

# Development of a Probe for Measuring In-situ the Thermal Properties of Building Materials

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**ABSTRACT:** Environmentally benign materials, such as cob, rammed earth, straw and hemp are increasingly being used in construction, often in efforts to develop sustainable buildings. While this is advantageous from the point of view of embodied energy and use of local resources, it does cause concerns in the thermal engineering of buildings constructed from such materials. The thermal properties are often unknown, dependent on their in-situ production process, moisture content and local resources used. They may be of a composition that has not been entered into material properties' handbooks or (in vernacular buildings) information on their composition may have been lost over time or be anecdotal.

A variety of technical equipment is available to identify the thermal properties of materials, the more common being the guarded hot plate apparatus. Most measurements undertaken with these techniques are carried out in laboratory conditions, often requiring long times to achieve valid results. This paper reports on the development of an improved thermal probe measurement technique to enable fast assessment of the thermal properties of building materials and reports on a range of in-situ material properties measurements.

**Keywords:** thermal conductivity, thermal diffusivity, in-situ measurement, thermal probe

## 1. INTRODUCTION

The need for a fast, economical and relatively non-destructive method to establish the thermal properties of building materials, whether in-situ, site based or laboratory samples, arises as carbon emissions from fossil fuelled energy, used to heat or cool homes, escalate, and as building designers increasingly seek materials with reduced environmental impact in their manufacture. These materials often have unknown thermal properties, properties which dictate the ongoing energy requirement of buildings employing them. The same problem occurs when upgrading older housing, usually the greater consumers of fossil fuelled energy, as no records of their material thermal properties are likely to exist.

An ongoing project at the University of Plymouth, currently in collaboration with the Carbon Trust (an independent, UK Government funded company formed to promote a low carbon economy), is seeking to develop a thermal probe to measure the thermal conductivity ( $\lambda$ ) and thermal diffusivity ( $\alpha$ ) of building materials with a view to facilitating thermal behaviour models of proposed and existing buildings. Values for  $\lambda$  will enable designers to show whether new materials reach required standards of insulation to exceed current regulatory requirements, under UK Building Regulations and the European Energy Performance of Buildings Directive. Values for  $\alpha$  will equip designers to employ zero or low carbon heating or cooling strategies through quantifying and predicting the level of capture, storage and release of

passive solar or internal heat gains. Likewise, in existing buildings, establishing the current levels of material thermal properties will provide a base value on which to develop designs or strategies aimed at improving thermal performance in relation to environmental impacts.

The thermal properties of construction materials are currently measured predominantly by the guarded hot plate (GHP) method [1]. Here, a substantial sample of the material is held between, and in good contact with, a heated and a cooled plate and the heat flow across the sample, once this has moved to a steady state, is measured. Some material properties can alter during the time taken to achieve steady state [2]. Earth based materials, and common concrete products, will invariably have a moisture content when in use as part of an external wall, which moisture content alters the thermal properties of the material. The steady state of heat transfer can not be reached while moisture is in the process of evaporation or migration, brought about by the action of the GHP. The thermal probe employs a transient measurement, which has a minimal effect on moisture content and so should give a more realistic representation of actual thermal properties of placed materials. The single, small hole required to take the measurement permits the method to be considered virtually non-destructive, removing the need to take large samples from existing buildings and potentially avoiding the reluctance of home owners to have tests carried out. The probe methodology is suitable for in-situ or sample measurements, where samples are

large enough to avoid heat from the probe reaching the boundary during a measurement.

Various materials, from cob walls at the Eden Project in Cornwall to unfired earth bricks in a Scottish eco-house, have been measured during the project. This paper reports on current progress and gives some provisional values for materials that have been measured in the laboratory and in-situ.

## 2. OBJECTIVE

The early objectives of this research project were to review the existing literature on thermal probe studies, especially in regard to practical measurement of building materials in the field and review current understanding of relevant heat transfer mechanisms. Many years of previous work on thermal probe studies has been carried out at Plymouth by Goodhew and Griffiths [3] [4] who developed laboratory apparatus and analysis routines to give  $\lambda$  and  $\alpha$  values under controlled environmental conditions for many reference and construction materials, with reasonable levels of confidence and repeatability. This provided a platform from which to work. The next stage was to take the thermal probe procedure from the laboratory to practical application in the field. This required the further development of apparatus, calibration and computer analysis methods. The implications of taking measurements in 'as built' structures, at varying temperatures and with varying moisture contents, was to be investigated. New results for a range of standard and sustainable materials, including concrete block, various stones, brick, earth structures such as cob and rammed earth, straw bale and timber, all subject to varying environmental conditions, were anticipated, along with a 'handbook' methodology to make the process accessible to others.

## 3. THE PROJECT

The measurement of  $\lambda$  and  $\alpha$  of building material samples and building materials in-situ using a thermal probe employs transient line heat source theory, which is based on the perfect model of an infinitely thin, infinitely long heating element in an infinite, homogenous sample. In the perfect model, the change in temperature created by a constant power input to the heating element charted against the natural logarithm of elapsed time would give a straight line from which  $\lambda$  and  $\alpha$  could be calculated, as its gradient is dependent on the level and nature of the radial heat flow from the element into the surrounding material. In practice, the heating element, and probe needle, have limited dimensions, with thermal resistance, or conductance (H), between the probe needle components and the sample. The sample is not infinite and the level of homogeneity of most building materials is questionable, leading to a term sometimes used in this connection, 'apparent thermal conductivity' (ATC). While, in this case, it is not the true thermal conductivity of a pure material, ATC is a closer guide to the physical nature of a building

material and the heat transfer mechanisms through it, including convection and radiant heat flows through voids and anisotropic conditions, that form the basis of calculations to assess real potential heat loss.

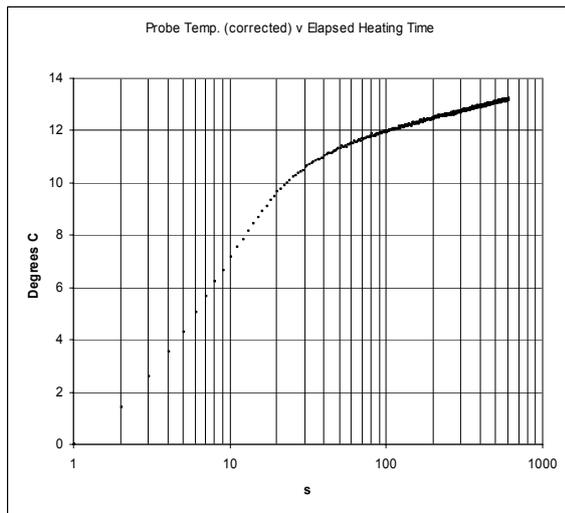
Fig. 1 shows an example of the probes used in this study with an example of a non homogenous building material, an unfired earth brick containing wood shavings, manufactured by the Errol Brick company in Scotland. Fig. 2 shows a typical heating curve, here of a cured block of lime and hemp, expressed as the change in temperature over elapsed time, plotted on logarithmic graph paper in MS Excel. The curve has a similar profile to that of change in temperature over the natural logarithm of elapsed time,  $\Delta T/\ln(t)$ . It can be seen that the line is not straight and, as the thermal properties are derived from the slope and intercept of the theoretical straight line, either assumptions have to be made concerning the behaviour of the heating pattern, or analysis of the temperature rise pattern influences has to be undertaken. An alternative method, which has been followed in the past, is to analyse the visible straight section of the line and compare results with those published. While this makes the probe viable for one material, the method does not necessarily transfer to other materials as those influences not yet quantified happen in varying proportions at different times for different types of material.



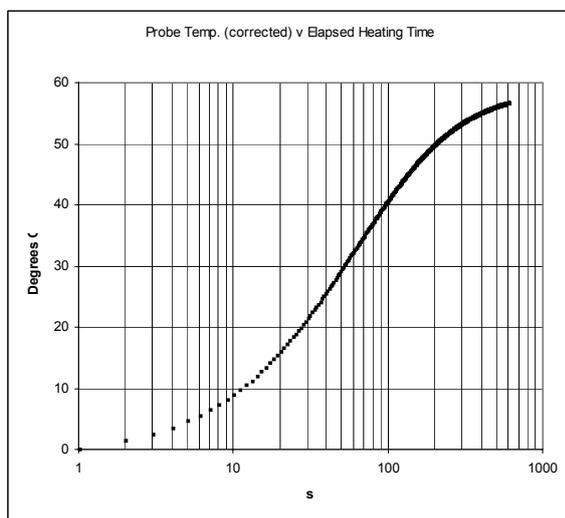
**Figure 1:** Hukseflux TP08 thermal probe and Errol unfired earth and wood shaving brick

A literature review and collaboration with mathematicians and physicists are employed in attempts to quantify the various influences acting on and around the probe during a heating cycle. These influences include the specific heat capacity and internal thermal resistances of the probe itself, the thermal resistance that always exists to varying degrees between the probe and the sample material, heat losses from the probe, apart from those radial losses to the sample which we are interested in measuring, and heat losses from the sample to other materials, including surrounding air. The first three influences have been assumed by many previous researchers to create the curve distortion at early times while the last two influences are assumed to

effect the curve at later times. What constitutes early and late times is dependent on  $\lambda$  and  $\alpha$ , creating a circular problem typical of this type of study. This creates uncertainty about results from thermal probe systems that are becoming commercially available in the food and agriculture industries should they use a measurement over the same time period for all materials. Fig. 3 illustrates a typical heating curve for an insulating material having different characteristics to those of the lime and hemp block in Fig. 2.



**Figure 2:** Heating curve at 3.24 W/m, change in temperature over elapsed time expressed logarithmically, for lime hemp block



**Figure 3:** Heating curve at 3.24 W/m, change in temperature over elapsed time expressed logarithmically, for phenolic foam insulation

It is proposed to utilise computer modelling in order to assess these current uncertainties. Work is underway in this direction, whereby the heat transfer properties of every part of the heating process can be modelled, using known heat transfer mechanisms, in

hopes that this will clarify the interaction of the various influences acting on and during the heating cycle.

Running concurrently with these explorations of theoretical physics, an experimental procedure has been developed whereby measurements are taken in the laboratory using materials of known thermal properties, the results then being compared with published results. This is complemented by measurements taken in the field, on real buildings, of similar materials, to ascertain whether results here can be given to a similar level of confidence.

This experimental procedure has led to the development, with the assistance of experienced University technicians, of a portable apparatus, rugged enough to withstand the rigours of transport and onsite activity. Early laboratory experiments and previous versions of the apparatus have informed this development.

The process of taking a measurement involves drilling a hole near to the 1.2mm diameter of the probe and just long enough, presently 72mm, to accept the length of the probe. This is currently proving impractical with hard materials such as stone or concrete and larger holes have been resorted to here. Blackwell [5] calculated the length to diameter ratio required in a thermal probe to enable confidence in the results and his calculations are generally accepted, with 20:1 being the minimum needed to achieve less than 1% inaccuracy from heat losses at the probe's ends. This imposes constraints on the probe whereby it must be strong enough to use in robust site conditions, be long enough to meet the Blackwell requirement and yet not be so long that it exceeds or comes too close to the dimensions of common building materials, often 100mm thick.

With limitations on available technology to form fine holes in many construction materials, various mediums have been trialled, with a twofold action, to compensate for larger holes, as a filler and as a contact medium, and their effect modelled experimentally. With softer mediums, such as most earth materials, a 1.5mm high speed steel drill is adequate. With light materials, such as phenolic foam insulants or spun mineral wool, the probe can simply be pushed in. Varying levels of contact filler of different types are the subject of ongoing experimental assessment.

Once the probe is inserted into the material, it is left for a time to reach thermal equilibrium and then heated at a known current, the potential difference across a series resistor is measured. The temperature rise and current are recorded at regular intervals, usually at 1 Hz. The probes are held in-situ with microphone stands when carrying out measurements onsite (see fig. 4). The data is subsequently downloaded, or it can be streamed, to a laptop computer and analysed using spreadsheets developed in MS Excel, using MS Excel macros to manipulate data, which is kept to a strictly patterned format.

Each result is stored electronically with an individual reference and kept in a directory tree. Detailed descriptions are recorded for each experimental run. Any individual result or description can be accessed from a central document containing a database of indexed hyperlinks, searchable by date, material or location. This allows any particular raw data set to be easily revisited as the analysis methodology is developed and the fixed storage pattern allows new macros to be developed as required.



**Figure 4:** Probes in-situ at a cob building at the Eden Project, Cornwall, here with reflective sheet under trial as a shading device

Building owners have generally been quite happy to have small holes drilled in their properties as a contribution towards sustainability related research with only some slight concerns about internal finishes in a newly decorated demonstration house. The 'field kit' can be easily transported by car (see fig. 5) and set up ready for a measurement in around half an hour



**Figure 5:** The 'field kit' stacked for transportation

### 3. PREVIOUS RESEARCH IN THE FIELD

The earliest reference found to transient line source theory, the basis of the thermal probe, is an

1888 study by Schleiermacher [6] of the thermal conductivity of gases by the hot wire method. Gases may be easier to measure as the contact resistance,  $H$ , is very much reduced and may be assumed as zero. In 1931, Stalhane and Pyk [7] developed a cased probe with a mercury thermometer. Seminal work was carried out by Hooper and Lepper [8], Blackwell [9], Vos [10] and Carslaw and Jaeger [11]. The limited resources available at those times, mercury thermometers, stopwatches and printed tables of logarithms rather than more sophisticated thermocouples, platinum resistance thermometers, dataloggers and computer analysis technology, limited their ability to compare multiple data sets. Each data analysis routine currently uses over 8,000 data points, many of them logarithmic and others individually calculated using fairly complex, data dependent equations.

The works of these, and many subsequent, researchers have led to the use of thermal probes and hot wire techniques in other industries, such as: refractory bricks [12] and plastics [13], where hot wires may be cast in samples during manufacture; the food industry, where fine probes can be inserted by simple pushing into samples, such as fruit, with reasonable thermal contact; and soil mechanics where probe length is not the limitation it is in building components. Various standards have been developed and are under constant review for these uses of the technique [14].

Other researchers have followed the path of a twin probe. While this facilitates the mathematical procedures of the analysis routine, it presents problems with construction materials as there is a difficulty in forming adequately parallel holes in construction materials and achieving sufficient thermal contact in each, and this technique may be more destructive than the single probe.

Despite the numerous researchers that have worked and are working in this field, one of the principal coordinators of the research, the Contact Transient Methods group of the European Conference on Thermophysical Properties currently states that claimed precision levels are not substantiated [15]. There is still much work to do to tie down the method and apply it reliably, in particular to construction materials with the range of types, thicknesses and locations.

### 4. PROGRESS AT THE UNIVERSITY OF PLYMOUTH, SCHOOL OF ENGINEERING

Building on the previous work of Goodhew and Griffiths, MS Excel analysis routines have been further developed, a 'field kit' has been created and over 600 measurement data sets have been produced, analysed and compared. Table 1 shows a sample of the results achieved so far, which should be considered merely indicative at this time. Each result is a mean average of a number of measurements taken in the same position. The

repeatability of these results, measured as the standard deviation divided by the mean value, is very good in laboratory work, as most other researchers have found, and the results from onsite measurements under various mild to extreme environmental conditions are generally within acceptable limits. While repeatability is not itself an indication of accuracy, it shows that field data may be sufficiently acceptable, once the analysis is resolved, to give reliable values for  $\lambda$  and  $\alpha$ .

The present level of repeatability is sufficient to allow consideration of comparative values for similar materials with varying levels of moisture content and work has been carried out over time in this regard measuring timbers and aerated concrete products at varying moisture content with interesting results.

Material	Mean $\lambda$ W/mK
Chestnut along the grain	0.192
Cob block internal	0.467
Cob block external	0.556
Agar immobilised water	0.613
Cob internal wall base	0.812
Cob external wall head	0.861
Cob internal wall head	0.935
Cob external wall base	1.139

**Table 1:** Indicative thermal conductivity results for a selection of studied materials

Table 1 is a small sample of results achieved. The spread of  $\lambda$  values for cob here, and in the rest of the data, shows that generic values for such materials are an unreliable method to employ for heat loss calculations. The same is likely to be true of  $\alpha$  values. The use of earth or other materials, without known thermal properties, as storage mediums for captured heat gains, solar and internal, to prevent overheating or to provide passive solar heating, would be advantaged by better understanding of this property,  $\alpha$  having a direct relationship with the volumetric heat capacity (VHC) of materials and, once the density is known, the specific heat capacity (SHC). A benefit of the methodology, if the analysis issues surrounding the calculation of  $\alpha$  can be resolved, is that only the VHC is needed to thermally model a building design, and this is potentially available for any sample, and for existing buildings without the destructive measures of taking samples to measure by other methods, such as water immersion or calorimeter.

The 'field kit' has been developed with four commercially available Hukseflux TP08 thermal probes connected to a dt800 datalogger, with independent rechargeable battery power to the heating elements and datalogger, controlled current switching, a resistor of known resistance enabling constant current monitoring and a laptop computer (see fig. 6).



**Figure 6:** The 'field kit' in its robust case, here measuring agar immobilised water during calibration exercises

Work continues building up a resource of measurement data for many material types while further investigating the physical theories involved. The H problem, how to quantify the contact resistance between the probe and sample when, in practice, hole sizes and contact levels will vary, has to be overcome. Drilling small holes, 1.5mm x 72mm, in hard materials without unduly effecting moisture content has not yet been possible despite contact with many drill bit manufacturers and alternative methods are being sought. Data scatter from thermocouple and platinum resistance thermometers has been found to have little effect on the results but work is ongoing with polynomial regression analysis being carried out to smooth small irregularities in the data before linear regression analysis routines are used to calculate thermal conductivity values.

## 5. CONCLUSIONS AND DISCUSSION

The thermal properties of so called sustainable, and common, materials need to be known when designing for low energy building, passive solar heating or passive cooling if using the physics of the building structure for these purposes. Locally produced sustainable building materials, earth, straw, lime, glass, wool, hemp and many others vary from site to site for many reasons, such as mixture proportions and soil properties. The costs and time taken to measure their thermal properties by GHP, calorimeter or water immersion may be prohibitive, preventing their uptake on regulatory or design confidence grounds. The thermal probe has potential to overcome these restrictions.

The thermal properties of existing building structures need to be known when modelling improvements in their thermal performance. The probe here has the potential to measure these in many cases, without significant damage, an important consideration in occupied or historic properties.

There are limitations to the method, practical and, currently, theoretical. It is not probable that data can be achieved to calculate heat transfer across a layered construction, such as an insulated cavity wall. Each leaf of the wall can be assessed but the filling is unlikely to be reached. Plastered walls create a difficulty as it may not be known whether the probe is penetrating the desired component or the jointing compound or the edge of each, and care has to be taken to avoid hidden services.

The thermal properties of non homogenous materials may vary greatly from place to place within the same structure, leading to the requirement for multiple measurements.

Further work is needed on the quantification of H and its effect, especially on thermal diffusivity values, where it exerts an exponential influence. Previous assumptions regarding straight line sections of the curve  $\Delta T/\ln(t)$  need to be challenged as the typical S curve achieved varies its properties as thermal values change, making reliable measurement of insulating materials currently unattainable and putting all measurements in doubt.

It is hoped that the computer modelling now embarked upon at the University of Plymouth, along with multiple measurements of a wide spectrum of materials and collaboration with other bodies will help resolve these issues.

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