Airtightness study

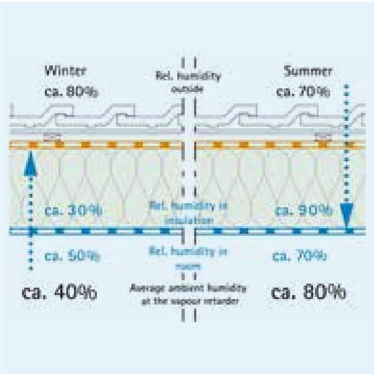
Calculation of potential protection against moisture damage

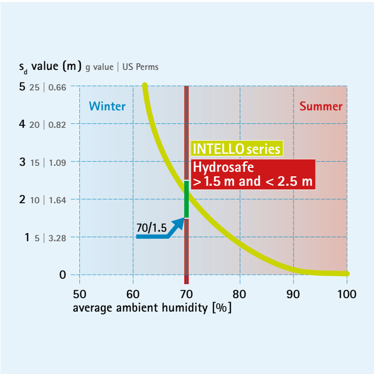
Calculation of potential protection against moisture damage to thermally insulated structures on timber and steel-framed constructions

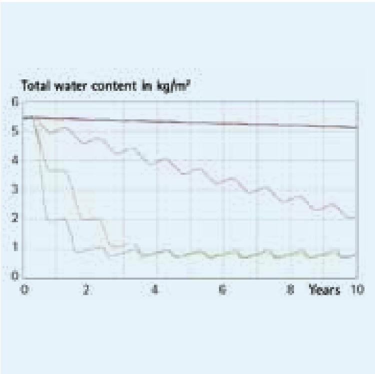
Humidity-variable vapour control membranes from the pro clima INTELLO series with intelligent moisture management

Roofs, walls, floors/ceilings

Computer-aided simulation of coupled heat and moisture transport in roof and wall structures, taking into account natural climate conditions and liquid transport within building materials.







International

Bibliography

[1] Konsenspapier des 2. Internationalen Holz[Bau]Physik-Kongresses: 10/11 February 2011, Leipzig

[2] Ten Wolde, A. et al.: »Air pressures in wood frame walls«, Proceedings of the Thermal VII. conference, Ashrae Publications, Atlanta, 1999

[3] IBP Mitteilungen 355: »Dampfdiffusionsberechnung nach Glaser – quo vadis?«

[4] Deutsche Bauzeitung; issue 12/89, page 1639 ff.

[5] DAB 1995; page 1479; issue 8

[6] Klopfer, Heinz; Bauschäden-Sammlung, Vol. 11, Günter Zimmermann (ed.), Stuttgart: Fraunhofer IRB Verlag, 1997

[7] Klopfer, Heinz; ARCONIS: Wissen zum Planen und Bauen und zum Baumarkt: Flankenübertragung bei der Wasserdampf-diffusion, issue 1/1997, pp. 8-10

[8] H.M. Künzel; Tauwasserschäden im Dach aufgrund von Diffusion durch angrenzendes Mauerwerk, wksb 41/1996; issue 37; pp. 34-36

[9] WUFI 2D 3.4 (Wärme und Feuchte instationär); PC software for one- and two-dimensional modelling of coupled heat and moisture in building components; Fraunhofer Institute for Building Physics; further information at www.wufi.de

[10] DIN 4108-3: Thermal protection and energy economy in buildings - Part 3: Protection against moisture subject to climate conditions - Requirements, calculation methods and directions for planning and construction, Beuth-Verlag, Berlin, 03/2024

[11] OENORM B 8110-2: Thermal insulation in building construction - Part 2: Water vapour diffusion, water vapour convection and protection against condensation, Austrian Standards International, Vienna, 01/2020

[12] SIA 180: Wärmeschutz, Feuchteschutz und Raumklima in Gebäuden, Swiss Society of Engineers and Architects, Zurich, 2014

[13] EN ISO 13788: Hygrothermal performance of building components and building elements - Internal surface temperature to avoid critical surface humidity and interstitial condensation - Calculation methods, 2012

[14] Delphin 5.9.3; Simulationsprogramm zur Berechnung des gekoppelten Wärme- und Feuchtetransports in Bauteilen; Institute of Building Climatology, Dresden; further information at www.bauklimatik-dresden.de

[15] WUFI 6.7 pro (Wärme und Feuchte instationär); simulation software for modelling of coupled heat and moisture in building components; Fraunhofer Institute for Building Physics; further information at www.wufi.de

[16] Meteonorm 8; global meteorological database for every location worldwide; Meteotest; further information at www.meteonorm.com

[17] EN 15026: Hygrothermal performance of building components and building elements - Assessment of moisture transfer by numerical simulation, 2023

[18] Robert Borsch-Laaks: Bauphysik für Fortgeschrittene – Bemessungsregeln für Flachdächer; Holzbau – die neue quadriga; Verlag Kastner; Wolnzach; 05/2011

[19] DIN 68800-2: Wood preservation - Part 2: Preventive constructional measures in buildings, 2022

[20] WTA-Merkblatt (information sheet) 6-8: Feuchtetechnische Bewertung von Holzbauteilen – Vereinfachte Nachweise und Simulation, Fraunhofer IRB-Verlag, 08/2016

[21] EN 13984: Flexible sheets for waterproofing - Plastic and rubber vapour control layers - Definitions and characteristics, 2013

Airtightness study

Protection against moisture damage to thermally insulated structures on timber constructions

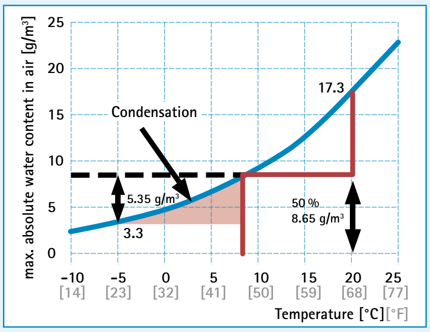
A question of drying reserves and intelligent moisture management

The physics of air humidity

- The (relative) humidity of air increases when air cools down.
- If the temperature falls below the dew point temperature, condensation will form.
- At higher relative humidities, the dew-point temperature increases.

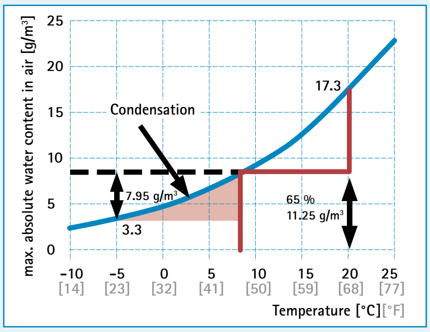
> The result is that condensation forms earlier.

1. The physics of air humidity at 50% relative humidity



In an indoor climate of 20 °C / 50% relative humidity, the dew point is reached at 8.7 °C. At -5 °C, the amount of condensate formed is 5.35 g/m³ of air.

2. The physics of air humidity at 65% relative humidity



At a higher relative humidity of 65%, the dew point is already reached at 13.2 °C. At -5 °C, the amount of condensate formed is 7.95 g/m³ of air.

1.1 Overview and introduction

This study describes the calculation of the potential protection against moisture damage to structures inherent in various roof and wall structures, explains how moisture damage can occur in thermal insulation structures, and demonstrates how structures can be reliably protected against moisture damage. Moisture damage occurs when the moisture entering into a given structure is greater than the component's drying capacity. When trying to prevent moisture damage to building structures, the usual approach is to concentrate on reducing the amount of moisture loading that structures are exposed to. However, building structures cannot be fully protected from the effects of humidity or moisture. In any case, predictable exposure to moisture from diffusion is very rarely the underlying cause of moisture damage. In general, unanticipated moisture loading can never be ruled out completely. For this reason, attention should be focused on the drying capacity of the structural system when trying to prevent mould and moisture damage. In this study, structures will be analysed and compared based on their potential for drying out.

1.2 Condensation – dew point – amount of condensation

In winter, the thermal insulation installed in the building envelope separates warm indoor air, which has a high moisture content, from cold outdoor air with its low absolute moisture content. If warm indoor air penetrates into the insulation structure, it will gradually cool down along its path through the component. The water vapour contained in this air may then condense in the form of liquid water. The physical behaviour of the air is responsible for the formation of condensation: warm air can hold more water than cold air. At higher relative humidities (e.g. around 65% in newly built buildings), the dew-point temperature rises and, as a direct result, the amount of condensation increases too (see Figs. 1 and 2). Condensation water may form in building components if the temperature drops below the dew-point temperature and if the water vapour present cannot dry out of the component through more impermeable component layers on the exterior. From a building physics viewpoint, component layers on the outside of the thermal insulation that are more diffusion-tight than the layers on the inside are unfavourable. Major problems can arise if warm, humid air enters into the structure by convection, which can happen as a result of leaks in the airtightness layer. According to the German standard that deals with protection against moisture (DIN 4108-3 [10]), building materials are deemed to be diffusion-open if their equivalent air layer thickness (s_d value) is less than 0.50 m. The s_d value is defined as the product of the vapour diffusion resistance coefficient (μ value), which is an intrinsic property of the material itself, and the thickness of the component in metres:

$$s_d = \mu \times s \text{ [m]}$$

In this study, the s_d value will be used; see Fig. 3 for details of conversions to other equivalent parameters that are used internationally. A low s_d value can be achieved either by combining a low μ value with a larger thickness (e.g. wood-fibre insulation panels) or by combining a higher μ value with a very low layer thickness (e.g. roofing underlay membranes). The μ value is the most important factor here, followed by the thickness of the relevant layer. Condensation formation can begin earlier with an external sealing membrane with a higher μ value compared to a lower value. There is only a low vapour pressure gradient across diffusion-open roofing underlay membranes due to the lack of a temperature or moisture difference, particularly during the colder period of the year. This explains why moisture damage to structures may still occur even with diffusion-open roofing underlays if there is an increased flow of moisture through the building component due to the unanticipated entry of moisture. Roofing underlay membranes with monolithic non-porous functional films, such as those in the pro clima SOLITEX range, are particularly advantageous in this regard as diffusion occurs actively along molecular chains rather than passively through pores. As a result, these membranes can facilitate extremely fast removal of moisture from building structures and thus protect the underlying structures against condensation and mould infestation in an ideal manner. If condensation occurs on the inside of a roofing underlay, frost or ice can form on the inner surface of membranes during cold winter conditions. Ice is impermeable to water vapour and can effectively result in the formation of a vapour barrier on the exterior of the building component. As a consequence, drying out to the outside is then significantly reduced or even completely hindered. Structures that have diffusion-inhibiting or diffusion-tight layers on the outside are more problematic from a building physics viewpoint than structures that are open to diffusion on the outside. Roofing underlay membranes with active moisture transport significantly reduce the risk of moisture damage to insulated structures. On flat roofs, strongly diffusion-inhibiting membrane materials on the outside are unavoidable. The reason for this is that membranes on flat roofs have to be waterproof and that high moisture contents are to be expected in the long term in the layers above the sealing layer, particularly on roof structures with greenery or gravel coverings. In these applications, diffusion-open or slightly vapour-checking materials would lead to high ingress of moisture into the building component from the outside. Other examples of diffusion-tight structures include non-ventilated pitched roofs with bitumen felt membranes and roofs with non-ventilated metal coverings. Moisture can build up at the diffusion-tight layer in these structures and condensation formation occurs.

1.3 Moisture loading in building structures

There are various possible causes of moisture loading within a thermal insulation structure. For example, water may penetrate into a structure through a leaky seal on a flat roof. The amounts of moisture involved can be so great that water drips down into the room below in a home. However, smaller leaks in sealing layers can also lead to a gradual build-up of moisture in an insulation structure. This often results in mould infestation of the component materials, or even in the formation of wood-damaging fungi. Moisture can also enter into a structure from the heated interior side in the following ways:

Anticipated moisture loading:
- Diffusion processes

Unanticipated moisture loading:
- Convection, i.e. air flow (leaks in the airtightness layer)
- Moisture transport as a consequence of the building design (e.g. flank diffusion through adjacent brickwork structures)
- Increased moisture levels contained in building materials when they are installed (e.g. in timber)
- Installation mistakes made during the construction process

1.3.1 Through diffusion

The higher the s_d value on the inside, the lower the risk of moisture damage to structures – this used to be the thinking. It was believed that the use of vapour barriers with high diffusion resistances would prevent damage to structures. However, it was demonstrated over 30 years ago that the reality is very different by means of building physics calculations carried out at the time of the market launch of the first humidity-variable vapour control membrane, DB+, with its s_d value of 2.30 m.
Currently, so-called tight-tight-designs for flat-roof structures (vapour barrier with s_d > 100 m on the inside – vapour-tight sealing on the outside) are no longer regarded as standard engineering practice in the opinion of leading experts in building physics and installation practice.
A consensus paper published at the end of an academic conference on timber construction in February 2011 [1] stated the following with regard to non-ventilated flat-roof structures on timber constructions: »vapour barriers prevent reverse diffusion in summer, which is necessary to dry out moisture that has entered in winter by means of convection through unavoidable residual leaks.«
As a result, this type of structure may only be implemented if it has functioning ventilation or if it has been verified that the building components have sufficient potential capacity for drying out. This can be achieved by selecting a suitable vapour control and airtightness membrane for the inside of the structure. Furthermore, investigations of outside walls conducted in North America back in 1999 [2] demonstrated that the entry of moisture as a result of convection through a vapour barrier, even if it has been professionally installed, leads to condensation of approx. 250 g/m² each winter (i.e. each 'dew period'). This corresponds to the amount of condensation that diffuses through a vapour control membrane with an s_d value of 3.3 m during a single winter [3].

1.3.2 Through convection

Convection – in other words the flow of air – transports significantly larger amounts of moisture into a given structure than diffusion does. In fact, the amount of moisture introduced by convection can easily be 1,000 times greater than that entering by diffusion (see Fig. 4).
Moisture that enters through leaks into building structures with diffusion-tight layers on the outside can quickly lead to moisture damage. Due to the high amounts of moisture loading involved, convective moisture entry can also be problematic even if building components are open to diffusion on the outside – particularly if condensation has already formed and if layers of ice have already

3. Conversions between parameters for expressing water vapour resistances

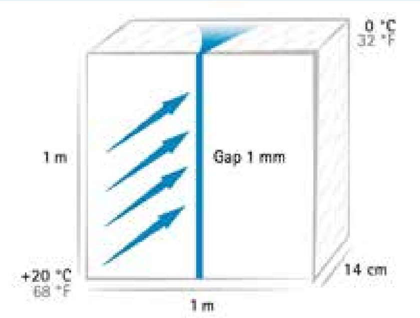
Conversion to g value:
g value [MNs/g] = s_d [m] x 5.1

Conversion to perms:
Δ [perms] = 3.28 / s_d [m]

Note that the permeance as expressed in perms is the reciprocal of the s_d or g value; i.e., a large s_d value is equivalent to a small permeance value, and vice versa.

Entry of moisture into structures through leaks in the vapour barrier layer

4. Amount of moisture due to convection



Moisture transport
through vapour barrier: 0.5 g / (m² x 24 h)
through 1 mm gap: 800 g / (m x 24 h)
Higher by a factor of 1,600

Parameters

Vapour barrier s_d value	= 30 m
Indoor temperature	= +20 °C
Outdoor temperature	= 0 °C
Pressure difference	= 20 Pa (corresponds to wind force 2-3)

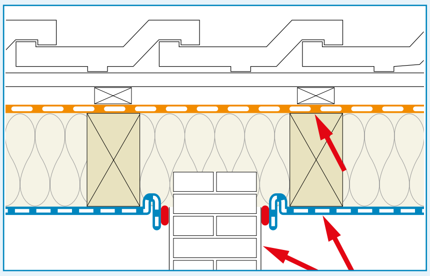
Measurements: Institute for Building Physics, Stuttgart [4]

Key takeaways

Significant amounts of moisture will still enter into insulation structures even with vapour barriers with an s_d value of 50 m, 100 m or more. However, vapour barriers do not allow drying out to occur, and this results in trapped moisture.

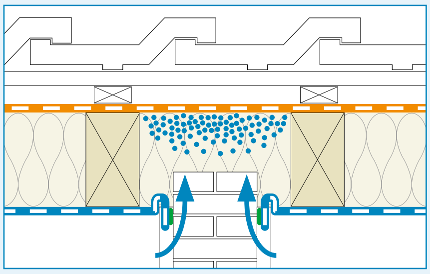
Flank diffusion

5. Moisture damage to structures: Entry of moisture despite airtight transitions and the installation of a vapour barrier



Airtight structure with vapour barrier membrane (PE) and an airtight layer of plaster, with bitumen roofing felt on the exterior

6. Cause of moisture entry: Moisture transport through flanks, i.e. through the brickwork



Moisture entry by means of flank diffusion through the adjacent brickwork that impinges on the insulation layer

formed during cold winter conditions, e.g. on the roofing underlay.

1.3.3 Moisture transport as a result of the building design – Flank diffusion

Various types of moisture damage have been described in technical publications that cannot be explained by diffusion or convection processes through vapour barriers alone. Ruhe [5] and Klopfer [6] have reported on the problem of flank diffusion in a case of moisture damage in the mid-1990s [7].

The insulation structure was as follows:
Pitched roof: bitumen felt sheeting on wood sheathing on the exterior; polyethylene (PE) vapour barrier on the interior; the intermediate space was fully insulated with mineral wool. Despite properly executed airtightness, water dripped out of the membrane joints onto adjacent building components below in summertime. It was initially assumed that high levels of initial 'built-in' moisture were the cause of this. However, the amount of water dripping out increased from year to year, which made this explanation implausible. After five years, the roof was opened up. It was observed that the wood sheathing already had considerable damage caused by wood-damaging fungi. The entry of moisture as a result of flank diffusion was also considered. The term 'flank diffusion' refers to the entry of moisture into the roof through the flank of the adjacent masonry structure (in this case: porous brickwork). In this way, the moisture manages to bypass the vapour barrier membrane (see Figs. 5 and 6).
This case was initially the subject of lively discussion among construction physicists at the outset, until Künzel [8] modelled flank diffusion in 1997 with the aid of two-dimensional simulations of heat and moisture transport using WUFI 2D [9]. In this simulation, the relative moisture content of the sheathing above the brickwork was approx. 20% after just 1 year, reaching 40% after 3 years and 50% after 5 years.

1.3.4 High 'built-in' moisture in building materials

If building materials are installed with a higher initial moisture content than they have later on in normal service, it is essential for the integrity of the overall structure that this moisture can dry out again. Pre-dried structural timber is generally used in construction nowadays; this has a relative material moisture content of less than 18%. If additional moisture is absorbed subsequently – for example, during exposure to the elements – this value can be exceeded significantly.

Here is an example:
A roof with 6 cm x 24 cm rafters and a rafter spacing of e = 0.70 m has 1.5 linear metres of rafter per m² of roof area. At 10% moisture content in the rafters, this roof area will contain about 1.1 litres of water from the rafter timber.

In the case of increased moisture, this means:
To protect timber that has been subjected to a relative humidity of over 20% during the construction phase, it is recommended that the timber moisture content should be reduced to less than 20% within a maximum of 3 months. This will avoid damage caused by the growth of mould or wood-damaging fungi, for example. If the relative timber moisture content is 30%, then 1.1 litres of water per m² of roof area must be able to dry out in order to achieve the recommended moisture level. This sample calculation also holds for a roof sheathing with a thickness of 24 mm. The moisture content at 10% timber moisture is approximately 1.2 litres of water per m². At an initial relative moisture content of 30%, which is not unusual after a rainy day, 1.2 litres of water must be able to dry out per m² of roof area in order to achieve a relative timber moisture content of 20%. If the rafters and timber sheathing are considered together, the sum is approx. 2.3 litres per m² of roof area. The total amount of moisture is often underestimated. For masonry structures, the 'built-in' moisture associated with new building work can add a considerable amount of additional moisture to timber. If a diffusion-tight polyethylene vapour barrier membrane is installed on the inside of a fully insulated structure and this is combined with a bitumen roofing felt as an overlay, moisture damage is unavoidable.

1.3.5 Summary of types of moisture loading

The various possible sources for the entry of moisture show that the possibility of moisture loads on a given structural system can never be fully ruled out in construction practice. If the overarching aim is to build structures that will be free of mould and moisture damage, the provision of increased drying reserves is a far more effective and reliable solution than simply concentrating on allowing as little moisture as possible into the structural system.

Rule of thumb for intelligent moisture management

Drying capacity > Moisture loading = Protection against moisture damage
Moisture damage to structures can only occur if their drying capacity is lower than the amount of moisture they are subjected to. »The larger a structure's drying reserves, the greater the amount of unanticipated moisture loading that it can deal with while remaining free of moisture damage.« Structures that are open to diffusion on the outside have greater drying reserves than structures that are closed to diffusion on the outside.

»Intelligent« vapour control membranes

2.1 Drying towards the inside

Making use of the interior drying-out area offers an important additional potential means of drying for building components: whenever the temperature is higher outside of insulation layer than inside the building, the direction of diffusion reverses and moisture contained in the component diffuses towards the inside of the building. This effect can begin on sunny days in spring and continues right through to autumn – and it is more pronounced during the summer months. If a diffusion-open airtightness membrane is installed instead of a vapour-retarding membrane, the moisture present in the structure can then dry out towards the inside.
However, a diffusion-open membrane would let too much humidity diffuse into the structure during winter and thus lead to moisture damage. A structure equipped with vapour barriers would appear at first glance to be well-protected against moisture. However, if moisture enters through convection, flank diffusion or increased 'built-in' moisture, drying out towards the inside in the summer is not possible in this case. Indeed, it is known that this type of structure is conducive to moisture traps on non-ventilated flat-roof structures in particular.
The ideal solution is a vapour control membrane with high diffusion resistance in winter and very low diffusion resistance in summer. For years now, »intelligent« vapour control membranes of this type with humidity-variable s_d values have been proving themselves in service. These membranes can adapt their diffusion resistance as a function of the average relative humidity of the surrounding air. In winter climate conditions, they become more diffusion-tight and protect the insulation structure against the entry of moisture. In summer climate conditions, they are more diffusion-open and thus allow moisture that may be present in the structure to dry out to the inside.
Ideally, the s_d value should be significantly less than 0.50 m in summer – as layers are classified as diffusion-open below this value. If the possible s_d value under summer conditions is above 0.50 m, drying out from the component is significantly reduced.

2.2 How humidity-variable diffusion resistance works

The direction of diffusion is determined by the gradient of the water vapour partial pressure, which in turn depends on the temperature and humidity content of the air inside and outside of the building. Taking the simplified approach of considering only the temperatures on either side of the building component, moisture diffuses from the warm side to the cold side – i.e. from the interior to the exterior in winter, and from the exterior to the interior in summer. Measurements of the moisture contents inside roof structures have shown that the vapour control layer is surrounded by an average humidity of approx. 40% in winter as a result of moisture transport within the space between the rafters. In summer conditions, increased levels of moisture occur at the vapour control layer during warm outdoor temperatures; sometimes 'summer condensation' can even form if unanticipated entry of moisture has occurred (see Fig. 7).
The applicable climate conditions determine the mode of functioning of humidity-variable vapour control membranes – as a result, they are more impermeable to diffusion in winter and more open to diffusion in summer.
Since 1991, pro clima DB+ has proven itself in service with millions of square metres already installed. The diffusion resistance of DB+ can vary between s_d values of 0.4 m and 4 m. In 2004, Moll bauökologische Produkte GmbH launched the high-performance INTELLO vapour control membrane. INTELLO – along with all the other membranes in the INTELLO series (INTELLO PLUS, INTELLO X and INTELLO X PLUS) – has a particularly wide humidity-variable range of diffusion resistances from 0.25 m to over 25 m and is effective in all climate zones (see Fig. 10). INTELLO and INTELLO PLUS can attain s_d values of up to 55 m according to ETA-18/1146. As a result, building components are well-protected in the winter scenario described above against moisture entry that would lead to moisture damage.

2.2.1 Verification of the long-term stability of properties

The European standard applicable to vapour control membranes (EN 13984 [21]) does not currently specify a validation process for testing the behaviour and long-term stability of humidity-variable properties. As a result, only vapour control membranes with a constant diffusion resistance can be tested in accordance with this European standard.
For this reason, the long-term stability of the humidity-variable behaviour of INTELLO and INTELLO PLUS has been verified according to a procedure specified by an independent committee of experts at the German Institute of Construction Engineering (DIBt). As part of this testing, these two vapour control membranes were subjected to accelerated ageing with significantly more demanding conditions (higher temperature and doubled ageing period) than those specified in EN 13984.
In addition, the permitted deviations between the aged diffusion resistances and the non-aged diffusion resistances were significantly more stringent in this evaluation as compared to the European standard.

Moisture situation in the insulation structure

The direction of diffusion is generally from the warm side to the cold side. This means:

In winter:
Higher humidity on the outside of the insulation structure

In summer:
Higher humidity on the inside of the insulation structure

7. Principle of the behaviour of humidity-variable membranes

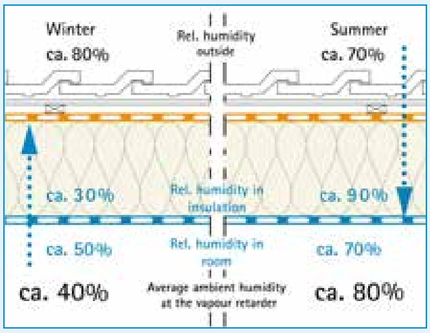


Illustration of the relative humidities on either side of the vapour control membrane depending on the season

Humidity level at the vapour control membrane

- In winter: Low air humidity
  → the humidity-variable vapour control membrane becomes more diffusion-tight
- In summer: High air humidity
  → The humidity-variable vapour control membrane becomes more diffusion-open

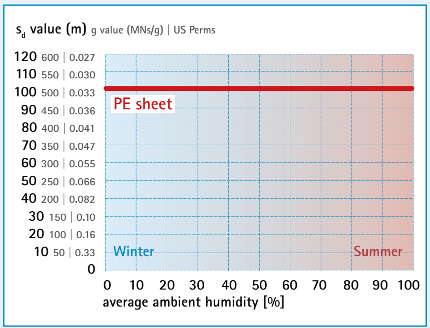
8. Diffusion flows through humidity-variable vapour control membranes from pro clima

Diffusion flow	W_{VTR} value in g/m² per week	
	In winter	In summer
Diffusion direction	To the outside, to underlay	To the inside, to vapour control membrane
INTELLO INTELLO PLUS INTELLO X INTELLO X PLUS	7	560

Behaviour of the s_d value of vapour control membranes

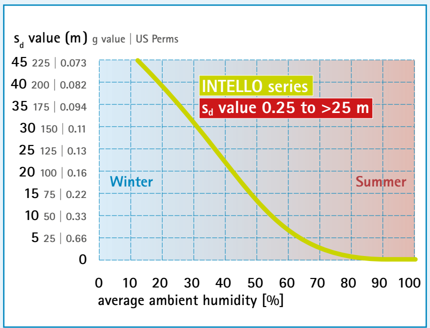
The level of protection offered by a vapour control membrane is directly related to the variability of its diffusion resistance between summer and winter.

9. Behaviour of the s_d value of PE sheeting



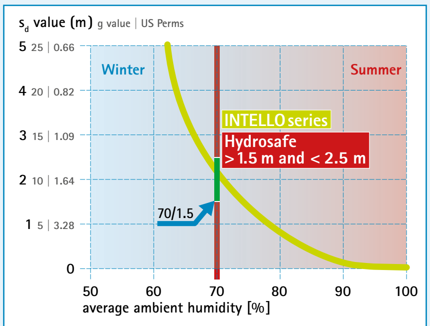
PE sheet: No humidity-variability

10. Behaviour of the s_d value of pro clima vapour control membranes



Membranes in the INTELLO series: High humidity-variability

11. Normal service period and construction phase (drying out and hydrosafe value)



A hydrosafe value of between 1.5 and 2.5 m is recommended to protect components during the construction phase.

The European Technical Assessment (ETA-18/1146) serves as documented verification of the durability of the humidity-variable behaviour of INTELLO and INTELLO PLUS.

2.2.2 High diffusion resistance in winter

The diffusion resistance of vapour control membranes with the INTELLO functional film has been engineered so that the membrane achieves an s_d value of over 25 m in winter conditions. As a result, the vapour control membrane will allow almost no moisture to enter into the insulation structure during the cold season, when the moisture load on the structure is at its highest. The behaviour of the humidity-variable diffusion resistance is independent of the altitude at which the building is located. This performance characteristic of the membrane remains active even during long, cold winters. These membranes can regulate the moisture content of structures with diffusion-tight sealing membranes on their exterior and provide effective protection against moisture for these building structures. The high s_d value is also beneficial for roofs that are designed to be diffusion-open on the outside if frost or ice effectively causes a vapour barrier to form on a roofing underlay membrane that would be diffusion-open under normal conditions (see Fig. 10).

2.2.3 Low diffusion resistance in summer

The diffusion resistance can drop to an s_d value of less than 0.25 m in summer. This allows for rapid drying out to the inside of any moisture that may be present in the structure. Depending on the vapour pressure gradient, this corresponds to a drying rate of 5 – 12 g/m² of water per hour, which is equivalent to around 80 g/m² of water per day or 560 g/m² of water per week (see Fig. 8).

This high drying-out capacity allows a building component cavity to start drying out quickly by as early as spring. The critical issue here is that vapour control membranes with variable diffusion resistance should have an s_d value significantly below 0.5 m under humid conditions (i.e. the summer scenario). If this is not the case, the potential protective capacity will be too low in the case of unanticipated entry of moisture.

2.2.4 Balanced diffusion profile

With improved levels of airtightness and the associated higher levels of indoor humidity in modern masonry-construction buildings, diffusion resistance at higher relative humidities has become an important consideration.

New buildings: Drying phase (the 60/2 rule)

High indoor relative humidities of around 70% can occur in new buildings and in humid rooms (bathrooms, kitchens) in homes as a consequence of recently completed construction work and also due to normal residential use. The diffusion resistance of a vapour control membrane should be selected such that an s_d value of at least 2 m is achieved at this relative humidity in order to adequately protect the structure against the entry of moisture from the indoor air and any associated mould formation. All INTELLO membranes have an s_d value of over 6 m at 60% average relative humidity (70% indoor relative humidity and 50% humidity within the thermal insulation) (see Fig. 11).

Construction phase: hydrosafe value (the 70/1.5 rule)

Very high indoor humidity of over 90% can occur in certain cases in buildings during the construction phase when walls are being plastered or screed is being installed.

The hydrosafe value quantifies the protection provided to insulated timber structures during the construction phase against increased indoor humidity caused by construction work (building moisture). This value specifies the minimum equivalent air layer thickness (s_d value) that a humidity-variable vapour control and airtight membrane installed on the interior must have in order to ensure that the insulation and overall structure are sufficiently protected against moisture during all phases of construction.

A hydrosafe value of at least 1.5 m has been specified as offering sufficient protection at an average relative humidity of 70%.

The membranes in the INTELLO series achieve an s_d value of greater than 2 m at an average humidity of 70% (90% indoor humidity and 50% in the insulation layer) and provide sufficient protection for building components even during the increased air humidities associated with construction work.

Excessive indoor humidity during the construction phase over an extended period can cause damage to all materials and components in buildings and causes a build-up of dampness in them. This humidity should be allowed to escape quickly and systematically by deliberately opening windows to provide ventilation. It may also be necessary to use dryers (see Fig. 11).

2.2.5 Highest possible level of protection

The 'intelligent' behaviour of humidity-variable vapour control membranes from pro clima provides excellent protection for thermal insulation structures, taking into account the construction type and site location. Insulated structures are protected even in the case of the entry of moisture due to unanticipated events such as adverse weather conditions, unavoidable residual leaks, flank diffusion or high levels of 'built-in' initial moisture in construction timber or insulation materials. Humidity-variable vapour control membranes from pro clima actively facilitate the drying out of moisture that has entered into components in an unanticipated manner.

Determining the level of potential protection of a roof structure

3.1 Modelling and assessment of building components

Both steady-state and dynamic calculation procedures can be used to model moisture loads inside building components. Steady-state assessments of building components can be carried out using the Glaser method. This method is the basis for various national and international standards (e.g. DIN 4108-3 [10], OENORM B 8110-2 [11], SIA 180 [12], EN ISO 13788 [13]). If a detailed description of the moisture profiles of individual elements is required, a non-steady (dynamic) method in accordance with EN 15026 [17] can be used.

3.1.1 Modelling based on the Glaser method (EN ISO 13788)
The Glaser method is a simplified, steady-state validation process for assessing moisture protection in building components. In this case, the diffusion transport is modelled at steady-state conditions and with standard conditions. This assessment process does not take into account a number of important physical phenomena, such as:

- Variations in material properties as a function of moisture content
- Capillary suction and transport of moisture in the liquid phase in building materials
- Air movement from the indoor space into the building component through gaps or in air spaces
- Hygroscopic behaviour of building components

As a result, this method is only applicable if the effects of these phenomena are negligible [13]. There are additional limitations associated with the simplicity of this method – for example, shading and additional component layers such as gravel or vegetation on green roofs cannot be taken into account.
For this reason, the Glaser method cannot be used to model timber structures with complex building physics behaviour.

3.1.2 Modelling of coupled heat and moisture transport
Detailed assessments of moisture contents inside building components can be carried out using time-dependent simulation methods. These methods are able to take into account the climate conditions (interior and exterior climates) that act on the building component as well as material properties such as moisture content, sorption and capillarity etc.
Established software packages for this purpose include Delphin [14] from the Institute of Building Climatology in Dresden and WUFI pro [15] from the Fraunhofer Institute for Building Physics in Holzkirchen, Germany. These simulation methods have been validated on numerous occasions, i.e. the results of their modelling calculations have been compared with the results of field testing. These methods require climate data over the course of a year in the form of hourly values. The required climate data can be generated for almost any location worldwide using the Meteonorm [16] meteorological database.
The simulation calculations treat the building components in terms of their layer structure and analyse the profiles of moisture contents over the course of a number of years for the entire component or for individual component layers.
The modelling results show whether the moisture contents of individual component parts or particular locations in the component are within the permitted limits, for example. Consideration of the profile of the overall moisture content allows the maximum possible drying-out of various components to be determined. This value is of critical importance, as it quantifies the potential protection against moisture damage offered by the structure.

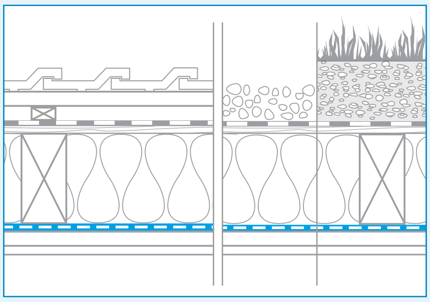
3.2 Definition of potential protection against moisture damage

The potential protection against moisture damage for insulation structures is a theoretical parameter that can be used to compare the performance of structures with regard to their potential capacity for drying-out. This quantity describes the maximum amount of moisture that could theoretically enter through unavoidable residual leaks, flank diffusion or building materials that contain moisture when they are installed. The potential protection is the quantity of moisture that can dry out of a component over one year; it can be used to evaluate the relative performances of various designs and approaches in terms of their inherent reliability against moisture damage to structures.

3.2.1 Calculation of potential protection against moisture damage
The following approach is used to quantify the degree of protection of a component against the unanticipated entry of moisture: At the start of the modelling calculation, the moisture content in the insulation layer is set to 20 kg of water per m³ of insulation material. The simulation then calculates how quickly this moisture dries out again. The amount of moisture that can exit the insulation structure per year under the assumption of this increased initial moisture quantifies the potential protection against moisture damage of the structure. The calculations are carried out under unfavourable conditions (e.g.

Building-physics assessment of roof structures

12. Cross-section of the roof structure



Structural layers:

- Diffusion-tight on the outside (sealing membrane s_d value = 300 m)
- Solid timber sheathing, 24 mm
- Fibrous insulation (mineral wool) WLG 0.035 W/mK, 200 mm
- Vapour checks/barriers with various s_d values
- Service cavity, 25 mm
- Plasterboard, 12.5 mm

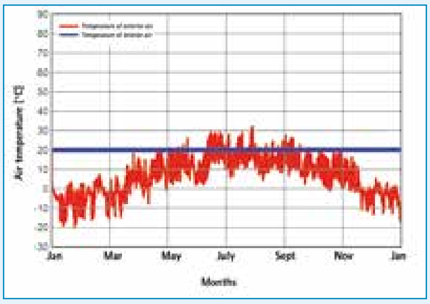
Roof variants considered here:

- Pitched roof with 40° pitch, north-facing, red roof tiles
- Flat roof with 5 cm gravel layer
- Green roof with extensive roof greenery: 10 cm plant substrate

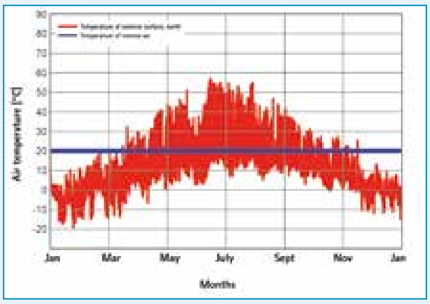
All constructions are unshaded.

Yearly temperature profiles, Holzkirchen, southern Bavaria, Germany, altitude: 680 m above sea level, roof: red roof tiles or gravel

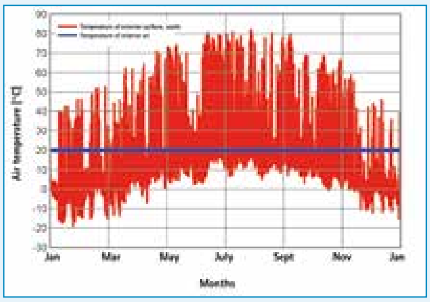
13. Air temperatures (humidity reference climate)



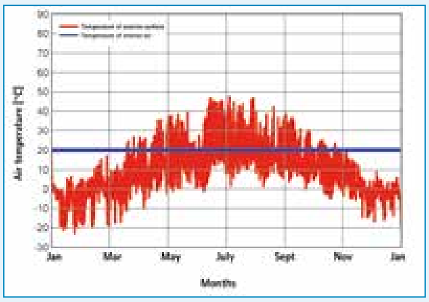
14. Roof surface temperature, north-facing, 40° pitch



15. Roof surface temperature, south-facing, 40° pitch



16. Roof surface temperature, gravel roof



north-facing slope of a pitched roof), in different climate zones (e.g. mountainous) and with different roof geometries and types (pitched roof, with gravel or greenery, etc.). Structures that are more favourable from a building physics perspective offer higher protection.
Another criterion for the performance of a building structure is the maximum moisture content that occurs in its component layers. Investigations of fitness for purpose in practical service are discussed from Section 3.3 onwards.

3.2.2 Roof structures

For the sake of comparison, a structure that is critical from a building physics perspective is considered here. The site locations and vapour control membranes used will be varied.

Structure:
This structure has 200 mm of insulation (WLG 035 mineral wool), and a diffusion-tight sealing membrane (see Fig. 12, left) on the outside.

Vapour control membranes:	**s_d value:**
• Vapour control membrane	5 m constant
• Vapour control membrane	0.8 – 35 m variable depending on direction
• pro clima INTELLO	0.25 - over 25 m humidity-variable (ETA-18/1146)

pro clima INTELLO is assumed in the calculations and is representative of all membranes in the INTELLO series.

Roof variants:
- Pitched roof with 40° pitch, north-facing, red roof tiles
- Flat roof with 5 cm of gravel above the sealing layer
- Flat roof with 10 cm greenery structure above the sealing layer

Site locations:
- Holzkirchen, southern Bavaria, Germany, altitude 680 m above sea level
- Davos in the Swiss Alps, altitude = 1,560 m above sea level

Modelling:
- With Delphin 5.9.3 [14]
- Initial moisture in the insulation: 4,000 g/m^2 (= 20 kg/m^3)

Shading (e.g. due to photovoltaic systems, protruding building elements, high trees or topography) is not taken into account in the modelling calculations.

3.2.3 Factors that affect potential protection against moisture damage to structures

An important factor that determines the potential protection against moisture damage is reverse diffusion in summer and the associated drying-out of the structure to the inside. The amount of drying-out depends on the exterior temperature, or on the temperature at the exterior boundary of the thermal insulation to be more exact, and on the diffusion-openness of the vapour control and airtightness membrane in the summer scenario. As a result of solar irradiation (including diffuse sunlight), component surfaces may be at a higher temperature than the surrounding air. The amount of time it takes for heat from the outside to arrive at the insulation is decisive here. This happens more quickly on a pitched roof compared to a gravel-covered or green roof structure.
On a pitched roof, the roof surface temperature depends on the roof pitch, the orientation of the roof surfaces (north/south) and the colour of the roof covering or sealing (light/dark). The potential protection against moisture damage is also dependent on the selected insulation thickness. Thick insulation layers lead to lower drying-out quantities, as the component heats up more slowly and the drying-out periods become shorter as a consequence.

Unfavourable factors include:
- North-facing roof orientation
- Steep roof pitches (> 25°)
- Roof coverings or sealing membranes with light colours
- Diffusion-tight seals on flat roofs
- Cold climates, e.g. mountainous
- Thick insulation layers
- Additional layers above the roof sealing (greenery, terrace decking, etc.)

To determine the influence of the diffusion resistance of vapour control or barrier membranes on potential protection against moisture damage, a diffusion-tight sealing membrane (s_d value = 300 m) is assumed on the exterior side in the modelling calculation. This approach can be used to model the effect of ice formation and of diffusion-tight roofing underlays on the moisture content inside the insulation structure during cold periods (below freezing) in winter.

3.2.4 Climate data for Holzkirchen, Germany

Holzkirchen is south of Munich at an altitude of 680 m and has a cold, harsh climate. Climate data for the reference moisture year of the Fraunhofer Institute for Building Physics in Holzkirchen was used, which represents a particularly cold, wet year. The diagrams on the left show the temperature profiles over the course of one year. The blue line represents the interior temperature and the red line the exterior temperature (see Figs. 13 to 16). Taking into account global radiation (direct sunlight plus scattered light), the roof surface temperatures are significantly higher than the air temperature in certain cases. When the exterior temperature (red) exceeds the interior temperature (blue), drying out to the inside takes place on structures with humidity-variable vapour control membranes. As a result, reverse diffusion is possible even on north-facing roof surfaces in Holzkirchen on many days during the year; on south-facing surfaces, reverse diffusion occurs even on sunny days in winter. In this simulation, the most unfavourable scenario was assumed: a north-facing roof surface with a 40° pitch.

3.2.5 Potential protection against moisture damage for a pitched roof, north-facing, 40° pitch

The amount of moisture in g/m² that dries out of the structure in one year is the potential protection against moisture damage, which quantifies the degree of protection against moisture that enters in an unanticipated manner (e.g. through convection, flank diffusion). The modelling results show that the PE sheeting (s_d value 100 m) does not allow for any significant amount of drying out of the 200 mm-thick insulation layer. Any condensation that forms in the insulation layer cannot escape in this case.
With a vapour control membrane with a constant s_d value of 5 m, the drying reserves are still very low. The direction-dependent variable vapour check membrane results in a drying reserve of 1,700 g/m² per annum.
The high-performance INTELLO vapour control membrane gives the structure the largest potential protection against moisture damage: according to the modelling calculation with Delphin [14], the structure can dry out approx. 3,500 g/m² per annum (see Fig. 17).

3.2.6 Potential protection against moisture damage for flat roofs

A range of different material datasets are available for modelling green and gravel-covered roofs. These datasets have been compiled based on measurements for various roof structures at a number of locations.
The datasets take into account the changes that can occur to green or gravel-covered roof structures over time – for example, the changing effects of the greenery such as shading due to plant growth are considered. As a result, reliable simulations of hygrothermal behaviour in and underneath green roofs and gravel-covered roofs are possible for any application in Central Europe.

3.2.6.1 Flat roof covered with gravel

A flat roof covered with gravel offers less inherent protection than a pitched roof, as the gravel above the roof seal heats up only slowly. As a consequence, there is delayed heating up of the component layers below, including the insulation layer. Figs. 14 to 16 show the temperatures of north-facing and south-facing pitched roof structures compared with those of a gravel-covered roof. The difference is particularly marked in the case of the south-facing pitched roof. However, the north-facing pitched roof also shows peak temperatures that are approx. 8-10 °C higher than the gravel-covered flat roof. As was the case with the flat roof, a gravel roof with PE sheeting does not allow for drying out due to its high s_d value of 100 m.
The vapour control membrane with a constant s_d value of 5 m also does not allow for any significant drying out reserves.
This is one consequence of the reduced component temperatures, which lead to less reverse diffusion. In this case, moisture damage to structures becomes unavoidable if there is unanticipated entry moisture. The direction-dependent variable vapour control membrane allows for drying out of 1,200 g/m² per annum.
Even though the surface temperature of the gravel roof is significantly reduced, the high-performance INTELLO vapour control membrane still delivers a very high degree of potential protection within the structure in comparison. According to the modelling calculation with Delphin [14], the structure studied here can dry out approx. 2,200 g/m² of water per annum (see Fig. 18).

3.2.6.2 Flat green roof

The behaviour of flat roof structures with greenery is slightly more sluggish than that of gravel roofs, due to the thick substrate layer and the amount of water stored in it. Temperatures at the sealing membrane attain maximum values of 35-40 °C in summer. Nonetheless, an unshaded structure with 200 mm of insulation fitted with INTELLO offers potential protection against moisture damage of 1,200 g/m² per annum (see Fig. 19).
The component offers sufficient drying reserves to deal with unanticipated entry of moisture. The influence of the greenery (shading) and the resulting increased protection becomes evident here.
The direction-dependent variable vapour control membrane and the membrane with an s_d value of 5 m both allow for under 1,000 g/m² per annum (see Fig. 19) and, as a result, offer significantly lower drying reserves. For flat roofs with greenery, a membrane from the INTELLO series is a better choice here due to the higher drying reserves that it delivers.

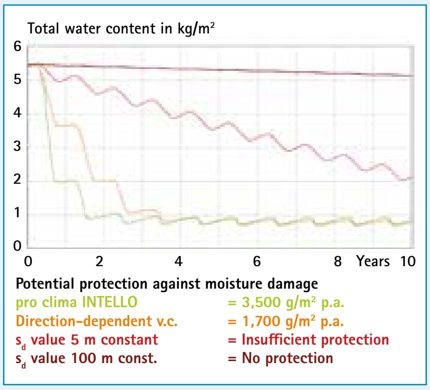
3.2.7. Influence of the insulation thickness

In recent years, factors such as the more stringent requirements of the legislation on energy efficiency have led to the use of thicker insulation layers. Insulation thicknesses of 300 mm or more used to be encountered very rarely on conventional buildings in the past, but are becoming increasingly common. However, building structures with a lot of thermal insulation offer reduced potential

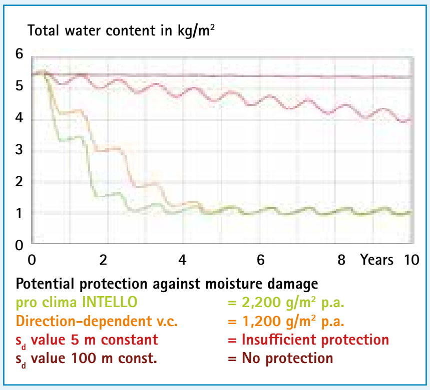
Calculation of potential protection against moisture damage, location: Holzkirchen, roof

Assumed additional initial moisture: 4,000 g/m² moisture content in the structure in its dry state (= moisture content of the timber sheathing at 15%): 1,700 g/m²

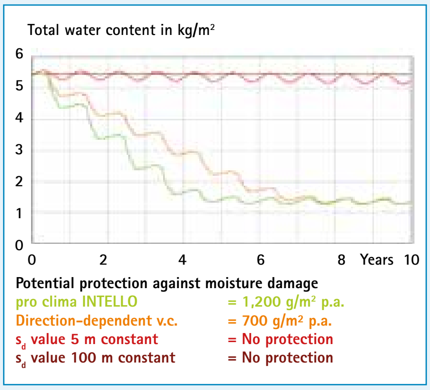
17. Potential protection against moisture damage, north-facing, 40° pitch



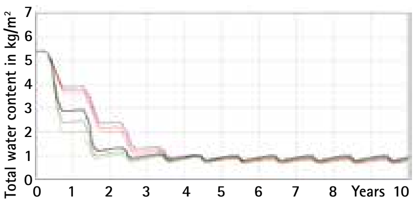
18. Potential protection against moisture damage, flat roof with 5 cm gravel



19. Potential protection against moisture damage, green roof with 10 cm plant substrate



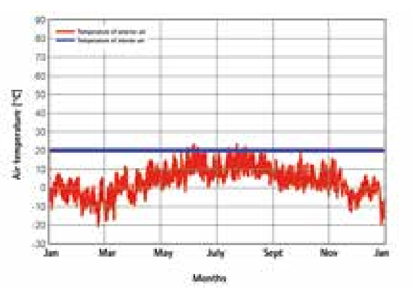
20. Potential protection against moisture damage with INTELLO and direction-dependent vapour control membrane: various insulation thicknesses



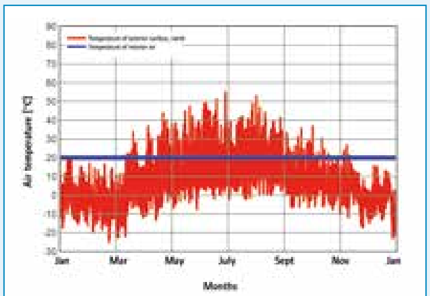
Potential protection against moisture damage:
INTELLO (400 mm) = 2,600 g/m² p.a.
INTELLO (300 mm) = 3,000 g/m² p.a.
INTELLO (200 mm) = 3,500 g/m² p.a.
Direction-dependent v.c. (400 mm) = 1,600 g/m² p.a.
Direction-dependent v.c. (300 mm) = 1,700 g/m² p.a.
Direction-dependent v.c. (200 mm) = 1,800 g/m² p.a.

Yearly temperature profiles, Davos, Switzerland, altitude: 1,560 m above sea level, red roof tiles/gravel

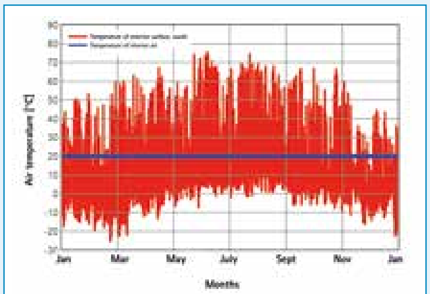
21. Air temperatures (Davos, cold)



22. Roof surface temperature, north-facing, 40° pitch



23. Roof surface temperature, south-facing, 40° pitch



protection against moisture damage. The reason for this is that the structure heats up more sluggishly with increasing insulation thickness. As a result, the process of evaporation of any moisture that enters in an unanticipated manner is slowed down. The amount of drying out over a year is thus reduced for the same exterior climate conditions.

INTELLO:
Fig. 20 illustrates the potential protection against moisture damage of the structure presented previously, with INTELLO and insulation layers of 200, 300 and 400 mm. For the 200 mm thickness, the potential protection is around 3,500 g/m² p.a., at 300 mm approx. 3,000 g/m² p.a. and at 400 mm the protection is 2,600 g/m² p.a.

Direction-dependent variable vapour control membrane:
This vapour control membrane provides lower potential protection than INTELLO. At 200 mm the protection is 1,800 g/m² p.a., at 300 mm it is 1,700 g/m² p.a. and at 400 mm the corresponding value is 1,600 g/m² p.a. (see Fig. 20).

s_d value 5 m:
At an insulation thickness of 200 mm, the structure with a vapour control membrane with a constant s_d value of 5 m already offers low potential protection against moisture damage.
The protection offered is even worse at higher thicknesses. However, the protection is so low even at smaller thicknesses that use in combination with diffusion-tight components on the outside is not recommended for low or high insulation thicknesses (no Fig. included).

Key takeaway for the INTELLO series:
With INTELLO, structures have better potential protection and are reliable in service, even for north-facing pitched roof structures (pitch 40°) that are diffusion-tight on the outside and have high insulation thicknesses and red roof tiles. Technical Support is available from pro clima to help with moisture modelling and assessment for pitched roofs, roofs with felt and flat roofs with additional structural layers above the sealing membrane (e.g. gravel, greenery, terrace deckings).

3.2.8 Climate data for Davos, Switzerland
Davos is at an altitude of 1,560 m and thus has a mountainous climate. The diagrams presented here show the temperature profiles over the course of one year. The blue line represents the interior temperature and the red line the exterior temperature (see Figs. 21 to 24). It can be seen from the air temperature profile in Davos that there are very few days in the year when the exterior temperature is higher than the interior temperature. Taking into account sunlight and global radiation, the roof surface temperatures are higher than the air temperature.
However, the temperatures on north-facing roofs are significantly lower than in Holzkirchen. As a result, reverse diffusion is possible on fewer days each year. Similar temperatures are achieved on south-facing roofs in summer in Davos and in Holzkirchen. The night-time temperatures in winter are characteristic of mountainous areas and are significantly lower.

3.2.9 Potential protection against moisture damage for a pitched roof, north-facing, 40° pitch
To minimise the solar irradiation, the least favourable scenario was again assumed for the modelling calculation, i.e. a north-facing roof with 40° pitch and red roof tiles. The extremely low temperature in winter led to high condensation formation, with the result that even the structure with PE sheeting experiences moisture accumulation, even if it was assumed that no unanticipated moisture loading occurred. With a vapour control membrane with a constant s_d value of 5 m, no protection is provided against moisture damage. The vapour control membrane with direction-dependent diffusion resistance offers relatively low potential protection of 1,300 g/m².
The high-performance INTELLO vapour control membrane ensures a reliable structure from a building physics viewpoint and offers additional protection against moisture damage. According to the modelling results with Delphin [14], 2,400 g/m² of water can dry out of this structure per annum (see Fig. 25).

3.2.10 Potential protection against moisture damage for green and gravel roofs
The drying reserves are insufficient in all scenarios with the current gravel and green roof datasets for the challenging mountainous climate in Davos. For a gravel roof, INTELLO provides a low, insufficient reserve of 800 g/m² per annum (see Fig. 26).
The potential protection against moisture damage of 500 g/m² p.a. with the direction-dependent variable vapour control membrane is even lower. The vapour control membrane with a constant s_d value of 5 m offers no significant protection for this structure. In the case of a green roof, the potential protection against moisture damage provided is worse for all configurations at Davos. These structures in mountainous areas would have to be fitted with external insulation above the framework either partially or completely, based on a project-specific modelling calculation. Please contact pro clima's Technical Support service in this regard.

3.2.11 Conclusions with regard to potential protection against moisture damage
Very high levels of potential protection against

moisture damage can be achieved with the pro clima vapour control and airtightness membranes in the INTELLO series for modelled pitched roof structures with 200 mm of insulation at altitudes of up to 700 m above sea level. These structures will not experience moisture damage even in the case of unanticipated moisture entry. Flank diffusion through brickwork, as described by Ruhe [4], Klopfer [6], [7] and Künzel [8], can be compensated for by INTELLO membranes, but it should be avoided at higher altitudes by appropriate planning measures. Millions of square metres of pro clima INTELLO have been installed on critical structures over decades, and the potential protection that these membranes provide against moisture damage has proven itself in service.
The installation of humidity-variable vapour control membranes from pro clima, as shown in Fig. 12, provides high levels of protection for gravel-covered roof structures in Holzkirchen. These membranes ensure effective protection against moisture damage for the overall structures.
The membranes in the INTELLO series can also ensure well-protected building components for green roof structures in this climate zone. The thickness of the insulating layer affects the level of protection against moisture damage. Based on the sample scenarios that have been modelled, the drying reserves are sufficient for typical insulation thicknesses of up to 400 mm for pitched roofs.
In mountainous areas at altitudes of up to 1,600 m above sea level, pitched roofs that are diffusion-tight on the exterior have sufficient potential protection against moisture damage if one of the INTELLO membranes is installed. In the case of flat roofs without rear ventilation with insulation fitted between the roof framework, it is recommended that the overall insulation should be divided into one part between the framework and one external part above the framework. The Technical Support service offered by pro clima can carry out project-specific assessments of structures for this purpose. When all types of structure layouts are compared, direction-dependent variable vapour control membranes offer less potential protection against moisture damage that a membrane from the INTELLO series. The reason for this is that the former have an increased diffusion resistance under humid conditions, which is categorised as diffusion-retarding (diffusion-checking) in DIN 4108-3 [10]. This prevents the drying out of moisture that has entered the structure in an unanticipated manner. With regard to potential protection against moisture damage, the possible drying reserves per annum are approximately 40% below those with high-performance vapour control membranes with the INTELLO functional film for all types of structures studied here.

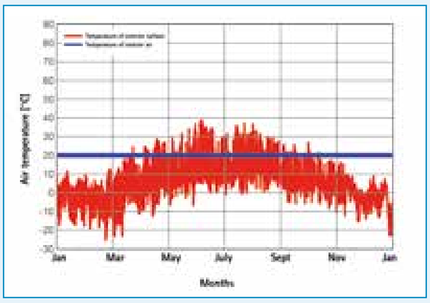
3.3 Assessment of fitness for purpose of insulation structures

Alongside potential protection against moisture damage, the moisture contents that will be attained inside building components during their service lives are another critical consideration. Any analysis of moisture behaviour first involves the identification of the component layers that need to be critically examined. These are generally timber sheathing or wood-based panels (OSB or three-ply boards) installed on the outside. Once the relevant layers have been identified, dynamic (time-dependent) modelling calculations are carried out and external insulation is gradually added above the supporting structure until moisture contents below the permitted values are achieved in the critical layer(s). The fitness for purpose of a structure in service is dependent on the sequence of the structural layers and also on the location of the planned building. For example, a building at the foot of a mountainous area will generally be exposed to more challenging climate conditions than one close to the sea. Modelling calculations to determine the fitness for purpose of a structure in service have been carried out here with WUFI pro.

3.3.1 Assessment calculation procedure

When carrying out moisture modelling, it is advisable to take into account moisture entry due to unavoidable residual leaks (convection). With WUFI pro, the entry of moisture into the thermal insulation layer by convection can be simulated with the aid of the air infiltration model. The criterion here is the air change rate per unit surface area of the building envelope, q_{50}, and not, in this case, the n_{50} value rate per unit volume. The q_{50} and n_{50} values have similar numerical values at an A/V ratio (ratio of the envelope area to the volume of the building in question) of around 0.9 1/m. At lower A/V ratios, the q_{50} value is less than the n_{50} value (e.g. A/V = 0.7 1/m: q_{50}value = 2.3 m³/m² h and n_{50} = 3 1/h) (cf. [18], p. 20).
The air infiltration model has three standard airtightness classes (A, B, C), which correspond to q_{50} values of 1 m³/m² h (Class A), 3 m³/m² h (Class B) and 5 m³/m² h (Class C). Class A can be assumed in the case of pre-fabricated elements or if airtightness has been tested by means of leak detection; Class B can be assumed if airtightness has been tested; and if airtightness has not been tested, then Class C can be assumed in order to simulate the unanticipated moisture load arising due to leaks. Airtightness testing with leak detection should be carried out for every structure to ensure maximum reliability. If this is done, Airtightness Class A can be used in the simulation. The cases modelled below and the resulting assessments of fitness for purpose apply to WLG 035 insulation made of mineral

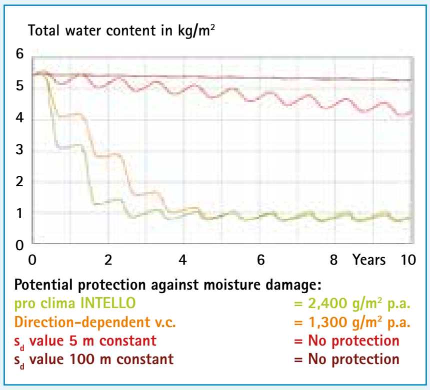
24. Roof surface temperature, gravel roof



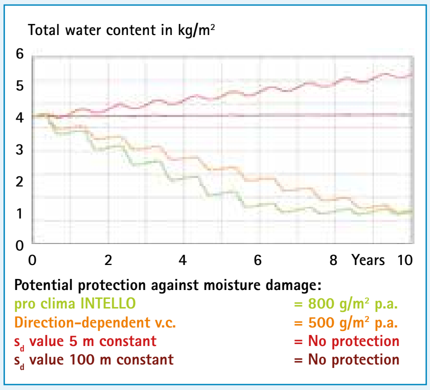
Calculation of potential protection against moisture damage, location: Davos, Switzerland, roof

For further details, see calculation for Holzkirchen on **page 12**

25. Potential protection against moisture damage, north-facing, 40° pitch

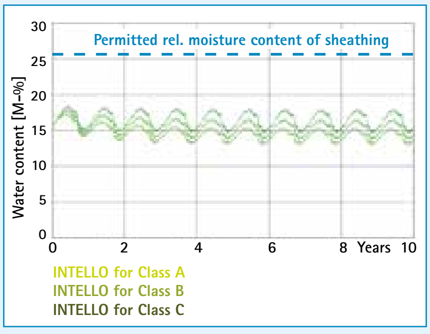


26. Potential protection against moisture damage, gravel roof

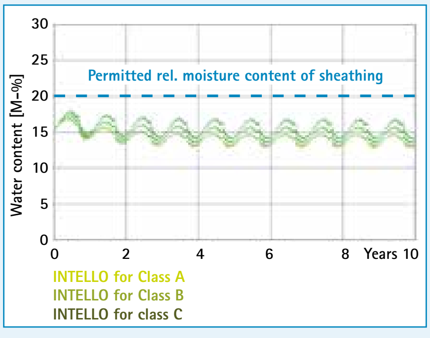


Assessment of fitness for purpose of structures as per Fig. 12

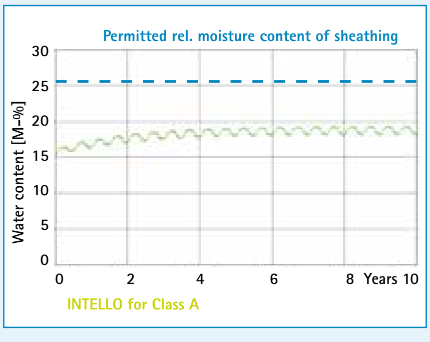
27. Fitness for purpose of pitched roofs (40°/ mineral wool 035 (INTELLO 400 mm) / Holzkirchen)



28. Fitness for purpose of gravel roofs (mineral wool 035 (INTELLO 300 mm) / Holzkirchen)



29. Fitness for purpose of green roofs (mineral wool 035 (INTELLO 200 mm) / Holzkirchen)



wool or rock wool. The applicable framework conditions for the simulation calculation and the evaluation of the results follow the recommendations of the WTA information sheets 6-8 [20] with regard to design considerations (Section 6.4b).
To achieve a well-protected structure, it may be advisable to specify additional insulation above the first sealing membrane at the planning stage. Even if this is not necessary from a building physics perspective, this nonetheless offers the advantage that moisture that enters through a leaky external sealing layer will not enter into the timber load-bearing structure. This structure will then be protected. Regular visual inspection (maintenance) of all structures is recommended.

3.3.2 Fitness for purpose of a pitched roof that is diffusion-tight on the outside

As a case study for determining fitness for purpose in Holzkirchen, the pitched roof structure in Fig. 12 with red engobe roof tiles and pro clima INTELLO was considered. This structure was modelled with a 400 mm thick layer of mineral wool insulation. Simulations with WuFi pro were carried out for three airtightness classes and at a height of 5 m on the insulated building envelope.
The critical layer in these structures is the spruce sheathing underneath the sealing layer. Fig. 27 shows the moisture contents in the 24 mm-thick sheathing over a period of 10 years. To be on the safe side, the moisture content in the spruce sheathing should stay below 20% (the corresponding limit for wood-based panels is 18%). If this is adhered to, the structure will work reliably when in normal service.
When INTELLO is installed, the spruce sheathing on the structure does not experience excessive levels of moisture in the calculations with all three airtightness classes; as a result, fitness for purpose has been verified for all airtightness classes. Indeed, further reserves are available to deal with additional unanticipated moisture loading.

3.3.3 Fitness for purpose of a gravel-covered flat roof

The gravel-covered roof structure with INTELLO has an insulation thickness of 300 mm of mineral wool. The moisture content in the spruce sheathing on this structure remains under the maximum permitted value of 20% when INTELLO is used, meaning that fitness for purpose has been verified for these structures (see Fig. 28).

3.3.4 Fitness for purpose of a flat roof with greenery

Green roof structures with INTELLO may be designed with an insulation thickness of 200 mm of WLG 035 mineral wool as shown in Fig. 12 for the climate in Holzkirchen (see Fig. 29). In this case, the airtightness needs to be checked and leak detection needs to be carried out (Airtightness Class A) so that moisture entry due to convection can be avoided. Simulation calculations with the other airtightness classes assume higher levels of convective moisture entry, which in turn leads to moisture contents of greater than 20% inside the sheathing. To avoid this situation, additional external roof insulation can be specified.

3.3.5 Conclusions with regard to fitness for purpose

The fitness for purpose of pitched roofs (40° pitch) that are closed to diffusion on the outside, gravel-covered or green roof structures has been analysed by carrying out simulations for the location Holzkirchen for the specified insulation thicknesses of WLG 035 mineral wool and for spruce sheathing. Different structural characteristics (greater insulation thicknesses, wood-based panels instead of timber sheathing, sorptive insulation materials instead of mineral wool) and different locations (cities/towns, shading) could require the specification of additional external roof insulation with a second sealing layer from a building physics perspective. External roof insulation generally has a positive impact on the reliability of a given structure for all fully insulated flat roofs, as the double sealing protects the supporting structure against the entry of moisture from the outside if a leak should occur in the upper sealing layer. In addition, annual inspection is recommended for all roof types (e.g. roofs with membranes, gravel-covered and green roofs) to ensure that the roof structure and all run-offs are working properly.
As a rule, it is helpful to have the fitness for purposes of all structures with diffusion-tight component layers on the outside checked by a building physics specialist. Please contact Technical Support at pro clima in Germany for assistance with verification and simulation of building components.

3.4 Flank diffusion

To determine the influence of moisture entry through 'flanks', the joint between a thermal insulation structure and an adjacent interior wall that penetrates into the insulation layer is examined. The roof structure has diffusion-tight bitumen roofing felt on the outside (see Fig. 30).
The masonry wall has lower diffusion resistance than the vapour barrier and airtightness layer installed on the adjoining timber structures. As a result, the 'flank' that is created allows for greater diffusion of moisture into the thermal insulation structure than the surrounding areas where a vapour control membrane is fitted.

A newly built scenario has been analysed here. In this case, the masonry wall and the plaster layer have a typical moisture content of 30 kg/m³. The fibrous insulating material has been installed in a dry state. The relative moisture content of the roof sheathing is 15%. In one variant, diffusion-inhibiting PE sheeting (s_d value 100 m) is installed as a vapour barrier and airtightness membrane, while the humidity-variable INTELLO membrane from pro clima (s_d value of 0.25 to over 25 m) is used in the second variant.

3.4.1 Results of the 2-dimensional simulation

When a structure of this type is modelled using a 2-dimensional procedure for heat and moisture flows such as that implemented in WUFI 2D [9], the following results are obtained (see Fig. 31): After an increase in the moisture content of both structures due to seasonal effects, the two structures are initially at similarly high levels.

In the variant with PE sheeting as its vapour barrier and airtightness membrane, a significant increase in the total water content can be observed for each year over a period of 4 years (indicated by the red line).

This structure experiences an accumulation of moisture in the building materials used, as no drying towards the interior is permitted by the PE sheeting. This will result in mould formation on the timber and the onset of timber degradation.

In the case of the structure with the high-performance INTELLO vapour control membrane, moisture in the structure can escape towards the interior. The design is protected against accumulation of moisture, as any moisture is quickly released to the interior space (see the green line). As a result, the moisture content decreases steadily over the 4-year period. Structures with INTELLO offer a high degree of potential protection against moisture damage.

3.4.2 Conclusions with regard to flank diffusion

Moisture that enters through flank diffusion at an adjacent interior wall that impinges on the thermal insulation structure, as described by Ruhe [4], Klopfer [6], [7] and Künzel [8], can escape from the insulation structure again if INTELLO membranes are used. Structures that offer low potential protection against moisture damage should be designed in such a way as to avoid flank diffusion processes.

3.4.3 Wall structures

Because of their vertical orientation, wall structures are subject to less solar irradiation heating than roofs. As a result, their potential for drying out is also lower. However, walls are generally not diffusion-tight on the outside, in contrast with roofs. Bitumen felt is not used as there are no demanding requirements in terms of watertightness, when compared with flat or green roofs.

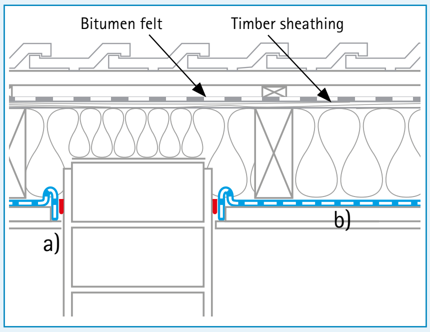
The temperatures present within exterior walls mainly depend on the colour of the facade. Solar irradiation leads to lower temperatures on light-coloured facades than on darker ones. The following temperature profiles are created on an outside wall with a typical light-coloured plastered facade (see Figs. 32 to 35).

The high-performance INTELLO vapour control membrane offers significant protection against moisture damage on wall structures too. Calculations carried out using Delphin [14] with climate conditions for Holzkirchen show that there is sufficient potential protection against moisture damage for a north-facing wall with diffusion-tight external cladding if membranes with the INTELLO functional film are used.

Membranes from the INTELLO series are ideal solutions that provide sufficient protection even with wood-based panels such as OSB or chipboard on the outside. The risk of mould formation is reduced significantly. Moisture protection is an integral part of the construction design and verification process, and should always be checked by a building physics specialist. The Technical Support service offered by pro clima can assess the moisture behaviour of proposed structures.

2-dimensional modelling of heat and moisture flows with WUFI 2D

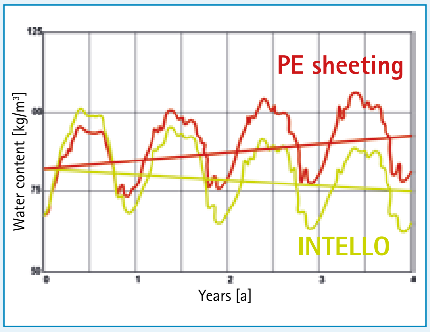
30. Structural situation: adjacent wall that impinges on the insulation layer



a) Interior wall: plastered brickwork;
b) Vapour control membranes:
- PE sheeting, s_d value = 100 m constant
- pro clima INTELLO, humidity-variable s_d value = 0.25 to over 25 m

31. Increase in moisture with PE sheeting ➔ Accumulation of moisture = moisture damage

Reduction in moisture with INTELLO ➔ Drying out = Protection against moisture damage

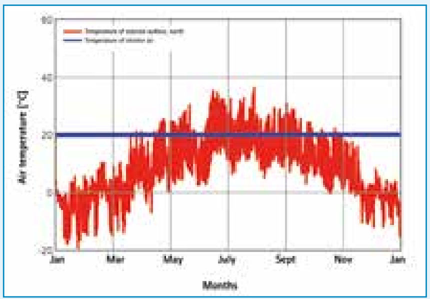


Increasing moisture content in component with PE sheeting, s_d value = 100 m constant

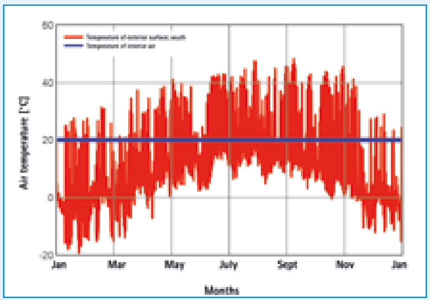
Decreasing moisture content in component with pro clima INTELLO, s_d value = 0.25 to over 25 m, humidity-variable

Temperature profiles, Holzkirchen, Germany, and Davos, Switzerland: Wall, light-coloured plastered facade

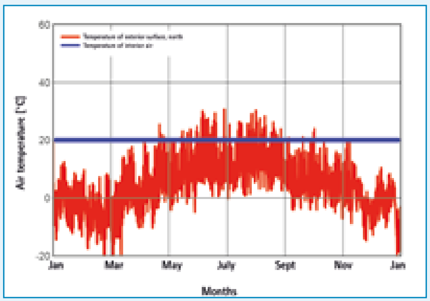
Holzkirchen:
32. Wall temperature, north-facing



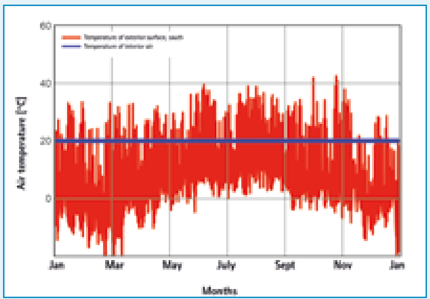
33. Wall temperature, south-facing



Davos:
34. Wall temperature, north-facing



35. Wall temperature, south-facing



Design recommendations

4.1 General remarks

Building physics simulations carried out with real climate data demonstrate the large degree of potential protection against moisture damage of structures that use high-performance vapour control membranes from the INTELLO series with their significant, humidity-variable diffusion resistance that is effective in all climate zones.
Structures that are implemented using humidity-variable vapour control and airtight membranes from pro clima are reliably protected against mould damage, even if there are increased levels of moisture loading. Any analysis of moisture protection needs to take into account the effects of diffusion-tight materials on the outside, additional component layers above the timber structure such as greenery or gravel, and shading caused by other buildings, topography or PV systems. Please contact a building physics specialist or Technical Support at pro clima in Germany for assistance in this regard.

4.2 Internal cladding

Unimpeded drying out to the interior is a prerequisite for ensuring sufficient protection reserves. Cladding with a diffusion-hindering effect, such as timber materials (e.g. OSB or plywood), on the inside of a humidity-variable vapour control membrane reduces the amount of moisture that can dry out to the inside, and thus also reduces potential protection against moisture damage. Diffusion-open materials – such as wooden board cladding, mineral-bonded wood-wool boards, plaster and plasterboard – are advantageous in this regard.
Structures with diffusion-tight component layers on the outside should only be used in combination with diffusion-open interior cladding. This will ensure that the overall structure is protected against moisture damage.

4.3 Permanently humid spaces

Humidity-variable vapour control membranes cannot be used in areas that are permanently humid, such as swimming pools, spas, plant nurseries or catering kitchens.

4.4 New builds: Drying phase (the 60/2 rule)

Adherence to the 60/2 rule ensures effective protection for thermal insulation structures on newly built projects, which are unavoidably subject to increased levels of indoor humidity. The membranes in the INTELLO series fulfil this requirement and thus ensure high degrees of intrinsic potential protection against moisture damage.

4.5 Humid rooms in homes

Increased indoor humidities are often unavoidable during the construction phase, so it is particularly important that humidity-variable vapour control membranes should have a sufficiently high hydrosafe value for this period. Wet and humid rooms in residential buildings can temporarily reach relative humidities of 70%.
Humidity-variable vapour control membranes with the INTELLO functional film provide optimal protection for rooms of this type, as they fulfil the 60/2 rule – i.e. they have an s_d value of greater than 2 m at 70% indoor humidity and 50% humidity in the insulation layer (60% average humidity). In this way, the structure is sufficiently protected against the entry of moisture arising from the humidity associated with the construction and initial use of new buildings (see Fig. 37).

4.6 Construction phase: hydrosafe value (the 70/1.5 rule)

The INTELLO functional film has a hydrosafe value of over 2.0 m and thus provides excellent protection against moisture loading that occurs during the construction phase (see Fig. 37).
As a result, structures fitted with humidity-variable vapour control membranes are well-protected against mould formation during the construction phase too.
Construction-related moisture should be removed quickly and systematically by continuous ventilation. Dryers will help to reduce the moisture loading. Reducing the moisture contents of materials that are installed in a moist state (brickwork, plaster, screed, concrete etc.) is important because this can also help to prevent the formation of mould on surfaces in new buildings.

4.7 Roofing underlay membranes

Diffusion-open materials are the optimal choice for the underlay system (e.g. wood-fibre underlay panels or SOLITEX underlay membranes with non-porous films), as they facilitate a high level of drying to the outside. Structures with diffusion-tight components on the outside – e.g. bitumen felts, flat roofs, green roofs, or roofs with metal coverings – reduce the level of inherent protection offered by the structure. With its high degree of humidity variability, the INTELLO series offers excellent protection potential for these applications.

4.8 Pitched roof structures

Structures that are open to diffusion on the outside offer drying reserves that are so large that there are no limits on the altitude of the building location if vapour control membranes from the INTELLO series are used. Structures built even at altitudes of over 3,000 m will still be reliably protected. Please consult a building physics specialist or pro clima's Technical Support in the case of pitched roof designs with diffusion-tight component layers on the outside.

4.9 Flat-roof and green-roof structures

Flat roofs always have a sealing membrane on the outside to ensure watertightness. These have a diffusion resistance greater than that of a strong vapour check, and they may even be fully vapour-tight (s_d value > 1,500 m) for bitumen felts with an aluminium foil barrier. In both cases, the amount of drying to the outside is reduced to a minimum.
Ventilated structures are possible as long as ventilation heights and lengths are taken into account and if a minimum cross-sectional area of air inlets and outlets is guaranteed. It is also important that these two openings are suitably aligned with one another to allow for unhindered airflow. Ventilation with labyrinth-like paths are generally useless and may even have a negative impact on the reliability of a structure as they give a false sense of security. On the other hand, ventilation leads to increased cross-sectional areas of components, which may in turn impact on the architectural design of a building. Ventilation cross-sections have to be designed and planned in detail, and it must be ensured that they work properly in practice; non-ventilated or poorly ventilated cross-sectional areas above insulated flat roof structures can result in moisture damage to these structures.
Non-ventilated flat roofs can be implemented efficiently and reliably using INTELLO membranes. Roofs of this type can be designed and installed with additional component layers such as gravel, substrates for green roofs, or terrace deckings above the sealing layer.
In these applications, high-performance INTELLO vapour control membranes deliver a high degree of potential protection against moisture damage in the case of unanticipated moisture entry thanks to their humidity-variable diffusion resistance. Significant amounts of moisture can then dry out of structures again, thus avoiding a build-up of moisture and the resulting risk of damage.
Analysis of moisture protection should be carried out by a building physics specialist or by pro clima Technical Support.

4.10 Pitched roof structures at high altitudes

Pitched roof structures that are closed to diffusion on the outside can be designed and built in a reliable manner at mountainous locations by using the INTELLO functional film, which delivers a high level of inherent protection against moisture damage.
In the case of pitched roof designs with diffusion-tight external layers, it is critical that the moisture protection should be analysed by a building physics specialist or pro clima Technical Support.

4.11 Walls

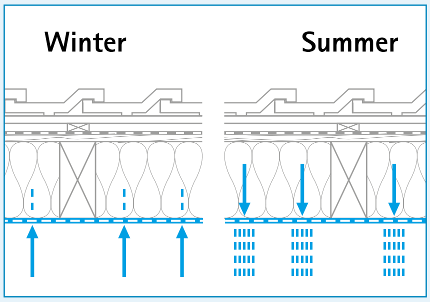
Timber-frame walls with diffusion-open layers on the outside (e.g. pro clima SOLITEX FRONTA WA, wood fibreboard or MDF boards) behind ventilated facades can be implemented with membranes from the INTELLO series for any site altitude. Humidity-variable vapour control membranes can also be used on timber-frame wall structures with thermal insulation composite systems (TICS) made from foam insulation materials or in combination with interior insulation on brickwork or concrete structures. The moisture behaviour must be assessed by a building physics specialist; pro clima Technical Support can also provide assistance in this regard.

4.12 Quality assurance

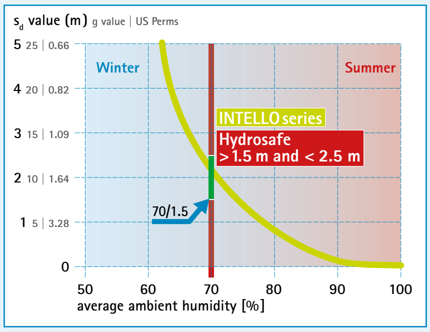
Ideally, the airtightness of built structures should be tested during the construction phase directly after completion of the airtightness layer. If leak detection is carried out at this stage, defects can be located and rectified with relative ease. This ensures that the built structure will be reliable and well protected. This testing can be carried out using a blower door test (Fig. 38) during the construction phase on temporarily sealed buildings (doors, windows etc.).
Final measurements with determination of n_{50} values can also be carried out after the building is complete, also by means of blower door testing. The best possible airtightness is a prerequisite for a pleasant, cosy indoor climate, low energy losses, and reliable protection against damage caused by dampness resulting from convection.

Prerequisite for the effectiveness of humidity-variable vapour control membranes

36. Only diffusion-open component layers may be present on the interior to facilitate drying out of moisture by means of reverse diffusion into the indoor space.



37. Protection for thermal insulation structures during the construction phase and on newly built projects



The s_d value of the membranes adapts to the applicable ambient humidity conditions. A hydrosafe value of between 1.5 and 2.5 m protects insulation structures against the increased humidity that is associated with construction work. This value also ensures a high degree of inherent protection against moisture damage for fully insulated timber structures.

38. Leak detection to test overall airtightness, and determination of the air change rate (n_{50} value)

Blower door testing

Key takeaways

Structures implemented using membranes from the INTELLO series have very large protection reserves, depending on their site location and structure type, and they prevent moisture damage and mould formation thanks to their intelligent moisture management. Even in the case of dampness that is an unavoidable consequence of construction activity or of unanticipated moisture loading during subsequent service, these structures enjoy very high inherent protection against moisture damage thanks to their high drying reserves, which result from humidity-variable diffusion resistances.
High-performance INTELLO vapour control membranes have particularly high variability of their diffusion resistance, which is effective in all climate zones, and these membranes thus offer unprecedented levels of reliability and protection for thermal insulation structures. This applies to structures that are diffusion-open on the outside and also to structures such as flat roofs, green roofs, roofs with metal coverings and roofs with diffusion-tight overlays, which are all more challenging from a building physics viewpoint.
The capabilities of the INTELLO functional film become particularly evident under extreme climate conditions, such as sites at altitude in mountainous areas. In addition, pro clima offers particular peace of mind and reliability with its comprehensive, transparent and fair system warranty.

»The greater the drying reserves of a structure, the more unanticipated moisture loading it can be exposed to without moisture damage occurring.«

This reliability principle underpins the intelligent operating principle of all membranes in the INTELLO series, thus allowing for the implementation of particularly well-protected structures.

Installation instructions for pro clima system products and CAD drawings showing typical on-site situations are available on our website at proclima.com.

Contact details for technical support in your country or region are available at:
proclima.info/en/technical-support

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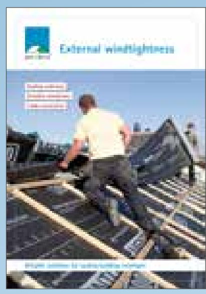
Internal airtightness brochure

Guide to pro clima's vapour control membranes for implementing internal airtightness, together with accessories for sealing joints and transitions.



External windtightness brochure

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