Journal of Building Engineering 44 (2021) 102604

Contents lists available at ScienceDirect

Journal of Building Engineering

journal homepage: www.elsevier.com/locate/jobe

An overview of factors influencing thermal conductivity of building insulation materials

Le Duong Hung Anh [a,b,c,*], Zoltán Pásztory [c]

[a] Department of Engineering Mechanics, Faculty of Applied Science, Ho Chi Minh City University of Technology (HCMUT), 268 Ly Thuong Kiet Street, District 10, Ho Chi Minh City, Viet Nam
[b] Vietnam National University Ho Chi Minh City, Linh Trung Ward, Thu Duc District, Ho Chi Minh City, Viet Nam
[c] Doctoral School of Wood Science and Technology, University of Sopron, 4. Bajcsy Zs. Str., Sopron, 9400, Hungary

A R T I C L E I N F O

Keywords:
Building insulation materials
Thermal conductivity
Influencing factors
Temperature difference
Moisture content
Density

A B S T R A C T

Solving the matter of traditional energy consumption and finding the proper alternative resources are vital keys to a sustainable development policy. In recent years, many different thermal insulation materials have been developed for better energy efficiency and less environment damage. These products have confirmed their usefulness in buildings due to their benefits such as low density, high thermal resistance, and cost effectiveness. The efficiency of thermal insulation depends on their thermal conductivity and their ability to maintain their thermal characteristics over a period of time. This study presents factors influencing the thermal conductivity coefficient of three main groups including conventional, alternative, and new advanced materials. The most common factors are moisture content, temperature difference, and bulk density. Other factors are explained in some dependent studies such as airflow velocity, thickness, pressure, and material aging. The relationship between the thermal conductivity values with the mean temperature, moisture content, and density which were obtained from experimental investigation has also been summarized. Finally, uncertainty about the thermal conductivity value of some common insulation materials is also reviewed as the basis of selecting or designing the products used in building envelopes.

1. Introduction

1.1. Energy consumption in the building sector

The global energy expenditure in industrial and residential construction has become one of the most important concerns in the third decade of the 21st century. Building construction, raw material processing, and product manufacturing are the largest sources of greenhouse gas emissions. Carbon dioxide compounds are the main by-products of fossil fuel consumption, and since buildings are among the biggest consumers of energy, they are also major contributors to global warming which is accelerating climate change and threatening the survival of millions of people, plants and animals. According to Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010, on the energy performance of buildings, new construction will have to consume nearly zero energy and that energy will be to a very large extent from renewable resources, because the construction sector has been identified as the largest energy consumer, generating up to 1/3 of global annual greenhouse gas emissions (GHG), contributing up to 40% of global energy, and consuming of 25% of global water worldwide [1]. Global energy consumption is predicted to grow by 64% until the year 2040 from the considerable increase in residential, industrial, commercial, and urban construction due to the industrial development and growth of population, according to the Energy Information Association in 2018 [2]. As a result, environmental disasters and climate change are becoming more apparent. For instance, global warming from the greenhouse effect (45% carbon dioxide emissions in which buildings and construction industry are major contributors, [3]) is predicted to raise the Earth's average surface temperature from 1.1° to 6.4 °C by the end of 2100 [4,5]. The increased consumption of natural resources for lighting, refrigeration, ventilation, recycling, heating, and cooling system in commercial buildings due to the acceleration of urbanization, causes an enormous expenditure for energy. Therefore, it is necessary to use insulation materials for better energy conservation, and to enhance sustainable energy strategies in the building sector.

* Corresponding author. Doctoral School of Wood Science and Technology, University of Sopron, 4. Bajcsy Zs. Str., Sopron, 9400, Hungary.
E-mail addresses: Duong.Hung.Anh.Le@phd.uni-sopron.hu, leduonghunganh@hcmut.edu.vn (L.D. Hung Anh).

https://doi.org/10.1016/j.jobe.2021.102604
Received 3 December 2020; Received in revised form 29 March 2021; Accepted 21 April 2021
Available online 7 May 2021

Nomenclature

PS	Polystyrene
EPS	Expanded polystyrene
XPS	Extruded polystyrene
PUR	Polyurethane
PIR	Polyisocyanurate
PE	Polyethylene
ENR	Expanded nitrile rubber
EVA	Ethylene vinyl acetate
VIPs	Vacuum insulation panels
GFPs	Gas filled panels
LWAC	Lightweight aggregate concrete
PCM	Phase change materials
OIT	Optimum insulation thickness

Greek symbols

λ	Thermal conductivity (W/(m.K))
ρ	Density (kg/m^3)
p	Pressure (Pa)
w	Moisture content (%)

1.2. The use of thermal insulation materials

As the energy becomes more precious, the use of thermal insulation materials is being enforced in buildings. Thermal insulation is a material or combination of materials that retard the rate of heat flow by conduction, convection, and radiation when properly applied [6]. Using thermal insulation products helps in reducing the dependence on heating, ventilation, and air conditioning (HVAC) systems to manage buildings comfortably. Therefore, it conserves energy and decreases the use of natural resources. Other advantages are profits, environmentally friendly materials, extending the periods of indoor thermal comfort, reducing noise levels, fire protection, and so on [7]. These materials will enable systems to achieve energy efficiency. They also have many applications in food cold storage, refrigeration, petroleum and liquefied natural gas pipelines [8]. Sustainable insulation products with lower embodied energy and reduced environmental emissions are also increasing in popularity and a large number of innovative types of insulation are constantly entering the market [9].

Some former detailed reviews of thermal insulation materials and their application in the building sector include Aditya et al. [10], and D'Alessandro et al. [11]. Insulation materials are applied in some groups including the walls, the roofs, the ceilings, the windows, and the floors. Their types, properties, benefits, and drawbacks were also discussed. The work of Abu-Jdayil et al. [12] has reviewed the different types, methods of manufacturing, and features in both the traditional and state-of-the-art thermal insulation materials in the last decades. Thermal insulating materials are generally comprised of a solid matrix material with a gaseous material interspersed randomly or regularly within the cells, pores or interstices [13].

Most of the available thermal insulation materials can be classified in four general groups including inorganic, organic, combined, and advanced materials. They are created in several forms including porous, blanket or batt form, rigid, natural form, and a reflective structure [14]. Inorganic materials (glass wool and rock wool) account for 60% of the market, whereas organic insulation materials are 27%. Conventional materials such as polyurethane (PUR), polyisocyanurate (PIR), extruded polystyrene (XPS), expanded polystyrene (EPS) are preferred in many buildings and thermal energy storage applications due to their low thermal conductivity and low cost [15].

Mineral wool includes a variety of inorganic insulation materials such as rock wool, glass wool, and slag wool. The average range of thermal conductivity for mineral wool is between 0.03 and 0.04 W/(m.K) and the typical λ-values of glass wool and rock wool are 0.03–0.046 W/(m.K) and 0.033–0.046 W/(m.K), respectively. These materials have the low thermal conductivity value, are non-flammable, and highly resistant to moisture damage. However, it can affect health problems, for example, skin and lung irritation [12]. Organic insulation materials are derived from natural resources which are currently used in buildings due to their attractiveness, renewable, recyclable, environmentally friendly and required energy to manufacture is less than that of traditional materials [10].

To retard the heat transfer in building envelopes, various of new insulation materials has produced to achieve the highest possible thermal resistance. They are vacuum insulation panels (VIPs), gas filled panels (GFPs), aerogels, and phase change materials (PCM). Among them, VIPs exhibit one of the lowest thermal conductivity values (lower than 0.004 W/(m.K)) and have a high life expectancy (over 50 years). This super-insulated material is created inside the panel which decreases the thickness of the thermal insulation materials, but the thermal conductivity will increase irreversible over time due to diffusion of water vapor and air through the envelope [12]. Aerogels are also considered as one of the state-of-the-art thermal insulators with the range of thermal conductivity values from 0.013 to 0.014 W/(m.K) and the density for buildings is usually 70–150 kg/m^3 [11]. However, its commercial availability is very limited due to the high cost production [16]. GFPs and PCM are the thermal insulation materials of tomorrow due to their low thermal conductivity values, 0.013 W/(m.K) and 0.004 W/(m.K), respectively. While GFPs are made of a reflective structure containing a gas insulated from the external environment by an envelope impermeable as possible, PCM stores and releases heat as the surrounding change by transforming from a solid state to liquid when heated and turning into a solid state when the ambient temperature drops [10,11,16].

Table 1 shows the thermal properties of some common insulation materials. The data are collected and synthesized according to the literature and practical experiment. Thermal insulating materials are usually tested which covered by standards such as EN 12664 (low thermal resistance) [17], EN 12667 (high thermal resistance) [18], EN 12939 (thick materials) [19], ASTM C518 (heat flow meter apparatus) [20], and ASTM C177 (guarded hot plate apparatus) [21]. Nevertheless, as a result of the wide range of thermal properties of insulation materials, there is no single measurement method for all thermal conductivity measurements [22].

There is uncertainty about the thermal conductivity values for inorganic, organic, and advanced materials which are 0.03–0.07 W/(m.K), 0.02–0.055 W/(m.K), and lower than 0.01 W/(m.K), respectively. Generally, the nominal thermal conductivity of porous materials range from 0.02 to 0.08 W/(m.K), while the thermal conductivity values of alternative insulation materials made from natural fibers vary from 0.04 to 0.09 W/(mK). Conventional materials such as mineral wool, foamed polystyrene are mainly used in thermal energy storage systems due to long term usage, and low cost. Natural fibers-based insulation materials derived from agricultural waste such as coconut, rice straw, bagasse, etc., currently applied in some building applications due to the environmentally friendly properties [33,34]. However, the main disadvantage is their relatively high-water absorption, resulting in high thermal conductivity. Therefore, the use of VIPs or PUR-PIR foams with lower thermal conductivity can be a good choice for reducing energy consumption as well as cost savings [15]. Additionally, there are efforts to make thermal insulation from wood waste products [35], but they should be protected against saturation, especially when used externally. Another new development material is aerogel and VIPs with a low thermal conductivity of just 0.017–0.021 W/(m.K) and 0.002–0.008 W/(m.K), respectively, which exhibits excellent thermal insulation properties. In fibrous insulating materials, the fineness of the fibers and their orientation play a main role. In foam insulating materials, the thermal conductivity is determined by the fineness and distribution of the cells and particularly by the gases in those cells. Insulating materials

Table 1
Classification of the commonly used insulation materials and uncertainty about their thermal conductivity.

Main group	Subgroup	Insulation Material	Temperature (°C)	Density (kg/m^3)	Thermal conductivity (W/(m.K))	Reference
Inorganic	Fibrous	Glass wool	−100–500	13–100	0.03–0.045	[11,12,23]
		Rock wool	−100–750	30–180	0.033–0.045	[7,11,12,23–26]
	Cellular	Calcium silicate	300	115–300	0.045–0.065	[24]
		Cellular glass	−260–430	115–220	0.04–0.06	[24]
		Vermiculite	700–1600	70–160	0.046–0.07	[7,24,27]
		Ceramic	N.A.	120–560	0.03–0.07	[24]
Organic	Foamed	EPS	−80–80	15–35	0.035–0.04	[7,11,16,23,24]
		XPS	−60–75	25–45	0.03–0.04	[7,11,15,16,23,24,28]
		PUR	−50–120	30–100	0.024–0.03	[11,16,23,24,29]
		PIR	−20–100	30–45	0.018–0.028	[11,30]
	Foamed, expanded	Cork	110–120	110–170	0.037–0.050	[11,16,24]
		Melamine foam	N.A.	8–11	0.035	[24]
		Phenolic foam	150	40–160	0.022–0.04	[11,24]
		Polyethylene foam	−40–105	25–45	0.033	[24]
	Fibrous	Fiberglass	−4–350	24–112	0.033–0.04	[7,28]
		Sheep wool	130–150	25–30	0.04–0.045	[24]
		Cotton	100	20–60	0.035–0.06	[24]
		Cellulose fibers	60	30–80	0.04–0.045	[7,11,16,24]
		Jute	N.A.	35–100	0.038–0.055	[11]
		Rice straw	24	154–168	0.046–0.056	[11]
		Hemp	100–120	20–68	0.04–0.05	[24]
		Bagasse	160–200	70–350	0.046–0.055	[11,31]
		Coconut	180–220	70–125	0.04–0.05	[11,24,31]
		Flax	N.A.	20–80	0.03–0.045	[24]
Combined	Boards	Gypsum foam	N.A.	N.A.	0.045	[24]
		Wood wool	110–180	350–600	0.09	[24]
		Wood fibers	110	30–270	0.04–0.09	[24]
Advanced materials		VIPs	N.A.	150–300	0.002–0.008	[11,24]
		Aerogel	N.A.	60–80	0.013–0.014	[11,16,24,32]

made from wood fibers or wood wool, the density factor is critical for the insulating capacity. The range of temperature shows the minimum and maximum service temperatures based on manufacturers information. Insulating materials can react very differently to hot and cold environment and there is no uniform test method that enables a direct comparison between insulating materials [24].

Previous studies have carried out the thermal conductivity coefficient strongly depends on the temperature, moisture content, density [7,11,12,16]. Some research gaps can be identified from existing literature and published studies. Firstly, there has been no detailed overview of all factors influencing in the thermal properties of building insulation materials. Secondly, few empirical data evaluates the thermal performance of insulation materials considering cost, environment impact, personal comfort and lessen attention to other properties such as embodied energy, embodied carbon, hygroscopic and fire protection. Furthermore, thermal properties of insulation materials are mainly determined by thermal conductivity, specific heat capacity, thermal diffusivity, coefficient of thermal expansion, and mass loss. However, most studied in the field of heat and moisture transport have only focused on the thermal conductivity for the steady state without evaluating the other properties. Hence, it is imperative to understand the combined influence of the many factors to gain useful insights into the actual performance of insulation materials for practical applications.

This review aims to provide a fundamental understanding of different building insulation materials and their thermal conductivities. The main research question is to discuss the factors influencing thermal conductivity coefficients of insulation materials used in building envelopes. Another object is to synthesize the relationship between mean temperature, moisture content, and density with thermal conductivity as a linear function. This article also exhibits the λ-values of some common traditional and state-the-art materials to understand insulating materials used in building construction.

This paper has been structured as follows. Section 2 explores the main role of the thermal conductivity coefficient when studies the heat transport in buildings as well as the values of various common building insulation materials are displayed. The effects of factors including temperature, moisture content, density, thickness, pressure, aging, and air surface velocity in the thermal conductivity are presented in section 3. Then, section 4 discussed how these factors influencing in the thermal conductivity. Finally, section 5 concludes the present study.

2. Thermal conductivity coefficient

Insulation materials are supposed to conduct heat badly in order to prevent large heat losses. The lower the heat conduction in a material, the less heat flows through it. The thermal performance of a building envelope depends to a great extent on the thermal effectiveness of the insulation layer which is mainly determined by its λ-value. Thermal conductivity is the time rate of steady-state heat flow through a unit area of a homogeneous material in a direction perpendicular to its isothermal planes, induced by a unit temperature difference across the sample [36]. At the microscopic level, the apparent thermal conductivity depends on numerous factors such as cell size, diameter and arrangement of fibers or particles, transparency to thermal radiation, type and pressure of the gas, bonding materials, etc. A specific combination of these factors produces the minimum thermal conductivity. At the macroscopic level, the apparent thermal conductivity largely depends on various factors, namely mean temperature, moisture content, density, and aging. Therefore, thermal conductivity coefficient is always a primary parameter measuring in every thermal calculation.

Thermal insulating materials can reduce the energy losses as well as minimize the emissions of the greenhouse gases from buildings. The choice of insulation material can have a great effect on energy efficiency in both cooling and heating, and on health problems. Heat transfer in thermal insulation materials is generally divided into heat conduction through the solid material, conduction through its gas molecules and radiation through its pores. Convection is insignificant because of the small size of the air bubbles. To develop insulation materials in an environmentally friendly manner, it is important to know their apparent thermal conductivity [14]. According to the DIN 4108, “Thermal insulation and energy economy in buildings”, materials with a λ-value lower 0.1 W/(m.K) may be classed as thermal insulating materials. Materials with thermal conductivity values lower 0.03 W/(m.K) can be regarded as very good, whereas values from 0.03 to 0.05 W/(m.K) are only moderate, and higher 0.07 W/(m.K) are less effective [16,24,37,38]. The published thermal conductivity of insulation materials are usually specified by manufactures and normally investigated under standard laboratory conditions [39–42], for example, a standardized mean temperature around 24 °C and relative humidity of 50 ± 10% [43].

3. Factors influence thermal conductivity coefficient

It is essential to examine the thermal properties of any insulation materials due to its important role affecting the heat transfer in building envelopes. Thermal properties are mainly defined by thermal conductivity, specific heat, thermal diffusivity, thermal expansion, and mass loss [44]. Among them, the thermal conductivity coefficient is the main key to measure the ability of a material to transfer or restrain heat flows through building insulation materials. At the macroscopic level, thermal conductivity largely depends on three main factors: operating temperature, moisture content, and density [33,37,42]. Other factors are a thickness, pressure, air surface velocity, and aging.

3.1. Temperature

The temperature dependency of thermal conductivity in building insulation materials has been investigated by a large number of theoretical and practical studies. Based on these results, the λ-value usually increases with increasing temperature [28,37,39,42,45–62].

3.1.1. Inorganic materials

Abdou and Budaiwi elucidated the dependence of thermal conductivity of inorganic materials under mean temperatures ranging from 4° to 43 °C. Their first study was conducted for rock wool and fiberglass with different densities [57]. Their results showed an increase in thermal conductivity values as a linear relation with mean temperatures. The variation was clearer with less density materials. An equivalent analysis of rock wool, mineral wool, and fiberglass with a thickness ranging from 5 to 100 mm in their next study indicated that higher operating temperatures are associated with higher λ-values, and the relationship is presented by a linear regression with temperature for most insulation materials [42]. Experiments with fiberglass and rock wool were observed in their third article in accordance with the impact of moisture content [63]. They assessed the changes in thermal conductivity with different densities not only the variation of operating temperatures ranging from 14° to 34 °C but also the effect of moisture content. Examination of their results continues to confirm that a higher operating temperature is always associated with higher thermal conductivity. The effective thermal conductivity of some conventional materials such as mineral wool and foam glass as a linearly increasing function at mean temperatures varying from 0° to 100 °C was studied with a protected heating plate device [47]. The λ-values of these insulation materials were 0.04 W/(m.K), 0.045 W/(m.K), and 0.05 W/(m.K) at mean temperature of 10 °C. Occasionally, inorganic open-cell materials, such as fiberglass or rock wool, have been proposed the linear temperature-dependent law that displays a decreased thermal conductivity at low temperatures [45].

3.1.2. Organic materials

The change of thermal conductivity of polystyrene (PS) and polyethylene (PE) with mean temperatures was evaluated [42,57]. The rate of heat exchanges of PE was the most sensitive to temperature, while PS insulation was the least affected, approximately of 0.000384 (W/(m.C)/°C) and 0.0001 (W/(m.C)/°C), respectively. According to the statistical data of expanded polystyrene (EPS) material in determining the impact of the temperature on thermal conductivity, Gnip et al. [64] calculated the λ-value at any point in a range temperature from 0° to 50 °C by using a calculated value of thermal conductivity at 10 °C. The relationships presented a slight increase with a rise of temperature. The changes in temperature have always been ascribed to the variation of thermal conductivity. Khoukhi et al. [65] showed that higher temperatures increase thermal conductivity for three types of polystyrene materials. Their next study demonstrated a linear rise in thermal conductivity with increasing temperatures in four PE insulation specimens with densities from low to super high [49]. Testing the effect of temperature on thermal conductivity on EPS and polyurethane (PUR) materials by using the hot wire method, Song et al. [56] revealed that at the same density, the thermal conductivity coefficient increases with increasing ambient temperature.

A series of empirical observations of some insulation materials including EPS, extruded polystyrene (XPS), PUR have shown the influence of temperature on their effective thermal conductivity [47]. The data shows the relationship between λ-values and temperatures is a linear function. An evaluation of alternative insulation materials based on sheep wool has also shown the linear increase with increasing temperature from 10° to 40 °C [66]. Koru [37] studied the effects of temperature on thermal conductivity closed-cell thermal insulation materials, namely EPS, XPS, expanded nitrile rubber (ENR), PUR, PE, and ethylene vinyl acetate (EVA) with a heat flow meter using the standards EN 12664, 12667, and ASTM C518. The results revealed that thermal conductivity increases with the rise of the range temperature between− 10° and 50 °C. Based on the empirical data, the author expressed the relationships among the λ-values and the temperature as linear equations. A similar assertion also comes from the experimental investigation of Berardi et al. [28]. Zhang et al. [8] investigated the change of thermal conductivity of five polyurethane foams occurs at temperatures varying from− 40° to 70 °C. Resembling the previous publication, Khoukhi also affirmed the incremental increases of thermal conductivity of polystyrene expanded insulation materials as the operating temperature increases when studying the combined impact of heat and moisture transfer on building energy performance [39]. Next, he continued to investigate the dynamic thermal effect of thermal conductivity at different temperatures of the same insulation materials. The experimental data showed that thermal conductivity increases linearly with temperature [67].

Besides the studies on temperature-dependent thermal conductivity of various traditional materials, there is an interesting in manufacturing natural fiber-based insulation materials with high thermal resistance. These insulators are derived from natural materials such as hemp, cotton, rice straw, or wood waste products. Manohar et al. [68] tested the apparent thermal conductivity of coconut and sugarcane fiber at a mean temperature of 24 °C with different densities. The λ-value of both biodegradable materials increased with an increase in temperature. The minimum thermal conductivity of coconut and sugarcane ranged from 0.048 to 0.049 W/(m.K) and 0.046 to 0.049 W/(m.K) showing low values when compared to some conventional insulation materials. Wood-based fiberboards are also used as thermal insulation materials due to their low density, and high thermal resistance, etc. However, they are sensitive to changes in environmental conditions because of their porous internal structures. Hence, the thermal conductivity will increase by approximately 50% as the temperature goes up from− 10° to 60 °C [50].

3.1.3. Combined materials

Bio-based materials can be used as an effective alternative product in buildings which reduce energy consumption and optimize the utilization of fossil fuels for the sake of sustainable development. Some natural materials such as hemp, flax, jute or rice straw can be combined with concrete to create material with high thermal resistance, low density, and high durability. According to the study of Rahim et al. [69], the effect of temperature on λ-values is important. The thermal conductivity of bio-based materials rose slightly with increasing temperature from 10° to 40 °C and the relationship is a linear function. The same trend was demonstrated in the work of Srivaro et al. [70], with empirical tests of some rubberwood specimens which had a linear change between their thermal conductivity and the varying temperatures. The thermal conductivity of three different samples sheep wool, goat wool, and horse mane increases significantly by approximately 55% with increases in temperature [46].

Lightweight aggregate concrete (LWAC) shows better thermal performance than conventional concrete, so, it is currently used in the construction sector [71]. The study of twelve mixtures of LWAC proved that its thermal conductivity increases with the temperature range between 5° and 35 °C [72]. A novel multilayer reflecting thermal insulation material called "mirror-panel" made from aluminum foil and coated paper using in building envelope was developed and tested to determine the temperature dependency of its thermal resistance. Experimental results showed that its thermal conductivity increases almost linearly with an increase of temperature [73].

A series of practical observations studied the temperature-dependent thermal conductivity of the composite materials [74–76]. Using water-based nanofluids, the results from measurements of Das et al. [77] and Mintsa et al. [78] showed a linear increase of effective thermal conductivity with temperature varying between 20° and 50 °C. Working with nanotube specimens, Khordad et al. [75] found that thermal conductivity increases as temperature increases. The same upward trend was also documented in a paper of Wang et al. [79] with the composite phase change materials. The data is expressed by a highly accurate linear fit. The recent study of Guo et al. [80] on aerogel blankets, phenolic, and polyisocyanurate foams has shown a linear increase in thermal conductivity by 24%, 13%, and 14% respectively when the mean temperature varies from 280° to 300 K.

3.1.4. New technology materials

The combination of technical development and advanced materials produced state-of-the-art thermal building insulation including vacuum insulation panels (VIPs), aerogels, gas filled panels (GFPs), phase change material (PCM), and closed-cell foam [10]. Among them, VIPs exhibit the lowest thermal conductivity. Its main benefit is the reduction of the required thickness of the insulation layers compared to conventional materials in buildings [81].

Fantucci et al. [82]. investigated the temperature dependence of thermal conductivity in fumed silica-based VIPs. The main advantage is its relatively low thermal conductivity in the case of a complete loss of vacuum. Experimental analyses of two samples with different thickness showed an increase up to 45% when the temperature increases from 2° to 50 °C. The next study noted that a 53% increase in thermal conductivity of the raw VIPs from 0.0049 to 0.0075 W/(m.K), and from 0.0021 to 0.0028 W/(m.K) in fumed silica over the range of temperatures between- 7.5° and 55 °C [48].

Aerogel is one of the thermal building insulations of tomorrow due to its low density, high porosity, small average pore size, and very low thermal conductivity. They have found potential practical applications for thermal insulation systems including energy storage, construction and building [83]. Several studies have investigated the effect of temperature on thermal models of aerogel composite insulation materials [84–86]. The data of Liu et al. [87]. showed a low effective thermal conductivity of silica aerogels from 0.014 to 0.044 W/(m.K) and a nonlinear increasing correlation with increasing temperature from 28° to 108 K. There was the same result of three samples of silica aerogel but different densities with temperature ranges from 300° to 700 K [86]. Thermal conductivity of aerogel blankets increased from 0.0135 to 0.0175 W/(m.K) at mean temperatures varying from- 20° to 80 °C and the relationship was almost linear [32]. Same conclusions with increasing slightly were also shown in the study of Nosrati et al. [88].

Table 2 shows practical equations to illustrate the temperature-dependent thermal conductivity of different insulation materials using data collected from articles.

A higher operating temperature is always associated with higher thermal conductivity for most insulation materials. As the temperature rises, the rate of heat conduction increases, then increasing the λ-value but within the limited temperature range, usually from- 10° to 50 °C and typically up to 20%–30%. This is the case with inorganic fiber insulation and some petrochemical insulating materials which show lower thermal conductivity at lower temperatures [45]. Additionally, the relationship between thermal conductivity and temperature is almost linear. Firstly, the measurements are focused separately on the effect of these influencing factors. Secondly, the experimental conditions are set up in a steady-state condition. According to the American Society for Testing and Materials ASTM-C518 standard, thermal conductivity is only given for standardized conditions and most of the published thermal conductivity values from experimental investigations as well as from manufacturers from laboratory work [37]. However, weather conditions, exterior temperature, and moisture values vary over the course of a day. Therefore, it is important to determine the thermal conductivity of insulation materials and their dependence on temperature.

Table 2
Temperature-dependent thermal conductivity shown as a linear function of insulation materials.

Main group	Insulation Materials	Relationship	Mean temperature (°C)	Reference
Inorganic	Rock wool	1.915e–4 × T + 0.0336	4–43	[42]
materials	Fiberglass	3.01e–4 × T + 0.0281	14–39	[89]
		3.368e–4 × T + 0.0414	4–43	[42]
Organic materials	EPS	1.476e–4 × T + 0.0356	0–50	[64]
		5e–5 × T + 0.0347	10–43	[67]
		6e–5 × T + 0.033	10–43	[39]
	XPS	1.045e–4 × T + 0.0276	10–43	[42]
	EVA	8.46e–5 × T + 0.03746	−10–50	[37]
	PE	3.19e–4 × T + 0.04589	−10–50	[37]
	PIR	2e–4 × T − 0.0273	7–27	[80]
	PUR	1.71e–4 × T + 0.027	0–100	[90]
	Hemp	2e–4 × T + 0.047	10–40	[69]
	Sheep wool	2e–4 × T + 0.0349	10–40	[66]
	Coconut	2.84e–6 × T + 0.0487	10–40	[68]
	Bagasse	2.38e–4 × T + 0.0456	10–40	[68]
	Rubberwood	4e–4 × T + 0.1246	−10–40	[70]
Combined materials	Wood wool	3.06e–4 × T + 0.0607	4–43	[42]
New materials	VIPs	4e–5 × T + 0.0049	−15–63	[48]
	Aerogel blanket	5e–5 × T + 0.0166	−10–50	[88]

3.2. Moisture content

In the normal environmental conditions around buildings, all these three stages of moisture (solid, liquid, gas) can be dangerous for building materials. Excessive moisture causes the following five problems: deteriorated habitation quality, reduced thermal resistance, additional mechanical stresses, salt transport, and material decay. This phenomenon is due to both obvious as well as more inconspicuous causes: moisture intrusion into building interior due to contact with liquid water, moisture deposition on the building surface due to contact with water vapor, moisture intrusion into the building due to contact with water vapor and built-in moisture [91]. For building envelopes, insulated walls, and roofs, moisture can diminish their effective thermal properties. Additionally, moisture migrating through building envelopes can also lead to poor interior air quality as high ambient moisture levels cause microbial growth, which may seriously affect human health and be a cause of allergies and respiratory symptoms [92]. As the thermal conductivity of water is about 20 times greater than that of stationary air, water absorption is always connected with an increase in thermal conductivity [24]. Therefore, it is crucial to study the impact of moisture on thermal performance, especially in building insulating materials.

It is essential to measure the initial and the increased moisture content of building insulation materials. Various techniques have been suggested for each type of measurement such as drilling techniques, electrical techniques, environmental monitoring, thermographic imaging [93]. Zhang et al. measured the moisture content from the change in volumetric heat capacity before and after the moisture acquirement using a hot wire [94]. The same method was adopted in another investigation but using the transient temperature [95]. The moisture content of a building material is calculated based on the weight of absorbed moisture to the dry weight of the material. According to the ASTM C1616, the moisture content of organic and inorganic insulation materials by mass is calculated from the following equation:

$$w = \frac{m - m_d}{m_d} \tag{1}$$

where w is the moisture content (%), m_d is the mass of the dried sample (kg), m is the mass of damped sample (kg).

3.2.1. Conventional materials

Some experimental investigations in building insulation materials including mineral wool, fiberglass, and polystyrene have found that an increase of thermal conductivity is always associated with rising moisture content [50,96–98]. Lakatos observed a slight increase of up to 0.2 W/(m.K) for mineral wool and fiberglass samples with varying of moisture content from 0 to 100% [98]. His previous study with extruded polystyrene (XPS) confirmed the influence of moisture content on thermal conductivity [99]. Jerman et al. [97] concluded that thermal conductivity of mineral wool rises quickly from 0.041 W/(m.K) to approximately 0.9 W/(m.K) with rising moisture content. Another investigation was concluded, in which the thermal conductivity of mineral wool increased from 0.037 to 0.055 W/(m.K) with increasing moisture content from 0% to 10% by volume [16]. Conversely, expanded polystyrene (EPS) is only slightly affected by an increase of moisture content. Its value was 0.037 W/(m.K) in a dry state and 0.051 W/(m.K) in saturated conditions. Another study investigated thermal performance by cooling polystyrene insulation materials documented the rise of thermal conductivity due to the increases in moisture content [39]. An increase of thermal conductivity of mineral wool can reach a maximum of 446% with increasing moisture content of 15% [63], compared to the thermal conductivity of rock wool which can increase 312.8% with an increase in moisture content of 13.6% in the latest study of Gusyachkin et al. [96], and thermal conductivity of fiberglass increases nearly 300% by the time if it gained 3% moisture [100]. It can be explained by the initial moisture content. Samples with higher initial moisture content always show higher percentage change of thermal conductivity.

Most of building insulation materials are normally porous and their the coefficient of thermal conductivity usually ranges from 0.02 to 0.08 W/(m.K) [101]. Due to the high porosity, porous materials can absorb large amounts of moisture under high humidity conditions resulting in an increase in the thermal conductivity coefficient [54]. A study of Liu et al. [102] showed that thermal conductivity of foam concrete rose rapidly in the low volumetric fraction of moisture content and slowly increased with increased moisture. The authors later measured the influence of water content on the thermo-acoustic performance of building insulation materials [103]. Samples of high porosity insulation materials were treated by heat treatment through some steps before measuring with the transient plane method to assess how thermal conductivity is influenced by water content. This showed a linear increase for four types of specimens including mineral wool, melamine foam, polyurethane, and cork. When the building materials are moistened, wet insulation can increase to the maximum ratio of thermal conductivity between the dry and wet samples by 3.51 with a maximum moisture content of 15.1% in the ambient temperature ranged from 24.9° to 38.6 °C after 55 days [104]. Thermal conductivity increases by approximately 200% when the moisture content reaches 10% in foam concrete [102]. In contrast to the above conclusions, another study with wood frame insulation walls made of spruce-pine-fir concluded that there was no obvious effect on thermal conductivity since moisture content was less than 19% [105].

A study carried out by Gawin et al. [106] measured the impact of the initial moisture content on the thermal conductivity of wood-concrete and EPS-concrete materials using a heat flow meter. The results showed an increase of thermal conductivity with increasing the water content in the range of 70%–85% relative humidity. Using the same lightweight specimens but with different densities, Taoukil et al. [107] also confirmed the influence of relative humidity on thermal properties. Thermal conductivity rose rapidly with water content and was presented as an exponential equation. The next laboratory study from Nguyen L.H. et al. [72] contributed to the assumption of the moisture dependence of thermal conductivity of lightweight concretes. In this case, the result showed a linear relationship.

3.2.2. Alternative materials

In recent years, thermal protection used of natural fibrous materials, agricultural wastes, forest product wastes as the raw materials of thermal insulation products. Therefore, the amount of harmful waste gas caused by petrochemical insulating materials in the atmosphere will decrease. However, these kinds of materials are more sensitive to moisture, so, it is necessary to evaluate their thermal performance due to the change of relative humidity. The moisture dependence of thermal conductivity values of different insulating materials made from hemp, jute, and flax was investigated in the study [108]. Results showed a high increase of thermal conductivity with increasing moisture content. Data for the effect of water content in thermal conductivity of three bio-based concretes derived from hemp, jute, flax noted that there is a linear increase in λ-values as the moisture content increases and its effect is more crucial due to the increase of thermal conductivity of air and water at high temperature [69]. An experimental study on the effect of humidity on thermal conductivity of binderless board made from date palm fibers was investigated in a study of Boukhattem et al. [109]. It showed a significant increase with volumetric water content ranges from 0 to 40% and the relationship was expressed as a polynomial function. As a result, date palm fiberboard can be used as insulation materials in buildings due to its low thermal conductivity of 0.033 W/(m.K) in a dry state. The effect of moisture content due to the changes of relative humidity on thermal performance of wood-based fiberboards was evaluated. Thermal conductivity increased almost linearly with increasing moisture content [50]. The tests carried out on twenty-four soft fiberboards made from wood fibers also showed that thermal conductivity increases linearly with increasing moisture content [110]. Abdou and Budaiwi [63] investigated the thermal performance of eleven different fibrous materials at different percentages of moisture content. The results showed that higher moisture content is always associated with higher thermal conductivity for different densities. The data fit a linear relationship for almost all the specimens except for mineral wool which was expressed by a non-linear function.

The natural insulators show a low value of thermal conductivity and better thermal technical characteristics than other conventional materials. However, a major drawback is their high wettability and absorbability due to an open structure of natural fiber, which can negatively affect the mechanical and thermal properties. Natural fiber can be activated with silane surfactant to combat effectively hydrophilicity and prevent rotting [111]. Some different products for hydrophobic treatment were chosen to deal with the water absorption and hygroscopicity of hemp fibers in the study. It was found that the hydrophobic-treated fibers have shown lower short-term absorbability compared to untreated ones [112].

3.2.3. Advanced materials

Aerogel is one of the new insulating materials, commonly used in construction due to its nano-porous structure and excellent thermal conductivity between 0.014 and 0.022 W/(m.K). In these studies [113, 114], there are some experimental steps, in which the thermal conductivity of aerogel in the form of blankets is significantly effect by the moisture content. The first one documented that the thermal conductivity increases by up to 15% as the relative humidity increases from 0% to 90%. Whereas the second study showed an increase by 36% in thermal conductivity in the same range of relative humidity. An increase in the thermal conductivity of aerogel-enhanced insulation materials due to high levels of moisture content was observed in the study [88]. Results showed that the thermal conductivity increased in a wide range of relative humidity from 0% to 95%. Additionally, there was a correlation between the density distribution and the increase in the λ-values in which the lower the density the lower the increasing rate of thermal conductivity.

The most beneficial conclusion from numerous studies mentioned above, is to elucidate the crucial impact of moisture content on thermal conductivity. As a result, thermal conductivity increases with increasing moisture content due to the presence of liquid phase. Moisture content is related to thermal conductivity in accordance with a linear law for most insulation materials. However, some experimental investigations of mineral wool and foamed insulation materials showed non-linear equations [46,66]. It could be caused by an increase in the quantity of air from the increasing the number and size of cells. Another reason could be the accuracy of experimental measurements and variable laboratory conditions or the imperfections of the materials. Supposing that higher moisture content increases thermal conductivity, Table 3 presents the increased linear between the λ-values and the moisture content of building insulation materials.

Table 3
Thermal conductivity as a linear function of moisture content.

Main group	Insulation Materials	Relationship	Moisture range (%)	Reference
Conventional materials	Fiberglass	4.6e–5 × w + 0.0372	0–50	[63]
		1.023e–3 × w + 0.0323	0–35	[89]
	Rock wool	1e–5 × w + 0.0398	0–50	[63]
	EPS	7e–4 × w + 0.035	0–80	[99]
		0.017 × w + 0.039	0–40	[67]
	PUR	0.00187 × w + 0.039	0–80	[100]
	Fiberboard	2.31e–4 × w + 0.0383	0–14	[110]
Alternative materials	Bagasse	7.2e–4 × w + 0.08807	5–30	[115]
	Hemp	0.298 × w + 0.118	0–80	[69]
	Flax	0.365 × w + 0.157	0–80	[69]
	Straw	0.239 × w + 0.088	0–80	[69]
Advanced materials	Aerogel	0.2 × w + 0,01859	0–6	[114]

3.3. Heat and moisture transport

Both operating temperature and relative humidity have a significant influence on the thermal energy performance of insulation materials. Employing experimental analyses, most of the studies have focused on determining the influencing temperature and moisture content in thermal conductivity in a steady state in which its value can be determined independently at a mean temperature and specific humidity. In reality, it is essential to determine a simultaneous calculation of the effect of influencing factors such as temperature, moisture levels, air velocity, and thickness in thermal conductivity due to the heat transport transient process. Therefore, many scholars focused on the combined effect of heat and moisture transfer simultaneously on the insulation λ-values of materials, based on numerical simulation and experimental investigation [50,72,92,99,116–119].

A numerical problem was modeled to study four stages of heat and moisture transfer in porous insulation materials [120]. The result showed that the effective thermal conductivity increases with increasing ambient humidity. The energy transfer in a multilayered building envelope was investigated through the coupled heat and moisture transfer. Modeling the problem in two dimensions and using the Comsol program [121], Liu et al. analyzed the change of temperature due to the change of moisture transfer with space and time in both horizontal and vertical directions. In order to obtain the actual thermal conductivity in the combined heat and moisture transfer mechanism of porous materials, i.e., normal concrete, clay brick and aerated concrete, Wang et al. [122] built a mathematical model calculating the actual thermal conductivity caused by moisture, different temperatures, and humidity. From the numerical model, there is an increase in the actual thermal conductivity when the temperature decreases, and the water vapor pressure increases. Khoukhi examined the combined effect of temperature and moisture content on the change of thermal conductivity of polystyrene materials and their impact on the energy performance of building [43]. The findings confirmed the increase of thermal conductivity as temperature and moisture content increase and the results can be used for reference to other insulation materials.

3.4. Density

3.4.1. Traditional materials

The density dependence of thermal conductivity of polystyrene, fiberglass, and mineral wool was investigated at various mean temperatures [42]. The thermal conductivity of expanded polystyrene (EPS) decreases from 0.043 and reached the minimum value of 0.032 W/(m.K) with rising density from 14 to 38 kg/m^3 at a mean temperature of 10 °C [64]. There was no discussion for this behavior in the article, however, it may be explained by the air bubble sizes of porous materials in case of low density which are bigger than in the higher density foam materials. The higher bubbles provide more intense heat transfer through the material. As the density increases the air bubbles will be smaller and the frame structure become more complex. In the smaller bubble the heat transfer is lower, and additionally the more complex solid matrix system has a higher thermal resistance. By increasing the density, the solid content of the system will be higher consequently the thermal conductivity of solid parts become more dominant. These three phenomena (bubble size, complexity of the frame, amount of solid content) results an effective thermal conductivity which can reach a minimum value. Another study also found that the thermal conductivity of EPS decreases with increasing density in the range of 10 and 25 kg/m^3 and the relationship was expressed by a linear function [123]. It is known that increasing density of the foam materials led to decreasing air content and size of the air inclusions. In this case, the convection of air and gas conduction are insignificant, and the heat flow is directed by the conduction of the solid particles resulting the decreased thermal conductivity. The experimental data of Khoukhi and Tahat contributed to the assumption that higher density produces lower thermal conductivity. In their first study [65], they measured thermal conductivity of three polystyrene samples with different densities at four different temperatures varying from 10° to 43 °C using the guarded hot plate method. The result showed that lower material density leads to higher thermal conductivity values. An equivalent experiment was conducted to support this hypothesis in their next studies [49,124]. When testing four heat-insulated EPS and PU samples at the same temperature, the thermal conductivity first went down and then increased with an increase in density and reached its minimum value at 0.029 W/(m.K) and 0.026 W/(m.K) in the range of 17 to 18 kg/m^3 and 30 to 45 kg/m^3, respectively [56]. Experimental studies of 17 different inorganic samples were investigated with changing densities from 8.9 to 60 kg/m^3 [37]. It is seen that the thermal conductivity decreases with increasing density for the same types of materials. Furthermore, the thermal conductivity of specimens having lower densities increased faster the others.

3.4.2. Alternative materials

Although conventional materials are mainly used in buildings, alternative materials derived from natural sources also show the same performance requirements in heating. A study with open-cell insulation materials which are made from hemp fibers found that a reduction of thermal conductivity with an increase of density due to the condensation inside the sample [125]. Whereas, the thermal conductivity of concrete-based hemp fibers increases by about 54% when the density increases by 2/3 [126]. The test of sheep wool showed the thermal conductivity decreases by up to 21% at 40 °C when the bulk density increases 50%, from 20 to 40 kg/m^3 [66]. However, Sekino concluded the opposite trend in his experiment with cellulose fibers [127]. The λ-values increase slightly by approximately 5% with increasing density from 20 to 110 kg/m^3. To explain this conclusion, a parameter named "the apparent thermal conductivity" was created to elucidate how density affects λ-values. The number of heat bridges formed by cellulose fibers increases with rising material density which causes increased thermal conductivity. The same result in investigating the effect of moisture on thermal conductivity at various of densities was obtained experimentally with three bio-based materials: hemp concrete, flax concrete, and rape straw concrete. It is showed that dry thermal conductivity was expressed as a linearly increasing function of the dry density [69]. Another study of G. Balčiūnas et al. [128] demonstrated that the thermal conductivity of hemp shives composites depends on 97% of density and the relationship shown as a multiple regression equation. Also, this specimen had low thermal conductivity from 0.055 to 0.076 W/(m.K) within the range of 210 to 410 kg/m^3 due to the low density of the sapropel binder addictive. Among the different types of natural fibers, coconut fiber has been used as the potential lightweight material when using as reinforcement in a composite. A study of three types of coconut samples exhibited that thermal conductivity decreased from 0.052 to 0.024 W/(m.K) with an increase in density from 30 to 120 kg/m^3 [129].

Table 4 shows the increased linear of some fibrous insulation materials.

3.4.3. New technology materials

A model consisting of aerogel, calcium silicate and xonotlite-aerogel composite insulation materials was built to determine the effect of their densities on their thermal conductivity [86]. In the range of optimal density from 110 to 160 kg/m^3, the thermal conductivity of aerogel reached the minimum value of approximately 0.016 W/(m.K) and the density of calcium silicate was the key factor to affect the λ-values of the aerogel composite. Moreover, with an increase of the density of the silicate up to 250 kg/m^3, the thermal conductivity of the aerogel composite increased by 200%. The relation between thermal conductivity and density is nonlinear, the limiting low value of thermal conductivity is 0.012 W/(m.K) which is denoted for density as 150 kg/m^3 [131]. Investigation of VIPs with wood fiber core materials noted that their thermal conductivity increases slowly with increasing density less than 240 kg/m^3 and rapidly increases since the density reaches 260 kg/m^3 [132].

Table 4
Thermal conductivity as a linear function of density.

Insulation Materials	Relationship	Density range (kg/m^3)	Reference
Cellulose fiber	$1.73e{-}4 \times \rho + 0.0262$	20–110	[127]
Hemp concrete	$2.37e{-}4 \times \rho + 0.0196$	200–600	[69]
Flax concrete	$2.48e{-}4 \times \rho + 0.0192$	200–600	[69]
Straw concrete	$1.61e{-}4 \times \rho + 0.0221$	200–600	[69]
Straw bale	$1.9e{-}4 \times \rho + 0.045$	50–130	[130]

3.5. Thickness

It is a common understanding that the thicker the insulation, the lower the heat transfer through it [133]. However, thermal conductivity is not dependent on the thickness of insulation, which instead affects its thermal resistance [134].

Lakatos et al. investigated the dependence of the thermal conductivity on the thickness of the expanded materials [123]. They proved that thermal conductivity does not depend on the thickness of the specimens, contrary to the R-values. The thermal resistance increased regarding to the calculated data from the measurement. In another study with sheep wool, the thermal resistance showed an increase with increasing thickness of samples from 40 to 80 mm at varying of mean temperature [66]. Mahlia et al. evaluated the correlation between the thickness and the thermal resistance of fiberglass, urethane, EPS through the thermal conductivity values [135]. The main objective of the research was to point out the optimum thickness to achieve the highest thermal conductivity or the lowest thermal resistance.

The impact of thickness on the thermal transmittance of expanded polystyrene, glass wool, and wood cement board for the external wall structure has been investigated [136]. For construction, the thermal transmittance and its thermal resistance have a reciprocal relationship; the lower the thermal transmittance, the higher the thermal resistance; and consequently, the higher thermal insulation of wall structure. The results indicated that the thermal resistance increased for all three types of insulation material as the thickness increased up to 0.2 m. In addition, there is a critical thickness for the thermal insulation of the external wall. One of the popular ways to improve thermal performance is to use an enclosed air layer in exterior building envelopes since the air has low thermal conductivity. Zhang et al. found that the thermal resistance increased by 14.77% when the thickness of the air layer increased from 10 to 20 mm, but the effect was limited when the thickness exceeded 20 mm [137].

Insulation thickness with material costs, energy saving, and energy consumption was investigated in some studies whose data is shown in Table 5.

3.6. Air surface velocity

Air surface velocity can affect the heat transfer coefficients, and therefore, it can affect the heat transfer process. Higher the rate of air movement across a surface, higher is the rate of heat transfer, and consequently, higher the surface coefficient [141]. The outside surface convective heat transfer coefficient is a function of windward speed which varied from 1 to 10 m/s in a study. From this relationship, the higher the rate of air speed across a surface, the higher the rate of heat transfer through the building envelope. Consequently, the higher heat transfer coefficient resulted in the moderation in the temperature difference between outdoor and indoor temperature. Therefore, it influences the thermal performances of insulation materials. Effects of wind velocity and orientation were investigated considering four surface-to-air temperature differences [142]. Results showed that the

Table 5
Insulation thickness with material cost energy saving, and energy consumption of various thermal insulation materials.

Insulation Materials	Thermal conductivity (W/(m. K))	Thickness (mm)	Material cost ($/m^3)	Energy Saving ($/m)	Energy Consumption (MJ/f. u. kg)	Reference
Rock wool	0.04	50	95	6.2	53.09	[134,138,139]
Glass wool	0.038	50	155	5.6	229.02	[15,139]
Fiberglass	0.05	50	350	25.6	–	[139,140]
XPS	0.035	50	224	27.2	127.31	[37,134,139]
EPS	0.035	50	155	28.4	80.8–127	[15,30,37, 139]
PUR	0.022	50	156	–	99.63	[15,139,140]
PIR	0.025	25	152	–	69.8	[15,139]
VIPs	0.008	5	247	–	149–226	[15,139]
Aerogels	0.015	20	547	–	53.9	[15,139]

wind velocity strongly affects the convective heat transfer coefficient, in which the wind direction had a notable effect for vertical walls and roofs, but the surface-to-air temperature difference had a negligible effect for wind velocity higher than 2 m/s. The obtained results are also useful for designing appropriate building envelopes. Moreover, when calculating the thermal properties of buildings and constructions, surface resistance should be considered on the outside and inside of the structure. Surface resistance generally comprises of the combined heat transfer by radiation and convection, it can be increased by decreasing the air velocity and can be used to calculate the energy need for heating or cooling [143].

In the laboratory, where sample is well-insulated and well-protected from the wind, there is negligible influence on the permeability of the insulation materials. However, in real climate conditions, there is a significant impact of wind on thermal performances of building envelopes, which has not yet been determined. Excellent thermal performance can be achieved by using thicker layer, higher airflow velocity, or lower thermal conductivity of porous material. The heat flux entering the indoor space can be reduced to practically zero, when the exhaust airflow velocity in porous layer reaches to 0.003 m/s [101].

3.7. Pressure

The most commonly used insulation materials in buildings are fibrous insulations. Heat transfers through a fibrous insulation involves combined modes of heat transfer: solid conduction through fibers, gas conduction and natural convection in the space between fibers, radiation interchange through participating media. If solid and radiative contributions are independent of gas pressure, changing pressure affects the effect of gas conduction to the effective thermal conductivity. This contribution investigated by Zhao et al. [144]. The results noted a significant increase in effective thermal conductivity of fibrous insulation materials from 0.01 to 0.04 W/(m.K) with an increase of pressure from 10^{-2} to 10^5 Pa.

Vacuum insulation panels (VIPs) are effective thermal insulators due to their lower thermal conductivity compared to other traditional insulation materials. The thermal conductivity coefficient of VIPs at vacuum pressure varied in the range of 0.001 to 0.002 W/(m.K). Some conventional materials used as the core in VIPs such as glass fiber, polyurethane foam, or polystyrene foam showed an increase in λ-values with increasing pressure in the range from 10 to 10^5Pa [145]. For instance, the thermal conductivity of extruded polystyrene showed an increase from 0.006 W/(m.K) at 10 Pa to 0.031 at 10^5 Pa [146]. A possible explanation is that the thermal conductivity of air inside the pore structures increases when the pressure increases from vacuum to ambient over the time [147]. Another potential insulation material, aerogel, has low thermal conductivity of approximately 0.0135 W/(m.K) at ambient pressure and can be reduced to 0.004 W/(m.K) at a pressure reduced to 50 mbar [83]. Liu Hua et al. [87] documented the effective thermal conductivity of silica aerogel increased nonlinearly from 0.014 to 0.044 W/(m.K) with raising the pressure using the inverse method. The other specimens of aerogel and xonotlite calcium silicate also showed a considerable decrease in thermal conductivity with a drop of pressure, and approach to a constant when pressure is less than 10^4 Pa, and 10^2 Pa, respectively [86]. The same trend was also derived from the experimental study of Tang et al. [61].

3.8. Aging

It is generally known that the mechanical properties and thermal performances of insulation materials alter significant over the time. One of the most impactful aging influences on the thermal conductivity is the diffusion of the highly insulating blowing agents, and the infusion of air from the environment which may absorb moisture into the material [148]. Bhattacharjee et al. has first given the model of thermal conductivity of foam insulation materials which experience three stages throughout their aging process [149]. The impact of environmental aging, through exposure to high temperature and moisture on the temperature and humidity dependent conductivity of polyurethane (PUR) and polyisocyanurate (PIR) foam materials has investigated in the study [148]. Results showed that the thermal conductivity of closed-cell PUR is much higher after the aging from 1 to 4.5 months and the change in the first month is greater than the rate change later in the process. Whereas the effect of aging in the open-cell PUR is minimal but the initial λ-value is higher than the measured closed-cell materials. In case of determining the moisture dependent conductivity, all samples were stored in the chamber to expose the materials from dry state to relative humidity of 90%. The effective thermal conductivity was subsequently observed that there was a slightly increase with higher humidity, especially at very low temperature. In the latest study of Winkler-Skalna et al. [90], the changes in the effective thermal conductivity of five PUR samples with the effects of density, thickness, and average temperature after the aging was analyzed. The first stage is to determine the initial thermal conductivity values at different mean temperature before heating for 7 days, 21 days, 90 days, and 175 days. For most PUR types, the highest increment in the value of λ coefficient with mean temperature was noted in the 7 days and 21 days of conditioning. Meanwhile, there was a distinct drop in the rise of the λ coefficient with increasing density from 40 kg/m^3 to 80 kg/m^3. To investigate the effect of the age of materials on the effective thermal conductivity of foam insulation, Berardi observed the impact of temperature and moisture content on thermal conductivity in a pristine condition and after heating for 4.5 months [148]. As a result, there is a minimal increase in thermal conductivity with temperature of polyurethane materials after aging. It is explained by the diffusion of gas in the material of lower density, because the lower is the apparent density of the foam material, the higher the percentage of gas filling up the cells, and thus the higher the impact of aging.

The main aging mechanism of VIPs are moisture penetration and air impact in which air causes the pressure growth inside the materials and moisture can penetrate the core structure [131]. The influence of aging on thermal properties was also tested for VIPs in some studies [146, 150]. Fantucci et al. [48] evaluated the changes in thermal conductivity of VIPs with aging. It showed a rapid increase of λ-values from 0.0048 to 0.0051 W/(m.K) after the first 20 months and a slow increase between 8% and 10% for the next 20 months. Generally, in order to predict the aging influence and further exceed the service life of VIPs, it is essential to determine the gas and water vapor permeance velocity as well as the relation between these parameters and the materials properties, size, and temperature of the VIPs.

In general, evaluation of the effects of aging through the temperature, moisture, density on the dependence of thermal conductivity is very useful to develop the hygrothermal models in order to assess how insulation materials perform over the life cycle of a building under real environmental conditions.

4. Discussion

Insulation materials can be classified as conventional and state-of-the-art materials. Specifically, conventional materials are fibrous materials including inorganic such as fiber glass, mineral wool (rock wool, glass wool) or natural/bio-based insulation materials and organic, like, polystyrene, polyurethane (PUR), polyisocyanurate (PIR). Besides, recent applications in building envelopes are using innovative materials such as vacuum insulation panels (VIPs), aerogel due to their high thermal resistance. Most of commonly used building insulation materials considerable influenced by the environmental conditions due to their porous structure and the proportional of air or other gas filling up the cells. The heat conduction of an insulator is strongly influenced by several factors: temperature, moisture content, density, aging time, along with secondary factors such as raw material, cell gases, nature and microstructural of solid component, air surface velocity, pressing, and sample thickness. A comparison of thermal conductivity and density in common building insulation materials collected from published studies are shown in Fig. 1 [8,12,28,32,35,37,42,46–48,63–66,80,89,96,151–157]. Materials having low thermal conductivity (below 0.05 W/(m.K)) and low density (below 100 kg/m^3) are placed in the first group. These are the most commonly used insulation materials in buildings today. The second group with aerogel and VIPs also has low thermal conductivity, but higher density than that in the first group. The last group shows materials with the highest thermal conductivity and the highest density.

Due to the fact that molecule movements is the basic of heat conduction, the temperature has a huge impact on thermal conductivity of insulation materials. Fig. 2 shows an increase in thermal conductivity for four groups of insulation materials with increasing mean temperature from - 10° to 50 °C [28,37,42,48,66,68,69,88]. Fibrous insulation materials such as fiberglass, hemp fibers, flax fibers, cellulose fibers, sheep wool are more affected by temperature than other insulation materials. Besides, thermal conductivity of samples having lower densities increased faster in relation to the increase in temperature. In other words, low density implies large pore volume and much more air content which causes a greater effect of operating temperature on λ-values. Additionally, the starting thermal conductivity of the open cell materials (fiberglass, rockwool) is much higher than that of the closed-cell materials (XPS, EPS, PUR). due to the high initial moisture content of the samples. Also, the thermal conductivity of aerogel and VIPs may be 2–3 times lower than that of conventional insulating materials. The increase in the thermal conductivity of new advanced materials is subjected to high levels of temperature, moisture content, and aging effect. Combined insulation materials also exhibit temperature-dependence due to the high density and water absorption from surroundings. It is reported that the temperature-dependent laws is linear.

Changes in thermal conductivity due to moisture variations can be explained by a shift in the division of the thermal and humidity distribution in the structure, which alters the sorption properties of the material. Fig. 3 [63,66,88,115,158] illustrates the changes in thermal conductivity as the moisture content increases. The thermal conductivity of natural fibrous insulating materials rises more sharply than that of foam materials for the same increase in moisture content at the same temperature of 24 °C. Since the fibrous materials are naturally hygroscopic and have a porous structure, they can accumulate moisture by adsorption from the air. The ability of moisture to penetrate into the internal open pore system at increased relative humidity significantly affects the temperature distribution as well as the thermal conductivity. Examination of results revealed that higher moisture content is always related to higher thermal conductivity for all densities. In addition, samples with higher density generally exhibit larger changes in λ-values at the same moisture content. Materials having similar density but conditioned at different initial moisture content exhibit different relationships between the thermal conductivity and moisture content. The rate of change in thermal conductivity with moisture content is higher at higher initial moisture content. The lower the density of open-cell insulation materials, the higher the effect of moisture content on the thermal conductivity. An increasing in thermal conductivity of aerogel with increasing moisture content reflects that the hydrophilic properties of the materials need to be investigated for use in building and construction.

Recent studies confirmed that thermal building materials are considerably influenced by moisture and to a lesser degree, by ambient

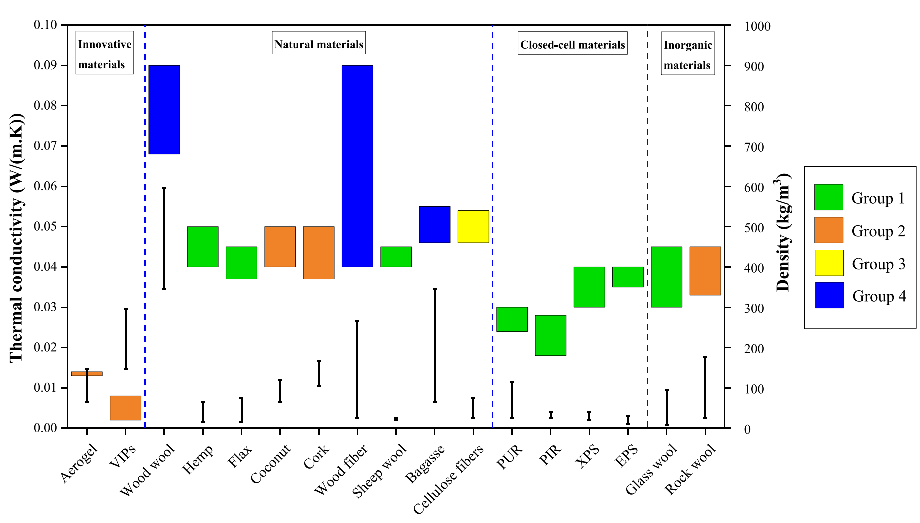

Fig. 1. Comparison of thermal conductivity and density in common insulating materials.

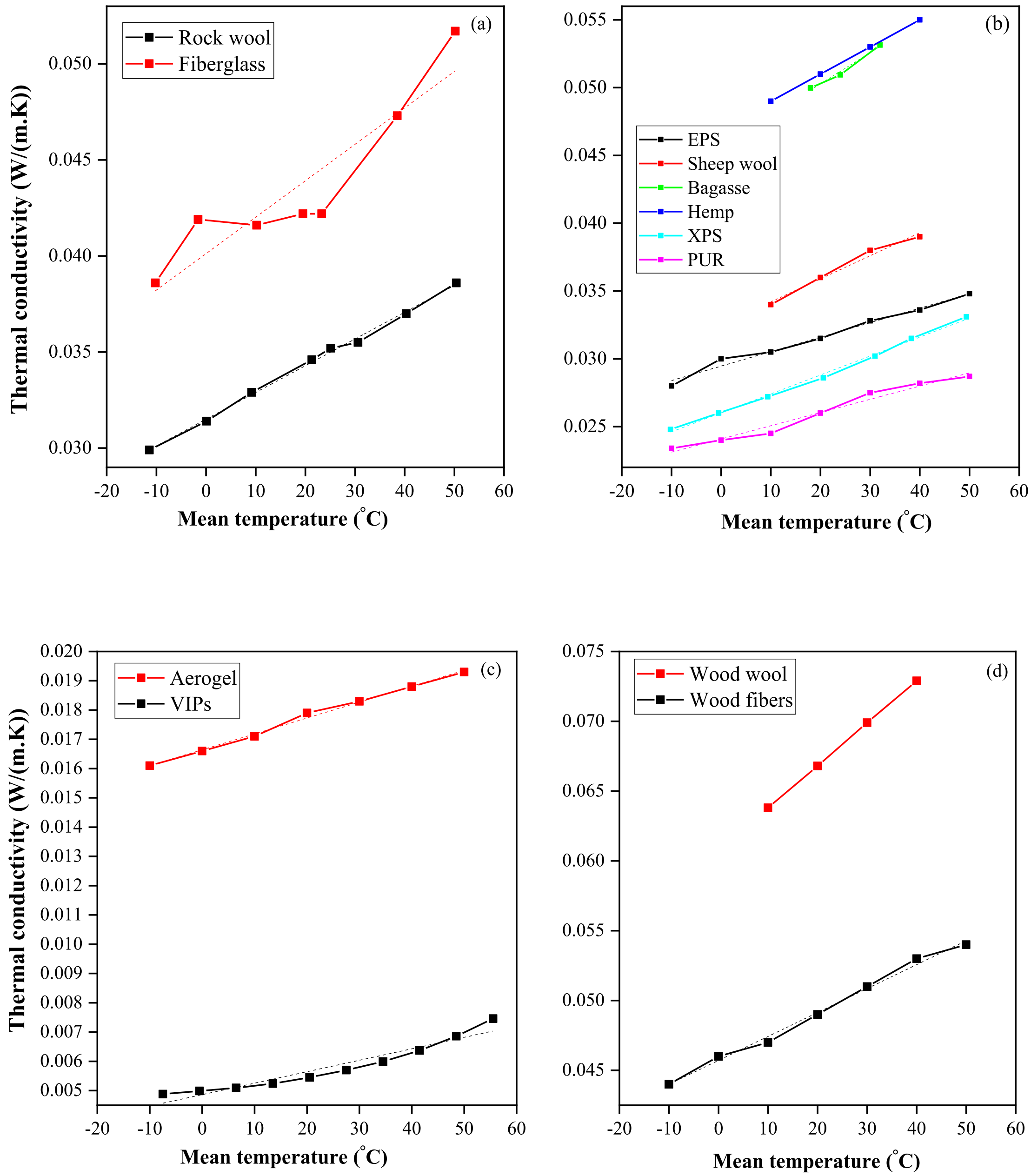

Fig. 2. Effect of mean temperature on thermal conductivity of various building insulation materials: (a) inorganic materials; (b) organic materials; (c) advanced materials; (d) combined materials.

temperature. Due to the accumulation of moisture on the surface of a building envelope, some vapor condenses into liquid and changes the relative humidity. This leads to an increase in thermal conductivity by an extent greater than that caused by the temperature variation. However, these studies have primarily focused on foam insulation materials with a large moisture content and latent heat storage capacity. Hence, it is crucial to study the combined effect of heat and moisture transfers on the thermal conductivity of building components.

The density is critical for the thermal performance of an insulating material. Fig. 4 illustrates the variation in thermal conductivity at mean temperature of 24 °C with density of conventional insulation materials (Fig. 4a) and natural fibrous insulating materials (Fig. 4b). Generally, the most favourable densities range for practical investigation falls between 20 and 140 kg/m^3.

For closed-cell materials, it can be stated that high density shows low thermal conductivity. At densities range from 20 to 40 kg/m^3, the thermal conductivity of EPS, XPS, and PUR insulation materials shows the trend that decreases as density increases as shown in Fig. 4a [37,42,63]. It is because higher density means smaller pores and less than air volume, resulting in the heat flow through the materials is mainly governed by the thermal conduction of the solid particles, while the effect of the heat transfer by convection and radiation becomes insignificant. This causes a decrease in λ-values. Besides, the variation in thermal conductivity values of EPS and PUR can be explained by the difference of microstructure, porosity, and pore dimensions of the foam insulation materials. The thermal conductivity of open-cell materials also shows the linear decrease as the density increases in the range of 40 and 140 kg/m^3 and the changes in thermal conductivity values of mineral wool and fiberglass can be explained by the air bubbles present in the porous structures. Besides, the effect of density on thermal conductivity of open-cell materials is generally lesser than that of closed-cell materials. It is because the diffusion of gas in the foam materials; the higher the apparent density the lower the proportional of gas filling up the cells, and thus the lower the impact of other influencing factors like

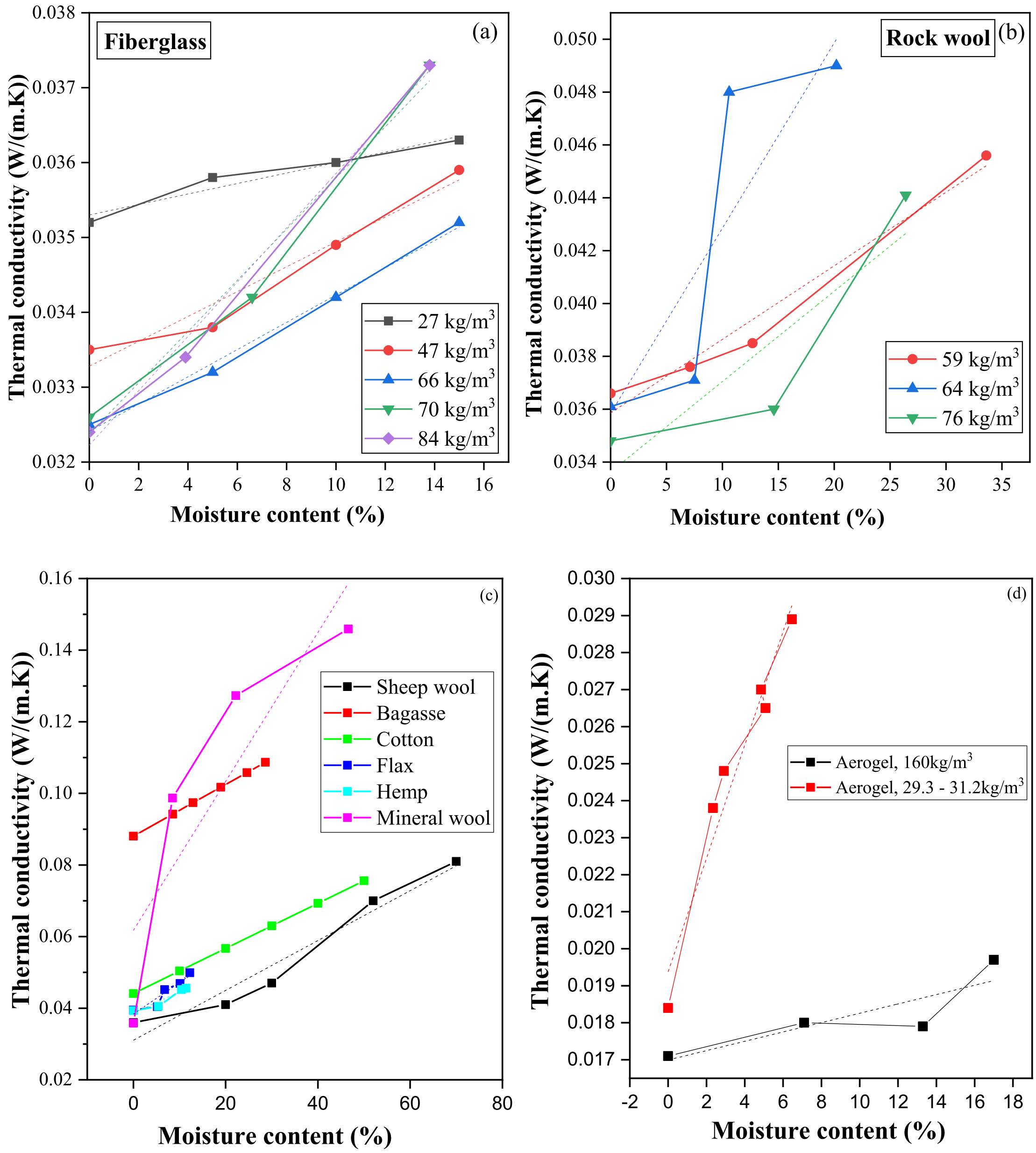

Fig. 3. Effect of moisture content on thermal conductivity of various building insulation materials: (a) fiberglass, (b) rockwool; (c) natural materials; (d) aerogel.

mean temperature, moisture content, or aging. On the other hand, fibrous materials such as bagasse, palm, coconut fibers showed the variation in which the thermal conductivity decreased to a minimum and then increased as density increased from the minimum possible value upwards [66,129,155]. This behavior shows the same reaction with the result in article [64], therefore, it can be explained by three phenomenon include bubble size, complexity of the frame, and the amount of solid particles. Besides, the non-linear decrease may come from the reduction of wettability and absorbability due to a reduction of the voids in open structure of the natural fiber since increased density. The decreased thermal conductivity may be explained by the heat conduction mechanism, if fibrous materials are high density, thermal conductance through the solid particles is more important than both radiation and convection. In this conduction, the thermal conductivity is decreased whit the density increases. Additionally, it is also shown that an increase in solid fiber density reflected an increase in thermal conductivity values of the fibrous batt after reaching the minimum value and it is consistent with loose fill materials having higher thermal conductivity than closed-cell insulation materials.

5. Conclusions

This comprehensive review provides a detailed discussion on the factors influencing the thermal conductivity of insulation materials. Temperature, moisture content, and bulk density are the primary factors significantly affecting the thermal conductivity coefficient, depending on the material. Other factors such as thickness, airflow velocity, pressure, aging also influence the thermal performances. In most cases, the thermal conductivity shows a linearly increasing trend with temperature. The moisture content strongly affects the thermal conductivity of both organic and inorganic materials. Bulk density also plays an important role in determining the thermal conductivity with opposite trends, it may exhibit a linear decrease for conventional materials and nonlinear variation for organic materials. This function seems to be linear decrease in types of conventional materials or shows a non-linear with natural fiber materials. Depending on the relationship between thermal conductivity and influencing factors, fibrous insulation materials show more sensitivity to temperature, moisture, and density compared to the other conventional materials. Understanding the

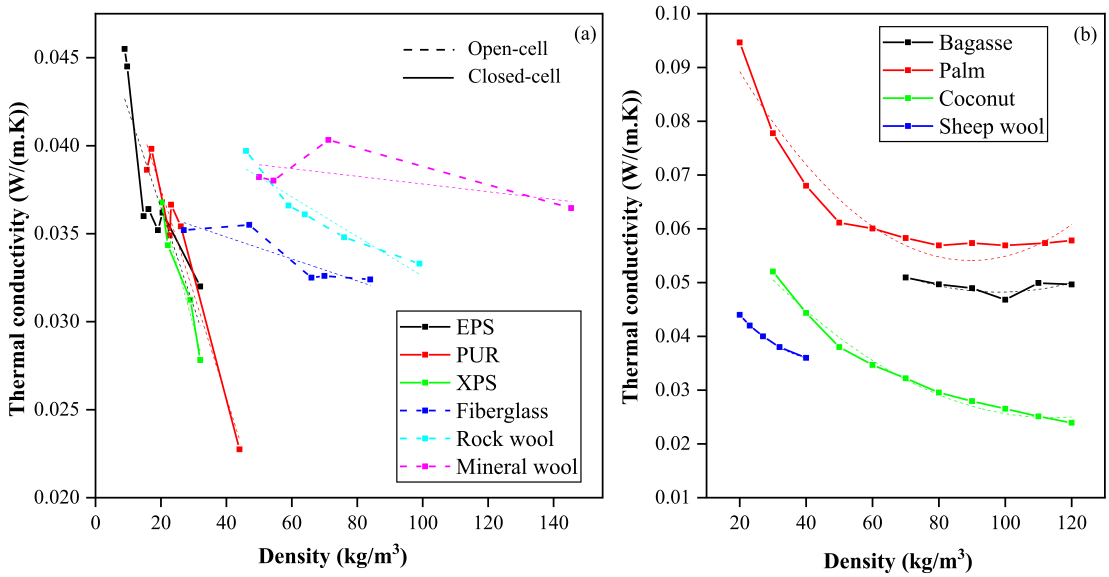

Fig. 4. Effect of density on thermal conductivity of various building insulation materials: (a) conventional insulation materials; (b) natural fibrous insulation materials.

quantitative relationship between the effective thermal conductivity and the influencing factors of the insulation materials is fundamental in determining the envelope heat, mass transfer, and building energy consumption.

Published studies demonstrate that influencing factors cannot be ignored. Recently, the design methods calculate with a standardized value, measured in ideal laboratory conditions and these results are shown in marketing products. However, reality is much more transient. With the increasing importance of energy savings and decreasing the embodied energy of insulation materials, more sophisticated calculation methods will be needed in the near future. These new methods can rearrange the evaluation aspects, but undoubtedly will need more complex technical equipment and calculation processes. In fact, new calculation methods could not determine the perfect values, but they provide a better approximation of the performance of insulation. Furthermore, the research gaps found in some publications and existing empirical studies should be considered in future works.

In further investigations, it would be interesting to compare the calculated thermal performance and the real performance on the site of an insulated structure. This finding provides the following insights for future research to examine the dependence of thermal properties including thermal conductivity, thermal diffusivity, heat specific capacity, coefficient of thermal expansion on their moisture content, temperature differences, density, and air velocity of the thermal insulators derived from natural fibers.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

The work was carried out as part of the “Sustainable Raw Material Management Thematic Network – RING 201”, EFOP-3.6.2-16-2017-00010 project in the framework of the Széchenyi 2020 Program. The realization of this project was supported by the European Union, and co-financed by the European Social Fund.

References

[1] S. Lemmet, Buildings and Climate Change. Summary for Decision-Makers, UNEP SBCI, 2009.
[2] E. Useia, International energy outlook 2018 - highlights. https://www.eia.gov/pressroom/presentations/capuano_07242018.pdf, 2018.
[3] J.G. Olivier, K. Schure, J. Peters, Trends in Global CO2 and Total Greenhouse Gas Emissions, PBL Netherlands Environmental Assessment Agency, 2017, p. 5.
[4] S. Solomon, IPCC (2007): Climate Change the Physical Science Basis vol. 2007, AGUFM, 2007. U43D-U01.
[5] R. Pachauri, A. Reisinger, Climate Change 2007. Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report, Cambridge University Press, Cambridge, 2008.
[6] R. American Society of Heating, I. Air Conditioning Engineers, ASHRAE Fundamentals Handbook 2001 (SI, American Society of Heating, Refrigerating & Air Conditioning Engineers, Incorporated, 2001.
[7] M.S. Al-Homoud, Performance characteristics and practical applications of common building thermal insulation materials, Build. Environ. 40 (3) (2005) 353–366.
[8] H. Zhang, W.-Z. Fang, Y.-M. Li, W.-Q. Tao, Experimental study of the thermal conductivity of polyurethane foams, Appl. Therm. Eng. 115 (2017) 528–538.
[9] R. Walker, S. Pavía, Thermal performance of a selection of insulation materials suitable for historic buildings, Build. Environ. 94 (2015) 155–165.
[10] L. Aditya, T. Mahlia, B. Rismanchi, H. Ng, M. Hasan, H. Metselaar, O. Muraza, H. Aditiya, A review on insulation materials for energy conservation in buildings, Renew. Sustain. Energy Rev. 73 (2017) 1352–1365.
[11] F. D'Alessandro, S. Schiavoni, F. Bianchi, F. Asdrubali, Insulation materials for the building sector: a review and comparative analysis, Renew. Sustain. Energy Rev. 62 (2016) 988–1011.
[12] B. Abu-Jdayil, A.-H. Mourad, W. Hittini, M. Hassan, S. Hameedi, Traditional, state-of-the-art and renewable thermal building insulation materials: an overview, Construct. Build. Mater. 214 (2019) 709–735.
[13] B. Peavy, A heat transfer note on temperature dependent thermal conductivity, J. Therm. Insul. Build. Envelopes 20 (1) (1996) 76–90.
[14] N. Yüksel, The Review of Some Commonly Used Methods and Techniques to Measure the Thermal Conductivity of Insulation Materials, Insulation Materials in Context of Sustainability, IntechOpen, 2016.
[15] W. Villasmil, L.J. Fischer, J. Worlitschek, A review and evaluation of thermal insulation materials and methods for thermal energy storage systems, Renew. Sustain. Energy Rev. 103 (2019) 71–84.
[16] B.P. Jelle, Traditional, state-of-the-art and future thermal building insulation materials and solutions–Properties, requirements and possibilities, Energy Build. 43 (10) (2011) 2549–2563.
[17] E.C.f. Standardization, Thermal Performance of Building Materials and Products - Determination of Thermal Resistance by Means of Guarded Hot Plate and Heat Flow Meter Methods - Dry and Moist Products of Medium and Low Thermal Resistance, 2001.
[18] E.C.f. Standardization, Thermal Performance of Building Materials and Products - Determination of Thermal Resistance by Means of Guarded Hot Plate and Heat Flow Meter Methods - Products of High and Medium Thermal Resistance, 2001.
[19] E.C.f. Standardization, Thermal Performance of Building Materials and Products - Determination of Thermal Resistance by Means of Guarded Hot Plate and Heat Flow Meter Methods - Thick Products of High and Medium Thermal Resistance, 2000.

[20] A.C.- ASTM International, Standard Test Method for Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus.
[21] A.C.- ASTM International, Standard Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Guarded-Hot-Plate Apparatus, pp.
[22] Y. N, The Investigation of Structure and Operating Parameters Effect on the Heat Transfer Coefficient in Porous Structures, Uludag University, Bursa, 2010.
[23] A.M. Papadopoulos, State of the art in thermal insulation materials and aims for future developments, Energy Build. 37 (1) (2005) 77–86.
[24] M. Pfundstein, R. Gellert, M. Spitzner, A. Rudolphi, Insulating Materials: Principles, Materials, Applications, Walter de Gruyter, 2012.
[25] A. Karamanos, S. Hadiarakou, A. Papadopoulos, The impact of temperature and moisture on the thermal performance of stone wool, Energy Build. 40 (8) (2008) 1402–1411.
[26] H. Wieland, D.P. Murphy, H. Behring, C. Jäger, P. Hinrichs, F.-J. Bockisch, Perspektiven für Dämmstoffe aus heimischen nachwachsenden Rohstoffen, Landtechnik 55 (1) (2000) 22–23, 22–23.
[27] H. Zhang, Building Materials in Civil Engineering, Elsevier, 2011.
[28] U. Berardi, M. Naldi, The impact of the temperature dependent thermal conductivity of insulating materials on the effective building envelope performance, Energy Build. 144 (2017) 262–275.
[29] J.-W. Wu, W.-F. Sung, H.-S. Chu, Thermal conductivity of polyurethane foams, Int. J. Heat Mass Tran. 42 (12) (1999) 2211–2217.
[30] S. Omer, S. Riffat, G. Qiu, Thermal insulations for hot water cylinders: a review and a conceptual evaluation, Build. Serv. Eng. Technol. 28 (3) (2007) 275–293.
[31] S. Panyakaew, S. Fotios, New thermal insulation boards made from coconut husk and bagasse, Energy Build. 43 (7) (2011) 1732–1739.
[32] A. Hoseini, C. McCague, M. Andisheh-Tadbir, M. Bahrami, Aerogel blankets: from mathematical modeling to material characterization and experimental analysis, Int. J. Heat Mass Tran. 93 (2016) 1124–1131.
[33] F. Domínguez-Muñoz, B. Anderson, J.M. Cejudo-López, A. Carrillo-Andrés, Uncertainty in the thermal conductivity of insulation materials, Energy Build. 42 (11) (2010) 2159–2168.
[34] A. Bakatovich, F. Gaspar, Composite material for thermal insulation based on moss raw material, Construct. Build. Mater. 228 (2019) 116699.
[35] I. Cetiner, A.D. Shea, Wood waste as an alternative thermal insulation for buildings, Energy Build. 168 (2018) 374–384.
[36] A.S. C168, Terminology Relating to Thermal Insulating Materials, 2013.
[37] M. Koru, Determination of thermal conductivity of closed-cell insulation materials that depend on temperature and density, Arabian J. Sci. Eng. 41 (11) (2016) 4337–4346.
[38] P. Čech, D. Tesařová, J. Hadačová, E. Jeřábková, The quality of indoor air in wooden based buildings and the factors with impact of them, Wood Res. 61 (4) (2016) 583–598.
[39] M. Khoukhi, The combined effect of heat and moisture transfer dependent thermal conductivity of polystyrene insulation material: impact on building energy performance, Energy Build. 169 (2018) 228–235.
[40] C. ASTM, 518, Standard Test Method for Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus, Annual Book of ASTM Standards, 2008.
[41] ISO, Thermal Insulation-Determination of Steady-State Thermal Resistance and Related Properties-Heat Flow Meter Apparatus, International Standards Organization Geneva, Switzerland, 1991.
[42] A.A. Abdou, I.M. Budaiwi, Comparison of thermal conductivity measurements of building insulation materials under various operating temperatures, J. Build. Phys. 29 (2) (2005) 171–184.
[43] M. Khoukhi, Simultaneous changes of temperature and moisture of thermal conductivity of EPS insulation material and its impact on building energy performance, Int. J. Smart Grid Clean Energy 8 (2) (2019).
[44] N.F. Shahedan, M.M.A.B. Abdullah, N. Mahmed, A. Kusbiantoro, M. Binhussain, S.N. Zailan, Review on Thermal Insulation Performance in Various Type of Concrete, AIP Conference Proceedings, AIP Publishing LLC, 2017, 020046.
[45] U. Berardi, The impact of temperature dependency of the building insulation thermal conductivity in the Canadian climate, Energy Procedia 132 (2017) 237–242.
[46] A. Ahmed, A. Qayoum, F.Q. Mir, Investigation of the thermal behavior of the natural insulation materials for low temperature regions, J. Build. Eng. 26 (2019) 100849.
[47] F. Ochs, H. Müller-Steinhagen, Temperature and Moisture Dependence of the Thermal Conductivity of Insulation Materials, NATO Advanced Study Institute on Thermal Energy Storage for Sustainable Energy Consumption (TESSEC), Izmir, Cesme, 2005.
[48] S. Fantucci, A. Lorenzati, A. Capozzoli, M. Perino, Analysis of the temperature dependence of the thermal conductivity in Vacuum Insulation Panels, Energy Build. 183 (2019) 64–74.
[49] M. Khoukhi, M. Tahat, Effect of temperature and density variations on thermal conductivity of polystyrene insulation materials in Oman climate, J. Eng. Phys. Thermophys. 88 (4) (2015) 994–998.
[50] E. Troppová, M. Švehlík, J. Tippner, R. Wimmer, Influence of temperature and moisture content on the thermal conductivity of wood-based fibreboards, Mater. Struct. 48 (12) (2015) 4077–4083.
[51] B. Suleiman, J. Larfeldt, B. Leckner, M. Gustavsson, Thermal conductivity and diffusivity of wood, Wood Sci. Technol. 33 (1999) 465–473.
[52] R. Besant, E. Miller, Thermal Resistance of Loose-Fill Fiberglass Insulation Spaces Heated from below, Thermal Performance of the Exterior Envelope of Building II, ASHRAE/DOE Conference, 1982, pp. 720–733.
[53] D. Aldrich, R. Bond, Thermal Performance of Rigid Cellular Foam Insulation at Subfreezing Temperatures, Thermal Performance of the Exterior Envelopes of Buildings III, ASHRAE/DOE/BTECC Conference, 1985, pp. 500–509.
[54] F. Ochs, W. Heidemann, H. Müller-Steinhagen, Effective thermal conductivity of moistened insulation materials as a function of temperature, Int. J. Heat Mass Tran. 51 (3–4) (2008) 539–552.
[55] Y. Xu, Z. Zeng, H. Lv, Temperature dependence of apparent thermal conductivity of compacted bentonites as buffer material for high-level radioactive waste repository, Appl. Clay Sci. 174 (2019) 10–14.
[56] H.Y. Song, X.X. Cheng, L. Chu, Effect of Density and Ambient Temperature on Coefficient of Thermal Conductivity of Heat-Insulated EPS and PU Materials for Food Packaging, Applied Mechanics and Materials, Trans Tech Publ, 2014, pp. 152–155.
[57] I. Budaiwi, A. Abdou, M. Al-Homoud, Variations of thermal conductivity of insulation materials under different operating temperatures: impact on envelope-induced cooling load, J. Architect. Eng. 8 (4) (2002) 125–132.
[58] Z. Misri, M. Ibrahim, A. Awal, M. Desa, N. Ghadzali, Review on Factors Influencing Thermal Conductivity of Concrete Incorporating Various Type of Waste Materials, IOP Conference Series: Earth and Environmental Science, IOP Publishing, 2018, 012141.
[59] S.B. Coşkun, M.T. Atay, Fin efficiency analysis of convective straight fins with temperature dependent thermal conductivity using variational iteration method, Appl. Therm. Eng. 28 (17–18) (2008) 2345–2352.
[60] Q. Zhong, H. Kou, L. Yang, Y. Tao, C. Luo, Z. Xu, Factors influencing variations in the thermal conductivity of polycrystalline ZnS and Cr2+: ZnS, Mater. Lett. 158 (2015) 222–224.
[61] Q. Tang, J. He, W. Zhang, Influencing factors of thermal contact conductance between TC4/30CrMnSi interfaces, Int. J. Heat Mass Tran. 86 (2015) 694–698.
[62] Y. Xu, Z. Zeng, H. Lv, Effect of temperature on thermal conductivity of lateritic clays over a wide temperature range, Int. J. Heat Mass Tran. 138 (2019) 562–570.
[63] A. Abdou, I. Budaiwi, The variation of thermal conductivity of fibrous insulation materials under different levels of moisture content, Construct. Build. Mater. 43 (2013) 533–544.
[64] I. Gnip, S. Vėjelis, S. Vaitkus, Thermal conductivity of expanded polystyrene (EPS) at 10 C and its conversion to temperatures within interval from 0 to 50 C, Energy Build. 52 (2012) 107–111.
[65] M. Khoukhi, M. Tahat, Effect of Operating Temperatures on Thermal Conductivity of Polystyrene Insulation Material: Impact on Envelope-Induced Cooling Load, Applied Mechanics and Materials, Trans Tech Publ, 2014, pp. 315–320.
[66] J. Zach, A. Korjenic, V. Petránek, J. Hroudová, T. Bednar, Performance evaluation and research of alternative thermal insulations based on sheep wool, Energy Build. 49 (2012) 246–253.
[67] M. Khoukhi, A. Hassan, S. Al Saadi, S. Abdelbaqi, A dynamic thermal response on thermal conductivity at different temperature and moisture levels of EPS insulation, Case Stud. Therm. Eng. 14 (2019) 100481.
[68] K. Manohar, D. Ramlakhan, G. Kochhar, S. Haldar, Biodegradable fibrous thermal insulation, J. Braz. Soc. Mech. Sci. Eng. 28 (1) (2006) 45–47.
[69] M. Rahim, O. Douzane, A.T. Le, T. Langlet, Effect of moisture and temperature on thermal properties of three bio-based materials, Construct. Build. Mater. 111 (2016) 119–127.
[70] S. Srivaro, Z. Börcsök, Z. Pásztory, Temperature Dependence of Thermal Conductivity of Heat-Treated Rubberwood, Wood Material Science & Engineering, 2019, pp. 1–4.
[71] H.-K. Kim, J. Jeon, H.-K. Lee, Workability, and mechanical, acoustic and thermal properties of lightweight aggregate concrete with a high volume of entrained air, Construct. Build. Mater. 29 (2012) 193–200.
[72] L. Nguyen, A.-L. Beaucour, S. Ortola, A. Noumowé, Experimental study on the thermal properties of lightweight aggregate concretes at different moisture contents and ambient temperatures, Construct. Build. Mater. 151 (2017) 720–731.
[73] Z. Pásztory, T. Horváth, S.V. Glass, S. Zelinka, Experimental investigation of the influence of temperature on thermal conductivity of multilayer reflective thermal insulation, Energy Build. 174 (2018) 26–30.
[74] K. Chu, C. Jia, X. Liang, H. Chen, Temperature dependence of thermal conductivity in SiCp based metal–matrix composites, Mater. Sci. Technol. 27 (1) (2011) 91–94.
[75] R. Khordad, F. Razi, Effect of temperature and distribution function of depolarization factor on thermal conductivity of carbon nanotube-based composites, Superlattice. Microst. 64 (2013) 439–450.
[76] M. Zain-ul-Abdein, S. Azeem, S.M. Shah, Computational investigation of factors affecting thermal conductivity in a particulate filled composite using finite element method, Int. J. Eng. Sci. 56 (2012) 86–98.
[77] S.K. Das, N. Putra, P. Thiesen, W. Roetzel, Temperature dependence of thermal conductivity enhancement for nanofluids, J. Heat Tran. 125 (4) (2003) 567–574.
[78] H.A. Mintsa, G. Roy, C.T. Nguyen, D. Doucet, New temperature dependent thermal conductivity data for water-based nanofluids, Int. J. Therm. Sci. 48 (2) (2009) 363–371.
[79] X. Wang, H. Yu, L. Li, M. Zhao, Research on temperature dependent effective thermal conductivity of composite-phase change materials (PCMs) wall based on steady-state method in a thermal chamber, Energy Build. 126 (2016) 408–414.
[80] H. Guo, S. Cai, K. Li, Z. Liu, L. Xia, J. Xiong, Simultaneous test and visual identification of heat and moisture transport in several types of thermal insulation, Energy 197 (2020) 117–137.

[81] R. Baetens, B.P. Jelle, J.V. Thue, M.J. Tenpierik, S. Grynning, S. Uvsløkk, A. Gustavsen, Vacuum insulation panels for building applications: a review and beyond, Energy Build. 42 (2) (2010) 147–172.
[82] A. Lorenzati, S. Fantucci, A. Capozzoli, M. Perino, The effect of temperature on thermal performance of fumed silica based vacuum insulation panels for buildings, Energy Procedia 111 (2017) (2016) 490–499.
[83] R. Baetens, B.P. Jelle, A. Gustavsen, Aerogel insulation for building applications: a state-of-the-art review, Energy Build. 43 (4) (2011) 761–769.
[84] J.-J. Zhao, Y.-Y. Duan, X.-D. Wang, B.-X. Wang, Radiative properties and heat transfer characteristics of fiber-loaded silica aerogel composites for thermal insulation, Int. J. Heat Mass Tran. 55 (19–20) (2012) 5196–5204.
[85] T. Xie, Y.-L. He, Z.-J. Hu, Theoretical study on thermal conductivities of silica aerogel composite insulating material, Int. J. Heat Mass Tran. 58 (1–2) (2013) 540–552.
[86] G. Wei, Y. Liu, X. Zhang, F. Yu, X. Du, Thermal conductivities study on silica aerogel and its composite insulation materials, Int. J. Heat Mass Tran. 54 (11–12) (2011) 2355–2366.
[87] H. Liu, X. Xia, Q. Ai, X. Xie, C. Sun, Experimental investigations on temperature-dependent effective thermal conductivity of nanoporous silica aerogel composite, Exp. Therm. Fluid Sci. 84 (2017) 67–77.
[88] R.H. Nosrati, U. Berardi, Hygrothermal characteristics of aerogel-enhanced insulating materials under different humidity and temperature conditions, Energy Build. 158 (2018) 698–711.
[89] I. Budaiwi, A. Abdou, The impact of thermal conductivity change of moist fibrous insulation on energy performance of buildings under hot–humid conditions, Energy Build. 60 (2013) 388–399.
[90] A. Winkler-Skalna, B. Łoboda, Determination of the thermal insulation properties of cylindrical PUR foam products throughout the entire life cycle using accelerated aging procedures, J. Build. Eng. (2020) 101348.
[91] M. Pinterić, Building Physics: from Physical Principles to International Standards, Springer International Publishing, 2017, p. 262.
[92] M. Qin, R. Belarbi, A. Aït-Mokhtar, A. Seigneurin, An analytical method to calculate the coupled heat and moisture transfer in building materials, Int. Commun. Heat Mass Tran. 33 (1) (2006) 39–48.
[93] M. Phillipson, P. Baker, M. Davies, Z. Ye, A. McNaughtan, G. Galbraith, R. McLean, Moisture measurement in building materials: an overview of current methods and new approaches, Build. Serv. Eng. Technol. 28 (4) (2007) 303–316.
[94] T.T. Zhang, R. Shen, C.-H. Lin, J. Yin, S. Wang, Measuring moisture content in a porous insulation material using a hot wire, Build. Environ. 84 (2015) 22–31.
[95] T. Zhang, Y. Luo, C.-H. Lin, Z. Wei, S. Wang, Measuring moisture content in porous insulation materials based on transient temperatures over a period of 100 seconds, Sci. Technol. Built Environ. 24 (6) (2018) 571–579.
[96] A. Gusyachkin, L. Sabitov, A. Khakimova, A. Hayrullin, Effects of Moisture Content on Thermal Conductivity of Thermal Insulation Materials, IOP Conference Series: Materials Science and Engineering, IOP Publishing, 2019, 012029.
[97] M. Jerman, R. Černý, Effect of moisture content on heat and moisture transport and storage properties of thermal insulation materials, Energy Build. 53 (2012) 39–46.
[98] Á. Lakatos, Moisture induced changes in the building physics parameters of insulation materials, Sci. Technol. Built Environ. 22 (3) (2016) 252–260.
[99] Á. Lakatos, F. Kalmár, Analysis of water sorption and thermal conductivity of expanded polystyrene insulation materials, Build. Serv. Eng. Technol. 34 (4) (2013) 407–416.
[100] T. McFadden, Thermal performance degradation of wet insulations in cold regions, J. Cold Reg. Eng. 2 (1) (1988) 25–34.
[101] J. Wang, Q. Du, C. Zhang, X. Xu, W. Gang, Mechanism and preliminary performance analysis of exhaust air insulation for building envelope wall, Energy Build. 173 (2018) 516–529.
[102] Y. Liu, C. Ma, D. Wang, Y. Wang, J. Liu, Nonlinear effect of moisture content on effective thermal conductivity of building materials with different pore size distributions, Int. J. Thermophys. 37 (6) (2016) 56.
[103] F. D'Alessandro, G. Baldinelli, F. Bianchi, S. Sambuco, A. Rufini, Experimental assessment of the water content influence on thermo-acoustic performance of building insulation materials, Construct. Build. Mater. 158 (2018) 264–274.
[104] W. Zhu, S. Cai, L. Cremaschi, Thermal performance and moisture accumulation of fibrous mechanical pipe insulation systems operating at below-ambient temperature in wet conditions with moisture ingress, Sci. Technol. Built Environ. 21 (6) (2015) 862–875.
[105] M. Liu, Y. Sun, C. Sun, X. Yang, Study on thermal insulation and heat transfer properties of wood frame walls, Wood Res. 63 (2) (2018) 249–260.
[106] D.J. Gawin, J. Kosny, K. Wilkes, Thermal Conductivity of Moist Cellular Concrete-Experimental and Numerical Study, American Society of Heating, Refrigerating and Air-Conditioning Engineers–ASHRAE, 2004.
[107] D. Taoukil, F. Sick, A. Mimet, H. Ezbakhe, T. Ajzoul, Moisture content influence on the thermal conductivity and diffusivity of wood–concrete composite, Construct. Build. Mater. 48 (2013) 104–115.
[108] A. Korjenic, V. Petránek, J. Zach, J. Hroudová, Development and performance evaluation of natural thermal-insulation materials composed of renewable resources, Energy Build. 43 (9) (2011) 2518–2523.
[109] L. Boukhattem, M. Boumhaout, H. Hamdi, B. Benhamou, F.A. Nouh, Moisture content influence on the thermal conductivity of insulating building materials made from date palm fibers mesh, Construct. Build. Mater. 148 (2017) 811–823.
[110] W. Sonderegger, P. Niemz, Thermal and moisture flux in soft fibreboards, Eur. J. Wood Wood Prod. 70 (1–3) (2012) 25–35.
[111] J. Erkmen, H.I. Yavuz, E. Kavci, M. Sari, A new environmentally friendly insulating material designed from natural materials, Construct. Build. Mater. 255 (2020) 119357.
[112] J. Zach, J. Hroudová, J. Brožovský, Z. Krejza, A. Gailius, Development of thermal insulating materials on natural base for thermal insulation systems, Procedia Eng. 57 (2013) 1288–1294.
[113] A. Hoseini, M. Bahrami, Effects of humidity on thermal performance of aerogel insulation blankets, J. Build. Eng. 13 (2017) 107–115.
[114] Á. Lakatos, Investigation of the moisture induced degradation of the thermal properties of aerogel blankets: measurements, calculations, simulations, Energy Build. 139 (2017) 506–516.
[115] A.K. Mahapatra, Thermal properties of sweet sorghum bagasse as a function of moisture content, Agri. Eng. Int.: CIGR J. 19 (4) (2018) 108–113.
[116] H.-J. Steeman, M. Van Belleghem, A. Janssens, M. De Paepe, Coupled simulation of heat and moisture transport in air and porous materials for the assessment of moisture related damage, Build. Environ. 44 (10) (2009) 2176–2184.
[117] P. Talukdar, S.O. Olutmayin, O.F. Osanyintola, C.J. Simonson, An experimental data set for benchmarking 1-D, transient heat and moisture transfer models of hygroscopic building materials. Part I: experimental facility and material property data, Int. J. Heat Mass Tran. 50 (23–24) (2007) 4527–4539.
[118] V.C. Mohan, P. Talukdar, Three dimensional numerical modeling of simultaneous heat and moisture transfer in a moist object subjected to convective drying, Int. J. Heat Mass Tran. 53 (21–22) (2010) 4638–4650.
[119] H.M. Künzel, Simultaneous Heat and Moisture Transport in Building Components, One-And Two-Dimensional Calculation Using Simple Parameters, IRB-Verlag Stuttgart, 1995, p. 65.
[120] N. Wijeysundera, B. Zheng, M. Iqbal, E. Hauptmann, Numerical simulation of the transient moisture transfer through porous insulation, Int. J. Heat Mass Tran. 39 (5) (1996) 995–1004.
[121] F. Liu, B. Jia, B. Chen, W. Geng, Moisture transfer in building envelope and influence on heat transfer, Procedia Eng. 205 (2017) 3654–3661.
[122] Y. Wang, C. Ma, Y. Liu, D. Wang, J. Liu, Effect of moisture migration and phase change on effective thermal conductivity of porous building materials, Int. J. Heat Mass Tran. 125 (2018) 330–342.
[123] Á. Lakatos, F. Kalmár, Investigation of thickness and density dependence of thermal conductivity of expanded polystyrene insulation materials, Mater. Struct. 46 (7) (2013) 1101–1105.
[124] M. Khoukhi, N. Fezzioui, B. Draoui, L. Salah, The impact of changes in thermal conductivity of polystyrene insulation material under different operating temperatures on the heat transfer through the building envelope, Appl. Therm. Eng. 105 (2016) 669–674.
[125] J. Zach, R. Slávik, V. Novák, Investigation of the process of heat transfer in the structure of thermal insulation materials based on natural fibres, Procedia Eng. 151 (2016) 352–359.
[126] F. Collet, S. Prétot, Thermal conductivity of hemp concretes: variation with formulation, density and water content, Construct. Build. Mater. 65 (2014) 612–619.
[127] N. Sekino, Density dependence in the thermal conductivity of cellulose fiber mats and wood shavings mats: investigation of the apparent thermal conductivity of coarse pores, J. Wood Sci. 62 (1) (2016) 20–26.
[128] G. Balčiūnas, J. Žvironaitė, S. Vėjelis, A. Jagniatinskis, S. Gaidučis, Ecological, thermal and acoustical insulating composite from hemp shives and sapropel binder, Ind. Crop. Prod. 91 (2016) 286–294.
[129] H. Bui, N. Sebaibi, M. Boutouil, D. Levacher, Determination and review of physical and mechanical properties of raw and treated coconut fibers for their recycling in construction materials, Fibers 8 (6) (2020) 37.
[130] C.H.A. Koh, D. Kraniotis, A review of material properties and performance of straw bale as building material, Construct. Build. Mater. 259 (2020) 120385.
[131] M. Tychanicz-Kwiecień, J. Wilk, P. Gil, Review of high-temperature thermal insulation materials, J. Thermophys. Heat Tran. 33 (1) (2019) 271–284.
[132] B. Wang, Z. Li, X. Qi, N. Chen, Q. Zeng, D. Dai, M. Fan, J. Rao, Thermal insulation properties of green vacuum insulation panel using wood fiber as core, Mater. BioResour. 14 (2) (2019) 3339–3351.
[133] D.K. Sahu, P.K. Sen, G. Sahu, R. Sharma, S. Bohidar, A review on thermal insulation and its optimum thickness to reduce heat loss, Int. J. Innov. Res. Sci. Technol. 2 (6) (2015) 2349–6010.
[134] F. Asdrubali, F. D'Alessandro, S. Schiavoni, A review of unconventional sustainable building insulation materials, Sustain. Mater. Technol. 4 (2015) 1–17.
[135] T. Mahlia, B. Taufiq, H. Masjuki, Correlation between thermal conductivity and the thickness of selected insulation materials for building wall, Energy Build. 39 (2) (2007) 182–187.
[136] J. Yuan, Impact of insulation type and thickness on the dynamic thermal characteristics of an external wall structure, Sustainability 10 (8) (2018) 2835.
[137] T. Zhang, H. Yang, Optimal thickness determination of insulating air layers in building envelopes, Energy Procedia 152 (2018) 444–449.
[138] N. Sisman, E. Kahya, N. Aras, H. Aras, Determination of optimum insulation thicknesses of the external walls and roof (ceiling) for Turkey's different degree-day regions, Energy Pol. 35 (10) (2007) 5151–5155.
[139] D. Kumar, M. Alam, P.X. Zou, J.G. Sanjayan, R.A. Memon, Comparative analysis of building insulation material properties and performance, Renew. Sustain. Energy Rev. 131 (2020) 110038.
[140] E.H. Ahmad, Cost Analysis and Thickness Optimization of Thermal Insulation Materials Used in Residential Buildings in Saudi Arabia, Proceedings of the 6th Saudi Engineering Conference, Dhahran, Saudi Arabia, 2002, pp. 14–17.

[141] N. Balaji, M. Mani, B. Venkatarama Reddy, Thermal Performance of the Building Walls, Preprints of the 1st IBPSA Italy conference Free University of Bozen-Bolzano, 2013, pp. 1–7.
[142] M.G. Emmel, M.O. Abadie, N. Mendes, New external convective heat transfer coefficient correlations for isolated low-rise buildings, Energy Build. 39 (3) (2007) 335–342.
[143] I. Chmúrny, Influence of External Surface Resistance and Thermal Insulation Level on Energy Need for Cooling, Applied Mechanics and Materials, Trans Tech Publ, 2016, pp. 445–452.
[144] S.-y. Zhao, B.-m. Zhang, X.-d. He, Temperature and pressure dependent effective thermal conductivity of fibrous insulation, Int. J. Therm. Sci. 48 (2) (2009) 440–448.
[145] A. Binz, A. Moosmann, G. Steinke, U. Schonhardt, F. Fregnan, H. Simmler, S. Brunner, K. Ghazi, R. Bundi, U. Heinemann, H. Schwab, H. Cauberg, M. Tenpierik, G. Johannesson, T. Thorsell, Vacuum Insulation in the Building Sector - Systems and Applications (Subtask B), vol. 39, IEA/ECBCS Annex, 2005, pp. 1–134.
[146] H. Simmler, S. Brunner, Vacuum insulation panels for building application: basic properties, aging mechanisms and service life, Energy Build. 37 (11) (2005) 1122–1131.
[147] M. Davraz, H.C. Bayrakci, Performance properties of vacuum insulation panels produced with various filling materials, Sci. Eng. Compos. Mater. 21 (4) (2014) 521–527.
[148] U. Berardi, The impact of aging and environmental conditions on the effective thermal conductivity of several foam materials, Energy 182 (2019) 777–794.
[149] D. Bhattacharjee, P.W. Irwin, J.R. Booth, J.T. Grimes, The acceleration of foam aging by thin-slicing: some interpretations and limitations, J. Therm. Insul. Build. Envelopes 17 (3) (1994) 219–237.
[150] A. Batard, T. Duforestel, L. Flandin, B. Yrieix, Prediction method of the long-term thermal performance of Vacuum Insulation Panels installed in building thermal insulation applications, Energy Build. 178 (2018) 1–10.
[151] A. La Rosa, A. Recca, A. Gagliano, J. Summerscales, A. Latteri, G. Cozzo, G. Cicala, Environmental impacts and thermal insulation performance of innovative composite solutions for building applications, Construct. Build. Mater. 55 (2014) 406–414.
[152] C.A. Bribian IZ, A. Aranda Urison, Life cycle assessment of building materials: comparative analysis of energy and environmental impacts and evaluation of the eco-ejficiency improvement potential, Build. Environ. 46 (2011) 1133–1140.
[153] Z. Ye, C. Wells, C. Carrington, N. Hewitt, Thermal conductivity of wool and wool–hemp insulation, Int. J. Energy Res. 30 (1) (2006) 37–49.
[154] A. Limam, A. Zerizer, D. Quenard, H. Sallee, A. Chenak, Experimental thermal characterization of bio-based materials (Aleppo Pine wood, cork and their composites) for building insulation, Energy Build. 116 (2016) 89–95.
[155] K. Manohar, Experimental investigation of building thermal insulation from agricultural by-products, Br. J. Appl. Sci. Technol. 2 (3) (2012) 227.
[156] M. Volf, J. Diviš, F. Havlík, Thermal, moisture and biological behaviour of natural insulating materials, Energy Procedia 78 (2015) 1599–1604.
[157] Y. Kobayashi, T. Saito, A. Isogai, Aerogels with 3D ordered nanofiber skeletons of liquid-crystalline nanocellulose derivatives as tough and transparent insulators, Angew. Chem. Int. Ed. 53 (39) (2014) 10394–10397.
[158] J. Hroudova, J. Zach, Acoustic and thermal insulating materials based on natural fibres used in floor construction, World Acad. Sci. Eng. Technol. Int. J. Civ. Environ. Eng 8 (2014) 1152–1155.