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Thermal insulation — Moisture effects on heat transfer — Determination of thermal transmissivity of a moist material

Isolation thermique — Effets de l'humidité sur les propriétés relatives au transfert de chaleur — Détermination de la transmissivité thermique d'un matériau humide

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

International Standard ISO 10051 was prepared by Technical Committee ISO/TC 163, *Thermal insulation*, Subcommittee SC 1, *Test and measurement methods*.

Annexes A, B, C, D and E of this International Standard are for information only.

Introduction

The thermal transmissivity of a moist material is needed for the assessment of design values of thermal conductivity and thermal resistance under service conditions as described in ISO 10456[1]. The thermal transmissivity of a moist material is also necessary for any calculation of combined heat and moisture transfer. Heat transfer within moist porous materials involves a complex combination of

- radiation,
- conduction in the solid, liquid and gas phases,
- convection (in some operating conditions),
- mass transfer (in the moist materials),

and their interactions. While these heat and mass flow phenomena are transitory in nature, some of them have a long term contribution that must be recognised in the evaluation of thermal insulation performance. This International Standard determines the long-term contribution of both material structure and moisture on thermal transmissivity. This transmissivity, called thermal transmissivity of a moist material, is a material property and a function of the moisture content of the material. Normally, thermal transmissivity of a moist material varies locally in the material and is a function of the moisture content of each layer.

The correct operation of the apparatus used to obtain the thermal transmissivity of a moist material and the interpretation of experimental results are difficult tasks that require great care. It is recommended that the operator and the user of measured data both have a thorough background knowledge of heat and moisture transfer mechanisms in the materials, products and systems being evaluated, coupled with experience of measurements made using guarded hot plate or heat flow meter apparatus.

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Thermal insulation — Moisture effects on heat transfer — Determination of thermal transmissivity of a moist material

1 Scope

This International Standard specifies a method to determine the thermal transmissivity of a moist material (λ^*) under steady-state moisture conditions, i.e. not affected by moisture movement. It is measured using standardized guarded hot plate and heat flow meter methods, at temperatures above 0 °C. This material property is a function of the moisture content and does not represent the thermal performance of a material under service conditions. However, it can be used, together with knowledge of the moisture conditions in the material, to predict the practical thermal performance.

The use of λ^*, the distribution of moisture under service conditions and consequently the prediction of thermal performance under service conditions are outside the scope of this International Standard. However, the moisture distribution under service conditions should, where possible, be considered when λ^* is determined. Furthermore, transient methods of measurement are not included due to the difficulty involved in analysing and interpreting the results of these methods.

2 Normative references

The following standards contain provisions which, through reference in this text, constitute provisions of this International Standard. At the time of publication, the editions indicated were valid. All standards are subject to revision, and parties to agreements based on this International Standard are encouraged to investigate the possibility of applying the most recent editions of the standards indicated below. Members of IEC and ISO maintain registers of currently valid International Standards.

ISO 7345:1987, *Thermal insulation — Physical quantities and definitions.*

ISO 9346:1987, *Thermal insulation — Mass transfer — Physical quantities and definitions.*

ISO 8301:1991, *Thermal insulation — Determination of steady-state thermal resistance and related properties — Heat flow meter apparatus.*

ISO 8302:1991, *Thermal insulation — Determination of steady-state thermal resistance and related properties — Guarded hot plate apparatus.*

ISO 6946-1:1986, *Thermal insulation — Calculation methods — Part 1: Steady state thermal properties of building components and building elements.*

ISO 9288:1989, *Thermal insulation — Heat transfer by radiation — Physical quantities and definitions.*

ISO 10456:—[2], *Thermal insulation — Building materials and products — Determination of declared and design thermal values.*

3 Definitions

For the purposes of this International Standard, the following definitions apply.

3.1 thermal transmissivity of a moist material, λ^*: Intrinsic material property dependent upon moisture content and temperature but not on testing conditions. It is often referred to elsewhere as thermal conductivity of a moist material. It is defined for

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[2] To be published.

a moist material by the following differential equation during steady-state conditions:

$$q_m = -\lambda^* \cdot \frac{dT}{dx}$$

when moisture distribution within the material is in the steady-state and there is no liquid movement within the material.

NOTE 1 The transmissivity, either for dry materials (see ISO 9288, ISO 8301 and ISO 8302) or for moist materials (see this document) expresses a material property that has the dimension of a thermal conductivity but that can replace it only in some expressions (in most cases those related to steady-state heat and mass transfer in a slab). Usually transmissivity cannot replace conductivity in most two- and three-dimensional flow patterns, in the expression of thermal diffusivity and non steady-state problems. Due to the complexity of heat and mass transfer problems, transmissivity can seldom be determined through one single experiment, rather a procedure or particular testing conditions are required, e.g. tests at high thicknesses for the determination of the thermal transmissivity and equilibrium of moisture distribution and absence of moisture flow for the determination of thermal transmissivity of a moist material (non steady-state methods are usually excluded from the determination of transmissivity).

3.2 hygroscopic range: Moisture content in equilibrium with 98 % relative humidity or lower.

4 Symbols and units

For the purposes of this International Standard the following symbols and units apply.

Symbol	Quantity	Unit
a	Material-related constant in a linear relationship	$W\cdot m^2/(kg\cdot K)$
d	Thickness	m
g	Density of moisture flow rate	$kg/(m^2\cdot s)$
g_t	Density of total moisture flow rate	$kg/(m^2\cdot s)$
g_v	Density of vapour flow rate	$kg/(m^2\cdot s)$
g_l	Density of liquid flow rate	$kg/(m^2\cdot s)$
h	Specific enthalpy	J/kg
h_e	Specific latent enthalpy of evaporation or condensation	J/kg
h_v	Specific enthalpy of vapour	J/kg
h_l	Specific enthalpy of liquid	J/kg
q	Density of heat flow rate	W/m^2
q_m	Measured density of heat flow rate at the hot and cold sides of the specimen	W/m^2
R	Thermal resistance	$m^2\cdot K/W$
t	Time	s
T	Thermodynamic temperature	K
v	Humidity by volume	kg/m^3
w	Moisture content mass by volume	kg/m^3
w_{cr}	Moisture content, below which g_l may be considered negligible	kg/m^3
w_v	Moisture content in vapour phase	kg/m^3
w_l	Moisture content in liquid phase	kg/m^3
δ_v	Moisture permeability	m^2/s
ρ	Bulk density of material	kg/m^3
λ	Thermal conductivity of dry material	$W/(m\cdot K)$
λ^*	Thermal transmissivity of a moist material	$W/(m\cdot K)$
ϕ	Relative humidity	

NOTE 2 In this International Standard, humidity by volume (v) has been used as the driving force for water vapour diffusion and moisture content mass by volume (w) as moisture content. The use of partial water vapour pressure (p_v) and moisture content mass by mass (u) respectively are equivalent provided that relevant material properties and boundary conditions are used.

Subscripts

b	Border between zones 1 and 2, see figure 2
cold	Cold surface of specimen
cr	See w_{cr}
hot	Hot surface of specimen
i	Arbitrary slice of specimen
l	Liquid
m	Measured
sat	Saturation
sur	Specimen surface
t	Total
v	Vapour

5 General considerations

5.1 Introduction

This clause describes the mechanisms by which moisture affects heat transfer in order to give the theoretical background for a test method which allows prediction of thermal performance in the presence of moisture.

Although the equations derived hereafter are as general as possible, examples of the use of these equations are given presupposing that measurements will be performed

- in standardized apparatus intended for a steady-state method (guarded hot plate or heat flow meter), and
- above freezing point.

5.2 Description of heat and mass transfers

Moisture flow is defined here to include flows of both vapour and liquid. Physically, moisture transfer is a combination of vapour and liquid flows in series and in parallel and it is normally not possible to clearly distinguish between the two kinds of flows. The specific enthalpy of vapour, however, differs considerably from that of liquid; it is therefore essential to treat moisture transfer as the sum of a vapour flow and a liquid flow:

$$g_{\mathrm{t}} = g_{\mathrm{v}} + g_{\mathrm{l}} \qquad \dots (1)$$

In a closed system (i.e. with constant moisture content), steady-state moisture flow is reached when:

$$g_{\mathrm{t}} = 0 \Leftrightarrow g_{\mathrm{v}} = -\, g_{\mathrm{l}} \qquad \dots (2)$$

In other words, steady-state moisture flow is reached when vapour and liquid transfers are equal and opposite, i.e. when movement of liquid by capillarity is balanced by movement of vapour by diffusion.

As vapour and liquid migrate, they carry their respective enthalpies, a condition which leads to an increase of heat transfer.

This heat transport caused by moisture flow is added to the conduction heat transfer described by Fourier's law, thus giving the following expression for the total density of heat flow rate, q:

$$q = -\,\lambda^{*}\cdot\frac{\mathrm{d}T}{\mathrm{d}x} + g_{\mathrm{v}}\cdot h_{\mathrm{v}} + g_{\mathrm{l}}\cdot h_{\mathrm{l}} \qquad \dots (3)$$

The first term in the right-hand part of equation (3) describes the heat flow caused by a temperature gradient. It consists essentially of

- conduction in the solid material and in the air in the pores of the material,
- conduction in water bound to the pore walls,
- evaporation and condensation within a pore or a local area, and
- thermal radiation and natural convection in the pores.

Each of these four heat flows is considered proportional to the gradient of temperature, so we can write by analogy with Fourier's law:

$$q = q_1 + q_2 + q_3 + q_4 = -\,\lambda^{*}\cdot\frac{\mathrm{d}T}{\mathrm{d}x} \qquad \dots (4)$$

In the case of thermal transmissivity of a moist material, increased conduction due to the presence of moisture in the material must be considered.

The second and third terms of equation (3) describe the parts of the heat flow associated with the enthalpies of vapour and liquid and the effects of evaporation and condensation. These fluxes are not proportional to the temperature gradient.

For the treatment of heat transfer in moist materials it is necessary to separate the mechanisms "conduction heat flux" and "heat flux by evaporation/diffusion/condensation".

In the past it has been customary to divide the total heat flux by the temperature gradient to obtain the thermal conductivity of a moist material. This procedure is clearly faulty, because it gives a variable value, dependent on conditions of measurement.

It is also important to distinguish carefully between moisture effects in service and those in laboratory test conditions.

Simulation of all the complex moisture effects, which occur under service conditions and during a test, is not considered within the framework of this document. Effects of moisture flow and phase changes depend entirely on the occurrence and magnitude of moisture transfer in the material. If these effects are allowed during the test, it is difficult to assess a material or component property. There will also be a great risk that these types of effects are estimated inaccurately. The main purpose of the test is therefore to determine λ^{*} which is a necessary basis for the prediction of the thermal performance in service conditions. The prediction itself is, however, outside the scope of this International Standard.

5.3 Determination of thermal transmissivity of a moist material

Determination of thermal transmissivity of a moist material requires a temperature gradient. Normally, a temperature gradient causes a redistribution of the moisture in the material, which leads to two types of problems:

- The test is carried out on material with changing and unknown moisture distribution.
- Redistribution of the moisture may simultaneously induce phase changes and heat transfer by moisture flow. Thus, heat is transported from the hot to the cold face by latent heat effects. However, by definition of the thermal transmissivity of a moist material according to this International Standard, such latent heat effects are not included. Therefore it is necessary to apply a correction to the measured heat flow (unless it is established that such a correction is zero or very small) before dividing by the temperature gradient.

During testing of a moist material the heat flow measured at the hot or cold surface will vary essentially as shown in figure 1: an initial phase A, with more or less constant heat flow due to the combined effect of conduction, effects of moisture flow and phase changes; a transition phase B, and finally phase C with moisture equilibrium.

Phase A is the period during the test, when the rate of evaporation at the hot face of the specimen is constant. This is only possible as long as the moisture content is above the hygroscopic range (relative humidity in the pores is approximately 100 %) and consequently the distribution of humidity by volume (or vapour pressure) is unaffected by changes in distribution of moisture content.

Phase A is deemed to occur if

- the moisture content at the hot face of the specimen is above the hygroscopic range, and
- the heat flow at the hot face of the specimen is constant for at least 2 h after thermal equilibrium has been reached.

During phase A there is evaporation of moisture at the hot face and vapour passes through the specimen. There is not an equal (counterbalancing) mass flow in the opposite direction in the liquid phase. Thus, there is net mass transfer and no moisture equilibrium.

In phase C, moisture evaporates at the hot face of the specimen, passes through the specimen in the vapour phase and condenses at the cold side. At the same time, water could be transferred in the liquid phase from the cold side to the hot side. In terms of mass, these two flows are equal and opposite, and there is equilibrium.

NOTE 3 Substantial moisture transfer in the liquid phase is very rare in thermal insulating materials and furthermore requires a moisture content above a critical level (w_{cr}).

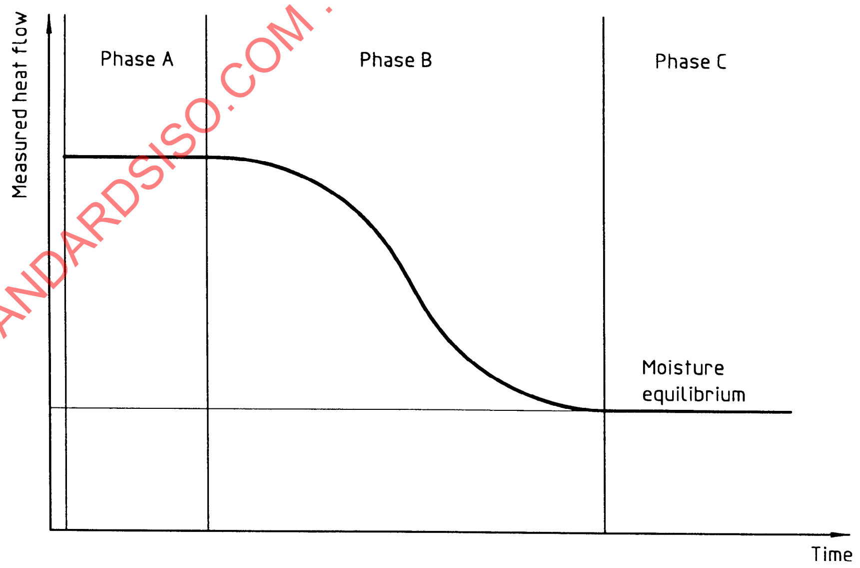

Figure 1 — Heat flow during a test to determine thermal transmissivity of a moist material

It can be derived [see annex A, equation (A.7)] that the measured heat flow at the hot and cold surfaces may be expressed as

$$q_{\mathrm{m}} = \left(-\lambda^{*} \cdot \frac{\mathrm{d}T}{\mathrm{d}x} \right)_{\mathrm{sur}} + (g_{\mathrm{v}} \cdot h_{\mathrm{e}})_{\mathrm{sur}} \qquad \ldots (5)$$

To determine $\lambda^{*}(w)$, the following must be known: the moisture content, the temperature gradient, the densities of heat flow and the moisture flow rates in the vapour phase at the surface.

6 Test apparatus

Heat flow meter apparatus according to ISO 8301 with two heat flux transducers (configuration b) is preferred. Heat flow meter apparatus (HFM) with one heat flux transducer at the hot side, or a guarded hot plate (GHP) according to ISO 8302 may also be used.

Downward vertical heat flow is recommended. If downward vertical heat flow is not used the risk of moisture redistribution by gravity air movements (convection) shall be considered.

Provision to record surface temperatures and heat flow(s) at the specimen's surface(s) as functions of time shall be made.

In some cases (see clause 7), additional temperature sensors to determine the temperature distribution within the test specimen shall be provided.

The test specimen shall be enclosed in a vapour-tight envelope, see 7.2 for details.

7 Test procedure

7.1 General

When carrying out tests on moist materials, the directions regarding test procedures for dry materials in the relevant International Standard for the apparatus shall be complied with.

Test temperatures shall not be high enough to damage the material. High temperatures may cause vapour pressures high enough to destroy the cell walls in closed-cell materials.

Further requirements for moist materials are given in 7.2. In case of discrepancies between this International Standard and the relevant International Standard for the apparatus, this International Standard takes precedence.

7.2 Specimen preparation and conditioning

The specimen shall be conditioned to the desired moisture content and moisture distribution.

Where possible, the moisture distribution under service conditions should be considered when λ^{*} is determined.

Conditioning may be by water immersion, with or without vacuum, absorption in humid air, spraying of water on the specimen or by subjecting the specimen to a temperature gradient. Combinations of these methods are also possible.

Note that, due to hysteresis effects, the moisture pre-history of the test specimen may influence the moisture content. The equilibrium moisture content at identical ambient conditions may depend on, for example, whether the equilibrium is reached by absorption or desorption.

Specimens having been conditioned under service conditions may also be tested.

The following guidance for conditioning in 7.2.1 and 7.2.2 covers most combinations of materials and moisture content levels.

7.2.1 Materials for which the effects of moisture movements may be neglected within the hygroscopic range

Condition the material at the desired relative humidity to constant mass. The moisture content may be considered uniform. Measure according to 7.4.1.1.

7.2.2 Materials for which the effects of moisture movements may be neglected above the hygroscopic range

Condition the specimen by subjecting it to a temperature gradient. Measure according to 7.4.1.

7.2.3 Other materials

Phase C is normally preferred. Condition the material under the same temperature gradient which is going to be used in the guarded hot plate or heat flow meter apparatus. Measure according to 7.4.2.

After conditioning the specimen it shall be enclosed in a vapour-tight envelope. The envelope shall prevent a change in moisture content greater than $0{,}01\ \mathrm{kg/\left(m^{3} \cdot h\right)}$.

If the presence of the envelope introduces significant thermal resistances between the specimen and the apparatus, the thermal resistance of the envelope must be considered as described in the relevant International Standard for the apparatus.

7.3 Selection of phase A or C

In theory either phase A or phase C can be selected for determining λ^*. In practice, however, only one of the phases is recommended, depending on material properties and moisture content and distribution.

Guidance on the choice of phase is given in 7.3.1 to 7.3.5.

7.3.1 Moisture permeability

For materials with a low moisture permeability it takes a very long time to reach moisture equilibrium (phase C) and at the same time the effects of moisture movements are small during phase A. For these materials phase A is recommended. An alternative is to condition the specimen to the equilibrium of phase C (see 7.2) and measure during phase C.

7.3.2 Moisture distribution

A uniform or almost uniform moisture distribution may be maintained only during phase A. In phase C the moisture content is always non-uniform. The rate of redistribution is smaller and the equilibrium moisture content is more uniform when working at low temperature gradients. If the moisture distribution during the test cannot be monitored simultaneously, it shall be estimated by either

- measurements of moisture distribution before and after the test, or;
- measurement of the moisture distribution before or after the test and calculation of the rate of redistribution.

If there is a risk of moisture redistribution by gravity, the evaluation of the results should be carried out extremely carefully.

7.3.3 Hygroscopicity and moisture content level

Phase A requires a moisture content above the hygroscopic range, where changes in moisture content do not affect the distribution of the humidity by volume. For materials with negligible effects of moisture transfer (see 7.4.1) phase A may be used for any moisture content level. In phase C the major part of the material has a moisture content in the hygroscopic range.

7.3.4 Thermal conductivity of dry material

In materials with a high value of thermal conductivity, λ, the relative importance of the effects of moisture movement are small and may be neglected. Compare this to the relation δ/λ (see 7.4.1).

7.3.5 Heat flow meter apparatus with two heat flux transducers

It is easier to judge moisture equilibrium when a heat flow apparatus with two heat flux transducers is used. This allows more information about the heat transfer and the mass transfer in the specimen to be determined and therefore improves the quality of the results.

7.4 Derivation of thermal transmissivity from measured values of heat flow and temperatures

7.4.1 Phase A

Two cases are possible:

- uniform or almost uniform distribution of moisture;
- non-uniform distribution of moisture.

7.4.1.1 Uniform or almost uniform distribution of moisture

The temperature distribution is considered linear in the specimen, and the temperature gradient is approximated by

$$\frac{\mathrm{d}T}{\mathrm{d}x} = \frac{T_{\mathrm{hot}} - T_{\mathrm{cold}}}{d} \qquad \ldots (6)$$

To derive thermal transmissivity λ^*, from the measured heat flow, it is necessary to either

- evaluate $(g_{\mathrm{v}})_{\mathrm{sur}}$ or,
- have conditions for which the term $(g_{\mathrm{v}} \cdot h_{\mathrm{e}})_{\mathrm{sur}}$ is negligible.

Evaluation of g_{v} is dealt with in B.1.

Cases for which $g_{\mathrm{v}} \cdot h_{\mathrm{e}}$ may be neglected are dealt with in B.2.

7.4.1.2 Non-uniform distribution of moisture

To derive $\lambda^*(w_{\mathrm{sur}})$ it is necessary to either

- evaluate $(g_{\mathrm{v}})_{\mathrm{sur}}$ or,

— have conditions for which the term $(g_v \cdot h_e)_{sur}$ is negligible, see B.2.

If g_v is evaluated, the left-hand side of equation (7) is known

$$q_m - (g_v \cdot h_e)_{sur} = -\left(\lambda^* \cdot \frac{dT}{dx}\right)_{sur} \qquad \ldots (7)$$

and consequently dT/dx at the surface has to be determined to evaluate $\lambda^*(w_{sur})$.

If $g_v \cdot h_e$ is negligible equation (5) may be written

$$q_m = -\left(\lambda^* \cdot \frac{dT}{dx}\right)_{sur} \qquad \ldots (8)$$

Note that this relationship is valid at the surface of the specimen.

In the specimen, equation (3) may be applied. If $g_v \cdot h_e$ is negligible, $g_v \cdot h_v$ may be neglected since $h_v \gg h_l$ and

$$h_e = h_v - h_l$$

In many cases $g_l \cdot h_l$ may also be neglected (for example when g_l is negligible) and then equation (8) may be applied through the whole specimen.

To derive λ^* as a function of w it is necessary to measure the moisture and temperature distributions. Note the possibility of determining temperature and/or moisture distribution in parallel specimens subjected to boundary conditions equal to those in the guarded hot plate or heat flow meter apparatus. An approximate solution, which requires measurement of the moisture distribution only, is given in C.1.

7.4.2 Phase C

In phase C both heat and mass flows are steady-state.

$$g_v + g_l = 0 \qquad \ldots (9)$$

Equation (5) is still valid at the surface

$$q_m = \left(-\lambda^* \cdot \frac{dT}{dx}\right)_{sur} + (g_v \cdot h_e)_{sur}$$

For heat flow in the specimen, $g_v = -g_l$, and equation (3) may be written

$$q = -\lambda^* \cdot \frac{dT}{dx} + g_v \cdot h_e \qquad \ldots (10)$$

which is the same equation as equation (5).

In practice liquid flow, if any, will generally be limited to a portion of the sample, creating a zone which has to be handled differently from the zone with no liquid flow. This is illustrated in figure 2.

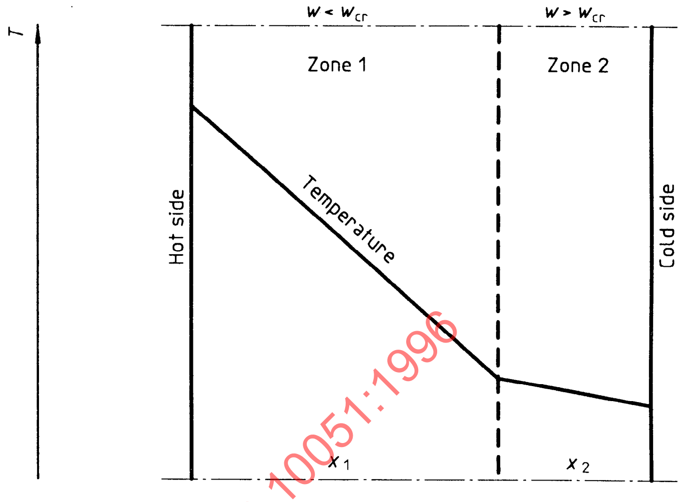

Figure 2 — Phase C, zone 1 and zone 2, with and without liquid flow

In theory, zone 2 is the portion of the material where the moisture content is above the critical moisture content, w_{cr}, which is defined as the moisture content below which negligible transfer of moisture in the liquid phase takes place. Two cases are possible:

a) moisture content never exceeds w_{cr};

b) moisture content exceeds w_{cr} in a zone of thickness x_2.

Case a) with liquid movement ($w > w_{cr}$ in zone 2) is treated in annex D.

For case b) with no liquid movement ($w < w_{cr}$ in the whole specimen) equation (5) and equation (10) become

$$q_m = q = -\lambda^* \cdot \frac{dT}{dx} \qquad \ldots (11)$$

Note that equation (11) is valid at the surface and through the whole specimen. To derive λ^* as a function of moisture content, both the moisture and temperature distributions shall be measured. Note the possibility to determine temperature and/or moisture distribution in parallel specimens subject to boundary conditions equal to those in the guarded hot plate or heat flow meter apparatus.

In annex C two approximate solutions are given; with only moisture distribution measured (see C.1) and with only temperature distribution measured (see C.2).

7.5 Flow chart of possible test procedures

The various possibilities to determine λ^* are summarised in the flow chart shown in figure 3. Note that three kinds of relationships between λ^* and w may be obtained in which:

a) thermal transmissivity of a moist material is a function of moisture content at the surface of the specimen, $\lambda^*(w_{sur})$

b) thermal transmissivity of a moist material is a linear function of moisture content, $\lambda^* = \lambda + a \cdot w$

c) there is an arbitrary relationship between thermal transmissivity of a moist material and moisture content, $\lambda^*(w)$

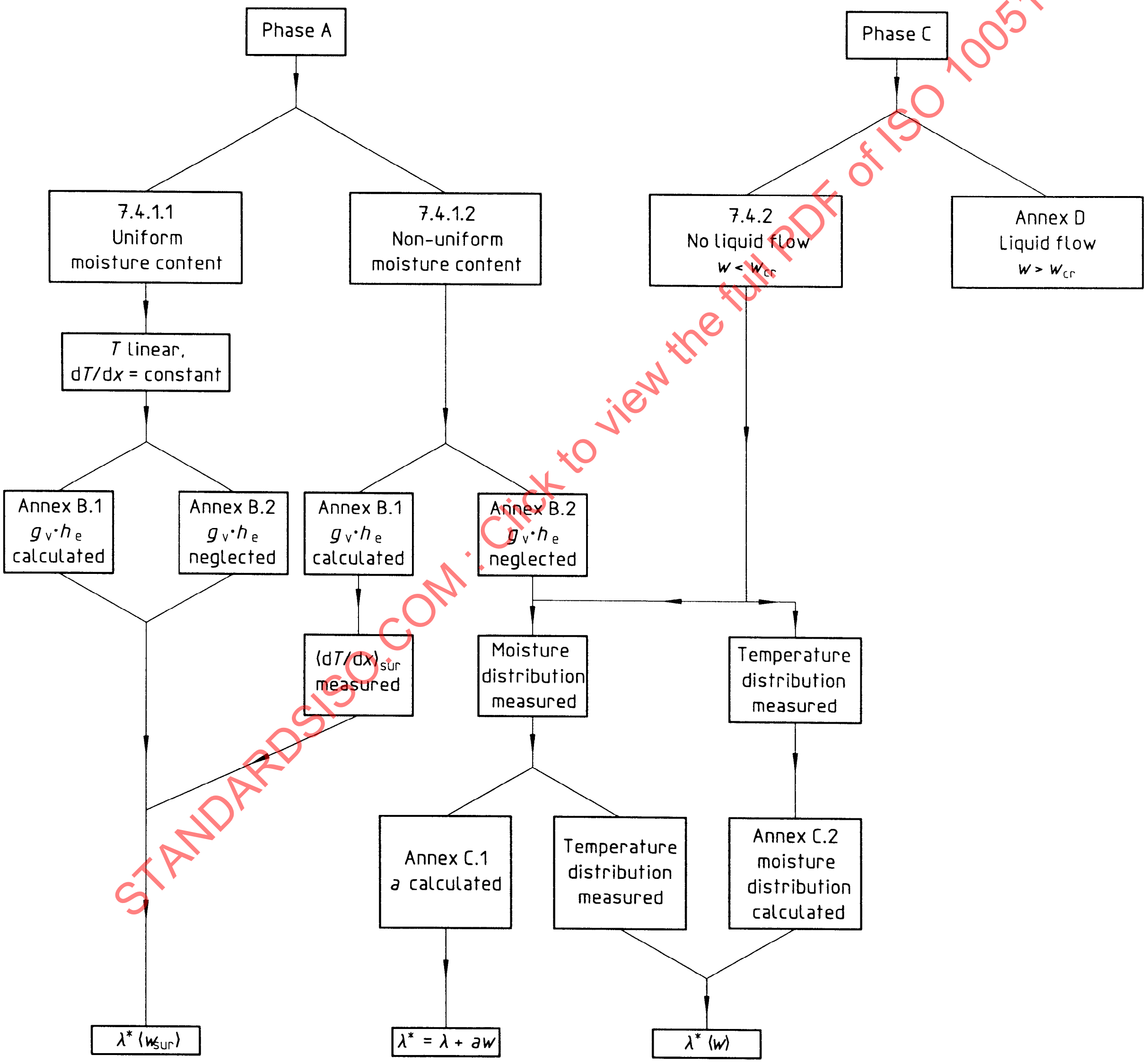

Figure 3 — Flow chart for determinations of thermal transmissivity

7.6 Sources of error

The total error is the sum of errors related to material properties and inhomogeneities, design and operation of apparatus and methods available to determine temperature and moisture distribution and moisture movements.

From equation (5) and equation (10) it is obvious that the possible sources of error are related to the determination of

a) the measured density of heat flow rate at the surface of the specimen, q_m. Compare the relevant International Standards for the apparatus (see ISO 8301 and ISO 8302);

b) moisture content in the specimen, w. Note errors due to moisture redistribution or moisture loss through the vapour-tight envelope during the test;

c) temperature, T, and temperature distribution, dT/dx, in the specimen;

d) the density of moisture flow rate in the vapour phase, g_v. Note that the expression used for example in B.1 and B.2

$$g_v = -\delta_v \cdot \frac{dv}{dx}$$

is only an approximation and the moisture permeability may vary considerably with temperature and moisture content. Inhomogeneity in the materials can cause variations in moisture transfer and distribution in the specimen;

e) the specimen thickness, d. In some cases there is a risk of change in dimension due to moisture variations.

Note also possible errors if the measurements are not carried out during a pure phase A or phase C, but in the transition phase between A and C.

7.7 Calculations

Calculate densities and mass changes of the specimen according to the relevant International Standard for the apparatus.

Calculate, when appropriate, temperature and moisture distributions, temperature gradients and densities of moisture flow rate in the specimen.

Calculate the thermal transmissivity of a moist material according to formulae and methods given in 7.4.

8 Test report

The report of the results of each test shall include the following.

a) name and any other pertinent identification of the material, including a physical description supplied by the manufacturer;

b) description of the specimen and its relationship to the sample, supplied by the operator, conformance to a material specification where applicable, method of specimen preparation for loose-fill materials with indication of the measured resistance of cover materials used for the containers;

c) thickness of the specimen(s) in metres and specify whether thickness is imposed or measured, criteria to define the imposed thickness, changes in thickness during the test, if any;

d) method of conditioning, including duration, temperature and moisture conditions;

e) densities of the conditioned specimen as tested, in kilograms per cubic metre;

f) type and configuration of apparatus used (guarded hot plate or heat flow meter) and specify the direction of heat flow;

g) temperatures at the specimen's cold and hot faces during the test and procedures for determination of these temperatures;

h) temperatures measured within the specimen during the test and type and arrangement of temperature sensors;

i) density of heat flow rate at the specimen's surface(s) as a function of time during the test;

j) for tests made using vapour-tight envelopes, information shall be given on the nature and thickness of the envelope;

k) relative mass changes during drying and/or conditioning (see 7.2);

l) relative mass change during test;

m) date of completion of the test; duration of the full test and of the steady-state part of the test if such information can help in interpreting results;

n) moisture contents measured and measurement procedure;

o) selection of phase and other relevant decisions regarding the test procedure (see figure 3);

p) calculations to evaluate density of vapour transfer and moisture content;

q) evaluated thermal transmissivity, λ^*, as a function of moisture content;

r) estimation of errors: a statement on the maximum expected error in each measured property is strongly recommended within the report (when one or more requirements stated in this International Standard are not fulfilled, it is recommended to include a complete report on the estimation of error or errors on the measured property);

s) statement of compliance: where circumstances or requirements preclude complete compliance with the procedure of the test described in this International Standard, agreed exceptions may be made but must be specifically explained in the test report; the suggested wording is: "This test met all requirements of ISO 10051 with the exception of ... (a complete list of the exceptions follows)".

Annex A
(informative)

Theoretical background

A.1 Introduction

This annex describes the mechanisms by which moisture affects heat transfer, in order to give the theoretical background for a test method which allows prediction of thermal performance in presence of moisture.

Although the equations derived hereafter are as general as possible, examples of the use of these equations are given presupposing that measurements will be performed

— in apparatus intended for a steady-state method (guarded hot plate or heat flow meter), and

— above the freezing point of pure water (0 °C).

A.2 Description of heat and mass transfers

A.2.1 Qualitative description of mass transfer phenomena in a simple case

Consider a homogeneous porous medium with horizontal flat boundaries at constant temperature (figure A.1).

At time $t = 0$, the temperature T_0 and the moisture content w_0 are uniform.

For the sake of simplicity, only vertical unidirectional transfer will be considered. Let us now imagine that at time $t > 0$, the upper boundary temperature is increased to the temperature $T_1 > T_0$.

The difference of temperature applied to the medium will modify the temperature distribution and create a mass transfer in the liquid and the vapour phase.

Those mass transfers result from different mechanisms which are described qualitatively in A.2.2, A.2.3 and A.2.4.

A.2.2 Vapour mass transfer

The temperature increase at the upper boundary induces a vaporization of any liquid water that might be present close to this boundary and consequently an increase of humidity by volume of air in this zone. Since equilibrium humidity is lower in cold regions, moisture migrates by a simple diffusion process of water vapour in air, from hot to cold regions.

As it migrates, part of this vapour condenses on the solid matrix of the porous medium and also on the existing liquid meniscus (figure A.2).

To maintain thermodynamic equilibrium, condensation at A is followed by evaporation at B.

Vapour therefore migrates towards the cold regions by alternately evaporating from and condensing on successive surfaces.

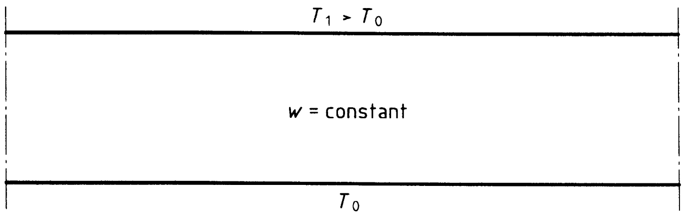

Figure A.1 — Homogeneous porous medium with horizontal flat boundaries at constant temperatures T_1 and T_0

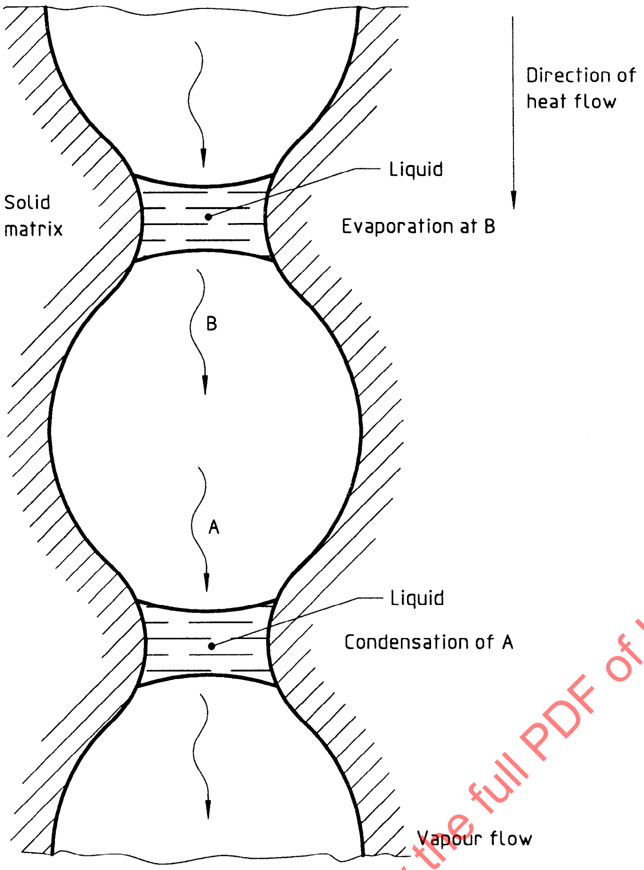

Figure A.2 — Vapour flow in porous medium

A.2.3 Liquid mass transfer

Vapour migration leads to a decrease in water content in the hot regions and therefore to a decrease of capillary pressure, in this zone. This pressure difference induces a liquid phase movement ("suction" effect) in a direction opposite to the vapour flow.

This liquid movement induced by a water content gradient is limited by the capillary pressure increase due to the gradient of temperature which tends to oppose the liquid migration (figure A.3). An increase in capillary pressure usually means that the capillary pressure becomes less negative.

A.2.4 Total mass transfer

Where g_v and g_l are the densities of mass flow rate in the vapour and liquid phases respectively, the total mass transfer g_t is equal to

$$g_t = g_v + g_l \qquad \dots (A.1)$$

In a closed system (i.e. with a constant moisture content), steady-state mass flow is reached when

$$g_t = 0 \Leftrightarrow g_v = - g_l \qquad \dots (A.2)$$

In other words, steady-state flow of mass is reached when vapour and liquid transfers are equal and opposite, i.e. when movement of liquid by capillarity is balanced by movement of vapour by diffusion.

A.2.5 Heat transfer equations

As vapour and liquid migrate, they each carry their respective enthalpies, which leads to an increase of heat transfer.

This heat transport caused by moisture flow is added to the conduction heat transfer described by Fourier's law, giving finally the following expression for the total density of heat flow rate (q)

$$q = -\lambda^{*}\cdot\frac{\mathrm{d}T}{\mathrm{d}x} + g_v\cdot h_v + g_l\cdot h_l \qquad \dots (A.3)$$

The first term in the right-hand part of equation A.3 describes the heat flow caused by a temperature gradient, see figure A.4. It consists essentially of:

- density of heat flow rate due to conduction in the solid material (1 a) and in the (humid) air in the pores of the material (1 b), q_1;
- density of heat flow rate due to conduction in water bound to the pore walls, q_2 (water acts as a parallel conductor which reduces the total effective thermal resistance);
- density of heat flow rate due to evaporation and condensation within a pore or a local area, q_3; moisture moves one way in the vapour phase and then back again in the liquid phase (note that this is a local process which is caused by temperature differences between the pore walls and takes place even if the moisture gradient is equal to zero); it must not be confused with effects of a large-scale flow or redistribution of the moisture in the specimen;
- density of heat flow rate due to radiation, q_4;
- density of heat flow rate due to convection in the pores, q_5; in most practical cases this can be neglected.

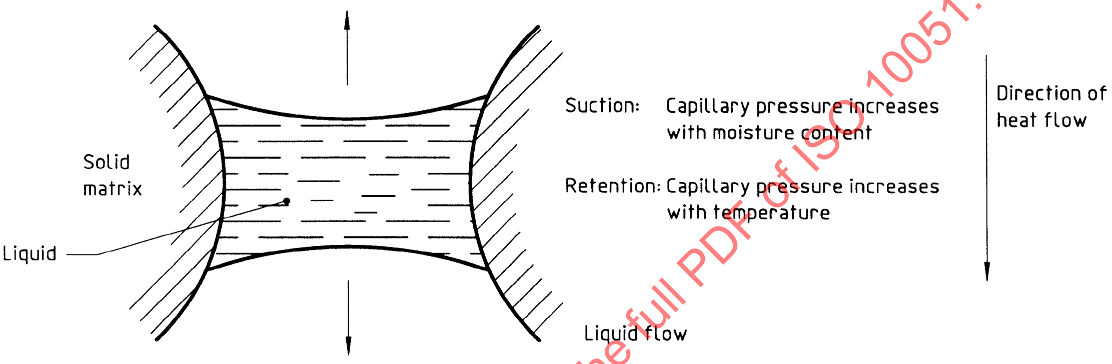

Figure A.3 — Liquid mass transfer in porous medium

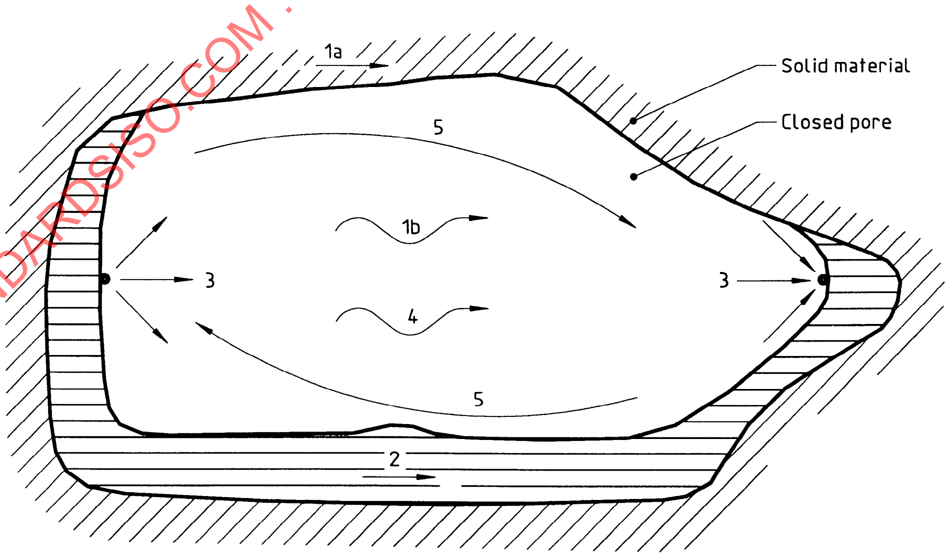

Figure A.4 — Description of heat transfer mechanisms in a pore

Each of these five heat flows is assumed to have a dominant first-order term proportional to the gradient of temperature, so we can write by analogy with Fourier's law

$$q = q_1 + q_2 + q_3 + q_4 + q_5 = -\lambda^{*} \cdot \frac{\mathrm{d}T}{\mathrm{d}x} \qquad \ldots \text{(A.4)}$$

It is important to distinguish carefully between moisture effects in service and those in laboratory conditions (during a test). Simulation of all the complex moisture effects in service conditions during a test is unrealistic and unnecessary. Effects of moisture flow and phase changes depend entirely on the occurrence and magnitude of moisture transfer in the material. If these effects are allowed during the test, it is difficult to assess a material or building component property. There will also be a great risk that these types of effects are overestimated. The main purpose of the test must therefore be to determine λ^{*}, which will in turn allow prediction of the thermal performances in service conditions.

A.3 Determination of thermal transmissivity of a moist material

A.3.1 General

Determination of the thermal transmissivity of a moist material always requires temperature gradients. Normally these will redistribute the moisture in the material, which leads to two types of problem:

- redistribution of the moisture means that the test is carried out on a material with a changing and unknown moisture distribution;
- redistribution of the moisture simultaneously induces heat transfer by moisture flow and phase changes; these effects are unlikely to be of exactly the same extent as the moisture effects in the material in service conditions, which is why these effects should be either negligible or well known during the test.

During a test of a moist material the heat flow measured at the hot surface will vary as shown in figure 1: an initial phase A, with more or less constant heat flow due to the combined effect of conduction, effects of moisture flow and phase changes; a transition phase B, and finally phase C with moisture equilibrium.

Existence of a phase A requires moisture content above the hygroscopic range so that the relative humidity in the material's pores will remain at 100 % even if the moisture content is changing. In some instances phase A may not be seen.

A.3.2 Derivation of an expression for the heat flow at the surface of the specimen (q_m)

One of the quantities measured during a test is the density of heat flow (q_m) at the hot and/or cold side of the specimen. It is therefore appropriate to derive an expression for q_m in terms of thermal transmissivity of a moist material (λ^{*}), temperature gradient, etc.

From equation (A.3) we have at the surface

$$q_m = -\lambda^{*} \cdot \frac{\mathrm{d}T}{\mathrm{d}x} + g_v \cdot h_v + g_l \cdot h_l \qquad \ldots \text{(A.5)}$$

with $h_e = h_v - h_l$ and

$g_v = -g_l$ at the surface, we get

$$q_m = -\lambda^{*} \cdot \frac{\mathrm{d}T}{\mathrm{d}x} + g_v \cdot h_e \qquad \ldots \text{(A.6)}$$

This expression is valid at both the hot and the cold surfaces:

$$q_m = \left(-\lambda^{*} \cdot \frac{\mathrm{d}T}{\mathrm{d}x} \right)_{\mathrm{sur}} + (g_v \cdot h_e)_{\mathrm{sur}} \qquad \ldots \text{(A.7)}$$

where subscript, sur, denotes hot or cold surface.

Annex B
(informative)

Evaluation of moisture flow and cases for which $g_\mathrm{v}\cdot h_\mathrm{e}$ is small

B.1 Evaluation of moisture flow, g_v, in vapour phase

To estimate g_v, Fick's law is applied assuming that the moisture flow is due to a gradient in humidity by volume. This is a reasonable simplification for many insulation materials.

In phase A, with moisture contents above the hygroscopic range, the relative humidity in the pores of the material is approximately 100 % and consequently the humidity by volume equal to the saturation humidity by volume, which is a function only of temperature.

$$g_\mathrm{v} = -\delta_\mathrm{v}\cdot\frac{\mathrm{d}v_\mathrm{sat}}{\mathrm{d}x} \qquad \ldots \text{(B.1)}$$

δ_v can be measured using methods for determination of "wet cup" values, allowing the derivation of g_v from equation (B.1).

NOTE 4 Water vapour pressure can be used as the driving force instead of humidity by volume.

Another way to estimate g_v would be to carry out parallel tests on similar specimens under similar boundary conditions and in these specimens determine the moisture redistribution and moisture flows.

B.2 Cases for which $g_\mathrm{v}\cdot h_\mathrm{e}$ is small

A case of interest is the case for which

$$h_\mathrm{e}\cdot\delta_\mathrm{v}\cdot\frac{\mathrm{d}v_\mathrm{sat}}{\mathrm{d}x} \ll \lambda^*\cdot\frac{\mathrm{d}T}{\mathrm{d}x} \qquad \ldots \text{(B.2)}$$

With

$$\frac{\mathrm{d}v_\mathrm{sat}}{\mathrm{d}x} = \frac{\mathrm{d}v_\mathrm{sat}}{\mathrm{d}T}\cdot\frac{\mathrm{d}T}{\mathrm{d}x} \approx k\cdot\frac{\mathrm{d}T}{\mathrm{d}x} \qquad \ldots \text{(B.3)}$$

where

$k = 0{,}6 \times 10^{-3}$ at 10 °C

$k = 1{,}0 \times 10^{-3}$ at 20 °C

$k = 1{,}6 \times 10^{-3}$ at 30 °C

and supposing that the requirement for neglecting $g_\mathrm{v}\cdot h_\mathrm{e}$ is that $g_\mathrm{v}\cdot h_\mathrm{e}$ is less than 3 % of $\lambda^*\cdot\mathrm{d}T/\mathrm{d}x$, it follows that

$$h_\mathrm{e}\cdot\delta_\mathrm{v}\cdot k\cdot\frac{\mathrm{d}T}{\mathrm{d}x} < 0{,}03\cdot\lambda^*\cdot\frac{\mathrm{d}T}{\mathrm{d}x} \qquad \ldots \text{(B.4)}$$

and finally

$$\delta_\mathrm{v} < \frac{0{,}03}{h_\mathrm{e}\cdot k}\cdot\lambda^* = \delta_\mathrm{cr} \qquad \ldots \text{(B.5)}$$

where δ_cr is the upper limit for neglect of $g_\mathrm{v}\cdot h_\mathrm{e}$

Note that this condition is independent of $\mathrm{d}T/\mathrm{d}x$, from this follows that working at low temperature gradients is not automatically a solution for obtaining a negligible value of $g_\mathrm{v}\cdot h_\mathrm{e}$

As a guide, figure B.1 shows values of δ_cr for three different temperatures. If an error of 3 % is accepted, $g_\mathrm{v}\cdot h_\mathrm{e}$ can be neglected for materials lying below the relevant temperature line. Values for some typical building materials are schematically shown in the figure.

Figure B.1 shows that the lower the temperature, the more correct it is to neglect $g_\mathrm{v}\cdot h_\mathrm{e}$. From this point of view a heat flow transducer at the cold side of the specimen would give the most accurate result.

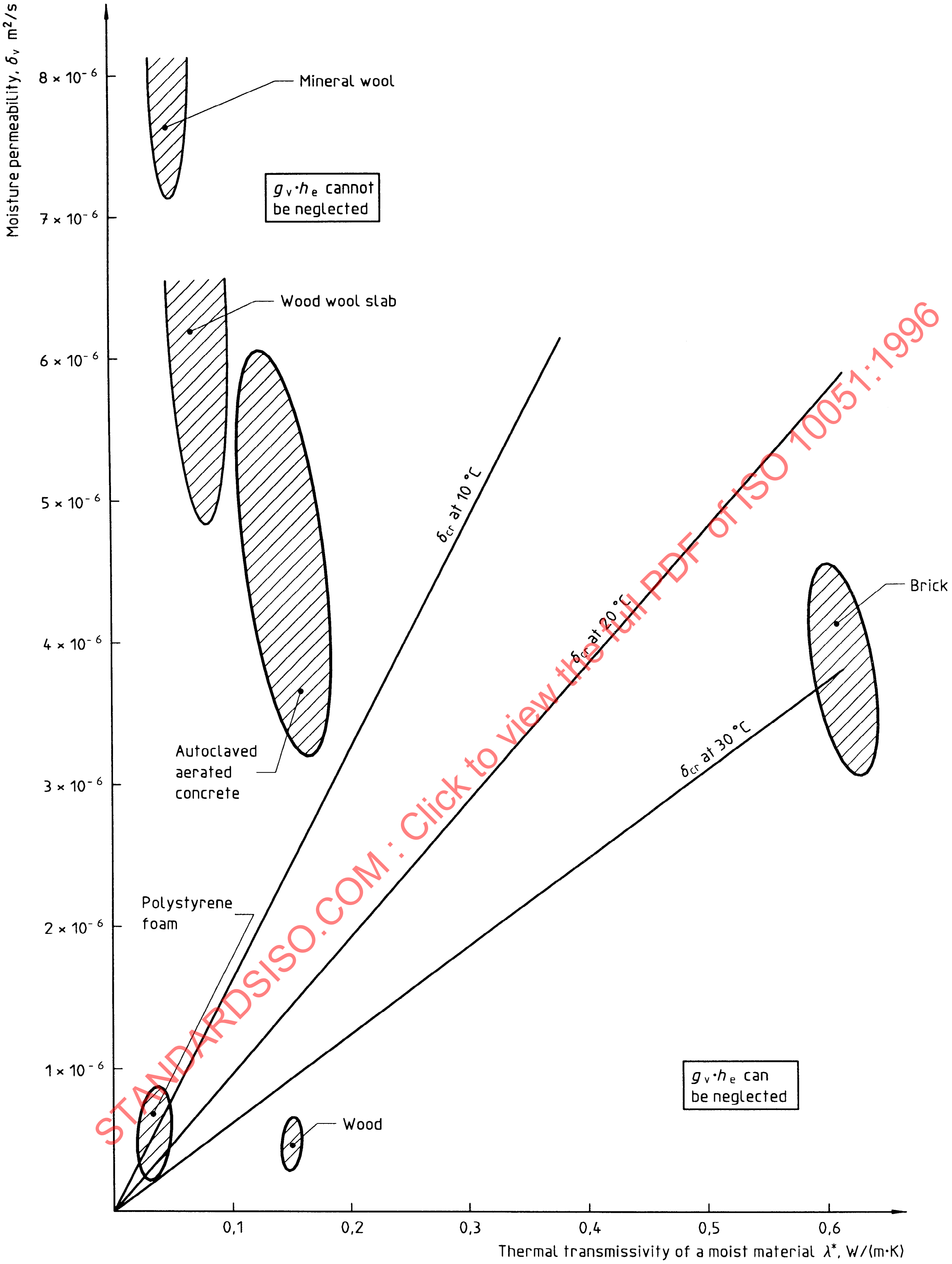

Figure B.1 — δ_{cr} at temperatures of 10, 20 and 30 °C