



Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

**Swiss Agency for Development
and Cooperation**
Embassy of Switzerland in India

Measuring Thermal Characteristics of Building Insulation Materials



**Indo-Swiss Building En-
ergy Efficiency Project**

Training Manual

Claude-Alain Roulet

CONTENTS

| | |
|--|-----------|
| FOREWORD | 7 |
| PREFACE | 9 |
| ACKNOWLEDGEMENTS | 11 |
| 1 THE CONTEXT: THE BUILDING ENERGY EFFICIENCY PROJECT (BEEP) | 13 |
| 1.1 Context of BEEP | 13 |
| 1.2 BEEP | 16 |
| 2 THERMAL INSULATION MATERIALS | 19 |
| 2.1 Energy, heat, and temperature | 19 |
| 2.2 Heat transfer | 20 |
| 2.3 Why use thermal insulation in buildings? | 21 |
| 2.4 What is a thermal insulation material? | 24 |
| 2.5 Thermal properties of a material | 25 |
| 2.6 Thermal properties of a product or building component | 29 |
| 2.7 Other characteristics of insulation materials and products | 32 |
| 2.8 Some thermal insulation materials | 32 |
| 3 USES OF THERMAL INSULATION IN THE BUILDING ENVELOPE | 43 |
| 3.1 Internal or external thermal insulation?..... | 43 |
| 3.2 Thermal insulation in the building envelope | 45 |
| 3.3 Summary of possible applications and materials | 51 |
| 3.4 Optimal insulating thickness | 51 |
| 3.5 Expected effects on comfort and energy use | 52 |
| 4 INSTRUMENTS TO MEASURE THE THERMAL CONDUCTIVITY | 55 |
| 4.1 Principle..... | 55 |
| 4.2 Guarded hot plate apparatus | 55 |
| 4.3 Heat flow meter apparatus..... | 56 |
| 5 MEASURING CHARACTERISTICS OF INSULATION MATERIALS AND PRODUCTS | 61 |
| 5.1 Preliminary note | 61 |
| 5.2 Sampling..... | 61 |
| 5.3 Preparing and conditioning the samples..... | 61 |
| 5.4 Measurement of dimensions and density | 61 |
| 5.5 Determination of thermal conductivity | 66 |
| 5.6 Other characteristics and measurement methods..... | 70 |
| 6 UNCERTAINTY ANALYSIS | 73 |
| 6.1 Definitions | 73 |
| 6.2 Uncertainty propagation law | 74 |
| 6.3 Uncertainty of thermal measurements | 75 |
| 7 THE INTER-LABORATORY COMPARISON (ILC) | 77 |
| 7.1 Objectives of this comparison | 77 |
| 7.2 Procedure and schedule | 77 |
| 8 REFERENCES | 81 |
| APPENDIX A CONVERSION OF THERMAL CONDUCTIVITY | 83 |
| APPENDIX B PROCEDURE TO COMPUTE THE DECLARED VALUE | 87 |
| APPENDIX C DEW POINT | 90 |
| APPENDIX D CHECK LIST FOR THE MEASUREMENT OF THERMAL CONDUCTIVITY | 91 |
| APPENDIX E REPORTING FORM | 92 |

APPENDIX F: SOME INSTRUMENTS MEASURING THE THERMAL CONDUCTIVITY..... 95

INDEX

| | | | |
|---|------------|-----------------------------------|------------|
| accuracy..... | 73 | flow rate..... | 21 |
| aerated concrete..... | 35 | transfer..... | 20 |
| alkali..... | 34 | transfer coefficient..... | 21, 30 |
| anisotropic medium..... | 25 | homogeneous wall..... | 45 |
| applications..... | 51 | hydrophobe..... | 35 |
| BEEP..... | 13, 16 | hygroscopic..... | 35 |
| between walls insulation..... | 48 | indoor environment quality..... | 21 |
| building energy efficiency..... | 13 | instruments..... | 55 |
| building envelope..... | 23, 43 | insulation thickness..... | 51 |
| calibration, heat flow meter ~..... | 58 | inter-laboratory comparison..... | 77 |
| cellulose..... | 33 | internal thermal insulation..... | 44 |
| check list..... | 91 | interpretation..... | 69 |
| cold climates..... | 53 | inverted flat roof..... | 46 |
| comfort..... | 22 | joule..... | 19 |
| compression strength..... | 32, 70 | kilowatt-hour..... | 19 |
| concrete, aerated ~..... | 35 | lightweight elements..... | 49 |
| conditioning..... | 61, 67 | loose-fill materials..... | 67 |
| conduction..... | 20 | margin of error..... | 73 |
| convection..... | 20 | material..... | 24 |
| conversion of thermal conductivity..... | 83 | methodology..... | 16 |
| cork..... | 37 | mineral | |
| database..... | 18 | fibres..... | 32 |
| declared value..... | 27, 87 | foams..... | 33 |
| density..... | 26, 29, 65 | MMMF, MMVF..... | 32 |
| density of heat flow rate..... | 25, 75 | nanogel..... | 38 |
| dew point..... | 90 | optimal insulation thickness..... | 51 |
| diffusivity..... | 28, 29 | organic fibres..... | 33 |
| dimension..... | 61 | perlite..... | 35 |
| dimensional stability..... | 32, 71 | permeability to water vapour..... | 32 |
| distributed insulation..... | 45 | polyethylene..... | 35 |
| ECBC..... | 13, 30 | polystyrene..... | 35 |
| effects of insulation..... | 52 | polyurethane..... | 36 |
| EIFS..... | 49, 71 | power..... | 19 |
| energy..... | 19 | precision..... | 73 |
| EPS..... | 35 | product..... | 24 |
| error..... | 73 | propagation law..... | 74 |
| ETICS..... | 49 | PUR..... | 36 |
| evaporation - condensation..... | 21 | purpose of buildings..... | 21 |
| exact differential..... | 74 | PVC..... | 35 |
| external thermal insulation..... | 43 | radiation..... | 20 |
| extruded..... | 36 | mat..... | 39 |
| fire resistance..... | 70 | reflecting mat..... | 39 |
| floor slabs..... | 48 | report..... | 69 |
| foam | | reporting form..... | 92 |
| glass..... | 33 | resistance to heat..... | 32 |
| organic..... | 35 | roof | |
| form, reporting~..... | 92 | decks..... | 46 |
| garden roof..... | 47 | thermal insulation..... | 47 |
| glass foam..... | 33 | sampling..... | 61 |
| green roof..... | 47 | silica aerogel..... | 38 |
| guarded hot plate..... | 55 | specific heat..... | 28, 29 |
| heat..... | 19 | standards..... | 17, 56, 57 |
| capacity..... | 28 | statistical method..... | 74 |
| flow meter..... | 55, 56 | straw..... | 37 |

| | | | |
|-----------------------------------|----------------|----------------------------|--------|
| temperature | 20 | trueness | 73 |
| tensile strength..... | 70 | UF | 37 |
| test temperatures..... | 68 | uncertainty | 73 |
| thermal conductivity | 25, 29, 69, 76 | uncertainty analysis | 73 |
| measurement of~ | 66, 68 | urea formaldehyde | 37 |
| thermal equilibrium | 68 | <i>U</i> -value | 30 |
| thermal insulation | 21 | vacuum insulation..... | 38 |
| thermal insulation material | 24, 32, 40 | ventilated walls | 48 |
| thermal resistance | 29, 69, 76 | vermiculite | 34 |
| thickness | 63 | warm climates..... | 53 |
| time constant..... | 68 | water absorption | 32, 71 |
| tolerance limit..... | 88 | watt | 19 |
| traction rupture strength | 32, 70 | wood fibre..... | 37 |
| transparent insulation | 50 | XPS..... | 36 |



ऊर्जा दक्षता ब्यूरो

(भारत सरकार, विद्युत मंत्रालय)

BUREAU OF ENERGY EFFICIENCY

(Government of India, Ministry of Power)

अजय माथुर, पीएच.डी.
महानिदेशक

Ajay Mathur, Ph.D.
Director General

Foreword

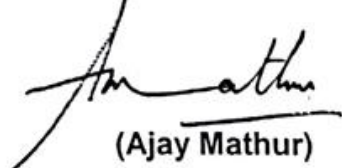
Building material plays a major role in achieving high operational energy efficiency in buildings. An informed procurement of building materials has the potential to achieve 40% energy savings in buildings. However, the Indian market for energy efficient materials and products is still in a very nascent stage. The rising demand for materials like insulation, high performance glass, reflective paints, etc. has led to a steady increase in the number of suppliers and manufacturers for the same.

Under the mandate of The Energy Conservation Act 2001, the Bureau of Energy Efficiency (BEE) is implementing various programmes to provide momentum to the energy efficiency movement in the country. The labelling scheme is one of the major thrust areas of BEE to do so. The key objective of this scheme is to empower the consumer to make an informed choice about the relevant marketed product.

The maximum heat gain in a building takes place through the building envelope and hence, it is essential for the market to cater to products like insulation and high performance fenestration solutions. Realising its importance, BEE is working towards developing endorsement labels for these products. However, the development of such an endorsement label is faced by challenges of defining the critical properties of each product and of the testing methodology. In case of building insulation materials, thermal properties are the key element that determine the insulation it can provide.

It is heartening to see that the Indo-Swiss BEEP is working towards creating standard test methodologies and facilities for building insulation material. I am pleased to note that the project team has devised a standard procedure to test the thermal properties of building insulation material. I have also been informed that the project has signed Memorandum of Understanding (MoU) with the 5 partner laboratories to augment their capacities.

I congratulate the BEEP team for their hard work in developing this manual and acknowledge the support extended by the other bi-lateral projects. This manual should be used by all the thermal insulation testing lab facilities in the country.



(Ajay Mathur)

स्वहित एवं राष्ट्रहित में ऊर्जा बचाएँ Save Energy for Benefit of Self and Nation

चौथा तल, सेवा भवन, आर० के० पुरम, नई दिल्ली-110 066

4th Floor, Sewa Bhawan, R.K. Puram, New Delhi - 110 066

टेली/Tel : 26178316 (सीधा/Direct) 26179699 (5 Lines) फ़ैक्स/Fax : 91 (11) 26178328

ई-मेल/E-mail : dg-bee@nic.in वेबसाइट/Web-Site : www.beeindia.in

PREFACE

The Indo-Swiss Building Energy Efficiency Project (BEEP) is a bilateral cooperation project between the Ministry of Power (MoP), Government of India, and the Federal Department of Foreign Affairs (FDFA) of the Swiss Confederation. The Bureau of Energy Efficiency (BEE) is the implementing agency on behalf of the MoP while the Swiss Agency for Development and Cooperation (SDC) is the agency in charge on behalf of the FDFA. The overall objective of the project is to reduce energy consumption in new commercial buildings and to disseminate best practices for the construction of low energy residential and public buildings.

The MoP and BEE in recent years have taken several initiatives to promote the implementation of Energy Conservation Building Code (ECBC) in India. ECBC prescribes application of good insulation practices in commercial buildings, as these can play a vital role in reducing energy consumption in buildings located in various climate zones of the country. Good awareness and testing of insulation products for their thermal characteristics are important before these are applied in real situations. Keeping this in view, BEEP in association with BEE has recently developed a network of five testing labs in India to enhance their technical and managerial capacity to undertake testing of insulation products available in the country.

As a part of this national-level activity, the Project with support from a team of Swiss and Indian specialists has recently conducted a common training programme for the labs, which was followed by on-site training programme in the individual labs. To further strengthen the testing abilities of the labs, this Training Manual has been developed as a reference document for the labs to undertake testing of insulation products in accordance with Indian and international standards. It is envisaged that these labs will provide much needed services to the building industry in India and support their energy-efficient efforts.

The Manual provides an overview of building insulation materials, their thermal characteristics, and how these affect the energy consumption and comfort level in the buildings. It elaborates how effectively various equipment can be used to test insulation materials for their thermal conductivity values on scientific basis with good accuracy under Indian and international standards.

The BEEP project endeavours to reach out through this Manual to professionals dealing with energy efficiency aspects in buildings and other concerned stakeholders including the India Insulation Forum, and will look forward to receiving comments and suggestions for further improvements in the Manual.

BEEP Team

ACKNOWLEDGEMENTS

This training manual on ‘Measuring the characteristics of thermal insulation materials’ has been developed under the Indo-Swiss Building Energy Efficiency Project (BEEP). It compiles the learning from the extensive research and experience of Indian and Swiss experts on building physics in relation to insulation. I am delighted to highlight the joint efforts put in by these experts, and would like to especially acknowledge the contribution of Prof. Claude-Alain Roulet from Switzerland, Mr Ravi Kapoor, and Dr Sameer Maithel from India. The suggestions provided by our partner labs namely, CEPT University, Ahmedabad; Spectro Analytical Labs Limited, New Delhi; Isolloyd Engineering Technologies Ltd, Baddi; Thermal Insulation Testing Lab, Nirma University, Ahmedabad; and Shriram Institute for Industrial Research, Bengaluru have been noteworthy.

I extend a sincere thanks to Dr Ajay Mathur, Director General, Bureau of Energy Efficiency (BEE) and Mr Sanjay Seth, Energy Economist, Bureau of Energy Efficiency (BEE) who have helped immensely in shaping this publication.

Overall guidance is provided by the members of the Joint Apex Committee (JAC) and the Joint Implementing Group (JIG) of the Project. I am grateful to the Co-Chair of the JAC – Mr Satish Kumar, Joint Secretary, Ministry of Power – for his leadership. I greatly appreciate the inputs provided in the implementation of the project work plan by Mr P T Bhutia, Director, Ministry of Power, and my colleague Dr Anand Shukla, Senior Advisor (Energy), Swiss Agency for Development and Cooperation, as Co-Chairs of the JIG and Mr Prabhakar Singh, Chief Engineer, Central Public Works Department; Dr Arun K Tripathi, Director, Ministry of New and Renewable Energy.

I extend a warm thanks to members of the UNDP-GEF project who have been instrumental in firming up this manual.

Daniel Ziegerer

Director of Cooperation

Swiss Agency for Development and Cooperation

Embassy of Switzerland, New Delhi

1 THE CONTEXT: THE BUILDING ENERGY EFFICIENCY PROJECT (BEEP)

1.1 Context of BEEP¹

1.1.1 India Energy Scenario and Policy Outlook

India's energy consumption is increasing by leaps and bounds due to her sustained economic growth. In 2008, India had approximately 170 gigawatts (GW) of installed electricity generation capacity, which is estimated to increase to 800 GW by 2031/32². The Integrated Energy Policy of Government of India states that 'lowering the energy intensity of GDP growth through higher efficiency is important for meeting India's energy challenge and ensuring its energy security'³. Considering the vast potential for energy savings, the Government of India in 2001 enacted the Energy Conservation Act (EC Act). The Act provides for a legal framework, an institutional arrangement, and a regulatory mechanism at the central and state levels to embark upon energy efficiency drive in the country. The Government of India has also given top priority to combat climate change as reflected in the 'National Action Plan on Climate Change (NAPCC)' [1].

1.1.2 Building Energy Efficiency in India

In India, the share of electricity consumption in the building sector has increased from 14% of the total electricity supply in the 1970s to nearly 33% in 2004/05. Commercial buildings in India account for nearly 8% of the total electricity supplied by utilities. Electricity use in commercial buildings has been growing at about 11%–12% annually, which is much faster than the average electricity growth rate of about 5%–6% in the economy [2]. Considering the importance of buildings, the Bureau of Energy Efficiency (BEE), Government of India, in its 11th Five year Plan (2007–2012) has granted high priority to the goal of upgrading energy efficiency in buildings. The National Mission on Sustainable Habitat (announced in 2010), which is one of the missions under Prime Minister's NAPCC, also identifies promotion of energy efficiency in buildings as an important part of the mission.

The BEE, Government of India, is a statutory body under the Ministry of Power responsible for the implementation of the EC Act, 2001, with the primary objective of reducing energy intensity in the economy. The Energy Conservation Building Code (ECBC), announced by BEE in 2007, attempts to optimise the energy demand of new and large commercial buildings through energy-efficient designs. ECBC sets minimum energy efficiency standards for design and construction of commercial buildings with a connected load of 100 kW or contract demand of 120 kVA and above. Adoption of ECBC is currently voluntary but it is likely to become mandatory in the future. In order to spur the demand for energy-efficient buildings, BEE has also launched the energy star rating programme for existing commercial buildings, such as offices, business process outsourcing buildings, and shopping malls with a connected load of 100 kW and more. Two online tools, ECONirman and ECObench, have been designed and developed under the USAID-supported ECO-III Project in collaboration with the BEE. ECONirman is an ECBC Conformance Check Tool. ECObench is a Benchmarking Tool that helps building owners to evaluate the performance of their buildings by comparing the energy consumption of their building with similar buildings.

¹ Chapter based on "Indo-Swiss Building Energy Efficiency Project (BEEP)", project description, 26 April 2012.

² Central Electricity Authority, 2009: All India Electricity Statistics, General Review 2009. Ministry of Power, New Delhi, India

³ Planning Commission, August 2006: Integrated Energy Policy- Report of the Expert Committee.

In addition to ECBC and energy star rating of BEE, India also has two broader green building rating systems: The Leadership in Energy and Environmental Design (LEED–India) administered by Indian Green Building Council (IGBC), and the Green Rating for Integrated Habitat Assessment (GRIHA) conceived by The Energy and Resources Institute (TERI) and developed jointly with the Ministry of New and Renewable Energy, Government of India. Both are point-based systems, and apart from energy, they also cover broader environmental aspects such as sustainable site development, water conservation, indoor environment quality, and materials selection.

1.1.3 Building Energy Efficiency in Switzerland

Switzerland has one of the lowest energy intensity in the world. This is partly explained by the nature of the economy, which is essentially driven by the services sector, but also by the fact that Switzerland has achieved significant success in the field of energy efficiency, particularly in buildings.

The first building code for the building envelope (SIA 180/1), which specified a maximum value for the overall heat transfer coefficient of the building envelope, was introduced in 1979. This was followed by codes that made heat recovery mandatory from ventilation systems (1981), a clean air act aiming among others to improve the efficiency of boilers (OPAir, 1985), a comprehensive building energy code (SIA 380/1 in 1985, revised in 2001, 2009, and 2015), and cooling justification code (SIA 382/3 in 1992, then 382/1 in 2007, revised in 2014).

The Swiss experience shows that successful implementation of energy conservation building codes was assisted by capacity building programmes, appropriate institutional mechanism for implementation, development and availability of specific services and products in the market, and availability of financing schemes and incentives.

1.1.4 The Swiss program related to thermal insulation materials

Within the frame of a wide governmental programme started in 1979 to give impetus to the Swiss economy, 11 groups of products used in building energy retrofit were tested between 1979 and 1984 in four federal laboratories. The objectives of these tests were the following:

- Determination of the principal characteristics of the product for its recommended use, using the same standardised testing methods for every product in one group.
- Publication of the results of the tests in comparative tables allowing a correct comparison of the properties.
- Elimination of improper use of some products.
- Establishment of a complete technical documentation on the tested products for lectures and the users thereof.

The factories or their agents were invited to submit, on a voluntary basis, their products for testing. They had to pay only a part of the testing cost, with the government sponsoring the balance amount, provided they accept that the results be published.

The 12 groups of products were the following:

1. Insulating materials for buildings
2. *In situ* injected foams
3. Insulating renderings
4. External insulation and finishing systems (EIFS)
5. Vapour barriers
6. Insulating blankets and reflecting sheets
7. Window retrofitting gaskets

8. Window frames
9. Tube insulation
10. Thermostatic valves for radiators
11. Solar collectors for hot water
12. Heat pumps.

The thermal insulation materials covered under this Swiss programme are listed below.

- Mineral wools
- Expanded and extruded polystyrene
- Polyurethane foam, both panels and on-site sprays
- Cork
- Foam glass
- *In situ* urea formaldehyde foam
- Few exotic materials (hemp fibres, wool, etc.)

All thermal insulation materials were tested for the following properties.

- Dimensions, using meter for length and width; plate and micrometre for thickness
- Density using dry weight and metered dimensions
- Thermal conductivity at 10 °C using either hot plate or heat flow meter instruments, based on measurements at 5, 10, and 15 °C
- Water vapour diffusion using salt solutions and climate chamber
- Fire resistance, flammability according to Swiss standard test.

The following properties depending on use were also tested and published.

- 10% compression strength for materials used in flat roofs and floors
- Traction rupture strength for external insulation and finishing systems (EIFS)
- Water absorption by immersion in water and floating on water for materials exposed to water
- Water adsorption in a thermal gradient for extruded polystyrene (e.g. ROOFMATE)
- Dimensional stability by temperature changes for roof materials
- Heat resistance for roof materials.

A reference insulating material (dense fibreglass from the National Institute of Standards and Technology, Washington, DC) was used to calibrate both thermal conductivity meters to better than 1% ($\pm 0.4 \text{ mW}/(\text{m}\cdot\text{K})$). The results of these tests depend on the group of materials. It was found that the insulating materials made in Switzerland generally agree with the national standards, with a few exceptions. The urea formaldehyde foams were rather new in Switzerland, and are no more used. These foams present a heavy shrinkage, and two foams out of the five tested did not meet the fire security requirements. The toxicity of these foams, resulting from formaldehyde emission, was especially tested, and it was found that the free formaldehyde content is much lower in the tested foams than prescribed, for example, in the Canadian standards.

Big differences between the products were found in the window gaskets and the reflecting sheets. These sheets have to be reflecting in the far infrared region (about 10 micron wavelength). They are made of aluminium coated sheet, but some of them have a protecting plastic film on the aluminium coating, and the reflecting power drops drastically for the thermal radiation. As to the solar collector group, a remarkable progress was observed during the campaign. The 1981 models were generally much better in efficiency than the 1978 models.

1.2 BEEP

A Memorandum of Understanding was signed between Swiss Federal Department of Foreign Affairs (FDFA) and the Ministry of Power, Government of India. This important agreement will help (i) to facilitate ties with state governments and civil society (ii) to adjust the project's activities to the actual needs of the Indian building sector (iii) to increase the project's expected impact and (iv) to bring expertise to Indian decision-makers in the field of energy efficiency policy.

1.2.1 Objectives

During the preparatory phase, several fields were identified as essential:

- Raising the awareness of private sector stakeholders such as architects, builders, developers, and practitioners for designing energy-efficient buildings.
- Developing design guidelines for improving energy efficiency in residential buildings.
- Improving building materials testing infrastructure for ECBC compliance.
- Training and building the capacity of Indian professionals to design energy-efficient buildings.

The main project components are therefore as follows:

1. An emerging culture of **Integrated Design** among India's prominent building sector stakeholders encourages design teams to address energy efficiency as a primary concern right from the start of the building design process.
2. **Quality assurance** mechanisms and labels for insulation products help to mainstream and enhance the quality of insulation practices in India.
3. The Building Energy Conservation Programme is extended to the residential sector and integrates BEEP **design recommendations** for residential buildings.
4. **Knowledge** and know-how of climate-responsive, high-performance, energy-efficient solutions for new buildings are increased among India's building sector professionals and policy makers.

The measurement of characteristics of thermal insulation products for buildings is part of Component 2. This component will have two main outputs:

1. Laboratory capacity in India is strengthened for conducting thermal performance testing of building/insulation materials and assemblies. Laboratories are selected; their equipment and their staff are upgraded where necessary.
2. Comprehensive data on the thermal characteristics of insulation materials and assemblies are accessible to building professionals. The results of measurements are centrally collected and published.

1.2.2 Achievements linked to Component 2 up to 2014

1.2.2.1 Development of a common methodology

Tested characteristics of thermal insulation materials include not only thermal conductivity, but also dimensions and density. In addition, other properties could be tested depending on the use of the material, such as compression or tensile strength, water absorption, dimensional stability, resistance to heat, and effects of fire. There are ISO and ASTM standards describing all these tests and Indian standards for some of them.

All these properties are important but it has been decided in BEE's Technical Committee Meeting that BEE wants to promote ECBC implementation first. For this, thermal conductivity and R-values of insulation products are essential. In collaboration with the Indian Insulation Forum, the association of Insulation product manufacturers recently created, it was de-

cided to measure, within BEEP, only the main characteristics in the first phase, i.e., thermal conductivity, dimensions of products and density, and this according to ISO standards.

The project also helped in developing testing methodology for assemblies (doors, panels).

1.2.2.2 Standards for the measurement of thermal conductivity

A comparative study of Indian (IS), American United States (ASTM), and international (ISO), standards on the measurement of the thermal conductivity using the heat flow meter or the guarded hot box method was performed. This has shown that the ASTM and ISO standards are equivalent, the main differences being in the reporting format and units used. In addition, measurements performed according to ISO or ASTM would comply with the requirements of Indian Standards. Therefore, it was decided to perform such measurements according to ISO standards.

1.2.2.3 Laboratories

Several laboratories were identified and visited. A selection methodology, based on a list of selected criteria, was defined. On this basis, six shortlisted laboratories were approached for their willingness, assessment, and participation under BEEP, and their need in equipment identified. The initial intention was to select one or two laboratories, thinking that very few laboratories were equipped for the measurement of thermal conductivity. However, as several laboratories are already equipped and have experience of such measurements, it was finally decided to keep five laboratories and to promote a network of laboratories, which are able to perform reliable measurements based on the most recent version of the ISO standards.

1.2.3 Further work to be performed within Component 2

1.2.3.1 Equipment

Two instruments to measure the thermal conductivity of thermal insulating materials would be partially financed to two laboratories, where the equipment is not up to a satisfactory level of functioning.

Training

The staff of the laboratories would be trained, in two steps:

1. A common training, using the present document as a basis, to ensure that the whole staff has the same basic knowledge.
2. A specific, practical training in each laboratory, just to check that measurements will be performed according to ISO rules.

1.2.3.2 Inter-laboratory comparison

The same materials, on rigid foam and a soft fibrous material, would be tested by the five laboratories and by the EMPA in Switzerland, to ensure that all the laboratories get the same results for the same material. This inter-laboratory comparison could be used to get the NABL certification.

The details of this inter-laboratory comparison are presented in Chapter 7 of this documentation.

1.2.3.3 Measurements

The main work within BEEP should be the measurements of products from Indian factories or importers. These measurements would be performed according to the commonly agreed methodology presented in Chapter 5.

1.2.3.4 Database

The results of all measurements would be sent to BEEP PMTU-India, where a person would be put in charge of creating and maintaining the database of the results. This base would allow the publication of all the results in a common format, in order to improve transparency in the market and information to the building professionals.

2 THERMAL INSULATION MATERIALS

2.1 Energy, heat, and temperature

Energy (from the Greek $\epsilon\nu\rho\nu\nu\nu\nu\nu\nu$, moving force) is a property of objects that allows doing something. It can be transferred to other objects or converted into different forms, but cannot be created or destroyed. Nothing can be done without transforming energy from one form into another.

Energy forms include the kinetic energy of a moving object; the radiant energy carrying electromagnetic waves (radio, infrared, light, ultraviolet, X and gamma rays); the potential energy stored by an object's position in a force field (gravitational, electric or magnetic); elastic energy stored by stretching or compressing solid objects; chemical energy released in a chemical reaction, e.g. when a fuel burns, thermal energy or heat; and mass, according to the Einstein's relation $E = mc^2$ where c is the speed of light.



Photo Mircea Madau

Figure 2.1: A typical lightning transform about 500 MJ or 140 kWh mainly into heat, light and sound energy.

In SI units, energy is measured in **joules** (J), the energy transferred to an object by the mechanical work of moving it 1 metre against a force of 1 newton.

The power is the ability to transfer energy in a short time. It is the amount of energy transferred by unit time. Its SI unit is the joule per second or **watt** (W).

A common energy unit is also the **kilowatt-hour** (kWh), the energy transferred when a power of 1000 watt is applied during one hour.

Heat is the kind of energy that rises the temperature of matter. At the molecular level, heat is the energy linked to the random movement of atoms and molecules. The higher the temperature of a piece of matter, the larger the movements are and the higher the amount of heat embedded in that piece.

The **temperature** scale quantifies this random movement. There are commonly three temperature scales.

1. The absolute or Kelvin temperature scale is the official SI temperature scale. It starts at 0 K at which all atoms and molecules are completely quiet, and, by definition, is at 273.16 K at the triple point of water, where ice, liquid water, and water vapour are in equilibrium.
2. The Celsius or centigrade scale is at zero at the melting point of ice under atmospheric pressure and at 100 at the boiling point of water under atmospheric pressure. The triple point of water is at 0.01 °C. One degree K equals one degree Celsius.
3. On the Fahrenheit's original scale the lower defining point (0 °F) was the lowest temperature to which Daniel Gabriel Fahrenheit (1686–1736) could produce cool brine, while the highest (100 °F) was that of the average human core body temperature. This scale is now defined on the basis of the Celsius scale: 0 °C = 32 °F and 100 °C = 212 °F.

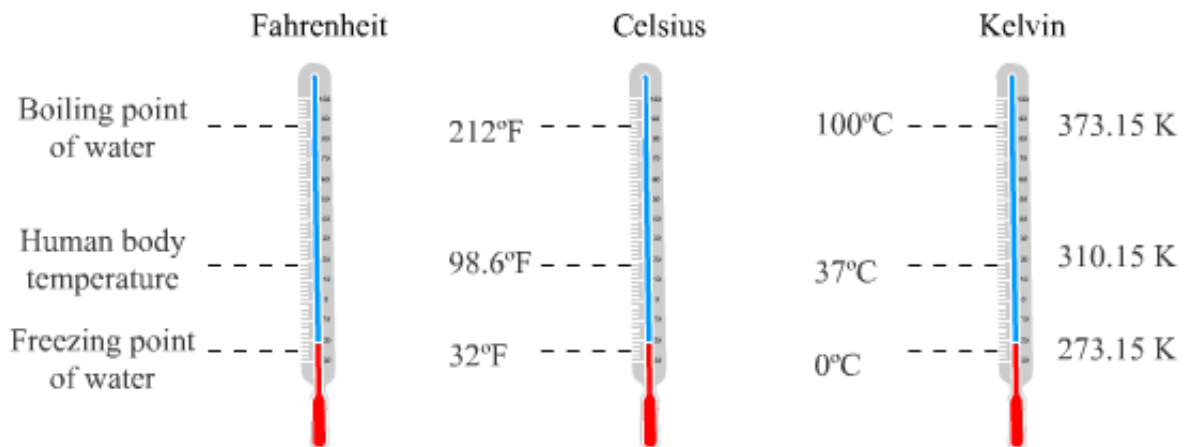


Figure 2.2: Temperature scales (from www.meritnation.com).

2.2 Heat transfer

Heat transfer is the propagation of these random movements from place to place. Heat naturally flows from hot places, where atoms and molecules are strongly agitated, to cold areas, where atoms and molecules are quieter.

The fundamental modes of heat transfer are briefly explained below.

Conduction: Conduction is the direct transfer of the thermal movements from atom to atom or molecule to molecule that are linked together in the matter. Good thermal conductors are dense. In metals, the free electrons conducting the electricity also widely contribute to transfer heat. To avoid conduction, there should be no matter. Vacuum does not conduct heat. To decrease conduction, low density materials should be used, including air, heavy gases, or non-metallic solids.



Convection: Convection is the transport of heat in moving warm fluids such as water or air, which give back their heat in contact with a colder surface. Convection is large when a fluid with a large heat capacity can easily and quickly move and exchange heat with a hot source at one place and a cold sink a bit further. To avoid convection, the fluids should be either avoided or locked. There is no convection in vacuum or in fluids that cannot move.



Radiation: Electrons, atoms, and molecules are electrically charged or polar. When they move, they emit electro-magnetic radiation at a wavelength corresponding to its movement's frequency. Reciprocally, when an



atom or molecule receives some electromagnetic radiation, it becomes agitated or heated. Depending on the temperature of the matter, this radiation is in the far infrared (up to about 500 Kelvins or 200 °C) or near infrared range (about 1000 K or 700 °C), or visible (first red at 1500 K, then white at 6000 K, then blue when very hot, etc.). Radiation is easily propagated through vacuum or transparent media such as air. Opaque screens or reflecting surfaces are used to stop radiation.

Evaporation-condensation: Much heat is needed to evaporate a heated liquid and, when this water vapour condenses on a cold surface, this heat is recovered and heats that condensing surface. Much heat (about 2,5 MJ or 0.7 kWh for 1 litre) is needed to evaporate water, this condensing water vapour also provides much heat. This very effective transfer process is used in heat pipes. Of course, evaporation-condensation cannot occur in dry places or dry materials.



The **heat flow rate** Q , in watts, between the warm and cold places can be expressed as a function of the temperature difference $T_1 - T_2$ (in K) between the heat source and sink:

$$Q = H (T_1 - T_2) \quad 1$$

H is the **heat transfer coefficient**, in W/K. In general, it depends on the temperature, but if the temperature does not vary much, it can be considered as constant. This approximation is widely used in the thermal models of buildings.

2.3 Why use thermal insulation in buildings?

2.3.1 Purpose of buildings

The main purpose of buildings is to provide a comfortable living environment for their occupants. This includes, among others, thermal, visual and acoustic comfort as well as indoor air quality. Except during the fifties and sixties, it has always been considered important that excess use of energy should be avoided in the construction and the management of a building, sometimes even at the cost of user comfort. Energy saving is however not the main purpose of the building. Indeed, if it were really so, the largest energy savings would be obtained by not erecting the building in the first place.

Since the Rio conference, there have been more and more incentives to save energy and lower the impact of buildings on the environment. Therefore, there is no excuse for the building sector not to adopt a sustainable development policy.

Buildings are erected in most cases to protect the occupants from the external environment (extreme temperatures, wind, rain, noise, solar radiation, etc.), thus providing a good indoor environment. A building that is well adapted to the climate protects its inhabitants against the extreme conditions observed outdoors, without creating uncomfortable internal conditions.

According to P Lavigne, a French architect: *The free floating building (that is without any HVAC system running) should be at least as comfortable as the outdoor environment.* Adaptation to climate requires an adapted architecture. Vernacular architecture (e.g. Malaysian huts, polar igloos, north African Kasbahs) is a good example of adaptation, but modern architecture may also, in some climates, be fully passive, like the Golconde, a dormitory of the Sri Aurobindo Ashram in Puducherry.

2.3.2 What is indoor environment quality?

From the occupant point-of-view, the ideal situation is an indoor environment that satisfies all occupants (i.e. they have no complaints) and does not unnecessarily increase the risk or severity of illness or injury. Both the satisfaction of people (comfort) and health status are influ-

enced by numerous factors: general well-being, mental drive, job satisfaction, technical competence, career achievements, home/work interface, relationship with others, personal circumstances, organisational matters, etc. and last but not least environmental factors, such as:

- indoor air quality: comprising odour, indoor air pollution, fresh air supply etc.,
- thermal comfort: moisture, air velocity, temperature,,
- acoustical quality: noise from outside, indoors, vibrations,
- visual or lighting quality: view, illuminance, luminance ratios, reflection, and
- aesthetic quality.

The perception of comfort is subjective. Therefore, the comfort yardstick is the well being or the satisfaction of occupants. However, under some conditions, the global comfort can be characterised separately by its components such as health, thermal comfort, indoor air quality, and visual and acoustical comfort. In addition, there could be other components for which there are yet no scientific evidence.

2.3.3 How to ensure indoor environment quality?

There are two types of ways to ensure a good indoor environment quality: active and passive.

- **Passive ways** are architectural and constructive measures that naturally provide a better indoor environment quality without or with much less energy use.
- **Active ways** allow reaching the objectives by mechanical actions, using energy for complementing the passive ways or even for compensating low building performance.

Examples of passive ways are listed below.

- Improving winter thermal comfort with thermal insulation, passive solar gains, thermal inertia, and controlled natural ventilation
- Improving summer thermal comfort with thermal insulation, solar protections, thermal inertia, and appropriate natural ventilation
- Ensuring indoor air quality by using clean materials and controlled natural ventilation
- Natural ventilation controlled by adjustable vents in an airtight building envelope
- Providing controlled daylighting
- Protecting from outdoor noise with acoustical insulation, adjusting the reverberation time for a comfortable indoor acoustics

Examples of active ways are listed below.

- Heating boilers and radiators for winter comfort
- Artificial cooling by air conditioning or radiant panels for summer comfort
- Mechanical ventilation
- Artificial lighting
- Actively diffusing background music to cover the ambient noise
- Screens showing images replacing a view from a window

Passive means are often cheap, use only renewable and free energy, and are much less susceptible to break down. However, they often depend on meteorological conditions and therefore cannot always fulfil the objectives. They should be adapted to the location and therefore need creativity and additional studies from the architect, and a design error may have dramatic consequences.

Active ways, when appropriately designed, built, and maintained, are perfectly adapted to the needs. The architect does not have to take much care of them, as these are designed and applied by specialised engineers using known technology. Flexible and relatively independent on meteorological conditions, they allow for correcting architectural errors. However, the

required technology is often expensive, uses much energy and may break down. Furthermore, active means require careful maintenance. The fact that they allow for correcting architectural ‘errors’ can also be considered as a disadvantage.

| Passive ways | Active ways |
|-----------------------|-------------------|
| 👍 Cheap | 👎 Expensive |
| 👍 No energy cost | 👎 Use energy |
| 👍 Don't break down | 👎 May break down |
| 👎 Need careful design | 👍 Easy to design |
| 👎 Control problems | 👍 Easy to control |

Table 2.1: Pros and cons of active and passive ways

It can clearly be seen from Table 2.1 that the advantages of passive ways correspond to the disadvantages of active ways and vice versa. Both ways are complementary to each other.

Passive ways are preferred for their advantages, but cannot always fulfil the comfort objectives. Therefore, the appropriate strategy is to use them as much as reasonably possible and to compensate for their insufficiencies with active systems, which will then be smaller. This strategy often allows more freedom in choosing the type and location of active systems, leads to smaller and cheaper active systems, and ensures a better indoor environment quality. It is also coherent with the policy of sustainable development.

2.3.4 The role of the building envelope

The building envelope is the barrier between the indoor and outdoor environment. It protects the inhabitants from rain, wind, extreme cold and heat, and external noise. This barrier is, however, not totally tight, as it contributes to daylighting and natural ventilation.

The building envelope is first a protection. It can also be an expression and visually pleasing to the building owner, the architect or even to the public; but it should first satisfy the occupants' needs and comfort.



Figure 2.3: Two typical examples of Indian building envelopes in Gurgaon. Left: a protection, right: an expression⁴.

⁴ Both are LEED certified. Left - LEED platinum post construction, right - LEED:EBOM gold.

To summarise the answer to the question in the title of this section, thermal insulation is an important and effective passive way to improve the indoor environment quality by reducing the heat transfer through the building envelope and improving the internal thermal stability. It also contributes to sound insulation. To be effective, it should be accompanied by other passive measures such as solar protection and (if possible) night ventilation cooling in hot climates and passive solar heating in cold climates.

2.4 What is a thermal insulation material?

By definition, a thermal insulation material is a material that restricts the transfer of heat. This kind of definition allows any material to pretend as a thermal insulation material. However, when building materials are considered, only materials that provide a significantly better resistance to heat flow than common materials used for the building fabric (stone, concrete, hollow and plain bricks or concrete blocks) can be considered as thermal insulation materials. So, a thermal insulating material is a material that, at relatively small thickness, presents a thermal resistance large enough for the envisaged purpose.

The physical principles used in insulating materials are the following:

- To reduce conduction by reducing as much as possible the amount of matter, and use low-conductivity materials. Most of the volume of an insulating material is air or, in a few cases, other gases or even vacuum. Thermal insulation materials are, therefore, all lightweight.
- To avoid convection by locking air (or another gases) between fibres that strongly hinder the air movement, or in foam bubbles that completely suppress air movement.
- To avoid radiation by using opaque or even reflecting materials. Glassy and plastic materials used for fibres and foam walls are not transparent to thermal radiation. Thermal insulation materials could be transparent or translucent to light, but should not transmit the infrared radiation linked to surrounding temperatures.
- To avoid evaporation-condensation by maintaining the product dry. When wet, an insulating material loses a large part of its thermal resistance.

These conditions are partly contradictory, and can be well realised only in vacuum, the surfaces of the warm and cold bodies being treated to make them reflective to electromagnetic radiation. Indeed, it is easier to isolate a cosmonaut from the sidereal cold than a building in the tropics! In buildings, the economic aspect is essential: so **it is locked air that is the main insulation material** used there. The air is locked in foams or between the fibres of the insulation materials. The walls of the foam bubbles, as well as the fibres are also screens to radiation.

Some definitions related to thermal insulation materials and their characteristics could be useful and are reported here. These are quoted in several ISO standards.

Material: piece of a product irrespective of its delivery form, shape, and dimensions, without any facing or coating.

Product: final form of a material ready for use, of given shape and dimensions and including any facing or coating.

2.5 Thermal properties of a material

2.5.1 Thermal conductivity

Thermal conductivity is the most important characteristic of an insulating material. Basically, it is the ratio of the density of heat flow rate to the thermal gradient along one direction. When the heat flows steadily in one direction only:

$$q = -\kappa \frac{\Delta T}{d}$$

where ΔT is the temperature difference across a thickness d .

In other terms, thermal conductivity is the amount of heat transferred per second through a block of material 1 m thick and 1 m² area when the temperature difference across it is 1 Kelvin (Figure 2.4). The smaller this figure is, the better is the thermal insulation provided by this material.

The official ISO symbol for thermal conductivity is the Greek letter λ (lambda), but in India, the Greek letter κ (kappa) or even k is still in use. Therefore, the symbol κ is used throughout this document for thermal conductivity.

The SI unit of thermal conductivity is watt per metre-Kelvin (W/[m·K]). As thermal insulation materials have low thermal conductivity, milliwatt per metre-Kelvin (mW/[m·K]) is also used. In some countries, the British thermal unit per hour and square foot for one inch thickness and one Fahrenheit temperature difference are still in use.

$$1 \text{ Btu}\cdot\text{in}/(\text{sq ft}\cdot^\circ\text{F}) = 0.1442278889 \text{ W}/(\text{m}\cdot\text{K})$$

$$1 \text{ W}/(\text{m}\cdot\text{K}) = 6.9811179 \approx 7 \text{ Btu}\cdot\text{in}/(\text{sq ft}\cdot^\circ\text{F})$$

An anisotropic⁵ medium, such as cork or fibrous materials, may have two or three thermal conductivities. However, for thermal insulation products used in buildings, one thermal conductivity only is usually given, even for non-isotropic materials. It is the thermal conductivity measured in the direction of the heat flow that usually goes through the product, e.g. the direction perpendicular to plates or mats, or along the radius for materials used to insulate pipes.

It should be noted that heat transfer by pure conduction is very close to be proportional to the thermal gradient, i.e. is a linear function of the temperature difference between the warm and cold environment, while heat transfer by radiation and convection are not. Heat transfer in thermal insulating materials involves not only conduction, but also radiation and convection. The thermal conductivity is indeed a conventional figure, which may change with the mean temperature of the material (Figure 2.5). It also increases when the material is wet, because evaporation-condensation may then take effect.

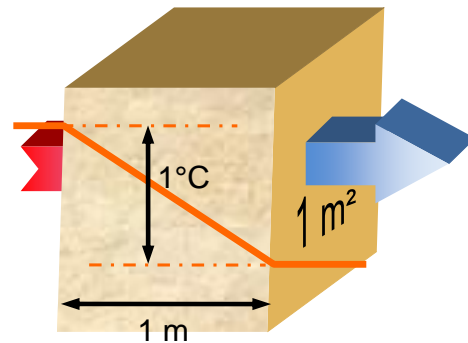


Figure 2.4: Thermal conductivity

2

⁵ A material is anisotropic for a given property when this property changes with the direction along which it is measured.

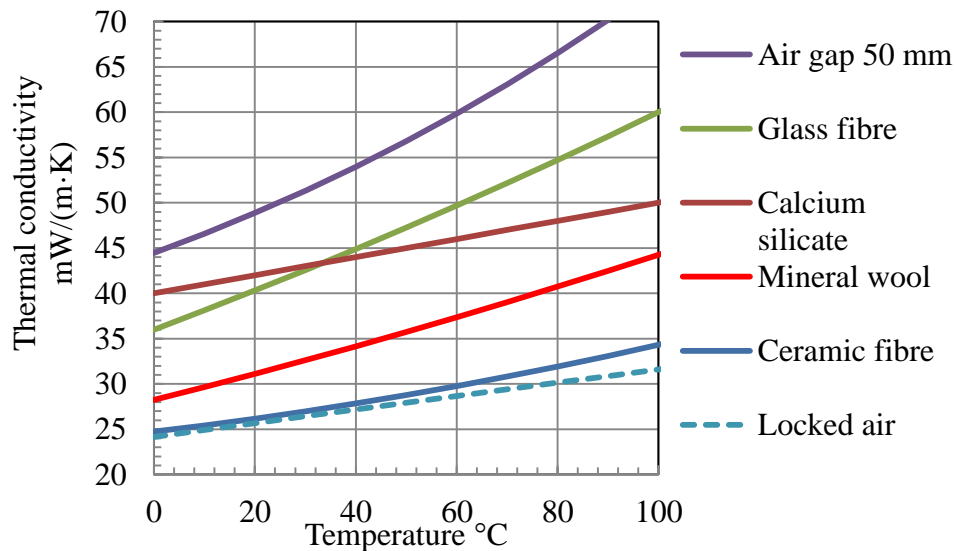


Figure 2.5: Apparent thermal conductivity versus temperature for various materials, including an air gap with non-metallic surfaces and locked air, with neither convection nor radiation.

The thermal conductivity of some common building materials is given in Table 2.2. It should be noted that there is a ratio of about 5000 between the thermal conductivity of aluminium and a common insulating material. An insulation layer of 2 cm² of an aluminium fixation trough creates a thermal bridge that transmits as much heat as 1 m² of insulation!

For most thermal insulating materials, the thermal conductivity is a function of the density (Figure 2.66). When the density is very low, thermal radiation can pass through the solid material and the air may transport heat by convection. At such densities, the apparent thermal conductivity depends on the thickness.

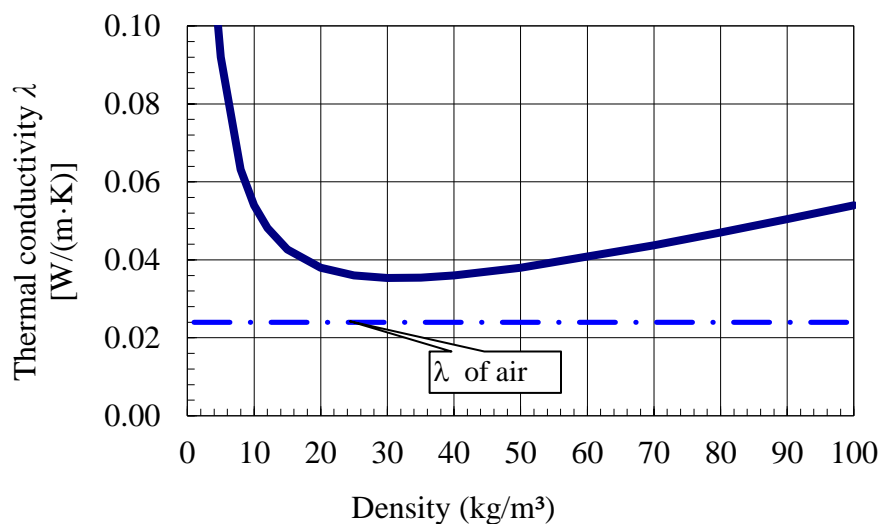


Figure 2.6: Thermal conductivity as a function of the density for a mineral wool.

When the density is large, the thermal conductivity of the solid material (organic fibre, glass, polymer) dominates. Each product has its own optimum density, at which the thermal conductivity is at its minimum, slightly larger than that of the surrounding gas, generally air. Some materials may, however, present a thermal conductivity smaller than that of the air (see Section 2.8.6)

2.5.2 Declared values of thermal conductivity

According to ISO 10456 [3], a declared thermal value of a building material is the ‘*expected value of a thermal property of a building material or product assessed from measured data at reference conditions of temperature and humidity, given for a stated fraction and confidence level, and corresponding to a reasonable expected service lifetime under normal conditions*’.

The manufacturer cannot produce materials that are exactly all the same. Any production process provides materials with some dispersion of their properties. In particular, several pieces of an insulating material may have slightly different thermal conductivities.

In addition, the declared values shall be given at reference temperatures of either 10 or 23 °C for aged products either dry or at equilibrium with air at 50% and the reference temperature, but the measurement could be performed at another temperature and humidity than the reference ones.

Therefore, the ISO 10456 standard specifies methods for the determination of declared thermal values for thermally homogeneous building materials and products. It also provides conversion coefficients for temperature and for moisture, which are valid for mean temperatures between 0 °C and 30 °C. The conversion procedure according to clause 7 of ISO 10456 is given in Appendix A.

The declared value shall be given *for a stated fraction* (e.g. 90th centile) *and confidence level* (e.g. 95%). This means that 90% of the production of this product will have an actual value better than the declared value, with a probability of 95%. Therefore, the declared value of the thermal conductivity is larger than the average of several measured value, the difference depending on the dispersion of the measured values (Figure 2.77).

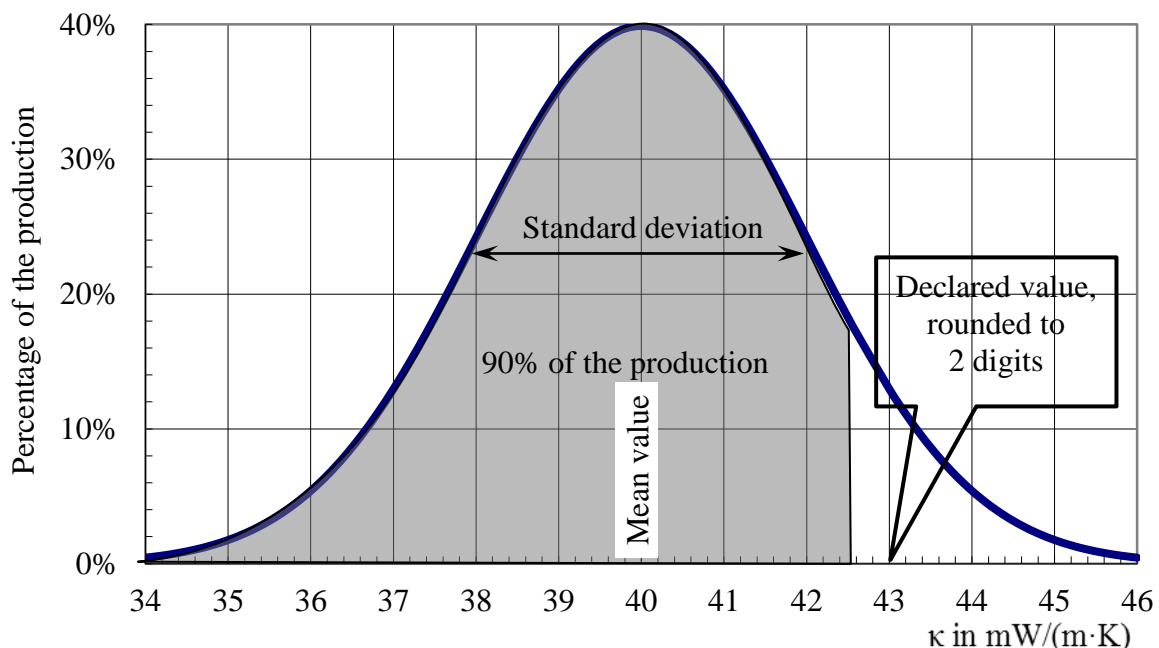


Figure 2.7: Theoretical distribution of the thermal conductivities of samples taken in a production and declared value. In this case, the declared value will be 43 mW/(m²K) while the average value of the production is 40 mW/(m²K).

The procedure for calculating the declared value of thermal conductivity of a product based on the measured values of this product is given in Appendix B.

2.5.3 Heat capacity

The amount of heat needed to increase the temperature of one unit mass of matter by one temperature unit is the heat capacity. In SI units, it is expressed in joule per kelvin (J/K) and often in kWh/K in practice.

The heat capacity per unit mass of a homogeneous material is the **specific heat capacity**, often simply called **specific heat**, of this matter. In SI unit, the specific heat is expressed in J/(kg·K).

2.5.4 Diffusivity

Heat takes time to propagate in the matter, as the thermal conductivity is not infinite and there is some resistance to the heat transfer, and the matter needs time to increase its temperature with the limited amount of heat. In order to quickly propagate heat, the matter should have a high thermal conductivity κ , a low heat capacity c , and a low density ρ .

The physical quantity that characterises the ‘speed’ of the heat transfer is the thermal diffusivity a , which is a combination of the quantities cited above:

$$a = \frac{\kappa}{\rho c} \quad 3$$

The thermal diffusivity is expressed in m²/s in SI units. If the surface temperature of a thick piece of matter is suddenly increased, the layers close to this surface are heated first, then the deeper layers, etc. Therefore, the temperature profile in the matter looks like the ones shown in Figure 2.88 left. We see there that a given temperature level, e.g. the one at 50% of the surface temperature increase, advances in the matter at a depth proportional to the square root of time. The penetration depth is \sqrt{at} .

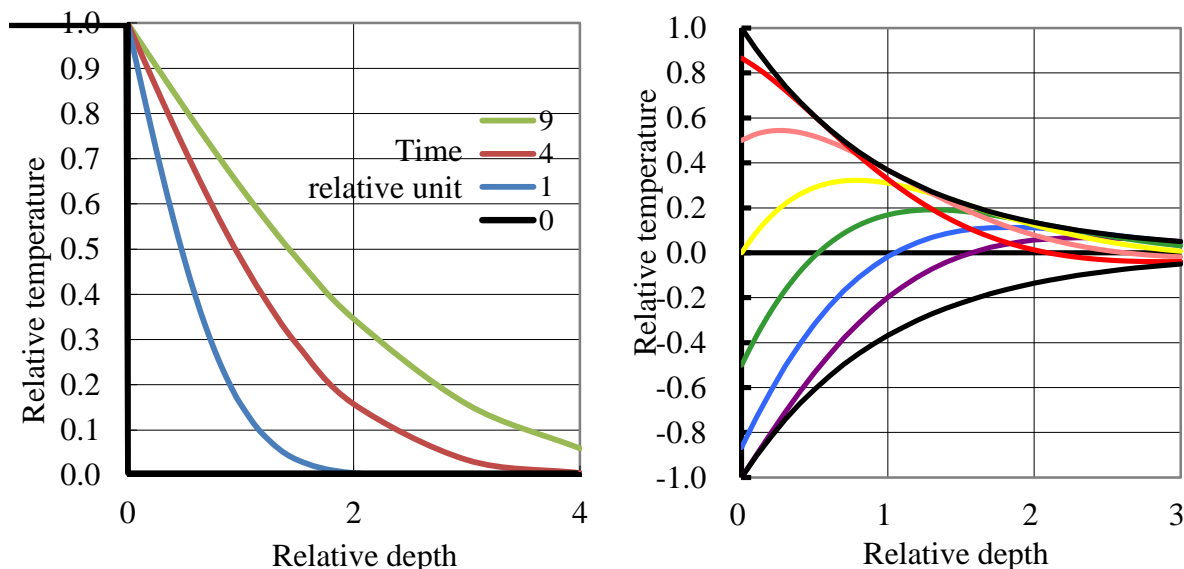


Figure 2.8: Propagation of heat in a homogeneous solid. Left: after a sudden increase of the surface temperature. Right: When the surface temperature oscillates sinusoidally.

If the surface temperature oscillates sinusoidally (Figure 2.88 right), the layers closest to the surface are periodically heated and cooled, heat periodically gets in and out. Therefore, the deeper layer does not get the full heat flow and heats at a lower maximal temperature or cools down, half a period later, at a higher minimal temperature. Therefore, the temperature ampli-

tude decreases with depth, by a percentage that is proportional to \sqrt{aP} where P is the period of the temperature oscillations.

More generally, the temperature distribution in a bunch of material in which the temperature or the heat flow at some places changes with time is a function of \sqrt{at} , where a is the diffusivity of that material.

When a sample of thermal insulation material, conditioned at a given temperature, is placed between the hot and cold plates of the apparatus to measure its thermal conductivity, some time is needed to get the steady state, i.e. when the temperatures and heat flow rates in the samples remain constant. The time needed decreases with diffusivity, therefore with thermal conductivity, but increases with the density and the square of the thickness of the sample. If the thickness doubles, the stabilisation time quadruples!

Table 2.2: Thermal properties of some common materials at ambient temperature(from [4])

| Material | Density ρ kg/m ³ | Specific heat capacity c J/(m ³ K) | Thermal conductivity κ W/(m.K) | Thermal diffusivity a mm ² /s |
|-----------------------|--|---|---|--|
| Locked air | 1.1 | 1000 | 0.025 | 30.00 |
| Expanded polystyrene | 20 | 1370 | 0.04 | 1.46 |
| Dense mineral fibre | 100 | 1000 | 0.04 | 0.40 |
| Pine wood | 500 | 2500 | 0.15 | 0.12 |
| Aerated concrete | 600 | 1000 | 0.17 | 0.28 |
| Clay brick | 1100 | 940 | 0.44 | 0.43 |
| Plaster | 1200 | 830 | 0.58 | 0.58 |
| Locked water | 1000 | 4180 | 0.59 | 0.14 |
| Snow | 500 | 2000 | 0.69 | 0.69 |
| Hollow concrete block | 1200 | 1000 | 0.70 | 0.58 |
| Adobe | 1768 | 823 | 0.76 | 0.52 |
| Glass | 2500 | 720 | 0.81 | 0.45 |
| Mortar | 1900 | 1000 | 1.0 | 0.53 |
| Concrete | 2400 | 1000 | 1.8 | 0.75 |
| Sandstone | 2200 | 940 | 2 | 0.97 |
| Steel | 7850 | 830 | 58 | 8.90 |
| Aluminium | 2750 | 830 | 204 | 89.38 |

2.6 Thermal properties of a product or building component

2.6.1 Thermal resistance or R -value of a layer of material

The resistance of a layer of material to heat transfer is proportional to its thickness, d , and inversely proportional to the thermal conductivity of the material, κ :

$$R = \frac{d}{\kappa}$$

4

This thermal resistance is often labelled on a product package, because it is the main thermal property of a product that has a definite thickness.

There is also a resistance to the transfer of heat from an open surface to the surrounding ambience. Such transfer involves radiation, convection, and conduction, and varies therefore with the temperature of the surface itself, of the air and of vicinal surfaces, and with the air velocity close to the surfaces. This heat transfer is often modelled with a surface heat transfer coefficient as the sum of the heat transfer coefficient by radiation and by convection-conduction. The inverse of this total surface heat transfer coefficient is surface resistance R_s .

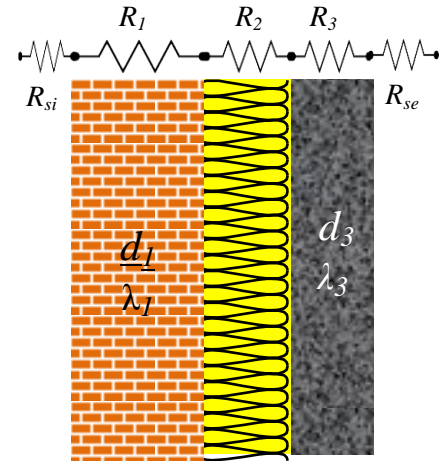


Figure 2.9: Thermal resistance

2.6.2 Overall thermal resistance of a component

The thermal resistance from surface to surface of a plane component consisting of thermally homogeneous layers perpendicular to the heat flow is calculated by the following expression:

$$R = R_1 + R_2 + \dots + R_n \quad 5$$

where R_j are the thermal resistances of the individual layers. Its total thermal resistance from ambience to ambience is obtained by adding two surface resistances to this resistance

$$R_T = R_{si} + R_1 + R_2 + \dots + R_n + R_{se} \quad 6$$

where R_{si} and R_{se} are the internal and external thermal resistances, respectively. The following values are conventionally used:

$$R_{si} = 0,13 \text{ m}^2\text{K/W} \quad \text{and} \quad R_{se} = 0,04 \text{ m}^2\text{K/W}$$

In building envelope components that include a layer of thermal insulating material, this layer is by far the most resisting one, and the total resistance is only slightly larger than the resistance of the thermally insulating layer. Therefore, the R -value labelled on a product package is often taken as the R -value of the complete building envelope component.

2.6.3 Overall heat transfer coefficient or U -value

The inverse of this total resistance is the overall heat transfer coefficient U of the building element:

$$U = 1/R_T \quad 7$$

For a given temperature difference, ΔT , across a building envelope component, the density of heat flow rate, q , is proportional to its U -value:

$$q = U \Delta T \quad 8$$

2.6.4 ECBC requirements

The ECBC (Energy Conservation Building Code - India, 2007) prescribes maximum overall U -values or minimum R -values of insulation alone for roof and wall insulation in commercial buildings for the various climate zones in India (Figure 2.1010).

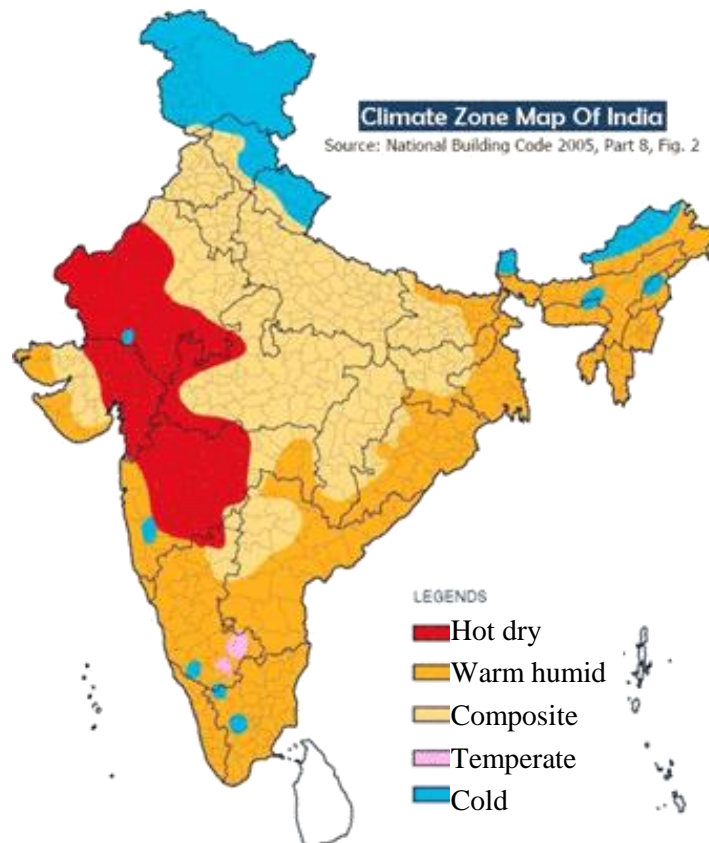


Figure 2.10: Climate zone map of India (ECBC)

The ECBC prescribed values are summarised in Table 2.33.

Table 2.3: ECBC Prescriptions regarding maximum overall thermal conductivity U of envelope components and minimum thermal resistance R of the insulation layer

| Envelope component | Climate Zone | 24-h use buildings, hospitals, hotels, call centres, etc. | | Day-time use buildings and other building types | |
|--------------------|----------------|---|--|---|--|
| | | Max. U-value W/(m ² K) | Min. R-value of insulation alone m ² K/W | Max. U-value W/(m ² K) | Min. R-value of insulation alone m ² K/W |
| Roofs | Composite | 0.261 | 3.5 | 0.409 | 2.1 |
| | Hot and Dry | 0.261 | 3.5 | 0.409 | 2.1 |
| | Warm and Humid | 0.261 | 3.5 | 0.409 | 2.1 |
| | Moderate | 0.409 | 2.1 | 0.409 | 2.1 |
| | Cold | 0.261 | 3.5 | 0.409 | 2.1 |
| Opaque walls | Composite | 0.440 | 2.10 | 0.440 | 2.10 |
| | Hot and Dry | 0.440 | 2.10 | 0.440 | 2.10 |
| | Warm and Humid | 0.440 | 2.10 | 0.440 | 2.10 |
| | Moderate | 0.440 | 2.10 | 0.440 | 2.10 |
| | Cold | 0.369 | 2.20 | 0.352 | 2.35 |

2.7 Other characteristics of insulation materials and products

In addition to thermal conductivity, properties that shall be determined for every product are the dimensions of the product and its density.

Other characteristics can be determined, depending on the use of the material, as shown in Table 2.44.

Table 2.4: Required characteristics for thermal insulation materials in relation to their use.

| Characteristics | Use |
|------------------------------|--|
| 10% compression strength | Flat roof and floors, where materials should stand some compression |
| Traction rupture strength | Materials used in EIFS (External Insulation and Finishing Systems) |
| Dimensional stability | Insulation materials used on flat roofs |
| Resistance to heat | Insulation materials under bituminous roofing |
| Water absorption | Materials exposed to water or underground |
| Permeability to water vapour | Materials that should present a resistance to water vapour diffusion |

2.8 Some thermal insulation materials

See also http://en.wikipedia.org/wiki/Building_insulation_materials

2.8.1 Inorganic fibrous materials or mineral fibres

Inorganic fibres are also known as mineral fibres, rock wool, stone wool, man-made mineral fibre (MMMf), and man-made vitreous fibre (MMVF).

These are fibres made out of glass, ceramic or rock manufactured by centrifugation spinning of a vitreous liquid obtained by fusion of minerals, similar to the process of manufacturing the 'cotton candy'. Fibreglass is made out of glass, often recycled glass, while rock wool is made out of artificial lava obtained by fusing together an appropriate mixture of various types of stones (Figure 2.11). Basalt, natural solidified lava, is also used to produce fibrous thermal insulation. For applications at ambient temperatures, the fibres are coated with a resin and laminated to make mats or plates.

Pure silica or aluminosilicates are also used for very high temperatures, for example to isolate industrial furnaces. These are delivered in nailed blankets, without any glue.

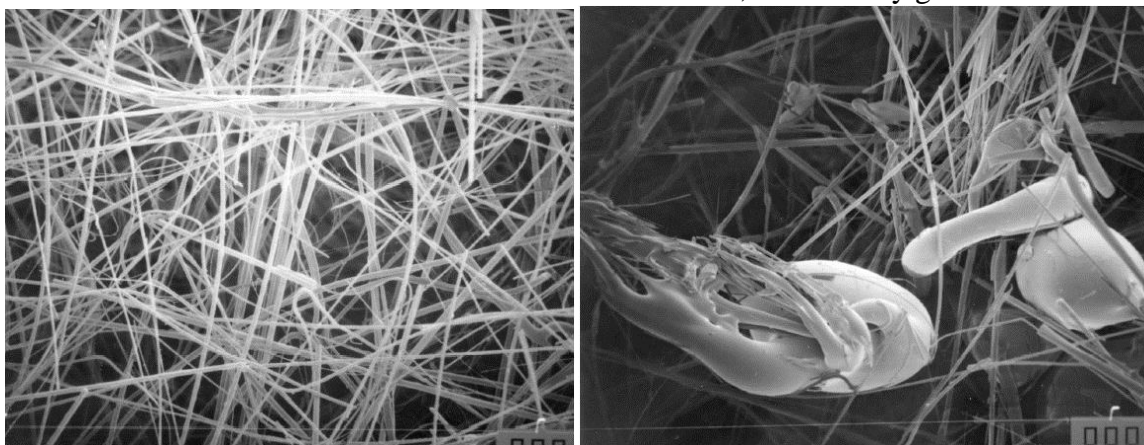


Figure 2.11: Photomicrographs of mineral wool (left) and rock wool (right) © St Gobain Isover

These materials have excellent resistance to fire and good thermal insulation and sound absorption qualities. They present a high durability and are resistant to rot, mould, and vermin. Permeable to air and water vapour, they easily absorb water by immersion but drip and dry easily.

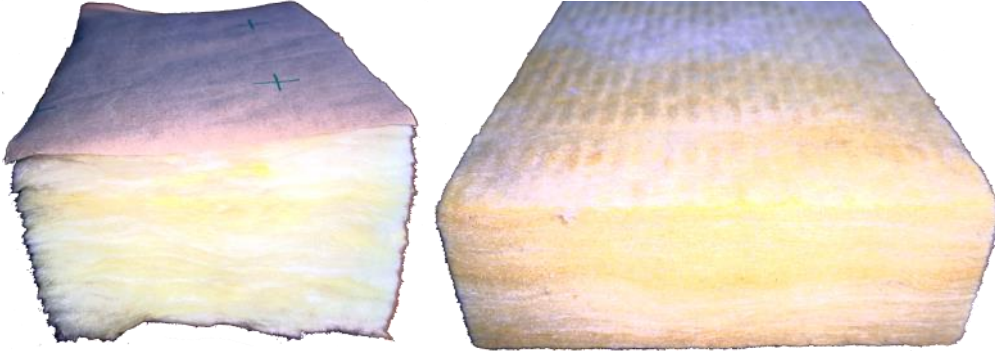


Figure 2.12: Light mineral wool (left) and dense (right)

Their density may vary by a factor of 10, which allows many applications (Figure 2.12). Lightweight fibre mats and panels are used for insulation in pitched roof or walls. Dense panels are installed where mechanical strength is needed, e.g. in slabs and flat roofs.

2.8.2 Organic fibres

Natural organic fibres are yet seldom used in buildings, but a marginal market tends to develop. Wool, cotton, cellulose, straw, and other fibres such as those from hemp plant, rice hulls, coconut or durian, can be used as insulating materials. Cellulose, used as loose fill material, has now generated a growing interest.

Organic fibres are sensitive to moisture, pests, mould, and fire. However, measures are taken by serious producers to improve the durability and fire resistance of these materials. However, it is recommended to check the toxicity of adjuvants used for this purpose, particularly in case of fire.



Figure 2.13: Organic fibres. Left: Hemp. Right: Cellulose

2.8.3 Mineral foams

Glass foam is obtained by baking at high temperature a mixture of fine glass powder with a bit of carbon powder, placed in a rectangular cake tin of refractory metal. The top surface of

the mixture melts first and prevents carbon dioxide resulting from the combustion of carbon from escaping. This gas is then encased in glass bubbles and the mixture grows up like a cake. Parts of various shapes are then cut in this 'cake' (Figure 2.14). Cellular glass also comes in the form of granulate that can be used as filler material.



Figure 2.14: Close view of a plate and various forms out of FOAMGLASS

This relatively expensive material is totally tight to water and water vapour, except at the joints and cracks. It has a good resistance to compression but is fragile. It is used on flat roofs and as insulation of foundations and slabs subjected to high loads, as well as in places where the water and water vapour tightness is essential. As it is fireproof, it can be used to service temperatures up to 450 °C, so far as fixations allow thermal expansion and stand the temperature. Very durable, it is resistant to solvents and acids (except hydrofluoric acid) as well as rot, mould, and vermin.

Vermiculite is a hydrous, silicate mineral with a lamellar structure that expands greatly by exfoliation when heated. Relatively expensive, it is used as filler material for thermal insulation at high temperature. Due to its non-combustible nature, it resists temperatures up to 1400 °C. It is a hygroscopic (absorbs moisture), but very durable, and resistant to acids and alkalis⁶. It is also mixed with calcium silicate slurry that is dried, pressed, and cured to form flat boards.



Figure 2.15: Vermiculite and perlite (©<http://blog.wormsway.com/>)

⁶ An alkali (from arabic *al-qâly*, 'ashes of the saltwort') is a substance that, in aqueous solution, reacts with acids to form salts. Examples are ammonia, soda, slaked lime, and potash.

Perlite is a volcanic amorphous glass that has rather high water content. Perlite softens at about 850–900 °C, and the water trapped in the structure of the material vaporises and causes the expansion of the material to 7–16 times its original volume. The expanded material is in the form of small white porous spherules, like pumice, with an apparent density of about 30 to 150 kg/m³. Non-combustible, it resists temperatures up to 850 °C. It is permeable to water vapour and hygroscopic⁷, but is hydrophobic⁸ when mixed in bitumen. Very stable and durable, it resists to rot, mould, and vermin.

Autoclaved aerated concrete (AAC) – also known as autoclaved cellular concrete (ACC), autoclaved lightweight concrete (ALC), autoclaved concrete, cellular concrete (YTONG) – is a lightweight, precast, concrete building material that provides structure and insulation. Products include blocks, wall panels, floor and roof panels, cladding (facade) panels, and lintels. It is expanded by the addition of aluminium powder to a cement mortar. Aluminium reacts with water and cement to release hydrogen. The resulting foam is cured in an autoclave, and then cut into blocks (Figure 2.16). Its insulating power is considerably less than that of a specific insulating material. This material is used on one hand as lightweight concrete, and on the other hand to construct homogeneous walls, because it has a good mechanical strength and provides some simultaneously thermal insulation. It easily absorbs water and is very sensitive to frost when wet.

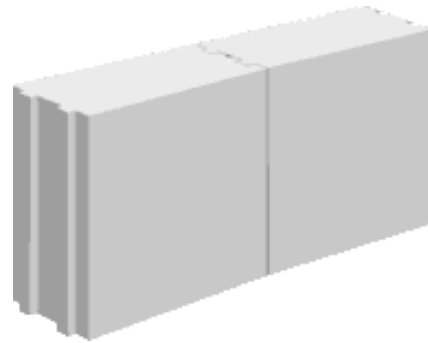


Figure 2.16: Blocks of aerated concrete (©YTONG)

2.8.4 Organic foams

These are foams from polymers such as polyurethane (PUR), polystyrene (PE), urea formaldehyde (UF), polyvinyl chloride or PVC, polyethylene, and polyisocyanurate (PIR). PE, PUR, and PIR are used in buildings. UF is used exclusively for injections on site. Other organic foams, more expensive, are marginal, and mostly for industrial use. These foams are naturally flammable, but their resistance to fire is improved with additives.

Polystyrene in small beads is expanded with warm water vapour in large rectangular boxes and then cut to make plates (Figure 2.177 left). Adding graphite improves the thermal conductivity because graphite reflects the infrared radiation in the pores (Figure 2.17 right). The expanded polystyrene is also abbreviated as EPS.

⁷Hygroscopic: tends to adsorb or absorb moisture.

⁸Hydrophobic: which repels water. It is the contrary of hygroscopic or hydrophilic.

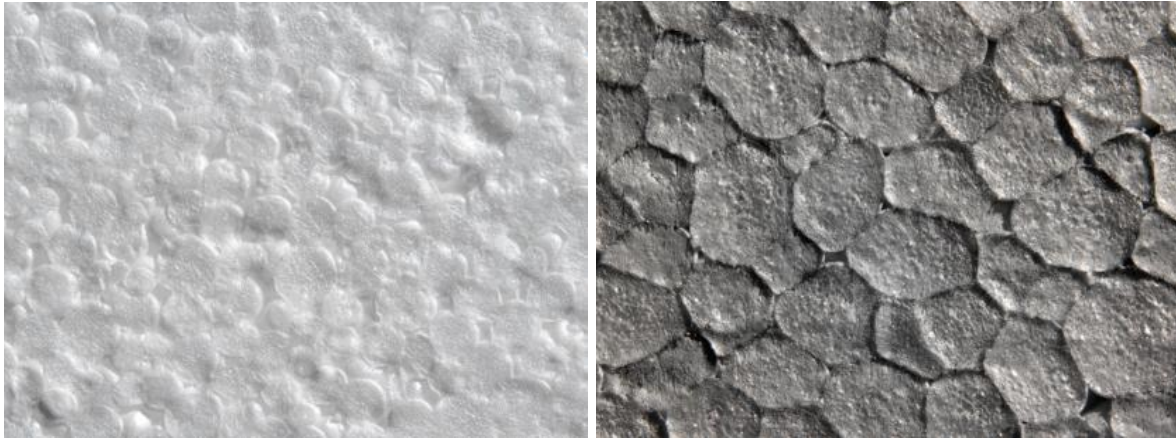


Figure 2.17: Microstructure of expanded polystyrene. Left: the common one; right: graphited.
© Swisspor.

Polystyrene can also be directly foamed and extruded⁹ into plates who then have a film on the surface, making them resistant to water (ROOFMATE, Figure 2.188 left). Extruded polystyrene or XPS is an excellent material for insulation of inverted flat roofs (see Section 3.2.3), because it is weather resistant. Polystyrene foam resists to mould and rot, but can be destroyed by rodents or insects. It does not resist to solvents and temperatures exceeding 80 °C.



Figure 2.18: Microstructure of extruded polystyrene (left) and polyurethane foam (right). © SWISSPOR.

Polyurethane or PUR is expanded simultaneously to the chemical reaction that makes it (Figure 2.188 right). It has a very low apparent thermal conductivity, at least when just manufactured. It also has a good resistance to compression. It absorbs water relatively easily, but is resistant to acids, alkalis, and many solvents. Durable and resistant to mould, it is very sensitive to ultraviolet light and must not be exposed to weather. It is used on flat roofs, under slabs, for industrial insulation. It can also be injected or sprayed on site (Figure 2.199) or used as glue. As PUR foam expands when hardening, it presses on the surrounding surfaces when injected in a cavity, and may deform the cavity walls.

⁹ Extrusion is a manufacturing process by which a soft material is compressed and pushed through a drawing plate having the section of the required profile. In this case, the section has a rectangular shape to extrude plates.



Figure 2.19 Left: PUR injected on site for sealing wooden beams. Right: Spraying PUR foam for thermal insulation in a frame wood roof.

Urea formaldehyde foam or UF is relatively easy to produce on site and can be injected into cavities without causing pressure, unlike the PUR foam. The resulting foam is with open pores, light, hard but without strength. Hardly combustible, it resists temperatures up to 100 °C, but has a high coefficient of expansion. It is permeable to water vapour and hygroscopic. Moreover, it becomes fragile when it is wet but still resists rotting. It can withstand a large number of solvents, but neither acid nor alkalis. It gives off formaldehyde when hardening; therefore good ventilation for several weeks is necessary if used indoors.

2.8.5 Woody materials

Wood fibre and straw: Light wood, straw, and light wood fibre panels can be used as insulating and acoustic absorbing materials. The thermal conductivity of these materials is generally higher than that of specific insulating materials such as mineral wools or organic foams. Wood insulation is sensitive to humidity, which swells them and induces mould growth and rot. These panels, which may be apparent, partly absorb airborne noise. The most common are wood fibre panels and cement-agglomerated straw. These panels adhere well to the concrete and mortars and can be used on the bottom of sheeting.

Cork, the bark of the cork oak, is a natural insulating material. It is used in raw form to make caps, in the form of aggregated granulates on floors, for impact sound insulation and seals, and heat expanded for thermal insulation (Figure 2.20).

Expanded cork panels are flame-retardant and resistant to temperature up to 130 °C. They have low thermal expansion and can therefore be directly plastered. Cork absorbs little water, but it rots if it remains wet for too long. It was much used, particularly as panels of asphalt agglomerated granulates, for flat roofs. Its cost is now too high and it is currently replaced by synthetic materials.

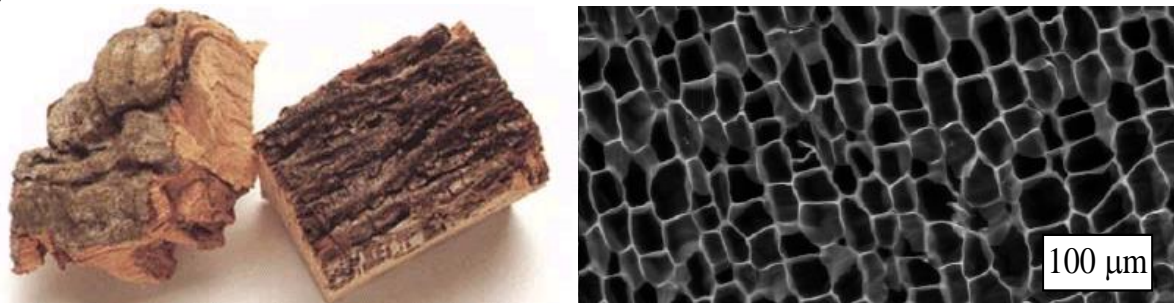


Figure 2.20: Cork: left: pieces of bark, at right, microstructure (Museum of Paleontology, University of California, Berkeley)

2.8.6 Super insulating materials

Super insulating materials are used to reduce the thermal conductivity of the insulation. They improve the insulating power beyond that of the air. Vacuum insulation and nanogel are the two means found on the market:

Vacuum insulation: Pack a porous core (open cell foam, mineral wool) sufficiently resistant to stand the atmospheric pressure, in a gas-tight enclosure, evacuate the air and seal the envelope. Without gas, there is no convection, and radiation is strongly reduced by the opacity of the material. Only the thermal conductivity of the core material remains and the apparent thermal conductivity of the product can be up to 10 times lower than that at atmospheric pressure (Figure 2.21).

One can thus obtain the same thermal insulation with 10 times less thickness. The vacuum should however remain for the whole building lifetime, and the sealed envelope should not suffer any damage on the construction site: no cut, no hole. This seems very hypothetical in the building industry. This type of material is still very useful to isolate industrially produced appliances such as freezers, stoves, and refrigerators.

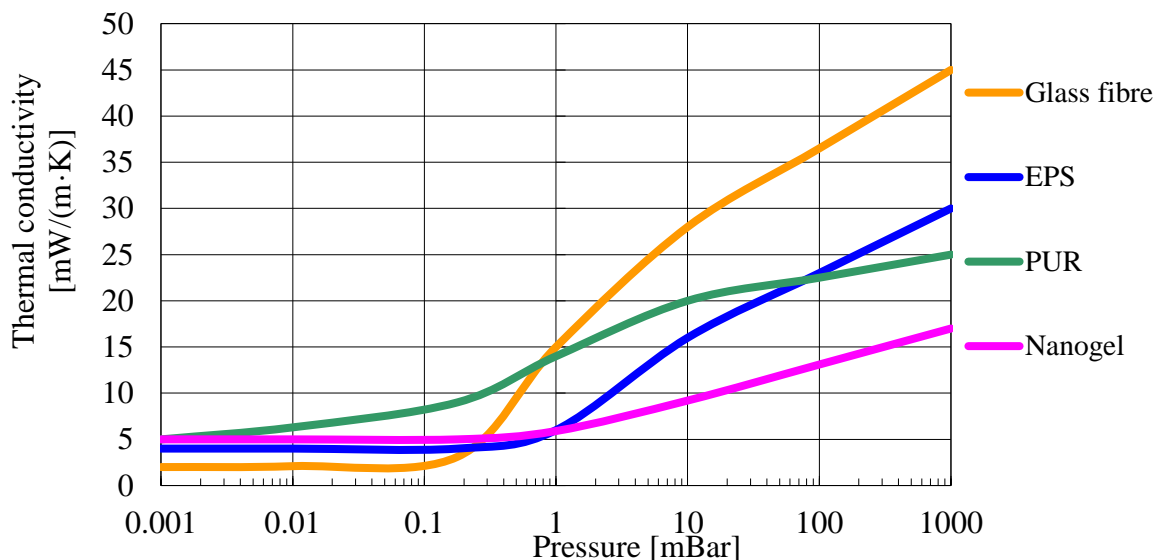


Figure 2.21: Thermal conductivity of some material as a function of air pressure

Nanogel: In foams produced by nanogel, the pores are so small that the molecules of air, in their thermal agitation, hit the walls more often compared to other molecules. As lightweight air molecules can hardly move the heavier walls of the pores, the thermal conductivity is strongly reduced. Silica aerogels are produced by extracting the liquid component of a silica gel through drying at a high temperature and pressure at which the liquid is in a supercritical state, so that it is neither a liquid nor a gas. This allows the liquid to be slowly dried off without causing the solid matrix in the gel to collapse from capillary action, as would happen with conventional evaporation. Silica nanogels are very lightweight (down to 2 kg/m³) and translucent.

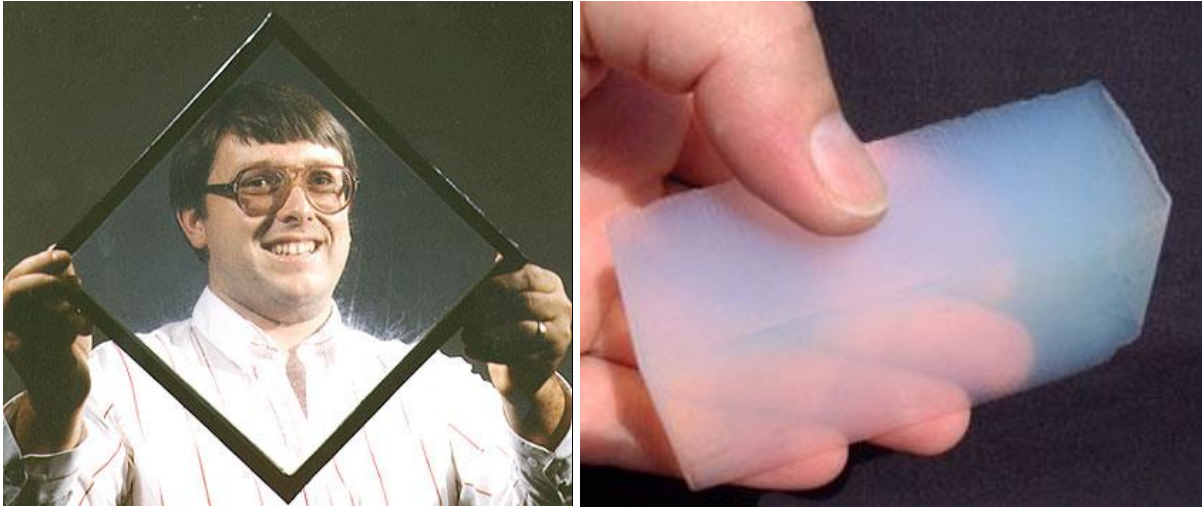
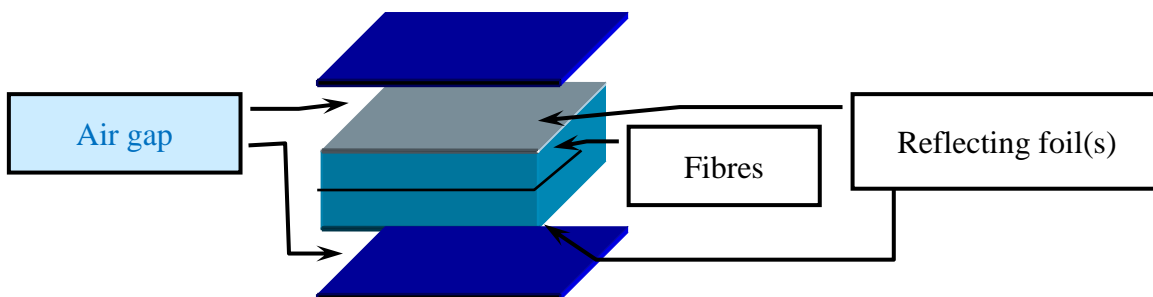


Figure 2.22: Left: a window pane filled with aerogel (Lawrence Berkeley Lab.) Right: chunk of aerogel (Boingboing)

Thermal conductivity lower than $0.018 \text{ W}/(\text{m}\cdot\text{K})$ is claimed for a silica aerogel-based insulation offered in the market. However, the cost of this material (more than US \$50 or INR 3000 per square metre) limits its use in buildings at present.

Reflecting mats are fibre mats sandwiched between metallised foils that reflect infrared radiation. The foils also add some airtightness. Some of these materials have several such metallised foils (Figure 2.233).

Some scammers do not hesitate to ascribe miraculous insulating qualities to these materials: advertisements claim that 2 cm of thickness of one of these materials has the insulating power equivalent to 16 cm mineral wool! This is not true at all, even if radiation is stopped. The other heat transfer modes remain, including the conduction in the air and materials of the mat. It follows that these mats, in the best of cases, have an insulating power equal to that of conventional insulating materials.



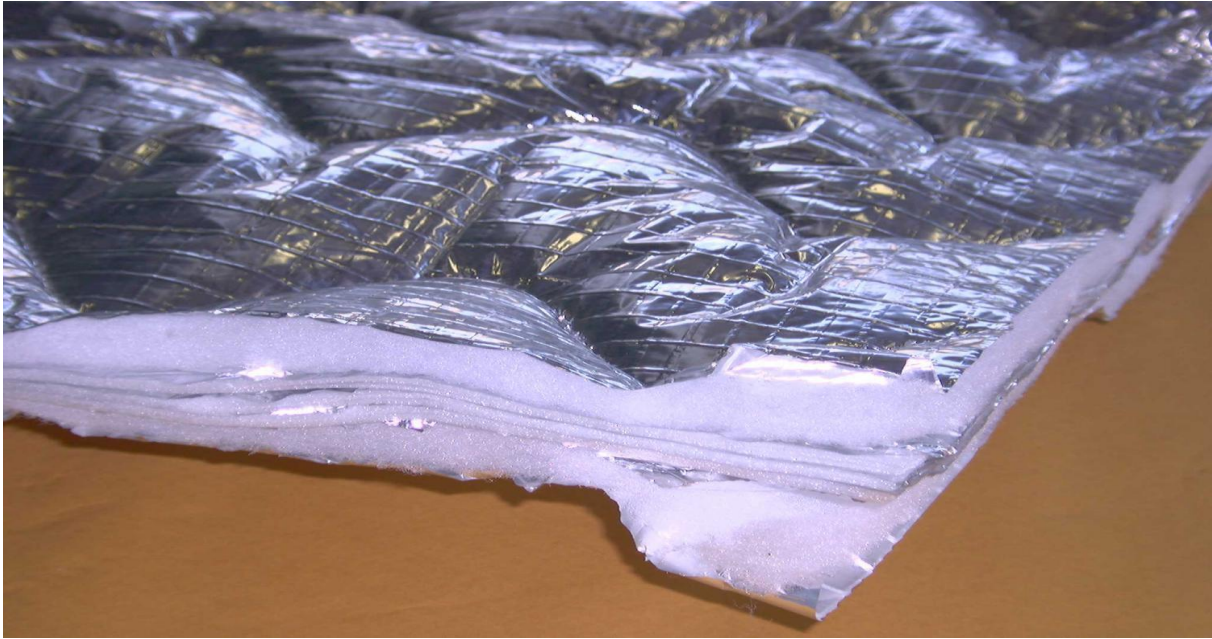


Figure 2.23: Structure and example of a reflecting thin mat

2.8.7 Overview of thermal insulation materials

Thermal conductivity is not the only property to be taken into account when choosing an insulating material. The following characteristics can be important depending on the applications, but are not always necessary.

- Fire resistance: easily flammable materials are generally not allowed as building material.
- Mechanical strength: to compression in decks and traction for EIFS.
- Resistance to water vapour diffusion is not essential because it can be provided by another specific layer (vapour barrier).
- Low water absorption by immersion, flotation or vapour diffusion is necessary in wet areas or outdoors.
- Dimensional stability is needed for flat roofs, where the temperature may strongly vary between day and night.
- Resistance to high temperature is necessary for flat roof with soldered watertight layer and other high temperature applications.
- Acoustic absorption to shock and airborne noise: where necessary, and generally not linked to a simultaneous thermal insulation.
- The cost given in Table 2.55 is indicative. Prices strongly depend on location, quantities, and market.

Table 2.55 summarises several qualities for most common insulating materials.

Table 2.5: Qualities of typical thermal insulating materials.
Evaluation may be different (often better) for industrial products

| Characteristics of insulating materials | Insulating power | Density | Fire resistance | Water vapour diffusion | Resistance to water | Compression strength | Traction strength | Heat resistance | Absorption of vibrations | Absorption of aerial noise | Cost at given insulation | Grey energy |
|---|------------------|---------|-----------------|------------------------|---------------------|----------------------|-------------------|-----------------|--------------------------|----------------------------|--------------------------|-------------|
| Light mineral wool | + | -- | ++ | -- | 0 | -- | -- | + | | ++ | \$ | -- |
| Dense mineral wool | ++ | + | ++ | -- | 0 | 0 | - | ++ | ++ | + | \$ | 0 |
| Hemp fibre | 0 | -- | 0 | -- | -- | 0 | -- | 0 | | ++ | \$ | -- |
| Wood fibres | 0 | ++ | 0 | -- | -- | + | -- | + | + | ++ | \$\$ | - |
| Wood straw-cement | - | ++ | + | -- | -- | + | 0 | + | 0 | + | \$\$ | - |
| Cellulose flakes | + | -- | 0 | -- | -- | -- | - | 0 | | ++ | \$ | -- |
| Cork | + | ++ | + | + | - | + | 0 | ++ | + | - | \$\$ | -- |
| Glass foam | + | + | ++ | ++ | ++ | ++ | ++ | ++ | -- | - | \$\$\$ | 0 |
| Cellular concrete | -- | ++ | ++ | - | - | ++ | + | ++ | -- | - | \$\$\$ | 0 |
| PUR | ++ | - | 0 | - | 0 | + | + | ++ | - | -- | \$ | ++ |
| EPS | + | -- | + | + | 0 | + | + | 0 | - | -- | \$\$\$ | - |
| Graphited EPS | ++ | -- | + | + | 0 | + | + | 0 | - | -- | \$ | - |
| XPS | ++ | 0 | + | ++ | + | + | ++ | 0 | - | -- | \$ | + |
| Silica aerogel | +++ | -- | + | -- | ++ | -- | - | + | ++ | -- | \$\$\$\$ | +++ |

- ++ : Very high + : high 0 : average, acceptable - : low -- : very low

| | | | | |
|-----------|------|--------|------|-----|
| Very good | Good | Medium | Poor | Bad |
|-----------|------|--------|------|-----|

3 USES OF THERMAL INSULATION IN THE BUILDING ENVELOPE

3.1 Internal or external thermal insulation?

If a wall is submitted to a temperature difference between both sides, the largest temperature fall will take place in the insulating layer. Thus, the part of the wall inside the insulating layer will be practically at the internal temperature and the part on the outside of the insulation layer will be close to the external temperature. The insulating layer may be installed outside or inside the bearing structure, or be distributed, the carrier material being the only thermal insulation.

Both external and internal thermal insulation reduce the heat flow through the building envelope in any case and in both directions. Therefore, it reduces the need for heating in cold climates and cooling in hot climates.

However, the position of the insulation in the building element, i.e. on the internal or external side of the building envelope component or even inside the components, has an important influence on the dynamic behaviour of the component and, in some climates, on possible condensation problems.

For composite and hot-dry climates, it is recommended to use insulation on the outside surface of the wall or inside the cavity, in a cavity wall configuration. As far as possible, insulation should not be applied on the internal surface of the walls, as this does not allow the thermal inertia of the masonry wall to contribute in stabilising the indoor temperature. The detailed reasons are given below.

3.1.1 External insulation

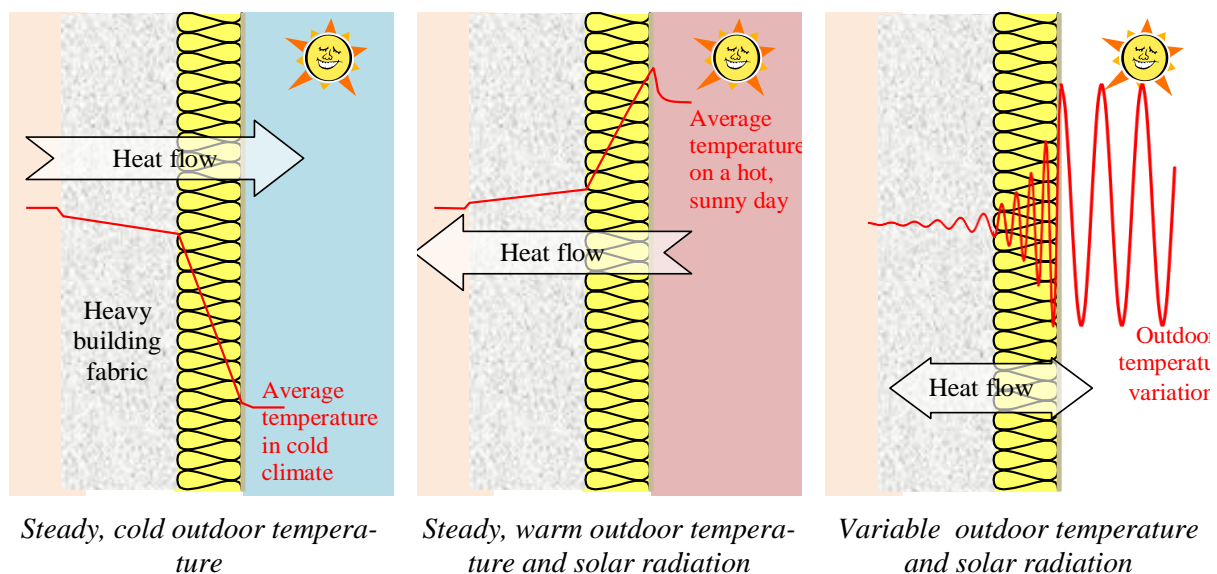


Figure 3.1: Typical temperature profiles with external insulation

In external insulation systems, the insulating layer is placed outside the bearing structure. It is protected from the weather and shocks by a protective layer, which can be a finishing, a cladding or even a relatively thin wall.

Advantages

- Increases the time constant of the building (i.e., the time it needs to change its internal temperature after a change of the external temperature), hence protects the indoor environment from external temperature variations.

- Stabilises the temperature of the structure and hence its dilatations and deformations.
- Allows using the thermal mass of the building to store excess heat or recover stored heat.
- Suppresses most thermal bridges.
- In cold climates, completely suppress the risk of water vapour condensation inside the building element.

Inconveniences

- Needs an application from outside, hence a scaffolding.
- Increases the time required to change the internal temperature. In air-conditioned buildings located in warm and humid climate, may increase the risk of water vapour condensation inside the building element.

3.1.2 Internal insulation

In most cases, the advantages of external insulation overshadow its disadvantages. One can, however, be obliged to isolate indoors, for example, when retrofitting historical buildings of which the external aspect must be kept intact. In these cases, it is essential to check that the risk of water vapour condensation is acceptable and that special attention is paid to residual thermal bridges.

In internal insulation systems, the insulating layer is placed inside the bearing structure. It is protected by a thin internal wall by plaster or wood plates. Unless special measures are taken, the decks and partition walls are therefore not insulated.

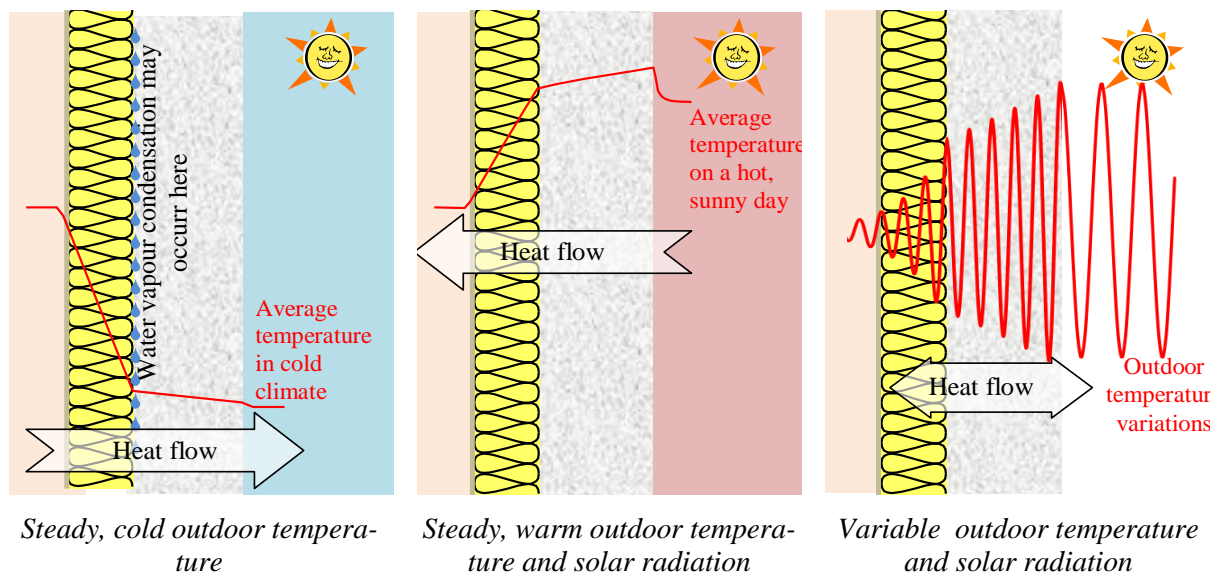


Figure 3.2: Typical temperature profiles with internal insulation

Advantages

- It is applied inside, at low cost.
- Decreases the time required to change the internal temperature, and that could be useful in rooms used part time.
- In air-conditioned buildings located in hot, humid climates, it completely suppresses the risk of water vapour condensation inside the building element.

Inconveniences

- In heated buildings located in cold climate, it may increase the risk of water vapour condensation inside the building element.
- Decreases the time constant of the building. The indoor temperature tends to follow the external temperature variations.
- Leaves the outer building structure exposed to external variations.
- Leaves thermal bridges, i.e., location on the building envelope, such as decks and partition walls, that are not insulated.

3.1.3 Distributed insulation

We have seen that homogeneous walls, common almost everywhere even in the last century, cannot be used in cold climates, because stiff enough materials have a limited insulating power, and the required thickness in cold climates becomes prohibitive. However, it has several advantages enough to recommend its use wherever possible.

- Simple construction: a single material is used.
- Regular distribution of the temperature in the wall.
- Relatively high internal thermal inertia.

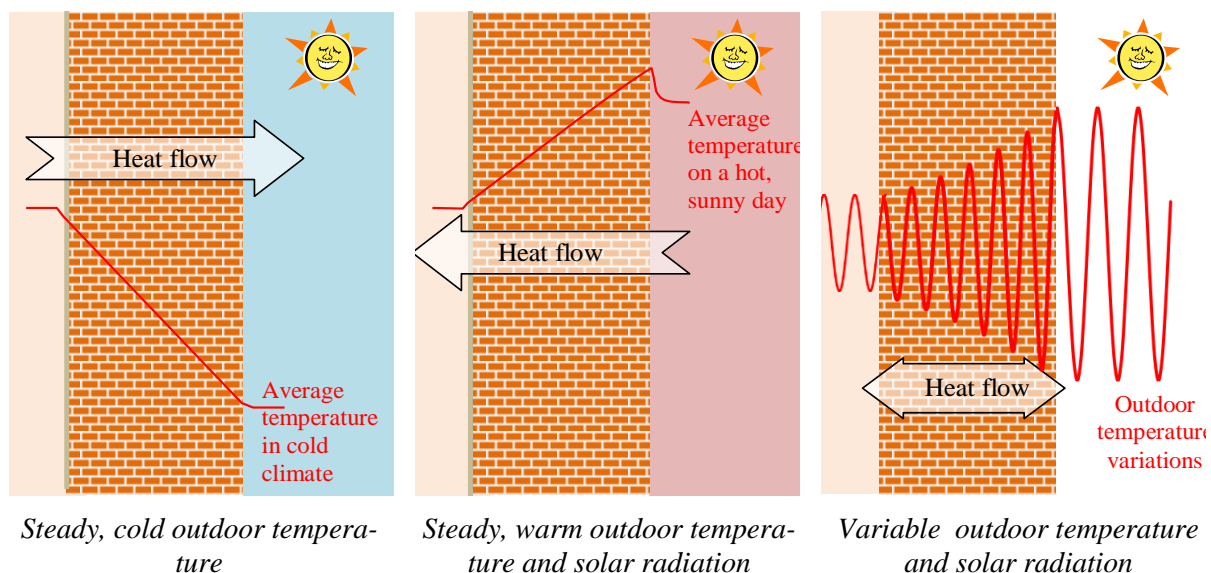


Figure 3.3: Typical temperature profiles with distributed insulation

Materials for this type of wall include solid wood; hollow, porous clay brick; mud, mud brick or adobe; and aerated concrete and compressed straw. The latter has a pretty good insulating performance and is used in cold climates.

Water vapour diffusion through the wall could condense against the colder surface (e.g. the outer face in winter). It is important that the finishing of this face be permeable to water vapour, to avoid condensation problems.

3.2 Thermal insulation in the building envelope

3.2.1 Homogeneous walls

Some materials have a relatively low effective thermal conductivity while having sufficient mechanical strength to build walls with them. They are solid wood, porosified clay brick, aer-

ated concrete and compressed straw. However, the apparent thermal conductivity of these materials is not as low as that of specific insulation and the wall thickness must be sufficient to ensure insulation complying with current standard.

Old buildings have been built with homogeneous walls of whitewashed masonry, adobe, mud, or stone. These materials do not provide sufficient thermal insulation according to modern criteria, but the thickness gives them a thermal inertia such that the interior comfort remains pleasant in climates where the temperature is comfortable but varies between uncomfortable extremes.

Solid wood has good thermal and mechanical qualities, and has been widely used in many countries for cottages. This solution is, however, rather expensive, and recent wooden buildings have a frame wood structure upholstered with panels or boards, internal voids being filled with insulating material.

3.2.2 Roof decks

Insulation in the conventional flat roofing slabs is placed between a barrier to the diffusion of vapour lying on the slab and the waterproofing layer (Figure 3.4). The waterproof layer can be protected from the sun by a layer of sand and gravel or tiles. The insulation shall withstand compression, and high temperatures that may occur either because of the sun, or when sealing by torch welding the bituminous layer. Cork for this application was much used. Now, polyurethane, polystyrene, foam glass, mineral fibres are used, the latter at high densities.

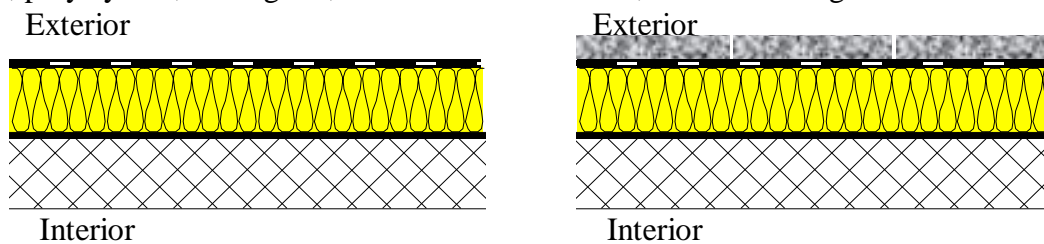


Figure 3.4: Usual flat roof, left: without protection, right: with protection above the waterproofing layer.

Some slope should be driven to drive rain water towards water discharge grid. This slope is provided by a cement layer, laid either under the thermal insulation layer or over it, the insulation being protected by a separation layer such as a geotextile membrane or polythene sheet. When the thermal insulation layer is thick enough, this slope can be provided by the insulation material itself, delivered in plates of decreasing thicknesses.

3.2.3 Inverted roof deck

In the inverted flat roof, the thermal insulation is placed above the waterproof layer, itself directly placed on the slab (Figure 3.5). This slab is often covered with a cement layer to provide a slope. Gravel or concrete plates load insulation plates, protecting them from the sun and preventing them from flying out. If the climate is not too rainy, insulation absorbs little water during the rains and dries completely meanwhile. Only the extruded polystyrene, with a waterproof film on both sides, is suitable for this application. A draining felt is installed under the insulation, preventing it from sticking to the waterproof layer. Another felt must be placed under the gravel, so that it does not go between the plates. It is essential that the water does not stagnate around insula-

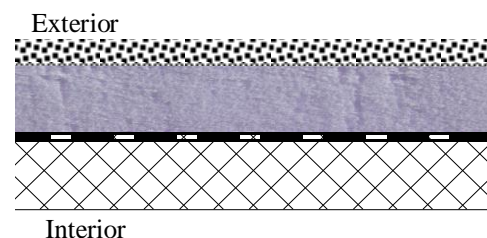


Figure 3.5: Inverted roof.

tion plates, so a slope towards the water disposal grids should exist under the waterproofing membrane.

This technique is also suitable for improving the thermal insulation of an existing roof that has a waterproofing membrane in good state.

3.2.4 Green roof

Seeding of flat roofs, either on some thickness of soil (garden roof), or on gravel with low content of soil (rough green roof) allows first to stabilise the temperature of the roof, and second to damp the floods following rain showers by keeping water longer on the roofs. Plants can also survive on sloping roofs in humid climates (Figure 3.6).



Figure 3.6: Green roofs: House in Iceland and flat roof in Geneva.

Evaporation also cools the roof in summer, thereby reducing heat islands at the centre of major cities. This type of roofing is therefore advisable, but requires special precautions with respect to its thermal insulation and waterproofing. First of all, avoid drilling the waterproofing by plant roots by avoiding perforating species and laying an anti-root foil on the waterproofing. Also the inverted roof is not appropriate in this case, because insulation cannot dry out between showers, as the water is retained by the soil or gravel with humus.

3.2.5 Importance of roof thermal insulation

Roofs are exposed to sun and to the sky that, when clear, can be much colder (down to 25 °C below) than the ambient air. Therefore, the roof upper surface experiences, in every climate, very large temperature variations. The roof surface temperature can be 10 K below the ambient air in a clear night, and may increase up to 70 K above air temperature on a sunny day. Clear coating or green roof reduces the maximum temperature, but a thermal insulation over a heavy deck strongly reduces these daily variations down to a level that cannot be noticed.

3.2.6 Ventilated walls and roofs

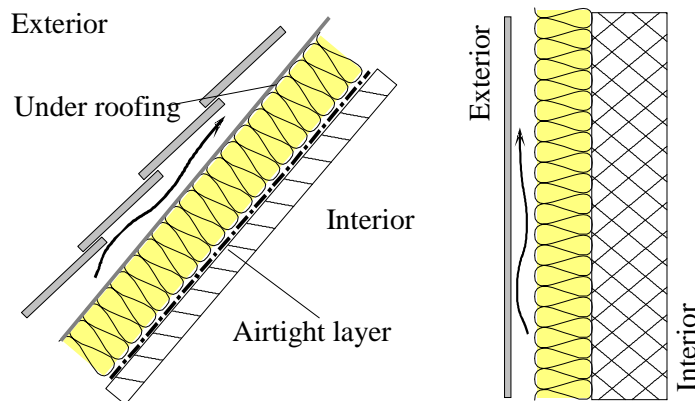


Figure 3.7: Ventilated roof and wall

Insulation in such building components is well protected from weather by tiles and roof decks or cladding, fixed to the structure (Figure 3.7).

Ventilation behind cladding serves to remove moisture from either water vapour that comes through the wall by diffusion, or driving rain or blown snow infiltrated behind the cladding. Any insulating material is appropriate, including the cheapest, for this type of construction. Often used are light mineral fibres in rolls, easy to install between the rafters. Low density expanded polystyrene is also appropriate.

Airtightness should be cared for, especially in wooden structures. If the ceiling is not airtight (as in a plaster ceiling), an airtight foil, e.g. a polyethylene film with glued joints, shall be laid between the interior panelling and the insulating layer.

3.2.7 Floor slabs

Ideally, the insulation should be under the slab to the outside (Figure 3.8). Insulation placed under a floor or a screed must resist compression. Expanded polystyrene and dense mineral wools are commonly used here. A 1–2 cm layer of mineral fibres or soft expanded polystyrene is often used under the screed to dampen the spread of shock noise.

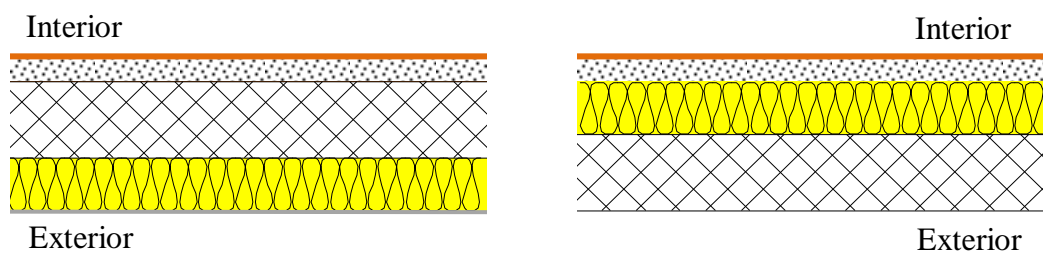


Figure 3.8: Floor slab. Left: insulation under slab, right: under the screed.

3.2.8 Insulation between walls

In these components, the thermal insulation is well protected, and almost any insulating material is appropriate. For practical reasons, panels of average density mineral fibres or expanded polystyrene are preferred. In principle, it is better to insulate outside the bearing structure (Figure 3.9), as this position avoids thermal bridges, reduces the risk of water vapour condensation, and increases the internal thermal inertia of the building (see Section 3.1).

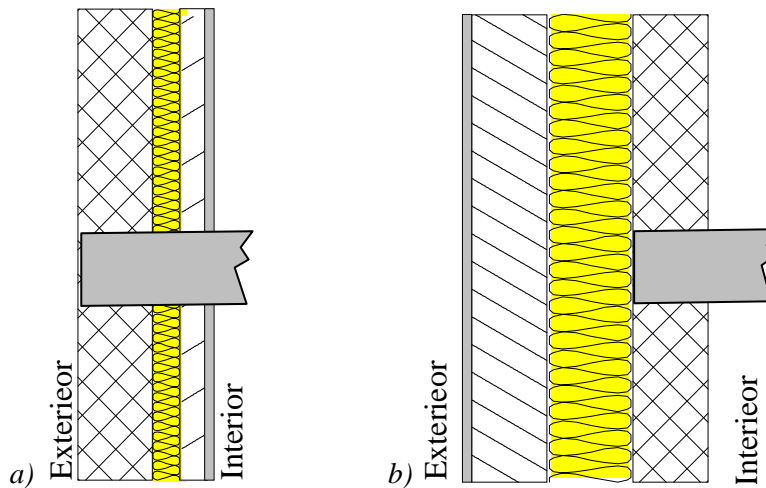


Figure 3.9: Insulation between walls. (a) Old method, interior insulation. (b) Modern construction, insulation outside the structure.

The old method of putting the insulation inside the bearing structure and protecting it with a brick facing (at left on Figure 3.9), is not justified if the insulating layer is thick (more than 5 cm).

Some materials lend well to injection inside air spaces that are inaccessible otherwise. Thus, ancient double walls and roofs with empty spaces can be retrofitted by injecting mineral fibres or cellulose flakes or organic foams (polyurethane, urea-formaldehyde). It is important to ensure the success of these operations, that they are carried out by specialists with experience, because the risk of incomplete filling or long-term settlement is real.

3.2.9 Lightweight curtain wall elements

Lightweight façade elements are prefabricated either by sticking sheets or plates inside and outside of a plate of insulating material (Figure 3.10), or by injecting PUR or PIR foam between two facing plates.

For this application, the insulation material must be rigid and present sufficient mechanical strength to traction and compression. Organic foams such as polyurethane and polystyrene foam are generally used for that purpose.

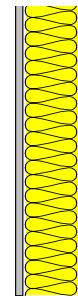


Figure 3.10: Lightweight panel

3.2.10 External Insulation and Finishing Systems (EIFS or ETICS)

This system includes several layers: the insulating material is pasted on the outer face of the façade, using cement (Figure 3.11). Plastic nails are sometimes used to attach the insulation. PUR can also be directly sprayed on the wall, in several passes.

The insulation material is then coated with a synthetic plaster reinforced with a fibreglass mesh to protect it from the weather and with layers of finishing giving it its final appearance. Compact external insulation systems exist for all major insulation materials (mineral fibres, organic and inorganic foams), but systems using expanded polystyrene or sprayed PUR currently dominate. It is essential for the sustainability of the system; that all the layers from the façade until the final coating are placed by specialists with experience in the system. All materials used must be part of the system proposed by the manufacturer. Doing it yourself in this area is virtually inviting failure. Such systems are relatively cheap, but certainly more fragile

and less durable than the insulation between walls or curtain wall. In addition, the separation of the layers for recycling during deconstruction is difficult.

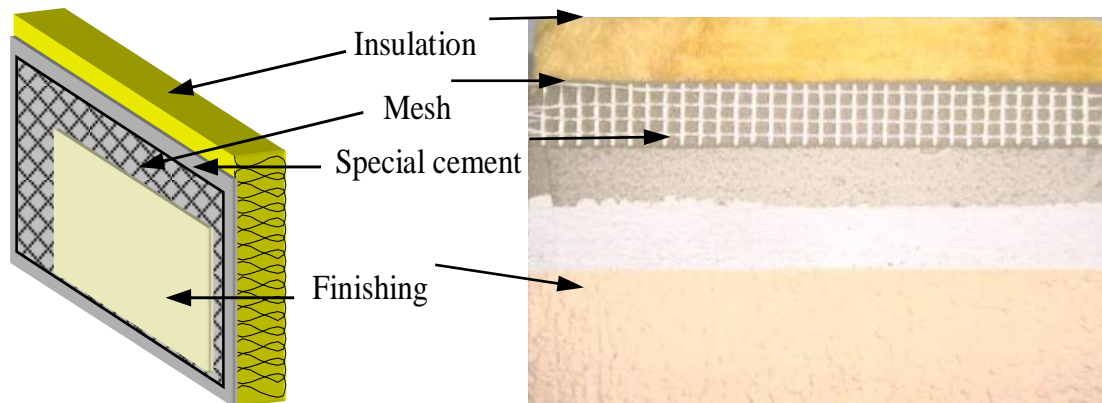


Figure 3.11: Compact external insulation: principle and example of a product

3.2.11 Transparent insulation

Solar gains from a regular opaque wall, during the heating season, are always a fraction of the losses. There is therefore no interest, in cold climates, to decrease the insulation of a South wall to increase solar gains because losses will also increase in a larger proportion. Indeed, solar radiation is converted to heat to the outer surface of the wall, and a large part of this heat is immediately lost to outdoor air.

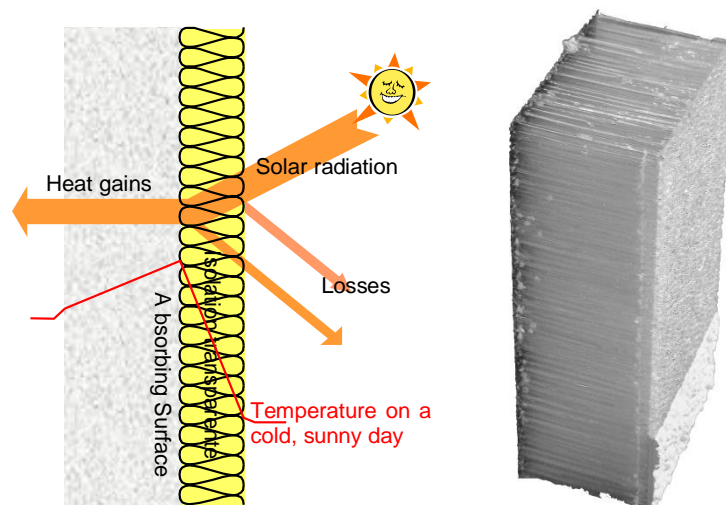


Figure 3.12: Transparent insulation: principle and example of a product to stick on a wall

On the other hand, placing a transparent insulation or a glazing on a dark wall converts it into solar collector (Figure 3.12). A significant portion of solar radiation passes through the transparent insulation layer and is converted into heat on the wall surface, behind the insulation. This insulating layer hinders the passage of heat to the outside, so most of the heat goes into the building through the wall.

A wall with transparent insulation on the sunny side of the building presents a positive heat balance during the heating season in cold climates. The cost of this technique is still relatively high, especially in mild climates where a movable solar protection is necessary to control the heat input and prevent summer overheating. It should, of course, not be used in hot and composite climates!

3.3 Summary of possible applications and materials

It can easily be seen in Table 2.55 that no material has all its characteristics at the top level. The insulating material should therefore be chosen depending on the required qualifications for each type of application. Glass foam and polyurethane are much too expensive to be placed between two walls, where mineral wool, cellulose or expanded polystyrene foam are ideal. On the other hand, it would be foolish to use fibrous materials in an application where they could be exposed to water, because they would be quickly soggy. Some materials are intended for very specific applications: extruded polystyrene is used in inverted roof, because it well stands the weather. Foam glass is suitable for applications where a high compressive strength or perfect water tightness is essential.

Possible applications of various thermal insulation materials are summarised in Table 3.1. We note once more that there is no totally polyvalent material, but that each material has its applications, and the materials choice for each application is limited. There is no poor material, but there are sometimes poor applications!

Table 3.1: Applications of insulating materials

| Applications | Homogeneous walls | Common flat roof | Inverted roof | Ventilated insulation | Between walls | Injected | Floors | Prefabricated panels | EIFS | Fire protection | Acoustic absorption | Isolation to shock noise |
|---------------------|-------------------|------------------|---------------|-----------------------|---------------|----------|--------|----------------------|------|-----------------|---------------------|--------------------------|
| Light mineral fibre | ✘ | ✘ | ✘ | ☺ | ☺ | ☺ | ✘ | ✘ | ✘ | ☹ | ☹ | ✘ |
| Dense mineral fibre | ✘ | ☺ | ✘ | ☺ | ☺ | | ☺ | | ☺ | ☺ | ☺ | ☺ |
| Organic fibres | ✘ | ✘ | ✘ | ☺ | ☺ | | ☹ | ✘ | ✘ | ✘ | ☺ | |
| Wood | ☺ | | ✘ | | | | ☺ | ☺ | ✘ | ☹ | | |
| Wood fibres | ✘ | ✘ | ✘ | ☺ | ☺ | | ☺ | ☺ | ✘ | ✘ | ☺ | ☺ |
| Cellulose fibres | ✘ | ✘ | ✘ | ☺ | ☺ | ☺ | ✘ | ✘ | ✘ | ✘ | ☺ | |
| Cork | ✘ | ☺ | ✘ | ☺ | ☺ | ☺ | ☺ | ☺ | ✘ | ☺ | ☺ | ☺ |
| Glass foam | ✘ | ☺ | ✘ | ☺ | ☺ | ☺ | ☺ | ☺ | ☺ | | ✘ | ✘ |
| Aerated concrete | ☺ | ☹ | ✘ | ☺ | ☺ | | ☺ | ☺ | | ☺ | ✘ | ✘ |
| PUR, PIR | ✘ | ☺ | ✘ | ☺ | ☺ | ☺ | ☺ | ☺ | ☺ | ✘ | | ☹ |
| PS expanded | ✘ | ☹ | ✘ | ☺ | ☺ | ☺ | ☺ | ☺ | ☺ | ✘ | ☹ | ☺ |
| PS extruded | ✘ | ☺ | ☺ | ☺ | ☺ | | ☺ | ☺ | ☺ | ✘ | ☹ | ☺ |
| Urea formaldehyde | ✘ | ✘ | ✘ | | | ☺ | ✘ | ✘ | ✘ | ✘ | | ✘ |

☺ : is convenient for this application.

☺ : can be used, but there are materials best suited to this application.

☹ : is not suitable because it does not have the required performance.

✘ : excluded for this application, the damage hazard is too high.

□ : (blank) does not apply.

3.4 Optimal insulating thickness

A question is often asked when designing an insulated building component: the cost or the energy used for the construction ('grey' energy) increases with the thickness of insulation. On the other hand, the energy used during the operation for heating and cooling and its cost decrease with this thickness. For the whole service life of the building and a given climate, which is the thickness at which the energy required to manufacture, transport, and insulate will offset the energy saving resulting from the insulation? The same reasoning can be done on a cost basis. As shown in Figure 3.13, the total cost (heating, cooling + insulation) plummets for the first few centimetres of insulation, reaches a minimum, and then increases again with the insulation cost.

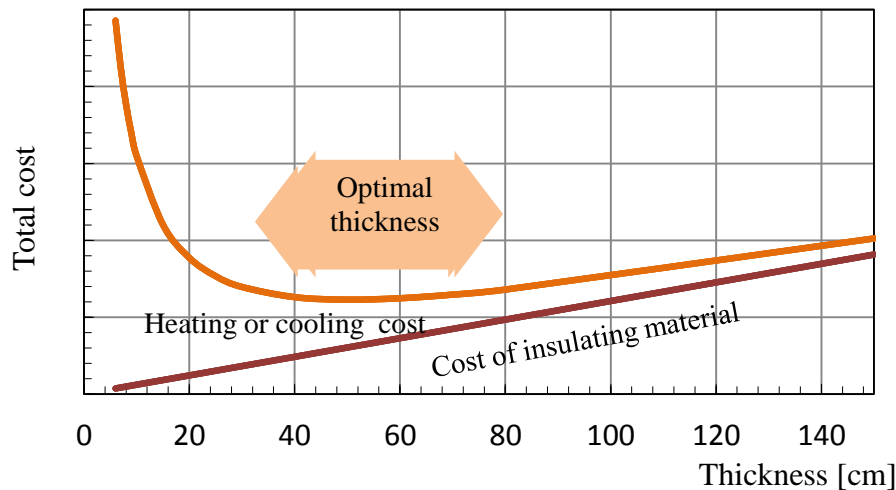


Figure 3.13: The financial or energy cost of insulation increases with its thickness, while the cost of heating or cooling decreases inversely to the thickness. The total shows a minimum for an optimal thickness.

Optimal thickness that gives the minimum total energy use depends not only on the climate and on the building lifetime, but also on the type of insulating material. The financial optimal thickness (minimum total cost) depends in addition on the energy price. Knowing that the energy price will likely strongly increase during the 21st century, there is a certain interest to ask for the largest possible insulation thickness when building or renovating. Note that the optimal thickness varies with the square root of the product of the indoor–outdoor temperature difference and the energy price. If one of these (e.g. the energy price) quadruples, the optimal thickness doubles.

3.5 Expected effects on comfort and energy use

3.5.1 Physical effects

Basically, the thermal insulation reduces the heat flow. Installed in the building envelope, it protects the indoor environment by both static and dynamic effects.

The **static effect** reduces the heat transfer, i.e., the energy needed to maintain an average temperature difference between the internal and external environment. It is characterised by the thermal resistance of the insulation layer and the thermal conductance of building envelope components.

The **dynamic effect** results from the combination of thermal insulation and thermal inertia or thermal mass. When heat is brought to some mass of material, such as an internal wall, it takes time to increase its temperature. The heavier the material is, the smaller is the temperature increase for a given amount of brought heat.

If the indoor air temperature increases for some reasons, some heat will be transferred to the walls and decks, which are colder than the air at this time. Therefore, the increase in air temperature will be slower. On the contrary, when the indoor air temperature decreases, the warmer decks and walls will give back the stored heat. Hence, heavy internal walls stabilise the internal temperature.

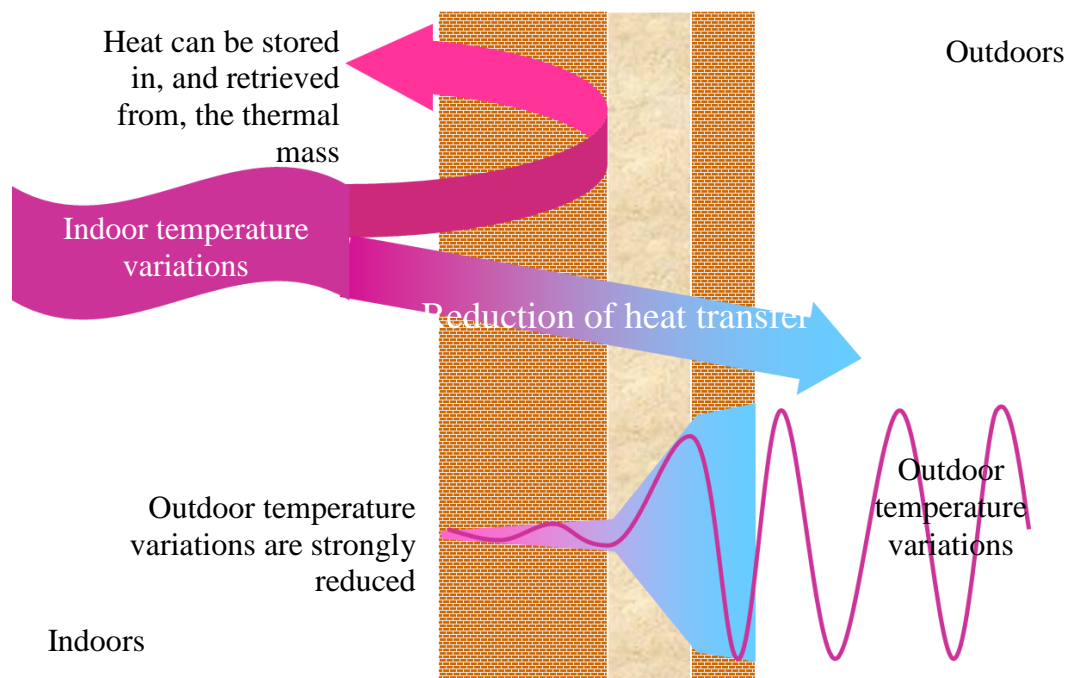


Figure 3.14: Static and dynamic effect of thermal insulation

A temperature increase outdoors first heats the outer part of the building envelope, and this heat slowly penetrates. Later (e.g., at night), when the outdoor temperature decreases, the heat goes back, some of it before being able to reach the internal component layers. The amount of heat reaching the insulating layers is reduced, and only a part of this heat passes through and reaches the internal, heavier part of envelope components. This reduced amount of heat can hardly heat this internal part. Hence, the combination of external insulation and internal heavy material in building envelope components strongly reduces the effect of outdoor temperature variations.

3.5.2 Practical effects

The effect of thermal insulation on thermal comfort and energy use for heating and cooling strongly depends on the climate. Thermal insulation is essential in cold climates, is not essential in temperate climates, where even the outdoor ambience is comfortable, and should be combined with other protective measures in warm climates.

In **cold climates**, thermal insulation is paramount to get an acceptable comfort at low energy cost, as it reduces the heat losses. Added to a masonry or lightweight structure, thermal insulation can strongly reduce (about 50%) the energy need and significantly improve the thermal comfort. Internal thermal mass, associated with large windows oriented to the sunny side, brings free heat that is welcome, but the solar radiation shall be controlled with efficient solar protections to avoid overheating outside the cold season. Experience shows that by applying these measures in cold climates, the energy needs for heating can be reduced by a factor of 4 when compared to past century building techniques.

In **warm climates**, thermal insulation is a necessary complement to other measures. The *Design Guidelines for Energy-efficient Multi-storey Residential Buildings for Composite and Hot-dry Climates* developed under BEEP provides the following recommendations to improve comfort and reduce the cooling energy demand.

Spatial arrangement:

- Orient the buildings to minimise solar exposure on external vertical surfaces
- Select the building shape to minimise solar exposure on wall surfaces
- Arrange building blocks to benefit from mutual shading to minimise solar exposure on walls during summer months.

For the building envelope, three packages are proposed:

- Package of Measures I (15%–20% reduction in cooling thermal energy)
 - Use of light colours on external wall surfaces
 - Design and build fixed window shades with extended overhangs to protect windows from direct solar radiation
 - U-values of walls $< 0.7 \text{ W/m}^2\text{K}$ (R-value of insulation $> 1.3 \text{ m}^2\text{K/W}$)
 - Optimise natural ventilation: ventilate strongly at night to cool down the structure and reduce it during the day to a minimum to reduce heat gains.
- Package of Measures II (40%–45% reduction in cooling thermal energy)
 - Package of Measures I
 - External movable shutters on windows to cut off solar radiation falling on windows.
- Package of Measures III (50%–60% reduction in cooling thermal energy)
 - Package of Measures II
 - Improved wall insulation (U- or R-values according to ECBC)
 - Use of double glazing in windows
 - Better building airtightness.

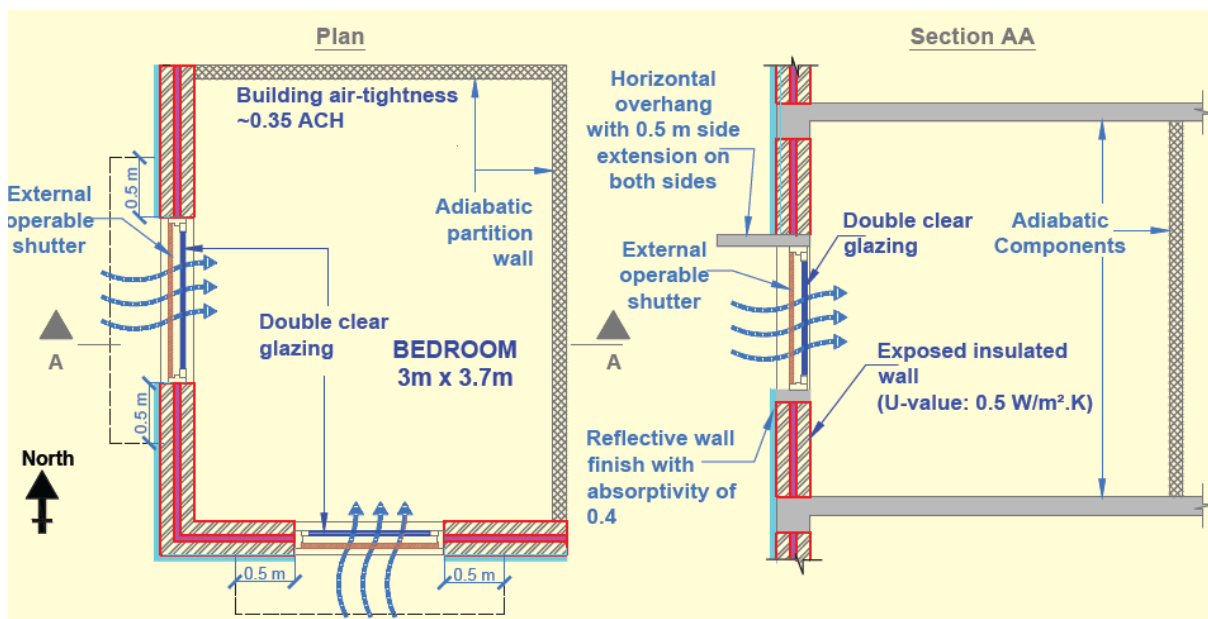


Figure 3.15: Schematic of package III measures on the envelope of a bedroom (from the BEEP design guidelines)

It is also recommended to provide over-deck insulation (ECBC levels or better) and high reflective surface on roof to minimise heat gain through roof. This strongly improves the comfort in the spaces under the roof and reduces their cooling energy use.

These guidelines also provide additional recommendations addressing daylighting, efficiency of the cooling system, and evacuation of heat generated indoors.

4 INSTRUMENTS TO MEASURE THE THERMAL CONDUCTIVITY

4.1 Principle

As we have seen in 2.5.1, the thermal conductivity is the ratio of the density of heat flow rate, q , to the thermal gradient $\Delta T/d$ along one direction. Reversing equation 2, we get:

$$\kappa = \frac{q \cdot d}{\Delta T} \quad 9$$

The thermal conductivity can therefore be measured by getting the density of heat flow rate and the thermal gradient. When a layer of material of thickness d is placed between two plates maintained at two different temperatures, the thermal gradient is simply the ratio of the thickness to the temperature difference.

The density of heat flow rate can be measured by two different ways.

A direct way is to build an instrument in such a way that all the heating power of the hot plate flows through the test sample. This heating power is given by an electrical resistance and is measured by the product of the electric current by the voltage across the resistance. Then, dividing the heating power by the hot plate area will provide the density of heat flow rate. The problem is to avoid any heat loss from the hot plate; this can be solved by surrounding the hot plate with a guarding zone maintained at the same temperature as the hot plate. This is the **guarded hot plate instrument**.

Another way is to pass the heat flowing from the hot plate to the cold plate first through a thin layer of known thermal resistance (the **heat flow meter**), then through the measured sample. Very sensitive temperature sensors located on both sides of the heat flow meter give the temperature difference across it, hence, knowing its resistance, the density of heat flow rate. This is an indirect method as the heat flow meter should be calibrated, generally by measuring a calibration sample whose thermal resistance was measured with a guarded hot plate instrument.

Other methods are used, generally for fast measurement of materials more conductive than thermal insulation materials. These are dynamic methods. For example, the sample is suddenly heated with a hot wire or a small hot disc, and the heating power and temperature are recorded. From the evolution with time of these quantities, the diffusivity (see Section 2.5.4) and heat capacity (Section 2.5.3) can be measured. The knowledge of the density enables calculating the thermal conductivity from these results. Such methods, however, do not provide accurate results for low conductivity materials. Therefore, only the guarded hot plate and the heat flow meter instruments are presented below.

4.2 Guarded hot plate apparatus

4.2.1 Principle

The two-slab guarded hot plate (GHP) apparatus is schematically built as shown in Figure 4.1. A hot plate, guarded by a ring with the same thickness at the same temperature, is placed between two identical samples, the other face of these being cooled at the same temperature. If the gap between the hot plate and its guard ring is very thin, and if they are at exactly the same temperature, the power converted to heat the hot plate will flow in two equal parts through the two samples.

In the single sample instrument, the second (top) specimen is a good, stable insulating material and the top plate, instead of being cooled, is heated at the same temperature than the hot plate. In fact, a guard plate is added to the guard ring.

After reaching the steady state, the thermal resistance is calculated from the power delivered to the hot plate, the area of the hot plate, and the temperature difference across the samples. The thermal conductivity is obtained by dividing the sample thickness by the thermal resistance. As no instrument is perfect, corrections are needed to take account of parasitic heat flows and to improve accuracy.

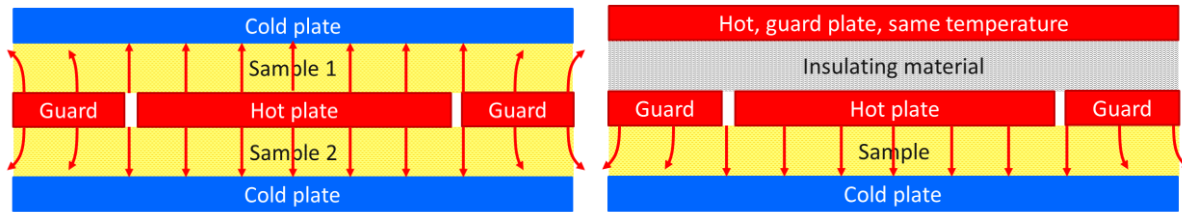


Figure 4.1: Schematic cut through guarded hot plate apparatuses. Left: two-slab instrument, right: one-slab instrument.

4.2.2 Standards

Measurements could be performed according to various standards, mainly:

- ISO 8302:1991 – Thermal insulation - Determination of steady-state thermal resistance and related properties - Guarded hot plate apparatus [13]. This standard was confirmed in 2014.
- ASTM C177 - 13 – Standard Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Guarded-Hot-Plate Apparatus [14].
- IS 3346:1980 – Method for the determination of thermal conductivity of thermal insulation materials (two slab, guarded hot-plate method) [15]. This standard was confirmed in 2004.

There is no contradiction among these three standards. IS 3346 accepts only the 2-samples configuration while the others accept both 1 and 2 samples. Indeed, it is possible to perform measurement according to the three standards if the most stringent requirements are fulfilled. In short, ISO 8902 should be used.

For measurements according to IS 3346, the following additional requirements should be fulfilled:

- 2 samples configuration
- Temperature unbalance across gap < 0.05 K
- Sample thickness measurement in the apparatus, accurate to within 0.5%
- Improved cooling power stability, so that temperature difference across the sample does not vary by more than 1%
- Rigid specimens made flat to $\pm 0.025\%$ with faces parallel within 1% of thickness
- Include in the report the moisture content of the specimen as received, before and after test (in addition to other items mentioned in ISO 8902 section 3.6)

4.3 Heat flow meter apparatus

4.3.1 Principle

The heat flow meter (HFM) apparatus is schematically built as shown in Figure 4.2. The sample covered is placed between a hot and a cold plate, both precisely maintained at two different but constant temperatures. The heat flow meter is fixed against one of these plates, generally the cold one.

This heat flow meter is made out of a layer of material on which sensitive temperature sensors are placed on both sides. In many cases, these sensors are multiple thermocouples connected in series, so that the signal of each thermocouple, proportional to the temperature difference between both sides, are added to provide a measurable voltage even at small temperature difference. The heat flow meter is placed on the centre of the cold plate and surrounded by a guard having the same thermal resistance than the heat flow meter, so that heat flows in a single direction perpendicular to the hot and cold plates.

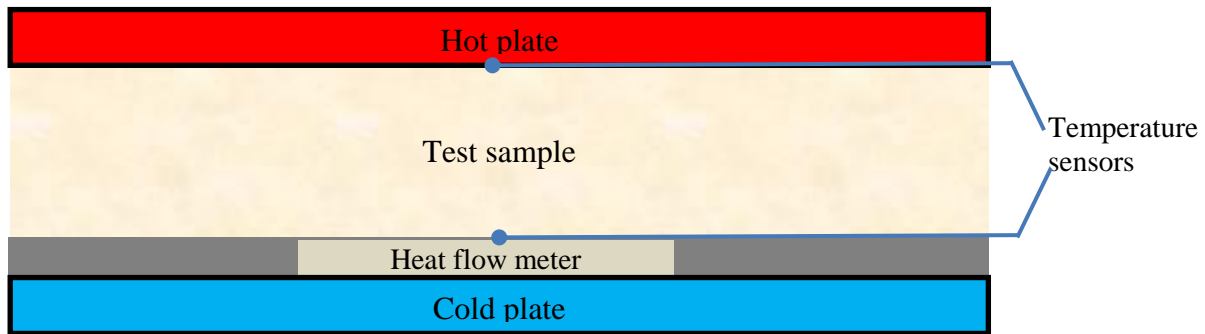


Figure 4.2: Transversal cut of a typical single heat flow meter apparatus.

Figure 4.3 shows possible configurations.

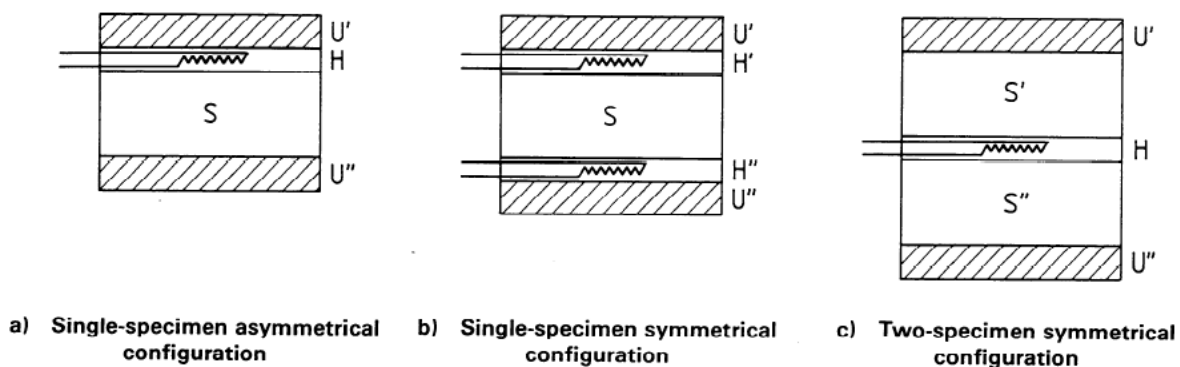


Figure 4.3: Three possible configurations U' and U'' are hot and cold plates, H is the heat flow meter and S the sample(s). (ISO 8301)

The thermal resistance of the sample is calculated from the signal delivered by the heat flow meter and the temperature difference across the sample. The thermal conductivity is obtained by dividing the sample thickness by the thermal resistance. Calibration of the heat flow meter is achieved by measuring a sample of known thermal conductivity.

4.3.2 Standards

Measurements could be performed according to various standards, mainly:

- ISO 8301:1991 – Thermal insulation - Determination of steady-state thermal resistance and related properties - Heat flow meter apparatus [9]. This standard has been reviewed and then confirmed in 2014.
- ASTM C 518-10 – Standard Test Method for Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus [11]. This standard last reviewed in 2010 is considered as equivalent to ISO 8301.

- IS 9489:1980 – Method of test for thermal conductivity of thermal insulation materials by means of heat flow meter [12]. This standard was confirmed and amended in 1999. This standard is based on ASTM C 518-76.

There is no contradiction between these three standards. ASTM C 177-10 is considered as equivalent to ISO 8301 despite slight differences in some requirements, so ISO 8301 can be used instead. IS 9489 is much older than and not as comprehensive as ISO 8301. Therefore, ISO 8301 should be applied, taking care that, in the report, moisture content of the specimen as received, before and after the test are mentioned in addition to other items mentioned in ISO 8301 section 3.6, so that the report will also comply to IS 9489. If compliance to ASTM C177-10 is also required, the report should also contain all items mentioned in its chapter 9.

4.3.3 Calibration

One of the following procedures shall be followed.

1. The test-laboratory instrument shall be calibrated within 24 h before or after the test using calibration standards that have been issued by a recognised standard laboratory. The reported test and the apparatus calibration test shall be carried out using approximately the same hot- and cold-side temperatures as were used in the official calibration of the standards.
2. Where both short- and long-term stabilities of the heat flow meter have been proved to be better than $\pm 1\%$ of the reading, the heat flow meter apparatus may be calibrated at less frequent intervals, for example 15 to 30 days. The specimens tested between the calibrations cannot be reported until after the calibration following the test and then only if the change in calibration from the previous test is less than 1%.

The average of the two calibrations shall be used as the calibration factor. When the change in calibration is greater than $\pm 1\%$, test results from this interval shall be considered void and the calibration performed within 24 h before and after the test.

Calibration procedure¹⁰: The calibration standard is introduced in the apparatus. As the heat flow rate varies with the thermal conductivity and with the inverse of the thickness, and because the thermal conductivity depends on the temperature, the measured distance of the plates, d , shall be as close as possible to the calibration standard thickness, d_c , given by the standard laboratory, and the measured hot and cold test temperatures T_h and T_c shall also be close to those given by the standard laboratory. The output e of the heat flow meter is measured when the steady state is reached (see Section 5.5.2.2). The calibration factor for the heat flow meter temperature T_H is then:

$$f(T_H) = \frac{\kappa_c \Delta T}{e d_c} \left[1 - \frac{\delta d}{d_c} + \frac{1}{\kappa_c} \frac{d\kappa_c}{dT} \delta T \right] \quad 10$$

Where $\delta d = d - d_c$ and δT is the difference between the mean temperature during the calibration and the mean temperature given by the standard laboratory when defining κ_c . The variation of thermal conductivity with temperature is deduced from the curve $\kappa_c(T)$ given by the standard laboratory. The term between brackets shall not differ from 1 by more than 2%.

Keep a running record of calibration tests. This record will also show the reproducibility of the heat flow meter apparatus as a function of time.

¹⁰ This procedure differs from that of ISO 8901, which needs two identical calibration standards. If the laboratory has such two calibration standards, the procedure defined in ISO 8301 section 2.4 shall be used.

The heat flow meter shall not be used at temperatures other than those used for the calibration. Extrapolation of a calibration curve is not allowed.

5 MEASURING CHARACTERISTICS OF INSULATION MATERIALS AND PRODUCTS

5.1 Preliminary note

The procedures described below are proposals that can be discussed during the training. The objective is that all laboratories of the network agree on common procedures.

5.2 Sampling

Materials to be measured should be representative of the manufacturer's production. Therefore the materials should be taken at random from the manufacturer's stock or bought from the market by a person delegated by the measuring laboratory, and not directly provided by the vendor or the manufacturer. If several measurements are planned for the same product, it is advisable to take samples manufactured at various dates.

Enough material should be taken to provide samples for all tests.

5.3 Preparing and conditioning the samples

Before testing, the samples should be conditioned to the reference conditions. These are at $(23 \pm 1) ^\circ\text{C}$ and $(50 \pm 10) \%$ relative humidity or at 23°C and dry, according to ISO standards. ASTM requires $22 ^\circ\text{C}$, which is compatible with $(23 \pm 1) ^\circ\text{C}$.

In tropical countries, different conditioning and testing conditions can be relevant. In this case, the conditions shall be $27 \pm 2 ^\circ\text{C}$ and $65 \pm 5\% \text{ RH}$. However, the high temperature and humidity conditioning put the sample in equilibrium with an atmosphere where the dew point is about $20 ^\circ\text{C}$. If any part of the sample is put later at a lower temperature (e.g. against a cold plate at 13°C), the water vapour contained in this part of the sample will condense. The dew point at 23°C and $50\% \text{ RH}$ is $11 ^\circ\text{C}$ only. Therefore, if tests are performed around 23°C , the samples should be conditioned at this temperature.

The conditioning temperature and humidity shall be stated clearly in the test reports.

Conditioning is performed by placing the samples in a climatic cabinet or chamber. The air in this space shall be conditioned at the required temperature and humidity. This space could as well be the laboratory itself, if it is conditioned at the reference conditions.

The duration of conditioning should be long enough to get constant weight. It is at least 6 h for the measurement of dimensions.

5.4 Measurement of dimensions and density

If it is necessary to check the dimension of manufactured rolls and plates, dimensions may be more than 1 m width and several metres long (rolls). The dimensions of samples are also used to determine their density.

5.4.1 Side dimensions of products or samples

Dimensions of plates are up to 1.2 m long and up to 0.6 m wide, with thicknesses up to 20 cm. Mats and blankets are delivered in compressed rolls up to 1.2 m large. For test samples, the largest dimension is 60 cm.

Method:

For dimensions of products: ISO 29465:2008: Thermal insulating products for building applications -Determination of length and width [5].

For dimensions of test samples: ISO 29768:2008: Thermal insulating products for building applications -Determination of linear dimensions of test specimens [6].

Tools:

Flat table and metal rule or metal tape, graduated in millimetres and permitting reading to an accuracy of 0.5 mm.

Procedure:

Lay the test specimen carefully on a flat surface.

All lengths and widths shall be read to the nearest millimetre.

For test specimens with both dimensions less than or equal to 1.5 m, take one measurement of length, l , and one measurement of width, b , at the positions shown in Figure 5.1 left.

For test specimens greater than 1.5 m long, make one additional width measurement for each extra metre of length, up to a maximum of five measurements, with the measurements equally spaced as shown in Figure 5.1 right. In this case, the length, l , is the mean value of all measured values of the length.

For test specimens greater than 1.5 m wide, make one additional length measurement for each extra 1 m of width, with the measurements equally spaced. In this case, the width, b , is the mean value of all measured values of the width.

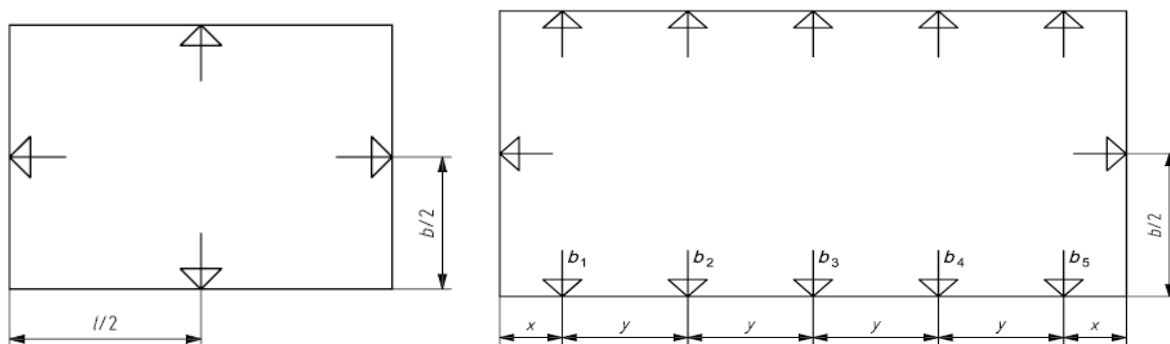


Figure 5.1: Positions for measuring length and width of a product (ISO ISO 29465:2008)

The **test report** shall include the following information:

- a) Reference to ISO 29465:2008;
- b) Product identification:
 - 1) product name, factory, manufacturer or supplier,
 - 2) production code number,
 - 3) type of product,
 - 4) packaging,
 - 5) form in which the product arrived at the laboratory,
 - 6) other information as appropriate, e.g. nominal dimensions, nominal thickness, nominal density.
- c) Test procedure:
 - 1) pre-test history and sampling (name of person taking the samples and sampling site),
 - 2) conditioning and testing conditions
 - 3) deviations from the procedure, if any,
 - 5) date of test,
 - 6) general information relating to the test,

- 7) any occurrences that can have affected the results.
- d) Results: all individual values and the mean value for each dimension expressed in millimetres to the nearest millimetre. For products 3 m long or greater, the mean length value is reported to the nearest 5 mm.

Information about the apparatus and identity of the technician should be available in the laboratory, but it need not be recorded in the report.

5.4.2 Thickness

Method:

For thickness of products: ISO 29466:2008: Thermal insulating products for building applications - Determination of thickness [7].

For dimensions of test samples: ISO 29768:2008: Thermal insulating products for building applications -Determination of linear dimensions of test specimens [6].

Tools:

- A hard, flat reference surface.
- A square, rigid plate 200 mm aside weighing 1020 ± 20 g to exert a total pressure on the test specimen of either 250 ± 5 Pa, including the force exerted by the dial gauge¹¹.
- A dial gauge, capable of measuring to an accuracy of at least 0.5 mm and mounted on a rigid frame fastened to a flat rigid base plate that is at least as large as the test specimen. For measurement of test samples, the accuracy shall be at least 0.05 mm.

Procedure

The test specimen could be the full size product or a sample prepared for other tests such as density or thermal conductivity.

The samples should be conditioned according to Section 5.3. Roll insulation shall be completely unrolled and cut into pieces of 1 m to 1.5 m long. The first and last 0.5 m length of roll shall be discarded. In addition, products that have been compressed in the package shall be prepared as follows:

- a) Hold the piece vertically in both hands by a long edge so that the other long edge is approximately 450 mm above the floor.
- b) Drop the piece once so that it strikes the floor.
- c) Repeat operations (a) and (b) on the opposite edge for all specimens in the package and for all pieces cut from a roll.
- d) Wait at least 5 min for the pieces to reach a state of equilibrium before taking any measurements.

Lay the test specimen carefully on the base plate, ensuring that the measuring area is in contact with the base plate. The facing or coating of the sample, if any, is placed against the base plate. Place the pressure plate on the specimen, exerting a total pressure of 250 ± 5 Pa at a designated position with the dial gauge centrally located.

Take two measurements for test specimens of lengths less than or equal to 600 mm, four measurements for test specimens greater than 600 mm and less than or equal to 1500 mm in length, and one additional measurement for each additional 500 mm exceeding 1500 mm in length (Figure 5.2).

¹¹ According to ISO 29466:2008, a pressure of 50 Pa only can be used as an alternative. The plate should then weigh 255 g only, assuming that the force from the dial gauge is negligible.

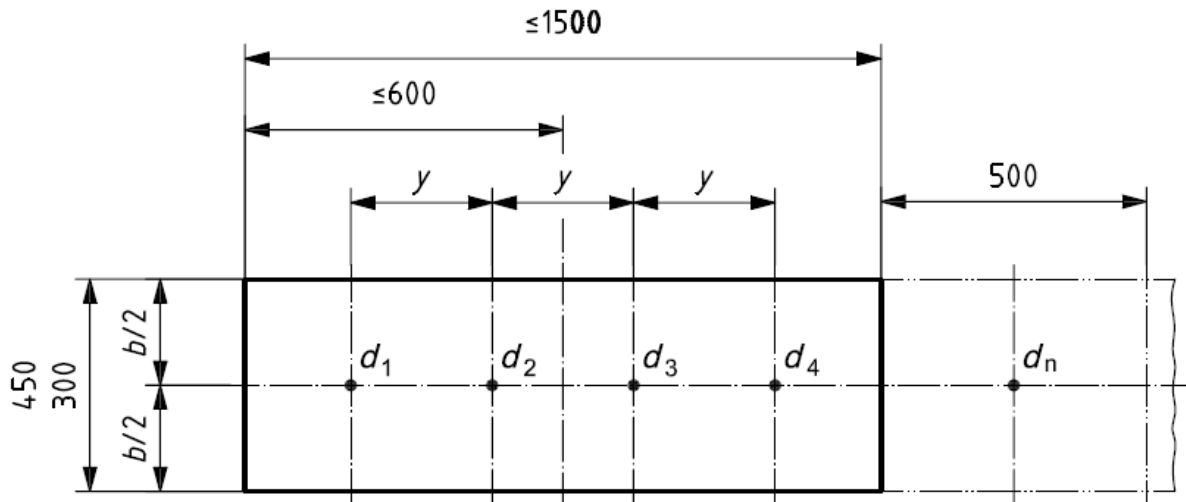


Figure 5.2: Positions for measuring the thickness of a sample (ISO ISO 29466:2008)

For samples larger than 450 mm, distribute the measurement positions across the width as shown in Figure 5.3

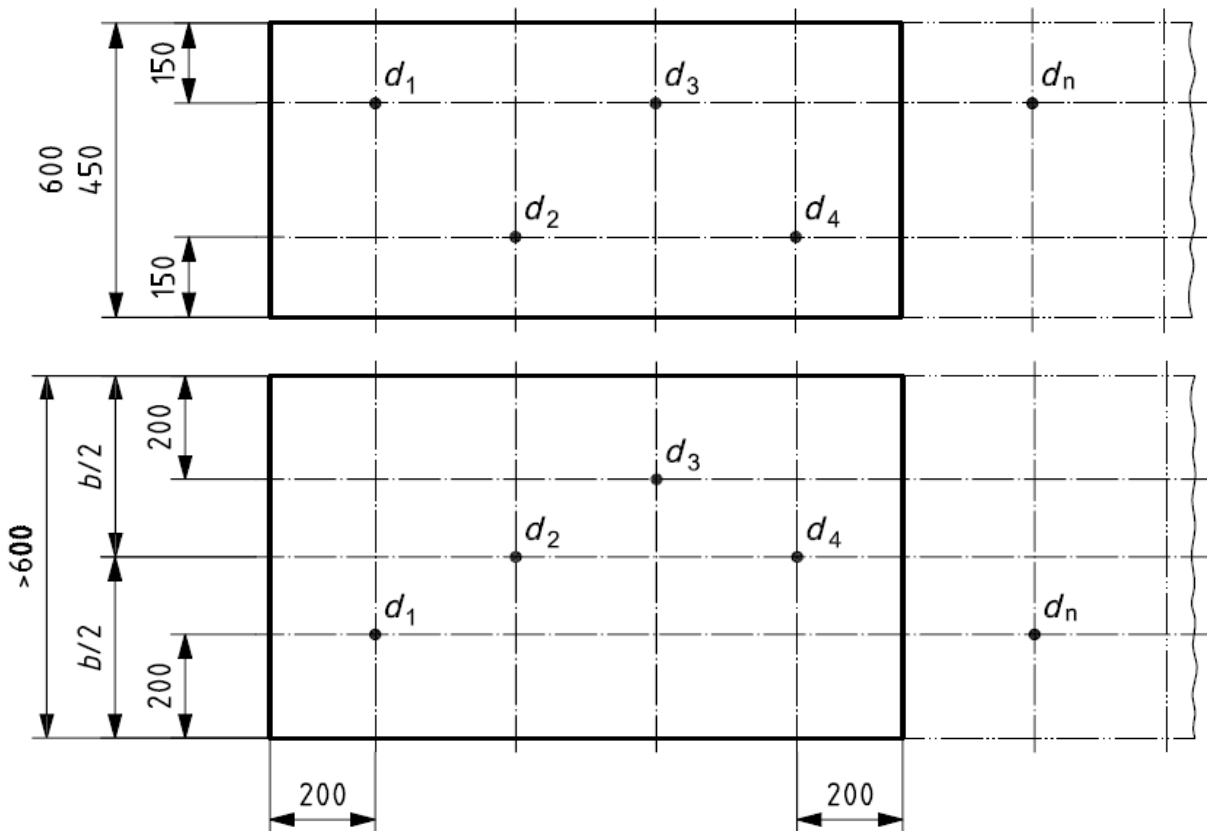


Figure 5.3: Positions for measuring the thickness of a large sample (ISO ISO 29466:2008)

Check the zero of the dial gauge or record its indication at every measurement locations. The measured thickness is the difference between readings with and without the test specimen.

The **test report** shall include the following information:

- Reference to ISO 29466:2008;
- Product identification:

- 1) product name, factory, manufacturer or supplier,
 - 2) production code number,
 - 3) type of product,
 - 4) packaging,
 - 5) form in which the product arrived at the laboratory,
 - 6) other information as appropriate, e.g. nominal dimensions, nominal thickness, nominal density.
- c) Test procedure:
- 1) pre-test history and sampling (name of person taking the samples and sampling site),
 - 2) conditioning and testing conditions
 - 3) deviations from the procedure, if any,
 - 5) date of test,
 - 6) general information relating to the test, including the applied pressure (250 Pa),
 - 7) any occurrences that could have affected the results.
- d) Results: all individual values and the mean value of thickness expressed in millimetres to the nearest millimetre. If the thickness measurement is used for interpreting the measurement of thermal conductivity, its accuracy should be equal or better than 0.5%.

Information about the apparatus and identity of the technician should be available in the laboratory, but it need not be recorded in the report.

5.4.3 Density

Method: ISO 29470:2008: Thermal insulating products for building applications - Determination of the apparent density [8]. The apparent density is determined from the dry weight and the sample dimensions measured according to sections 5.4.1 and 5.4.2.

Tools: Balance accurate to $\pm 0.5\%$ to measure the dry weight. Density is calculated from dry weight and metered dimensions.

Procedure:

The samples used for this are the square samples for thermal conductivity or plates as delivered. Maximum expected weight is 5 kg.

For determining the apparent overall density, any facings and/or coatings shall be removed from the product. If it is not possible to remove the facings and/or coatings without influencing the apparent density of the product, the mass of the facings and/or coatings shall be deducted by calculation.

Measure the sample dimensions according to sections 5.4.1 and 5.4.2. Calculate the volumes of the specimens from these measurements.

Weigh each specimen to an accuracy of 0.5% and record its mass expressed in kilograms. If the facings and/or coatings are retained, the mass of the product shall be calculated by deducting the mass of the facings and/or coatings and adhesives, if any, from the overall mass.

The apparent density of each specimen is the ratio of its mass to its volume. It is expressed in kg/m^3 and given to three significant figures.

The **test report** shall include the following information:

- a) Reference to ISO 29470:2008;
- b) Product identification:
 - 1) product name, factory, manufacturer or supplier,

- 2) production code number,
- 3) type of product,
- 4) packaging,
- 5) form in which the product arrived at the laboratory,
- 6) other information as appropriate, e.g. nominal dimensions, nominal thickness, nominal density.

c) Test procedure:

- 1) pre-test history and sampling (name of person taking the samples and sampling site),
- 2) conditioning and testing conditions,
- 3) presence of surface skins and the method of removal, if necessary,
- 4) presence of densification, stratification or defects on the specimens,
- 5) deviations from the procedure, if any,
- 6) date of test,
- 7) general information relating to the test, including the applied pressure (250 Pa),
- 8) any occurrences that could have affected the results.

d) Results: all individual values and the mean value of apparent density expressed in kg/m^3 and given to three significant figures.

Information about the apparatus and identity of the technician should be available in the laboratory, but it need not be recorded in the report.

5.5 Determination of thermal conductivity

The procedure below is valid for thermal insulating materials, at a thickness giving a thermal resistance larger than $0.1 \text{ m}^2\text{K/W}$. It is according to ISO 8301[9] and 8302 [10]. It assumes that the used instrument is built and tested according to the corresponding ISO standard by its manufacturer, and that the limitations of the apparatus (i.e. test temperatures, sample thickness) are known and not overpassed.

5.5.1 Preparation of the samples

5.5.1.1 Rigid materials

Samples of the material, large enough to fully cover the hot and cold plates of the thermal conductivity measurement instrument should be cut from the material made available.

The surfaces of the test specimens shall be made plane by appropriate means so that close contact between the specimens and the working surfaces can be obtained. For rigid materials, the faces of the specimens shall be made flat to within 0.025% and shall be parallel over the total surface area within 2% of the sample thickness.

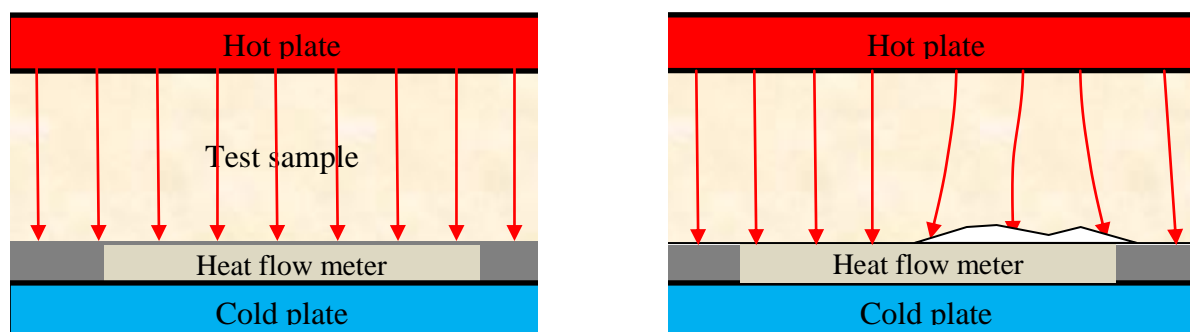


Figure 5.4: Effect of non-flat samples: the air gap distorts the heat flow lines, introducing a bias in the measurement.

When two specimens are required, they shall be as nearly identical as possible with thicknesses differing by less than 2%.

5.5.1.2 Loose fill materials

When testing loose-fill materials, the thickness of the specimen should be at least 10 times – and whenever possible 20 times – the mean dimension of the beads, grains, flakes, etc. of the loose-fill material. Most critical conditions are those when beads, grain, etc. are rigid (Figure 5.5).

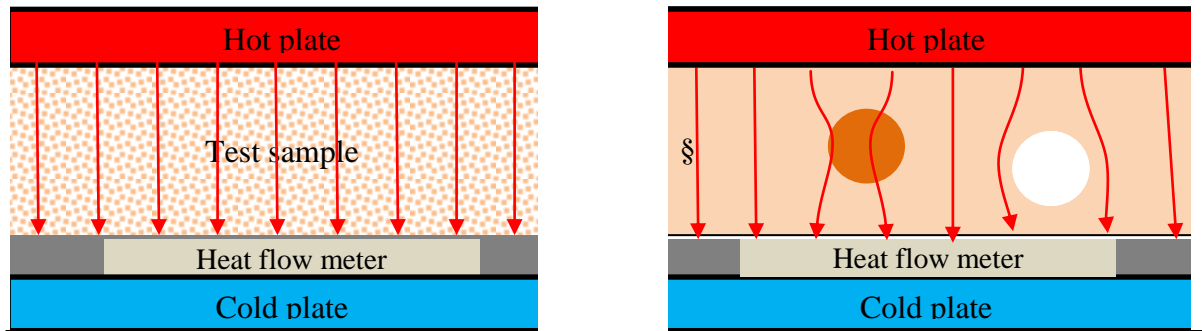


Figure 5.5: Effect of large non homogeneities. Left: homogeneous sample; right: sample with two large non-homogeneities, with larger and smaller thermal conductivities than the bulk.

The following method is suggested when operating the apparatus horizontally¹². Use a shallow container¹³ of thin-walled low-conductivity material having outside dimensions the same as those of the hot plate, and the height equal to the thickness at which the material will be tested. Place spacers of small cross-sectional area, made of low thermal conductivity materials, with a thickness equal to the test thickness in the corners of the container to ensure that the spacing between the covers for the frame is equal to the test thickness. Make covers for the open faces of the container, using a thin, non-reflective sheet of material not more than 50 micron thick. The thermal resistance of these sheets shall be negligible when compared to that of the test sample. These sheets shall be glued or fastened to the edges of the container. The total hemispherical emittance of the surfaces seen from the specimen shall be 0.8 or greater at operating temperatures. With one cover in place, and with the container lying horizontally on a flat surface, place the test sample in the container, taking care to produce a specimen of uniform density throughout. Then apply the remaining cover, to make closed specimen that can be put into position in the heat flow meter. Fluff compressible materials during placement, so that the covers bulge slightly and will make good contact with the working surfaces of the apparatus at the desired density. For some materials, material loss during preparation of the specimens may necessitate reweighing before test; in this case, determine the mass of the container and covers after the test.

5.5.1.3 Conditioning before testing

Test samples are conditioned to constant mass in a climatic cabinet or room, at the standard temperature and relative humidity (5.3). The relative loss of mass is calculated from the mass determined before and after conditioning. After conditioning to a constant mass, the samples that are not immediately tested can be stored in a sealed box or in a sealed, partially evacuated, polyethylene bag. To prevent moisture migration to or from the specimen during the test,

¹² An alternative method to be used when the apparatus is vertical is given in ISO 8301.

¹³ Two containers may be needed for an apparatus needing two identical samples, such as the guarded hot plate apparatus.

the specimen itself may be enclosed in a vapour-tight envelope. This is particular needed when the cold plate temperature is below the dew point of the laboratory atmosphere (Appendix C). The thermal resistance of this envelope shall be negligible when compared to the thermal resistance of the test sample.

To reduce test time, the samples may be conditioned to an appropriate mean temperature prior to being placed in the apparatus. Tests samples are weighed with accuracy better than 0.5% and installed in the instrument immediately before testing.

The density of each test sample is determined from its side dimension measured according to Section 5.4.1, its thickness in the thermal conductivity measuring instrument and the mass measured before the test.

5.5.2 Measurement of thermal conductivity

5.5.2.1 Starting the test

The conditioned test sample is introduced in the instrument after weighing it. The instruments, hot and cold plates, are set to test temperatures. The mean temperature is generally set to 10 °C in temperate and cold countries, while it may be set to a higher temperature (e.g. 23 °C) in warm and hot climates.

Another issue is the temperature difference. If large, the result of the measurement will be more accurate, but it can no more be associated to a given temperature, as parts of the sample are at significantly different temperatures. If small, the change of thermal conductivity with temperature can be assessed, but the result is less accurate. ASTM standards require a temperature difference of at least 10 K, and ISO standards state that the temperature difference should be small, but large enough to get sufficient accuracy. Several laboratories in India work usually with 20 K temperature difference, as recommended by the provider of their instrument.

If the cold plate temperature is close to or below the dew point of the surrounding air (see table in Appendix C), measures shall be taken to avoid water vapour condensation in the test sample. There are two possibilities:

1. Place the instrument in a room with air conditioned at a dew point that is 5 K above the temperature of the cold plate.
2. Pack the sample prior to testing in an airtight envelope, such as a sealed plastic bag.

5.5.2.2 Waiting for the thermal equilibrium

The thermal equilibrium is reached when the output(s) of the heat flow meter(s) or the heating power of the guarded plate do not vary anymore. The duration of time required for this depends on the construction of the instrument itself – in particular its control system – and on the time constant of the hot plate (in guarded hot plate instrument) and tested sample:

$$\tau = (\rho_p c_p d_p + \rho_s c_s d) R \quad 11$$

Where:

- ρ_p is the density of the hot plate in kg/m³
- c_p the thermal capacity of the hot plate in J/(kg·K)
- d_p the thickness of the hot plate in m.
- ρ_s the density of the test sample in kg/m³
- c_s the thermal capacity of the sample in J/(kg·K)
- d the thickness of the test sample in m

- R the thermal resistance of the test sample(s) in $\text{m}^2\text{K}/\text{W}$, $R = d/\kappa$
 κ its thermal conductivity in $\text{W}/(\text{m}\cdot\text{K})$

In heat flow meter instruments, $\rho_p c_p d_p = 0$

For example, a typical expanded polystyrene 5 cm thick with $20 \text{ kg}/\text{m}^3$ density will have a time constant of about 30 minutes, while it will be about 7 hours for a heavy mineral wool ($100 \text{ kg}/\text{m}^3$) 10 cm thick. Depending on its construction, the hot plate may add a few hours.

Make observations at intervals equal to the time constant of the specimen or 5 minutes, whichever is greater, until five successive observations yield a thermal resistance value agreeing to within 1% without changing monotonically in one direction. If an accurate estimate of settling time is not possible or when there is no test experience on similar specimens in the same apparatus at the same test conditions, continue the observations for 24 hours.

Monitoring of the evolution of the heat flow meter output or the hot plate heating power as a function of time can be helpful to check the stability of the equilibrium, particularly with an unknown type of material or when there is some doubt about risks of sensitivity to environmental humidity of the material tested. If this output varies by more 1.5% in respect of its mean value, make investigations to discover the reasons.

5.5.2.3 Interpretation of results

Once the steady state is reached:

- in heat flow meter instruments, read the output of the heat flow meter, e , and the temperatures T_h and T_c on both faces of the sample and compute the thermal resistance using the calibration factor f valid for the temperature of the heat flow meter:

$$R = \frac{T_h - T_c}{f e} \quad 12$$

If there are two heat flow meters replace $f e$ by $0.5(f_h e_h + f_c e_c)$ where the indices h and c are for the flow meters on the hot and cold sides, respectively.

- In guarded hot plate instruments, read the average power P supplied to the metering section of the heating unit and the average temperatures T_h on the hot faces and T_c on the cold faces of the samples and compute the thermal resistance using:

$$R = \frac{T_h - T_c}{N P} A \quad 13$$

where A is the metering area given by the manufacturer of the instrument and N the number (1 or 2) of test samples in the apparatus.

If the specimen is thermally homogeneous or homogeneous porous, i.e. such that any non-homogeneity have dimensions smaller than one-tenth of the specimen thickness, a mean apparent thermal conductivity is calculated by

$$\kappa = \frac{d}{R} = \frac{f e d}{T_h - T_c} \quad 14$$

Weigh again the test sample immediately after the test and report any mass change with respect to the weight before test.

5.5.3 Reporting

The report shall include at least:

- Name and address of the laboratory

- Type of instrument used (Heat flow meter with one or two heat flow meters, guarded hot plate, one or two test samples, vertical or horizontal heat flow rate)
- Date of the test, the date of the last heat instrument calibration, and the type, or types, of calibration materials used
- Name and any other pertinent identification of the material, including a physical description supplied by the manufacturer
- Dimensions of test samples, method of specimen preparation for loose-fill materials
- Thermal resistance of sheet material interposed between the test sample and apparatus plates or of cover materials used for the containers for loose-fill materials
- Thickness as tested with uncertainty range, specifying if this thickness is imposed or measured
- Method, temperature, and air humidity for the conditioning
- Relative mass changes during conditioning with uncertainty range
- Density of the conditioned samples with uncertainty range
- Relative mass change during test with uncertainty range. Observed thickness and volume changes during test
- Hot and cold temperatures, temperature difference, and mean test temperature, with uncertainty ranges
- Density of heat flow rate through specimen at the equilibrium, with uncertainty range
- Thermal resistance of test samples, with uncertainty range. Where applicable, the thermal conductivity (with uncertainty range) and range of thickness for which these values have been measured or are known to apply
- For direct-reading apparatus, the results of the calibration of electronic circuitry and equipment, or a statement of compliance including date, and a statement of compliance on linearity requirements shall be included
- Statement of compliance with the appropriate ISO and possibly other standards with exceptions if applicable. A suggested wording is: ‘This test has conformed to all requirements of the Standard Test Method ISO 8301 (or 8302) with the exception of .. (a complete list of the exceptions follows).’

5.6 Other characteristics and measurement methods

These are only briefly mentioned below, as these are not measured within the BEEP programme.

5.6.1 Fire resistance

If needed by Indian building code. Method and tools according to Indian standards.

5.6.2 10% compression strength

For materials that are submitted to compression.

Method: ISO 29764:2008: Thermal insulating products for building applications - Determination of deformation under specified compressive load and temperature conditions.

Tool: Mechanic or hydraulic press able to provide a pressure up to 1.5 MPa on a square plate 30 cm aside (i.e. 135 kN) with controlled displacement.

5.6.3 Traction rupture strength

Method: ISO 29766:2008: Thermal insulating products for building applications - Determination of tensile strength parallel to faces.

Tools: Tensile testing machine

30 cm square steel plates, bees or paraffin wax.

Mechanic or hydraulic machine able to provide traction strength up to 200 kPa on a square plate 30 cm aside (i.e. 20 kN).

5.6.4 Water absorption by immersion

Method: ISO 29767:2008: Thermal insulating products for building applications - Determination of short-term water absorption by partial immersion.

Tools: Vats or buckets able to contain the samples that are 10 to 20 cm aside.

Balance (the same as that for density).

5.6.5 Dimensional stability

Method: ISO 29472:2008: Thermal insulating products for building applications - Determination of dimensional stability under specified temperature and humidity conditions.

Tools: Climatic cabinet at 50 °C or more.

Meter (the same as that for dimensions).

5.6.6 Test for EIFS (External Insulation and Finishing Systems) materials

Methods

ISO 29804:2009: Thermal insulation products for building applications - Determination of the tensile bond strength of the adhesive and of the base coat to the thermal insulation material.

ISO 29805:2009: Thermal insulation products for building applications - Determination of the mechanical properties of glass fibre meshes.

Tools (see standards).

6 UNCERTAINTY ANALYSIS

6.1 Definitions

As measurements cannot be performed with perfect accuracy, the true value of the measured parameter is not equal to the result of the measurement. It is, however, likely within an interval of some width around the measured value. Therefore, any directly or indirectly measured quantity should always be given with its uncertainty.

The following definitions are proposed by the Joint Committee for Guides in Metrology (JCGM), in its international vocabulary [16]:

Trueness is the closeness of agreement between the average of an infinite number of replicate measured quantity values and a reference quantity value.

Precision is the closeness of agreement between indications or measured quantity values obtained by replicate measurements on the same or similar objects under specified conditions.

Accuracy is the closeness of agreement between a measured quantity value and a true quantity value of the quantity intended to be measured¹⁴.

Although the words accuracy, precision, and trueness can be synonymous in common use, they are deliberately contrasted in metrology.

A measurement system can be true but not precise, precise but false, neither, or both (Figure 6.1). For example, if an experiment contains a systematic error, then increasing the sample size generally increases precision but does not improve trueness. Eliminating the systematic error improves trueness but does not change precision.

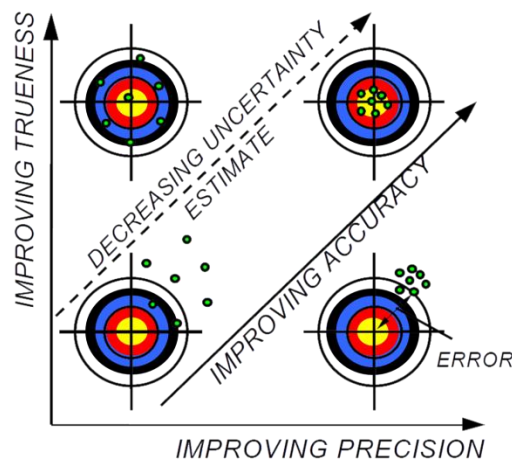


Figure 6.1: Trueness, precision and accuracy of a series of archery shoots. From [17]

A measurement system is considered valid if it is accurate, hence both true and precise. The **error of measurement** or shortly **error** is the difference between the measured quantity value and a reference quantity value [16]. The **uncertainty** or **margin of error** of a measurement is stated by giving a range of values likely to enclose the true value.

According to [18], the 'uncertainty of measurement comprises, in general, many components. Some of these components may be evaluated from the statistical distribution of the results of series of measurements and can be characterized by experimental standard deviations. The other components, which also can be characterized by standard deviations, are evaluated

¹⁴ Note that accuracy is often confused with trueness.

from assumed probability distributions based on experience or other information. It is understood that the result of the measurement is the best estimate of the value of the quantity to be measured, and that all components of uncertainty, including those arising from systematic effects, such as components associated with corrections and reference standards, contribute to the dispersion.'

6.2 Uncertainty propagation law

When measured data are introduced in formulas to compute a deduced quantity, the uncertainties of input data propagate through the formula and result in an uncertainty linked to the deduced quantity. The purpose of the error analysis is to determine the uncertainty of the latter.

6.2.1 General propagation law

There are several ways to estimate the uncertainty δQ of a quantity $Q(x_1, x_2, x_j..)$ that is derived from several other quantities x_1, x_2, x_j, \dots , themselves having uncertainties $\delta x_1, \delta x_2, \delta x_j$. None of them is exact, but they all provide an interval in which the actual value has a high probability to be.

One of them, rather simple, adds the absolute values of the possible uncertainties resulting from each variable, and uses for this the exact differential of $Q(x_1, x_2, x_j..)$:

$$\delta Q = \sum_j \left| \frac{\partial Q}{\partial x_j} \right| \delta x_j \quad 15$$

This method provides the maximum possible uncertainty, when deviations from all the causes go in the same direction. This is seldom the case, in particular when the variables are not correlated, and this is why the statistical method proposed here is of a more common use.

It assumes that the variables have a statistical distribution that is close to a Gaussian one. The propagation law is then:

$$\delta Q = \sqrt{\sum_j \left(\frac{\partial Q}{\partial x_j} \right)^2 (\delta x_j)^2} \quad 16$$

As the square root of a sum of squares is always smaller than the sum of absolute values, the statistical method results in an estimate of the uncertainty that is smaller than the exact differential method.

When the nonlinearity of Q is significant, higher-order terms in the Taylor series expansion must be included in this expression for δQ . When the distribution of each x_j is normal, the most important terms of the next highest order to be added under the square root are:

$$\sum_i \sum_j \left[\frac{1}{2} \left(\frac{\partial^2 Q}{\partial x_i \partial x_j} \right)^2 + \frac{\partial Q}{\partial x_i} \frac{\partial^3 Q}{\partial x_i \partial x_i \partial x_j^2} \right] (\delta x_i)^2 (\delta x_j)^2 \quad 17$$

6.2.2 Uncertainty of a sum or a difference

It follows that the uncertainty of a sum or a difference is the square root of the sum of the squares of the uncertainties of the summed quantities:

$$\delta(\sum_j x_j) = \sqrt{\sum_j (\delta x_j)^2} \quad 18$$

6.2.3 Uncertainty of a product

The relative uncertainty of the result of a product is the square root of the sum of the squares of the uncertainties:

$$\frac{\delta(xy)}{xy} = \sqrt{\left(\frac{\delta x}{x}\right)^2 + \left(\frac{\delta y}{y}\right)^2} \quad 19$$

6.2.4 Uncertainty of a ratio

A ratio being nonlinear, its propagation law is a bit more complex. Its relative uncertainty is:

$$\frac{y}{x} \delta\left(\frac{x}{y}\right) = \sqrt{\left(\frac{\delta x}{x}\right)^2 + \left(\frac{\delta y}{y}\right)^2 + \frac{5}{2} \left(\frac{\delta x}{x}\right)^2 \left(\frac{\delta y}{y}\right)^2} \quad 20$$

Note that the third term, added for nonlinearity, remains negligible as long as the product of the relative uncertainties is much smaller than half their sum. If the relative uncertainties are the same, it is negligible if the square of the uncertainty is much smaller than the uncertainty itself. Therefore, we can say that this term can be neglected if both relative uncertainties are smaller than 10%.

6.3 Uncertainty of thermal measurements

6.3.1 Uncertainty of an average

When several measurements are performed on the same quantity with the same instruments, the uncertainty of the average is, assuming that all measurements have the same uncertainty δx :

$$\delta(\bar{x}) = \delta\left(\frac{1}{n} \sum_j x_j\right) = \frac{1}{n} \sqrt{n(\delta x)^2} = \frac{\delta x}{\sqrt{n}} \quad 21$$

This is the case not only of an average taken from several successive measurements at steady state, but also, for example, of the temperatures deduced from the average of several sensors, or the average heat flow rate of two heat flow meters.

6.3.2 Uncertainty of the density of heat flow rate

Heat flow meter: If δf and δe are the respective uncertainties of the calibration factor and the measured signal, the uncertainty δq of the density of heat flow rate $q = f e$ is:

$$\delta q = f e \sqrt{\left(\frac{\delta f}{f}\right)^2 + \left(\frac{\delta e}{e}\right)^2} \quad 22$$

Hot plate: The density of heat flow rate q is the ratio of the heating power, P , to the metering area A : $q = P/A$. Then, according to equation 19:

$$\delta q = \frac{P}{A} \sqrt{\left(\frac{\delta P}{P}\right)^2 + \left(\frac{\delta A}{A}\right)^2 + \frac{5}{2} \left(\frac{\delta P}{P}\right)^2 \left(\frac{\delta A}{A}\right)^2} \quad 23$$

where the uncertainties δP and δA are provided by the manufacturer of the instrument. Note that if P varies slightly at random when the thermal equilibrium is reached, a better estimate can be obtained by recording several successive values of P and taking the average. In this case, δP is reduced by the square root of the number of records (see Section 6.3.1).

6.3.3 Uncertainty of the thermal resistance

Let δT be the uncertainty of the temperatures (assumed to be the same for the hot and cold ones), and $\Delta T = T_h - T_c$ the temperature difference across the sample, then the relative uncertainty $\delta(\Delta T)$ is:

$$\frac{\delta(\Delta T)}{\Delta T} = \frac{\sqrt{2}\delta T^2}{\Delta T} = \sqrt{2} \frac{\delta T}{\Delta T} \quad 24$$

If δq is the uncertainty of the density of heat flow rate, the relative uncertainty of the thermal resistance, δR is:

$$\frac{\delta R}{R} = \sqrt{2 \left(\frac{\delta T}{\Delta T}\right)^2 + \left(\frac{\delta q}{q}\right)^2 + 5 \left(\frac{\delta T}{\Delta T}\right)^2 \left(\frac{\delta q}{q}\right)^2} \quad 25$$

6.3.4 Uncertainty of the apparent thermal conductivity

If δd is the uncertainty of measured thickness, the relative uncertainty of the apparent thermal conductivity, $\delta \kappa$, is:

$$\frac{\delta \lambda}{\lambda} = \sqrt{\left(\frac{\delta d}{d}\right)^2 + \left(\frac{\delta R}{R}\right)^2 + \frac{5}{2} \left(\frac{\delta d}{d}\right)^2 \left(\frac{\delta R}{R}\right)^2} \quad 26$$

6.3.5 Example of error analysis

Let us assume that all uncertainties of measured quantities are at the limits accepted by ISO 8301. These are summarised as relative errors in Annex A of this standard, as follows:

| | |
|--|-------------|
| Expected accuracy of the HFM calibration factor $\delta f/f$ | $\pm 2\%$ |
| Required accuracy of the measurement of output signal of the HFM $\delta e/e$ | $\pm 0.6\%$ |
| Required accuracy of the measurement of temperature difference $\delta(\Delta T)/\Delta T$ | $\pm 1\%$ |
| Required accuracy of the measurement of sample thickness $\delta d/d$ | $\pm 0.5\%$ |
| Maximum value of the edge heat loss error on heat flow rate | $\pm 0.5\%$ |

Then the relative uncertainty $\delta q/q$ of the density of heat flow, taking the edge errors into account:

$$\frac{\delta q}{q} = \sqrt{(0.02)^2 + (0.006)^2 + (0.005)^2} = 0.02147 \text{ or } 2.15\%$$

The relative uncertainty of the thermal resistance is, according to equation 24:

$$\begin{aligned} \frac{\delta R}{R} &= \sqrt{2(0.01)^2 + (0.0215)^2 + 5(0.01)^2(0.0215)^2} = 10^{-2} \sqrt{2 + 4.62 + 5(4.62 \cdot 10^{-4})} \\ &= 2.57\% \end{aligned}$$

We see that the term added for nonlinearity is negligible here.

Finally, the relative uncertainty of the apparent thermal conductivity is

$$\frac{\delta \kappa}{\kappa} = \sqrt{(0.005)^2 + (0.0257)^2} = 2.62\%$$

The term for nonlinearity being negligible is not added here.

We see that this result is within the HFM method accuracy, when the mean temperature of the test is near the room temperature, which is $\pm 3\%$ according to ISO 8301.

7 THE INTER-LABORATORY COMPARISON (ILC)

7.1 Objectives of this comparison

The objective is to ensure that all participating laboratories get the same results (within a given uncertainty margin) for the same material at the same temperature.

In order to perform a good comparison between the selected laboratories and the EMPA that could be considered as a reference, a minimum of two materials (e.g. hard polymer foam and a soft mineral fibre) should be tested. In order to have a significant statistics to take account of the variability of the samples, a minimum of three but preferably five samples of each material should be tested in each laboratory. Therefore, each laboratory has to perform a minimum of 6 but preferably 10 tests. This inter-laboratory comparison could be used for NABL or other accreditation.

7.2 Procedure and schedule

7.2.1 Participating laboratories

The following laboratories are expected to participate in this ILC.

- EMPA, Dübendorf, Switzerland
- CEPT University, Ahmedabad
- Nirma University, Ahmedabad
- Shriram Institute for Applied Research, Bangalore
- Spectro Analytical Labs Inc., New Delhi
- Isolloyd Engineering Technology, Baddi, Dist. Solan

Each laboratory must have an ILC supervisor to oversee the conduct of the ILC within the laboratory and to communicate with the ILC coordinator.

7.2.2 Task group

The task group includes a coordinator, a statistician, and representatives of the PMTU¹⁵ of BEEP. This task group will mostly communicate by internet.

7.2.2.1 Coordinator

The ILC will be coordinated by Ravi Kapoor, of Greentech Knowledge Solutions Pvt. Ltd, New Delhi. He will supervise the distribution of materials and protocols to the laboratories and receive the test result reports from the laboratories. Scanning the reports for obvious errors and checking with the laboratories, when such errors are found, will also be the responsibility of the coordinator. The coordinator may wish to consult with the statistician in questionable cases.

7.2.2.2 Statistician

C.-A. Roulet will assist the task group in interpreting the collected data and draw conclusions.

7.2.3 Design

7.2.3.1 Type of ILC

An ILC can be performed according to a 'round robin test', where the same samples are tested in all the laboratories or to a 'star robin test' where each laboratory receives simultaneously a

¹⁵ Project Management Technical Unit

set of samples. The round robin test has the advantage that the same sample is tested by all laboratories, but has the disadvantage that it takes longer time. As each lab has its own sample size requirements, the larger original sample gets destroyed as smaller samples are cut through the original sample. The star robin test is much faster, but cautions should be exercised in giving samples as similar as possible to each laboratory.

To gain time and ease the process, a star robin test is preferred. So, similar samples will be sent to each laboratory. It is advisable that one laboratory does the tests on all 50 samples at the beginning of the ILC, so that the characteristics of each individual sample are accurately known. The characteristics measured by the reference laboratory shall, however, not be communicated to the laboratories before they perform the tests.

7.2.3.2 Samples

Five samples of two materials will be distributed to each laboratory. Materials are rigid expanded plastic foam and a soft mineral fibre mat. To ensure that the samples are as similar as possible, they will be cut in packages of plates and rolls that come from one factory each and are produced the same day. The plastic foam should be aged to have stable characteristics.

There are two laboratories equipped with instruments for 30 cm square samples and one with 60 cm square samples. The instruments of two laboratories should still be defined. In addition, the EMPA has an instrument for 50 and 75 cm square samples. Once all instruments are known, a list of necessary samples should be prepared.

Spare samples of both dimensions should be added at this stage. Each sample is identified by a letter (P for plastic foam and F for the fibre) and a single number, the number being different for each sample. Record is kept on the package or the location in the roll from which each sample is taken.

Then the five samples sent to each lab are taken at random from the pile of samples.

For example, in a single roll of glass fibre 50 mm thick, 120 cm wide and 8.5 m long¹⁶, it is possible to cut 20 samples 60 cm² and 24 samples 30 cm².

7.2.3.3 Tests

The main quantity to be tested is the thermal conductivity at 23 °C mean temperature. The thickness, side dimensions, and weight of the samples delivered for measuring the thermal conductivity should also be measured, as these characteristics shall be reported together with the thermal conductivity. All measurements are performed according to the method described in Chapter 5 of this manual.

In each laboratory, every sample is measured once. In addition, the thermal conductivity of one sample of each material is measured four times more, taking the sample out of the instrument and reinstalling it, to check the reproducibility of the instrument.

Results for each test sample (dimension, thickness, weight, density, thermal resistance, and thermal conductivity) are reported, together with their uncertainty range, in the form given in Appendix E or the corresponding EXCEL spreadsheet, and returned (by e-mail) to the coordinator and the statistician only. They shall not be communicated to other laboratories.

¹⁶ This is a package of UNIROLL 035 available by Isover-Saint Gobain)

7.2.3.4 Interpretation

This method is inspired from ASTM E 691-14[19]. This document does not have the same objective as that of the ILC. The document aims to determine the accuracy of a test method, whereas the ILC should test the accuracy of the laboratories and, when needed, take measures so that the labs give, for one material, results close enough to each other. This document nevertheless contains useful information on how to conduct and interpret such a comparison.

The results for each type or material (plastic foam and fibre mat) and each property (dimension, thickness, weight, density, thermal resistance, and thermal conductivity) are reported in a table with a line for each laboratory and a column for each tested sample.

Then the following statistics are calculated:

The mean and the standard deviations of the results of each laboratory

$$\bar{x}_i = \frac{\sum_{j=1}^n x_{ij}}{n} \quad \text{and} \quad s_i = \sqrt{\frac{\sum_{j=1}^n (\bar{x}_i - x_{ij})^2}{n-1}} \quad 27$$

where n is the number of measured samples in each laboratory.

The average of the mean results from all laboratories and the standard deviation of these mean results:

$$\bar{\bar{x}} = \frac{\sum_{i=1}^p \bar{x}_i}{p} \quad \text{and} \quad s = \sqrt{\frac{\sum_{i=1}^p (\bar{x} - \bar{x}_i)^2}{p-1}} \quad 28$$

The deviation of each laboratory from the global average:

$$d_i = \bar{x}_i - \bar{\bar{x}}$$

The repeatability standard deviation:

$$s_r = \sqrt{\frac{\sum_{i=1}^p (s_i - s)^2}{p}} \quad 29$$

The inter-laboratory variance

$$s_L^2 = \max\left(s^2 - s_r^2/n; 0\right) \quad 30$$

The reproducibility standard deviation

$$s_R = \sqrt{s_L^2 + s_r^2} \quad 31$$

The between-laboratory consistency statistics for each laboratory

$$h_i = \frac{d_i}{s} \quad 32$$

The within-laboratory consistency statistic for each laboratory

$$k_i = \frac{s}{s_r} \quad 33$$

An example is shown in Table 7.1¹⁷. The global average of all results is 35.49 W/(m·K). Laboratory A has a mean result very close to the global average, but one of the largest standard

¹⁷ Note that for this example, artificial results are calculated using random numbers equally distributed between 35 and 36 mW/(m·K), so the statistics do not reflect the actual performance of the laboratories!

deviation. Laboratory F has a small standard deviation, so a rather good internal consistency k_F , but a mean result that differs from the global average by 0.36, that is $h_F = 2.43$ times the standard deviation of the average. This means that the results of this laboratory likely differ from the global average. The relative difference is, however, only 1% in this example.

Table 7.1: Example of table for the results for thermal conductivity of one material.

| Laboratory | Thermal conductivities at 23 °C | | | | | Mean \bar{x}_i | s_i | d_i | h_i | k_i |
|------------|---------------------------------|------|------|------|------|---------------------|-------|-------|-------|-------|
| A | 35.1 | 35.6 | 35.8 | 35.2 | 35.7 | 35.50 | 0.30 | 0.01 | 0.04 | 0.50 |
| B | 35.3 | 35.2 | 35.6 | 35.4 | 35.5 | 35.41 | 0.18 | -0.07 | -0.41 | 0.30 |
| C | 35.6 | 35.9 | 35.2 | 35.3 | 35.3 | 35.48 | 0.28 | 0.00 | -0.02 | 0.47 |
| D | 35.8 | 35.0 | 35.3 | 35.6 | 35.3 | 35.40 | 0.31 | -0.08 | -0.26 | 0.53 |
| E | 35.0 | 35.4 | 35.6 | 35.2 | 35.2 | 35.27 | 0.23 | -0.22 | -0.92 | 0.40 |
| F | 35.6 | 35.9 | 35.8 | 35.9 | 36.0 | 35.85 | 0.15 | 0.36 | 2.43 | 0.25 |

Action will be taken on the basis of these statistics. For example, if a laboratory has a within-laboratory or between-laboratory consistency statistics out of reasonable limits, the causes of the dispersion or respectively the discrepancy should be found and fixed.

8 REFERENCES

1. Prime Minister Council on Climate Change, *National Action Plan on Climate Change*, 2008, Government of India. p. 56.
2. Kumar, S., et al., *Performance based rating and energy performance benchmarking for commercial buildings in India* in *BauSIM 2010*: Vienna.
3. ISO, *10456 Building materials and products - Hygrothermal properties - Tabulated design values and procedures for determining declared and design thermal values*, 2007, ISO: Geneva. p. 24.
4. Roulet, C.-A., *Santé et qualité de l'environnement intérieur dans les bâtiments*. 2004, Lausanne: PPUR. 368.
5. ISO, *29465: Thermal insulating products for building applications -Determination of length and width*, 2008: geneva.
6. ISO, *29768: Thermal insulating products for building applications -Determination of linear dimensions of test specimens*, 2008: Geneva.
7. ISO, *29466: Thermal insulating products for building applications - Determination of thickness*, 2008: geneva.
8. ISO, *29470: Thermal insulating products for building applications - Determination of the apparent density*, 2008: geneva.
9. ISO, *8301 - Thermal insulation - Determination of steady-state thermal resistance and related properties - Heat flow meter apparatus.*, 1991: Geneva.
10. ISO, *8302 - Thermal insulation - Determination of steady-state thermal resistance and related properties - Guarded hot plate apparatus.*, 1991: Geneva.
11. ASTM, *C 518-10: Standard Test Method for Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus.*, 2010, ASTM: Philadelphia, PA.
12. Indian_Standards, *IS 9489 - Method of test for thermal conductivity of thermal insulation materials by means of heat flow meter.*, 1999: New Delhi.
13. ISO, *8301 - Isolation thermique - Détermination de la résistance thermique et des propriétés connexes en régime stationnaire - Méthode fluxmétrique*, 1991: Genève. p. 38.
14. ASTM, *C177 – 13: Standard Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Guarded-Hot-Plate Apparatus*, 2013, ASTM: Philadelphia, PA.
15. Indian_Standards, *IS 3346 - Method for the determination of thermal conductivity of thermal insulation materials (two slab, guarded hot-plate method)*, 2004: New Delhi.
16. JCGM, *200: International vocabulary of metrology (VIM) - Basic and general concepts and associated terms - Vocabulaire international de métrologie - Concepts fondamentaux et généraux et termes associés*, 2008.
17. AMC, *Terminology - the key to understanding analytical science. Part 1: Accuracy, precision and uncertainty*, in *AMC technical brief* 2003, Royal Society of Chemistry London. p. 2.
18. JCGM, *100: Evaluation of measurement data — Guide to the expression of uncertainty in measurement (GUM)*, 2010.
19. ASTM, *E691 – 14 Standard Practice for Conducting an Interlaboratory Study to Determine the Precision of a Test Method*, 2014, ASTM: West Conshohocken, PA 19428-2959. United States.

Appendix A CONVERSION OF THERMAL CONDUCTIVITY

According to ISO 10456[3], the declared values are given at reference temperatures of either 10 or 23 °C for aged products either dry or at equilibrium with air at 50% RH and the reference temperature. When measured at other temperature or humidity, they can be converted to reference condition using the following procedure given in clause 7 of this standard.

Conversions of thermal values from one set of conditions (T_1, u_1) to another set of conditions (T_2, u_2) are carried out according to the following equations:

$$\kappa_2 = \kappa_1 F_T F_m \quad 34$$

where F_T and F_m are the temperature and the moisture factors, respectively. These are calculated as follows:

$$F_T = e^{f_T(T_2-T_1)} \quad \text{and} \quad F_m = e^{f_m(u_2-u_1)} \quad \text{or} \quad F_m = e^{f_\psi(\psi_2-\psi_1)} \quad 35$$

Where:

f_T is the temperature conversion coefficient

T_2 and T_1 are the absolute temperatures for the second and first set of conditions

f_m is the mass moisture conversion coefficient

u_2 and u_1 are the mass moisture content for the second and first set of conditions

f_ψ is the volume moisture conversion coefficient

ψ_2 and ψ_1 are the volume moisture content for the second and first set of conditions

Table A.1: Conversion coefficients for temperature

| Material | Product type | Conductivity κ in W/(m·K) | Conversion coefficient f_T in 1/K |
|-------------------|-----------------------------|----------------------------------|-------------------------------------|
| Mineral wool | Batts, mats, and loose fill | 0.035 | 0.004 6 |
| | | 0.040 | 0.005 6 |
| | | 0.045 | 0.006 2 |
| | | 0.050 | 0.006 9 |
| | Boards | 0.032 | 0.003 8 |
| | | 0.034 | 0.004 3 |
| | | 0.036 | 0.004 8 |
| | | 0.038 | 0.005 3 |
| | Rigid boards | 0.030 | 0.003 5 |
| | | 0.033 | 0.003 5 |
| | | 0.035 | 0.003 5 |
| | Expanded polystyrene | Thickness $d < 20$ mm | 0.032 |
| 0.035 | | | 0.003 6 |
| 0.040 | | | 0.004 1 |
| 0.043 | | | 0.004 4 |
| $20 < d < 40$ mm | | 0.032 | 0.003 0 |
| | | 0.035 | 0.003 4 |
| | | 0.040 | 0.003 6 |
| $40 < d < 100$ mm | | 0.032 | 0.003 0 |
| | | 0.035 | 0.003 3 |
| | | 0.040 | 0.003 6 |
| | | 0.045 | 0.003 8 |
| | | 0.050 | 0.004 1 |
| $d > 100$ mm | | 0.032 | 0.003 0 |
| | | 0.035 | 0.003 2 |
| | | 0.040 | 0.003 4 |
| | | 0.053 | 0.003 7 |

| Material | Product type | Conductivity κ in W/(m·K) | Conversion coefficient f_T in 1/K |
|--|--|----------------------------------|-------------------------------------|
| Extruded polystyrene | Without skin | 0.025 | 0.004 6 |
| | | 0.030 | 0.004 5 |
| | | 0.040 | 0.004 5 |
| | With skin, fine cell products without skin | 0.025 | 0.004 0 |
| | | 0.030 | 0.003 6 |
| | | 0.035 | 0.003 5 |
| With impermeable cover | 0.025 | 0.003 0 | |
| | 0.030 | 0.002 8 | |
| | 0.035 | 0.002 7 | |
| | 0.040 | 0.002 6 | |
| Polyurethane foam | Products without facings | 0.025 | 0.005 5 |
| | | 0.030 | 0.005 0 |
| | Products with impermeable facings | 0.022 | 0.005 5 |
| | | 0.025 | 0.005 5 |
| Phenolic foam | Closed cell foam 0 °C to 20 °C 20 °C to 30 °C ^{a, b} | up to 0.025 | 0.002 0 |
| | | | 0.005 0 |
| | Open cell foam 0 °C to 30 °C | 0.032 | 0.002 9 |
| Cellular glass | | 0.035 | 0.004 3 |
| | | 0.040 | 0.003 7 |
| | | 0.045 | 0.003 3 |
| | | 0.050 | 0.003 0 |
| | | 0.055 | 0.002 7 |
| Rigid boards of perlite, fibres, and binders | | all | 0.003 3 |
| Wood wool boards | | 0.070 | 0.004 0 |
| | | 0.080 | 0.004 1 |
| | | 0.090 | 0.004 6 |
| Expanded cork | | all | 0.002 7 |
| Loose-fill cellulose fibre | Density < 40 kg/m ³ | | 0.004 0 |
| | Density W 40 kg/m ³ | | 0.004 0 0.003 5 |
| Concrete, fired clay and mortar | Lightweight concrete | 0.100 | 0.003 |
| | | 0.150 | 0.002 |
| | | 0.400 | 0.001 |
| | Dense concrete, fired clay, and mortar | all | 0.001 |

a Conversions shall be applied separately between 0 °C and 20 °C and between 20 °C and 30 °C. To convert from 10 °C to 25 °C, first convert from 10 °C to 20 °C, then from 20 °C to 25 °C.

b Conversion coefficients apply for blowing agents of pentane or hydro-fluoro-carbon (HFC). They may differ for other blowing agents.

Table A.2 — Conversion coefficient for moisture, for thermal insulation materials (From ISO 10456)

| | Density kg/m ² | Moisture content @ 23 °C, 50% RH | | Moisture content @ 23 °C, 80% RH | | Moisture conversion coefficients | | | |
|---------------------------------------|------------------------------|-------------------------------------|--------------------------------|-------------------------------------|--------------------------------|----------------------------------|-------|---|----------|
| | | kg/kg | m ³ /m ³ | kg/kg | m ³ /m ³ | Moisture content u kg/kg | f_u | Moisture content ψ m ³ /m ³ | f_ψ |
| Expanded polystyrene | 10–50 | 0 | | 0 | | | | < 0.10 | 4 |
| Extruded polystyrene foam | 20–65 | 0 | | 0 | | | | < 0.10 | 2.5 |
| Polyurethane foam, rigid | 28–55 | 0 | | 0 | | | | < 0.15 | 6 |
| Mineral wool | 10–200 | 0 | | 0 | | | | < 0.15 | 4 |
| Phenolic foam | 20–50 | 0 | | 0 | | | | < 0.15 | 5 |
| Cellular glass | 100–150 | 0 | | 0 | | 0 | 0 | | |
| Perlite board | 140–240 | 0.02 | | 0.03 | | 0 to 0.03 | 0.8 | | |
| Expanded cork | 90–140 | | 0.008 | | 0.011 | | | < 0.10 | 6 |
| Wood wool board | 250–450 | | 0.03 | | 0.05 | | | < 0.10 | 1.8 |
| Wood fibreboard | 40–250 | 0.1 | | 0.16 | | | | < 0.05 | 1.4 |
| Urea-formaldehyde foam | 10–30 | 0.1 | | 0.15 | | < 0.15 | 0.7 | | |
| Spray applied polyurethane foam | 30–50 | | 0 | | 0 | | | < 0.15 | 6 |
| Loose-fill mineral wool | 15–60 | | 0 | | 0 | | | < 0.15 | 4 |
| Loose-fill cellulose fibre | 20–60 | 0.11 | | 0.18 | | < 0.20 | 0.5 | | |
| Loose-fill expanded perlite | 30–150 | 0.01 | | 0.02 | | 0 to 0.02 | 3 | | |
| Loose-fill exfoliated vermiculite | 30–150 | 0.01 | | 0.02 | | 0 to 0.02 | 2 | | |
| Loose-fill expanded clay | 200–400 | 0 | | 0.001 | | 0 to 0.02 | 4 | | |
| Loose-fill expanded polystyrene beads | 10–30 | | 0 | | 0 | < 0.10 | 4 | | |

The effect of mass transfer by liquid water and water vapour, and the effects of water phase changes, are not covered by these data.

The moisture content is the range for which the coefficients are valid.

Data are not valid when there could be a continuous supply of moisture to the warm side of the insulation.

Appendix B PROCEDURE TO COMPUTE THE DECLARED VALUE

The statistical methodology used to calculate the declared value from the measured ones is as follows (all calculations are performed with at least three digits):

1. Measure the characteristics to be declared, i.e. the thermal conductivity on a given number, n , of samples of the same product. This gives n values of thermal conductivities, κ_j . To apply the method, n should be larger than 1 and for good results, n should be larger than 7.
2. Compute the mean value $\bar{\kappa}$ and the standard deviation s of the measured thermal conductivities:

$$\bar{\kappa} = \frac{\sum_{j=1}^n \kappa_j}{n} \quad \text{and} \quad s = \sqrt{\frac{\sum_{j=1}^n (\bar{\kappa} - \kappa_j)^2}{n-1}} \quad 36$$

3. The declared value is then:

$$\kappa_d = \bar{\kappa} + k_2(n, p, 1 - \alpha)s \quad 37$$

where:

$\bar{\kappa}$ is the mean measured thermal conductivity;

k_2 is the coefficient used to determine the declared value when the standard deviation is estimated for one-sided tolerance interval (Table in B.1);

n is the number of samples;

p is the fractile giving the minimum proportion of the population claimed to be lying in the statistical tolerance interval (i.e., 0.9 for 90% of the production);

$1-\alpha$ is the confidence level for the claim that the proportion of the population lying within the tolerance interval is greater than or equal to the specified level p ;

s is the sample standard deviation.

4. If the measurements were not performed at the reference conditions, convert the declared value to reference temperature and humidity according to Appendix A.
5. The declared value is finally rounded off to the two most significant digits.

Note that this procedure assumes that the accuracy of the measurements (see Section 6.1) is good enough to provide individual results of each sample with an uncertainty much smaller than the dispersion of the production.

As an example, take the measured values of the thermal conductivity of nine samples of the same material:

0.0382 0.0391 0.0391 0.0380 0.0385 0.0393 0.0386 0.0383 0.0398

The mean value is $\bar{\kappa} = 0.0388$ W/(m²K), and the standard deviation $s = 0.0006$ W/(m²K)

From Table B 1, the factor k_2 for the fractile $p = 90\%$ and confidence level $1-\alpha = 0.95$ is 2.454 Therefore, the declared value $\kappa_d = 0.0388 + 2.454 \cdot 0.0006 = 0.0403$, rounded to 0.040

If only three measurements were available, with the same mean value, the standard deviation is larger: $s = 0.0011$ and the factor k_2 is much larger: 6.156. In this case, the declared value were

$$\kappa_d = 0.0388 + 6.156 \cdot 0.001 = 0.0456, \text{ rounded to } 0.046$$

Table B 1: One-sided statistical tolerance limit factors
 $k_2(n; p; 1 - \alpha)$, for unknown σ

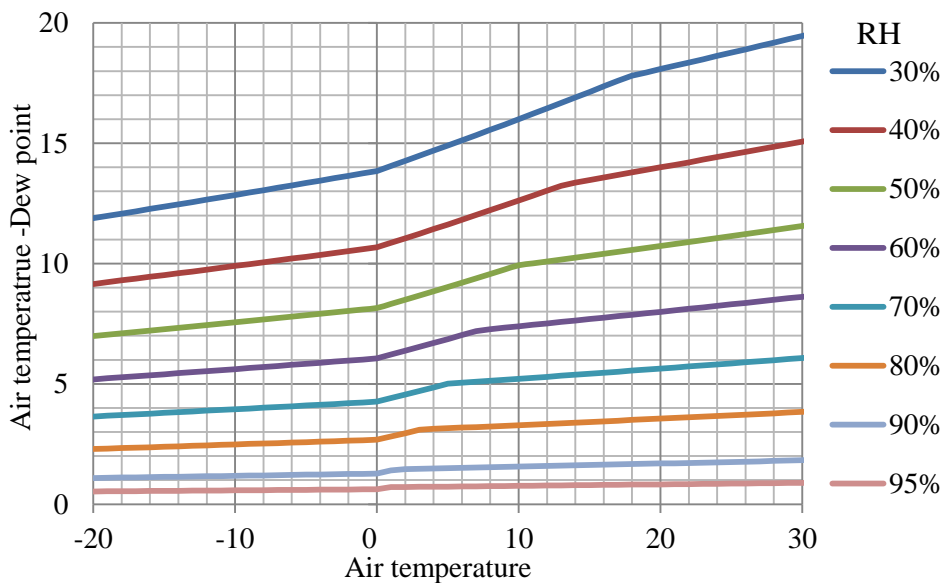
| Confidence level 90 % ($1 - \alpha = 0.90$) | | | | | | | Confidence level 95 % ($1 - \alpha = 0.95$) | | | | | | |
|--|------|------|-------|-------|-------|-------|--|------|-------|-------|-------|-------|-------|
| | p | | | | | | | p | | | | | |
| n | 0.50 | 0.75 | 0.90 | 0.95 | 0.99 | 0.999 | n | 0.50 | 0.75 | 0.90 | 0.95 | 0.99 | 0.999 |
| 2 | 2.17 | 5.84 | 10.25 | 13.09 | 18.50 | 24.58 | 2 | 4.46 | 11.76 | 20.58 | 26.26 | 37.09 | 49.27 |
| | 7 | 3 | 3 | 0 | 1 | 2 | | 5 | 3 | 2 | 0 | 4 | 6 |
| 3 | 1.08 | 2.60 | 4.259 | 5.312 | 7.341 | 9.652 | 3 | 1.68 | 3.807 | 6.156 | 7.656 | 10.55 | 13.85 |
| | 9 | 3 | | | | | | 6 | | | | 3 | 8 |
| 4 | 0.81 | 1.97 | 3.188 | 3.957 | 5.439 | 7.130 | 4 | 1.17 | 2.618 | 4.162 | 5.144 | 7.043 | 9.215 |
| | 9 | 3 | | | | | | 7 | | | | | |
| 5 | 0.68 | 1.69 | 2.743 | 3.400 | 4.666 | 6.112 | 5 | 0.95 | 2.150 | 3.407 | 4.203 | 5.742 | 7.502 |
| | 6 | 8 | | | | | | 4 | | | | | |
| 6 | 0.60 | 1.54 | 2.494 | 3.092 | 4.243 | 5.556 | 6 | 0.82 | 1.896 | 3.007 | 3.708 | 5.062 | 6.612 |
| | 3 | 0 | | | | | | 3 | | | | | |
| 7 | 0.54 | 1.43 | 2.333 | 2.894 | 3.973 | 5.202 | 7 | 0.73 | 1.733 | 2.756 | 3.400 | 4.642 | 6.063 |
| | 5 | 6 | | | | | | 5 | | | | | |
| 8 | 0.50 | 1.36 | 2.219 | 2.755 | 3.783 | 4.955 | 8 | 0.67 | 1.618 | 2.582 | 3.188 | 4.354 | 5.688 |
| | 1 | 0 | | | | | | 0 | | | | | |
| 9 | 0.46 | 1.30 | 2.133 | 2.650 | 3.642 | 4.772 | 9 | 0.62 | 1.533 | 2.454 | 3.032 | 4.144 | 5.414 |
| | 6 | 3 | | | | | | 0 | | | | | |
| 10 | 0.43 | 1.25 | 2.066 | 2.569 | 3.532 | 4.629 | 10 | 0.58 | 1.466 | 2.355 | 2.911 | 3.982 | 5.204 |
| | 8 | 7 | | | | | | 0 | | | | | |
| 11 | 0.41 | 1.22 | 2.012 | 2.503 | 3.444 | 4.515 | 11 | 0.54 | 1.412 | 2.276 | 2.815 | 3.853 | 5.037 |
| | 4 | 0 | | | | | | 7 | | | | | |
| 12 | 0.39 | 1.18 | 1.967 | 2.449 | 3.371 | 4.421 | 12 | 0.51 | 1.367 | 2.211 | 2.737 | 3.748 | 4.901 |
| | 4 | 9 | | | | | | 9 | | | | | |
| 13 | 0.37 | 1.16 | 1.929 | 2.403 | 3.310 | 4.341 | 13 | 0.49 | 1.329 | 2.156 | 2.671 | 3.660 | 4.787 |
| | 7 | 2 | | | | | | 5 | | | | | |
| 14 | 0.36 | 1.13 | 1.896 | 2.364 | 3.258 | 4.274 | 14 | 0.47 | 1.296 | 2.109 | 2.615 | 3.585 | 4.691 |
| | 1 | 9 | | | | | | 4 | | | | | |
| 15 | 0.34 | 1.11 | 1.867 | 2.329 | 3.212 | 4.216 | 15 | 0.45 | 1.268 | 2.069 | 2.567 | 3.521 | 4.608 |
| | 8 | 9 | | | | | | 5 | | | | | |
| 16 | 0.33 | 1.10 | 1.842 | 2.299 | 3.173 | 4.164 | 16 | 0.43 | 1.243 | 2.033 | 2.524 | 3.464 | 4.536 |
| | 6 | 1 | | | | | | 9 | | | | | |
| 17 | 0.32 | 1.08 | 1.820 | 2.273 | 3.137 | 4.119 | 17 | 0.42 | 1.221 | 2.002 | 2.487 | 3.415 | 4.472 |
| | 5 | 5 | | | | | | 4 | | | | | |
| 18 | 0.31 | 1.07 | 1.800 | 2.249 | 3.106 | 4.079 | 18 | 0.41 | 1.201 | 1.974 | 2.453 | 3.371 | 4.415 |
| | 5 | 1 | | | | | | 1 | | | | | |
| 19 | 0.30 | 1.05 | 1.782 | 2.228 | 3.078 | 4.042 | 19 | 0.39 | 1.183 | 1.949 | 2.424 | 3.331 | 4.364 |
| | 6 | 8 | | | | | | 8 | | | | | |
| 20 | 0.29 | 1.04 | 1.766 | 2.208 | 3.052 | 4.009 | 20 | 0.38 | 1.167 | 1.926 | 2.397 | 3.296 | 4.319 |
| | 7 | 6 | | | | | | 7 | | | | | |
| 22 | 0.28 | 1.02 | 1.737 | 2.174 | 3.007 | 3.952 | 22 | 0.36 | 1.138 | 1.887 | 2.349 | 3.234 | 4.239 |
| | 3 | 6 | | | | | | 7 | | | | | |
| 24 | 0.27 | 1.00 | 1.713 | 2.146 | 2.970 | 3.904 | 24 | 0.35 | 1.114 | 1.853 | 2.310 | 3.182 | 4.172 |
| | 0 | 8 | | | | | | 0 | | | | | |
| 26 | 0.25 | 0.99 | 1.692 | 2.121 | 2.937 | 3.862 | 26 | 0.33 | 1.093 | 1.825 | 2.276 | 3.137 | 4.115 |
| | 9 | 3 | | | | | | 5 | | | | | |
| 28 | 0.24 | 0.97 | 1.674 | 2.099 | 2.909 | 3.826 | 28 | 0.32 | 1.075 | 1.800 | 2.246 | 3.098 | 4.066 |
| | 9 | 9 | | | | | | 2 | | | | | |
| 30 | 0.24 | 0.96 | 1.658 | 2.080 | 2.884 | 3.795 | 30 | 0.31 | 1.059 | 1.778 | 2.220 | 3.064 | 4.023 |
| | 0 | 7 | | | | | | 1 | | | | | |
| 35 | 0.22 | 0.94 | 1.624 | 2.041 | 2.833 | 3.730 | 35 | 0.28 | 1.026 | 1.733 | 2.167 | 2.995 | 3.934 |
| | 1 | 3 | | | | | | 6 | | | | | |
| 40 | 0.20 | 0.92 | 1.598 | 2.011 | 2.794 | 3.679 | 40 | 0.26 | 1.000 | 1.698 | 2.126 | 2.941 | 3.866 |
| | 7 | 3 | | | | | | 7 | | | | | |
| 45 | 0.19 | 0.90 | 1.577 | 1.986 | 2.762 | 3.639 | 45 | 0.25 | 0.978 | 1.669 | 2.093 | 2.898 | 3.811 |
| | 4 | 7 | | | | | | 1 | | | | | |
| 50 | 0.18 | 0.89 | 1.560 | 1.966 | 2.735 | 3.605 | 50 | 0.23 | 0.961 | 1.646 | 2.065 | 2.863 | 3.766 |
| | 4 | 4 | | | | | | 8 | | | | | |
| 60 | 0.16 | 0.87 | 1.533 | 1.934 | 2.694 | 3.553 | 60 | 0.21 | 0.933 | 1.609 | 2.023 | 2.808 | 3.696 |
| | 8 | 3 | | | | | | 6 | | | | | |

| | | | | | | | | | | | | | |
|----------|-----------|-----------|-------|-------|-------|-------|----------|-----------|-------|-------|-------|-------|-------|
| 70 | 0.15 5 | 0.85 7 | 1.512 | 1.910 | 2.663 | 3.513 | 70 | 0.20 0 | 0.912 | 1.582 | 1.990 | 2.766 | 3.643 |
| 80 | 0.14 5 | 0.84 5 | 1.495 | 1.890 | 2.638 | 3.482 | 80 | 0.18 7 | 0.895 | 1.560 | 1.965 | 2.733 | 3.602 |
| 90 | 0.13 7 | 0.83 4 | 1.482 | 1.875 | 2.618 | 3.457 | 90 | 0.17 6 | 0.882 | 1.542 | 1.944 | 2.707 | 3.568 |
| 100 | 0.13 0 | 0.82 5 | 1.471 | 1.862 | 2.601 | 3.436 | 100 | 0.16 7 | 0.870 | 1.527 | 1.927 | 2.684 | 3.540 |
| 150 | 0.10 6 | 0.79 6 | 1.433 | 1.819 | 2.546 | 3.366 | 150 | 0.13 6 | 0.832 | 1.478 | 1.870 | 2.612 | 3.448 |
| 200 | 0.09 1 | 0.77 9 | 1.412 | 1.794 | 2.515 | 3.326 | 200 | 0.11 7 | 0.810 | 1.450 | 1.838 | 2.570 | 3.396 |
| 250 | 0.08 2 | 0.76 8 | 1.397 | 1.777 | 2.493 | 3.299 | 250 | 0.10 5 | 0.795 | 1.431 | 1.816 | 2.543 | 3.361 |
| 300 | 0.07 5 | 0.76 0 | 1.387 | 1.765 | 2.478 | 3.280 | 300 | 0.09 6 | 0.784 | 1.417 | 1.800 | 2.522 | 3.336 |
| 400 | 0.06 5 | 0.74 8 | 1.372 | 1.748 | 2.457 | 3.253 | 400 | 0.08 3 | 0.769 | 1.398 | 1.778 | 2.495 | 3.301 |
| 500 | 0.05 8 | 0.74 0 | 1.362 | 1.737 | 2.442 | 3.235 | 500 | 0.07 4 | 0.759 | 1.386 | 1.764 | 2.476 | 3.277 |
| 1000 | 0.04 1 | 0.72 1 | 1.338 | 1.709 | 2.407 | 3.191 | 1000 | 0.05 3 | 0.734 | 1.354 | 1.728 | 2.431 | 3.221 |
| ∞ | 0.00 0 | 0.67 5 | 1.282 | 1.645 | 2.327 | 3.091 | ∞ | 0.00 0 | 0.675 | 1.282 | 1.645 | 2.327 | 3.091 |

Appendix C DEW POINT

Dew point in °C for relative humidity =

| | 30% | 40% | 50% | 60% | 70% | 80% | 90% | 95% |
|----|-------|-------|-------|-------|-------|-------|-------|-------|
| 10 | -6.00 | -2.62 | 0.07 | 2.60 | 4.79 | 6.71 | 8.44 | 9.24 |
| 11 | -5.22 | -1.82 | 0.99 | 3.55 | 5.75 | 7.69 | 9.42 | 10.23 |
| 12 | -4.45 | -1.03 | 1.91 | 4.49 | 6.71 | 8.66 | 10.41 | 11.22 |
| 13 | -3.68 | -0.23 | 2.83 | 5.43 | 7.66 | 9.63 | 11.40 | 12.22 |
| 14 | -2.90 | 0.63 | 3.75 | 6.37 | 8.62 | 10.61 | 12.39 | 13.21 |
| 15 | -2.13 | 1.53 | 4.67 | 7.31 | 9.58 | 11.58 | 13.37 | 14.21 |
| 16 | -1.37 | 2.42 | 5.59 | 8.25 | 10.54 | 12.55 | 14.36 | 15.20 |
| 17 | -0.60 | 3.32 | 6.51 | 9.19 | 11.49 | 13.53 | 15.35 | 16.19 |
| 18 | 0.19 | 4.21 | 7.43 | 10.13 | 12.45 | 14.50 | 16.34 | 17.19 |
| 19 | 1.05 | 5.11 | 8.35 | 11.07 | 13.41 | 15.47 | 17.32 | 18.18 |
| 20 | 1.92 | 6.00 | 9.27 | 12.00 | 14.36 | 16.44 | 18.31 | 19.17 |
| 21 | 2.78 | 6.90 | 10.19 | 12.94 | 15.32 | 17.42 | 19.30 | 20.17 |
| 22 | 3.64 | 7.79 | 11.11 | 13.88 | 16.28 | 18.39 | 20.28 | 21.16 |
| 23 | 4.51 | 8.68 | 12.02 | 14.82 | 17.23 | 19.36 | 21.27 | 22.15 |
| 24 | 5.37 | 9.58 | 12.94 | 15.76 | 18.19 | 20.33 | 22.26 | 23.15 |
| 25 | 6.23 | 10.47 | 13.86 | 16.70 | 19.15 | 21.31 | 23.24 | 24.14 |
| 26 | 7.09 | 11.36 | 14.77 | 17.63 | 20.10 | 22.28 | 24.23 | 25.14 |
| 27 | 7.96 | 12.25 | 15.69 | 18.57 | 21.06 | 23.25 | 25.22 | 26.13 |
| 28 | 8.82 | 13.14 | 16.61 | 19.51 | 22.01 | 24.22 | 26.20 | 27.12 |
| 29 | 9.68 | 14.03 | 17.52 | 20.44 | 22.97 | 25.19 | 27.19 | 28.12 |
| 30 | 10.54 | 14.93 | 18.44 | 21.38 | 23.92 | 26.17 | 28.18 | 29.11 |
| 31 | 11.40 | 15.82 | 19.35 | 22.32 | 24.88 | 27.14 | 29.16 | 30.10 |
| 32 | 12.26 | 16.71 | 20.27 | 23.25 | 25.83 | 28.11 | 30.15 | 31.10 |
| 33 | 13.11 | 17.59 | 21.18 | 24.19 | 26.79 | 29.08 | 31.13 | 32.09 |
| 34 | 13.97 | 18.48 | 22.10 | 25.13 | 27.74 | 30.05 | 32.12 | 33.08 |
| 35 | 14.83 | 19.37 | 23.01 | 26.06 | 28.70 | 31.02 | 33.11 | 34.08 |
| 36 | 15.69 | 20.26 | 23.92 | 27.00 | 29.65 | 31.99 | 34.09 | 35.07 |
| 37 | 16.54 | 21.15 | 24.84 | 27.93 | 30.60 | 32.96 | 35.08 | 36.06 |
| 38 | 17.40 | 22.04 | 25.75 | 28.87 | 31.56 | 33.93 | 36.07 | 37.05 |
| 39 | 18.25 | 22.92 | 26.66 | 29.80 | 32.51 | 34.90 | 37.05 | 38.05 |
| 40 | 19.11 | 23.81 | 27.58 | 30.73 | 33.46 | 35.88 | 38.04 | 39.04 |



Difference between air temperature and dew point for various percentages of relative humidity.

Appendix D CHECK LIST FOR THE MEASUREMENT OF THERMAL CONDUCTIVITY

| Task | § |
|--|----------|
| Sample the material to be tested at random from the manufacturer's stock | 5.2 |
| Collect at least 1 roll, or 5 plates, or 200 litre loose fill material | |
| Record the product identification product name, factory, manufacturer or supplier, production code number, type of product, packaging, form in which the product arrived at the laboratory, other information as appropriate, e.g. nominal dimensions, nominal thickness, nominal density. | |
| Prepare specimens for the measurements: | 5.3 |
| Dimensions of product and density: at least 1 roll, or 5 plates | |
| Thermal conductivity: square samples the dimensions of the instrument | |
| For flow meter: 5 samples | |
| For guarded hot plate: 10 samples | |
| Samples are taken at random from the collected material. | |
| Weigh all specimens with an accuracy of 0.5% or better and record the 'as received' weight | |
| Condition the samples at 23 ± 2 °C and 50 ± 5 % RH. Weigh them daily until the change in weight is less than 1%. | |
| Measure and record the dimensions and density of all samples | 5.4 |
| If, for the measurement of thermal conductivity, the temperature of the cold plate is less than 5 K above the dew point of the air laboratory, pack the samples in a sealed, slightly evacuated polyethylene bag or ensure a dry atmosphere around the sample in the instrument. | |
| Heat flow meter measurement: calibrate the instrument | 4.3.3 |
| Measure the thermal conductivity | 5.5.2 |
| Weigh the sample (without bag) after the test, record the change in weight. | |
| Heat flow meter measurement: calibrate the instrument at the latest 24 h after test | 4.3.3 |
| Interpret the measurements (5.5.2.3) and prepare the report. | 5.5.3 |

Appendix E REPORTING FORM

This form contains all information related to thermal conductivity measurement, including samples, dimensions, and density. It can be adapted to the laboratory characteristics and equipment, but should nevertheless contain all the data required by ISO ISO 29470:2008 and ISO 8301 or 8302, whichever applies.

Name of the laboratory

Product name:.....

Supplier:

Production code number:

Type of product:

Packaging:

Product sampled onby

Form in which the product arrived at the laboratory.....

Nominal length..... m; Width..... m; Thickness mm; Density..... kg/m³

Conditioning

Samples conditioned at °C and %RH for days

| Sample | 1 | 2 | 3 | 4 | 5 | |
|---------------------|---|---|---|---|---|----|
| Initial weight | | | | | | kg |
| Weight after 1 day | | | | | | kg |
| Weight after 2 days | | | | | | kg |
| Weight after 3 days | | | | | | kg |
| Weight after 4 days | | | | | | kg |
| Weight after days | | | | | | kg |
| Weight after days | | | | | | kg |
| Final weight | | | | | | kg |
| Mass change | ± | ± | ± | ± | ± | g |

After conditioning:

Test samples packed no yes with.....

Loose-fill materials packed in

Thermal resistance of sheet material interposed between the test sample and apparatus plates or of cover materials used for the containers for loose-fill materials..... m²K/W

Measurement of density according to ISO 29470:2008;

Samples tested at °C and %RH on

Presence of surface skins no yes, removed no yes, by cutting/sanding/.....

Any defects on the specimens

Deviations from the procedure: no yes:

Applied pressure for thickness measurement: 250 Pa

Comments:

Results:

| Sample | 1 | 2 | 3 | 4 | 5 | |
|----------------|---|---|---|---|---|-------------------|
| Length 1 | | | | | | |
| Length 2 | | | | | | |
| Mean length | ± | ± | ± | ± | ± | m |
| Width 1 | | | | | | |
| Width 2 | | | | | | |
| Width 3 | | | | | | |
| Width 4 | | | | | | |
| Width 5 | | | | | | |
| Mean width | ± | ± | ± | ± | ± | m |
| Thickness 1 | | | | | | |
| Thickness 2 | | | | | | |
| Thickness 3 | | | | | | |
| Thickness 4 | | | | | | |
| Thickness 5 | | | | | | |
| Mean Thickness | ± | ± | ± | ± | ± | m |
| Weight | ± | ± | ± | ± | ± | kg |
| Density | ± | ± | ± | ± | ± | kg/m ³ |

Measurement of thermal conductivity

This test conformed with all requirements of Standard Test Method ISO 8301 (or 8302) with the exception of

Name and address of the laboratory

Type of instrument used: Heat flow meter with one/two heat flow meters
 Guarded hot plate, one/two test samples
 vertical or horizontal heat flow rate

Date of the test.....

Date of the last calibration with..... sample

Thickness as tested \pmmm imposed measured in the instrument.

| Sample | 1 | 2 | 3 | 4 | 5 | |
|----------------------|-------|-------|-------|-------|-------|----|
| Initial weight | | | | | | kg |
| Weight after test | | | | | | kg |
| Mass change | \pm | \pm | \pm | \pm | \pm | g |
| Initial thickness | | | | | | mm |
| Thickness after test | | | | | | mm |

Testing conditions

| Tests | A | B | C | |
|------------------------|-------|-------|-------|----|
| Hot plate temperature | \pm | \pm | \pm | °C |
| Cold plate temperature | \pm | \pm | \pm | °C |
| Mean test temperature | \pm | \pm | \pm | °C |
| Temperature difference | \pm | \pm | \pm | K |

Test results

| | Sample | 1 | 2 | 3 | 4 | 5 | |
|--------|---------------------------|-------|-------|-------|-------|-------|--------------------|
| Test A | Density of heat flow rate | \pm | \pm | \pm | \pm | \pm | W/m ² |
| | Thermal resistance | \pm | \pm | \pm | \pm | \pm | m ² K/W |
| | Thermal conductivity | \pm | \pm | \pm | \pm | \pm | W/(m·K) |
| Test B | Density of heat flow rate | \pm | \pm | \pm | \pm | \pm | W/m ² |
| | Thermal resistance | \pm | \pm | \pm | \pm | \pm | m ² K/W |
| | Thermal conductivity | \pm | \pm | \pm | \pm | \pm | W/(m·K) |
| Test C | Density of heat flow rate | \pm | \pm | \pm | \pm | \pm | W/m ² |
| | Thermal resistance | \pm | \pm | \pm | \pm | \pm | m ² K/W |
| | Thermal conductivity | \pm | \pm | \pm | \pm | \pm | W/(m·K) |

For direct-reading apparatus, the results of the calibration of electronic circuitry and equipment, or a statement of compliance including date, and a statement of compliance on linearity requirements shall be included.

APPENDIX F: SOME INSTRUMENTS MEASURING THE THERMAL CONDUCTIVITY**Heat flow meter instruments**

| Provider Model | Waters India, Bangalore Fox 600 | Netsch Technologies, Chennai HFM 436/3/1 rev HFM 436/6/1 | | Taurus Inst. Weimar, Germany TCA 500 PGX |
|-----------------------|---------------------------------------|---|-------------|---|
| Sample size (mm) | 610 | 305 | 610 | 500 |
| Max. thickness (mm) | 203 | 100 | 200 | 200 |
| Temperature range | -10 to 65 °C | 0 to 40°C | -20 to 70°C | 18 to 24 °C |
| Humidity range | — | Airtight enclosure | | 5% to 65% |
| Thickness measurement | ±0.025 mm | Better than ±0.1 mm | | ±0.1 mm |
| Relative cost | 1.35 | 1 | 2.65 | 1.25 |

Guarded hot plate instruments

| Provider Model | Lambdda Messtechnik D-01214 Dresden EP500e | Waters India, Bangalore GHP 600 | Taurus Inst., Weimar, Germany TLP 500 GX1 |
|-----------------------|--|---------------------------------------|---|
| Sample size (mm) | 500 | 610 | 500 |
| Max. thickness (mm) | 200 | 75 | 200 |
| Temperature range | 10 to 40 °C | 20 to 250 °C | 18 to 24 °C |
| Humidity range | — | — | 5% to 65% |
| Thickness measurement | ±0.05 mm | ±0.025 mm | ±0.1 mm |
| Relative cost | 1 | 4 | 1.5 |