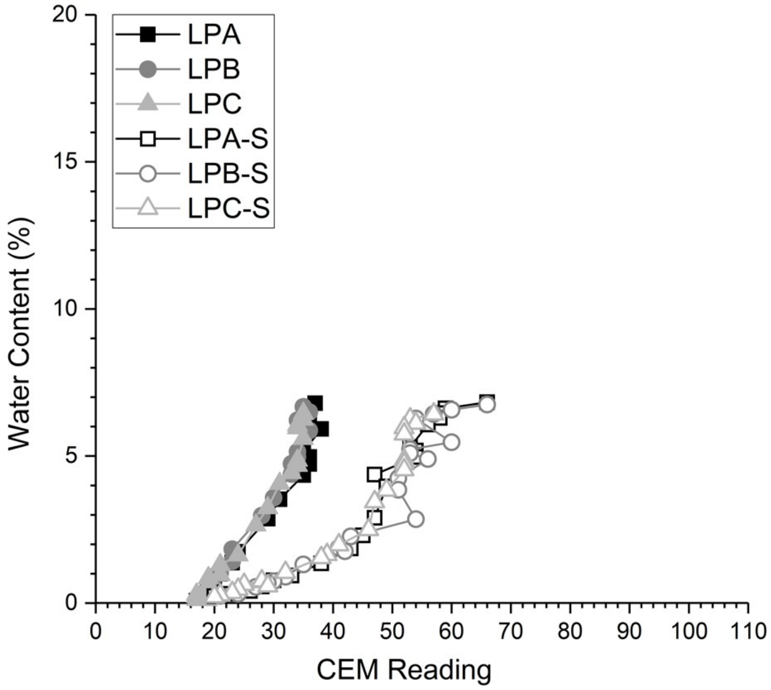


Fig A.32: CEM readings vs gravimetric measurements of water contents for large Portland limestone samples wetted with clean water (LPA, LPB, LPC) and saline water (LPA-S, LPB-S, LPC-S) (drying test).

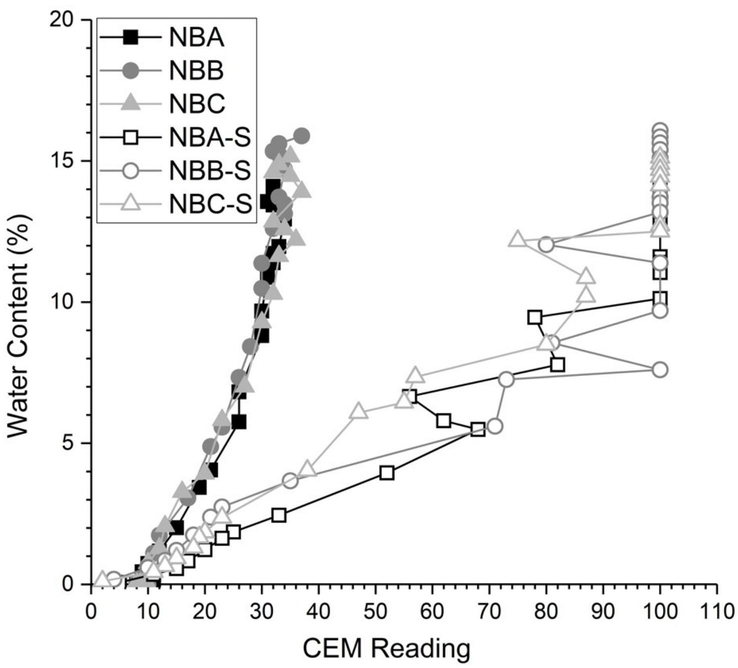


Fig A.33: CEM readings vs gravimetric measurements of water contents for large handmade brick samples wetted with clean water (NBA, NBB, NBC) and saline water (NBA-S, NBB-S, NBC-S) (drying test).

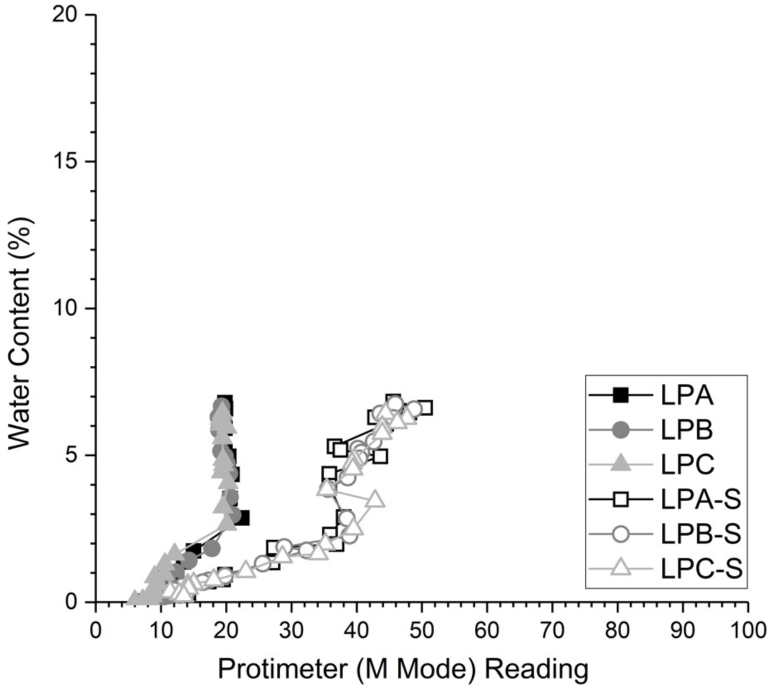


Fig A.34: Protimeter (resistance ['Measure'] mode) readings vs gravimetric measurements of water contents for large Portland limestone samples wetted with clean water (LPA, LPB, LPC) and saline water (LPA-S, LPB-S, LPC-S) (drying test).

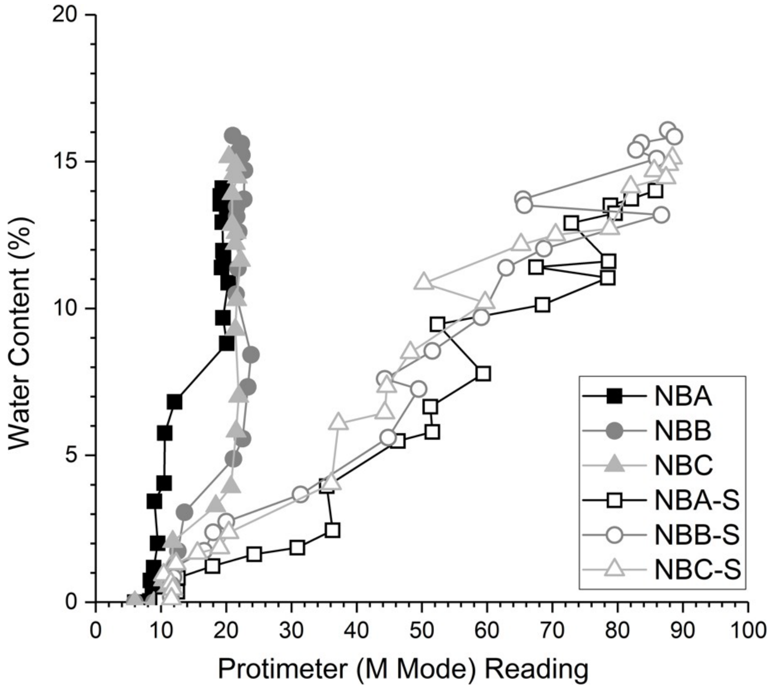


Fig A.35: Protimeter (resistance ['Measure'] mode) readings vs gravimetric measurements of water contents for large handmade brick samples wetted with clean water (NBA, NBB, NBC) and saline water (NBA-S, NBB-S, NBC-S) (drying test).

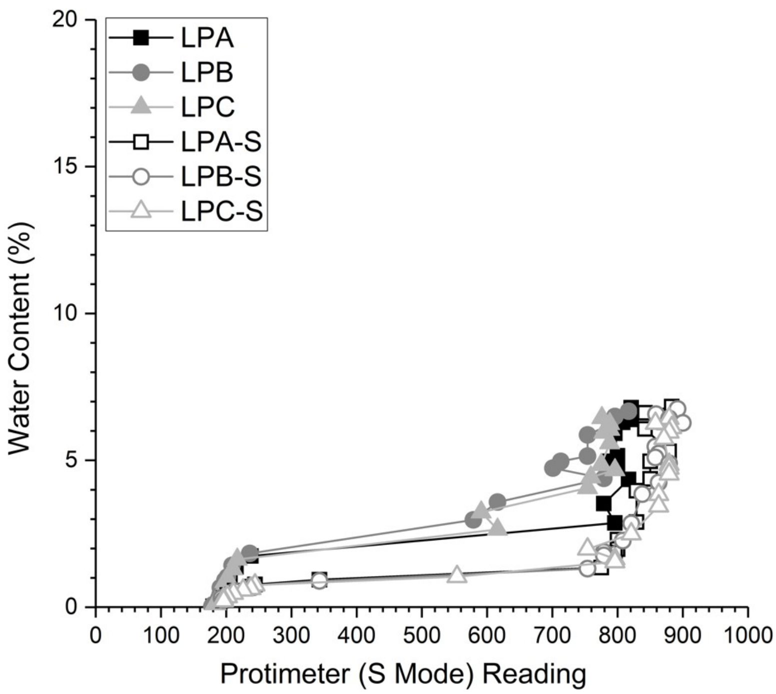


Fig A.36: Protimeter (capacitance ['Search'] mode) readings vs gravimetric measurements of water contents for large Portland limestone samples wetted with clean water (LPA, LPB, LPC) and saline water (LPA-S, LPB-S, LPC-S) (drying test).

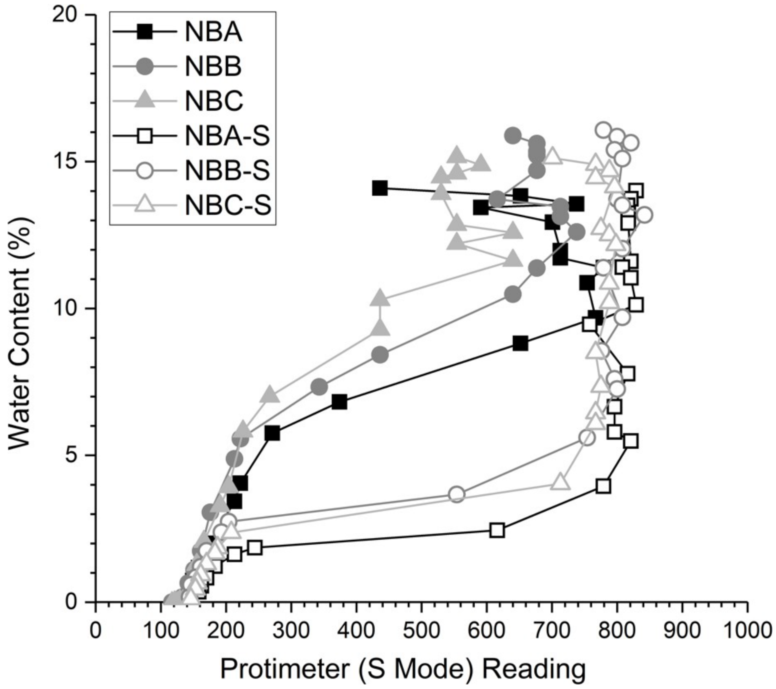


Fig A.37: Protimeter (capacitance ['Search'] mode) readings vs gravimetric measurements of water contents for large handmade brick samples wetted with clean water (NBA, NBB, NBC) and saline water (NBA-S, NBB-S, NBC-S) (drying test).

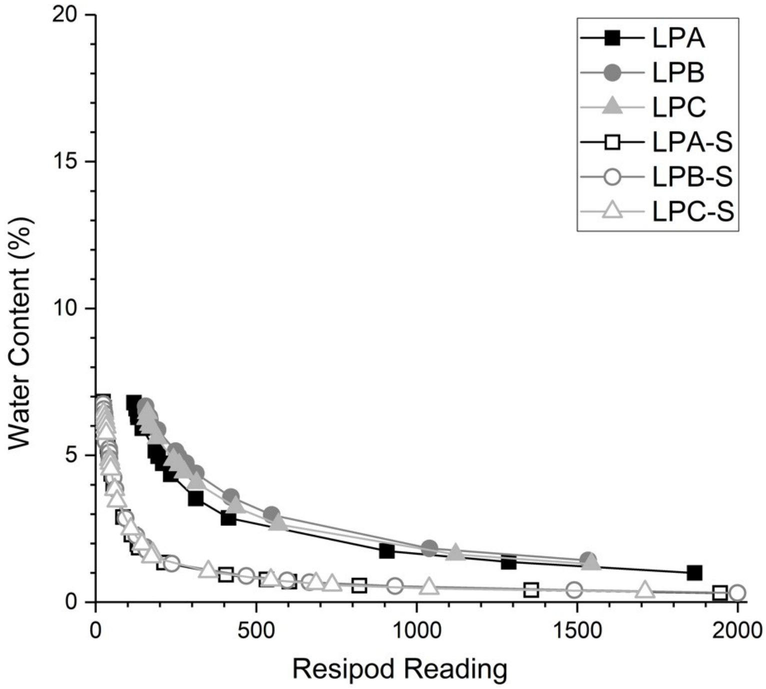


Fig A.38: Resipod readings vs gravimetric measurements of water contents for large Portland limestone samples wetted with clean water (LPA, LPB, LPC) and saline water (LPA-S, LPB-S, LPC-S) (drying test).

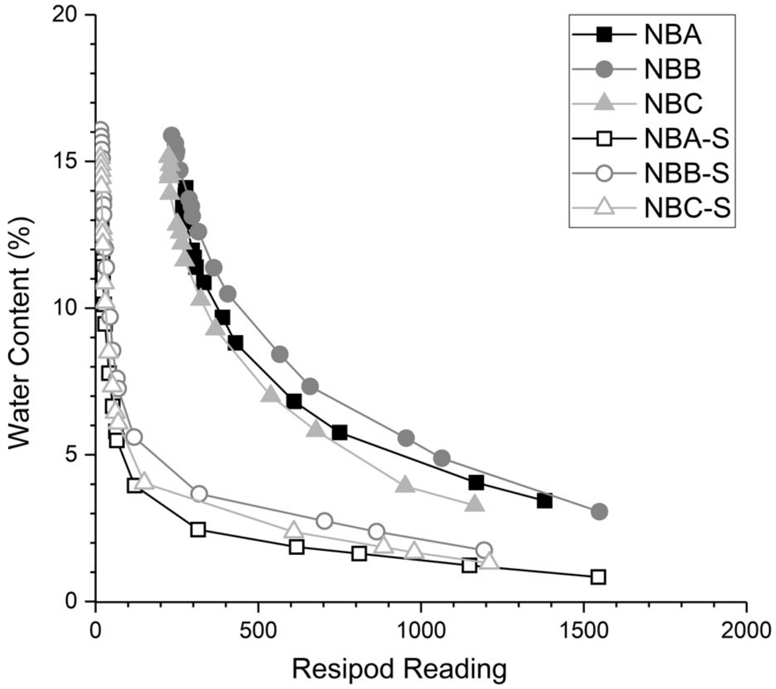


Fig A.39: Resipod readings vs gravimetric measurements of water contents for large handmade brick samples wetted with clean water (NBA, NBB, NBC) and saline water (NBA-S, NBB-S, NBC-S) (drying test).

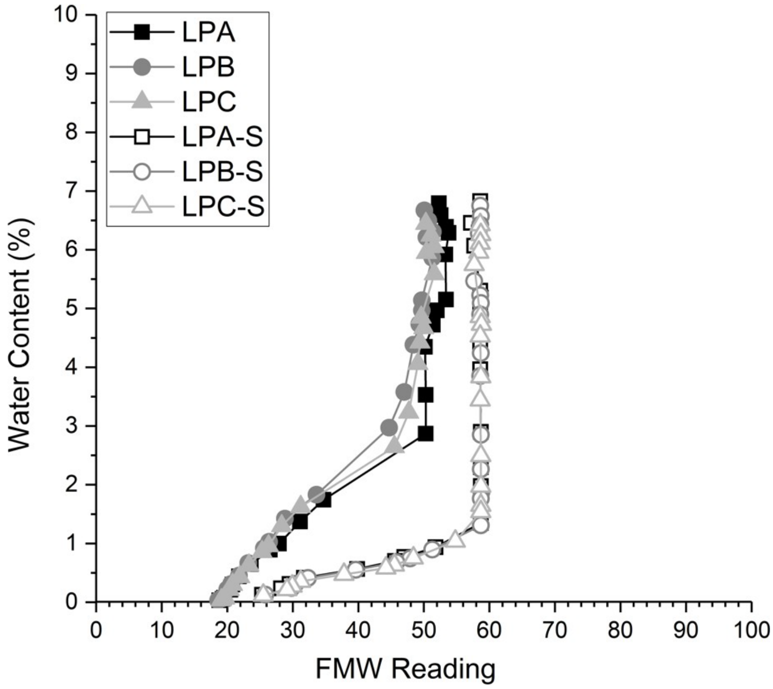


Fig A.40: FMW (20mm mode) readings vs gravimetric measurements of water contents for large Portland limestone samples wetted with clean water (LPA, LPB, LPC) and saline water (LPA-S, LPB-S, LPC-S) (drying test).

APPENDIX B: PHASE 2 RESULTS

Sample code	Sample dimensions (cm)	Material type	Notes
LPA	20 x 10 x 7.5	Portland limestone (Coombefield Whitbed)	Used in Stage 1
LPB	20 x 10 x 7.5	Portland limestone (Coombefield Whitbed)	Used in Stage 1
LPC	20 x 10 x 7.5	Portland limestone (Coombefield Whitbed)	Used in Stage 1
NBA	22 x 10.5 x 6.7	Handmade brick (H G Matthews)	Used in Stage 1
NBB	22 x 10.7 x 6.5	Handmade brick (H G Matthews)	Used in Stage 1
NBC	22 x 10.7 x 6.5	Handmade brick (H G Matthews)	Used in Stage 1
SSA	20 x 10 x 7.5	Stoke Hall sandstone	Used in Stage 1
SSB	20 x 10 x 7.5	Stoke Hall sandstone	Used in Stage 1
SSC	20 x 10.2 x 7.3	Stoke Hall sandstone	Used in Stage 1
DBA	23.5 x 10 x 9.8	Old brick from Shrewsbury Flaxmill Maltings	Used in Stage 1
DBB	23.5 x 11.2 x 10	Old brick from Shrewsbury Flaxmill Maltings	Used in Stage 1
DBC	23.5 x 11.5 x 9.5	Old brick from Shrewsbury Flaxmill Maltings	Used in Stage 1
LPD	12.4 x 8.4 x 7	Portland limestone (Coombefield Whitbed)	Used in Stage 2
LPE	12.3 x 8.4 x 7	Portland limestone (Coombefield Whitbed)	Used in Stage 2
EP	40 x 20 x 20	Elm Park limestone	Used in Stage 2
SSD	24.6 x 23.8 x 1.6	Stoke Hall sandstone	Used in Stage 3
SSE	24.6 x 23.8 x 1.6	Stoke Hall sandstone	Used in Stage 3
SSF	24.6 x 23.8 x 1.6	Stoke Hall sandstone	Used in Stage 3
SSG	24.6 x 23.8 x 1.8	Stoke Hall sandstone	Used in Stage 3
CL1-39	30 x 30 x 1	Clipsham limestone	39 identical samples Used in Stage 3
CL40	30 x 30 x 0.5	Clipsham limestone	Used in Stage 3

Stage 1 results: Drying tests (run 1)

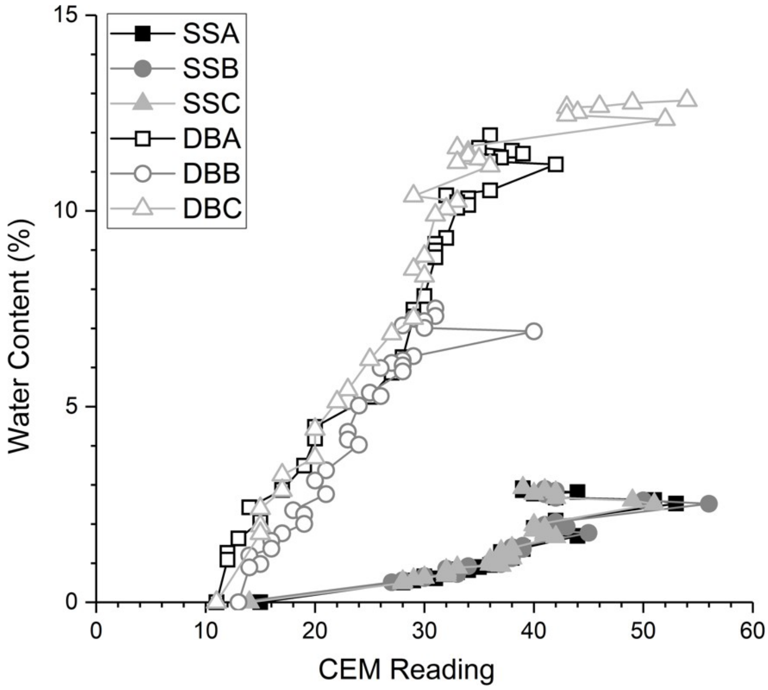


Fig B.1: CEM readings vs gravimetric measurements of water contents for large Stoke Hall sandstone (SSA, SSB, SSC) and Shrewsbury Flaxmill Maltings brick (DBA, DBB, DBC) samples (drying test run 1).

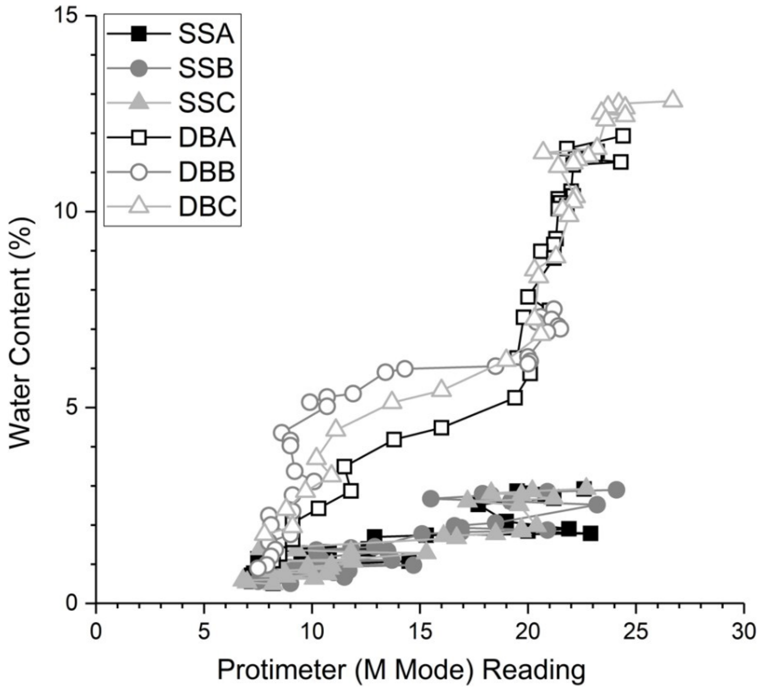


Fig B.2: Protimeter (resistance ['Measure'] mode) readings vs gravimetric measurements of water contents for large Stoke Hall sandstone (SSA, SSB, SSC) and Shrewsbury Flaxmill Maltings brick (DBA, DBB, DBC) samples (drying test run 1).

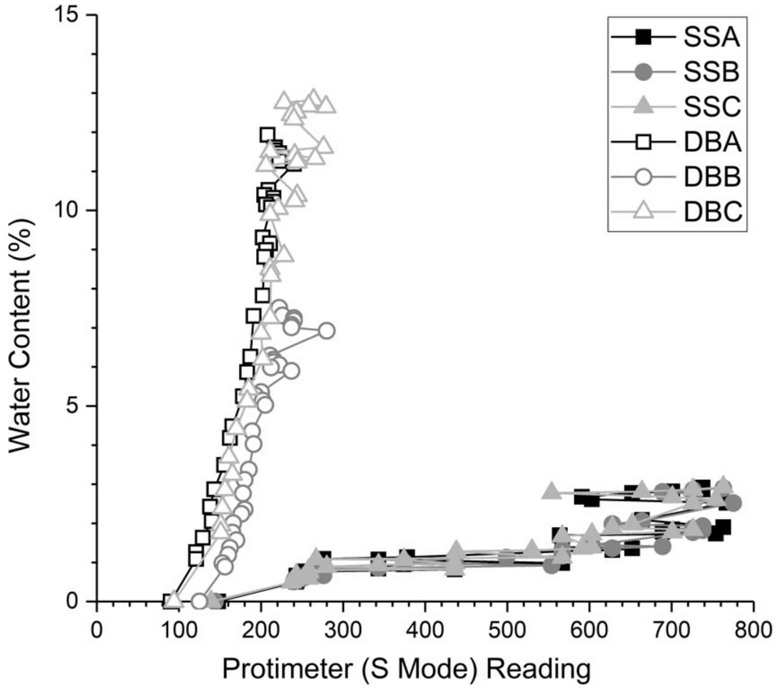


Fig B.3: Protimeter (capacitance ['Search'] mode) readings vs gravimetric measurements of water contents for large Stoke Hall sandstone (SSA, SSB, SSC) and Shrewsbury Flaxmill Maltings brick (DBA, DBB, DBC) samples (drying test run 1).

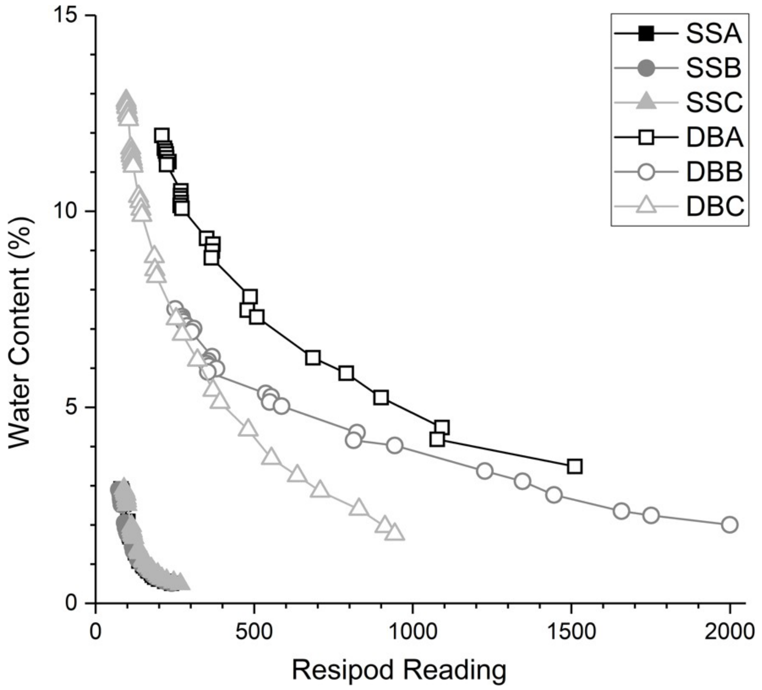


Fig B.4: Resipod readings vs gravimetric measurements of water contents for large Stoke Hall sandstone (SSA, SSB, SSC) and Shrewsbury Flaxmill Maltings brick (DBA, DBB, DBC) samples (drying test run 1).

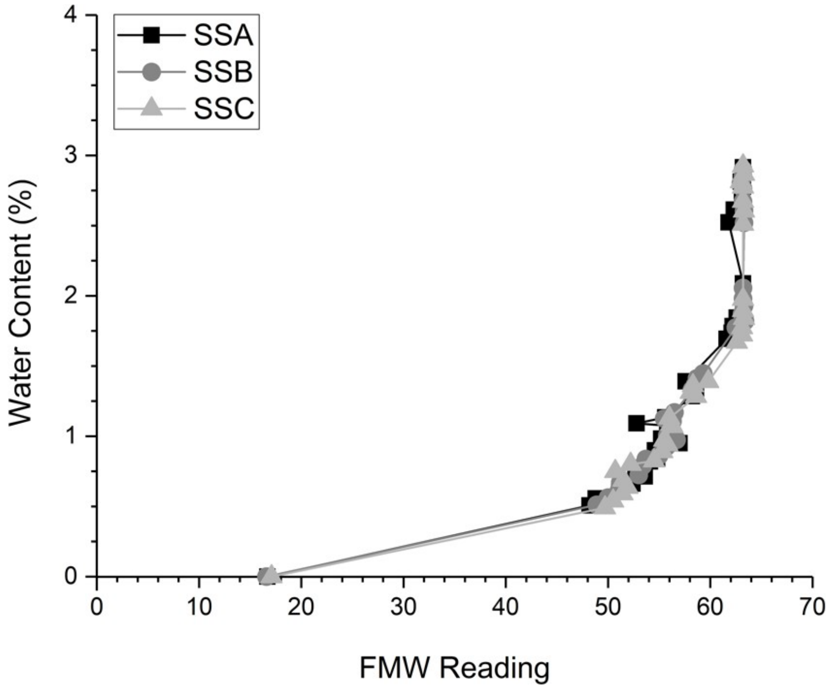


Fig B.5: FMW (10mm mode) readings vs gravimetric measurements of water contents for large Stoke Hall sandstone (SSA, SSB, SSC) samples (drying test run 1).

Stage 1 results: Drying test (run 2)

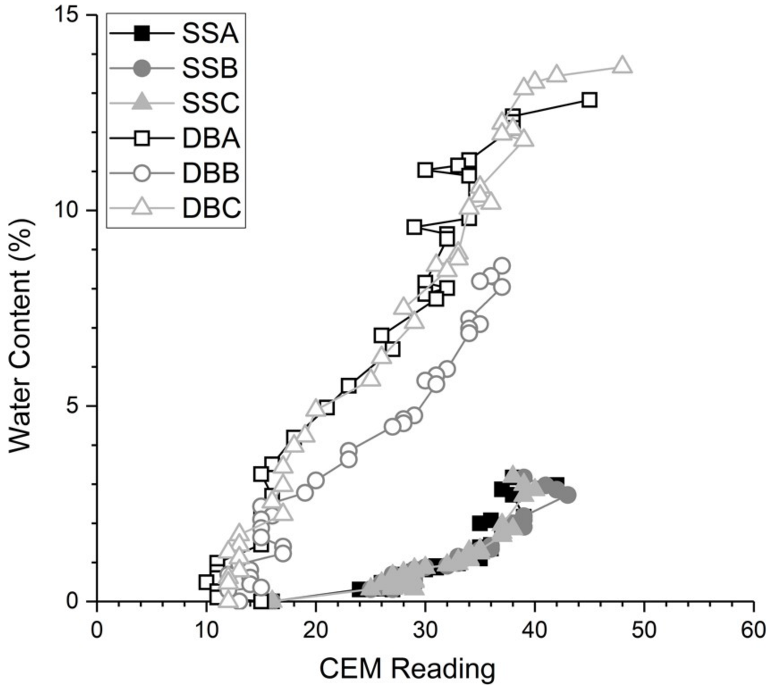


Fig B.6: CEM readings vs gravimetric measurements of water contents for large Stoke Hall sandstone (SSA, SSB, SSC) and Shrewsbury Flaxmill Maltings brick (DBA, DBB, DBC) samples (drying test run 2).

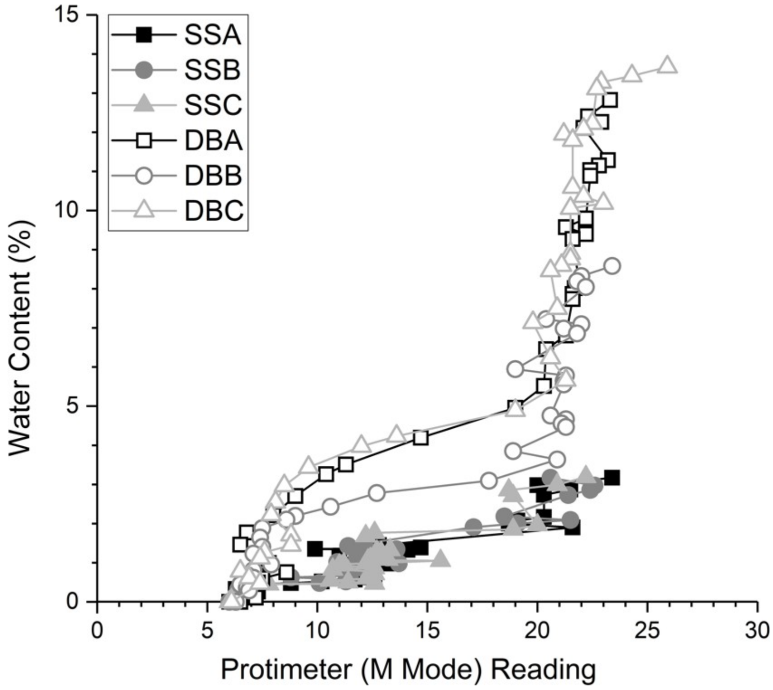


Fig B.7: Protimeter (resistance ['Measure'] mode) readings vs gravimetric measurements of water contents for large Stoke Hall sandstone (SSA, SSB, SSC) and Shrewsbury Flaxmill Maltings brick (DBA, DBB, DBC) samples (drying test run 2).

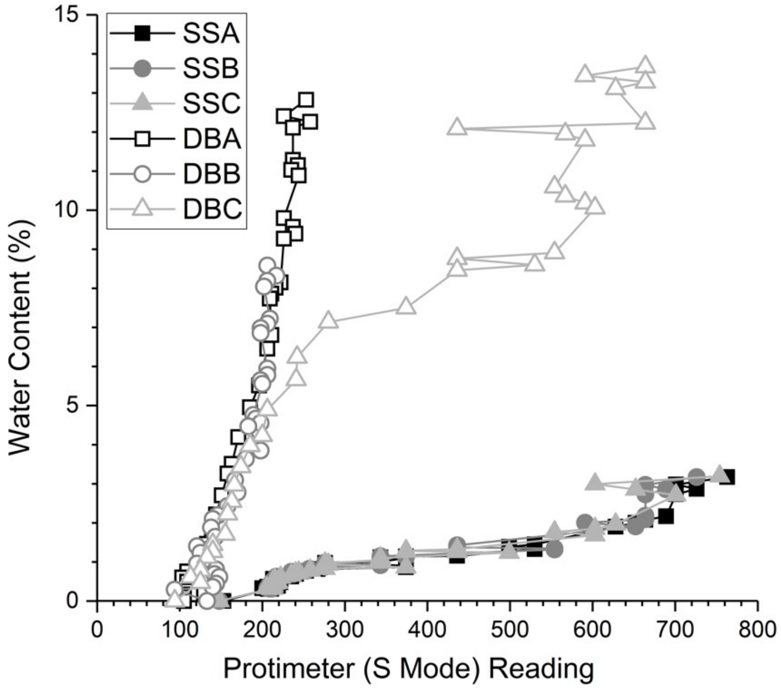


Fig B.8: Protimeter (capacitance ['Search'] mode) readings vs gravimetric measurements of water contents for large Stoke Hall sandstone (SSA, SSB, SSC) and Shrewsbury Flaxmill Maltings brick (DBA, DBB, DBC) samples (drying test run 2).

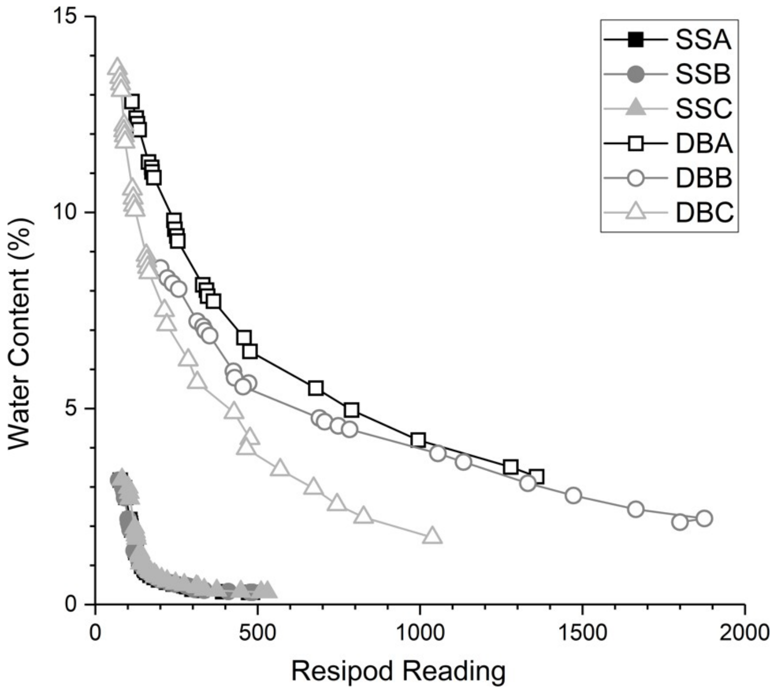


Fig B.9: Resipod readings vs gravimetric measurements of water contents for large Stoke Hall sandstone (SSA, SSB, SSC) and Shrewsbury Flaxmill Maltings brick (DBA, DBB, DBC) samples (drying test run 2).

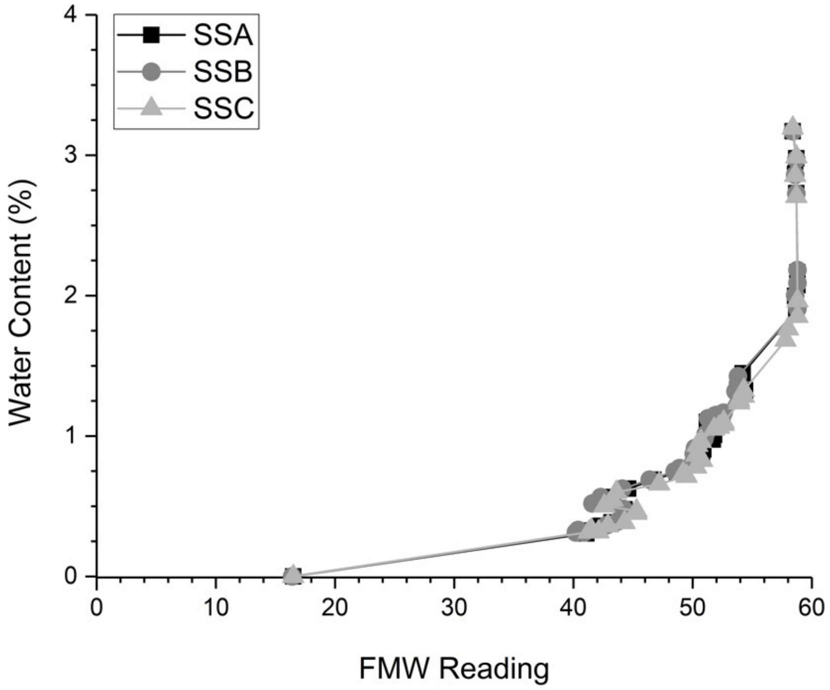


Fig B.10: FMW (10mm mode) readings vs gravimetric measurements of water contents for large Stoke Hall sandstone (SSA, SSB, SSC) samples (drying test run 2).

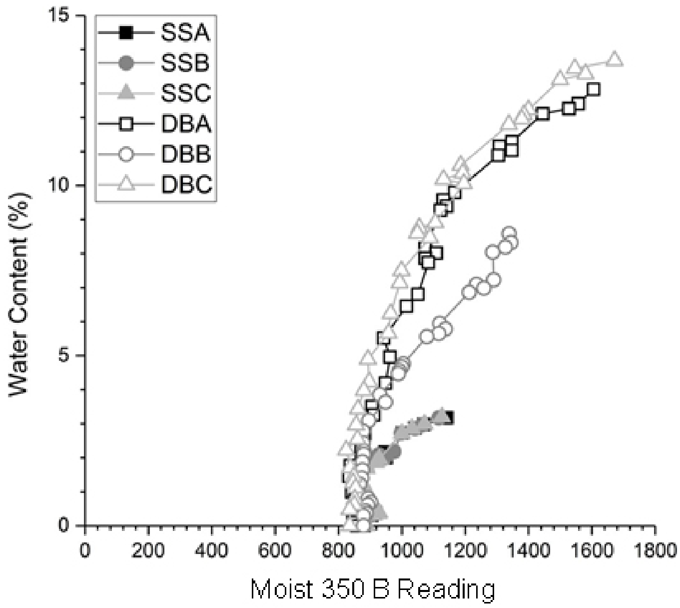


Fig B.11: MOIST 350 B (R1M) readings vs gravimetric measurements of water contents for large Stoke Hall sandstone (SSA, SSB, SSC) and Shrewsbury Flaxmill Maltings brick (DBA, DBB, DBC) samples (drying test).

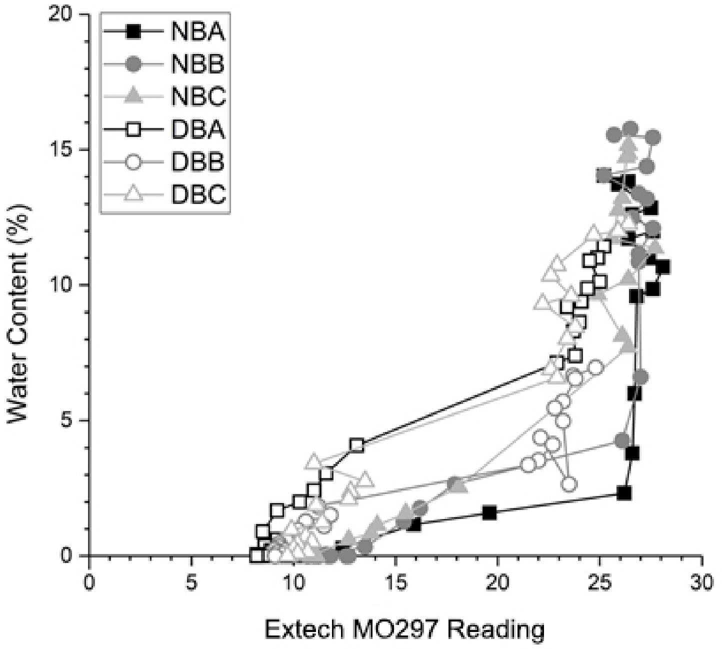


Fig B.12: Extech MO297 (resistance ['Pin'] mode) readings vs gravimetric measurements of water contents for large new handmade brick (NBA, NBB, NBC) and old Shrewsbury Flaxmill Maltings brick (DBA, DBB, DBC) sample (drying test).

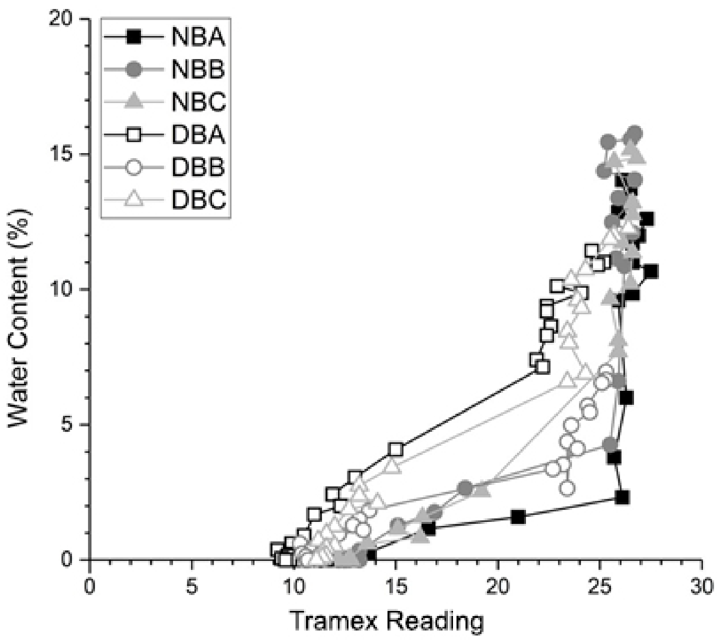


Fig B.13: Tramex (resistance ['Pin'] mode) readings vs gravimetric measurements of water contents for large new handmade brick (NBA, NBB, NBC) and old Shrewsbury Flaxmill Maltings brick (DBA, DBB, DBC) samples (drying test).

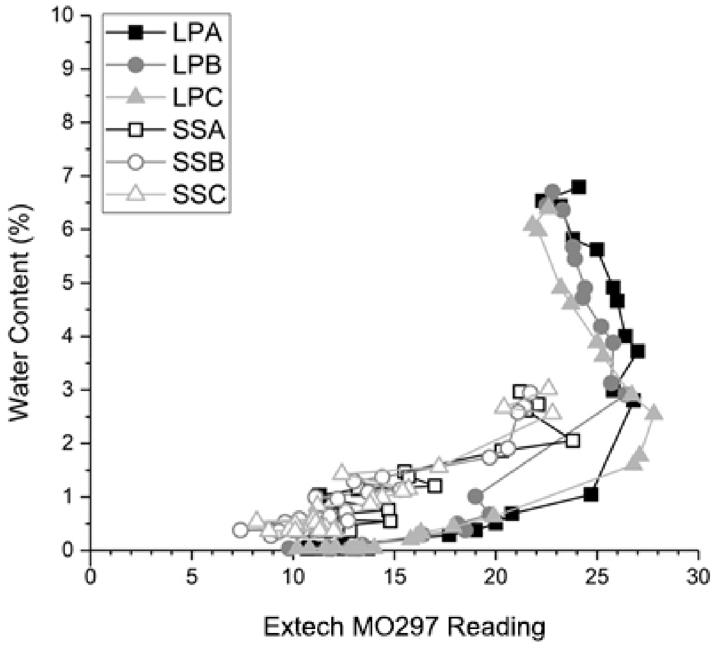


Fig B.14: Extech MO297 (resistance ['Pin'] mode) readings vs gravimetric measurements of water contents for large Portland limestone (LPA, LPB, LPC) and Stoke Hall sandstone (SSA, SSB, SSC) samples (drying test).

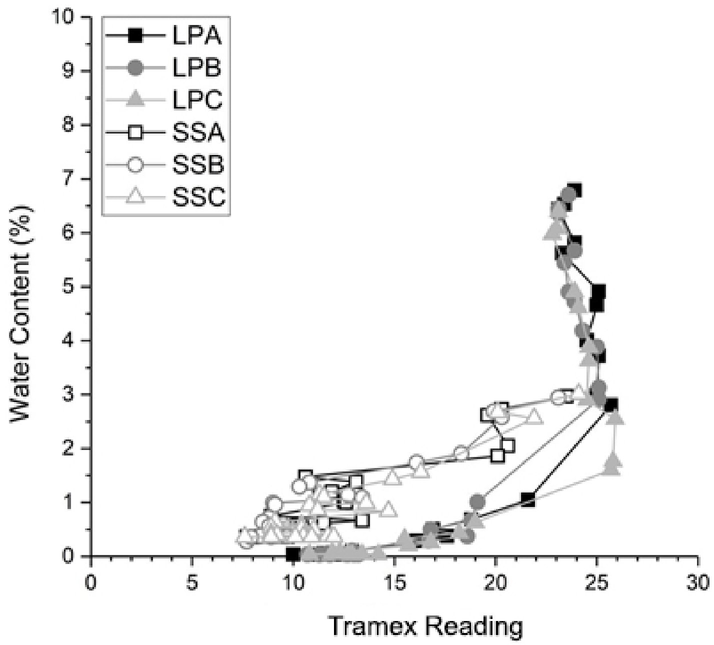


Fig B.15: Tramex (resistance ['Pin'] mode) readings vs gravimetric measurements of water contents for large Portland limestone (LPA, LPB, LPC) and Stoke Hall sandstone (SSA, SSB, SSC) samples (drying test).

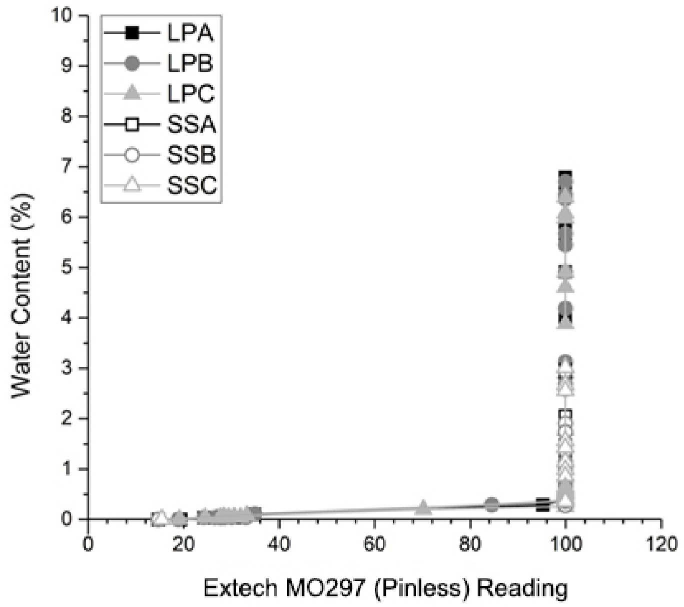


Fig B.16: Extech MO297 (capacitance ['Pinless'] mode) readings vs gravimetric measurements of water contents for large Portland limestone (LPA, LPB, LPC) and Stoke Hall sandstone (SSA, SSB, SSC) samples (drying test).

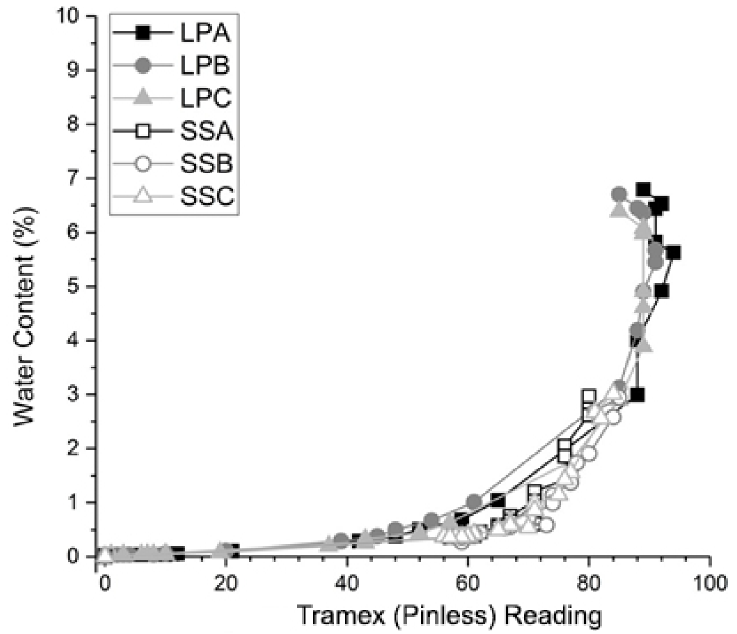


Fig B.17: Tramex (capacitance ['Pinless'] mode) readings vs gravimetric measurements of water contents for large Portland limestone (LPA, LPB, LPC) and Stoke Hall sandstone (SSA, SSB, SSC) samples (drying test)

Stage 1 results: Wetting up experiments

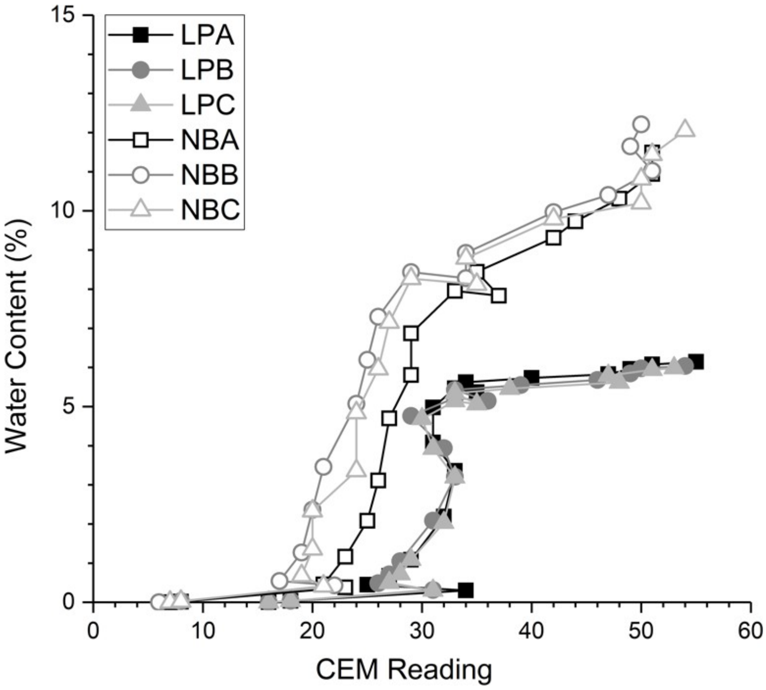


Fig B.18: CEM readings vs gravimetric measurements of water contents for large Portland limestone (LPA, LPB, LPC) and large handmade brick (NBA, NBB, NBC) samples (wetting up tests run 1).

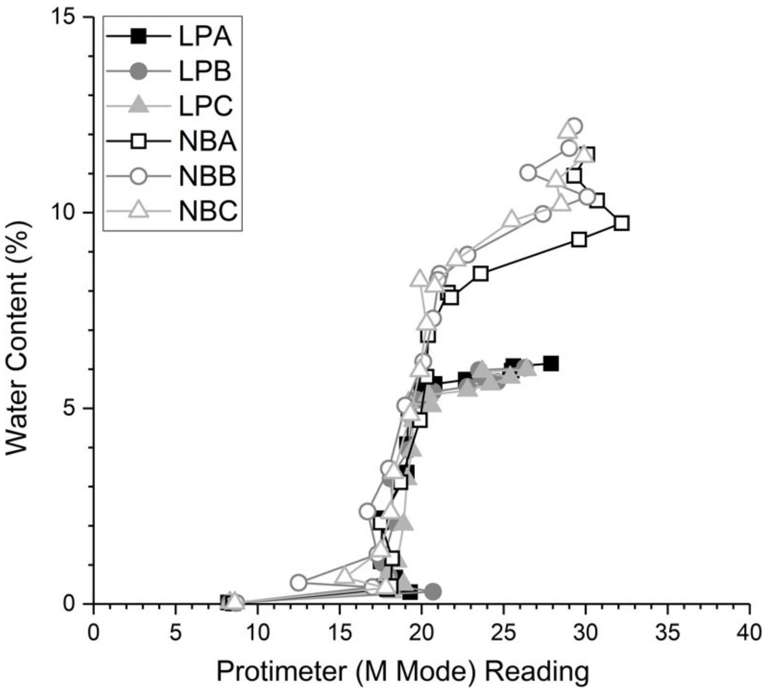


Fig B.19: Protimeter (resistance ['Measure'] mode) readings vs gravimetric measurements of water contents for large Portland limestone (LPA, LPB, LPC) and large handmade brick (NBA, NBB, NBC) samples (wetting up tests run 1).

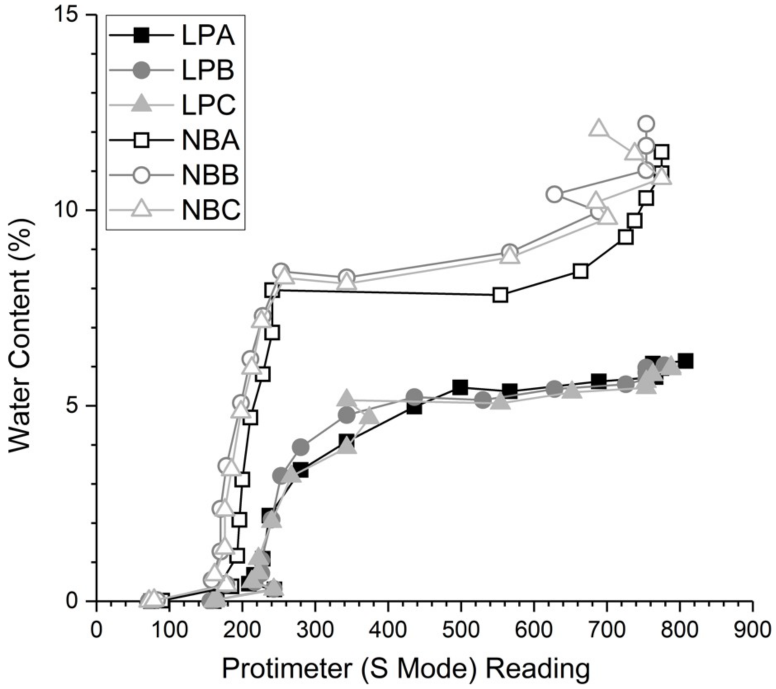


Fig B.20: Protimeter (capacitance ['Search'] mode) readings vs gravimetric measurements of water contents for large Portland limestone (LPA, LPB, LPC) and large handmade brick (NBA, NBB, NBC) samples (wetting up tests run 1).

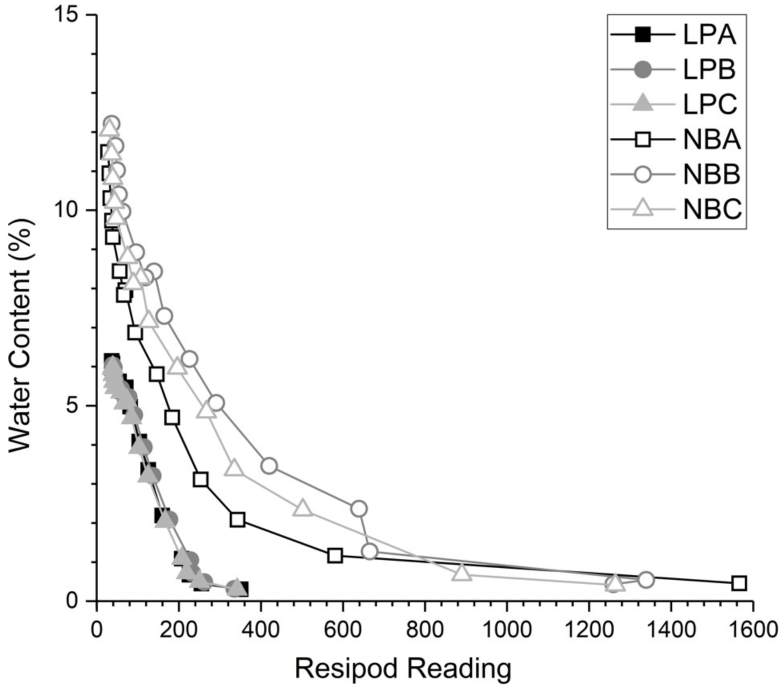


Fig B.21: Resipod readings vs gravimetric measurements of water contents for large Portland limestone (LPA, LPB, LPC) and large handmade brick (NBA, NBB, NBC) samples (wetting up tests run 1).

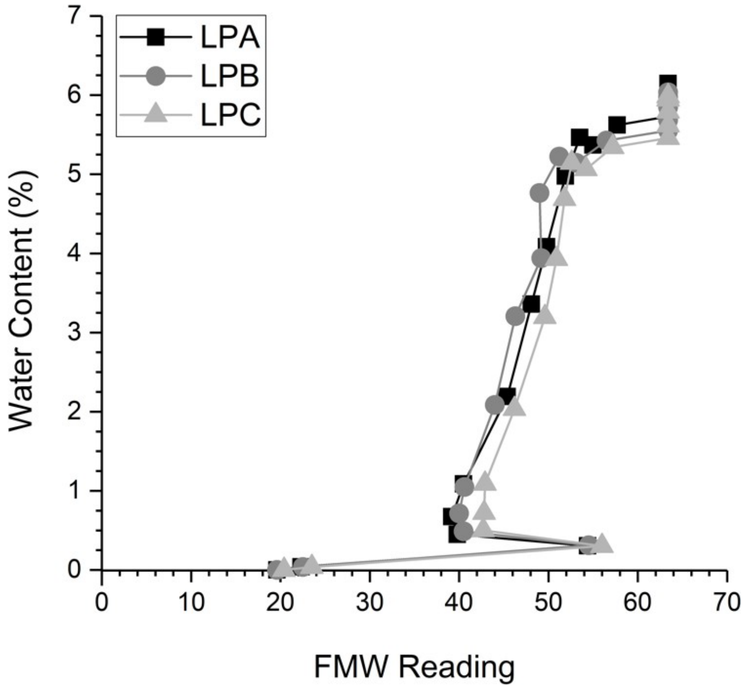


Fig B.22: FMW (10mm mode) readings vs gravimetric measurements of water contents for large Portland limestone (LPA, LPB, LPC) samples (wetting up tests run 1).

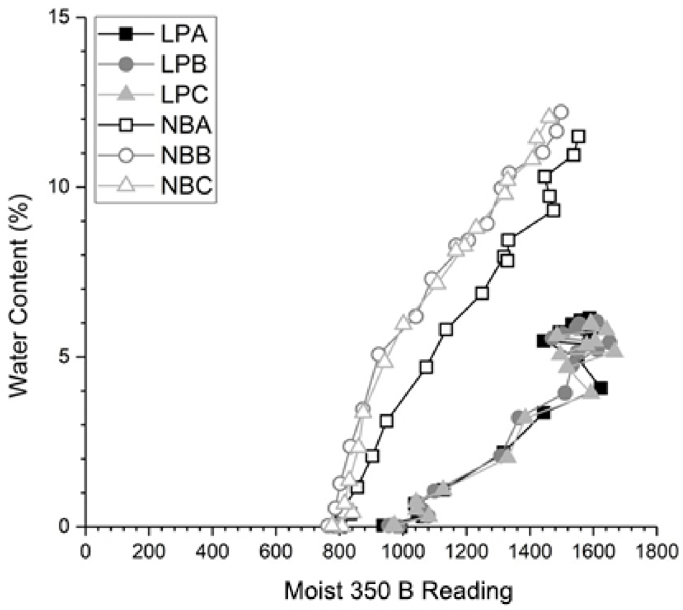


Fig B.23: MOIST 350 B readings vs gravimetric measurements of water contents for large Portland limestone (LPA, LPB, LPC) and large handmade brick (NBA, NBB, NBC) samples (wetting up tests run 1).

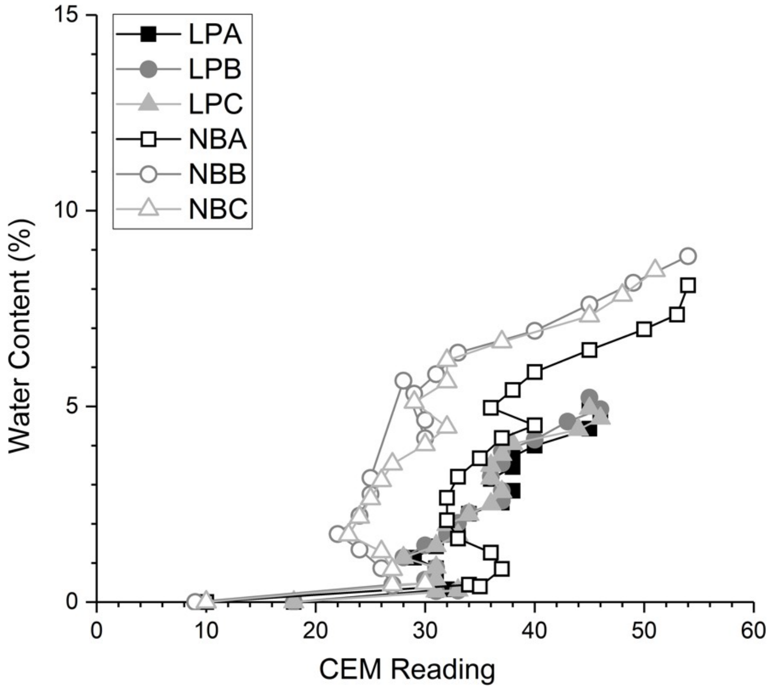


Fig B.24: CEM readings vs gravimetric measurements of water contents for large Portland limestone (LPA, LPB, LPC) and large handmade brick (NBA, NBB, NBC) samples (wetting up tests run 2).

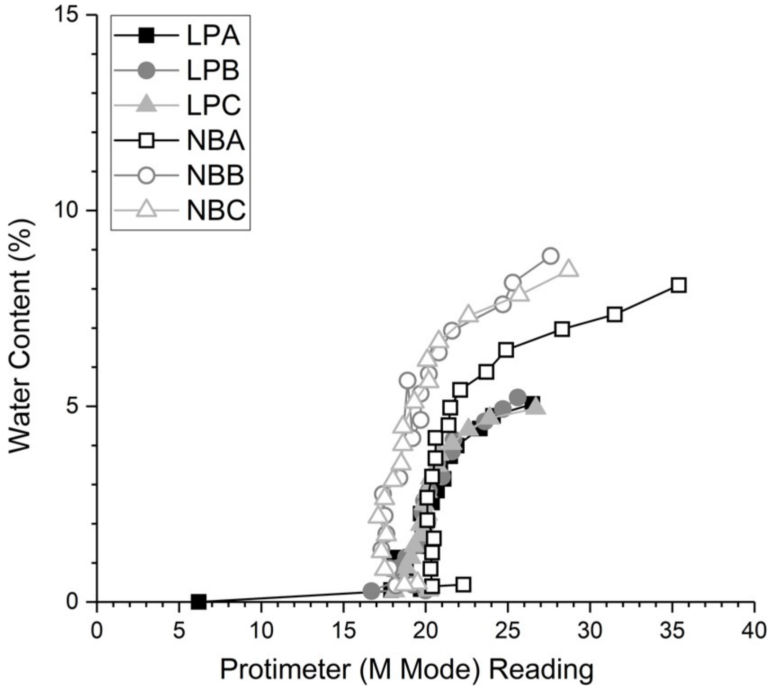


Fig B.25: Protimeter (resistance ['Measure'] mode) readings vs gravimetric measurements of water contents for large Portland limestone (LPA, LPB, LPC) and large handmade brick (NBA, NBB, NBC) samples (wetting up tests run 2).

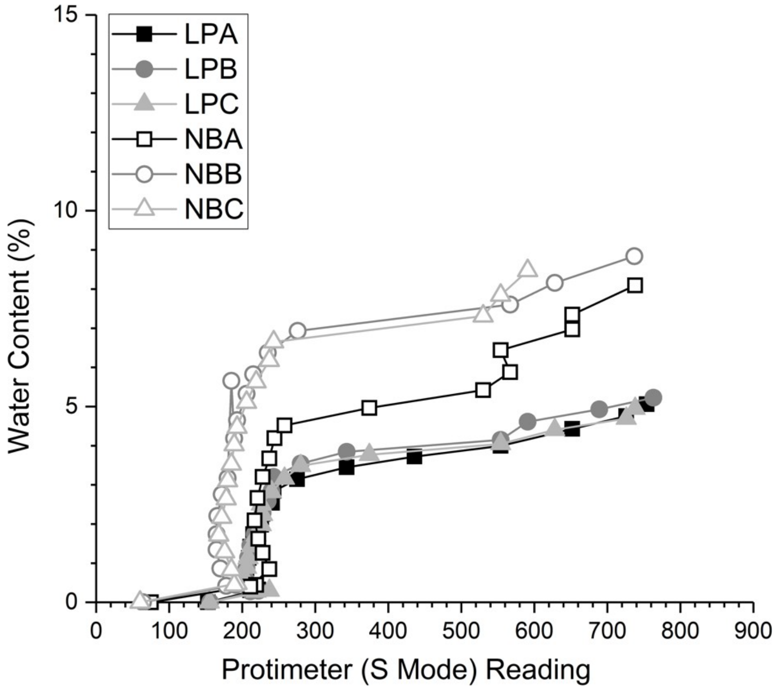


Fig B.26: Protimeter (capacitance ['Search'] mode) readings vs gravimetric measurements of water contents for large Portland limestone (LPA, LPB, LPC) and large handmade brick (NBA, NBB, NBC) samples (wetting up tests run 2).

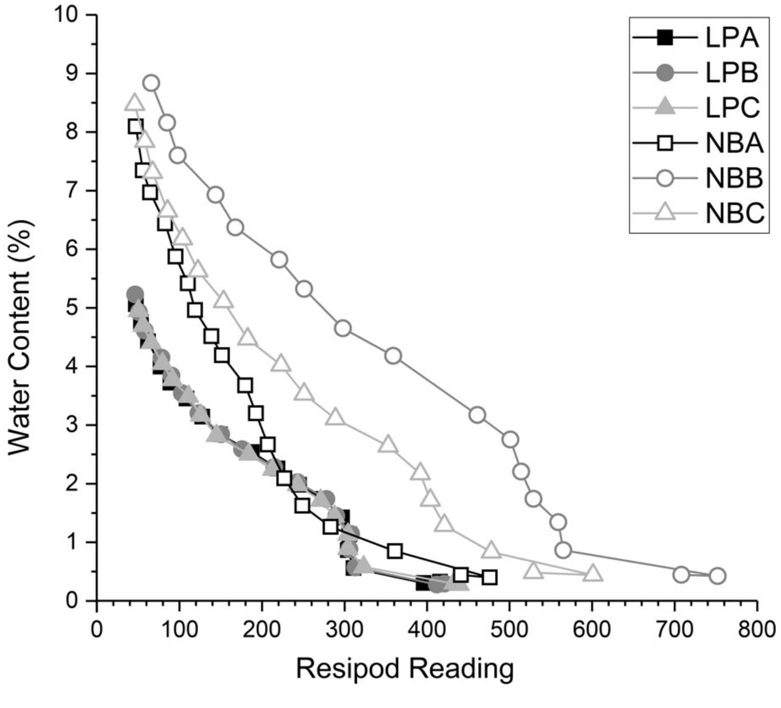


Fig B.27: Resipod readings vs gravimetric measurements of water contents for large Portland limestone (LPA, LPB, LPC) and large handmade brick (NBA, NBB, NBC) samples (wetting up tests run 2).

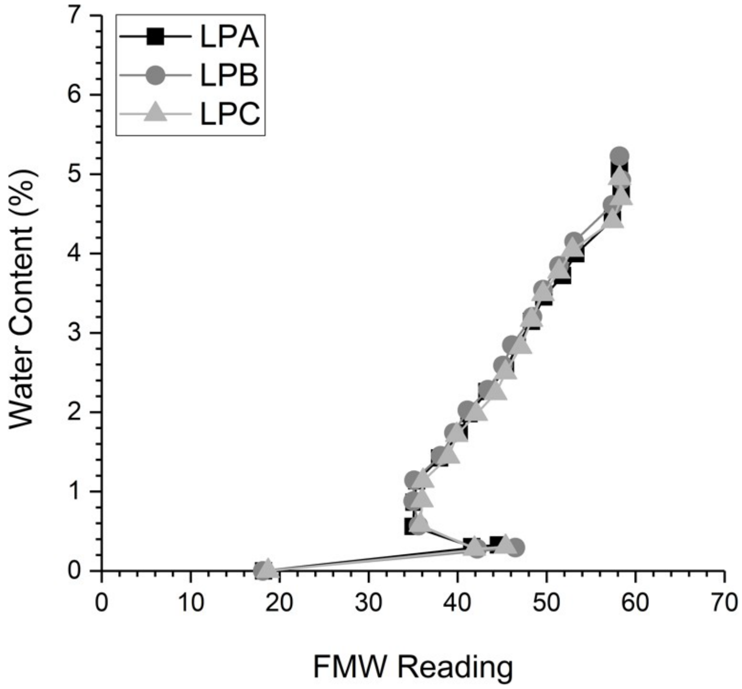


Fig B.28: FMW (20mm mode) readings vs gravimetric measurements of water contents for large Portland limestone (LPA, LPB, LPC) samples (wetting up tests run 2).

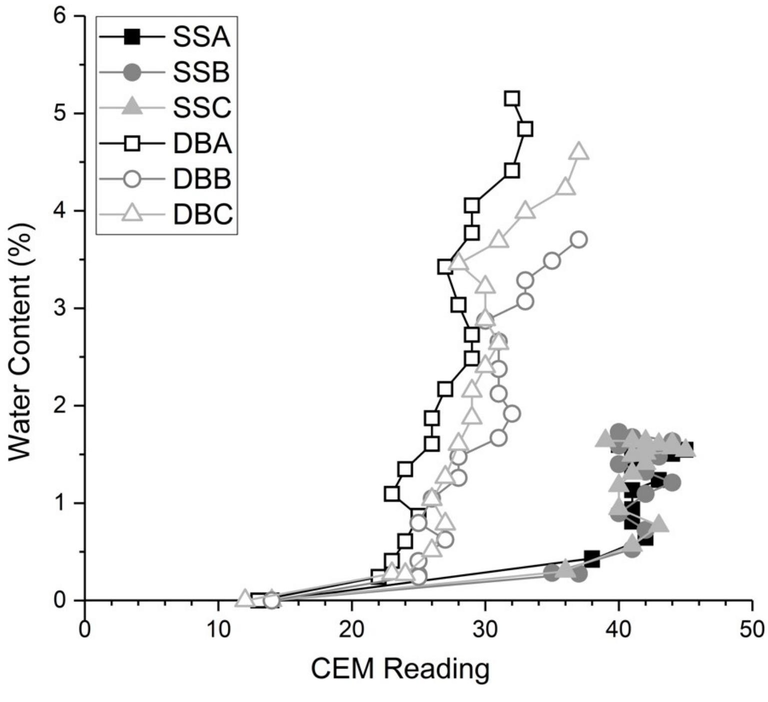


Fig B.29: CEM readings vs gravimetric measurements of water contents for large Stoke Hall sandstone (SSA, SSB, SSC) and old Shrewsbury Flaxmill Maltings brick (DBA, DBB, DBC) samples (wetting up tests run 2).

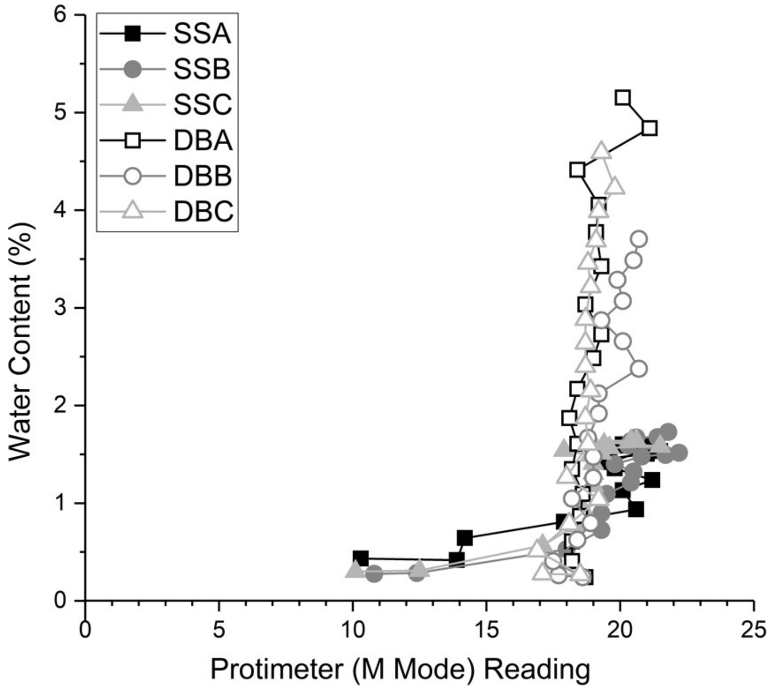


Fig B.30: Protimeter (resistance ['Measure'] mode) readings vs gravimetric measurements of water contents for large Stoke Hall sandstone (SSA, SSB, SSC) and old Shrewsbury Flaxmill Maltings brick (DBA, DBB, DBC) samples (wetting up tests run 2).

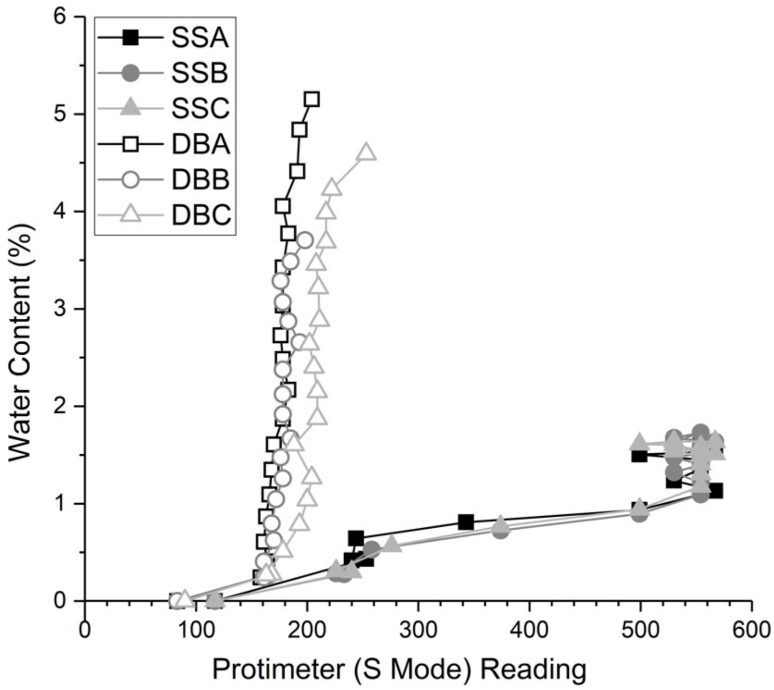


Fig B.31: Protimeter (capacitance ['Search'] mode) readings vs gravimetric measurements of water contents for large Stoke Hall sandstone (SSA, SSB, SSC) and old Shrewsbury Flaxmill Maltings brick (DBA, DBB, DBC) samples (wetting up tests run 2).

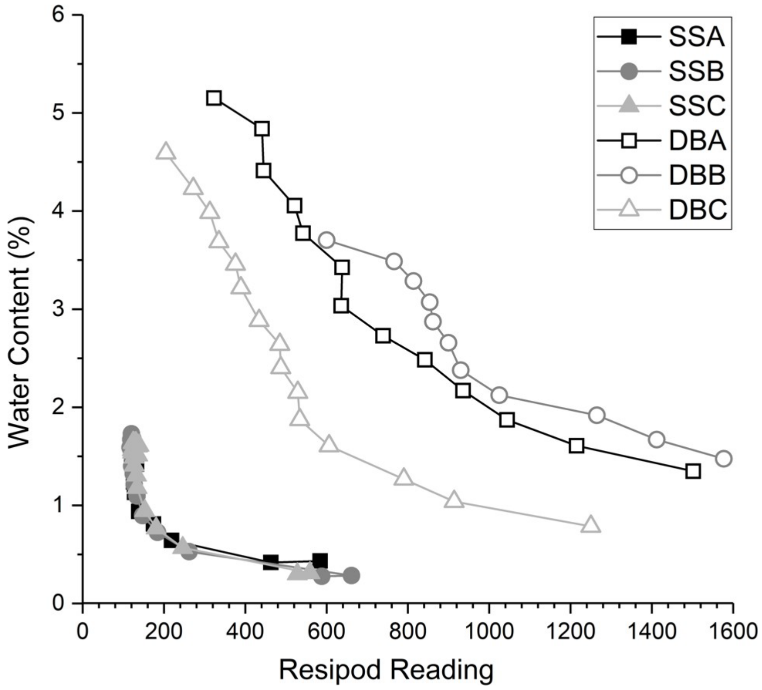


Fig B.32: Resipod readings vs gravimetric measurements of water contents for large Stoke Hall sandstone (SSA, SSB, SSC) and old Shrewsbury Flaxmill Maltings brick (DBA, DBB, DBC) samples (wetting up tests run 2).

Stage 2 results: Comparative evaluation of timber and ceramic dowels

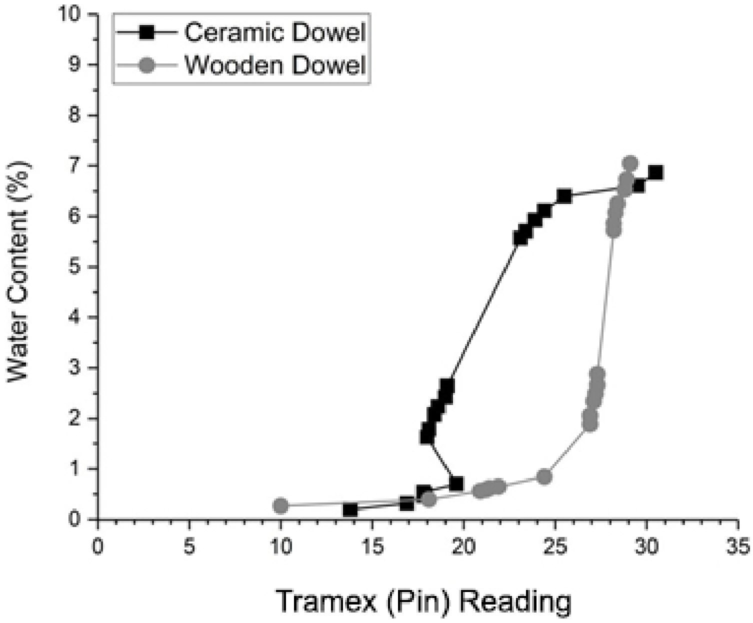


Fig B.33: Tramex (resistance ['Pin'] mode) readings of ceramic and wooden dowels vs gravimetric measurements of water contents embedded in Portland limestone samples (LPD, LPE).

Stage 3 results: Depth penetration of handheld moisture meters

Results from experiments with dry/wet Clipsham limestone stacks

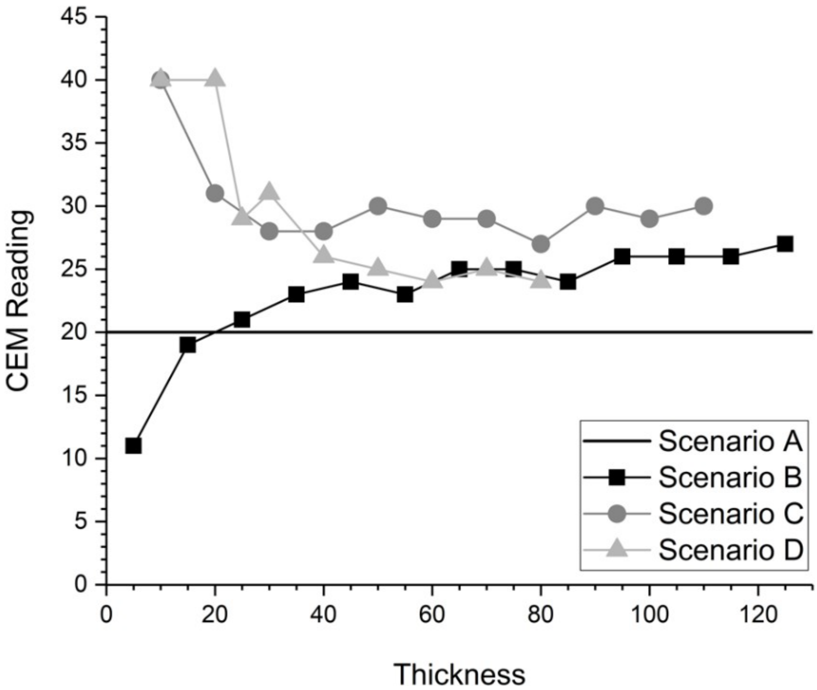


Fig B.34: CEM readings in the four measurement scenarios as a function of the total stack thickness. The measurement at 10mm stack thickness in Scenario C and those at 10 and 20mm stack thickness in Scenario D were taken without a dry upper layer.

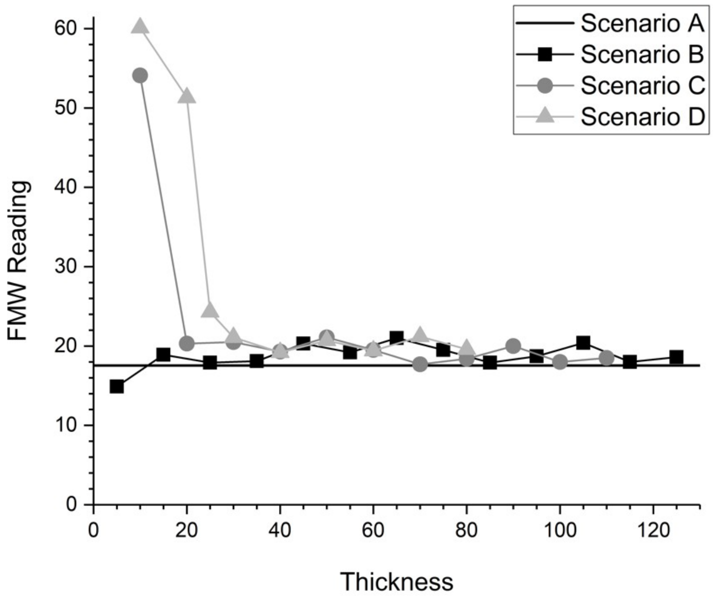


Fig B.35: FMW (10mm mode) readings in the four measurement scenarios as a function of the total stack thickness. The measurement at 10mm stack thickness in Scenario C and those at 10 and 20mm stack thickness in Scenario D were taken without a dry upper layer.

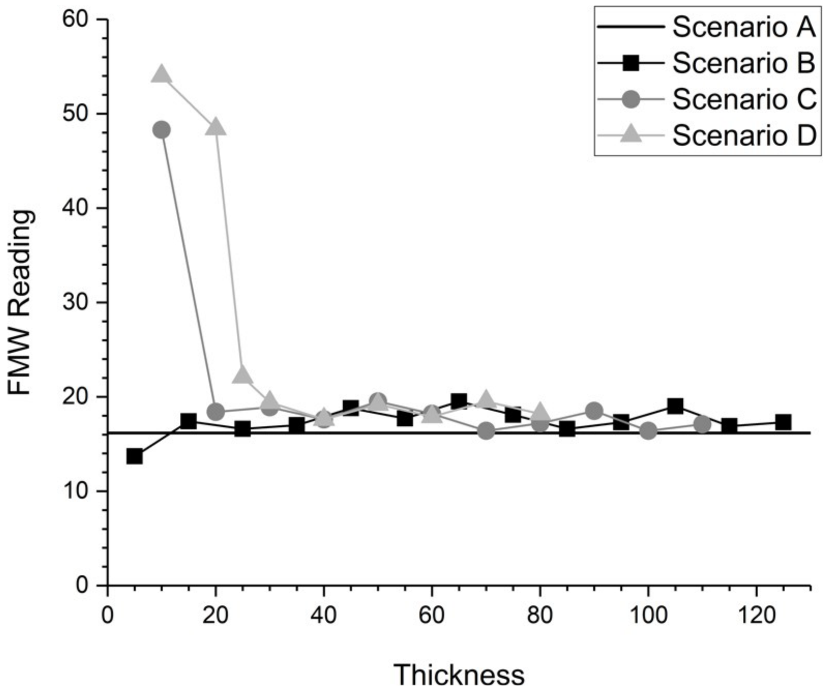


Fig B.36: FMW (20mm mode) readings in the four measurement scenarios as a function of the total stack thickness. The measurement at 10mm stack thickness in Scenario C and those at 10 and 20mm stack thickness in Scenario D were taken without a dry upper layer.

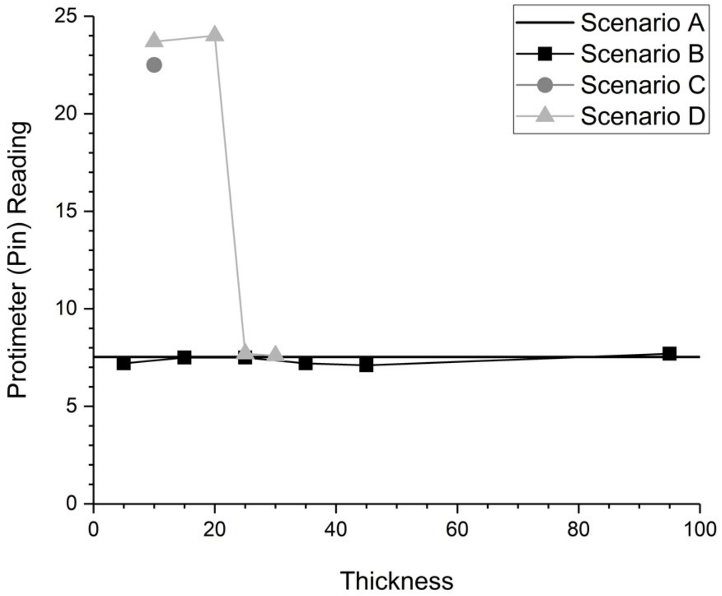


Fig B.37: Protimeter (resistance ['Measure'] mode) readings in the four measurement scenarios as a function of the total stack thickness. The measurement at 10mm stack thickness in Scenario C and those at 10 and 20mm stack thickness in Scenario D were taken without a dry upper layer.

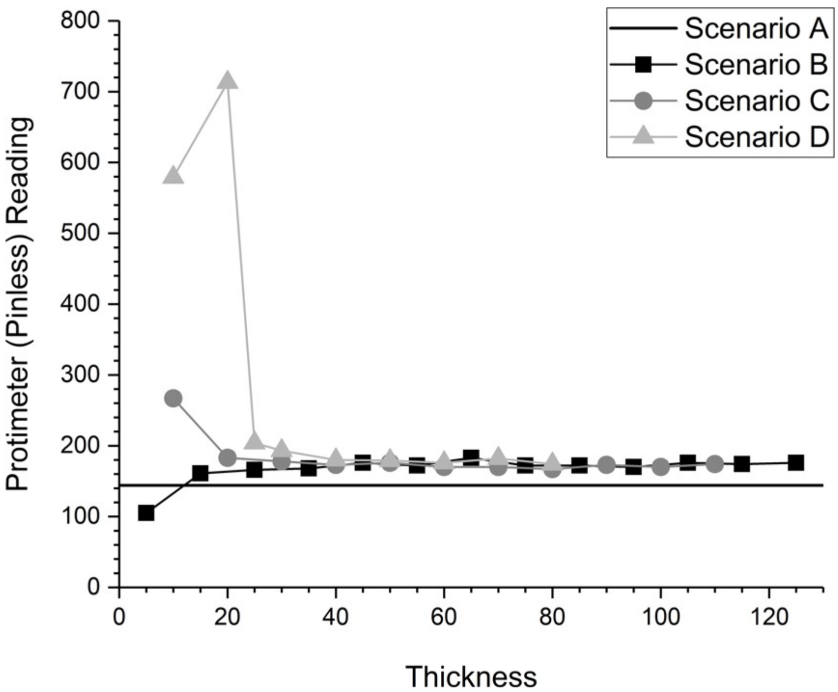


Fig B.38: Protimeter (capacitance ['Search'] mode) readings in the four measurement scenarios as a function of the total stack thickness. The measurement at 10mm stack thickness in Scenario C and those at 10 and 20mm stack thickness in Scenario D were taken without a dry upper layer.

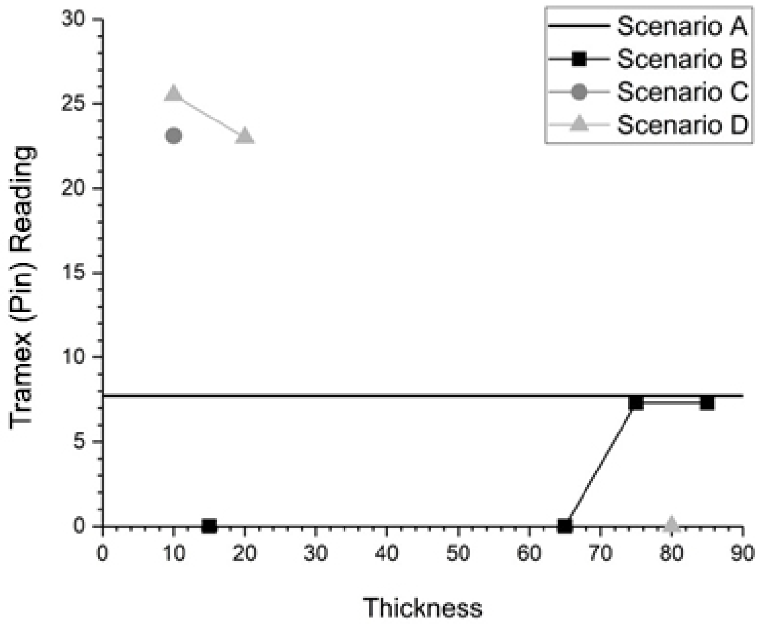


Fig B.39: Tramex (resistance ['Pin'] mode) readings in the four measurement scenarios as a function of the total stack thickness. The measurement at 10mm stack thickness in Scenario C and those at 10 and 20mm stack thickness in Scenario D were taken without a dry upper layer.

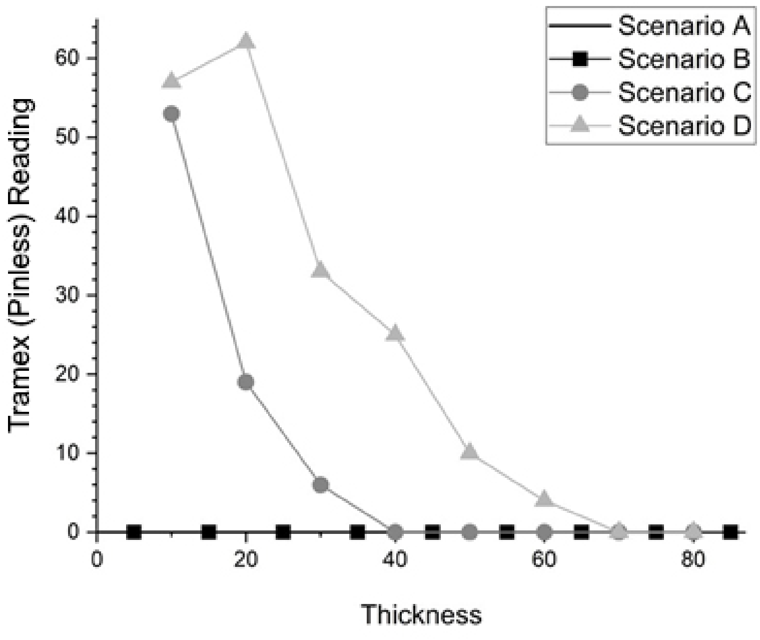


Fig B.40: Tramex (capacitance ['Pinless'] mode) readings in the four measurement scenarios as a function of the total stack thickness. The measurement at 10mm stack thickness in Scenario C and those at 10 and 20mm stack thickness in Scenario D were taken without a dry upper layer.

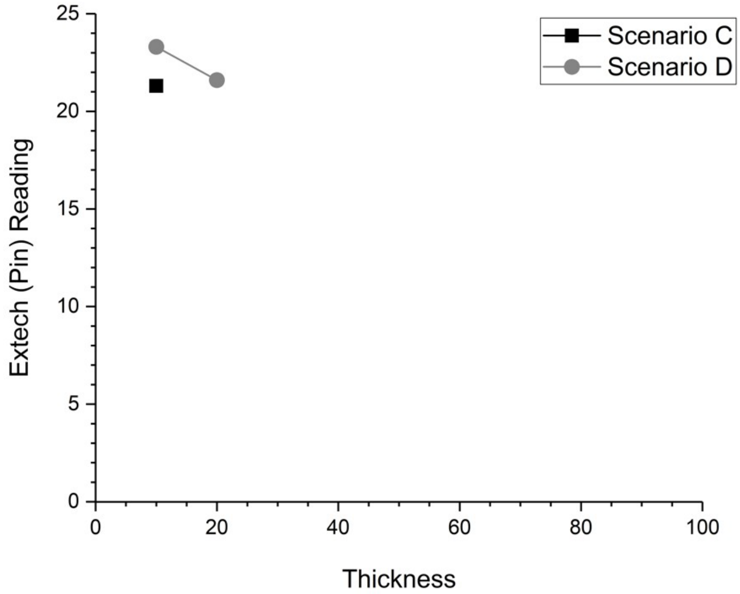


Fig B.41: Extech (resistance ['Pin'] mode) readings in the four measurement scenarios as a function of the total stack thickness. The measurement at 10mm stack thickness in Scenario C and those at 10 and 20mm stack thickness in Scenario D were taken without a dry upper layer.

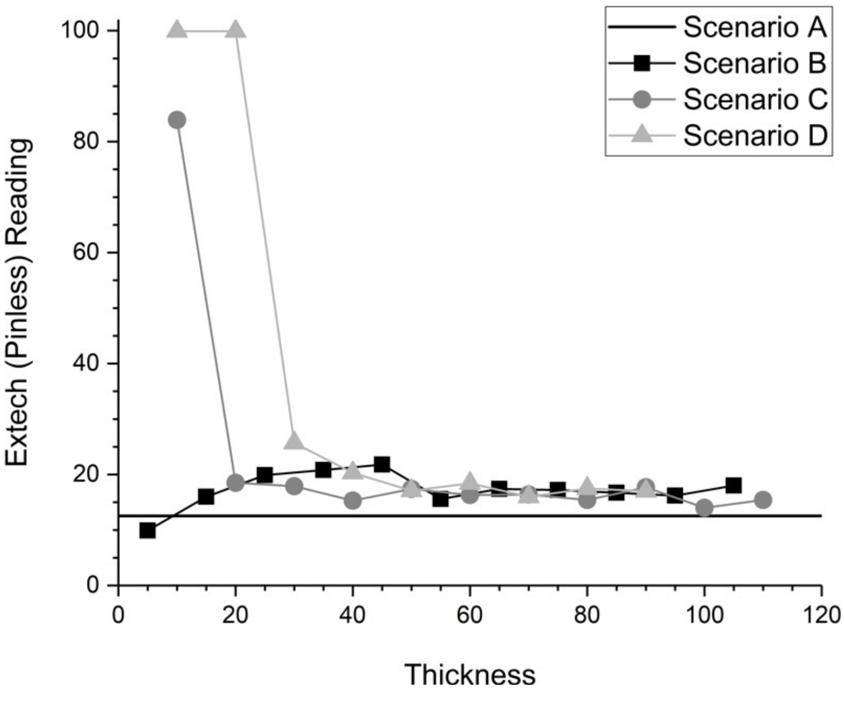


Fig B.42: Extech (capacitance ['Pinless'] mode) readings in the four measurement scenarios as a function of the total stack thickness. The measurement at 10mm stack thickness in Scenario C and those at 10 and 20mm stack thickness in Scenario D were taken without a dry upper layer.

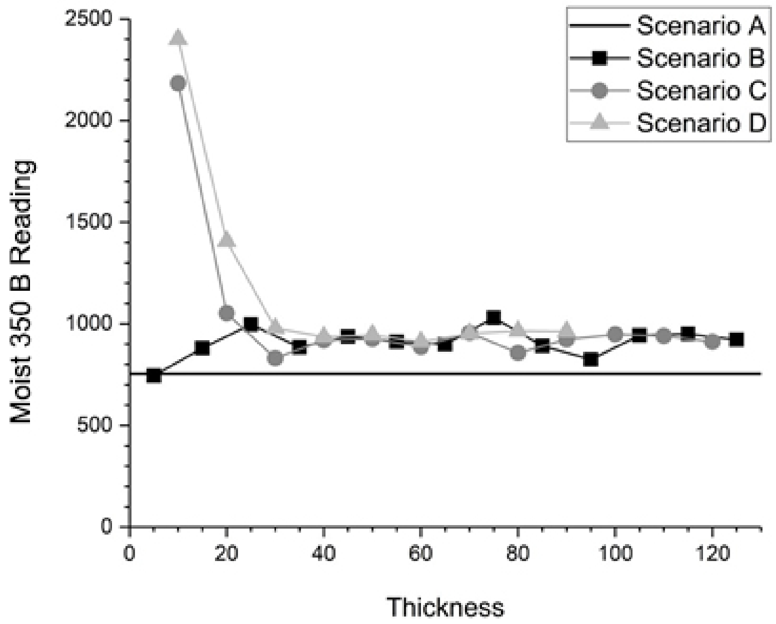


Fig B.43: MOIST 350 B (R1M sensor head) readings in the four measurement scenarios as a function of the total stack thickness. The measurement at 10mm stack thickness in Scenario C and those at 10 and 20mm stack thickness in Scenario D were taken without a dry upper layer.

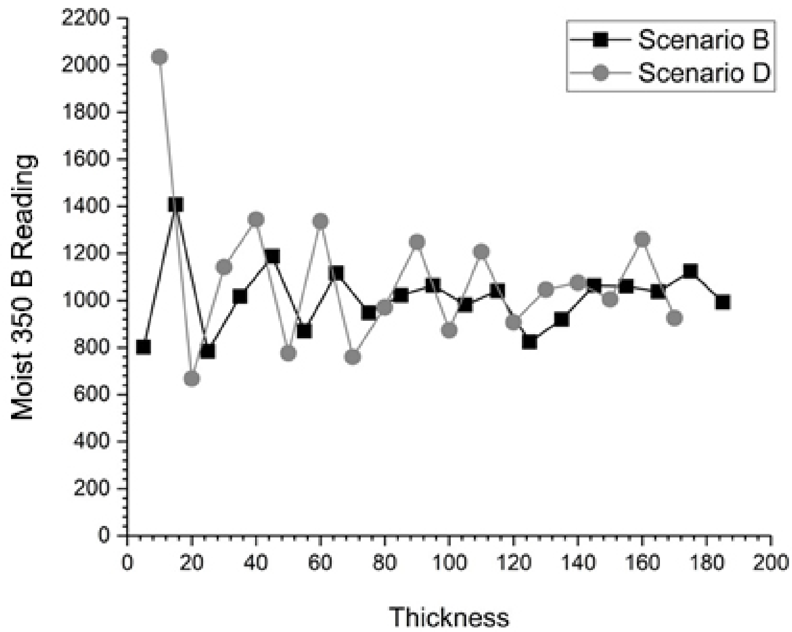


Fig B.44: MOIST 350 B (DM sensor head) readings in the four measurement scenarios as a function of the total stack thickness. The measurement at 10 mm stack thickness in Scenario C and those at 10 and 20 mm stack thickness in Scenario D were taken without a dry upper layer.

Results from experiment with metal plate under Clipsham limestone stacks

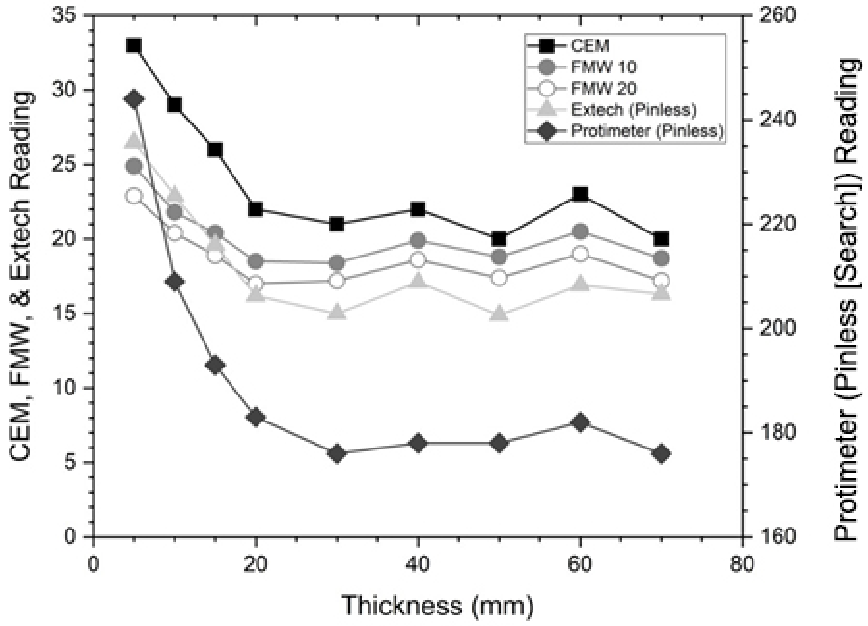


Fig B.45: Readings of CEM, FMW (10 and 20), Extech (capacitance ['Pinless'] mode) and Protimeter (capacitance ['Search'] mode) with increasing thickness of Clipsham limestone stacks on top of a thin metal plate. Note: Protimeter (capacitance ['Search'] mode) uses different y axis.

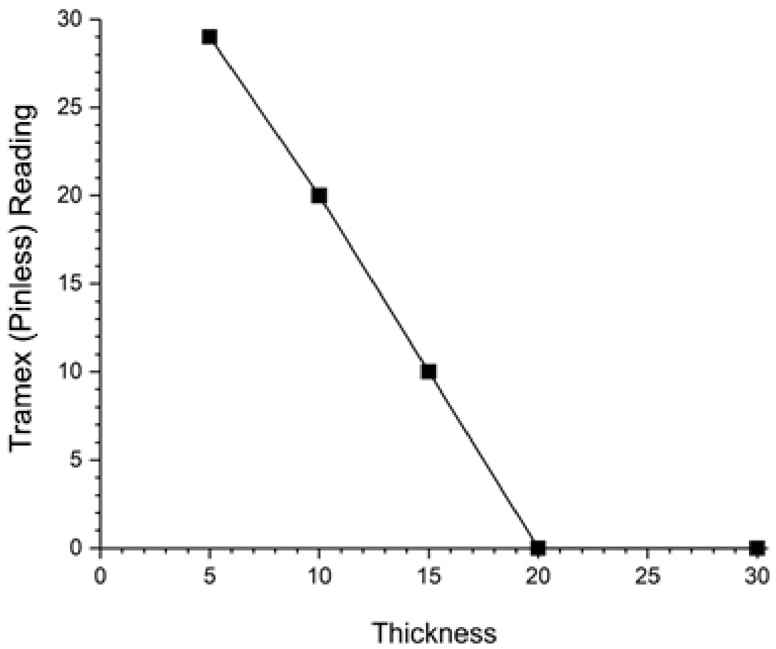


Fig B.46: Readings of Tramex (capacitance ['Pinless'] mode) with increasing thickness of Clipsham limestone stacks on top of a thin metal plate.

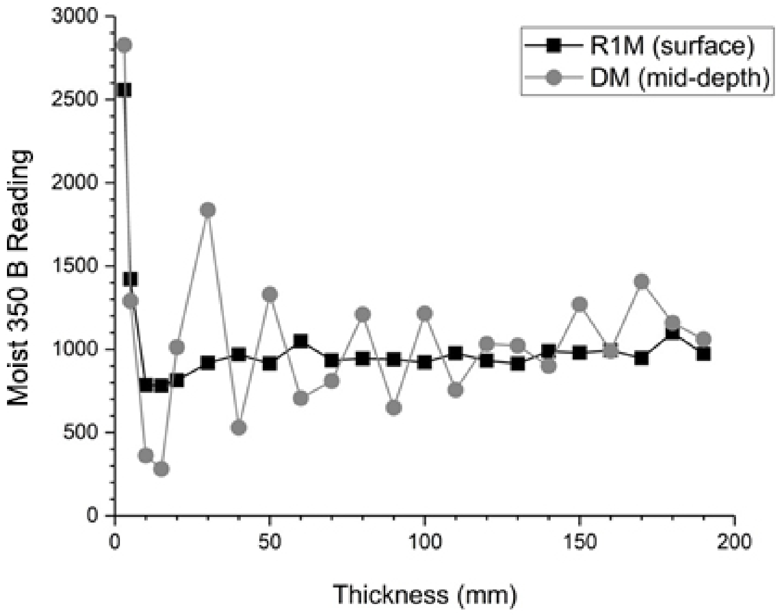
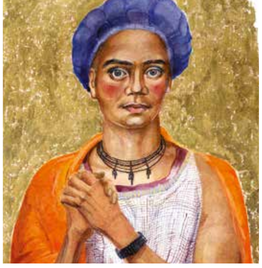


Fig B.47: MOIST 350 B readings (with R1M and DM sensor heads) with increasing thickness of Clipsham limestone stacks on top of a thin metal plate.



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