6. The quality of living environment and the sustainability of building structures

6.1. Introduction

Many people living in urban areas spend more than 90% of their life time in indoor circumstance, where they can be exposed to up to five-time higher pollution. Poor indoor environment quality can reduce not only quality of life and productivity, but it also can cause wide range of diseases [1]. Nowadays, creating comfortable conditions with acceptable level of indoor air quality (IAQ) in buildings is one of the most important target that asks about 40% of total used energy [2]. However, rising concerns about the environment – climate change related to greenhouse gas emissions (according to Kyoto Protocol, Paris Agreement) – and the increasing cost of energy result in the need to remarkably reduce energy consumption.

In practice, energy saving, according to obligations of legislation relating to nearly Zero Energy Buildings (nZEB) (European Directives 2002/91/EC and 2010/31/EU), is mainly carried out by further improvement of the building thermal performance using different 'passive' means: reducing thermal transmittance and air permeability of the envelope, i.e., by using considerable thickness of insulation and high-performance glazes components. These 'passive' measures also include more efficient heating (or cooling) and ventilation systems, e.g., the use of earth-air heat exchangers to pre-heat or pre-cool building ventilation air [2, 3].

These various methods can determine new ways of heat and moisture exchange in the building envelope [3, 4]. The airtightness of the internal environment, if it is not properly managed with suitable ventilation strategy, may lead to poor IAQ, including high internal moisture load that decrease thermal and respiratory comfort and can cause favourable circumstances for mould development [3, 5]. Internal moisture comes from a wide range of sources: occupant respiration and perspiration, bathing and showering, cleaning, cooking, plants. In addition, the change of temperature in rooms can result in temporary high air humidity. For single-family houses the internal moisture can reach 23 l per day [6]. Consequently, despite the fact that over the past decades building energy efficiency has improved, the number of reports on the presence of microorganisms indoor is still increasing. At the same time, however, there is still lack of information on the relationship between nZEB and the microbiological contamination. It is the reason why the problems regard to maintaining of appropriate IAQ in nowadays buildings, especially in nZEB, still requires persistent attention and further investigations. The proliferation of microorganisms in buildings is not welcomed not only because of the implications for human health, but also because of their contribution to the defacement and biodeterioration of building materials [3].

6.2. Risk of development of microbiological contamination

The life on the Earth would not be possible without microorganisms (e.g. fungi, bacteria) as they are important components of our ecosystem. These ubiquitous organisms are responsible for the decomposition of dead organic materials, splitting them up into their components and, thereby, giving them a new access to a further life cycle [7]. Although, microorganisms are omnipresent in indoor environment and on/in building materials, their proliferation should not be permitted. The most critical factors for mould fungi development are the moisture level and temperature conditions on the material surface as well as the substrate type and exposure time (Fig. 6.1).

Moisture is key factor limiting mould growth. The most important parameters that characterize the degree of humidity are following: water activity (a_w) – characterizes the amount of free water available to microorganisms; relative humidity of the air ($a_w \times 100$ = % relative humidity (RH)) and also the moisture content of the materials [8]. In different researches, RH threshold, the most often mentioned, which must not be exceeded to prevent the mould growth, is 70 – 75 %. However, there are also mould fungi that can proliferate, if RH is only 62 – 65% [9]. For the most of these microorganisms the optimum RH is 96 – 98%. Relative humidity, what is required to spore germination, is usually slightly higher than what is necessary for the growth of mycelium. In turn, the moisture content of the substrate itself should be over 20% to favour fungal growth. As fungi cannot use humidity that is accumulated deeper in the substrate, therefore, the moisture condition directly on the surface of the material is crucial [10, 11].

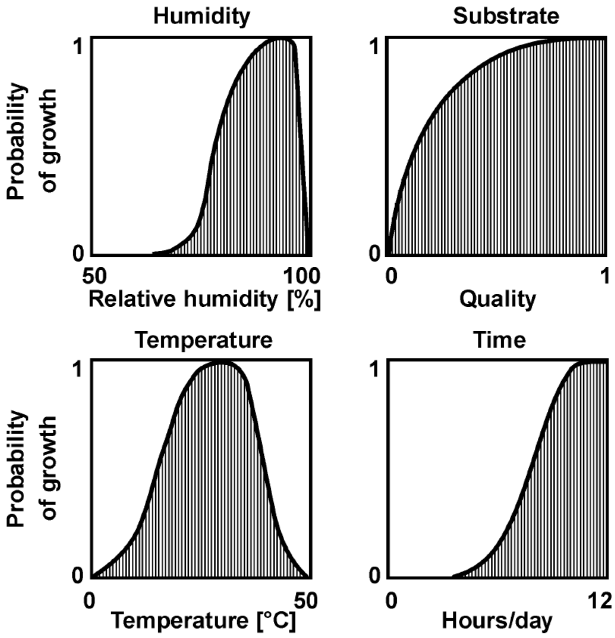


Figure 6.1. *Qualitative assessment of the growth conditions for mould fungi in dependence on various influence factors. Growth probability: 0 – no growth; 1 – optimal growth [7]*

According to moisture requirements, mould fungi can be grouped into as follows:

- primary colonisers capable of growth at a_w < 0.8, including such xerophytes as *Wallemia*, *Penicillium*, *Aspergillus* and *Eurotium*;
- secondary colonisers capable of growth at 0.8 < a_w < 0.9, mostly including species of the phylloplanes: *Cladosporium, Phoma, Ulocladium* and *Alternaria*;
- tertiary colonisers, demanding a_w > 0.9, including such hydrophytes as: *Stachybotrys*, *Chaetomium, Trichoderma*, *Auraeobasidium* as well as actinomycetes and other bacteria [11, 12].

Moulds have adapted to a very wide range of **temperatures**: from 0 to 50 °C, while the optimum temperature for development is from 20 to 35 °C. But, it is known that several fungi also can grow under more extreme conditions, e.g., at -5 to -7 °C and at 55 °C. Meanwhile, the minimum temperature must be above 0 °C to ensure spore germination [13].

Nutrients are also necessary for proliferation of fungi. However, mould fungi are very modest organisms, and they often have enough negligible amount of organic matter (soot, pollen, human and animal skin particles, etc.) that has been deposited in dust on different surfaces [14]. They prefer simple feed substrates – sugars, amino acids etc., however, they can use complex organic compounds as nutrients, such as starch, cellulose, lignin, etc. Stone-based, inorganic materials (concrete, bricks, etc.) do not contribute to the development of mould. In turn, such widely used building materials as timber and their products provide fungi plentifully with the necessary nutrients

(Fig. 6.2). These materials are also hygroscopic, what also helps to create more favourable environment for the development of microorganisms [13].

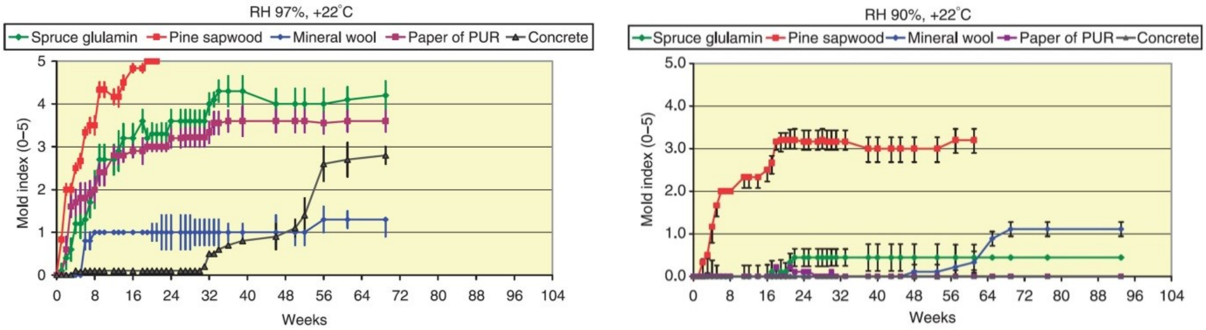


Figure 6.2. *Response of some building material to mould growth at RH 97%/20 °C (left) and RH 90%/20 °C (right) [13]*

However, for mould development on wood surfaces suitable conditions have to be there. The researches show that the lower limit for fungal growth on wood, wood composites and strach-containing materials were:

78 – 80% RH at 20 – 25 °C,
80 – 90% RH at 10 °C,
>90% at 5 °C (Figure 6.3.A) [13, 15].

Whilst for the decay development, the humidity conditions should be much higher than that for mould growth – the critical RH > 95% (Figure 6.3.B). Time period, what is necessary for decay development, is also significantly longer than that for development of mould [13].

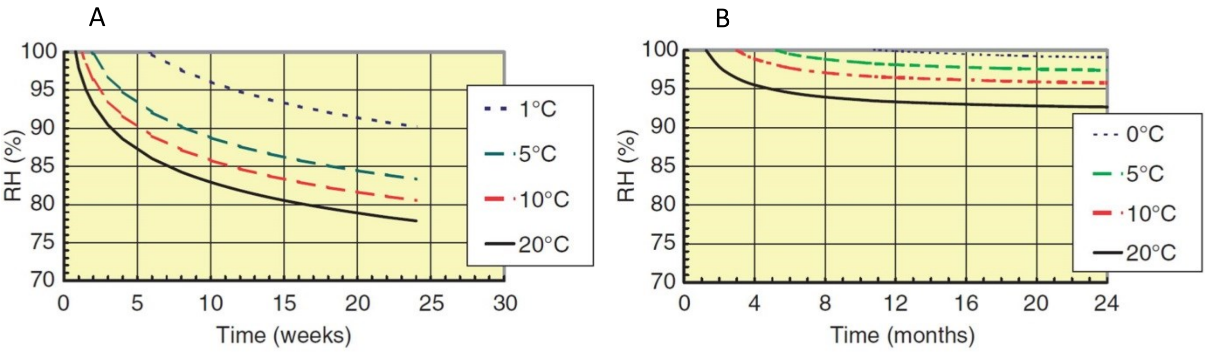


Figure 6.3. *Critical humidity (RH%), time (weeks/months) and temperature needed to start mould growth on pine sapwood (A) and early stage for brown rot development (B) in pine sapwood.*
Both figures are modeled, not measured [13]

In Latvia the most common mould and bluestain fungi, what are found on timber materials in damp buildings, are shown in Table 6.1 and Figure 6.4. Regarding to decay – brown-rot damage is found more frequently (78.1%) than the white-rot (21.9%). This can be explained by the fact that the coniferous trees (pine, spruce) are used more widely in Latvia and brown-rot are mainly detected in this type of timber, while white-rot fungi infect more the hard-wood (deciduous tree timber) materials [16].

Table 6.1. *Moulds and bluestain fungi in damp buildings [16]*

Fungus	*Localization of infection*
Aspergillus	roof rafters, veneer ceiling
Aureobasidium	veneer ceiling, roof construction
Chaetomium	OSB plates
Cladosporium	roof construction, wood platform, wallpaper, beams, boards
Graphium	roof construction
Ophiostoma	roof construction, floor beams, log house walls
Penicillium	beams, wallpaper, wood ceiling and walls, roof, wood laths
Trichoderma	beams, roof construction, floor beams, log house walls

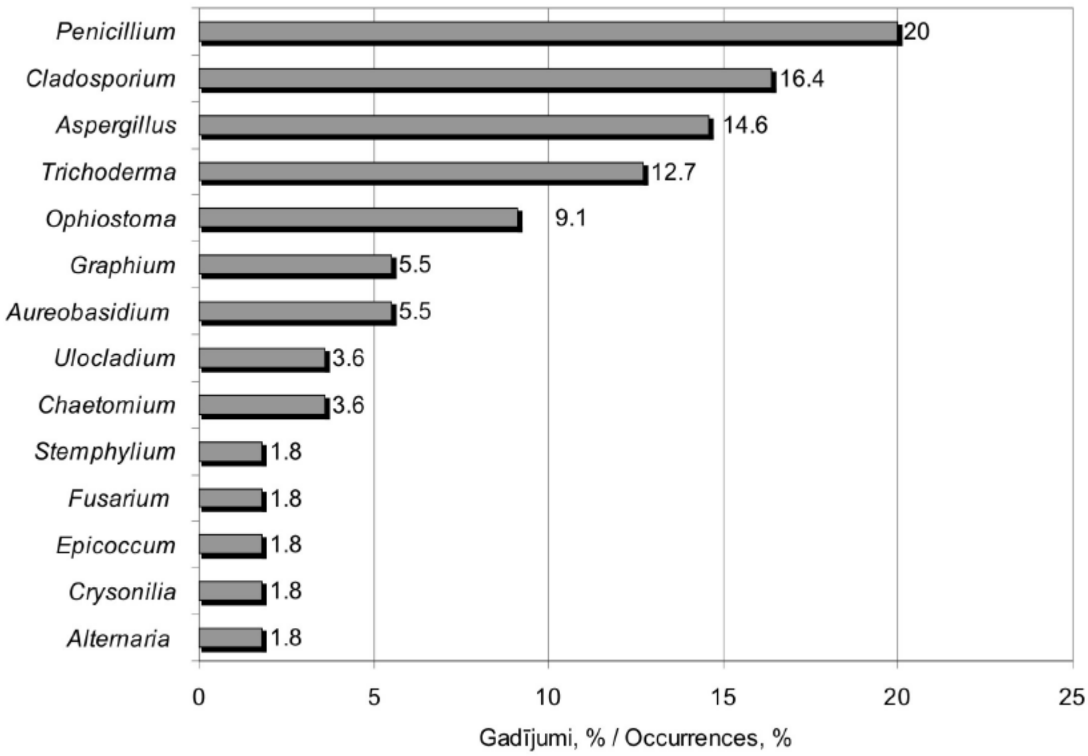


Figure 6.4. *Frequency of moulds and bluestain fungi on building materials [16]*

As already mentioned, **the time** is also very significant component for fungi development. It is important for how long time the environment and materials are exposed to high humidity. If the room is exposed to very high RH (95%) only for a few hours, while the rest of the time RH is less than 75% – it is not enough to provide development of fungi [13]. In turn, to provide spore germination, there is required for several days under the suitable humid conditions [10]. Under fluctuating moisture conditions, the development of fungi occurs slower than in constant favourable moisture conditions. If the relative humidity of the substrate is changed periodically, it is important how long the periods of high and low humidity are, and how fast the material can dry out. The longer the moisture periods and the slower drying process – they both contribute the development of fungi [10, 13].

It should be noted that, usually, conditions for fungal growth are not ideal and their development is determined by complex combination of various factors. For example, the accumulation of dirt and dust on the material surfaces (also on stone-based, inorganic materials) increases their hygroscopicity, which is a contributing factor to mould fungi development. Thereby, for the construction materials that are covered with dust, soil particles and other dirt, mould fungi can begin to develop at lower moisture content than on clean building materials [10, 13].

6.3. Requirements for the indoor climate quality

According to Law and regulations of EU, there is reference to recommendations, made by World Health Organization, Regional Office for Europe (2000),regarding to different chemical pollutants (e.g. carbon monoxide, nitrogen dioxide, ozone etc.), including volatile organic compounds (VOC) (e.g. formaldehyde, toluene etc.) in indoor air: "Air Quality Guidelines for Europe" [17, 18]. This organisation has also prepared material: "Dampness and Mould" (2009) for indoor conditions [19]. However, there is not any direct information regarding to permissible level or quantitative thresholds of microbiological contamination as the results obtained in numerous studies vary widely and it is often impossible to establish the statistically significant relationship among relative moisture level, microbial contamination indoors and their negative health effects. It is only pointed out that if problem with moisture and mould development is aroused, it should be eliminated.

As water is the key factor for possibility of mould development indoors, the RH has one of major parameter to describe the room climate, the European Standard EN 15251 prescribes the guidelines for RH in indoor environment. The Table 6.2 presents the levels of RH set down in EN 15251.

Table 6.2. *Relative humidity indoors according to Standard EN 15251*

Category		*Relative humidity (%)*
I	High level of expectation – for spaces occupied by very sensitive and fragile people	30 - 50
II	Normal level of expectation – for new buildings and renovations	25 - 60
III	Moderate level of expectation – used for existing buildings	20 - 70
IV	Values outside the criteria for the above categories – accepted for a limited part of the year	<20 or >70

In Latvia, there are the regulations regarding to indoor temperature and humidity in both living- and work-places:

- The Regulations No 340 (30.06.2015) of the Cabinet of Ministers of Latvia
  The Regulations on the Construction Standard of Latvia LBN 211-15
  "Residential buildings" [20]:
  indoor air RH – 55%,
  temperature – 18 – 25 °C.
- The Regulations No 359 (28.04.2009) of the Cabinet of Ministers of Latvia Labour Protection Requirements in Workplaces [21]:

The Requirements for indoor microclimate if the work does not involve physical effort or requires very little or little physical effort are presented in Table 6.3.

Table 6.3. *Requirements for indoor microclimate according to the Regulations No 359 of the Cabinet of Ministers of Latvia*

Annual period	*Temperature (°C)*	*Relative humidity (%)*
The cold season (average outside temperature ≤ + 10 °C)	19 – 25	30 – 70
The warm season (average outside temperature ≥ + 10 °C)	20 – 28	30 – 70

High humidity level can favour the development of house dust mites, too. Hart [23] and Korsgaard [24] have found larger house dust mites populations when the absolute indoor air humidity has been above 7g/kg (RH 45% at +20 °C). Arlian et al. [25] has observed the effective restriction of dust mite growth with the maintenance of mean daily RH of below 50%.

The main health risks, associated with poor IAQ, are based on RH level and concentration of VOC [26]. In order to provide a comfortable and healthy room climate, attention should be paid to the correct application of all elements that lead to minimisation of mould risk and of VOC concentration in buildings.

6.4. Use of moisture buffering materials

Selected materials for building, especially insulation – as one of the key element of the building envelope – and interior finishing materials, play pivotal role and can affect IAQ noticeably. In last few decades, many investigations have been focused on a promising strategy related to the use of "moisture buffering" materials. The "moisture buffering" effect is known as the capacity of the interior finishing and furnishing materials to moderate indoor humidity in buildings, thanks to their hygroscopic ability. Moisture buffering materials are able to adsorb and desorb moisture from the adjacent air and can be used to control indoor humidity variations without additional energy costs [27 - 29].

Building materials with high moisture buffering capacity are e.g. (Fig. 6.5):

- unfired clay masonry bricks [29, 30],
- clay plasters [29],
- unsealed ceramic tiles [31],
- wood panels (e.g. pine along the grain) [5],
- different natural insulation materials [5, 26].

The Table 6.4 presents a summary of the moisture capacities of different building materials determined in the researches carried out by Salonvaara et al. [5] during the 8-hour period of wetting and 16-hour period of drying.

6.5. Natural insulation materials

Nowadays, specialists of building industry, mowing toward sustainable and environmentally friendly construction, advise to replace insulation material, that are manufactured from non-renewable either mineral or petro-chemical resources, with renewable, low-embodied energy materials of natural origins. Another trend in the building industry is to assess the applicability of "breathing" walls or "vapour open" walls that are hygroscopic active and not require vapour barriers [32]. Vapour-open constructions based on the right choice of layers and their order within the multi-layer system: the most vapour open materials should be placed as the outer insulation layer; the inner side should be more damp-proof [26]. In both these cases natural fibre insulation materials give a great contribution but further investigations and testing are necessary in practical situations.

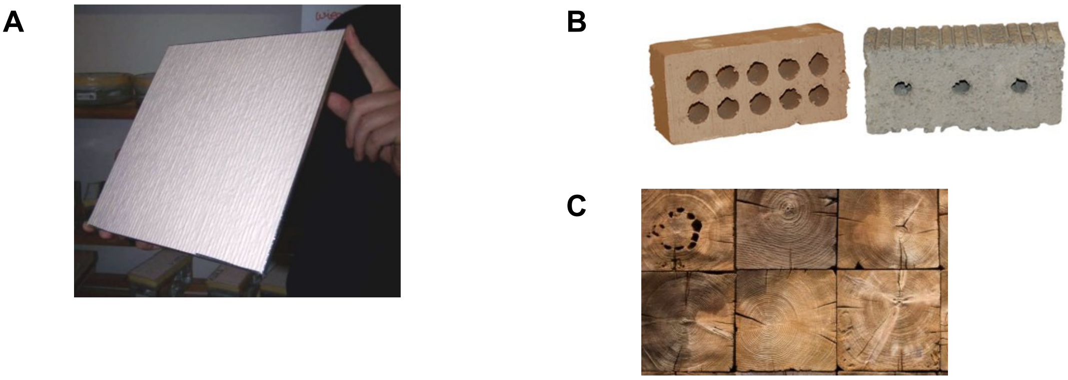


Figure 6.5. *Examples of the building materials with high moisture buffering capacity: A – unsealed ceramic tiles; B – unfired clay masonry bricks; C – wood panels (along the grain)*

Table 6.4. *Measured change in the mass of moisture during the 8 hour wetting period and 16 hour drying period in 50/23% RH and 75/50% RH tests [5]*

Case	*Change in mass of moisture, g/m^2*	
	Wetting in 8 h	*Drying in 16 h*
Wood, pine, smooth surface, against the grains	12	10
– " – @ 75/50% RH	22	16
Wood, pine, along the grains	90	70
Gypsum, painted twice	<1	0
Gypsum, unpainted	12	12
Porous wood fiberboard	45	45
– " – @ 75/50% RH	36	32
Gypsum, unpainted + mineral wool insulation	16	15
Gypsum, unpainted + cellulose fiber insulation	24	20

The technical performance of many renewable insulation materials (e.g., cellulose, wood fibre, hemp, sheep's wool, flax wool) is comparable to that of the mineral or fossil insulation material (e.g., glass wool, rick wool, polyurethane, polystyrene) (Tab. 6.4) in such benchmarks as thermal conductivity, sound-reducing. The microbiological risks associated with bio-based building materials can be diminished through the addition of natural anti-fungal agents. Likewise, fireproof salts reduce the flammability of these materials to the legally required level. Boron salt or ammonium phosphate is usually applied to insulation materials based on flax, cellulose or wood fibres to decrease its inflammability and increases mould resistance. Labels on materials provide information about the level of certification [26]. Problems with microbiological contamination and flammability can be resolved in different ways accordingly to properties of each material.

Bio-based insulation materials are very different regarding source materials; however, most of them (e.g., hemp, flax, wood fibre, sheep's wool) have some common unique properties providing higher living comfort:

– high moisture buffering capacity (without influencing the insulation value of the product) that can help to ensure more stable and moderate RH;

– high heat storage capacity that can help to avoid room overheating during the summer [16].

There are also some exceptions – e.g., cork and reed conduct moisture, but they have low moisture accumulating potential.

Table 6.5. *Insulation at a glance [26]*

Insulation material	λ (W/(m·K)	ρ (kg/m³)	μ	c (J/kg·K)	Fire class (DIN 4102)
Flax mats	0.036–0.040	30–60	1–2	1.600	B2
Hemp mats	0.040–0.050	30–42	1–2	1.600–1.700	B2
Hemp (loose)	0.048	40–80	1–2	1.600–2.200	B2
Wood shavings	0.045	75	1–2	2.100	B2
Wood fibre insulation board	0.040–0.052	140–180	2–5	2.100	B2
Wood fibre insulation board (flexible)	0.040–0.052	40–55	2–5	2.100	B2
Wood fibre (loose)	0.040	30–40	1–2	2.100	B2
Wood wool boards[1]	0.090	330–500	2–5	2.100	B1
Cork scrap	0.050	160	1–5	1.800	B2
Cork board	0.040	100–220	5–15	1.800	B2
Sheep's wool	0.0326–0.040	30–90	1–5	1.720	B2
Reed (rush)	0.055	190	6.5	*	B2
Straw bale construction	0.052–0.080	90–110	2	2.000	B2
Meadow grass	0.040	25–65	1–2	2.200	B2
Cellulose flakes	0.040	30–55	1–2	2.100	B2
Cellulose sheets	0.040	70	2–3	2.000	B2
Seagrass	0.037–0.0428	70–130	1–2	*	B2
Conventional insulation materials for comparison:					
Polystyrol PS (Styrofoam)	0.035–0.040	11–30	30–100	1.400	B1
Rock wool	0.033–0.040	33–130	1	840–1.000	A1

[1] Only used as plaster base.
Source: Fachagentur Nachwachsende Rohstoffe (FNR), composition based on estimates from suppliers.

Used symbols: λ – thermal conductivity, ρ – density, μ – vapour diffusion resistance factor, c – specific heat capacity, Fire class – European fire class system according to DIN 4102.

Some insulation materials of natural origin can accumulate moisture to up 30% of their weight, while insulation materials of fossil or mineral origin only show a fraction of this moisture accumulating ability. Holcroft and Shea [33] have compared the moisture accumulating potential of three building materials of natural origin (hempcrete, hemp fibre and sheep wool) with what of glass wool, either in combination with or without plaster (Fig. 6.6). The materials have been exposed to increasing and decreasing RH over periods of 12 hours. The RH has varied between 53 and 75%. Hempcrete appeared to show the largest moisture buffering capacity, twice as large as that of hemp fibre and sheep wool. However, plastering greatly reduced the moisture capacity, by 50 – 60%. The results highlighted the importance of using finishing materials with good moisture accumulating and/or conducting potential.

The results of the studies showed that the hygric properties of the different hemp insulation materials also can vary widely depending on their constituents and fibrous structure. These differences potentially can influence their hygrothermal performance as a part of a building thermal envelope (Tab.6.6, Fig.6.6). It was found that the highest moisture buffer value $MBV_{practical}$ was achieved for Hemp-2 followed by Hemp-5, while Hemp-4 showed the lowest value [34].

Another important performance indicator is high specific heat capacity (Tab. 6.5). This property can be beneficial in buffering indoor temperature – during the summer it can reduce the need for cooling. For instance, during the summer the peak temperature outdoors usually occurs at around 2 pm, but with a 20 cm thick insulation layer, the indoor temperature peak can be shift to 8 pm, at which time the outdoor air has cooled down and ventilation and cooling can be achieved by opening windows [26].

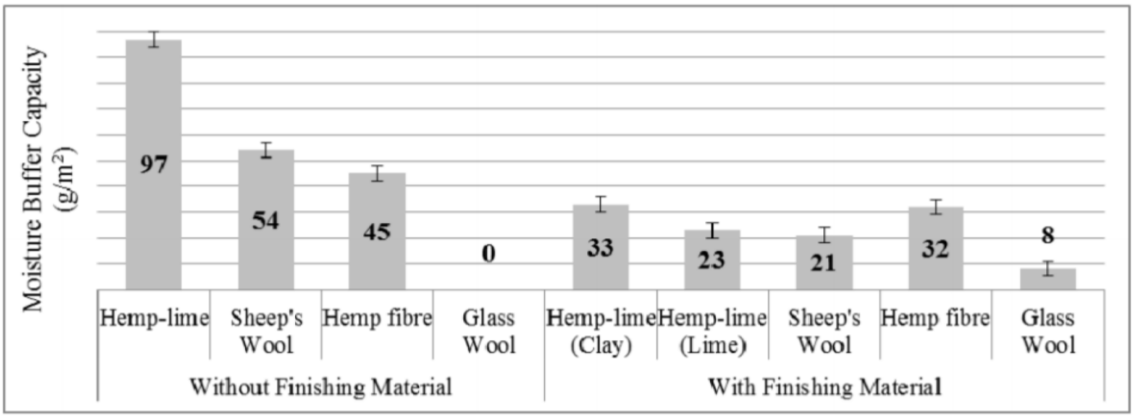


Figure 6.6. *Moisture absorbtion capacity of natural insulation materials, with and without finishing materials (plaster), compared with that of glass wool [23]*

Table 6.6. *Summary of the hemp insulation properties [43]*

Materials	*Measured mean density (Kg/m3)*	*Measured mean thickness (mm)*	*Constituents*	*Declared specific heat capacity (J/kg.K)*	*Declared dry thermal conductivity (W/m.K)*
Hemp-1	55	48	30% hemp fibre, 60% wood fibre, 10% polyester	1700	0.038
Hemp-2	50	55	85% hemp fibres, 10-12% bi-component fibres and 3-5% soda	1600	0.038
Hemp-3	60	47	70% hemp fibres, 15% hemp shive, 8% mmonium phosphate, 7% polyolefin fibres	1700	0.043
Hemp-4	39	45	95% hemp fibres and 5% combination recycled adhesive binder	1700	0.039
Hemp-5	45	57	35% hemp fibre, 35% recovered waste cotton fibre, 15% bi-component polyester fibre and 15% fire retardant	1700	0.039

Some bio-based insulation materials have individual unique characteristics:

- Neptune grass (*Posidonia oceanica*) has natural resistance to moulds, is free from vermin and non-flammable (code B2) – it could be associated with high titre of silicic acid in this material [26].
- sheep wool has an air purification effect (Fig. 6.7.) – it neutralizes indoor air pollution such as VOC (found in paints, varnishes, adhesives, glues, binders, hot fat and disinfectants etc.), ozone, nitrogen oxides and sulphur dioxide etc., because of property of proteins (keratin) in sheep wool to bind permanently these toxic organic compounds that are later destroyed [36 – 38].

There is still a lot of discussions on the use of natural insulation materials in the vapour-open building envelope. Many participants in this discussion refer to the risks of moisture accumulating and condensing within building envelope insulation layers. This

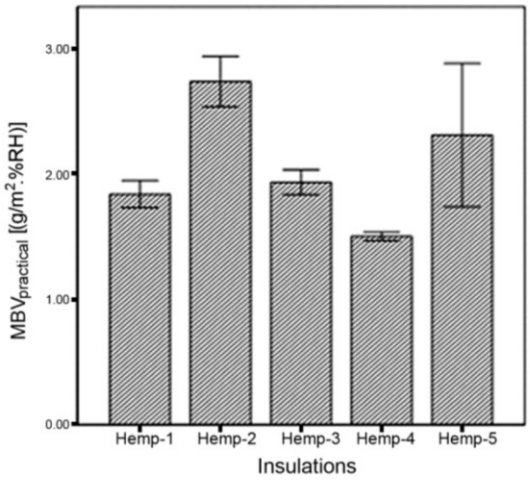
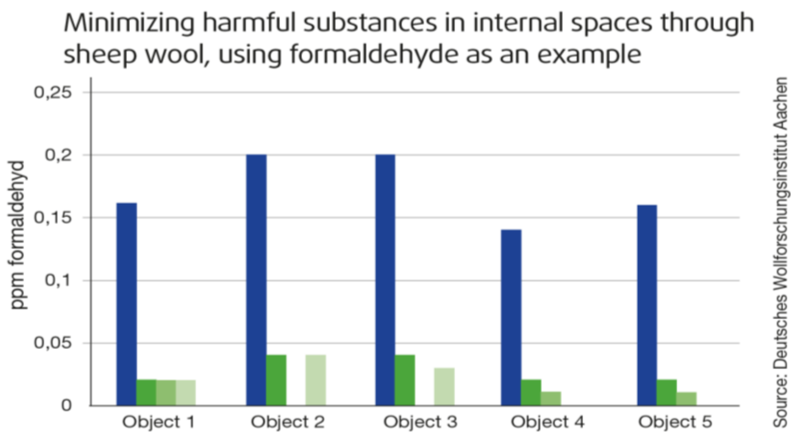


Figure 6.6. *Practical moisture buffer value of the different hemp insulation materials [34]*



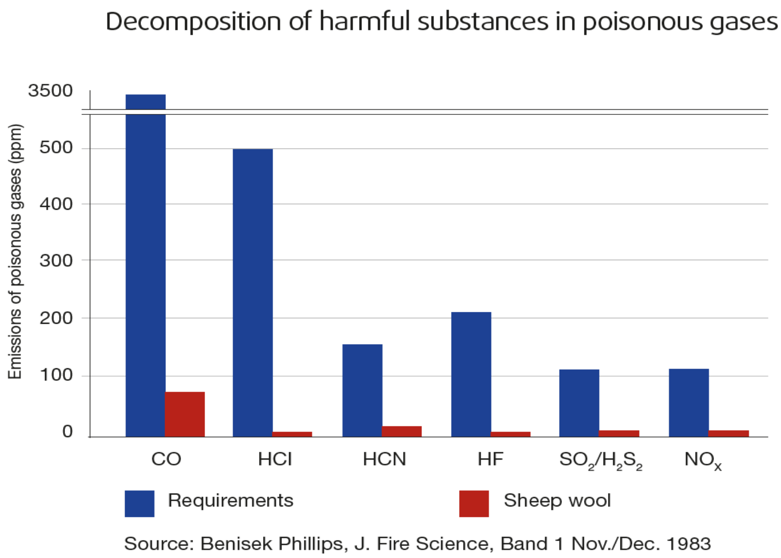


Figure 6.7. *Property of sheep wool to minimising harmful substances [35]*

would lead to mould growth and associated problems [26, 32]. However, the results from same researches show that the moisture content inside a vapour open wall can be better managed [5, 39, 40], while the use of a vapour barrier can result in high interior RH, large oscillations in the interior RH and excessive moisture load on the construction. This importance of vapour permeability of building envelope is well presented in the research what has been carried out by Mlakar and Štrancar [39]. There have been compared three different lightweight test passive houses (A – cellulose insulation, no vapour barrier (with vapour retarder); B – wood-fibre board insulation, no vapour barrier (with vapour retarder); C – mineral wool insulation, with vapour barrier) and the related temperature and RH pattern. The humidity conditions have been provided by humidifiers to humidify all the houses for 1 h/day to imitate rooms in real houses. After 10 days of the experiment, the results showed that the RH in A and B houses (with natural insulation material, no vapour barrier) has increased only about 5%, while in C house (mineral wool, with vapour barrier) the increase has been about 30%. It clearly demonstrates how vapour barrier has prevented any vapour exchange with the outdoors, so all produced vapour has remained in the house. In addition, mineral wool as non-hygroscopic material could not balance variations of internal RH. In a real situation, this would mean that an excess of water vapour should be removed with ventilation, which would increase energy consumption [3].

It is apparently that there is some gap of the investigation results in this field, and it could be helpful to get more data from practice studies in real climate conditions. It is to be also assessed, how much area of moisture buffering material needs to be installed for different building types. This will allow an optimization of building energy use and comfort conditions under an economical point of view [31].

So, the multi-functionality of natural fibre insulations is a major benefit of these products:

- ✓ a positive effect on human health related to improvement of IAQ threatened by pollutants and contaminants;
- ✓ a positive effect on living comfort:
  - o the high moisture absorption capacity of bio-based building materials can stabilise RH indoors,
  - o the use of bio-based materials in walls and ceilings can provide sound insulation and thus decrease noise nuisance, while improving acoustics;
- ✓ a positive effect on energy use – this would be associated with:
  - o the insulation value of bio-based materials,
  - o improved heat absorption capacity and thereby increased heat buffering, resulting in a decrease in energy use;
- ✓ a positive effect on the ecological sustainability of constructions related to carbon sequestration and less energy use during the production process [26].

There are some examples of bio-based insulation materials that could be used for building construction.

I. Sheep wool

Characteristics of sheep wool isolation:

- has a high moisture buffering capacity (one of the most hygroscopic natural fibres) – wool can absorb water up to 33% of its own weight – bind it inside the fibres – and release to the environment if it is required without changes in thermal conductivity properties; so, the insulating ability of sheep's wool remains even in moist condition – thanks to high air lock in the wool fibres;
- neutralize wide range of indoor air pollution (VOC, ozone, nitrogen oxides etc.);
- the absorption of moisture generates warmth – so, the cooling process is retarded considerably;

- sheep wool fibres as a protein fibre – does not form a breeding ground for mould, therefore, it is protected against mould by its very nature;
- surface of sheep wool has hydrophobic (water-repellent) properties;
- excellent sound absorption values;
- exceptional long-term elasticity and stability ;
- low flammability; flammability class E = B1 (self-ignition temperature of approximately 560 °C, with wood about 270 °C);
- no formation of toxic compounds in case of fire [25, 36];
- does not settle – the naturally occurring "pliable memory" of wool fibres eliminates settling; wool also actually expands to fill every space completely, while many loose insulation (e.g. cellulose) settle over time, resulting in air gaps that seriously reduce the insulation capability;
- installation safety – natural wool insulation requires no safety equipment for its installation [41].

However, there is necessity to process sheep wool insulation material against moth damage, as well as to improve ability regarding fire and mould resistance. Different companies offer varied solutions for this problem:

- material is treated by newer proprietary processes chemically bond a naturally occurring element to provide even more flame resistance as well as a vermin repellent to the wool fibre; contains borate molecules that resist mould propagation [41];
- material is equipped with an enzyme – thus it is absolutely mothproof according to current knowledge [36];
- material is treated by the innovative, patent-protected process, known as plasma ionic treatment (IONIC PROTECT®) – altering the outside of the sheep wool fibres, while sheep wool retained all of its great insulating properties – result is a 100% pure insulation product pesticide-free, with ZERO additives [35, 42]. This insulation product of Austrian company ISOLENA is awarded by The International Association for Sustainable Building and Living with **"**NaturePlus**"** certificate [35]. It indicates that these products fulfil high standards relating to climate protection, healthy accommodation and sustainability [43].

II. Hemp fibre insulation materials

In comparison to other annual fibre crops such us flax, jute or cotton, hemp fibres are characterised by a unique combination of fibre length, fibre stiffness and breaking strain. Therefore, hemp is considered to be the strongest native natural fibre and is classed the second one only to coco fibres for durability in use [44].

1. Thermo-Hemp is a natural insulation material manufactured in Germany [45].

Components: 82 – 85% hemp fibres, 10 – 15% bi-component fibres, 3 – 5% soda for fireproofing.

Benefits of hemp insulation:

- thermal performance – 0.04 W/mK;
- hygroscopic properties regulates humidity offsetting condensation risk (water absorption ≤ 4.2 kg/m^2);
- high specific heat capacity – 2300 J/(kgK);
- excellent sound insulation;
- low density & high thermal mass;
- semi-rigid/flexible;
- fire behaviour: class B2 according to DIN 4102;
- never slumps – have a natural resilience that enables them to maintain their structure (do not compact over time).
- Environmental friendly product:

- made from natural hemp plant fibres grown without any chemicals or toxic additives;
- is totally safe and easy for you to install;
- it's naturally resistant to mould growth (resistance against mould fungus – 0 according to EN ISO 846: 1997) and insect attack;
- having low embodied energy during the manufacture, hemp is carbon negative as it locks in carbon during its growth (1 hectare of hemp will absorb up to 18 tonnes of $C0_2$ as it grows);
- is awarded with "NaturePlus" certificate.

2. **SteicoCanaflex** (production of STEICO) [44].

Components: hemp fibres, polyolefin fibres, ammonium phosphate.

Benefits of hemp insulation:

- thermal conductivity – 0.04 W/mK,
- specific heat capacity – 1700 J/(kg·K),
- fire class B2 according to DIN 4102.

Environmental friendly product: is awarded with **"**NaturePlus**"** certificate.

3. **NatuHemp** (production of BlackMountain, UK) [46]

Components: 95% natural hemp fibres, 5% combination recycled adhesive binder.

Benefits of hemp insulation:

- thermal conductivity – 0.039 W/mK,
- specific heat capacity – 1700 J/(kg·K),
- fire class B2 according to DIN 4102,
- moisture absorption 20% w/w.

III. Wood fibre insulation

Gutex wood fibre insulation (made in Germany) [47].

Benefits of wood fibre insulation:

- thermal conductivity – 0.038 W/mK,
- superior specific heat capacity (Fig. 6.8),
- moisture absorption 15% w/w and vapour diffusion permeable,
- fire class B2 according to DIN 4102,
- acoustic insulation.

Environmental friendly product:

- recyclable,
- awarded with "NaturePlus" certificate.

IV. Straw bales, straw panels

Nowadays, in the constructions, the growing interest in using of straw is associated with the appearance of large, pressed straw bales (e.g., 46/37/50–130 cm) during harvesting process and they are a widely available as local product in major places of the world. Like other products such as hemp and wood fibre, the straw is a cellulose-based material. So, as the straw bales are made from a waste product, they have a very low-embodied energy. The only energy, what is used to make them, is in the bailing process and transportation to the worksite [48] (Fig. 6.9). Although, straw bales have proven themselves as sustainable building material, however, there are still, little scientific studies on their hygrothermal performance and possible mould and decay development during the building service life [50].

Benefits of straw insulation:

- thermal conductivity – 0.045 – 0.06 W/mK,
- moisture absorption approx. 25% w/w and vapour diffusion permeable,
- more breathable than many other building materials,

– acoustic insulation
– more flame retardant than conventional wood-frame construction [48, 50, 51].

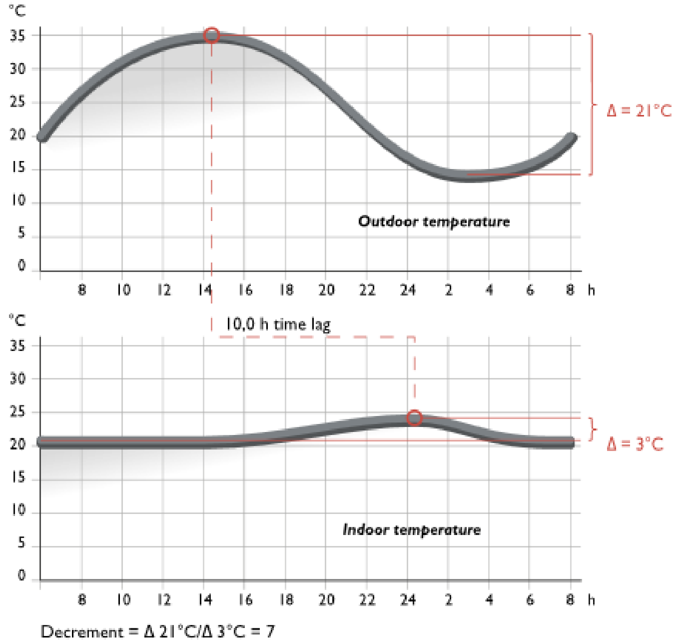


Figure 6.8. *The following example demonstrates the high heat capacity of wood fibre insulation:* *the time lag (it takes time for heat to reach building interior from building exterior through insulation) for 180-mm GUTEX Thermosafe-homogen insulation is 10 hours [47]*

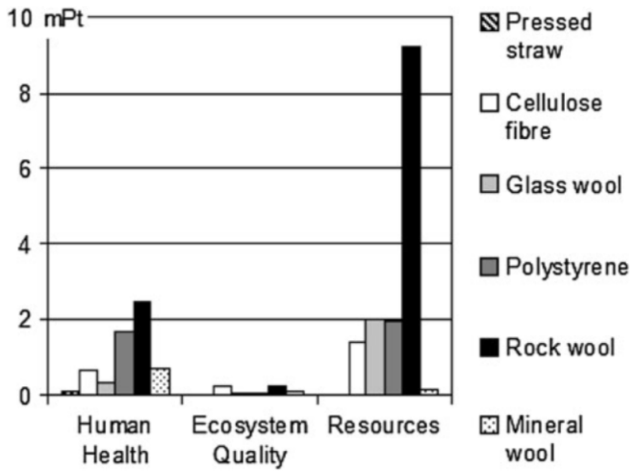


Figure 6.9. *Normalized environmental impact of different thermo insulating materials [49]*

V. Neptune Grass (NeptuTherm®) [52, 53]

Materials for an insulation is the leaf fibres of the withered Neptune Grass (*Posidonia oceanica*) that are rolled up into balls on the bottom of the sea and washed up on Mediterranean beaches by waves and wind. When it is compared with other natural fibres, sea grass is in a unique position as it is not produced by agricultural or forestry processes and therefore, it is not in the competition for land space with food production.

NeptuTherm® has the following positive characteristics:
– the thermal conductivity – 0.039W/mK;
– the best protection against the summer heat.

NeptuTherm® possesses the following without any chemical treatment and additives:

- low inflammability – it corresponds to B2 (fire resisting category);
- high resistance to mould;
- it contains only about 0.5 – 2% of salts which means – it is barely hygroscopic and is non-corrosive;
- the fibres absorb condensation, hold it and restore it without harming the insulation quality;
- there is no living creature (e.g. crabs, insects, mice) interested in the fibre – apart from human beings.

NeptuTherm®

- is not hazardous waste;
- have a very low environmental impact throughout their lifetime.

6.6. Effective ventilation system – earth-air heat exchanger

The provision of optimal ventilation is important task in nZEB construction. One of the well-known concept for ventilation is the using of earth-air heat exchangers (EAHE) (Fig. 6.10.A), which have received much attention during the recent years [2]. The EAHE is one of the passive heating and cooling systems, having benefits of reduced energy consumption and CO_2 emission. Due to the high thermal inertia of the ground, the soil temperature below an approximate depth of 3 m remains constant throughout the year and is in close range with mean annual ambient air temperature. Therefore, the soil can, be used as a heat source in winter. As ambient air travels through the EAHE, it receives heat from surrounding soil, resulting in higher outlet temperature of EAHE as compared to the ambient. The outlet air from EAHE may be used directly for space heating if it is at sufficient temperature, or it may be heated additionally. In summer, there is opposite situation – the air becomes cooler passing through the pipes buried in the ground [2, 54].

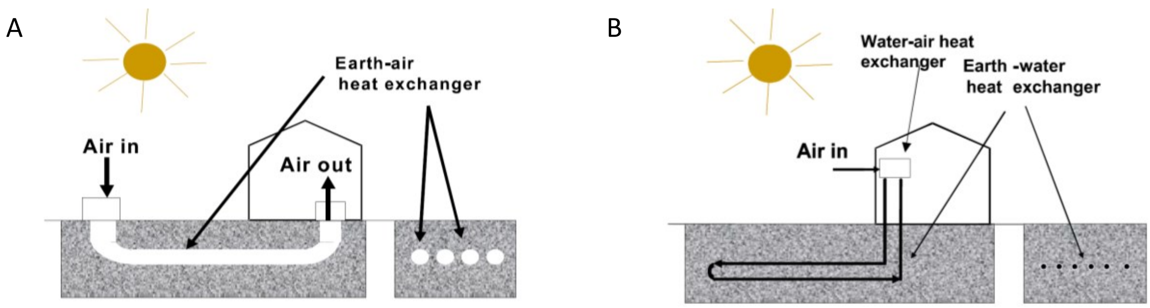


Figure 6.10. *The heat exchangers coupled to a building:*
A – earth-air heat exchanger; B – earth-water heat exchanger [2]

Though the results of some researches demonstrate that the EAHE mostly do not support growth of microorganisms in the pipes [55, 56], nevertheless several studies show that during the summer condensation can occur inside the pipes under high humidity conditions, and it can favour the development of microbial contamination, worsening IAQ. So, the possibility of humidity-related mould and bacteria growth has been taken into consideration [55, 57].

For examples, REHAU ECOAIR™ Ground-Air Heat Exchange System [58] offers the complex solution of this problem:

- ✓ condensate drainage,
- ✓ pipes with antimicrobial-protected inner surface,
- ✓ inlet-air filtration.

Condensation management. The first defence is removing the moisture through proper condensation management. The REHAU ECOAIR™ system offers two options:

- integrated
  in building with a basement, condensate is removed through the drain of the building. This is achieved via a condensate branch located at the lowest point in the EAHE pipe system;
- stand alone
  this solution drains condensate through an external condensate collection shaft for buildings without basements or where external drainage is preferred. Water is discharged from the EAHE pipe to condensate shaft and then it is pumped out using a standard submersible pump.

Properties of REHAU ECOAIR™ pipes. The pipes have been engineered to meet the requirements of an EAHE system. They inhibit ground-water intrusion, provide good thermal conductivity with the ground, have sufficient strength and inhibit microbial growth:

- high longitudinal rigidity –
  it promotes effective condensate drainage, preventing the formation of puddles;
- antimicrobial-protected inner pipe surface (Fig. 6.11) –
  AgION® Antimicrobial silver ions are embedded in the inner layer of the pipes.

The efficacy of this antimicrobial compound has been tested against numerous microorganisms such as bacteria, algae, fungus. AgION® compound provides continuous protection against microorganisms by releasing silver ions to surface at a slow and steady pace. Silver fights microbes in three ways: breaking cellular metabolism, inhibiting transport processes in the membrane and preventing multiplication of the cells [59].

Air filtration. In order to grow, microbes also require some food resource. From the incoming air, effective particle removal by using filters is one another important step [58].

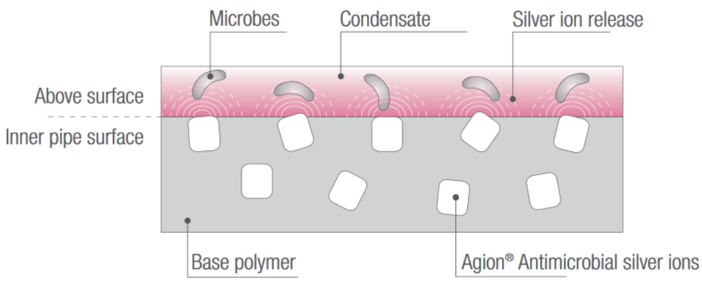


Figure 6.11. *Embedded silver paricles create an antimicrobial inner pipe surface that inhibits microbial growth. Silver ions are released when moisture is present, just when antimicrobial protection is the most needed [58]*

Summary, EAHE represents a relatively high investment cost for installation (ground jobs) and the surroundings of the building have to allow for the laying of the tubes. During the construction a great care has to be taken. Firstly, it is not always easy to dig deeply and collapsing of the pit walls has to be avoided. Secondly, the tubes need to be installed carefully to prevent formation of condensation e.g. tubes have to be tilted to evacuate the water [2, 60]. They also require a considerable length to provide a necessary capacity [61].

As an alternative, earth-water heat exchangers are now started to get used (Fig. 6.10.B). In these systems water is circulated to a matrix of small diameter tubes (diam. 2 – 5 cm) which are put into the ground. These tubes are coupled to a water-air heat exchanger placed in the ventilation inlet, thus obtained the same effect as earth-air heat exchanger. This system is thus cheaper and easier to install compared to the air based system [2, 61]. A brine liquid (heavily salted water) or water-glycol mixture can be used as the heat exchanger fluid [2, 56].

In order to increase the air pressure difference and efficiency of the EAHE, the EAHE can be combined with a passive ventilation system – a solar chimney (Fig. 6.12). The solar chimney uses natural convection to create a vacuum and enhance the natural stack ventilation through a building [56, 62]. In turn, so-called Trombe wall also can be used as solar chimney (Fig. 6.13) [63].

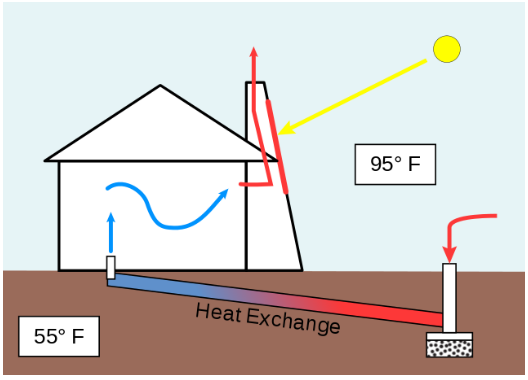


Figure 6.12. *The solar chimney draws air through a geothermal heat exchange to provide passive home cooling* [62]

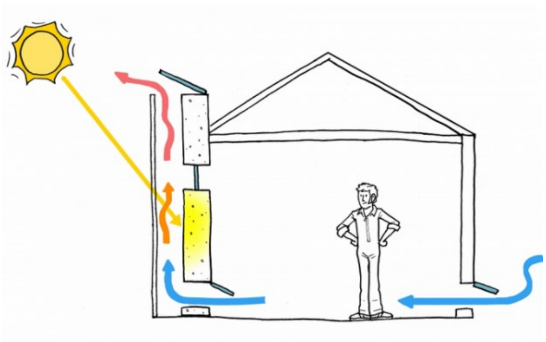


Figure 6.13. *A Trombe wall can act as a solar chimney [63]*

Trombe wall (also known as storage wall or Solar Heating Wall) is one of the solutions in passive architecture. The name of the wall was given after a French engineer Félix Trombe, who suggested this type of wall as an additional source of heat in overall heat load of the buildings. A typical Trombe wall consists of a massive vertical structure (generally made of stone, brick or concrete with high inertia) painted in a dark, heat-absorbing colour and covered with a single or double layer of glass, to provide greenhouse effect [63, 64]. In one research (carried out in the Utah, USA), where Trombe wall was used as an additional element to the conventional heating system (HVAC system), it was concluded, that up to 20% of the annual heating was supplied by the Trombe wall [65].

However, there are also some disadvantages of this wall type:

- in the climate with extended cloudy periods, without employing the adequate operable insulation, the wall may become heat sink;
- the Trombe walls have low thermal resistance causing to transfer the heat flux from the inside to the outside of a building during the night or prolonged cloudy periods;
- the amount of gained heat is unpredictable due to changes occur in solar intensity [66].

6.7 Intelligent facades

Facades are crucial to energy consumption and comfort in buildings. During the last decades, façade technologies have undergone to substantial innovations by integrating specific elements to adapt to various outside environments. Incorporating intelligence in their design is an effective way to achieve comfort condition for occupants, minimize energy consumption in buildings and additionally mitigate the environmental impact. The ventilated and double-skin façade are some types of those building elements [67].

Ventilated façade is a complex, multi-layer system that mainly becomes very popular because of their numerous advantages. The ventilated facades system consists of:

- support wall,
- an isolation layer,
- an external cladding layer joined to the building,

- an air gap between the isolation material and the final exterior cladding; the air chamber creates a natural ventilation by the so-called "chimney effect", thereby maintaining the isolation material dry and achieving a major saving in the energy consumption (Fig. 6.14) [68].

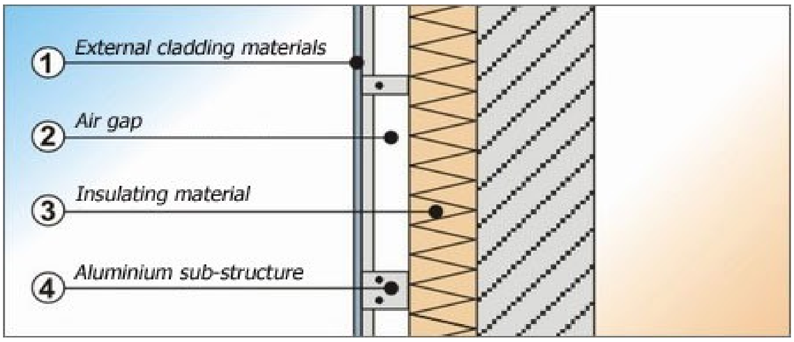


Figure 6.14. *Elements of ventilated façade [69]*

The most important benefices of ventilated façade regarding indoor comfort and energy saving:

- Enhanced interior climate

A building will be more comfortable for its inhabitants if the surface temperature of the interior walls remains as close to room temperature for as long as possible. The benefits of external insulation are twofold: in winter, the walls store heat so the internal room temperature remains high; in summer, the amount of heat accumulated by the perimeter walls falls dramatically, so the heat that reaches the interior is greatly diminished.

- Increased soundproofing

An improvement is up to 10 – 15 dB.

- Elimination of condensation

When two environments, separated by a wall, have a different temperature and RH, vapour tends to migrate towards the face of the wall facing the environment with the lowest actual pressure. Condensation will form if the actual pressure decreases more rapidly than the saturation pressure during this migration following the lowering of the temperature. The curves of the effective- and saturation pressure will never cross if the insulation is fitted on the outside of the wall and so condensation will never form. The internal humidity eliminated through the higher breathing perimeter walls is also rapidly removed by natural ventilation before it has the chance to settle on the outside face or wall covering.

- Improved performance of thermal insulation

Less heat bridging, damping and phase shift of the thermal wave and reduction in the thermal loads on the surface.

- Elimination of heat bridging

A modern building is typified by the discontinuity of the shapes and materials used in its construction, leading to heat bridging. In turn this leads to an uneven distribution of the temperature with a negative impact on the climate inside and promoting the formation of condensation and mould. A continuous layer of external insulation protects it in a more uniform way and the outdoor facing blocks the sun's rays: together, they lower its thermal instability and improve the building's energy performance [70].

Double skin façade technology is another design solution for energy saving that it can be implemented to build low-energy buildings [71]. The building with the double-skin facade has an envelope consisting of two walls – the outer wall is usually out of glass, while the inner wall can be out of any building materials (Fig. 6.15). A cavity between the walls usually varies from 12 to 120 cm. A larger cavity allows for installations such as HVAC, electrical and shading devices between the walls. The ventilation of the cavity can be natural or mechanical. The most important arguments for using a double-skin façade are:

- improved thermal performance,
- pre-heating of ventilation air,
- enhancement of thermal comfort,
- better sound insulations etc.

Usually the benefits of a double-skin façade are larger in cold climate countries [72, 73].

Double skin façade has some disadvantages:

- higher cost for designing, constructing, maintaining compared to the traditional single façade;
- increasing the weight of building's structure due to the application of this façade;
- risk of overheating can be increased during the sunny days; complicated process of designing;
- additional maintenance and operational costs;
- increased airflow velocity inside the cavity;
- potential issues associated to fire propagation [66].

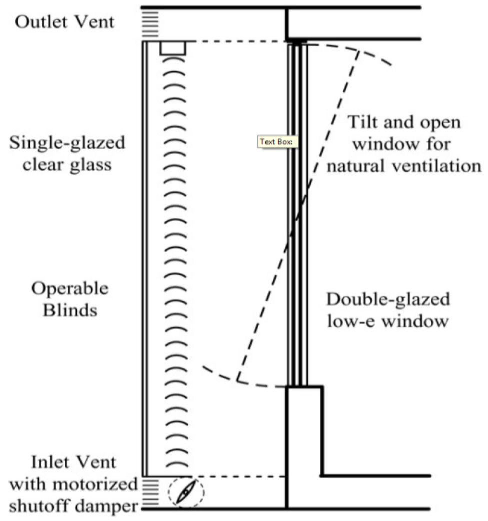


Figure 6.15. *Typical double façade components [74]*

6.8. Innovative finishing materials

One problem, that has become apparent in the recent years related to nZEB, is growth of algae and fungi on building facades. Development of microorganisms can impaired seriously not only aesthetic quality, but also durability of an external building envelope.

As modern exterior insulation finish systems do not have much thermal inertia and they are more subjected to undercooling, there is often observed condensation on the surface and a consequent higher biological growth risk. This undercooling phenomenon is due to the "thermal decoupling" that occurs in the envelope. "Thermal decoupling" is the complete breaking between the thermal behaviour of the inner part of the envelope (completely influenced by the interior conditions) and the external part (subject to climate conditions) due to high insulation of building envelope. Condensation commonly occurs on building facades when their surface temperature drops below the dew point of ambient air [3]. The main reason for this temperature drop is the long-wave radiation exchange of the façade with the atmosphere [75]. Mostly it is observed in intermediate seasons (fall and spring) during the clear and cold nights [3, 76]. In the Northern hemisphere, deterioration due to algae is found generally on the north and northwest facing surfaces, since these are hardly ever irradiated by the sun throughout the day and remain damp for a longer time [3].

So, in order to prevent growth of microorganisms, moisture has to be diverted away from the façade as quickly as possible and should be prevented from getting onto or into the façade at all. Geometrical characteristics of the building facades, roof projections, well-directed water flow and sufficient distance between the façade and trees or bushes all can help to reduce moisture. The physic-chemical characteristics of finishing materials also have a great importance on possibility of microorganisms to settle on façade surface [3, 77].

One of the most promising strategies to resolve the problem with the growth of algae and fungi is the development of innovative materials that use nanoparticles for conferring new functions on traditional materials. "Nanoparticles" are engineered particles with at least one dimension in the range of 1 – 100 nm (ISO/TS 27687 2008). They can improve, for example, the paint properties, such as water repellence, scratch resistance, durability as well as antimicrobial properties [78].

Among nanomaterials, there are TiO_2 (titanium dioxide) based coatings, which provide improved or new properties to paints in order to optimise their rheological or mechanical properties or to give them self-cleaning properties through dirt repellent, photocatalytic and superhydrophylic properties. Photocatalytic effect of titanium dioxide begins when TiO_2 reacts photochemically, stimulated by the UV radiation in sunlight [79].

Here are some recommended products.

- **ThermoSan NQG** (product of the company "Caparol") – **façade paint** with essential benefit [80]:

organically cross-linked nano-quartz particles form a compact, mineral-hard, three-dimensional quartz matrix structure against soiling and keep facades clean for a longer period – providing clean, fast-drying facades.

Material properties:

- ✓ provided with an encapsulated preservative against deterioration in the coating film due to algal and fungal attack;
- ✓ alkali-resistant, hence unsaponifiable,
- ✓ highly CO2 permeable,
- ✓ non-film-forming, micro-porous,
- ✓ is able to wash fine shrinkage cracks in render surfaces,
- ✓ contains special pigments, showing a photocatalytic effect,
- ✓ reduces visible marks on dark colours, if surfaces are subjected to mechanical loads.

- **StoLotusan** (product of company "Sto Ltd") – a breakthrough in render technology [81]. StoLotusan is the only render with the patented Lotus-Effect®, demonstrating unbeatable water and dirt repellence, and providing the best natural protection against the growth of algae.
As StoLotusan cures, the surface forms a unique microstructure similar to that found on the lotus leaf, greatly reducing the surface contact of water and dirt particles. Every time it rains, the rainwater simply rolls off the facade, picking up the loose dirt as it goes.

Features and benefits:

- ✓ water and dirt are unable to grip the surface, so the facade is cleaned every time it rains,
- ✓ very high CO_2 and water vapour permeability,

- ✓ provides the best natural resistance against the growth of algae and fungus by removing the conditions required for them to thrive.

- **StoColor Lotusan®** (product of company "Sto Ltd") – **façade paints** incorporate the unique Lotus-Effect® Technology [82].

This involves transferring the natural self-cleaning effect of the lotus plant – the lotus effect – to modern façade coatings.
Rainwater runs off the lotus plant in the droplets, taking all the dirt particles on the surface with it. On the façade, this effect guarantees active, moisture-regulating weatherproofing.
The result: dirt runs off with the rain and the façade stays clean and attractive for longer.

6.9. Greening systems

Greening systems, as green roofs and green walls, are frequently used as an aesthetical feature in the buildings for centuries [83]. But nowadays, there is an increasing interest in using them as a tool for a thermal regulation in the buildings with the aim of energy saving. In addition, both green roofs and walls protect building elements and extend their service-life. At the city scale, they also improve the urban environment by contributing to urban biodiversity, water run-off quality, stormwater management, air quality, temperature reduction and mitigation of the heat island effect [83, 84]. It is important to notice that these greening systems contribute to the insertion of vegetation in the urban areas without occupying any space at the street level. In this context, green walls have a greater potential than green roofs considering that in urban centres the extent of facade greening can be double the ground footprint of buildings [83].

Green roofs

A building roof that is either fully or partly covered with a layer of vegetation is called a green roof. It is a layered composite system consisting of a waterproofing membrane, growing medium and the vegetation layer itself. Often, green roofs also include a root barrier layer, drainage layer and, where the climate demands, an irrigation system. There are two main classifications of green roofs; extensive and intensive. "Intensive" green roofs have a deeper substrate layer that allows cultivating deep rooting plants such as shrubs and trees. In turn, "extensive" green roofs have thinner substrate layer that allows growing a low level planting such as lawn or sedum. Extensive type is more commonly used and they have been proven to be fairly successful in cold climates. The green roof as energy saving element can not only reflect the solar radiation, but also acts as an extra thermal insulation layer [69] and they can be more effective for low-rise buildings [85]. There are at least such parameters of green roofs what influence their thermal performance: substrate thickness, substrate moisture content (Fig. 6. 16) and density of vegetation [86, 87]. The green roofs are only meant to improve thermal protection of a building and should not replace the roof insulation layer. It is observed, that green roof system incurs higher annual savings when installed on a poorly insulated roof rather than a well-insulated roof [64].

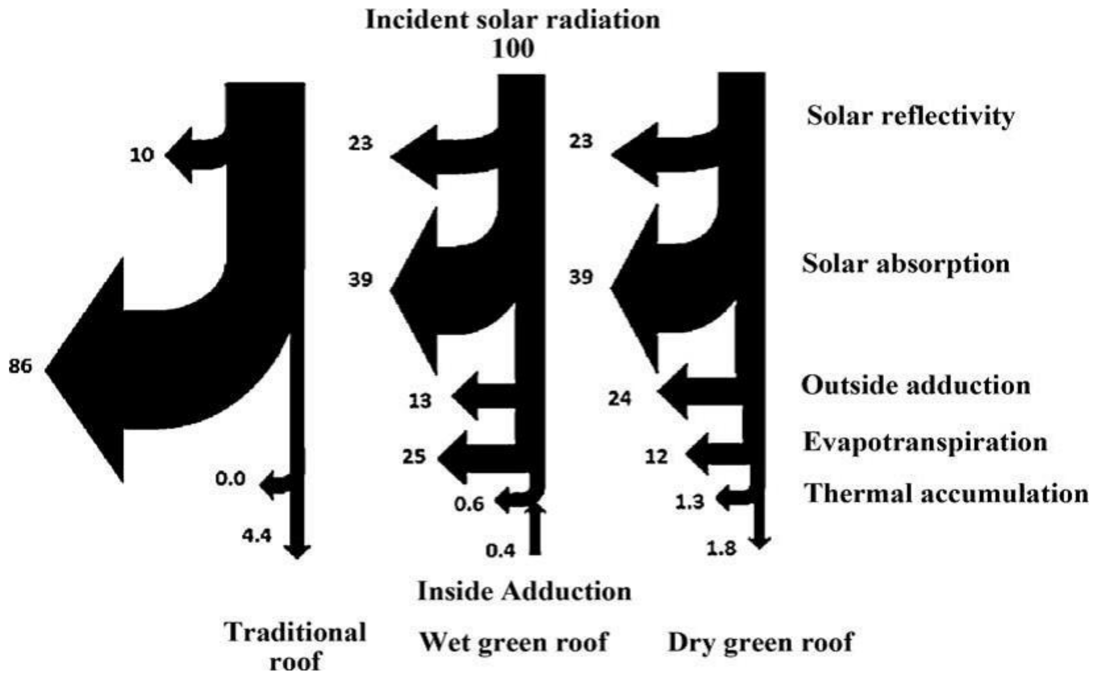


Figure 6.16. *Comparison of the energy exchanges of the dry and wet green roof with a traditional roof in summer season [88]*

Green walls

Green walls can be classified into two groups based on their construction:

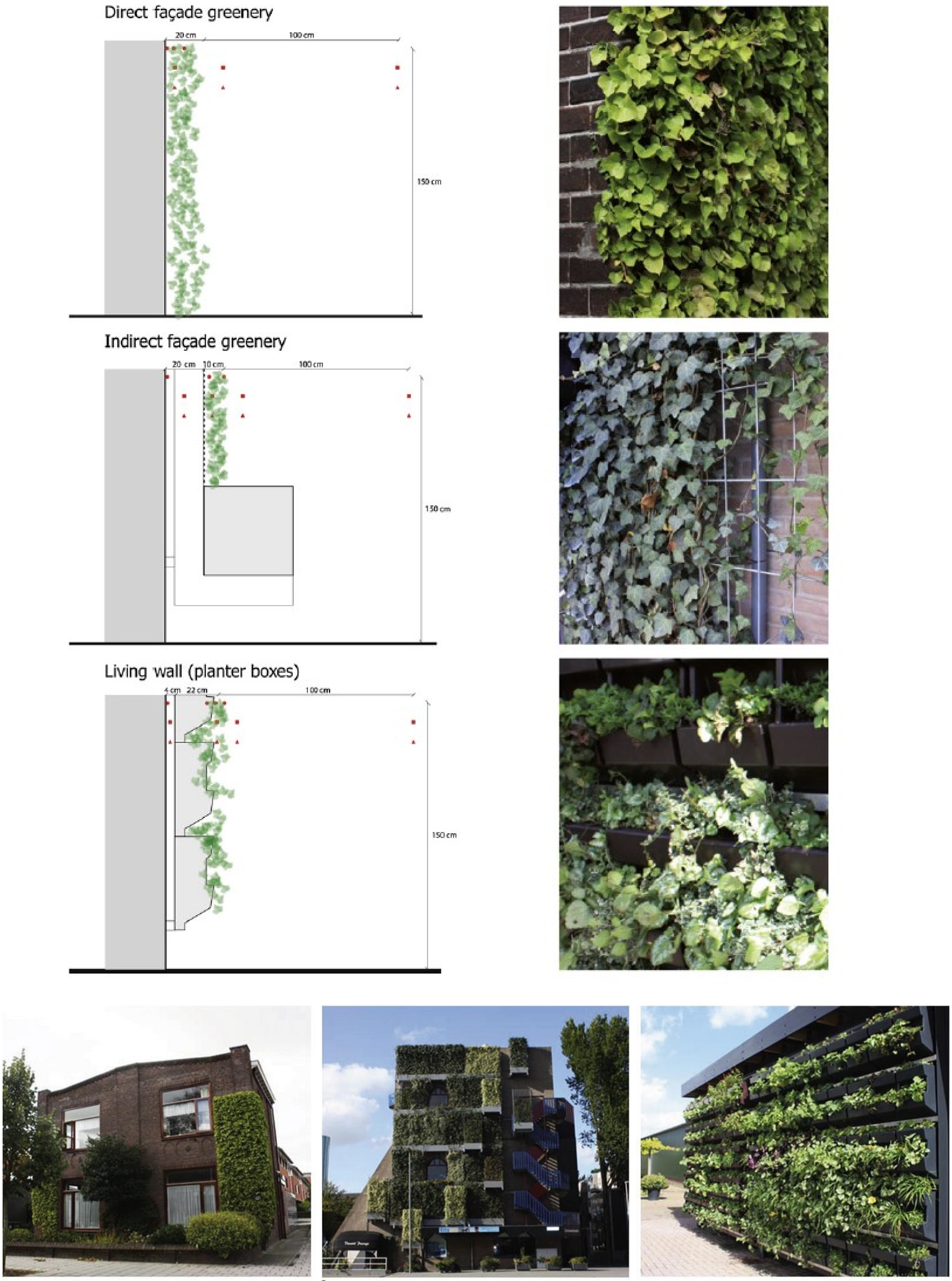
- green facades – are based on the use of climbers (evergreen or deciduous) attached themselves directly to the building surface (as in traditional architecture), or supported by steel cables or trellis;
- living wall systems, which are also known as green walls and vertical gardens – are constructed from modular panels, each of which contains its own growing medium; they demand a more complex design, are often very expensive, energy consuming and difficult to maintain (Fig. 6.17) [66, 89].

In Table 6.6, there are presented the most important factors that influence behaviour of green walls as passive energy saving systems [90].

Table 6.7. *Key factors that influence thermal properties of green walls [90]*

Interception of solar radiation. Shadow	*Thermal insulation and storage*	*Evaporative cooling*	*Variation of the effect of the wind*
Density of the foliage (number of layers)	Density of the foliage (number of layers) Changes in the air in the intermediate space Barrier effect of wind Substrate: thickness, bulk density and moisture content[a]	Type of plant Exhibition Climate (dry/wet) Wind speed Substrate moisture [a]	Density of the foliage (number of layers) Orientation of the façade Direction and wind speed

[a] Only in certain types of green verticals systems, such as living walls.



a Direct façade greening system **b** Indirect façade greening system **c** Living wall system

Figure 6.17. *Types of green walls [89]*

The green walls provide some of the same benefits as green roofs – they reduce the transfer of solar heat into the walls of buildings both by direct shading and by evaporative cooling and they also increase thermal insulation [85]. Cooling effect of green walls is well studied [90, 91], while there is much less known about their effectiveness during the cold season. One research has been carried out in Manchester (UK) with *Hedera helix* (English ivy – evergreen climber) on North wall of solid brick-walled building during the late winter. The ivy covering has increased the mean external wall temperature by 0.5 °C and slightly has reduced diurnal temperature fluctuation. Calculated energy losses have been reduced by 8%. It has been found, that the covering was more effective on cold days, but at temperatures above 12.2 °C the ivy covering has increased energy loss, because it has shaded the outside of the wall from warming by short wave radiation. The researchers have highlighted the main finding – there is the limited effectiveness of green walls at reducing winter heating costs, even for poorly insulated brick buildings. It could indicate that for well insulated modern buildings, green walls would provide negligible added insulation effect in winter. Nevertheless, the results suggest that evergreen green walls can reduce heating costs, particularly when placed them on the North of buildings, whereas on the South side deciduous climbers might be more effective [85]. So, it would be useful to evaluate the effect of different climbing plants (evergreen and deciduous) on thermal performance of buildings throughout the year in local weather conditions.

6.10. Mould prediction models

In order to provide favourable indoor climate condition for inhabitants and avoid damage of building materials, the possibility of prediction of mould formation risk is very important in constructions. It is the reason why there is a growing request for reliable calculation methods in building engineering to evaluate the moisture performance in building elements and probability of fungal growth. Different methods for hydrothermal analysis of building are developed to simulate the coupled transport processes of moisture and heat, aiming to predict microbiological risk, such as, IEA-Annex 14, time-of- wetness (TOW), Clarke and Rowan's isopleth model (ESP-r model) etc. [3, 92]. However, some of the well-known and commonly used models are Viitanen or VTT (VTT – Technical Research Centre of Finland) model as well as Sedlbauer's isopleth and the biohygrothermal model [93].

International Energy Agency-Annex 14 defined a surface RH threshold for mould growth dependent on the elapsed time. This threshold was defined on the lowest isopleth for *Aspergillus versicolor* (typical mould fungi in humidity damaged buildings) on agar, resulting in RH threshold equal to 80, 89 or100% for respectively an exposure time of 1 month, 1 week and 1 day. This proposal was simplified into a design value for temperature ratio (Eq. 6.1):

$$\tau = \frac{\theta_{s,\min} - \theta_e}{\theta_i - \theta_e} \geq 0.7 \tag{6.1}$$

with $\theta_{s,min}$ (°C) the minimum indoor surface temperature and θ_s and θ_e the inside and outside temperature (°C), respectively. A temperature ratio of 0.7 is proposed as criterion, related to an acceptable mould risk of 5%. A lower ratio introduces an unacceptable high mould risk. One of the limitations of this model is that humidity values (main influencing parameters) are taken into account only indirectly [3, 92].

Model of Time-of-Wetness (TOW) was developed by Adan. He carried out a series of experiments, evaluating development of *Penicillium chrysogenum* on gypsum board, to study fungal growth under transient RH conditions. Adan observed that also short periods of high RH should not be neglected in mould analyses. In order to indicate the water availability under transient conditions, the TOW was introduced, given by Eq.6.2.:

$$\mathrm{TOW} = \frac{\text{cyclic wet period } (\mathrm{RH} \geq 0.8)}{\text{cyclic period } (\text{wet } + \text{dry})} \tag{6.2}$$

The performed experiments showed that *P. chrysogenum* on gypsum board was only weakly affected for the TOW ≤ 0.5, while the TOW ≥ 5 results in a non-linear relation between the TOW and the mould growth and an increased mould damage. However, it is clear that this model cannot be used to predict mould development in cases of other species and substrates [3, 92].

Hens found that *Aspergillus versicolor* has the lowest critical growth isopleth among various mould fungi. After laboratory studies, the critical relative humidity of *A. versicolor* was obtained, based on a quadratic function of temperature correspond to the long-term risk, and a logarithmic function of the number of days correspond to the short-term risk [94]

Clarke and Rowan [95] developed a simulation model based on an analysis of published data using the growth limit curves for six categories: highly xerophilic, xerophilic, moderately xerophilic, moderately hydrophilic, hydrophilic and high hydrophilic (Fig. 6.18). These limits have been incorporated whithin the ESP-r system for the assessment of the environmental and energy performance of buildings [3, 13, 94].

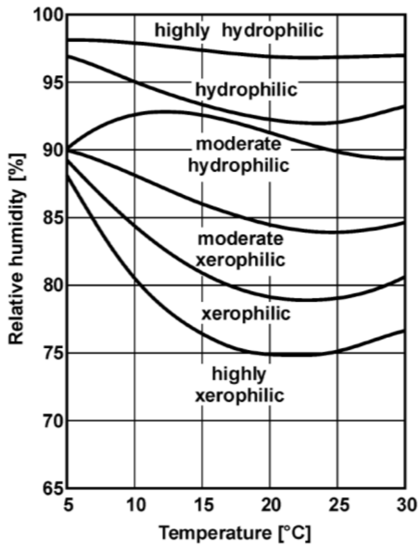


Figure 6.18. *Representation of the lower envelope curves of the respective growth range for different mould fungus categories, in dependence of temperature and relative humidity according to Clarke and Rowan [7]*

VTT model is an empirical model based on large-scale experiments in the steady-state as well as dynamic conditions [96, 97]. The basic version of a model was based on extensive laboratory studies with Scots pine (*Pinus silvestris*) and Norway spruce (*Picea abies*) sapwood. The mould growth intensities were determined using mould indexes *M* (Table 6.7). Based on studies under varied and fluctuated humidity conditions, the mould growth model (Eq. 6.3) was developed:

$$\frac{dM}{dt} = \frac{1}{7 \cdot exp(-0.68 lnT - 13.9 lnRH + 0.14W - 0.33SQ + 66.02)} k_1 \, k_2 \tag{6.3}$$

The influence of temperature *T* (0.1 – 40 °C), relative humidity *RH* (%), wood specie *W* (0 = pine, 1 = spruce), surface quality *SQ* (0 for resawn, 1 for original kiln-dried timber), exposure time t and dry periods are included in the model. The incremental mould index in- or decrease also can be calculated. The factor k_1 is used to scale the growth intensity under favourable conditions. The factor k_2 is included to implement a moderation of the growth intensity when mould index approaches to maximum peak value (4<M<6).

Table 6.7. *Original mould index classification together with update based on experiments with different building materials (in bold) [92]*

Index	Growth rate	Description		
0	No mould growth	Spores not activated		
1	Small amounts of mould on surface	Initial stages of growth	Microscopic level	
2	<10% coverage of mould on surface		Microscopic level	
3	10-30% coverage of mould on surface, **or < 50% coverage of mould (microscope)**	New spores produced	Microscopic level	Visually detectable
4	30-70% coverage of mould on surface, **or > 50% coverage of mould (microscope)**	Moderate growth	Microscopic level	Visually detectable
5	>70% coverage of mould on surface	Plenty of growth		Visually detectable
6	Very heavy, dense mould growth covers nearly 100% of the surface	Coverage around 100%		Visually detectable

Carrying out numerous laboratory and field tests, the VTT model was developed further for other typical building materials: spruce board (with glued edges), concrete (maximum grain size 8mm), aerated concrete, cellular concrete, polyurethane thermal insulation (PUR, with paper surface and with polished surface), polyester wool, expanded polystyrene (EPS) and glass wool. As an investigation of all building materials is not possible to simplify analysis, therefore, four mould sensitivity classes are presented (Table 6.8). In equation 6.3, for other materials except pine and spruce, is W=SQ=0 [92, 93, 97, 98].

Table 6.8. *Mould sensitivity classes and their material groups for VTT model [98]*

Mould sensitivity class	Typical materials
Very sensitive	Untreated wood, Materials including nutrients
Sensitive	Planed wood, Paper coated products, Wood based boards
Medium resistant	Cement based materials, Plastic based materials, Mineral fibers
Resistant	Glass products, Metal products, Materials with protective compound treatments

Sedlbauer's isopleth and biohygrothermal model. Referring to the information available in the science literature, Sedlbauer has gathered data about approxim. 200 species of mould fungi what can cause health risk and can be detected on buildings materials. He has subdivided these fungi in three hazardous classes:

- class A: mould species which are highly pathogen and not allowed to occur in buildings;
- class B: mould species which are pathogen when exposed over a longer period or which cause allergic reactions;
- class C: mould species which are not dangerous to health, but they may cause building materials damage.

Class B and C have been combined in one class B/C, as the results obtained of them differed only slightly. According to the results regard to LIM-curve (Lowest Isopleth for Mould – the conditions below which no spore germination or growth occur) for each classes representative fungi have been determined: for class A – *Aspergillus versicolor*; for class B/C – *Aspergillus amstelodami*, *Aspergillus candidus*, *Aspergillus ruber* and *Wallemia sebi*. Based on data about the growth of these fungi on an optimal culture medium, the isopleth systems for each hazardous class are developed. There have also been made separate isopleth system for spore germination and mycelium growth (growth rate is mm per day). In the later researches, the hazardous classes have been combined the single hazardous class [3, 7, 92].

The influence of building substrate and its possible contaminations (dust, dirt, etc.) have been taken into account during the second subdivision of model. Isopleth systems for four groups of substrates that can be derived from experimental examinations, as well as making some simplistic assumptions, have been suggested. An overview of them is given in table 6.10.

Table 6.10. *Sedlbauer's substrate categories [92]*

Substrate category 0	Optimal culture medium
Substrate category I	Biologically recyclable building materials like wall paper, plaster cardboard, building materials made of biologically degradable raw materials, material for permanent elastic joints
Substrate category II	Biologically adverse recyclable building materials such as renderings, mineral building material, certain wood as well as insulation material not covered by I
Substrate category III	Building materials that are neither degradable nor contains nutrients

Figure 6.19 presents for these substrate groups the generalized isopleth systems for spore germination and mycelium growth valid for all relevant species of mould fungi occurring in the construction. No any isopleth system for substrate category III is developed, as for these substrates no mould growth will be expected. The isopleth systems are made in such a way that always the worst case scenario is taking into account [3, 92, 93].

Biohygrothermal model developed by Sedlbauer (2001) describes the mode of action for the fundamental means of influence on the germination of spores, i.e. the humidity available at the certain temperatures in a correct way from the physical point of view. This model allows the calculation of the moisture content in a spore in dependence on transient boundary conditions. If the critical water content is achieved inside the spore, germination can be regarded as completed and mould growth will begin. So, the necessary time until spore germination and the mould growth can be calculated [92, 93].

In Figure 6.20 and Table 6.11, there is shown the comparison among several prediction models of mould growth. Comparing both VTT model and Sedlbaur's isopleth and biohygrothermal model, it is seen that these models are quite different. The VTT model is an empirical model based on laboratory investigations, while the biohygrothermal model is a theoretical model. Growth, what is calculated under unfavorable conditions, can be

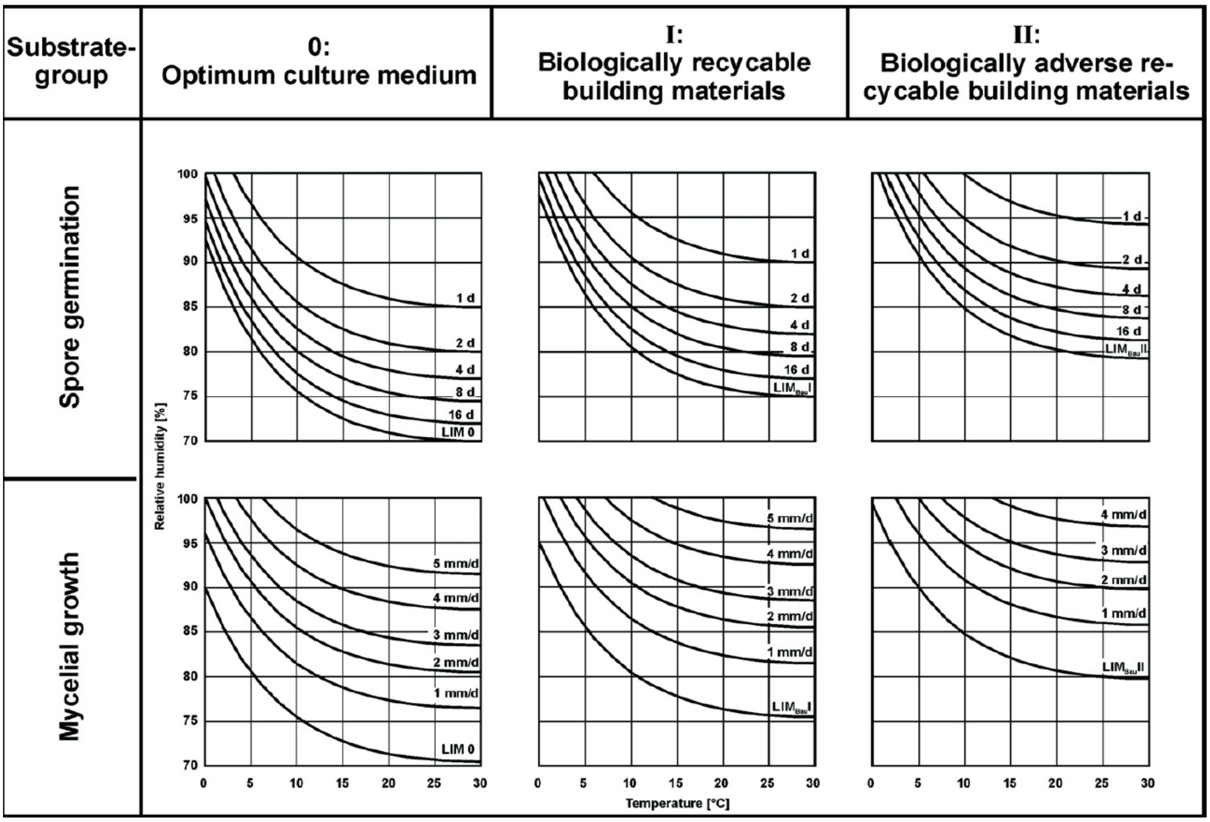


Figure 6.19. *Generalized isopeth systems for spore germination and mycelium growth valid for all kinds of mould fungi on corresponding substrates [7]*

retrogressive in case of the VTT model in contrast to the biohygrothermal model which shows zero growth in these periods. However, the most essential difference is that the VTT model limits the predicted mould growth rate to climate specific maximum value, while the biohygrothermal model allows continuous growth as long as there are suitable conditions [93, 99]. As well as comparing the results obtained with both methods, there can be seen that the germination criteria, what are used in the VTT model (M>1), seem to be less severe comparing to the germination criteria used by Sedlbauer (Fig. 6.21) [92]. For the purpose to transform the results, what are obtained by using the biohygrothermal model (mould growth in mm), into corresponding mould index (according to VTT model) conversion function has been developed with high level of coincidence (Fig. 6.22) [93, 99].

Table 6.11. *Overview of the different mould prediction methods: (1) temperature ratio, (2) TOW, (3) updated VTT model, (4) ESP-r isopleth mode, (5) isopleth curve Hens, (6) Sedlbauer's isopleth system, (9) biohydrothermal model [92]*

	1	2	3	4	5	6	7
T influence included?	Yes	No	Yes	Yes	Yes (long exposure time) No (short exposure time)	Yes	Yes
Growth at $T < 0$ °C?	Yes		No	No	Yes	No	Slight growth
RH influence included?	Indirectly	Yes	Yes	Yes	Yes	Yes	Yes
Substrate taken into account?	No	No	Yes	No	No	Yes	Yes
Estimation of growth (G) or only indication of start (S)?	S	S	G	S	S	G	G
Growth delay possible?			Yes			No	No (zero growth)
Limit growth value?			Yes			No	No
Corresponding simulation tool			TCCC2D or Latenite	ESP-r			WUFI-Bio

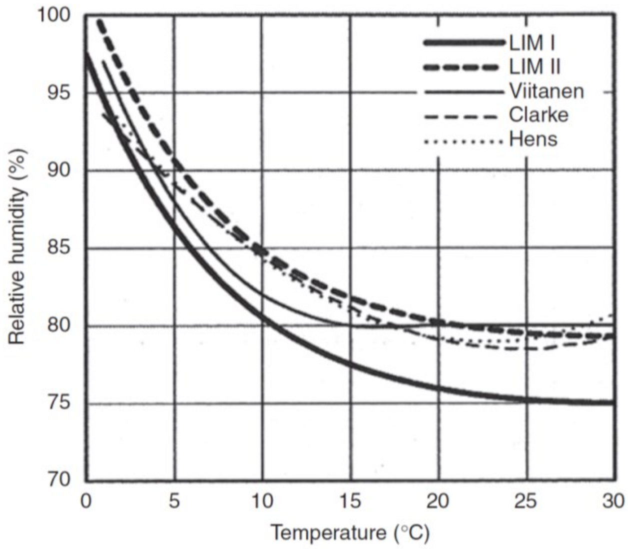


Figure 6.20. *Comparision of the LIMs of substrate class I (LIM I – biodegradable materials) and substrate class II (LIM II – porous materials) after Sedlbauer with data from results of original VTT model, and Clarke et al. (for xerophilic fungi), and Hens [13]*

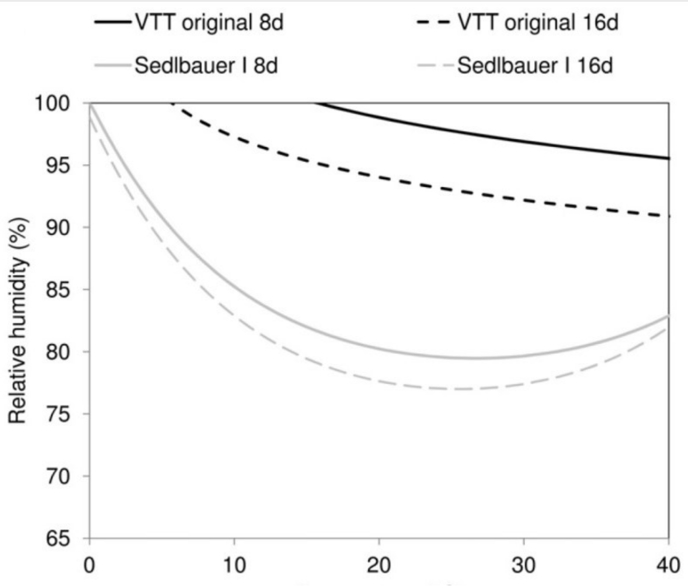


Figure 6.21. *Comparision between the germination time according to Sedlbauer's germination graph for substrate category I (biodegradable materials) and the original VTT model – isopleths indicating germination after eight and sixteen days [92]*

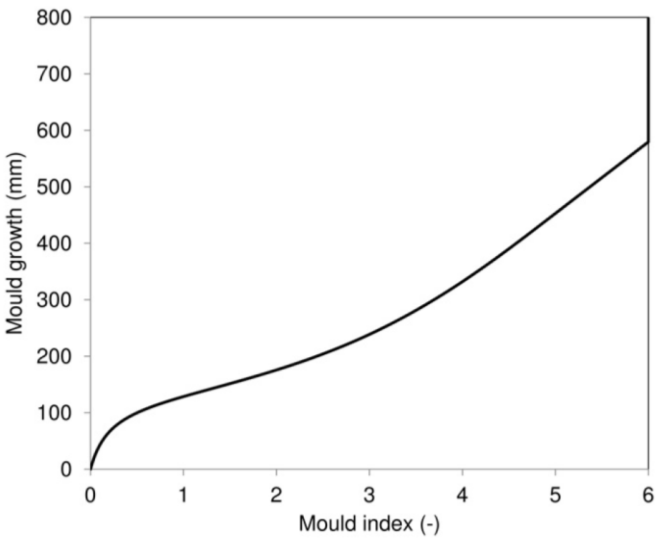


Figure 6.22. *Relationship between the mould (accorging to the VTT model) index and mould growth in mm (according to the biohygrothermal model [92]*

In summary, it should be remarked that still more and deeper studies are necessary, especially evaluating the mould formation under transient conditions to be able to develop the most reliable prediction model and to solve current contradictions among the models. In order to do it, additional measurements are required in laboratory conditions as well as in situ [92].

6.11 Comments and recommendations

In order to pursue sustainable construction, green building industry requires the focus on using renewable as well as low-embodied energy building materials such as timber and its products, various natural insulation materials. In this context, it is noted that lightweight timber-framed buildings can provide low thermal transmittance requiring for nZEB. Among all criteria, that influence the indoor comfort level, temperature and humidity are the most important. The previous studies and observations have shown that there is a gap in knowledge in terms of understanding the hygrothermal performance of eco-friendly materials in wall assembles of passive houses and, obviously, further studies are necessary.

One of the most important tasks, to maintain the confortable indoor environment, is the careful selection of proper building material and their arrangement within construction blocks. In order to ensure acceptable and stable relative humidity and to minimize the possibility of mould fungi development it could be advised: to use interior finishing materials with high moisture buffering capacity, e.g., clay plasters, wood panels. In turn, to fully utilize the advantage of natural insulation materials to accumulate and conduct moisture, damping humidity oscillations, it could be necessary to realize the idea of "vapour open" walls (using vapour retarders instead of vapour barriers) what made the buildings able to breathe and remove excess moisture outdoor, thereby, noticeable improving indoor microclimate. It allow to save energy used for additional ventilation. It may be also possible to reduce the heating and cooling energy consumption by up to 5% and 30%, respectively, when hygroscopic materials with well-controlled heating, ventilation and air conditioning system are applied [39, 100]. The examples of appropriate light construction are shown in table 6.12.

Table 6.12. *Composition of test building walls from inside to outside with their U values [39]*

	House A	House B
	$U = 0.099\ W/m^2\ K$	$U = 0.15\ W/m^2\ K$
Inside	Gypsum board 0.015 m Cellulose insulation 0.14 m OSB/3 board 0.015 m Cellulose insulation 0.18 m in wooden construction 0.18 m Wood-fiber board 0.08 m	Gypsum board 0.015 m Wood-fiber insulation 0.08 m OSB/3board 0.015 m Cellulose insulation 0.18 m in wooden construction 0.18 m Wood-fiber board 0.08 m
	Facade plaster 0.008	Wind barrier membrane Ventilated air gap 0.02 m
Outside		Wooden facade 0.015 m

It also would be necessary to pay particular attention to use of natural insulation materials that can be made from local waste products of agriculture and forestry such as hemp and wood fibre. An interesting model for vapour permeable construction from local waste products is a straw building. In this case 40 – 50 cm thick wall are made of straw bales. Interior finishing material (vapour retarder) is clay plaster (at least 3 cm thick), while the walls from outside are protected by lime render and additionally by ventilated wooden façade.

In order to reduce energy consumption in energy efficient house, the use of different types of heat exchangers (air-air, earth-air, earth-water etc.) are essential. However, in any case, it is necessary to provide protection against microbial contamination. This task can be solved in different ways, depending on the option chosen, e.g., using easy-to-clean or replaceable filters or components to prevent accumulation of dirt and dust in the devices; preventing the formation of condensation. A good example for ground-air heat exchange system is REHAU ECOAIR that offers complex solution of microbial contamination problems: inlet-air filtration, condensate drainage and antimicrobial-protected inner surface [58].

The preferred solution for designing of energy efficient house is ventilated façade and also the double skin façade, which is the favoured for cold climate condition. In Latvia, a good example, how coupling the idea of double skin façade and using of materials with high moisture buffering capacity, is Saldus Music and Art School (finished in 2013). The façade consists of massive timber panels (34 cm), air gap (5 cm) and profile glass – this construction is a part of energy efficient natural ventilation system, preheating inlet air during the winter. Massive wood walls with lime plaster accumulate humidity, providing the good climate and work as passive environmental control element [101].

Greening systems is attractive element especially in urban environment. In Latvia climate conditions, the indirect green façades could be one of recommended solution. There are some plants that could be used for these green façades in our climate:

- evergreen climbers
  - *Hedera helix*,
  - *Euonymus fortunei*;
- deciduous climbers
  - Parthenocissus quinquefolia,
  - *Aristolochia macrophylla*,
  - *Clematis tangutica*,
  - *Clematis vitalba*.

A careful selection of construction materials allows to design moisture safe exterior walls, providing the conditions imposed to the nZEB. It is observed that even small alterations in building envelope may be a reason causing significant changes in the hygrothermal performance of the wall, consequently – energy efficiency of the house, lifetime of the construction materials as well as life quality of inhabitants. This is the reason why the research and simulation of hydrothermal performance of wall assemblies should already be done during the design phase of the building, thoroughly considering properties of different materials. It gives the opportunity to analyse parameters of humidity and temperatures in the constructions and to prevent the development of structures that allow formation of microbial contamination.

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