TECHNICAL REPORT 9165

Published 1988-12-01

INTERNATIONAL ORGANIZATION FOR STANDARDIZATION • МЕЖДУНАРОДНАЯ ОРГАНИЗАЦИЯ ПО СТАНДАРТИЗАЦИИ • ORGANISATION INTERNATIONALE DE NORMALISATION

Practical thermal properties of building materials and products

Caractéristiques thermiques utiles des matériaux et des produits de construction

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ISO/TR 9165 was prepared by Technical Committee ISO/TC 163, *Thermal insulation.*

The reasons which led to the decision to publish this document in the form of a Technical Report type 2 are explained in the Introduction.

UDC 691 : 536.2 **Ref. No. ISO/TR 9165 : 1988 (E)**

Descriptors: buildings, construction materials, thermodynamic properties, thermal conductivity, thermal insulation, thermal resistance.

Price based on 21 pages

Contents

0 Introduction

Whilst the technical committee accepts the need for an International Standard in this field, it recommends immediate publication in the form of a Technical Report which is urgently needed as guidance for developing national standards in this field. The technical committee will discuss this matter further to develop an International Standard.

1 Scope and field of application

This Technical Report deals only with the thermal characteristics of building materials and products related to thermal conductivity or thermal resistance. It gives the procedures needed to correct laboratory test values to practical values for building materials or products.

These practical thermal values are needed for use in calculations of thermal properties of building components, but the procedures given here may not be applicable to composite structures.

The procedures are in general applicable in the temperature range −30 to +30 °C.

No specific procedures for allowing for the influence of workmanship are given.

2 References

ISO 2859, *Sampling procedures and tables for inspection by attributes.*

ISO 3951, *Sampling procedures and charts for inspection by variables for percent defective.*

ISO 7345, *Thermal insulation — Physical quantities and definitions.*

ISO 8301, *Thermal insulation — Determination of steady-state specific thermal resistance and related properties — Heat flow meter method.* 1)

ISO 8302, *Thermal insulation — Determination of steady-state areal thermal resistance and related properties — Guarded hotplate apparatus.* 1)

ISO 8990, *Thermal insulation — Determination of steady-state thermal transmission properties — Calibrated and guarded hot box.* 1)

3 Definitions and symbols

3.1 Symbols

λ_{mean}	Mean value of thermal conductivity	W/(m·K)
λ_b	Basic thermal conductivity (based on laboratory tests and corrected for statistical variations)	W/(m·K)
λ_p	Practical thermal conductivity (design value)	W/(m·K)
R_{mean}	Mean value of thermal resistance	$m^2 \cdot K/W$
R_b	Basic thermal resistance	$m^2 \cdot K/W$
R_p	Practical thermal resistance (design value)	$m^2 \cdot K/W$
s_λ	Estimated standard deviation of thermal conductivity	W/(m·K)
s_R	Estimated standard deviation of thermal resistance	$m^2 \cdot K/W$
α_λ	Correction coefficient for thermal conductivity	
α_R	Correction coefficient for thermal resistance	
d	Thickness	m

3.2 Basic thermal characteristics

The basic thermal characteristics (λ_b, R_b) are measured in accordance with International Standards, under reference conditions of temperature and state.

3.2.1 Standard reference temperature

A temperature selected as the base at which these characteristics, that are dependent upon temperature, will be measured and reported for comparison.

Currently, a mean temperature of 10, 20 or 24 °C is used as standard reference temperature.

3.2.2 Standard reference state

A state of equilibrium selected as the base at which these characteristics, that are dependent upon equilibrium conditions, will be measured and reported for comparison.

3.3 Practical thermal characteristics

The practical thermal characteristics of a building material are the values of its thermal conductivity (λ_p) and its thermal resistance (R_p) in conditions that can be considered as typical of buildings.

These conditions take account of

— the moisture content of the material in normal use;

— ageing (that is, the change in thermal properties with time due to gas diffusion when the pores contain a gas other than air, and/or dimensional changes after application, including the effect of cracking, settlement, shrinkage, etc.);

1) To be published.

— the temperature of use, if it is different from the standard reference temperature;

— the density, if it is different from the density at which the basic properties were determined;

— workmanship (the practical thermal properties of buildings are influenced by the correctness of execution of the insulation work, and the thermal properties of building components should therefore be corrected for average imperfections in workmanship).

It is difficult or even impossible to fix internationally agreed procedures to take workmanship into account because it depends not only on the type of insulating material, but also on conditions such as the position of the insulation within the building, the average skill of the installers in a particular geographical area, the average weather conditions during transportation, handling and installation and the building technology.

The effect of workmanship on the final thermal performance of a building can be negligible or can exceed 10 %, even when good installation practices are followed.

On a nation-wide basis, more homogeneous conditions can be expected, and hence the evaluation of the effect of workmanship may be attempted.

Depending on the case considered, one has the option of quoting the practical thermal conductivity or the practical thermal resistance if a specific thickness is used, or both values. However, the practical thermal resistance as a function of thickness shall be quoted if the concept of thermal conductivity does not apply (see the annex).

4 General considerations and principles

4.1 The thermal properties of a building material or product may be determined by various methods.

1) By testing the material as such using a hotplate apparatus, a heat flow meter apparatus or a hot box apparatus under laboratory conditions and adding corrections to allow for the different conditions in practical use. The thermal property of a construction may then be found by a standard calculation.

2) By testing a complete component, which includes the material concerned, in a hot box apparatus under laboratory conditions. The thermal resistance (or conductivity) of each material layer may be found by internal temperature measurements or by calculation, and may need the same types of correction as above.

3) By measurements in existing buildings under practical conditions. It is possible to calculate, by means of a standard calculation, from such measurements what the thermal resistance (or conductivity) of the material or product must be.

Testing of or measurements on complete constructions are expensive, and it is often difficult to cover all insulation combinations and insulation thicknesses by method 2) or 3). However, such measurements are important in checking the validity of the procedures used to calculate design values.

The thermal conductivity of a building material and the thermal resistance of a building product obtained by method 1) from laboratory measurements correspond to well defined physical test conditions that in most cases are different from the conditions encountered in practice.

Even though it is desirable to carry out tests in conditions as close as possible to end-use conditions, measured values may have to be corrected to give an acceptable description of the expected performance under service conditions. Measured values corrected in this way are called practical values.

4.2 Practical thermal properties of building materials may be needed for various purposes.

1) For use in calculations to prove that a certain construction meets the requirements of building codes. It is important here that the practical thermal properties ensure equal and fair treatment of each product.

2) For calculating heating and cooling loads for the design of heating and ventilation systems and for protection against frost heave. In this case, safety factors may be relevant.

3) For calculating the annual energy consumption, the optimization of thermal insulation costs and the evaluation of energy-saving measures. In this case, average values may be the most relevant.

In view of this variety of uses, it is not surprising that design values and practical values are not the same in all cases. Any attempt to give specific figures for each particular application leads, however, to complicated tables. For this reason, it is better to stick to one representative condition and try to allow for variations due to different conditions by introducing safety factors or reduction factors in design guidelines.

4.3 When quoting thermal properties, it is important to realize that there is a fundamental difference between the properties of materials and those of products.

4.3.1 Material properties are independent of the size and shape of the product being considered. Material properties are related to the nature of the material of which the product is made (structure, density, chemical composition, etc.). For practical purposes, the thermal conductivity is often referred to as a material property, even though it is not a true material property for all materials. For the applicability of the concept of thermal conductivity, see the annex of ISO 7345.

4.3.2 Product properties are related to the shape and dimensions of the product. A typical product property is thermal resistance — the ratio of the temperature difference to the density of heat flow rate (thermal flux density). Thermal resistance can be defined and measured for a particular specimen, of known shape and size, of an unknown material.

Many combinations of materials of different thermal conductivities (λ) and thicknesses can give the same thermal resistance.

The determination of thermal resistance from the material properties, the shape and the size (ratio between thickness and thermal conductivity) should be considered a special case.

As a consequence, the analysis and correction of properties of materials and those of products may be different, and care shall be taken to avoid confusion between the two.

5 Test methods and test conditions

5.1 Test methods

Laboratory testing should be carried out according to one of the following methods:

a) guarded hotplate ISO 8302;

b) heat flow meter ISO 8301;

c) guarded or calibrated hot box ISO 8990.

However, for some measurements, for example those on moist materials, it may be necessary to use methods which are not covered by International Standards. In such cases, the method used shall be described in the test report.

5.2 Test conditions

The conditions under which the tests are carried out shall be described in the test report and shall be consistent with the method used.

The following information is important in the interpretation of the results, and shall be specified in the test report:

- the test method used;
- the mean test temperature;
- the temperature difference between the faces of the test piece(s);
- the sampling method used;
- the conditioning procedure used;
- the thickness of the test piece(s);
- the density, in the standard reference state, of the material(s) under test;
- the duration of the test (when meaningful);
- the moisture content, by weight or by volume, of the test piece(s)
  - as received (when meaningful);
  - after conditioning;
  - before and at the end of the test;
- the time elapsed since production of the test piece(s);
- any other useful information.

6 General principles for correcting measurements

The procedure for converting measured values to practical values can be logically split into two steps.

a) The first step consists of collecting the available measured values and making them consistent with each other. As an example, the mean test temperature may have been 10, 20 and 24 °C in various tests. A standard reference temperature shall be chosen and all values converted to that temperature so that they can subsequently be compared with each other.

b) The second step is correcting the data to the actual operating conditions. Using temperature as the example again, the measured data may have been converted to a reference temperature in the first step but, in view of the different climatic conditions which exist in different parts of the world, the mean working temperature for an insulating material or product in a building application can be anywhere between − 40 and + 30 °C. This means that further correction is required to convert the measurements from the standard reference temperature to the mean working temperature.

6.1 Preliminary measurements

For each family of materials, the thermal conductivity, or thermal resistance, data could first be processed to give the following:

— A reference curve of thermal conductivity, or thermal resistance, plotted as a function of mean temperature, with the material conditioned to the standard reference state.

— A reference curve of thermal conductivity, plotted as a function of bulk density, with the material conditioned to the standard reference state.

— A reference curve of thermal conductivity plotted as a function of moisture content, provided suitable methods are available (if not, the literature should be referenced). In calculating the moisture content, a conventional definition of the dry state should be assumed.

— A curve showing the variation in thermal conductivity, or thermal resistance, with the age of the specimen, when relevant.

— A curve showing the variation in thermal conductivity with thickness, when relevant.

— A curve showing the relationship with any other relevant parameter.

6.2 Corrections

The difference between the minimum and the nominal thickness shall be considered in the correction process in order to give the appropriate design values.

All other corrections are given, for each family of materials, in clause 8.

7 Statistical considerations

The statistical interpretation of the test results assumes that the purpose of the calculation is known.

The thermal properties of the product or material should be given as mean values together with a standard deviation.

The basic thermal properties are thus defined as follows:

$$\lambda_b = \lambda_{mean} + \alpha_\lambda \cdot s_\lambda \quad \ldots (1)$$

and

$$R_b = R_{mean} - \alpha_R \cdot s_R \quad \ldots (2)$$

where

λ_b is the basic thermal conductivity;

λ_{mean} is the mean thermal conductivity;

R_b is the basic thermal resistance;

R_{mean} is the mean thermal resistance;

s_λ and s_R are the standard deviations for the thermal conductivity and the thermal resistance, respectively;

α_λ and α_R are correction coefficients specific to a particular group of materials and the purpose of the calculation.

NOTE — See ISO 2859 and ISO 3951 for guidelines to the statistical interpretation of results. National regulations may define the values of α_λ and α_R.

8 Corrections for materials

8.1 Mineral fibres

The comments in this sub-clause are limited to bonded mineral fibre mats and boards. Their thermal performance is given in this clause in terms of thermal resistance or thermal conductivity. Thermal conductivity is a function of density and thickness. Corrections for these parameters may be required (examples are given in the annex).

The standard reference state is a conventional dry state. In practice, this state is obtained by conditioning in a standard laboratory atmosphere.

The main correction factors for insulating materials used in building are dealt with in turn below.

For those correction factors which are relevant to mineral fibre insulating products, standardized procedures are given.

8.1.1 Variability

Fibrous insulating products shall comply with the particular specifications relative to each application for which they have been adopted.

These specifications point out, among other things, that, due to differences in production processes, materials of different density can have the same thermal resistance. The thermal resistance is therefore not related to the density alone.

For mineral fibre, the thermal conductivity/density curve has a minimum. At densities less than that corresponding to this minimum, the thermal conductivity increases faster than at densities greater than that corresponding to the minimum (i.e. the slope of the curve is numerically greater at lower densities than at higher densities — see figure 2 in the annex). Mineral fibres are usually produced with a density between 10 and 200 kg/m^3.

8.1.2 Effect of temperature

Corrections for the effect of temperature could be made using the procedure described in the annex.

Temperature coefficients range from 0,25 % to 1 % per kelvin.

Depending on the expected operating temperature and the reference temperature, it will be necessary to run experiments or to use the expression given in the annex.

8.1.3 Effect of thickness

If the thermal performance is expressed in terms of thermal resistance, the effect of thickness need not be considered.

If the thermal performance is expressed in terms of thermal conductivity, the effect of thickness shall be considered. For low-density materials and small thicknesses, see the annex.

8.1.4 Effect of moisture

Provided that the insulating products are protected from condensation, water leakage and ground water, and thus in equilibrium with air, the moisture content of mineral fibres is usually less than 1,5 % (m/m).

In these conditions, the effect on the thermal resistance and the thermal conductivity can be neglected in the majority of applications.

8.1.5 Effect of ageing

Mineral fibre products owe their thermal performance to the presence of air trapped in the fibre matrix. The dimensions of such products are usually stable. Therefore it is not usually necessary to make any corrections for ageing. However, exposure to hot and damp environments can damage the products.

8.1.6 Recovered thickness

Storing thermal insulation in a state of compression may, when the compressive force is removed, result in the product having a thickness which is less than or more than the declared nominal thickness when it is received by the purchaser.

8.1.7 Effect of permeability to air

Mineral fibre products are generally permeable to air. This characteristic only effects the thermal resistance or thermal conductivity under certain temperature conditions and in particular applications. Examples are given below.

— Internal convection may occur in constructions in which high-air-permeability insulating products have been used when these products are exposed to large temperature differences. In building applications, such extreme conditions are unlikely to occur.

— Mineral fibre insulating products facing ventilated air spaces may be affected by the air flow over the surface, but in building applications air speeds are normally not high enough to affect the thermal performance.

— Provided that such situations are avoided by using appropriate constructional methods, no correction for permeability to air is necessary.

8.1.8 Effect of workmanship

See 3.3.

8.2 Cellular plastics — polystyrene and polyurethane boards [1)]

Polystyrene products can be divided into two categories : expanded products and extruded products. Expanded polystyrene is usually produced as unfaced boards cut from blocks.

Extruded polystyrene is usually produced as unfaced boards with or without a skin. The blowing agent is frequently a mixture of gases which may have a thermal conductivity lower than that of air.

Polyurethane boards are cut from blocks or produced by a continuous process. They are frequently faced. The facing can vary from paper sheet to metal foil. The blowing agent used for polyurethane has a thermal conductivity lower than that of air, and the facing therefore plays a dominant role in the ageing process.

Time affects the thermal properties of cellular plastics when the blowing agent has a conductivity lower than that of air. This ageing effect depends on the blowing agent, the thickness and the facing.

The thermal performance of cellular plastics is expressed either in terms of the thermal resistance or in terms of the thermal conductivity, although the applicability of the thermal condictivity may be limited due to the effect of thickness (see 8.1.3).

The standard reference state is usually the equilibrium with the standard laboratory atmosphere after drying at a specified temperature for a specified length of time.

8.2.1 Variability

The way in which the thermal properties of these products vary depends on the density, the cell structure and the chemical composition of the blowing agent (when its thermal conductivity is different from that of air).

The chemical composition of the gas within the cells is the most important factor. Cell size has less influence on thermal performance. Small cells give best results.

Soon after production, air tends to enter the cells of polyurethane, polyisocyanurate and extruded polystyrene products and to dilute the blowing agent. The simultaneous diffusion outwards of the blowing agent is far slower. As a consequence, the thermal performance is influenced by time since production, the initial composition of the blowing agent and the surface coating.

1) Also applies to polyisocyanurate boards.

When products come from a single production line subject to strict quality control, and are tested under the same reference conditions and at the same age (excluding the first weeks of life), the standard deviation from the mean value of the thermal performance of the product will usually be less than a few percent.

8.2.2 Effect of density

For cellular plastics, the thermal conductivity/density curve has a minimum.

Expanded polystyrene is usually produced at densities between 10 and 40 kg/m^3, and the minimum thermal conductivity occurs at a density within this range.

For a 10 kg/m^3 product, a 1 % increase in density corresponds to a decrease in thermal conductivity of less than 0,5 % (examples are given in the annex).

Extruded polystyrene and polyurethane are usually produced at densities not far from that corresponding to the minimum of the thermal conductivity/density curve. For these materials, a change in density implies a change in cell structure, so care shall be taken in applying a simple correlation.

8.2.3 Effect of temperature

The annex gives guidance in predicting the effect of temperature. The effect is larger when the density is low and when the thermal conductivity of the blowing agent is low.

Typically, the correction ranges from 0,4 % to 0,6 % per kelvin, but it cannot be smaller than 0,3 % per kelvin or larger than 1 % per kelvin. The relationship between thermal conductivity and temperature is a linear one at around room temperature, and usually no correction is required to convert data from 10, 20 or 24 °C to any other one of these temperatures. However, below 0 °C the thermal conductivity of polyurethane increases in a fashion which is not easy to predict, and at about − 60 °C begins to decrease again. This means that cold store data cannot be used for building applications, and *vice versa*.

8.2.4 Effect of thickness

The thickness of most boards made of expanded or extruded polystyrene or of polyurethane ranges from 20 to 100 mm. Within this range, the effect of thickness on thermal conductivity can be detected, although it is not large in any given situation. This means that these materials do not have a thermal property dimensionally equivalent to thermal conductivity, and that their thermal resistance is not strictly proportional to the thickness. (See the annex for a detailed analysis and numerical examples.)

For thicknesses ranging from 20 to 100 mm, the change in the ratio d/R may range from less than 1 % to more than 5 %. The last figure applies to low-density expanded polystyrene.

8.2.5 Effect of moisture

Provided the insulating product is protected from water condensation and from any contact with liquid water, the equilibrium moisture content of polystyrene and polyurethane boards is usually less than 2 % (m/m).

The increase in thermal conductivity is usually less than 0,3 % per % (m/m) moisture content. This is so low that the effect can be neglected in most applications.

NOTE — The above figures do not apply to inverted roofs and similar constructions.

8.2.6 Effect of ageing

There are two ways in which ageing takes place. The first is due to the change in composition of the gas filling the cells and the second results from the dimensional changes which occur with time.

8.2.6.1 Gas diffusion

Whenever the blowing agent is not air, cellular plastics undergo an ageing process in which the blowing agent diffuses outwards from the cells and air inwards into the cells. The air diffuses in much more rapidly than the blowing agent diffuses out. After a long time, the thermal performance of these materials is the same as if air had been used as the blowing agent. This is an upper limit that cannot be exceeded. The time required for this condition to be reached may be many years and is affected by the cell structure, the percentage of the volume occupied by the cells, the cell wall material, the board thickness, the facing and the temperatures to which the board is exposed (high and cyclic temperatures accelerate ageing). The annex gives guidance as to the parameters needed to predict the ageing process due to gas diffusion.

8.2.6.2 Dimensional stability

Cellular plastics are stable as long as the geometry of the cells is not modified. With polystyrene, high temperatures and organic solvents may damage the material. The same applies to polyurethane, although the latter material is less sensitive to these other forms of ageing.

Even in a standard laboratory atmosphere, some polyurethane boards exhibit problems of dimensional stability. Increasing the temperature adversely affects this phenomenon for all cellular plastics, and it shall be described in material specifications.

8.2.7 Effect of permeability to air

Boards of cellular plastics generally have low permeability to air, but incorrect installation, shrinkage and warping can create air passages around and between boards.

8.2.8 Effect of workmanship

See 3.3.

NOTE — Stiff cellular plastics boards need to be cut to exact dimensions in order to fill a cavity completely.

8.3 Cellular glass

The comments in this sub-clause are limited to closed-cell materials which, because of their thermal properties, are the ones which are mainly used, although some open-cell materials are produced for acoustic insulation purposes. Thermal performance is usually expressed in terms of thermal conductivity, sometimes as thermal resistance. Cellular glass produced in blocks, without facing or skin, can be used as the core in the manufacture of panels.

The closed cells contain a mixture of gases, CO_2 being the main component.

8.3.1 Variability

The properties of cellular glass depend on several parameters, the main ones being the chemical composition, the cell gas composition, the foam density and the cell structure.

When products come from a single production line which is fully automated and subject to strict quality control, tests run under the same conditions will indicate variations (positive or negative) of

- about 10 % in the density;
- about 5 % in the thermal conductivity;
- about 20 % in the compressive strength.

8.3.2 Effect of density

The density of cellular glass usually varies from 100 to 150 kg/m^3. For special applications, it can be as high as 260 kg/m^3. Other factors remaining constant, an increase in density results in an increase in the thermal conductivity and compressive strength. This rule should be applied with care since changing the density can lead to changes in other factors.

8.3.3 Effect of temperature

In the − 30 to + 30 °C temperature range, an increase in temperature results in an increase in the thermal conductivity, the increase being virtually linear. For materials with densities ranging from 100 to 150 kg/m^3, the increase in thermal conductivity ranges from 2 % to 5 % for every 10 °C increase in temperature.

NOTE — The relationship between the thermal conductivity of cellular glass and temperature cannot be assumed to be linear outside the temperature range − 30 to + 30 °C.

8.3.4 Effect of thickness

The minimum thickness manufactured is about 30 mm. At this thickness, there is no significant thickness effect on the thermal conductivity.

8.3.5 Effect of moisture

In all the normal applications of cellular glass, no moisture absorption has been noticed, either in vapour form or in liquid form. Consequently, the thermal conductivity can be assumed to be unaffected by moisture.

8.3.6 Effect of ageing

8.3.6.1 Gas diffusion

No effect of ageing has been noticed with cellular glass. The gas-tight nature of the material prevents any diffusion of gas through the material.

8.3.6.2 Dimensional stability

The length and width of cellular glass products are stable with time and are not affected by a change in any parameter other than temperature. When temperature changes occur, the length and width vary according to the coefficient of expansion.

The thickness is not modified by storage to any significant extent.

8.3.7 Effect of permeability

Cellular glass is impermeable to air, but incorrect installation can create air passages around and between blocks.

8.3.8 Effect of workmanship

See 3.3.

8.4 Wood and wood products

The practical thermal conductivity of solid wood depends on

- the species of tree concerned;
- the oven dry density;
- the orientation of the fibres with respect to the direction of heat flow;
- the temperature;
- the moisture content by mass.

These factors interact with each other.

Because of the interdependence of the various factors which affect the thermal conductivity, measured values of the thermal conductivity in real conditions shall be preferred to computed ones. The standard reference state is usually taken as equilibrium with the standard laboratory atmosphere or the state after drying.

8.4.1 Effect of density and temperature

No reliable information is available on the effect of these parameters.

8.4.2 Effect of moisture

For moisture contents between 5 % and 20 % (m/m) the thermal conductivity increases by about 1,2 % for every percent increase in moisture content.

8.5 Concrete

As far as its thermal performance is concerned, concrete can be divided into the following types:

- normal concrete (NC);
- lightweight concrete (LC);
- aerated concrete (AC).