

A Rational Approach to the Harmonisation of the Thermal Properties of Building Materials

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Abstract

The Energy Systems Research Unit at the University of Strathclyde in Glasgow was contracted by the Building Research Establishment to review existing data-sets of thermo-physical properties of building materials and devise vetting and conflation mechanisms. The UK Chartered Institute of Building Services Engineers subsequently commissioned a project to extract a sub-set of these data for inclusion in Guide A, Section 3. This paper reports the project process and outcome. Specifically, it describes the source of existing data, comments on the robustness of the underlying test procedures and presents a new approach to data classification and conflation.

Keywords: material thermo-physical properties, test methods, CIBSE Guide data.

Introduction

By the early 90's several modelling systems had emerged that were capable of predicting the environmental states and energy demands of a building on the basis of inputs defining form, fabric and operation. In support of this capability, the Building Research Establishment commissioned the Energy Systems Research Unit at the University of Strathclyde in Glasgow to compile a quality-assured collection of material thermo-physical properties. The project had the following objectives.

- To review existing data-sets in terms of data source, underlying test procedures and degree of consensus.
- To devise and apply a conflation mechanism.
- To comment on the underlying test procedures and the need for harmonisation.
- To extract a robust sub-set of data for inclusion in Section 3 of CIBSE Guide A.

Six material properties were included within the project's scope: thermal conductivity ($\text{W/m}\cdot\text{K}$), density (kg/m^3), specific heat capacity ($\text{J/kg}\cdot\text{K}$), surface emissivity (-), surface shortwave absorptivity (-), and vapour resistivity or resistance ($\text{MN}\cdot\text{s/g}\cdot\text{m}$ and $\text{MN}\cdot\text{s/g}$ respectively). In particular, an attempt was made to obtain data that described the variation of these properties as a function of temperature and moisture content. Note that the project excluded some significant material properties – such as those relating to moisture absorption/desorption and liquid water transport. Should such properties be available, it is possible to use a specialist modelling tool to adjust, for example, the thermal conductivity as a function of moisture content. Clearly, understanding the limits of a program in a particular application is an important part of the modelling process.

Project Process

The project comprised four stages. First, model users/developers and material testing groups were contacted in order to obtain information on the data-sets in current use and their underlying test procedures. A wide range of organisations were polled: professional bodies (such as CIBSE, ASHRAE and IBPSA), architectural and engineering practices, government agencies, research organisations, academic groups, software vendors, material manufacturers, and testing laboratories. In total 400 questionnaires were despatched and 100 replies received. Second, a selective follow-up was initiated to obtain significant data-sets identified in the questionnaire returns and to appraise these in terms of source, content and associated test procedures. Third, a mechanism for merging the data-sets was elaborated. Finally, a set of rules were devised to guide the extraction of a sub-set of data suitable for inclusion in Section 3 of CIBSE Guide A.

On analysing the collected data-sets, it was apparent that some collections were derivatives of other, more authoritative ones. In essence some 13 independent data-sets were identified: ASHRAE (US), BRE (UK), BS5250 (UK), CIBSE (UK), CSTC (Belgium), DOE-2 (USA), ESP-r (UK), Leeds University (UK), Leuven University (Belgium) and national data-sets from France, Germany, India, Italy and The Netherlands.

From the questionnaire returns from testing organisations, it was apparent that there existed little information on specific heat capacity, indicating that the measured thermal conductivities were intended for use in steady-state applications. The decision by ASHRAE in 1985 to quote only recommended U-values for building assemblies, as determined by hot box tests, is consistent with this conclusion. This suggests that the then extant testing procedures were not well matched to the requirements of dynamic building performance modelling.

Vapour resistivity was determined by under two thirds of the respondents, with the quoted test standards leading, at most, to a two point result, which is insufficient to generate a differential permeability curve of the kind required to define the behaviour of hygroscopic materials.

Few testing organisations measured longwave emissivity and even fewer measured material shortwave properties. In the case of glazing systems, manufacturers are relied on to provide specific product values. In other cases, such measurements are likely to be subcontracted to research institutions or reliance placed on published results from various sources.

Thermal conductivity apart, the evidence suggested that organisations concerned with the use of thermo-physical property values do not generate the information first hand. This raises the question of the quality control of such data. The fact that a standard exists does not guarantee that it is actually in use. Standards tend to vary by material and there are, for example, hundreds of standards in the USA alone. Any one organisation is likely to test only a limited subset of what is possible. A listing, by thermo-physical property, of standards that were quoted in the questionnaire returns is given in the Table 1.

While standards evolve – an examination of the BSI and ASTM yearbooks revealed that, typically, standards change every 3 to 5 years – a current standard will not affect data already in use for some time to come. For example, much of the CIBSE thermal properties data-set predated 1970 and several amendments of BS 874 – Methods for Determining Thermal Insulating Properties (now withdrawn). Further, particular national standards may not cover certain areas and, in any case, a catalogue of standards would fail to reveal the use of in-house testing procedures.

Table 1: Standards relating to thermo-physical property measurement.

Thermal Conductivity:	
UK	BS 874, BS 1142, BS 3837, BS 3927, BS 4370, BS 4840, BS 5608, BS 5617
USA	ASTM C-158, ASTM C-177, ASTM C 236, ASTM C 335, ASTM C 518, ASTM C 687, ASTM C 691
West Germany	DIN 52612
Belgium	NBN B62-200, NBN B62-201, NBN B62-203
Density:	
UK	BS 874, BS 2972, BS 4370, BS 5669
USA	ASTM C-158, ASTM C-177, ASTM C-209, ASTM C-302, ASTM C-303, ASTM C-519, ASTM C-520, ASTM C-1622
Belgium	STSO8.82.41, STSO8.82.5
Specific Heat Capacity:	
UK	Yarsley: in-house
USA	ASTM C-351
East Germany	TGL 20475
Longwave Emissivity:	
UK	Draft BS 87/12988
USA	ASTM E-408, Manville: in-house
Australia	CSIRO: in-house
Shortwave Properties:	
UK	BS 87/12988
USA	ASHRAE 74-73
East Germany	Sonntag's Pyranometer
Vapour Resistivity:	
UK	BS 2782, BS 2972, BS 3177, BS 4370: 1973, Part 2, DD 146
USA	ASTM C755, ASTM E96
West Germany	DIN 52615
Austria	ONORM B 6016

Review of Collected Data-sets

The following observations can be made on the structure and contents of the collected data-sets.

- There is no consensus on the manner in which materials are grouped for presentation of data to users. What is needed is a common system such as the CIB Master List of Materials [1], which integrates thermal properties within a broad material classification system.
- The range of properties for which values are quoted is generally restricted. Commonly, the properties are thermal conductivity, density and vapour resistivity, as required for simple steady-state heat loss and condensation calculations.
- Data source is generally not identified and, where it is, little information is presented on the underlying experimental conditions. Data merging is therefore an uncertain process because it is difficult to ensure compatibility between different entries.
- It is suspected that much of the agreement that does exist between different data-sets can be attributed to a degree of historical 'borrowing'. This, in turn, is likely to lead to an optimistic assessment of the inherent uncertainty.
- Many values are quoted without any statement as to whether they correspond to single or multiple measurements. A random inspection of several referenced works would suggest that values are usually derived from the work of a single researcher on the basis of a small sample size.
- Much of the data is derived from work carried out with non-standard apparatus and from a date that precedes modern standards of equipment and operation.
- No guidance is given on the variation in properties such as density and internal structure as inherent in the production of many building materials.

- There is no agreement on the procedure for the determination of the thermal conductivity of materials in the moist state.
- There is tacit agreement that the uncertainty within the data is use-context dependent. The various calculation methods proposed are clearly expected to yield no more than crude estimates of real conditions.
- For any material, density, moisture content and internal structure are the major determinants of its thermal and hygroscopic behaviour. In some cases, the effects of temperature and ageing can also be significant.

The following sub-sections consider how and where these properties and environmental conditions give rise to uncertainties in the data. A scheme for data classification and conflation is subsequently introduced that reflects this uncertainty.

Thermal Conductivity

Thermal conductivity is correlated with material density. For example, Jakob [2] established a relationship between average thermal conductivity and density for completely dry building materials. This relationship was later confirmed by work undertaken at BRE [3]. With respect to accuracy, Jakob suggested that individual values might deviate by up to $\pm 15\%$. He also suggested that the internal structure of a material affected the thermal conductivity according to whether it was amorphous or crystalline. This relationship, between the thermal conductivity of dry materials and their density, was also examined by Billington [4]. Although the magnitude of the deviations is not explicitly discussed, it is implied that deviations of 50% or more are not uncommon. Billington also draws attention to the influence of internal structure on thermal conductivity, particularly in the case of concretes, but concluded that the conductivity depended on whether the material was cellular or granular in structure rather than

amorphous or crystalline. The deliberate application of control of internal structure has shown that, in the case of concrete, the thermal conductivity can differ by up to 30% for a given density.

For fibrous and cellular insulations, the apparent thermal conductivity is a function of density and fibre or cell size. In general, a specific combination produces minimum thermal conductivity.

Concrete and masonry present a particular problem in that the variable nature of the constituents has a strong influence on the thermal conductivity. Several reports give correlations of conductivity with density for concrete [5, 6] and for masonry [7, 8]. It can be concluded that the prediction of the thermal conductivity of these materials from these correlations is approximate, particularly in the case of masonry.

Quite apart from trying to produce predictive algorithms, the inherent scatter in the relationship between thermal conductivity and density has important consequences for the retrieval of values from a database. Once a material is located, density is invariably the key parameter in locating the correct value of thermal conductivity. The essential problem is that the location on the thermal conductivity curve of the test sample or samples that gave rise to the value held is generally unknown, as is that of the material to be used on site. In the worst scenario, the value held may be derived from material with a high positive deviation, while the material to be used on site has a high negative deviation. In practice the density assumed for thermal conductivity database retrieval will commonly be a nominal one supplied by the manufacturer. An error will arise if this deviates significantly from the actual density of the product as supplied and installed. A study of the properties of lightweight concrete blocks carried out by BRE Scottish Laboratory found substantial deviations between the density quoted by manufacturers and the actual

mean density of the block samples as measured. Out of seven cases where comparisons could be made, four showed differences of around 20% between the actual mean density and the quoted value. In addition, the actual spread of densities about the mean was, in most cases, substantial as illustrated in Figure 1. The remedy for these problems lies in quality control procedures, which can guarantee the delivery of materials to within a known density tolerance. Until this is achieved, the error introduced will be an unknown quantity.

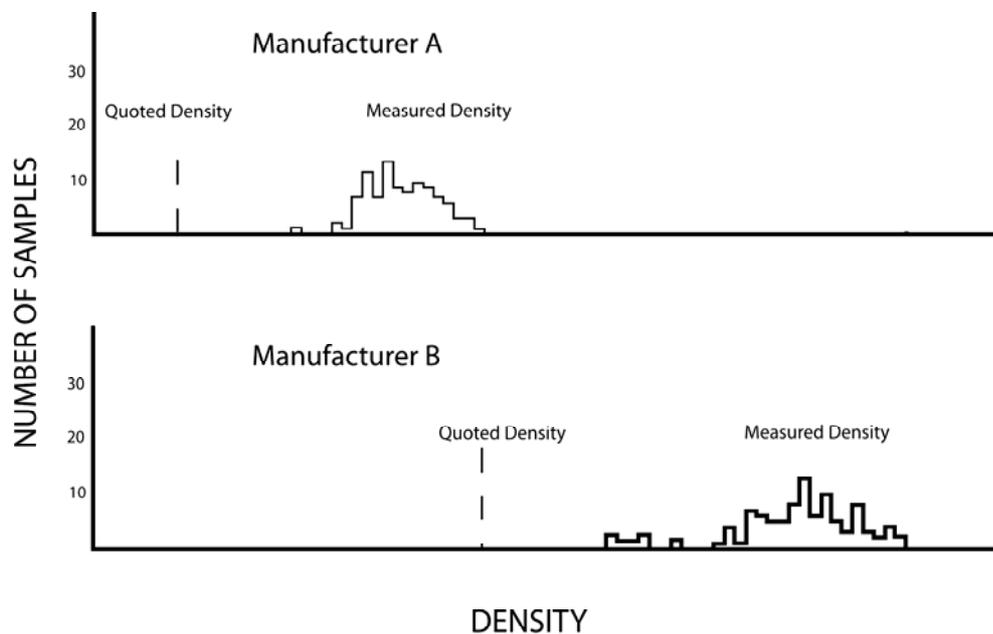


Figure 1: Spread in measured densities and their relation to the quoted density for lightweight concrete blocks supplied by two different manufacturers.

The thermal conductivity of a material is also strongly affected by the presence of moisture. Jakob proposed that the thermal conductivity of a mineral building material containing a known percent of moisture by volume could be obtained by multiplying the thermal conductivity in the dry state by a correction factor that depended only on the moisture content by volume. This method of correction has been widely used and applied to masonry materials [2]. Later thermal conductivity measurements on moist materials by

Jespersen showed that the behaviour of different materials was not well represented by a single characteristic [9]. He found that both the magnitude of the initial rise at low moisture content, and the moisture content at which the relationship between thermal conductivity and moisture content becomes linear, are significantly different for different groups of materials. He also noted that, in general, there is an initial region, corresponding to the transition from dry to the point of hygroscopic equilibrium under normal internal environmental conditions, where the thermal conductivity is little affected by increasing moisture content. As a result, he concluded that the equilibrium hygroscopic moisture content under such conditions – literally defined as ‘laboratory dry’ – has little effect on the thermal conductivity of materials.

In considering the rates of change of thermal conductivity with moisture content, Jespersen distinguished three kinds of behaviour associated with different material types. These were timber products, inorganic lightweight insulating materials and masonry. At one extreme, the organic materials proved to be little affected by moisture content, the relationship between the thermal conductivity and moisture content being approximately linear throughout, with no rapid increase in thermal conductivity observed at low moisture contents. Consequently, the use of a single value of conductivity for such materials (when determined at the in-use moisture content) should be of adequate accuracy. At the other extreme, mineral fibre insulating materials showed a violent increase in thermal conductivity with only small increases in moisture content, thereafter assuming a linear relationship. Fortunately, such materials contain very small amounts of hygroscopic moisture under normal ‘air dry’ conditions so that the value of thermal conductivity determined for the dry state, or an appropriately conditioned one, should yield the same value. However, should it be suspected that such materials may be exposed to conditions that involve, for example, condensation or wetting then the use of such thermal conductivity values would be extremely inaccurate. The range of behaviour

of masonry materials was found to lie in a broadly defined zone located between the two extremes. Since the types of masonry tested were not fully representative, especially of concretes, the extent and shape of the zone is conjectural. Given the underlying physical processes, it is probable that a subdivision into cellular and granular materials would be useful.

Since masonry materials are usually subject to conditions involving significant moisture content, it is not surprising that there have been numerous attempts to define their behaviour [2, 4, 6, 9, 10, 11]. There is evidence that the relationship between thermal conductivity and moisture content can be represented by linear expressions in terms of moisture content by volume or by weight. In order to compare published results, it is useful to express them as the percentage change in thermal conductivity per 1% change in moisture content by volume (or by weight). It is also useful to adopt the convention of moisture correction factors such that the thermal conductivity, k , at some percentage moisture content, m , is related to that at reference moisture content, m_r :

$$k/k_r = (1 + C.m) / (1+C.m_r)$$

from which it follows that

$$(k- k_r) / k_r (m-m_r) = C / (1+C.m_r).$$

where C is independent of m for linear relationships. Thus, the percentage change in k per 1% change in m is determined not only by C but also by the choice of m_r . Jespersen found significant linear behaviour for all masonry materials between 2% and 10% moisture content by volume [9]. Above a reference moisture content of 2%, the upper and lower bounds of his curves for the percent change in k with m yield a rate of 6% to 7%. For lightweight concrete, his regression equation for k versus m can be rearranged to yield C by dividing his coefficient, a , by a reference thermal conductivity consisting of the air-dry conductivity plus a diffusion conductivity. By using his quoted data and working in

the units used by Jespersen, a reasonable mean for the air-dry conductivity is 0.9 BTU in/ft² h °F (equivalent to 0.13 W/m K).

The mean value of a is 0.056 with little variation. The mean value of the reference conductivity is close to unity so that an estimate of C is 0.06. These results may be compared with the linear change in k per 1% change in m by volume of about 6% given by the moisture correction factors in DIN 52612 [10]. By comparison, analysis of the non-linear Jakob correction factors for m in the range 2.5% to 10% by volume yields mean interval rates of 10% falling to 7%. This suggests that the Jakob corrections are atypical, particularly at low moisture contents. Arnold examined the validity of the correction proposed by Jakob [7] and from published results produced a curve of the thermal conductivity of masonry materials corrected to 1% moisture content against dry density. The fit was concluded to be satisfactory. If the Jakob corrections were correct, the resulting curve should have reduced, after removing the dependence on moisture content, to the same form as the dry thermal conductivity versus density curve with the same associated scatter. However, only passing reference was made to the scatter of the results but others have examined it in some detail [12]. Whereas a maximum deviation for this type of curve of $\pm 15\%$ could be expected [2], the average spread was 15% with individual deviations of over 40% and particularly poor agreement below 2% moisture content by volume [12]. A linear change in k per 1% change in moisture content by weight has been given as 4% for lightweight concrete [11] and 6% for brick [4]. For the former material, relationships have been quoted giving C as 0.06 [6]. The respective rates of change are 3%-6% and 4%-6% over the range of validity of the latter relationship in moisture content and density. Minimum moisture contents quoted for linear behaviour have been 1% by volume and 1.5% by weight [11]. Dependence quoted in terms of moisture content by weight implies a dependence on density when quoted in terms of volume since, with increasing density, the same change in moisture content causes less

change in thermal conductivity. This agrees with the finding of Jespersen that lightweight materials have the greatest overall sensitivity to changes in moisture content (by volume).

In general, the corrections proposed in DIN 52612 seem more appropriate than those proposed by Jakob, particularly if referenced to a moisture content of not less than 1% to 2% by volume. For relationships expressed in terms of moisture content by weight, there is considerable agreement that the factor C lies in the range 0.04 to 0.06 when referenced to a minimum moisture content of 1.5% by weight or 1% by volume.

The inherent scatter in results due to experimental error and, just as importantly, to differences in internal composition between samples that cannot be eliminated by density dependency, means any quest for further accuracy is questionable. The relationship for lightweight concrete given by Valore seems credible in current circumstances [6]. The question of what moisture contents actually exist in practice is a vexed one. The standard moisture contents quoted for design purposes in Section A3 of the CIBSE Guide (as current at the time of the project) covered the range 1% to 5% moisture content by volume. By contrast, Jakob gives the range as 5% for inner walls and 10% for outer walls and draws attention to the possibility of great deviations [2]. The choice of the standard moisture contents for the UK was admitted to be based on sparse evidence [7]. Even so, the data shows considerable spread. It follows that the uncertainty in specifying the moisture content in a real situation could be a major source of error in predicting thermal conductivity. In fact, such errors could match or exceed the kind of errors noted in connection with the use of the Jakob corrections.

In general, the thermal conductivity of dry materials increases with temperature. The changes are small at normal temperatures and are usually neglected. Possible exceptions

are the fibrous and porous insulation materials where the apparent conductivity may vary significantly in extreme environmental conditions.

The presence of moisture increases the effect of temperature on the thermal conductivity of inorganic materials. This is particularly acute for lightweight inorganic insulating materials but for any material with a moisture-corrected thermal conductivity of less than 0.5 W/m K, the effect of temperature will have doubled or more [9].

Thickness also has an effect on the apparent conductivity of low density fibrous and cellular insulations due to radiative heat transfer. According to the ASHRAE Handbook of Fundamentals (Chapter 20), the effect is relatively small over thicknesses of 25 mm to 150 mm. Measurements at the Electricity Council Research Centre found no evidence of a thickness effect in mineral fibre quilt of thickness 90 mm to 360 mm [13]. The evidence suggested that neglecting the effect of thickness will result in an insignificant error.

Finally, ageing can be identified as a significant cause of increase in thermal conductivity for foamed insulations blown with gas of a thermal conductivity below that of air. In time, the gas diffuses away and the thermal conductivity increases. Hence, only values for aged insulation should be used.

Specific Heat Capacity

The seemingly straightforward definition of specific heat capacity as the amount of heat energy required to be added or removed to change unit weight of a material by unit temperature belies the difficulty of measuring such a value. The difficulty of obtaining reliable values for different materials and the absence of a predictive method has been well noted in the literature. One of the difficulties of measurement, particularly for materials of low conductivity, is that it is difficult to input or extract heat quickly, making

the design of accurate practical experimental apparatus difficult. Perhaps partly because of such difficulties, very few of the laboratories that responded to the project questionnaire measured this quantity. The test techniques identified included a conventional absolute calorimetric method and an indirect dynamic test method based on Fourier's equation and computer regression analysis of test results [14]. Both are in-house methods.

Because of the high specific heat capacity of water, the effect of moisture content on the specific heat of a material is significant and must be taken into account. In principle, the overall specific heat capacity of a material is simply the linear addition of that of the dry material to that due to the amount of water present in the material. In practice, this requires knowledge of the in-use moisture content. While calculations can be based on standard design values, the absence of a practical, non-destructive test method for determining on-site moisture content gives rise to an inherent uncertainty in calculating values of specific heat capacity for moisture containing materials. This uncertainty is compounded when it is realised that it is the volume heat capacity (i.e. the product of density and specific heat capacity) that is important in determining thermal capacity. Hence, the uncertainty in density, as discussed above, is added to the uncertainty in specific heat capacity for volume heat capacity.

A further source of error may arise from the fact that conditions are dynamic in practice. In general, materials will be subject internally to temperature and moisture gradients that do not correspond to equilibrium distributions. Hence, both the thermal resistivity and capacity will vary from point to point within the material. It is also the case that the specific heat capacity is a function of temperature.

However, given the relatively small range of temperature involved in calculating the hygrothermal performance of buildings, the error associated with adopting a single figure value will be insignificant compared to the scale of error from other causes.

Water Vapour Transmission

The behaviour of a material where gaseous diffusion is the vapour transport mechanism is relatively simple. Where a material can absorb water, the diffusion process can be complemented by other forms of transport, which are capable of causing a considerable increase in the permeability of the material [15]. There is a fundamental distinction to be made between hygroscopic and non-hygroscopic materials. Fortunately, there exists an approach to measuring vapour permeability that can identify and evaluate these differences in behaviour [16].

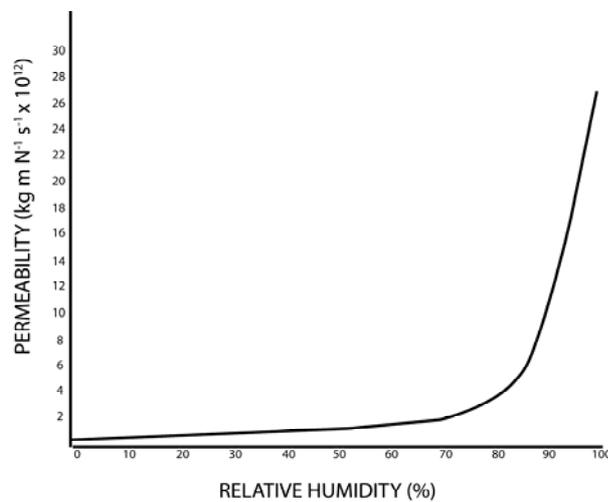


Figure 2: Differential permeability of a 5-ply, 12mm thick sample of exterior quality plywood at 20°C [from 17].

This method has been applied to the measurement of the vapour permeability of plywood (strongly hygroscopic) and plasterboard (non-hygroscopic) [17]. The results obtained, as

shown in Figures 2 and 3, typify the differences in behaviour between hygroscopic and non-hygroscopic materials. In the latter case, the vapour permeability is little affected by relative humidity and is adequately represented by a single value. There is the possibility of a slight increase with increasing humidity. Where more than one value is quoted, a rational way to limit variation and represent real conditions would be to select the value obtained under the highest conditions of humidity where this can be identified.

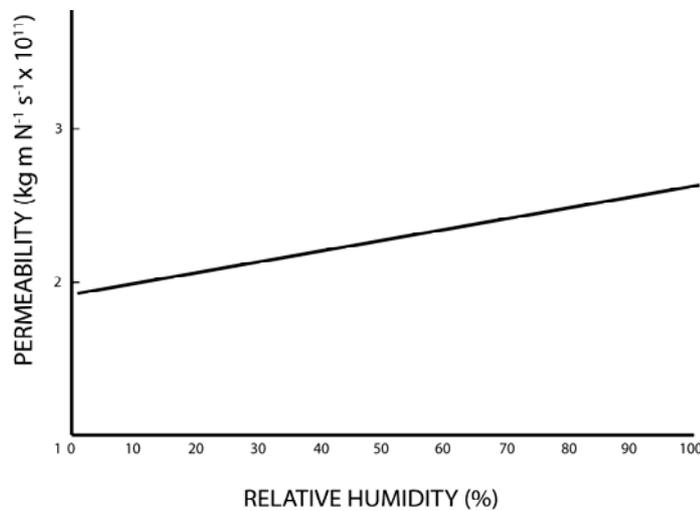


Figure 3: Predicted permeability derived from regression analysis of experimental data for a 9mm thick sample of gypsum plasterboard at 20°C [from 17].

The behaviour of hygroscopic materials shows two distinct regions. At low relative humidity (RH), where gaseous diffusion dominates, the behaviour is like that of non-hygroscopic materials. However, above 60% RH the behaviour becomes non-linear with vapour permeability showing rapid changes with small changes in humidity. In the tests referred to above, the permeability of plywood at 95% RH was found to have increased twenty-fold over the low humidity value. The behaviour at high humidity might be even more complicated. High moisture content causes plywood to undergo dimensional changes and swell; consequently, the pore sizes can increase and reduce the hygroscopic effects [18]. A limiting effect on the increase in the permeability of wood based materials

could operate at very high humidity. Most quoted data on water vapour transmission properties are based on measurements at one or, at most, two values of humidity. While this is reasonable for non-hygroscopic materials, it can be seen to be an entirely inadequate description of the behaviour of hygroscopic materials above the transition point. One result is that there is a wide variation in values quoted for hygroscopic materials since they are extremely sensitive to relatively small changes in test conditions; as between different national standards for example. A survey of quoted values for plywood revealed the highest value to be some forty times the smallest [17].

The best that can be done with the data is to represent the vapour transmission data for hygroscopic materials as a range so that they at least convey some idea of the magnitude of the changes to expect beyond 60% RH. This is obviously important in the context of choosing values for condensation risk assessment. The vapour permeability of non-hygroscopic materials can be defined with much greater certainty than for hygroscopic materials. It would therefore make sense to distinguish such materials from each other. Unfortunately, the data is not of a form to allow such a distinction to be made reliably for all the degrees of hygroscopic behaviour displayed by building materials. It is, however, possible to attempt a breakdown of materials into groups according to the certainty with which their vapour permeability can be established. Clearly timber based products (organic and very hygroscopic) are the least certain. Equally clearly, there are materials such as metal and glass that are impermeable and have effectively zero permeability. Between these two extremes are the inorganic materials that are permeable. These can again be broken down into two groups: non-hygroscopic inorganic materials, such as mineral fibre insulations, which behave in a simple manner; and masonry materials, which are inorganic but display weak to strong hygroscopic behaviour.

It is interesting to note that, impermeable materials apart, these groupings correspond closely to those used by Jespersen to distinguish the behaviour of moist materials in terms of thermal conductivity as can be seen in Figure 4. Masonry materials occupied a broad zone, with timber displaying the least variation and lightweight, non-hygroscopic, inorganic materials the most.

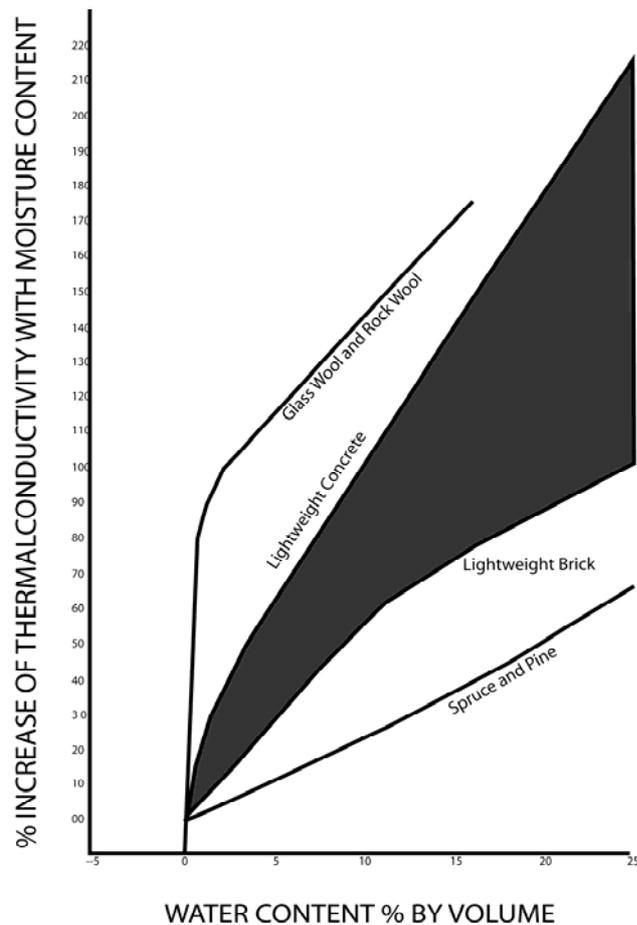


Figure 4: Effect of moisture on the thermal conductivity of different types of materials [from 9].

With regard to the dependence of vapour permeability on temperature, it is only of significance in the case of the least permeable membranes [16]. Such membranes would

naturally fall under the impermeable grouping adding further to its significance in terms of defining behaviour.

Surface Properties: Opaque Materials

Radiative heat transfer properties are conveniently considered together and, indeed, are commonly tabulated together. Unlike the bulk properties considered above, such surface properties can be determined with considerable accuracy. The properties are wavelength, and therefore source temperature, dependent. For opaque bodies, although emissivity and absorptivity are equal to each other at the same wavelength, the difference in the spectrums of radiation at normal environmental temperatures and solar temperatures results in significantly different values. It is usually considered sufficiently accurate to quote a single value for the relatively small range covered by normal environmental temperatures.

In practice, one possible source of inaccuracy is to use values of laboratory tested materials that compare to a pristine surface state as opposed to the in-use surface state after a material has been subject to ageing through weathering, chemical attack and/or dirt accumulation. Where possible, values appropriate to an in-use condition should be quoted.

Quoted values of emissivity are commonly for the total normal emissivity. The actual power emitted depends on the hemispherical emissivity which may differ. For non-conductors, the hemispherical emissivity may be lower by up to 7% and for highly polished metallic surfaces it may be greater by up to 30%.

The hemispherical emissivity can be calculated by multiplying the total normal emissivity by 1.2 for bright metal surfaces, by 0.98 for non-conducting rough surfaces and 0.95 for

non-conducting smooth surfaces. A casual inspection of the values quoted by various sources suggests excellent agreement. Closer inspection revealed the extent of the borrowing that underlies this commonality. As an example, a compilation of solar absorptivity and emissivity by Penwarden (BRE) borrows extensively from an earlier review carried out at the CSIRO and published in 1951 [19]. In turn, many of the solar absorptivity values quoted in this earlier review can be traced back to the work carried out at BRE (BRS as it was then) and published in 1935 [20]. In a similar way, many emissivity values can be traced to a 1941 publication [21].

The listing by Penwarden includes additional new values and represented the most up to date amendment of the historical data on solar absorptivity and emissivity to hand [22]. It was therefore adopted as the core data within the project reported here.

Surface Properties: Transparent Materials

Transparent materials have the added property of transmission in addition to those of reflection and absorption. As the sum of the three properties must equal unity, it is only necessary to measure two properties. It is universal practice to refer to glazing manufacturers for data on the solar optical properties of the various forms of sheet glass used in window systems. Unlike many building materials, both the quality control of glass and also the precision with which the manufacturers determine the properties of their products are high. The general way of treating the data is to provide values of the properties including, perhaps, total transmittance at normal incidence. The behaviour at other angles of incidence is then supplied in a graphical form that depicts the fractional change in properties as a function of the angle of incidence. The value of any property at other than normal incidence can then be estimated with good accuracy by adjusting its value at normal incidence by the appropriate fractional change indicated by the graph. In the case of coated versions of glass, the behaviour at oblique angles of incidence above

30° is not so well approximated by the characteristics of the non-coated glass although even then the error is only around $\pm 3\%$. If greater accuracy is required then separate graphical corrections will be needed for coated glass. Transparent plastic materials are used in a number of speciality glazing applications. Appropriate data on their properties may be obtained from manufacturers as for glass.

Review of Test Methods Underlying the Data

This section reviews the test methods underlying thermal conductivity, water vapour transmission, longwave emissivity and solar optical properties as quoted in the acquired data-sets.

Thermal Conductivity

Quoted data are derived from measurements carried out by either the hot-plate or heat flow meter techniques. Both are steady-state methods and primarily designed for measurements in the dry state. As such, the design and behaviour of equipment had already received considerable attention [23]. Tests using the hot-plate method make absolute measurements of the conductivity for one dimensional (longitudinal) heat flow. It is possible to achieve an accuracy of $\pm 3\%$ although in practice the accuracy is very dependent on the operation of the apparatus and the skill of the operator. Schemes, such as the one operated by NAMAS (now UKAS the United Kingdom Accreditation Service), had been introduced to remedy this by rationalising operation and inspecting equipment. Measurements made prior to such schemes may be subject to larger errors. Even so, the assumption of accuracy within 5% for later measurements may be misplaced. Inspecting agencies have some discretion on uncertainty, and in particular cases the error for some materials may rise from 5% to 20% [24].

The heat flow meter technique is a relative technique, which requires the use of calibration samples measured by the hot-plate method. As such, the error associated with measurements carried out using this technique are about twice that of the hot-plate – that is the error in the hot-plate calibration sample measurement plus the heat flow meter error. It is, however, simpler to use and less dependent on operator error. Success in use depends on the existence of a well defined set of calibration samples.

The behaviour of both sets of apparatus has received considerable analysis and improvement, including the development of standard samples for heat flow meter calibration [25]. Nevertheless, what is apparent by its omission was any reference to the measurement of moist samples. Indeed, at the time, the ISO draft standards on hot-plate and heat flow metering simply referred to the matter as complex and considered only measurements in the dry state [26, 27]. In principle, this is correct because neither form of apparatus is suited to the measurement of moist materials. Since such measurements for masonry materials are of such practical importance, the problems are worth considering in detail.

The essence of the problem is that the application of a temperature difference to a moist specimen results in a moisture gradient, causing moisture to migrate from the higher temperature. This affects the spot conductivity through the specimen and thence the temperature distribution. It has been observed that the spot thermal conductivity decreases more rapidly in the warmer (drier) region than it increases in the colder (moister) region. At constant applied temperature difference, the same sample will have different moisture gradients for different moisture contents while, at constant moisture content, the same sample will have different moisture gradients for different applied temperatures.

In addition, as the moisture content increases, condensate will appear at the cold side of the specimen [12]. This suggests that the measured conductivity will increasingly fall below the conductivity for a linear moisture distribution with increasing moisture content.

In the absence of knowledge of the moisture gradient, quoting applied temperatures at constant moisture content does not uniquely define the measurement. As such, measurements become particular functions of temperature, moisture content, sample thickness, sample orientation (up- or down-ward heat flow) and length of measurement period.

Such a situation is unsatisfactory and is unlikely to be resolved in terms of test methods that are specifically designed for measurement in the dry state. A method of measurement involving a much lower applied temperature difference than is required by either the hot-plate or heat flow meter methods would help reduce the problem of moisture migration. One possibility identified as deserving investigation is the thin-heater thermal conductivity apparatus. In describing developments with this apparatus, Hager drew specific attention to the potential of this method in minimising water vapour migration because of the low temperature difference involved [29].

Water Vapour Transmission

It was apparent that there was a need to modify wet- and dry-cup techniques to determine at least five points on the vapour permeability versus relative humidity curve so that differential permeability curves can be generated. This is required not only for hygroscopic materials but to identify all the materials that are significantly hygroscopic. In the longer term, more realistic results would be obtained if tests could be carried out for simultaneous vapour pressure and temperature differences rather than isothermally. Such a capability is beginning to emerge from the research phase [28]

Moisture Content

There is a need to establish the true distribution of moisture content in building materials in different regions for statistically significant large samples. The UK is a particular case in point. Destructive testing in the form of drilling out core samples and weighing them would not be acceptable to many building owners and would take a long time. A review of alternative methods available at the time was not very optimistic except in promoting a capacitance measuring technique [30].

Longwave Emissivity and Solar Optical Properties

The techniques of pyrometry and photometry are well established and supported by well developed instrumentation (both total and spectral). However, there was a lack of standards relating to the measurement of such properties, in particular in relation to in-use building surfaces.

Data Classification

There was little agreement between the collected data-sets in terms of classification although all have the common purpose of supporting design calculations carried out to ensure compliance with set target values for conditions as specified in building regulations and codes. Such calculations only make sense, of course, if they are referred to a single database of material properties. As a result, standard lists of values have been generated in many countries to support design calculations. The context of such calculations is not to simulate real behaviour but to minimise the risk of failure as in excessive winter heat loss, summertime overheating or the occurrence of condensation. In practice, the choice of calculation procedures, target conditions and associated standard lists of material property values reflects the need for robust methods of risk assessment that implicitly accept the inherently uncertain nature of building material property values.

The disadvantage of such procedures is that they are not capable of providing much insight into the detailed hygrothermal behaviour of buildings, particularly where new materials, systems or situations may be involved. Nevertheless, the inherent uncertainty of present building material property values has to be recognised as also placing a limit on the accuracy with which any real situation can be modelled, irrespective of the degree of accuracy of the computational model.

The recognition that all predictive methods concerning the behaviour of buildings and their components operate within a probabilistic context has been a source of considerable interest and concern. A useful overview of the problem has been presented by Keeble [31]. Computational techniques also influence the choice of data. Given that design calculations have evolved within the context of simplified, steady-state models, the range of properties required to be listed has been restrictive and has influenced the range and kind of test procedures in use. One aspect of this has been the move towards the steady-state testing of whole building assemblies, first in North America and latterly in Europe, as a preferred option to computing behaviour from individual material constituents.

The 1985 edition of the ASHRAE Handbook of Fundamentals departed from previous practice by removing tables of calculated U-values for building assemblies in favour of placing reliance on U-values determined by calibrated or guarded hot-box tests. The justification was based on the difficulty of calculating the thermal performance of heat-bridged assemblies. Irrespective of the merits of the argument, current hot-box test methods provide only steady-state values of overall heat conductance for particular assemblies not materials. This suggests that testing procedures may be less helpful in providing data to meet the needs of dynamic building performance modelling.

Data Classification and Conflation

From consideration of the use context of the materials (e.g. insulants are normally used in the air-dry state while masonry is often wetted by rain) and the reliability/scope of their underlying test procedures (e.g. the more moisture a material contains, the greater the difficulty of enacting the test procedure), the material thermo-physical property data were conflated and organised within four material type categories as follows.

Category 1: Impermeables

This category contains materials that act as a barrier to water in the vapour and/or liquid states and do not alter their hygrothermal properties by absorbing or being wetted by water.

Category 2: Non-Hygroscopic

Lightweight insulants, such as mineral wools and foamed plastics, that display water vapour permeability, zero hygroscopic water content and an apparent thermal conductivity, and which operate under conditions of air-dry equilibrium normally protected from wetting by rain.

Category 3: Inorganic-Porous

Masonry and related materials that are inorganic, porous and may contain significant amounts of water due to hygroscopic absorption from the air or wetting by rain, which affects their hygrothermal properties and their thermal conductivity in particular.

Category 4: Organic-Hygroscopic

Organic materials such as wood and wood based products that are porous and strongly hygroscopic and which display a highly non-linear water vapour permeability characteristic.

Such a classification system is strongly related to the reliability of the test procedures, with the certainty decreasing from Category 1 to 4. For example, the vapour permeability of Category 4 materials is underestimated in the databases for materials at high humidity. A complete listing of the conflated data-set is available from esru@strath.ac.uk.

In order to generate a robust data-set for use by practitioners, reduction rules were established and applied to the conflated data-set:

1. removal of duplicates;
2. removal of non-consensual values where disagreements existed; and
3. removal of materials with missing parameters (except where it is the only entry of its type).

This gave rise to the data as now incorporated in Appendix 3.A7 of Section 3 of CIBSE Guide A and which first appeared in the 1999 edition. With respect to this data-set, it is important to note that:

- not all materials have a complete set of data, especially in relation to vapour diffusivity and surface absorptivity/emissivity;
- the set is also incomplete in that it does not include materials that have entered the market since the study was concluded;
- the set includes only materials that are common within the European construction industry – the original data-set may be consulted where more esoteric materials are the target;
- some of the entries correspond to test procedures that predate current standards – such materials should be retested and, where appropriate, their data replaced; and

- materials in the organic-hygroscopic category continue to present a challenge in relation to the production of reliable and applicable data.

Concluding Discussion

Major sets of material thermo-physical properties were gathered, organised and conflated as a function of the expected reliability of the underlying test procedures. Reduction rules were then used to produce a robust sub-set of data for incorporation within Section 3 of CIBSE Guide A. The process highlighted the deficiency of the information available at the time of the project and the inconsistencies in the underlying test methods as summarised above in the section ‘Review of Collected Data-sets’. Progress towards resolving these deficiencies and inconsistencies as evidenced in international and regional standards introduced since the project is now examined for some important areas.

With regard to the thermal performance of materials, the guarded hot plate and heat flow meter methods continue to be the basis for measurement standards with the aim of determining heat transfer properties in the steady state for materials of either low-to-medium thermal resistance or of medium-to-high thermal resistance, with a further subdivision of the latter by thickness [32, 33, 34]. For materials of low-to-medium thermal resistance, measurements on moist materials are covered albeit limited to within the hygroscopic range (i.e. no moisture movement) and subject to the explicit advice that ‘routine measurements should, as far as possible, be carried out on dry materials’ [32]. The Standard contains considerable discussion on measurement limitations such as set by inhomogeneous materials with a relatively large aggregate or pore size and, in the case of moist materials, acknowledges that substantial errors can occur. One source of error is that the temperature difference needed to maintain a uniform moisture distribution across a test specimen falls below that recommended to minimise

errors in temperature-difference measurement. As noted at the time of the project, the thin-heater apparatus [29] offers an alternative method of measurement that could avoid this problem. This apparatus now has its own Standard [35]. In the particular case of moist masonry, the conclusion of the project that a 6% change in thermal conductivity per percent change in moisture content by volume was a reasonable approximation is reflected in European Standard EN 1745:2002 (Masonry and masonry products – methods for determining design thermal values).

With regard to the thermal performance of building materials when assembled into building envelope components, the hot box method of testing was noted as gaining acceptance at the time of the project. This method has been, and continues to be, developed as a preferred method of testing assemblies, especially where complicated forms of heat flow take place. The introduction of an international standard for hot box testing of insulating materials and insulated structures [36] has been followed by the later introduction of standards for masonry [37] and for window and door assemblies [38, 39]. All hot box methods are directed at the determination of steady state thermal transmission properties.

While reviewing the data on thermal performance, an associated problem concerning the relation of quoted densities to actual product densities was identified in the case of masonry. This can be seen as part of a broader issue of the quality control and assurance of the properties of masonry products. Within the European Union, for example, this issue has been addressed through the introduction of harmonised standards for the specification and testing of masonry units, namely the multi-part standards EN 771 – Specification for masonry units and EN 772 – Methods of test for masonry units.

Water vapour transmission was another property reviewed in the project where the difference in the behaviour of materials as determined by whether a material was hygroscopic or non-hygroscopic was not adequately represented in the collected data. This was deemed problematic, particularly for condensation risk assessment, since many building materials are hygroscopic and display highly non-linear water vapour permeability characteristics with changing ambient relative humidity. It was suggested that the water vapour transmission data for such materials should be represented over a range of relative humidity. Subsequently, such data have been quoted in the ASHRAE Handbook of Fundamentals (Chapter 25) for several such building materials with reference to their use in condensation risk assessment and the modelling of transient hygrothermal behaviour. Another source, however, continues to quote two point results only [40]. While standards for wet and dry cup test methods have come into existence since the time of the project [41, 42], care in the use of data so derived needs to be exercised since agreement should not be expected between results obtained by different methods: a value obtained under one set of conditions may not be representative of the value under a different set of conditions [42]. In fact, as acknowledged in EN ISO 13788 [43] and reinforced in CIBSE Guide A, moisture transfer is a complex process where many sources of error can affect calculations given the current state of knowledge of moisture transfer mechanisms. In recent times Yik and Chau [44] have explored the possibility of improving on the standard cup test method in terms of accuracy and speed by utilising a surface air dew-point probe. They concluded that the accuracy required for the measurement of the air dew point in the case of low permeability materials was unattainable. Phillipson *et al* [45] provide a useful overview of current methods and new approaches to moisture measurement in building materials.

From the above discussion, it can be concluded that progress has been made on one of the recommendations arising from the project: that there was a need for a world-wide set of testing standards in order to harmonise material properties for use with building modelling tools that do not recognise regional boundaries. The detailed reports now required by the international standards for test methods noted above, in conjunction with an international standard for determining values under design conditions [46], should mean that future data does not have many of the deficiencies and inconsistencies of earlier data.

In the meantime, the ASHRAE Handbook of Fundamentals observation that “it can be problematic finding accurate data for all materials in a component” still stands.

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