Study

Calculating Potential Freedom from Structural Damage of Thermal Insulation structure in Timber-Built Systems

– Roof, Wall, Ceiling –

Humidity-Variable Vapour Membranes pro clima DB+ and INTELLO®

Computer-aided simulative calculation of coupled transport of heat and moisture in roof and wall systems, taking account of natural climatic conditions and transport of liquids within building materials

pro clima®

Content

Freedom from Structural Damage of Thermal Insulation in Timber-Built Structural Systems: A Question of Drying Reserves

1. Freedom from Structural Damage of Thermal Insulation in Timber-Built Structural Systems: A Question of Drying Reserves

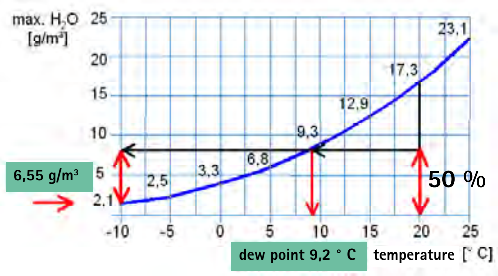
Atmospheric humidity

Atmospheric humidity increases when the air cools down.

Condensation develops below the dew-point temperature.

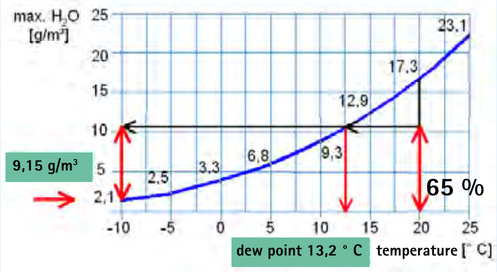
When the internal humidity increases the dew ⟶ point temperature rises and condensation develops sooner.

1. Development of condensation at 50% relative atmospheric humidity



Under normal climatic conditions (20° C/50 % rel. atmospheric humidity), dew point is reached at 9.2° C.
At -10°C, condensation precipitates at a rate of 6.55 g/m³ air.

2. Development of condensation at 65% relative atmospheric humidity



At a high internal rel. humidity of 65 %, dew point is already reached at 13.2° C.
Then, at -10°C condensation precipitates at a rate of 9.15 g/m³ air.

3. To convert to Irish and British standards:

$$s_d\ (m) \times 5.1 = mvtr\ (MNs/g)$$

s_d = water vapour diffusion-eqivalent air layer thickness
mvtr = moisture vapour transmission rate

1.1 Summary and Introduction

The present study describes how structural damage may arise in thermal insulation systems and how such systems may be reliably and safely protected from damage of this kind.

Structural damage occurs when the moisture stress on a structural system is greater than the system's drying capacity.

To prevent structural damage, the usual approach is to concentrate on reducing moisture stress. However, structural systems cannot be fully protected from the effect of humidity or moisture. Planned moisture stress produced by diffusion is virtually never the cause of structural damage, the usual culprit being unanticipated moisture stress that cannot be entirely ruled out by building design.

To exclude the likelihood of structural damage and mould growth, it is advisable, apart from considering moisture stress, to concentrate on the drying capacity of a structural system. Systems with a high drying capacity and a simultaneous reduction in moisture stress, as provided by vapour membranes with a variable s_d value, are still very safely and reliably protected against structural damage even if subjected to unanticipated moisture stress.

1.2 Condensation – Dew Point – Quantity of Condensation

Thermal insulation in timber-built structural systems separates warm indoor air with its high humidity content from cold outdoor air with low absolute humidity.

When warm inside air penetrates the structure, it cools – in wintry weather conditions outdoors – as it passes on its way through the structural system. Moisture may condense in the process, this precipitation of water being attributable to the physics of airborne humidity. Warm air can absorb more moisture than cold air. At a greater internal relative humidity (e.g. 65%), the dew-point temperature rises and, as a direct consequence, the quantity of condensation increases as well (see figures 1 and 2).

Condensation develops whenever a more diffusion-tight layer of building components is below the dew-point temperature, which means that:

Building-component layers which are more diffusion-tight on the outside of the thermal insulation than the layers on the inside are unsatisfactory. A major problem is posed should warm air leak into the structure by convective stream, which happens as a result of leaks in the air seal.

Building components are deemed very open to diffusion when their s_d value is less than 0.20 m (<1 MNs/g). The s_d value is defined as the multiple of the vapour diffusion resistance coefficient (µ value) - as material constant - and the thickness of the component in metres:

$s_d = \mu \times s\ (m)$ $s_d \times 5.1 = mvtr\ (MNs/g)$
(see figure 3)

A low s_d value can thus be obtained by means of a low µ value and a greater layer thickness (e.g. wood fibre board), or by a higher µ value and a very small layer thickness (e.g. roofing felts). Water vapour is influenced in the first place by the µ value, and only then by the thickness of the building material. This means that precipitation of condensation begins earlier at a higher µ value than at a low one. Moreover, roofing felts produce only a low drop in vapour-pressure because there is little or no difference in temperature and humidity.

This explains why structural damage may still occur with diffusion-open roofing felts when the flow of moisture in the building component is high.

Roofing felts with non-porous, permeable membranes such as SOLITEX UD and SOLITEX PLUS are advantageous in this context, as diffusion proceeds actively along the molecular chains rather than passively through pores. Once water has condensed in a structural system, hoarfrost or even ice may develop underneath the roofing felt

in cold winter conditions. Water and ice are impervious to water vapour and can cause an insulating sheet to act as a vapour barrier on the outside.
Structural units with a diffusion-inhibiting or even a diffusion-tight layer on the outside are more exacting in terms of construction physics than building-component layers that are open to diffusion towards the outside. Diffusion-tight structural systems include steep-pitched roofs with diffusion-inhibiting underlay, e.g. bitumen felts, roofs with flexible metal sheeting, flat roofs and green roofs.

1.3 Moisture Stress on a Structural System

There are several different reasons for moisture stress within a thermal insulation system when building with timber. In the first place, water may penetrate through a leaking roof skin. Large volumes of moisture can develop, causing water to drip into the accommodation area. Minor leaks can lead to creeping moisturisation, which is often accompanied by mildew or mould on the materials contained in the structural system.
A structural system may also be subjected to moisture stress from the inside, due to

Foreseeable or planned moisture stress:
- diffusion processes

Unanticipated moisture stress:
- convection, i.e. air flow (leaks in the air barrier)
- heightened moisture in the building components used
- design-induced transport of moisture (e.g. flank diffusion through adjoining masonry)

1.3.1 Moisture Stress through Diffusion

The smaller the amount of moisture that can penetrate a structural system, the greatly reduced risk of structural damage is. At least that used to be the preceived opinion. In other words, very dense vapour barriers would prevent damage to the building. The fact that this is not actually true was already proven some ten years ago, by construction-physics calculations on the occasion of the market launch of pro clima's DB+ with its s_d value of 2.30 m (12 MNs/g).

Furthermore, investigations on outside walls conducted in North America in 1999 [1] demonstrated that the entry of moisture through a vapour barrier as a result of convection, even where professionally installed, produces a condensation quantity of about 250 g/m^2 per dew period. That corresponds to the quantity of condensation diffusing through a vapour membrane with an s_d value of 3.3 m (16.5 MNs/g) during one winter [2].

Summary:
Substantial quantities of moisture will still penetrate structural systems with vapour barriers having a calculated s_d value of 50, 100 m (250-500 MNs/g) or higher.
But vapour barriers do not permit subsequent evaporation, so moisture traps develop as a result.

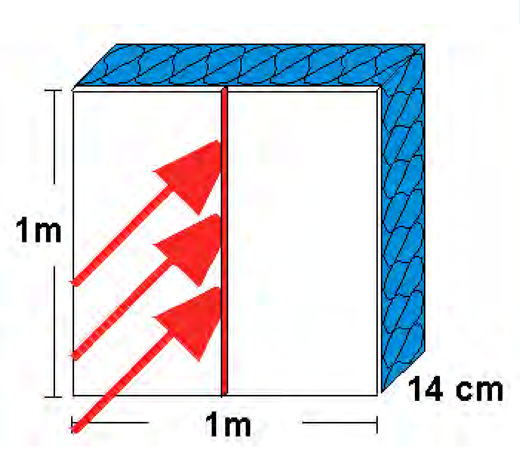
1.3.2 Moisture Stress through Convection

Convection, in other words airflow, transports substantially larger quantities of moisture into a structural system than diffusion does. The volume of moisture carried in by convection can easily exceed a thousand times the quantity introduced by diffusion. (see figure 4).

Once condensation develops convective quantities of moisture can, due to their high moisture load, present a risk to the outside even where building components are open to diffusion. Waterfilms can act as a vapour barrier in the same way as ice. Such a situation generally results in structural damage similar to where structural systems have diffusion-tight components on the outside.

Entry of moisture into the structural system due to leaks in the vapour barrier

4. 1 mm Gap = 800 g/24h per m Gap Length



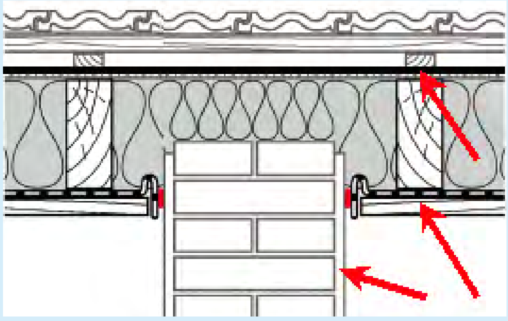
Moisture transfer
through vapour barrier: 0.5 g/m^2 x 24h
through 1 mm joint: 800 g/m^2 x 24h
Factor: 1,600

Boundary conditions:
vapour barrier s_d-value = 30 m (150 MNs/g)
indoor temperature: +20° C
outdoor temperature: -10° C
pressure difference: 20 Pa corresponding to wind force 2-3

Measurements by:
Institute for Building Physics, Stuttgart

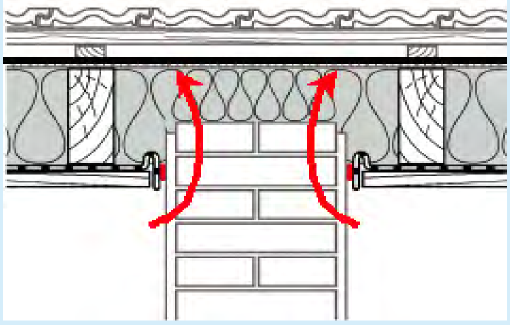
Flank Diffusion

5. Structural damage: Entry of moisture despite airtight junctions and the use of a vapour barrier



Airtight construction using a PE sheet and an airtight layer of plaster with bitumen felts on the outside

6. Cause of moisture entry: Moisture transfer across the flanks, here through masonry



Moisture entry due to flank diffusion through adjoining masonry

1.3.3 Design-Induced Moisture – Flank Diffusion

In practice, structural damage occurs in ways that cannot simply be explained by diffusion or convection processes. Ruhe [4] and Klopfer [5], [6] reported in 1995 and 1997 respectively on the problem of flank diffusion in an instance of structural damage.

The structural system in question comprised of a roof with timber decking and bitumen felt on the outside, a PE sheet on the inside, and mineral wool in between. Despite a perfect airtight seal, water dripped, in summer, from the junctions of the sheeting onto the adjoining building components underneath. It was initially assumed that the phenomenon was attributable to high incorporated moisture. However, this had to be ruled out because the dripping increased from year to year. After five years, the roof was opened. Most of the timber decking had already begun to rot.
The possibility of moisture entry as a result of flank diffusion was discussed. Flank diffusion is understood to mean the penetration of moisture into the roof via the flank or edge of the lateral airtight seal flashing, which comprised porous brickwork in the case investigated. The current of moisture virtually bypasses the vapour barrier (see figures 5 and 6).

The situation was much disputed among construction physicists at the outset, until Künze [7], in 1997, furnished mathematical proof of flank diffusion with the aid of two-dimensional calculations of heat and moisture transport using WUFI 2D 2.1 [8]. According to his calculation, wood moisture above the brickwork had risen to about 20% after just one year, thus already exceeding the mould-critical limit; after three years, the moisture content rose to 40%, and then to 50% after five years.

1.3.4 High Incorporated Moisture in Compound Units

Where building materials with a high moisture content are installed, it is essential to ensure that the structural system is capable of letting this moisture dry out again. Although it has become general practice by now to use dry timber for building purposes, just a shower of rain can increase the quantity of moisture in the wood.

Expressed in concrete figures:

A roof with 8/18 rafters and a rafter spacing of e = 0.70 m has 1.5 linear metres of rafters per m^2 of roof area. At 10 % moisture, this quota of rafters will contain about 1.1 litres of water. Consequently:
If the moisture of the wood is 30 % at the outset, it must be possible for 1.1 litres of water per m^2 of roof area to evaporate so as to come below the mould-critical moisture of 20%.

This sample calculation is consistent for 20-mm thick timber roof boarding as well. The moisture content at 10 % wood moisture amounts to approximately 1.2 litres of water.
At 30 % initial moisture, by no means a rarity after a day of rain, it is essential for 1.2 litres of water per m^2 of roof area to evaporate in order to fall below the mould limit.
Together, this amounts to about 2.3 litres per m^2 of roof area.
The total quantity of moisture is often underestimated. In concrete construction work, the humidity associated with new building work may add a further quantity of moisture. Structural damage rapidly ensues if a PE sheet is then placed on the inside and bitumen felt on the outside.

1.3.5 Moisture Stress Summarised

The numerous ways in which moisture can enter are a clear indication that, in everyday building practice, the possibility of moisture stress on a structural system can never be ruled out. When the object of the exercise is to build without likelihood of damage, the provision of increased drying reserves is a far more effective and reliable solution than any strict concentration on letting as little moisture as possible into the structural system.

Safety Formula:

drying capacity > moisture stress
=> freedom from structural damage

Structural damage can only occur when drying capacity is less than moisture stress.

„The greater a structural system's reserves for drying, the greater the unanticipated moisture stress it can take and the structure still remain free from structural damage".

Structural systems that are open to diffusion on the outside have greater drying reserves than systems with a diffusion-tight exterior.

2. „Intelligent“ Vapour Membranes

Structural humidity situation

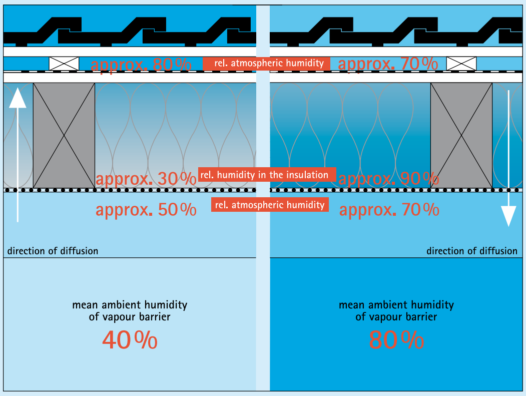
Diffusion stream always goes from the warm to the cold side:

In winter:
Increased humidity on the outside

In summer:
Increased humidity on the inside

7. The vapour membrane is exposed

- **to dry atmospheric humidity in winter.**
  > The humidity-variable vapour membrane is tighter against diffusion
- **to high atmospheric humidity in summer.**
  > The humidity-variable vapour membrane is more open to diffusion



Seasonal dependency of relative atmospheric humidity at the vapour membrane

8. Diffusion streams of the humidity-variable pro clima vapour membrane

Diffusion Current	W_{DD}-value in g/m^2 per week in winter	W_{DD}-value in g/m^2 per week in summer
Direction of diffusion	Towards sub-roof: Humidification	Towards vapour-membrane: Evaporation
DB+	28	175
INTELLO®	7	560

2.1 Drying towards the inside

Drying towards the inside is another important option for structural components. Whenever the temperature of an insulation layer is higher outside than inside, the diffusion stream reverses and moisture streams inwards out of the component. This can happen on sunny days in spring and autumn and all the more so during the summer months.

If a vapour-membrane or airtightness layer were then to be open to diffusion, moisture that may be present in the structural system could dry out towards the interior.

However, a diffusion-open vapour membrane would let too much humidity diffuse into the structural system during winter and thus give rise to structural damage.

A structural system would appear at first glance to be well protected against moisture when equipped with vapour membranes. However, if moisture enters through convection, flank diffusion or high component moisture, the system is incapable of evaporating again towards the inside in the summer. Depending on its design, the vapour membrane becomes a moisture trap. A vapour membrane with a high diffusion-resistance in winter and a low diffusion resistance in summer is ideal.

„Intelligent“ vapour membranes with a humidity-variable s_d value have proven their worth for years by now. They alter their diffusion resistance in relation to the relative atmospheric humidity.

In winter conditions, they become more diffusion-tight and protect the structural system from moisture.
In summer, they are more diffusion-open and thus allow moisture, which may be present in the system to evaporate towards the inside.

2.2 How Humidity-Variable Diffusion Resistance Works

The direction of the diffusion stream is determined by the difference in water vapour partial pressure, which depends on the temperature and humidity content of the air inside and outside a building. Just to concentrate on the temperature aspect, moisture streams from the warm side to the cold side, so, in winter, from the inside to the outside, and, in summer, from the outside to the inside.

Measurements on roof systems have shown that, in winter, the transport of moisture within the roof space towards the outside leaves the vapour membrane at a mean ambient humidity of about 40 %. In summer, on the contrary, moisture in the roof space produces increased relative atmospheric humidity at the vapour membrane, sometimes even producing ‚summer condensation‘ (see figure 7).

Vapour membranes having a humidity-variable diffusion resistance are tighter to diffusion in a dry environment and more open to diffusion in a humid environment.
pro clima DB+ has proven its worth in millions of square metres installed since 1991, its diffusion resistance ranging from 3.5 to 0.8 m (16.5 to 4 MNs/g).

Moll bauökologische Produkte GmbH developed their pro clima INTELLO® high-performance vapour membrane in 2004. INTELLO® has the world‘s most effective humidity-variable diffusion resistance, ranging from 0.25 m to over 10 m (1.25 to over 50 MNs/g) to suit every type of climate (see figures 9– 11).

2.2.1 High Diffusion Resistance in Winter

The diffusion resistance of the pro clima INTELLO© vapour membrane has been designed so that the membrane can provide a s_d value of over 10 m (50 MNs/g) in winter conditions. As a result, the vapour membrane will allow almost no moisture to penetrate a structural system during winter, when humidity pressure on the system is at its highest. The same can also be said of extreme climatic conditions as encountered in alpine regions, where winters are cold and long. Effective protection against humidity is also provided for roofs with diffusion-tight underlay sheeting (e.g. bitumen sheeting), and roofs with flexible metal sheeting. In roofs with diffusion open sub roofs, the high s_d is an obvious advantage in case of hoarfrost and ice formation (= diffusion barrier) on diffusion-open insulation sheeting. (see figure 10)

2.2.2 Lower Diffusion Resistance in Summer

Diffusion resistance in summer can be reduced to an s_d of 0.25 m (1.25 MNs/g) permitting moisture that may be present in the roof system to evaporate rapidly towards the inside.
Depending on the magnitude of the vapour pressure difference, this corresponds to an evaporation rate of 5 to 12 g/m^2 of H_2O per hour corresponding to approx. 80 g/m^2 of H_2O per day or 560 g/m^2 of H_2O per week. (see figure 7)
This high evaporation capacity means that a building component framework will start drying out rapidly by as early as spring.

2.2.3 Well-Balanced Diffusion Profile

In times of improved levels of airtightness with associated higher atmospheric humidity in new buildings made of masonry, diffusion resistance to cater for increased relative atmospheric humidity becomes an important factor.

2.2.3.1 New Buildings: The 60/10 Rule

Due to the recently completed construction work and short time of occupation, the internal relative humidity in new buildings is high. The diffusion resistance of a vapour membrane should be designed in such a way that an s_d value of at least 2 m (10 MNs/g) is reached even at 60 % mean relative humidity in order to adequately protect the construction from moisture. At a relative humidity of 60 % INTELLO® has a s_d value of 4 m (20 MNs/g).

2.2.3.2 Construction Time: The 70/7,5 Rule

During the construction time, after plastering or installing a screed, the relative humidity in a building is very high. At a mean relative humidity of 70 %, the diffusion resistance of a vapour membrane should be above 1.5 m (7.5 MNs/g) in order to protect the construction against excessive entry of moisture from the building site and from mould growth. An effective protection against moisture is needed particularly where derived-timber boards are installed on the outside of a structure. At 70 % with a s_d value of 1.5 m (7,5 MNs/g) INTELLO exceeds this requirement by far. Generally, building moisture should quickly escape from the structure via open windows. Dehumidifiers can speed up this process during the winter.

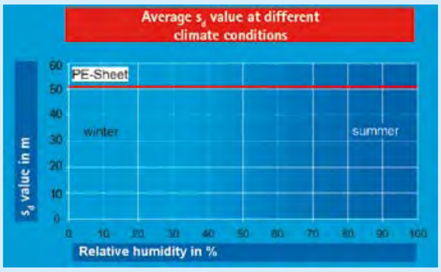
2.2.4 Maximum Safety

The 'intelligent' humidity-variable vapour membranes provide for highly reliable, safely protected thermal insulating systems, even where moisture entry into the structural system cannot be anticipated, e.g. because of adverse weather conditions, leaks, flank diffusion, or a high moisture content in timber or insulation materials. The pro clima humidity-variable vapour membranes act as a moisture transfer pump by actively extracting any unexpected moisture which may be present in a structural component. Pro clima DB+ and INTELLO provide high safety even in climates with high humidity.

Diffusion Graphs for Various Vapour Membranes

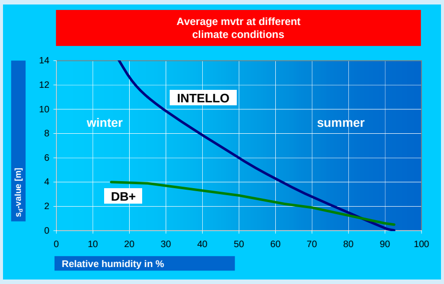
The more the diffusion resistance varies between winter and summer, the more safety and reliability is afforded by the vapour membrane.

9. Diffusion graph for a PE sheet. No humidity variability.



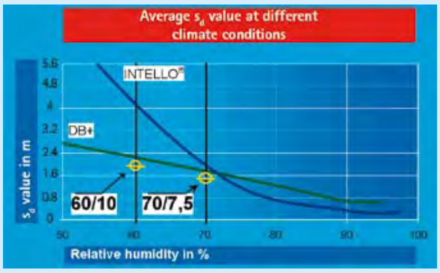
Constant s_d-value
PE sheet

10. Diffusion graph pro clima DB+ and INTELLO. Medium and high humidity variability.



Humidity-variable s_d-value
pro clima DB+ and INTELLO

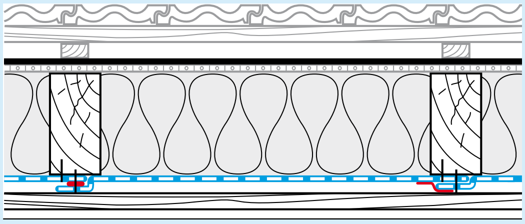
11. Diffusion graph INTELLO® High moisture variability



INTELLO and DB+ meet the 60/1 and 70/7.5 rule

Physical assessment of roof structure

12. Design of roof structure



- diffusion-tight on the outside (bitumen roof sheeting, s_d value = 300 m)
- 24 mm solid timber decking
- fibrous insulation
- vapour membranes having different s_d values
- latting
- gypsum building boards

Roof variants:

- steep-pitched with 40° pitch to north side, red clay roof tiles
- flat roof with 5 cm of gravel
- green roof with 5 cm of gravel (18/32) and 8 cm vegetable substrate with extensive grassing

3.1 Various Methods of Calculating Moisture Transports

Drying reserves are the consequence not only of diffusion processes, but also of sorption and capillarity processes within the building-component layers.

3.1.1 Calculation according to Glaser EN ISO 13788

EN ISO 13788 still relies heavily on Glaser's method, which calculates ensuing quantities of condensation in structural systems under the assumption of a monthly block climate:

3.1.2 Calculation of Coupled Heat and Moisture Transport under Natural Climatic Conditions

The Glaser method provides an approximation for the assessment of structural systems, but does not represent reality. On the one hand, the block climate data differs from the real climate, and, on the other hand, such important transport mechanisms as sorption and capillarity are not taken into account.
EN ISO 13788 therefore points out that this method is not suitable as means of verifying the freedom of green roof systems from structural damage, in which case heat and moisture transport has to be calculated by means of a non-transient simulation program.
Recognised software solutions in this area are Delphin by the Institut of Building Climatology in Dresden and WUFI by the Fraunhofer Institute of Building Physics in Holzkirchen.
These programs calculate the coupled transport of heat and moisture in multiple-layer building components under natural climatic conditions, jointly allowing for temperature and humidity, light absorption, wind, latent heat, sorption and capillarity.

The programs have been validated repeatedly, which is to say the result of their computations have been compared with those of field trials. Actual weather data over the period of 1 year is required here for hourly values.
Climatic data is available from throughout the world, viz. Europe, North America and Asia, including both temperate and extreme climatic regions.

To carry out a normal simulative calculation of the coupled transport of heat and moisture under natural climatic conditions, the building structure with its sequence of layers is entered into the program, and heat and moisture stream are analysed over a period of several years under boundary conditions closely conforming to reality.

The result then shows if moisture has accumulated in the structure, i.e. whether the overall moisture content of the structural system has risen over the period under observation, or if the component has remained dry.
However, it is not possible by this method to recognise the drying reserves of a structural system.

3.2 Calculating the Potential Freedom from Structural Damage for a Structural System

One further input is used in order to calculate how reliably and safely protected a structural system is against unanticipated entry of moisture, e.g. as a result of convection, flank diffusion, or heightened incorporated humidity:

The thermal insulation is moisturized at the beginning of the calculation, and the rate at which this moisture dries out is duly examined. **The quantity of moisture that dries out of the structural system in relation to the extra moisture added to it represents the safety potential from structural damage of the system before it will suffer structural damage.**
Using various vapour membranes, calculations are performed on several structural systems deemed difficult from the construction physics point of view: under adverse conditions (north side), in different climatic zones (lowlands and alpine), with various forms of roofs (steep-pitched, flat, green). Less sophisticated systems in terms of construction physics naturally offer even greater levels of safety potential.

3.2.1 Roof structures

Design of structure:
(see figure 12 on the left hand side)

Vapour barriers:

• PE sheet	s_d value/mvtr constant 50 m (25 MNs/g)
• Vapour Membrane	s_d value/mvtr constant 2.3 m (12MNs/g)
• pro clima DB+	s_d value/mvtr humidity-variable 2.3 m: 3.5-0.8 m (12: 17-4 MNs/g)
• pro clima INTELLO®	s_d value/mvtr humidity-variable 7.5 m: 10-0.25 m (38: 50-1.25 MNs/g)

Roof variants:

- steep-pitched with 40° pitch to north side, red clay roof tiles
- flat roof with 5 cm of gravel
- green roof with 5 cm of gravel (18/32) and 8 cm soil with extensive grassing

Locations:

- Holzkirchen, Germany, altitude above mean sea level = 680 m
- Davos, Switzerland, altitude above mean sea level = 1,560 m

Calculation

- using WUFI 3.3 pro [10]
- initial moisture in thermal insulation: 4,000 g/m^2

One important factor in determining protection against structural damage and mould growth is the back-diffusion capacity in summer and, associated therewith, the ability of the structural system to evaporate towards the inside. Back-diffusion can occur when the partial vapour pressure on the outside of the insulation is greater than on the inside, or to put it more simply, when the temperature at the outside of the insulation is higher than in the living area. The ruling temperature in this context is that recorded at the outside of the insulation, not that on the surface of the roof. This means it is essential to allow for the time it takes for the heat to penetrate the layers above the insulation. The heat penetration time is shorter for a steep-pitched roof than for a flat one with gravel layer, or even a green roof. Flat roofs without gravel, for instance, have greater safety reserves than north-facing steep-pitched roofs.

The temperature at the outside of the insulation is influenced by surrounding air temperature and by exposure to sunlight.

3.2.2 Climatic Data: Holzkirchen Location

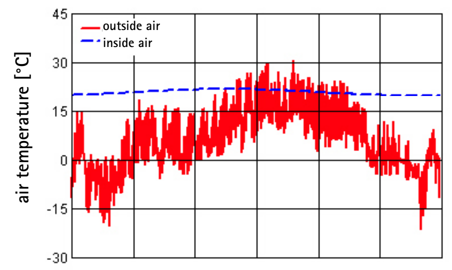
Holzkirchen lies between Munich and Salzburg at 680 m above sea level. The climate is characteristically harsh and cold. The following diagrams show the temperature curve over one year. The blue line indicates inside temperature, and the red bars represent outside temperature (see figures 13-16).

Taking solar and global radiation into account, roof-surface temperature is occasionally substantially higher than the air temperature. As a result, back-diffusion is feasible in Holzkirchen on many days of the year even in the north-facing direction, and even on sunny days in winter on the south-facing side.

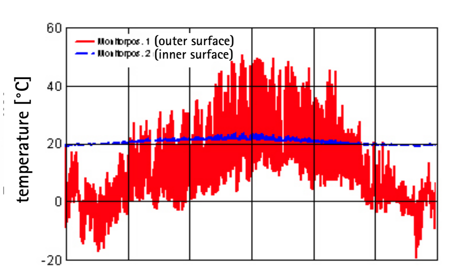
We based our own calculation on the least favourable situation, i.e. a 40° pitched roof facing north. The chosen calculation period was ten years.

Temperature graphs, Holzkirchen 680 m above mean sea level, Southern Bavaria, Germany Roof: red tiles or gravel

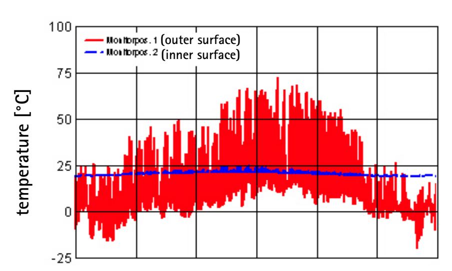
13. Air temperature



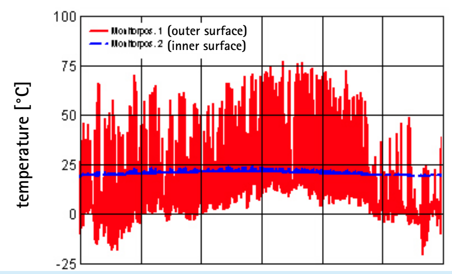
14. Roof surface temperature, north side, 40° roof pitch



15. Roof surface temperature, south, 40° roof pitch



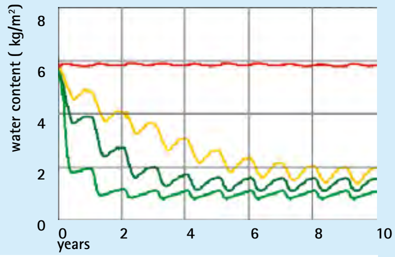
16. Roof surface temperature, flat roof



Calculating the potential freedom from structural damage at Holzkirchen, Roof

Assumed additional moisture at the start: 4,000 g/m^2
Moisture content of the structure in a dry state (= Moisture content of the timber sheathing at 15 %): 1,700 g/m^7

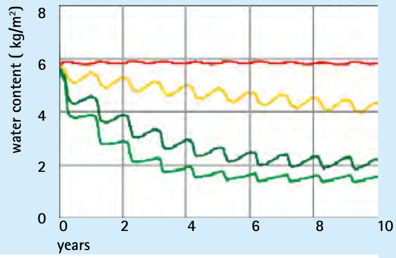
17. Course of drying under excess moisture, steep-pitched roof, north side, 40° roof pitch



Potential freedom from structural damage:

pro clima INTELLO® = 4000 g/m^2 per year
pro clima DB+ = 2100 g/m^2 per year
s_d-value 2,30 m constant = 500 g/m^2 per year
s_d-value 50 m constant = < 10 g/m^2 per year

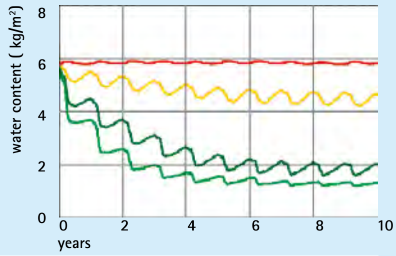
18. Course of drying under excess moisture, green roof with 13 cm soil/gravel



Potential freedom from structural damage:

pro clima INTELLO® = 2000 g/m^2 per year
pro clima DB+ = 1000 g/m^2 per year
s_d-value 2,30 m constant = to humid
s_d-value 50 m constant = < 10 g/m^2 per year

19. Course of drying under excess moisture, flat roof with 5 cm gravel



Potential freedom from structural damage:

pro clima INTELLO® = 2100 g/m^2 per year
pro clima DB+ = 1300 g/m^2 per year
s_d-value 2,30 m constant = to humid
s_d-value 50 m constant = < 10 g/m^2 per year

3.2.3 Potential Freedom from Structural Damage – Steep-Pitched Roof in Holzkirchen, North Side, 40° Roof Pitch (see figure 17)

The evaporation rate of the initial moisture, assumed to be increased, defines the structural system's potential freedom from structural damage in relation to unanticipated moisture (convection, flank diffusion, etc.).
It can be seen that the PE sheet does not allow the structural system to dry out. Moisture present in the system can no longer escape.
A vapour membrane having a constant s_d value of 2.30 m (12 MNs/g) does provide us with a structural system that functions well under the laws of construction physics, but the system's drying reserves are minimal.
The structural system equipped with pro clima DB+ evaporates considerably faster and possesses substantial safety reserves. The high-performance INTELLO® vapour membrane offers the greatest degree of safety potential of the structural system. Within one year, the system, according to the WUFI 3.3 pro [10] computation, can be moisturized with 4,000 g/m^2 of water p.a. without suffering structural damage.

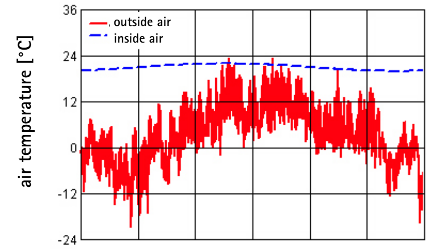
3.2.4 Potential Freedom from Structural Damage – Green Roof and Flat Roof

(see figures 18 and 19)

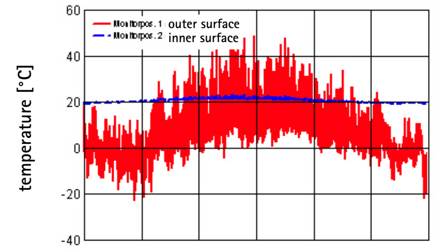
Both structural systems are not as safe as the steep-pitched roof, as heat takes longer to penetrate the thick layers of building components above the thermal insulation layer. Because of its thinner gravel layer, the flat roof offers greater safety than the green roof.
As with the steep-pitched roof, it is evident that evaporation cannot take place with the PE sheet, structural damage already occurring at quite a low level of unanticipated moisture stress. Too high an overall moisture content establishes itself in the structural system with a vapour membrane having a constant s_d value of 2.30 m (12 MNs/g). Structural damage would occur in this case also. The structural system with pro clima DB+ dries out faster and has high safety reserves. The high-performance INTELLO® vapour membrane offers the greatest safety potential for the structural system. Within one year, the system, according to the WUFI 3.3 pro [10] computation, can cope with, respectively, about 2,000 or 2,100 g/m^2 of water p.a. without suffering structural damage.

Temperature Curves – Davos 1,560 m above mean sea level Switzerland, red tiles/gravel

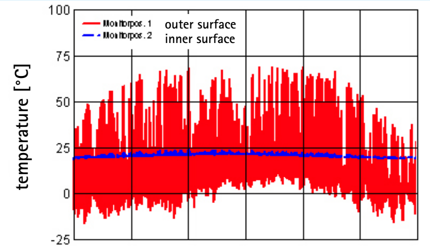
20. Air temperature



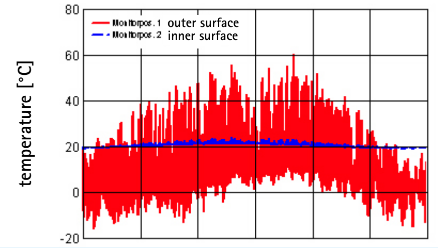
21. Roof surface temperature, north side, 40° roof pitch



22. Roof surface temperature, south, 40° roof pitch



23. Roof surface temperature, flat roof



3.2.5 Climatic Data – Davos Location

Davos is situated 1,560 m above sea level and therefore enjoys an alpine climate. The following diagrams show the temperature curve over a period of one year. The blue line indicates indoor temperature and the red bars represent outside temperature (see figures 20-23). Simply observing the air temperature in Davos, the outside temperature is higher than the inside temperature on only a very few days of the year.
Taking solar and global radiation into account, roof-surface temperature is higher than the air temperature.
On the north-facing roofs, however, temperatures are substantially lower than in Holzkirchen, back-diffusion being feasible only on a few days of the year. The south-facing roofs in Davos reached almost the same temperatures as in Holzkirchen.
Night-time temperatures during winter are specific to alpine regions, being substantially lower.
To minimise the effect of solar radiation, we once again based our calculation on the least favourable situation, i.e. a north-facing roof with a 40° pitch.

3.2.6 Potential Freedom from Structural Damage – Steep-Pitched Roof in Davos, North Side, 40° Roof Pitch

(see figure 24)
The extremely low temperature in winter gives rise to the high precipitation of condensation, so that, even where there is assumed to be no unanticipated moisture stress, a structural system becomes damp despite being equipped with PE sheet.
Saturation occurs very rapidly in the presence of a vapour membrane having a constant s_d value of 2.30 m (12 MNs/g).
Even pro clima DB+ is incapable of keeping the structural system dry.

The high-performance INTELLO® vapour membrane is the only membrane which provides the structural system with the perfect answer in terms of construction physics, while also providing it a higher safety potential. Within one year, according to the WUFI computation, the system can take as much as 800 g/m² extra of water without suffering structural damage.

3.2.7 Potential Freedom from Structural Damage – Green Roof and Flat Roof

(see figures 25 and 26)
Both structural systems are less safe than the steep-pitched roof, as it takes longer for heat to penetrate the thick building-component layers above the thermal insulation.
As in the structural-system calculation based on Holzkirchen's climatic data, the PE sheet will not allow the system to dry out, structural damage occurring even at a minimal level of unanticipated moisture stress.

Both structural systems saturate very rapidly when constructed with a vapour membrane having a constant s_d value of 2.30 m (12 MNs/g).
Equipped with pro clima DB+, the moisture in the flat-roof system is too high.
The high-performance INTELLO® vapour membrane does provide high safety potential for the flat roof with 5 cm of gravel, but for the grass roof, the outside temperature in Davos is not sufficient to permit back-evaporation.

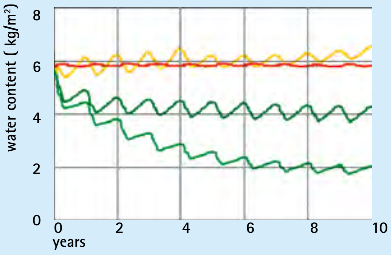
3.2.8 Conclusions in Respect of Roof Structures

pro clima DB+ and INTELLO® provides roof systems with the highest degree of safety in respect to freedom from structural damage, even in the presence of additional moisture as a result of unanticipated influencing factors.
INTELLO® and DB+ can also compensate for flank diffusion in a brickwork system as described by Ruhe [4], Klopfer [5], [6] and Künzel [7].
Over the past 10 years, pro clima DB+ has built up a track record of several million square meters of successful solutions free from structural damage.
Using INTELLO® in conjunction with externally, diffusion-tight steep pitched roofs and flat roofs with gravel in alpine regions show sufficient potential for freedom from structural damage.

Calculating the potential freedom from structural damage at Davos, Roof

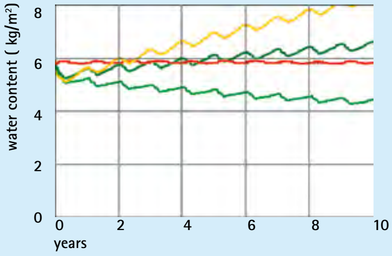
Please refer to test conditions at page 12 at Holzkirchen

24. Potential Freedom from Structural Damage – Steep-Pitched Roof in Davos, North Side, 40° Roof Pitch



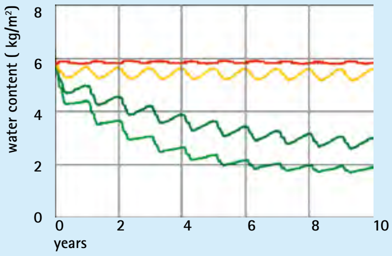
Potential freedom from structural damage:
pro clima INTELLO® = 1500 g/m² per year
pro clima DB+ = to humid
s_d-value 2,30 m constant = humidification!
s_d-value 50 m constant = < 10 g/m² per year

25. Potential Freedom from Structural Damage – Green Roof with 13 cm soil/gravel



Potential freedom from structural damage:
pro clima INTELLO® = 200 g/m² per year
pro clima DB+ = humidification!
s_d-value 2,30 m constant = humidification!
s_d-value 50 m constant = < 10 g/m² per year

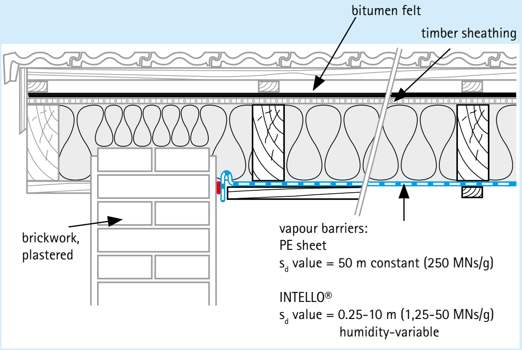
26. Potential Freedom from Structural Damage Flat Roof with 5 cm gravel



Potential freedom from structural damage:
pro clima INTELLO® = 1200 g/m² per year
pro clima DB+ = 500 g/m² per year
s_d-value 2,30 m constant = < 10 gm² per year
s_d-value 50 m constant = < 10 gm² per year

2-dimensional calculation of the heat and moisture transports using WUFI

27. Design of structural system: Integrating wall

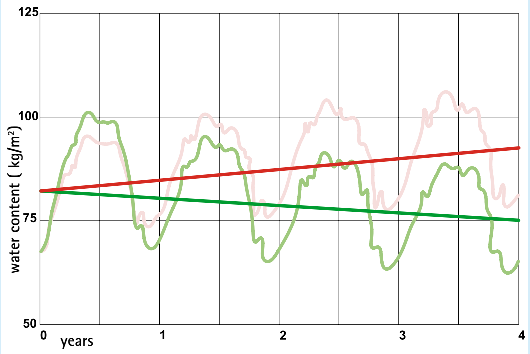


28. Increase in moisture when using a PE sheet

→ Saturation = structural damage

Reduction in moisture when using INTELLO®

→ EVAPORATION = freedom from structural damage



Increasing moisture content in the construction with PE sheet s_d value = 50 m constant (250 MNs/g)

Decreasing moisture content in the construction with INTELLO® s_d value = 0.25 – 10 m humidity-variable (1,25-50 MNs/g)

3.2.9 Flank Diffusion

To establish the impact of moisture entry via component flanks, the junctions between integrated outer walls and thermal insulation components need to be examined. On the outside, the structure comprises of diffusion-tight bitumen felts in the sub-roof system.
(see illustration 27)

Masonry usually has a considerably lower diffusion resistance than the vapour barrier and airtight seals of the adjoining timber structures. This facilitates the diffusion of moisture through the flanks into the thermal insulating components.

A new building will serve as an example here. In a new building, masonry and plaster have an average moisture content of 30 kg/m³. The fibrous insulating material has been dry-fitted, the relative moisture content of the timber in the roof is approximately 15 %.

One building is fitted with a diffusion-inhibiting PE sheet (s_d-value 50 m = 50 MNs/g). serving as a vapour barrier and airtight seal. The second building is fitted with the humidity-variable pro clima INTELLO® (s_d-value 0.25 to 10 m = 1.25-50 MNs/g).

3.2.10 Results of Two-Dimensional Simulative Calculation of Heat and Moisture Transports

The results shown in illustration 28 occur when a structural system is calculated using the 2-dimensional calculation method for heat and moisture transfer as implemented in WUFI 2D see 2.1 .

Following a seasonal increase in the moisture content, both structural systems virtually reach the same level of moisture. In the case of the PE sheet acting as a vapour barrier and an airtight seal, a distinct increase in the total water content can be observed for each year over a period of 4 years (see figure 28 red line). This system shows an accumulation of moisture in the building materials used as the PE sheet prevents subsequent drying towards the interior.

The result is mould growth on the timber and the onset of decay.

In the system using the high-performance INTELLO® vapour membrane, the moisture can escape towards the inside. The structural component is protected against accumulation of moisture, as moisture is swiftly released towards the inside (see figure 28 green line). Thus the moisture content decreases steadily over the 4-year period. This structural system shows a high potential freedom from structural damage.

3.2.11 Wall Systems

As walls are vertical they absorb less light than roof structures, so there is less potential for back-diffusion.

Usually, unlike roofs, walls are not diffusion-tight on the outside. Bitumen felts are not used. Walls do not need to meet such high demands in respect to water-tightness as, say, a flat roof or a green roof.

Temperatures of outside walls depend mainly on the colour of the façade. The solar radiation produces lower temperatures on light-coloured facades than on darker ones. The following temperature profiles on the outside wall are obtained from a normal, light-coloured plaster façade. (see figures 29-32)

For wall systems too, the high-performance INTELLO® vapour membrane provides a substantial potential for freedom from structural damage. Using WUFI 3.3 pro [10] to calculate a north-facing outer wall in the Holzkirchen climate, with a bitumen felt (s_d value = 300 m (mvtr=1,500 MNs/g)) on the outside having a normal light-coloured outer façade, the structural system still provides substantial safety potential when fitted with the INTELLO® vapour membrane.

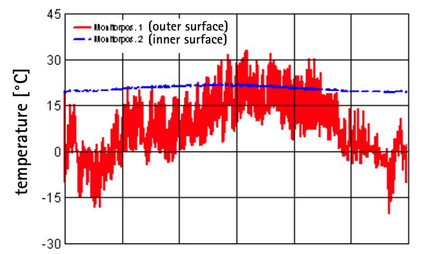
Even in colder climates, at alpine locations like Davos, wall systems with building-component layers outside the insulation are ‚safe' with the INTELLO® high-performance vapour membrane as long as these layers have an s_d value of less than 10 m (50 MNs/g).

In the case of DB+, the building components outside the insulation may have a max. s_d-value of 6 m (30 MNs/g) for the Holzkirchen climate and 0.10 m (0.5 MNs/g) for Davos.

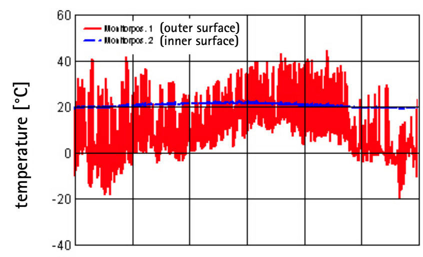
Temperature curves Holzkirchen and Davos Wall, light-coloured plaster façade

Wall temperatures Holzkirchen location

29. Wall temperature, north side

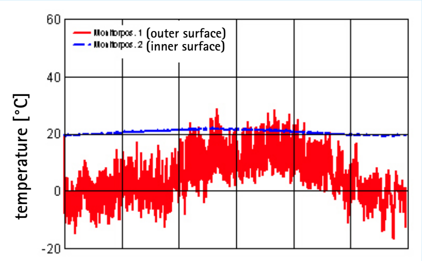


30. Wall temperature, south side

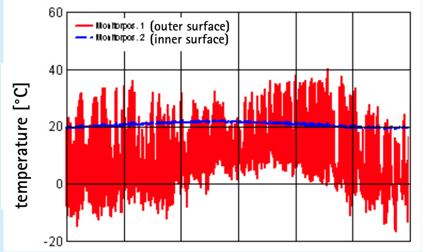


Wall temperatures Davos location

31. Wall temperature, north side

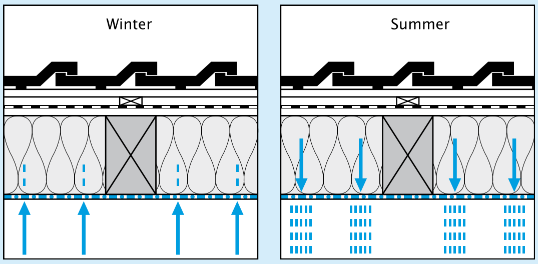


32. Wall temperature, south side



Preconditions for the effectiveness of humidity-variable vapour membranes

Only building components which are open to diffusion may be used on the inside in order to facilitate the evaporation of moisture by way of back-diffusion towards the interior.



4.1 Structural Systems

These construction-physics investigations based on real climatic data, demonstrate the extremely high potential for freedom from structural damage provided when using the high-performance pro clima INTELLO® vapour membrane (which possesses the world's most effective variability of diffusion resistance in any climatic zone) and the pro clima DB+ humidity-variable vapour membrane which has proven its worth over a period of more than ten years by now.

pro clima DB+ and INTELLO® provide a high level of safety for structural systems even when under high moisture stress.

This requires an unshaded situation, i.e. no trees or neighbouring buildings providing shade.

4.2 Inside compound unit layers

High safety reserves are dependent on unimpeded evaporation to the interior. Building compound layers inside the humidity-variable vapour membrane that have a diffusion-inhibiting effect (timber materials like OSB boards or laminated boards) reduce the quantity of moisture back-evaporated towards the inside and thus minimise the potential freedom from structural damage. Materials having an open structure are more advantageous, for instance matchboard sheathing, wood wool slabs with plaster and gypsum boards.

4.3 Permanently Humid Spaces

Humidity-variable vapour membranes cannot be used in permanently humid climatic conditions, for instance swimming pools, garden centres or large-scale catering establishments.

4.4 Humid/Damp Rooms in Residential Buildings

Wet or humid rooms in residential buildings are no more than temporarily subjected to increased humidity. Temporary humidity stress of this kind does not interfere with the function of and the safety provided by pro clima DB+ or INTELLO®.

4.5 Construction Moisture on the Site

The vapour membrane must be installed as soon as the thermal insulation has been put in place, so as to avoid the development of condensation in the insulation.

Additionally, relative atmospheric humidity on the building site should not exceed 75% in winter. Care should be taken after plastering and screed work to ensure adequate ventilation. A commercial drying unit should be installed if necessary (i.e. dehumidifier). The diffusion profile of the humidity-variable pro clima vapour membrane ensures that the diffusion resistance of the membranes is over 1 m (5 MNs/g) at a relative atmospheric humidity of 75%. The moisture stress on the structure during the construction phase due to unwanted entry of moisture can thus be minimised. However, increased atmospheric humidity during construction should be avoided as the potential freedom from structural damage would be reduced by the moisture stress.

4.6 Sub-Roof System

Diffusion-open materials are the best choice for the sub-roof system (e.g. wood fibre soft boards, SOLITEX-roofing felts with non-porous, permeable membrane), provide excellent conditions for evaporating towards the outside.

Structural systems having diffusion-tight external components, for instance bitumen felts, flat roofs, green roofs and roofs with flexible metal sheeting, reduce the safety of the structure from the construction-physics point of view. Solid wood sheathing provides greater safety than derived-timber-product boards (e.g. OSB), as wood has a humidity-variable diffusion resistance and is conductive by capillary action. INTELLO®'s high degree of humidity-variability provides a very high safety potential, similar to derived-timber-products as well. Panels or boards of this kind should be avoided on diffusion-tight roof support systems when using pro clima DB+.

4.7 Steep-Pitched Roof Systems

Drying reserves are so high when pro clima DB+ or INTELLO® vapour membranes are used in conjunction with externally diffusion-open structural systems that there is no limit to the altitude of the site, structural systems still being safe at heights of over 3,000 m. The limitations in figure 33 should be noted with regard to externally diffusion-tight steep-pitched roof systems (e.g. bitumen felt underlays).

4.8 Flat Roof and Green Roof Systems

Flat roofs always have a diffusion-tight external skin on the outside, which serves as water seal and protects against roots. Generally these roofs cannot be ventilated effectively, because there is no up-draught of air due to the absence of a roof pitch.

The insulating layer will be heated a lot less from the outside by solar radiation the more gravel or substrate (green roof) there is on a flat roof. Back-diffusion towards the interior is reduced as a result, and safety reserves are lower. In this case, the humidity-variable diffusion resistance of the high-performance INTELLO® vapour membrane provides the structural system with a high degree of safety against structural damage, even under unanticipated humidity stress. Our simulative calculations based on real climatic data indicated the limitations to usage on flat roofs (see figure 34).

Flat roofs and green roofs are among the most demanding and critical thermal insulation constructions in terms of building physics. pro clima INTELLO® offers the safest solution for these structures due to the extremely high humidity variability of its diffusion resistance. Moisture which may have entered or which is present in the structure can evaporate to a great extent without leading to harmful re-humidification. For the highest degree of safety, flat roofs and green roofs should be specified with the INTELLO® vapour membrane.

4.9 Roof Systems in Alpine Regions

Externally diffusion-tight steep-pitched roofs can be constructed safely with INTELLO® up to an altitude of 1,600 m showing a high potential for freedom from structural damage. Externally diffusion-tight steep-pitched roofs constructed with INTELLO® have a high potential for freedom from structural damage even in arctic climates such as Alaska (e.g. in Anchorage) and Russia (e.g. Yakutsk), In higher regions such as 1.600 m in Europe and external diffusion tight sub-roof ventilation should be considered. Ventilation systems must however fulfil special functional requirements due to the long period of snow on the roof.

If required, please contact the pro clima hotline for advice on structural details.

4.10 Walls

As wall systems are less exposed to solar radiation, they have less back-diffusion potential and therefore they have a lower safety reserve. See figure 35 for wall diffusion-resistances outside the insulation.

Areas of application for INTELLO® and DB+

33. Steep-Pitched Roof Systems

Structural Systems	INTELLO®	DB+
for externally diffusion-tight structural systems without ventilation, (no shade, no barrier layers inside)	up to 1,600 m above mean sea level	up to 1,000 m above mean sea level; no derived-timber-product boarding
for structural systems sub-roof open to diffusion	no altitude limit	no altitude limit

34. Flat Roof and Green Roof Systems

Structural Systems	INTELLO®	DB+
Flat roof with max. 5 cm gravel layer, no ventilation (no shade, no barrier layers inside)	up to 1,600 m above mean sea level	up to 800 m above mean sea level; no derived-timber-product boarding
Green roof with max. 15 cm gravel and substrate, no ventilation (no shade, no barrier layers inside)	up to 1,000 m above mean sea level	up to 800 m above mean sea level; no derived-timber-product boarding

35. Walls

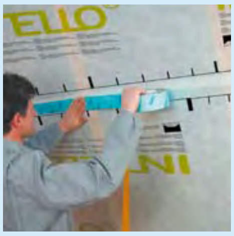
Structural Systems	INTELLO®	DB+
External component layers, walls up to altitude of 700 m (no barrier layers inside)	unlimited diffusion resistance	diffusion resistance max. 6 m
External component layers, walls up to altitude of 1,600 m (no barrier layers inside)	diffusion resistance max. 10 m	diffusion resistance max. 0.10 m

5. Installation INTELLO® and DB+

Installation in five easy steps

1. Installation / Fixing

2. Bonding



3. Joining to gables

4. Joining to windows

5. Joining at intersection

5.1 For Board-Type and Mat-Type Insulating Materials

Install INTELLO® with foil side (lettering) facing the room.

INTELLO® will still work function in construction-physics terms if it has been installed with the fabric on the room side. Press down the adhesive tapes firmly. Bonding on the foil side is preferable.
pro clima DB+ is symmetrically designed, so the side of the vapour membrane that faces towards the interior may be chosen at will.

5.2 Direction of Installation

pro clima INTELLO® and DB+ felts may be installed parallel or horizontal to the supporting structure. The overlapping of the sheets must be arranged on the structural timbers when installing in parallel. The maximum spacing of the structural-system timbers should be no more than 100 cm when installing horizontally.

5.3 Recommended pro clima System Components for Bonding

Any of pro clima's adhesive tapes are suitable for bonding the sheet overlaps. Particularly recommended are pro clima RAPID CELL quick application adhesive tapes and the UNI TAPE universal adhesive tape for pro clima DB+ and INTELLO®.
TESCON PROFIL adhesive tape with a high puncture resistance and a double-divided release film is the most suitable type for junctions with windows or doors and corner bonding.

ORCON F flashing/joining adhesive (for INTELLO®) and ECO COLL (for DB+) provides a reliable junction with adjacent compound units (plastered gable walls, for instance). CONTEGA PV flashing/joining tape with integrated plaster reinforcement ensures a well-defined connection to unplastered masonry.

Please refer to our ‚pro clima System Interior Sealing' brochure for further information.

5.4 Blown-In Thermal Insulating Materials

pro clima DB+ may be used as a confining layer for all kinds of blown-in thermal insulating material. A transverse batten should be placed on the inside at a spacing of at most 65 cm to take the weight of the insulating material. See pro clima system brochure for further details on laying.

Because it stretches very readily, the high-performance INTELLO® vapour membrane is not suitable as a means of confining blown-in thermal material on the inside. This purpose is best served by INTELLO® PLUS reinforced with robust PP fabric offering the same potential for freedom from structural damage.
Please see ‚pro clima System Interior Sealing' for further details.

5.5 Foam Insulating Materials

Variable diffusion-resistance is of little benefit in connection with foam-type insulating materials, because back-diffusion is substantially inhibited. Accordingly, foam insulating materials should be avoided in structural systems as they pose a challenge in respect of construction physics, for instance systems that are diffusion-tight on the outside.

5.6 Dimensional Stability

The high-performance INTELLO® vapour membrane will not shrink and it may be installed taut. INTELLO® is highly capable of stretching without tearing.

pro clima DB+ shrinks slightly after wetting and subsequent drying, so the sheet should not be stretched taut.
An expansion loop must be arranged at junctions with adjoining compound units so as to take up component movements.

5.7 Mechanical Strength

INTELLO® and DB+ are highly resistant to the removal of nails, so the sheets are well protected at their bonding points against splitting and propagated tearing.

5.8 Translucent Structure

The high-performance INTELLO® vapour membrane is translucent, meaning that materials behind the sheet can be identified through it. INTELLO® is not fully transparent, so the edges of the sheets are readily visible, an advantage when attaching to adjacent compound units like ridge purlins, middle purlins, roof windows and chimneys,
and when bonding the sheet overlaps.

5.9 Recycling and Ecological Considerations

The high-performance INTELLO® vapour membrane and INTELLO®Plus is made from 100% polyolefin – the special membrane is made from a polyethylene copolymer and the fabric is polypropylene – so it is easily recycled.

pro clima DB+ comprises of 50% recyclable cellulose and can only be recycled thermally on account of its glass-fibre inlay.

6. Summary

Structural systems using DB+ and INTELLO® have extremely high safety reserves, thus preventing structural damage and mould. Even where moisture stress is unanticipated, or where it is unavoidable in normal building practice, the high drying reserves of these humidity-variable safety vapour membranes provide structural systems with a very high potential freedom from a structural damage.

The high-performance INTELLO® vapour membrane has the world's most effective humidity-variable diffusion resistance in any climatic zone, offering thermal insulation systems the utmost in safe protection – whether the structural system is open to diffusion on the outside, or presents a more challenging example of construction physics like a flat roof, green roof, roof with diffusion-tight underlay, or flexible metal sheet roof.

INTELLO® performs effectively under extreme climatic conditions too, like those encountered in alpine regions for example. The proven pro clima DB+ provides a high degree of safety for roof systems up to medium altitudes (e.g. Holzkirchen location).
Conforming to DIN Standard 68 800-2, chemical wood preservatives need not be used where humidity-variable vapour membranes are installed.
pro clima offers a six-year system warranty to provide even greater safety and protection.
Once again, with the vapour membranes and airbarrier INTELLO®and DB+, the pro clima safety rule is once more put into practice,
„The greater a structural system's reserves for evaporating, the greater the unexpected moisture stress it can absorb and still remain free from structural damage".

pro clima's „Inside Sealing" brochure contains further information on working with and installing this product. Contact pro clima's technical ‚hot line' on

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email: technik@proclima.de

Unique safety for
young and old
all over the world

INTELLO® – intelligent and
ecological mould protection

INTELLO® vapour membrane and airbarrier

INTELLO®

The intelligent membrane for your home

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