Thermal probe technology for buildings: the transition from laboratory to field measurements

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Abstract

This article reports the results of an investigation into the transfer of thermal probe measurement technology from laboratory use to actual buildings in order to undertake the in situ determination of thermal material properties. The imperative for using in situ measurements is 1) the impact of moisture content on thermal properties, 2) the possible wide range of variation of properties across most materials used in construction, and 3) the lack of data for new and innovative materials. Thermal probe technology offers the prospect of taking building specific data, addressing these issues.

Based on commercially available thermal probes a portable measurement kit and accompanying measurement procedure have been developed. Three case study buildings, each having different materials, have been studied to ascertain whether or not the technique can be transferred to relatively uncontrolled environments while remaining capable of achieving a precision that is similar to an ASTM standard that can be related to thermal conductivity measurements of building materials. The results show that this is indeed the case, and that the use of thermal probe technology may yield thermal properties that vary significantly from the laboratory values currently used in building thermal engineering calculations.

Keywords: thermal probe; measuring building material properties, thermal conductivity, energy use, earth buildings, cob.

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The rationale for in situ thermal measurements

Energy use in buildings has a significant effect on the global environment with some 15% of UK greenhouse gas emissions attributable solely to the heating of domestic properties DTI (2002). Reduced energy consumption in buildings, whether existing or proposed, requires reliable data on the thermal properties of building materials. This data is now invariably obtained from measurements carried out on samples under laboratory conditions and not from in situ measurements, which gives rise to the following 3 problems in practice:

(a) The moisture content of the representative material sample used in laboratory studies can have a significant effect on its effective thermal conductivity Salmon, et al (2002), and may be different to that of the actual material in the building on site and under actual use conditions.

(b) The steady state techniques, such as guarded hot plate or two box methods, commonly used in laboratory measurements, require long times to achieve thermal equilibrium. As shown by Doran (2000), during this time, moisture present within typically hygroscopic building materials migrates and evaporates, resulting in altered thermal properties.

(c) A material sample used in the laboratory may not share all qualities of the bulk material on site through varied manufacturing processes and/or differences in raw materials. As an example, a standard reference work Touloukian, et al (1970) gives 338 thermal conductivity values for the building material concrete.

Using a thermal probe offers an alternative transient method to laboratory-based thermal measurement techniques that has good prospects for measuring the thermal conductivity and potentially, the thermal diffusivity of building materials on site. This technique has already been used successfully in other industries, such as geotechnics ASTM CommitteeD18 (2000), food Xie and Cheng (2001), plastics ASTMD20 (2005) Underwood and McTaggart (1960) Zhang and Fujii (2003) and refractory brick manufacture ASTMC8 (2004) Davis (1984); it has been successfully applied to building materials under laboratory conditions by Goodhew and Griffiths (2004). However, when this method is to be used in situ to undertake measurements on actual buildings the technique will be subject to a relatively uncontrolled environment with fluctuations, for example. changes in air temperature, wind speed and solar irradiation.

The prime goal of the research described in this article is to investigate the transferability of the thermal probe technique from the laboratory to in situ measurements upon materials in real buildings. As criterion for the success of the transfer, the accuracy obtained in situ will be compared to a ±15% precision that can be obtained by adhering to an ASTM standard for measuring the properties for soils and soft rock ASTMD18 (2000). This existing standard has been selected as it applies to materials that are in some ways similar to commonly used construction materials like brick and concrete.

Apart from general applicability and accuracy, the problems with transferring thermal probe technology from existing uses in other disciplines and the laboratory to the measurement of building materials in situ also includes probe size, contact resistance between the probe and material, and performance in thermally unstable environments. In geotechnics, long probes of 600mm or more can be used; this is not the case in buildings, where material layers are of the order of 20 to 50mm, with a wall of 200mm being considered thick. In food industries, materials are generally soft and easily penetrated allowing minute diameter probes and good thermal contact between probe and sample; in construction many materials, especially those on the outside of the building shell, are rather hard in order to withstand environmental conditions. In plastics and refractory brick industries, uncased wires may be cast into samples during manufacture, providing excellent thermal contact; with a wide variation in construction materials, the number of wires that would need to be cast into samples to cover such eventualities would make this approach economically and practically prohibitive. This article will describe the approach taken in developing a procedure that is suitable for the measurement of construction materials in existing buildings taking into account the construction-specific context.

Brief history of thermal probe theory and practice

The thermal probe employs transient line source theory, the application of which has been under development since the nineteenth century. A chart of the probe temperature rise plotted against the natural logarithm of elapsed heating time of an infinitely thin and long line source heated at constant power within an infinitely large and homogenous sample, referred to as the ‘perfect model’, should have an asymptote with slope dependent on the thermal conductivity of the sample and the intercept dependent on its thermal diffusivity. Thermal diffusivity describes the relationship between thermal conductivity and volumetric heat capacity, hence the latter is theoretically obtainable from the ratio of conductivity to diffusivity.

Schleiermacher (1988) first attempted measurements of the thermal conductivity of gases using a hot wire technique in Germany in the late nineteenth century. Stalhane and Pyk (1931), in Sweden in the early twentieth century, adapted the technique and encased the hot wire, with a mercury thermometer attached, forming a similar style probe to that used today, albeit with older technology. Seminal work was carried out in the 1950s, in the Netherlands, UK and Canada, by, for example: Van der Held and van Drunen (1949); Hooper and Lepper (1950); Carslaw and Jaeger (1959); Blackwell J.H. (1952, 1954); Vos (1955); and Woodside (1958). These developed guidelines for sample size, recommendations on probe length to radius ratios, and mathematical corrections to emulate the perfect model. An equation, sometimes known as Blackwell's equation, based on Fourier's theories of heat conduction, was developed to describe the chart of temperature rise over natural logarithm of elapsed time. Derivations of this equation are in use today in the various industries referred to above, where various iterative line fitting routines and regression analysis techniques are used to establish thermal properties. An accuracy of better than 3% for thermal conductivity and 5% for thermal diffusivity is often claimed for individual measurements, although recent comparative studies have shown variations greater than 10% for thermal conductivity values achieved for similar materials, and greater again for thermal diffusivity, when the technique is used across a range of materials in separate laboratories Tye, et al (2005) Kubicar (1999) Spiess, et al (2001). Thermal probes are currently commercially available from different companies like Decagon and Hukseflux, albeit for use in non-building related disciplines.

Transfer from laboratory to in situ measurements on buildings

Thermal probe measurements are normally undertaken in thermally stable conditions, such as can be created in a laboratory. This research bases itself on an apparatus and analysis methodology created by Goodhew and Griffiths (2004) to measure thermal properties of building materials in the laboratory, with development of a portable apparatus for in situ measurements.

The following research and development steps have been undertaken to transfer the existing analysis technique from the laboratory to in situ measurements on buildings:

(1) development of a portable and autonomous measurement apparatus that can be operated by one person, is rigid enough to withstand transport, and allows measurements to take place on site and within a limited time frame;

(2) development of a procedure for installing the equipment on site, carrying out the actual measurements, and storing and processing the resulting data;

(3) field tests on three case study buildings in order to assess the use of the measurement apparatus and procedure to measure the thermal properties of materials in actual buildings, within relatively uncontrolled environmental conditions. An existing ASTM standard for measuring the properties of soils and soft rock ASTM18 (2000) has been used as criterion for considering the technique either applicable, or not. This ASTM standard has been demonstrated to achieve a measurement precision in between ± 10% and ± 15% in a study comparing probe results with known values of materials studied. It is applicable to a ‘limited range’ around ambient room temperatures.

Experimental measurement equipment

The measurement apparatus developed for this research is built around the use of four commercially available Hukseflux TP08 thermal probes. These are connected to a power circuit running from batteries, a 16 bit datalogger, and a display unit, all mounted in a rugged transit case. If so desired the apparatus can be connected to a laptop for on-site data analysis; alternatively this data can be post-processed away from the site.

Figure 1 shows a TP08 thermal probe consisting of a base and needle. The base contains a platinum resistance thermometer and the two cold junctions of a K type thermocouple. The needle is a stainless steel tube, 72mm long, 1.2mm external diameter, containing a hairpin heater of known resistance per unit length, and the hot junction of the thermocouple, which is placed near the centre of the heater Hukseflux (2001). The probe size was chosen as the needle length is suitable for many building material applications found in practice, where 100mm is a commonly encountered thickness of walling and other materials, and as thereby the ratio of length to diameter of the probe needle at 60:1 exceeds Blackwell's recommendation of 20:1 Blackwell and Misener (1951) to mimimise error from heat losses at the probe end.

The power circuit, driven by dry cell batteries in the transit case, is arranged to run at three power settings, delivering in the region of 0.1W, 0.25W or 0.5W to either one of four probes, or to a dummy heater. This dummy heater is installed to prevent excessive fluctuations in the power when the current is first directed to a probe; it has a resistance which is close to that of a TP08 heater, allowing a simple redirection of power. The current through a probe heater is determined by measuring the potential difference across a standard resistor placed in series with it. Knowing the current in the circuit and the resistance of the probe heater per unit length enables the power, or heat, emitted per unit length of the probe (Q') to be established.

A high resolution dt800 data logger by Datataker is used to observe and record: 1) the potential difference across the standard resistor, 2) the resistance of the platinum resistor in the probe base, and 3) the electromotive force of the K type thermocouple, all at 1Hz. The data acquisition is observed by running the dedicated software package Delogger Pro v.4 on a connected laptop.

Experimental measurement procedure

For the equipment as described in the previous paragraph a routine field measurement technique has been developed following Batty et al (1984) and Yang et al (2002) but adapting the procedure to the specific conditions encountered with building materials.

Arriving on site holes are drilled to accept the probes. The probes are placed in situ surrounded by a high thermal conductivity filler paste, originally developed to improve thermal contact between computer processor units and heat sinks. The datalogger and laptop are set to run and record and the power circuit is switched on with power directed to the dummy heater

Previous work in the laboratory has shown that hole diameters up to 2mm do not significantly effect thermal conductivity value outcomes (Pilkington, 2005a). Here, 1.5mm diameter HSS drill bits are used in softer materials, such as aerated concrete block, and 2mm diameter HSS drill bits used to penetrate harder materials, such as lime mortar.

Probes are left in situ for 30 minutes to ensure thermal equilibrium with the material. Power is then directed to each probe in turn for 5 or 10 minutes with a suitable break between heating cycles. The heater current is initially set after a visual assessment of the material to estimate its thermal conductivity and can be adjusted following the first heating shedule to ensure the temperature rise meets appropriate levels, speeding up the process which alternatively would involve trial-and-error to obtain correct settings. The heating cycles are repeated after at least an hour, when the residual heat from the previous measurement has dissipated. Temperature stabilisation can be observed via a chart in the data acquisition window of the software program. A number of measurements are recorded for each specific probe position and data stored for later analysis.

A semi-automated work book has been built in MS Excel to carry out post measurement analysis, either on site on a laptop or away from the site in an office environment. The platinum resistance measurement is converted to temperature using the standard formula to give the probe base temperature. The electromotive force of the thermocouple is converted to a temperature difference using an appropriate formula provided by the probe manufacturer that sufficiently approximates the K type polynomial expression Childs, (2001) over the small range of temperature changes encountered, typically in the region of 7-10°C.

Data is arranged into standardised electronic files and stored for each heating cycle. Datasets are then imported into the MS Excel workbook where a macro is run to carry out the calculations required to convert resistance and voltages to probe temperature and power. The current technique charts the temperature of the probe for 200 seconds prior to the heating cycle to enable the user to assess potential drifts in the material sample temperature that might impact results.

A chart of probe temperature rise over the natural logarithm of time is created, which can be visually assessed for a linear asymptote. The macro calculates a series of thermal conductivity values by traditional regression analysis using equation (1) over 10s, 50s, 100s and 150s periods starting at each second of the heating cycle, and charts the results.

$$\lambda = Q' / 4\pi \, [\Delta T / \ln (t)] \qquad (1)$$

From a visual inspection of the charts of ΔT / ln(t) and of λ for the periods above, an appropriate time section can be chosen, where a linear asymptote exists through sufficient data points, for further analysis. The methodology previously developed by Goodhew and Griffiths (2004) is then employed to establish values of thermal conductivity using this time section, with 95% confidence.

In situ measurements on case study buildings

Testing of the measurement equipment and procedure took place by means of application to three case study buildings, where properties of materials incorporated in those buildings were measured in situ. The buildings were chosen as they were easily accessible, the wall thicknesses were suitable for the probe, and previous laboratory based studies had been carried out on similar materials, which allowed comparison of data quality and results between laboratory and field measurements.

During field studies the external conditions with regard to the weather, ambient temperature and relative humidity were logged. Where practically feasible the equipment was sheltered from direct solar radiation. For each material, measurements were taken using four different probe positions, and using multiple heating cycles on each probe.

Results of field testing

Three case study buildings were chosen for this study: an eco-house in North Cornwall with walls constructed of insulating aerated concrete blocks with lime render (building one); a mass cob bus shelter and toilet block at the Eden Project in Cornwall (building two); and a summerhouse in Devon formed with cob blocks, some with a sheep's wool binder (building three). For those readers unfamiliar with the term cob, it is used in South West England to describe the use of a vernacular building material. Cob is a mixture of subsoil and straw and produces monolithic walls approximately 500mm thick in layers approximately 300mm deep without the use of formwork. Cob blocks are made from similar ingredients, but are produced from moulds and can be used in more flexible circumstances.

Building one – aerated concrete block

Figure 2 shows building one, a single storey dwelling, constructed of 250mm thick solid walls formed from Celcon Solar aerated concrete blocks. The interior is fully lime rendered and externally lime rendered and part timber clad on a foundation of Celcon aerated concrete foundation blocks. The building sits on a slope with foundation blocks exposed to the lower side. Internal and external measurements were taken at wall head and wall foot and also externally below damp course level.

The manufacturer's literature gives thermal conductivity values of 0.11 $Wm^{-1}K^{-1}$ and 0.15 $Wm^{-1}K^{-1}$ for Solar and Foundation blocks, respectively. Celcon Solar samples were previously measured with the thermal probe methodology under laboratory conditions at various moisture contents, giving results for thermal conductivity from 0.193 $Wm^{-1}K^{-1}$ at 4.6% moisture content by weight to 0.113 $Wm^{-1}K^{-1}$ for a dry block (Pilkington, 2005b).

The in situ measurements took place in June 2005, during hot, sunny weather. External measurements were taken in the morning on a west facing wall (see figure 2) with ambient temperatures in the region of 19°C and relative humidity starting at 74%, dropping to 62% through the morning. Internal measurements were taken during the afternoon in the kitchen area on a south facing wall, exposed to an expanse of east facing glazing, with ambient temperatures in the region of 29°C and relative humidity in the region of 48%.

Figure 3 shows measurements of a probe's needle and base temperatures before, during and after an internal measurement. The needle temperature stabilises with that of the sample after approximately 150s, from insertion at 14:07, and remains reasonably stable until the heating cycle starts at 15:14. The temperature drift (y) with time (x) of the probe for 200s prior to heating, found by calculating the slope of the data trend in MS , was given by equation (2). The drift was found to be insignificant in comparison with the requirements of the standard test method, ASTM Committee (2000).

$$y = 27.193-6E-10^{-6}x \tag{2}$$

Figure 4 shows the temperature rise of the heating period for the same measurement, plotted on a logarithmic scale, becoming linear after approximately 60s. A similar pattern was found in all 6 locations and a section from 60s to 250s was used for analysis in each case. The resulting thermal conductivity values are given in table 1.

Table 1. Thermal conductivity results for aerated concrete measurements

Building two – mass cob.

Figure 5 shows building two, a single storey bus shelter and toilet block known as The Body, at the Eden Project in Cornwall. Walls are of mass cob, 450mm thick, comprising approximately 39% white china clay, 59% red Devon clay and 2% barley straw, by weight. They are left exposed externally and are finished with 10mm of clay plaster internally. The cob walls sit on a 450mm high stone plinth and are protected from water ingress at their head by wide projecting eaves. The building has permanent unglazed openings, allowing free ventilation. The roof is predominantly of translucent Perspex sheet with some corrugated metal sheet. Measurements were taken externally at the foot and head of the north west facing wall and internally at the foot and head of an internal partition wall of matching construction.

Many values for the thermal conductivity of cob or unbaked earth can be found in the literature. Goodhew et al (2000) use 0.45 $Wm^{-1}K^{-1}$ for cob made from Devon earth, while Goodhew & Griffiths, (2005) notes values used in practice are often approximations based on materials with similar density. Norton (1997) gives values of 0.45 $Wm^{-1}K^{-1}$ or 0.65 $Wm^{-1}K^{-1}$ with added stabiliser. Oughton (1986) gives a range of earth values between 0.43 $Wm^{-1}K^{-1}$ for relatively dry mud to 1.7 $Wm^{-1}K^{-1}$ for damp Liverpool clay. Little and Morton (2001) suggest 0.65 $Wm^{-1}K^{-1}$ whereas Middleton (1987) gives a range between 1.3 $Wm^{-1}K^{-1}$ and 1.4 $Wm^{-1}K^{-1}$. Previous thermal probe laboratory studies by the authors have produced values similar to all the above, dependent on density, soil types, mix proportions and moisture content.

The in situ measurements took place over two hot days with broken cloud in June and July 2005. Ambient temperatures ranged from 23°C to 37°C and relative humidity from 22% to 62%. The layout of the building and the glazed roof areas meant that hole positions were sometimes exposed to direct solar irradiation and sometimes shaded.

Figure 6 shows measurements of a probe's needle and base temperatures before, during and after five measurements at the internal wall head while intermittently exposed to solar irradiation under a clear Perspex roof. The thermal lag of the cob creates a dampening of the ambient environmental conditions within the material. For example, the temperature drift y with time x of the 200s prior to the third heating cycle, given by equation (3), is approximately 0.01°C, or only 10% of the ASTM standard allowance ASTM Committee, (2000).

$$y = 6E\text{-}05x + 26.013 \tag{3}$$

Figure 7 shows the temperature rise of the heating cycle for the same measurement, plotted on a logarithmic scale, becoming linear after approximately 50s. A similar pattern was found in all 4 locations and a section from 50s to 200s was used for analysis in each case. The resulting thermal conductivity values are given in table 2.

Table 2. Thermal conductivity results for mass cob measurements at The Body

Building Three – cob blocks

Figure 8 shows building three, a single storey summerhouse located in a sheltered setting in the UK county of Devon. It is constructed with a mixture of exposed cob block types, with and without a lambswool binder, over a stone plinth, forming 240mm thick walls, under a thatched roof.

Internal and external measurements were taken at the wall head and foot on an overcast day in September 2005. Ambient temperature was in the region of 18°C and relative humidity 87%.

Figure 9 shows the measurement of a probe's needle and base temperature before, during and after one heating cycle of a cob block measurement. The ambient temperature fluctuation is slight and not immediately reflected in the probe needle temperature. The temperature drift y with time x of the 200s prior to this heating cycle, given by equation (4), is approximately 0.03°C.

$$y = 0.0001x + 17.041 \tag{4}$$

Figure 10 shows the temperature rise of the heating cycle for a cob block measurement, plotted on a logarithmic scale. The best estimation of linearity for this measurement was between 150s and 250s. The pattern varied between measurements and various time sections were used in the analysis. The resulting thermal conductivity values are given in tables 3-6.

Table 3. Cob Block with lamb's wool, external, wall head**.**

Table 4. Cob Block, external, above plinth.

Table 5. Cob Block with lamb's wool, internal, wall head.

Table 6. Cob Block, internal, above plinth.

Conclusions and recommendations

The prime goal of this article is to investigate the transferability of the thermal probe technique from the laboratory to in situ measurements on real buildings through in situ measurements on three case study buildings.

Data analysis shows that in situations where ambient environmental fluctuations are slight, as at buildings one and three, similar accuracy to that obtained in laboratory studies can be achieved: variability values (SD/mean) as calculated are in between 0.11 and 7.03 percent. Where more extreme fluctuations occur, as at building two, variability increases to a range of 4.60 to 11.60%. The precision of all measurements undertaken on the three case study buildings has an accuracy that is in excess of precision of ± 15% that is indicated on the ASTM standard for soils and soft rock (2000). As far as can be concluded from the work on three cases only, it therefore is valid to apply the thermal probe technique to in situ measurements on real buildings.

The case studies also confirm the high level of variation found in similar materials. The thermal conductivities of the various cob types studied here ranged from 0.448 $Wm^{-1}K^{-1}$ to 1.165 $Wm^{-1}K^{-1}$ despite similar location and apparent density. The thermal probe will measure the thermal conductivity of materials as actually present in a building, accounting for variations according to location, moisture content, mix and manufacturing processes.

Part of the rationale for developing the thermal probe technique for field measurements on buildings on site and in use is the impact of moisture content on the thermal properties of materials. While the initial case studies do not allow for hard conclusions on the impact of moisture content on the values obtained, it is noted that for instance the thermal conductivity of the internal walls of building one were higher than those achieved in dry blocks: the calculated design U value for the walls was 0.44 $Wm^{-2}K^{-1}$ whereas, if using an average of values found above the damp proof course, the value becomes 0.51 $Wm^{-2}K^{-1}$. It is highly probable that these findings relate to moisture content, either through hygroscopic moisture uptake or through moisture transfer through the solid walls. If this is indeed the case, this raises substantial doubts on the use of thermal properties that are obtained with other techniques like the guarded hot-plate method that evaporate the moisture content of a material sample during measurement. Consequently, there might be a substantial margin of error in using 'established data' for energy calculations.

During this research three important issues have been identified that need further study:

(1) The derivation of values for thermal diffusivity from collected field data has been attempted, which would then give values for volumetric heat capacity. The results show potential through levels of repeatability similar to that found with thermal conductivity measurements, but need further analysis.

(2) Further work is needed to analyse the effects of contact resistances within the probe and between the probe and the material. This may lead to an improved temperature measurement methodology for the probe, such as the resistance of the heater wire being used to establish the probe temperature, to reduce compound scatter in the data.

(3) Problems have been encountered in drilling small diameter holes in hard materials, such as stone, as making a hole of length 70 mm and diameter 2 mm is not a trivial task

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Notation

The following symbols are used in this paper:

λ = Thermal conductivity ($\mathrm{Wm^{-2}K^{-1}}$)

Q' = Power to the probe per unit length ($\mathrm{Wm^{-1}}$)

ΔT = Change in probe temperature (°C)

t = Elapsed heating time (s)

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Table 1. Thermal conductivity results for aerated concrete measurements

Measurement location	Mean λ $Wm^{-1}K^{-1}$	S.D.	S.D. / Mean
Foundation block, external 120mm above ground level	0.509	0.00385	0.76%
Foundation block, external 1.5m above ground level 120mm below damp proof course	0.239	0.008816	3.69%
Solar block, external 200mm above damp proof course	0.173	0.008486	4.90%
Solar block, external 1.4m above damp proof course	0.153	0.001245	0.81%
Solar block, internal 100mm above finished floor level	0.136	0.000155	0.11%
Solar block, internal 1.68m above finished floor level	0.132	0.00016	0.12%

Table 2. Thermal conductivity results for mass cob measurements at The Body

Measurement location	**Mean λ** $Wm^{-1}K^{-1}$	**S.D.**	**S.D. / Mean**
External, 180mm above plinth 600mm above ground level	1.165	0.098	8.44%
External, 650mm below wall head 2.67m above ground level	0.810	0.094	11.60%
Internal, 180mm above plinth 600mm above finished floor level	0.824	0.038	4.61%
Internal, 900mm below wall head 2.23m above finished floor level	0.987	0.100	10.09%

Table 3. Cob Block with lamb's wool, external, wall head

Run	Probe	Time Period for RegAnls	Mean λ
A	TP08 131	50-150s	0.850
E	TP08 131	60-160s	0.877
L	TP08 142	60-160s	0.870
P	TP08 142	60-160s	0.826
S	TP08 141	50-150s	0.867
		Mean:	0.858
		Standard Deviation:	0.0205
		SD/Mean	2.38%

Table 4. Cob Block, external, above plinth

Run	Probe	Time Period for RegAnls	Mean λ
B	TP08 132	150-250s	0.536
F	TP08 132	60-160s	0.521
K	TP08 141	60-160s	0.547
T	TP08 142	70-170s	0.536
		Mean:	0.535
		Standard Deviation:	0.0107
		SD/Mean	2.00%

Table 5. Cob Block with lambs wool, internal, wall head

Run	Probe	Time Period for RegAnls	Mean λ
C	TP08 141	60-160s	0.644
G	TP08 141	100-200s	0.699
J	TP08 132	100-200s	0.718
N	TP08 132	70-170s	0.649
Q	TP08 131	90-190	0.760
		Mean:	0.694
		Standard Deviation:	0.0487
		SD/Mean	7.02%

Table 6. Cob Block, internal, above plinth

Run	Probe	Time Period for RegAnls	Mean λ
D	TP08 142	120-220s	0.474
H	TP08 142	80-180s	0.423
I	TP08 131	70-170s	0.444
M	TP08 131	50-150s	0.433
R	TP08 132	100-200s	0.466
		Mean:	0.448
		Standard Deviation:	0.0216
		SD/Mean	4.82%

Figure 1. A TP08 thermal probe

Figure 2. Building one, with a thermal probe inserted in the foundation blocks 120mm below the DPC, supported on a boom stand.

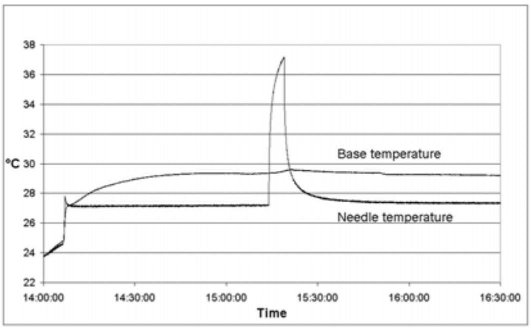

Figure 3. Probe base and needle temperatures, before, during and after a measurement of aerated concrete exposed to ambient temperature changes.

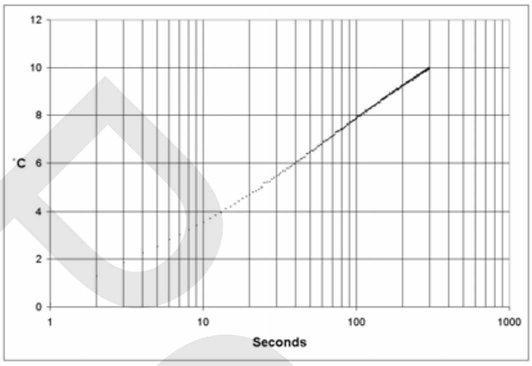

Figure 4. Temperature rise of a measurement in aerated concrete plotted against elapsed time on a logarithmic scale.

Figure 5. Building two, The Body at the Eden Project, Cornwall

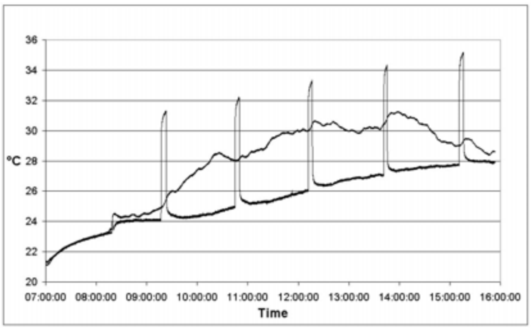

Figure 6. Probe base and needle temperatures, before, during and after five needle heating cycles for mass cob measurements, with apparatus and wall surface intermittently exposed to solar irradiation

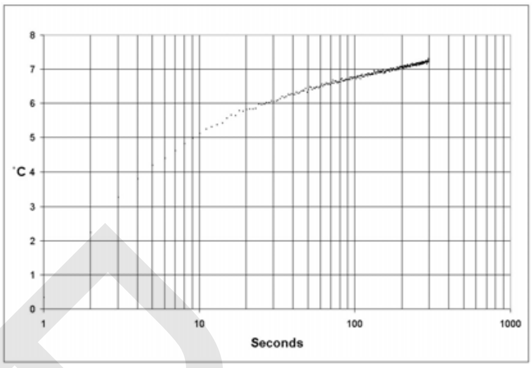

Figure 7. Temperature rise of a measurement in mass cob plotted against elapsed time on a logarithmic scale.

Figure 8. Building three, Summerhouse, Bovey Tracy, Devon

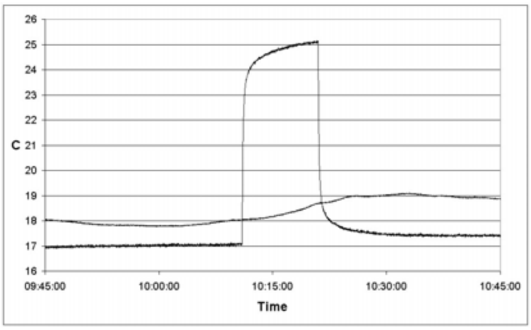

Figure 9. Probe base and needle temperatures, before, during and after a heating cycle for a cob block measurement.

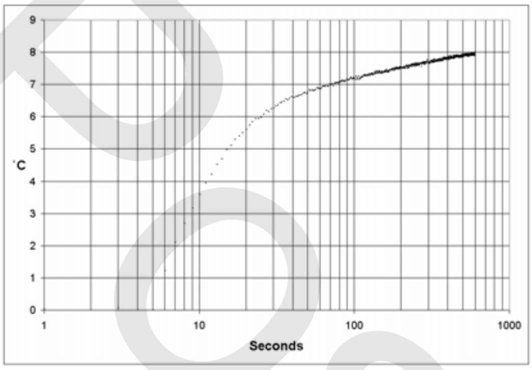

Figure 10. Temperature rise of a measurement in cob block plotted against elapsed time on a logarithmic scale.

Figure 1. A TP08 thermal probe

Figure 2. Building one, with a thermal probe inserted in the foundation blocks 120mm below the DPC, supported on a boom stand.

Figure 3. Probe base and needle temperatures, before, during and after a measurement of aerated concrete exposed to ambient temperature changes.

Figure 4. Temperature rise of a measurement in aerated concrete plotted against elapsed time on a logarithmic scale.

Figure 5. Building two, The Body at the Eden Project, Cornwall

Figure 6. Probe base and needle temperatures, before, during and after five needle heating cycles for mass cob measurements, with apparatus and wall surface intermittently exposed to solar irradiation

Figure 7. Temperature rise of a measurement in mass cob plotted against elapsed time on a logarithmic scale.

Figure 8. Building three, Summerhouse, Bovey Tracy, Devon

Figure 9. Probe base and needle temperatures, before, during and after a heating cycle for a cob block measurement

Figure 10. Temperature rise of a measurement in cob block plotted against elapsed time on a logarithmic scale.