MOISTURE DAMAGES

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Overview

Introduction

- Damages due to Moisture
- Current state of damage assessment

Surface effects

- Mould
- Algae

Moisture inside building elements

- Introduction
- Ice forming
- Insect infestation
- Mechanical damages

Introduction

Introduction

Possible moisture damages:

- Destruction of moisture-sensitive materials (e.g. rotting, degradation)
- Biological damages due to mould, fungi, insects
- Corrosion of metals
- Penetration of frost boundary into the condensation zone (Freeze/Thaw-cycle, crystallation pressure)
- High vapour pressure due to high temperatures in moist areas
- Shrinkage and swelling (cracks)
- Salt transport with moisture transport (efflorescence, spalling).

Moisture assessment

Current state of moisture assessment in Germany

Standard compliant assessment for different constructions according DIN 4108-2, DIN 4108-3 und DIN EN ISO 13788:

$$\underbrace{\hspace{20em}}_{}$$

Avoidance of…

- Moisture damages at surface (Condensation, Mould)
- Interstitial condensation
- (Avoidance/Reduction of driving rain penetration)

Moisture assessment

Standard compliant assessment for different constructions according DIN 4108-2, DIN 4108-3 und DIN EN ISO 13788:

Methods partially old, with many simplifications and restrictions.
New numerical methods only mentioned.

Which climatical influences, damage potentials, boundary conditions (e.g. climate, initial conditions) or physical processes are considered?

Are the results meaningful for the damage or the calculation methods of the current procedures leads to excessively critical or wrong declarations?

Moisture assessment

Properties and restrictions of calculation methods

DIN 4108-2, DIN 4108-3 and DIN EN ISO 13788:

- All methods: steady state
- Thermal methods: 1D - (Minimum heat protection R), 2D or 3D (f_{Rsi}-factor)
- Hygrothermal methods („*Glaser*“): only heat and vapor transport

More analytical methods (COND) :

- Steady state, one-dimensional, heat, vapor and liquid water transport as well as moisture storage

Numerical methods (Delphin, Wufi):

- Arbitrary climate conditions (e.g. rain) and initial conditions
- one- and two-dimensional (in future also 3D)
- heat, vapor and liquid water transport and more physical phenomena (e.g. air flow, pollutant)
- Detailed information from every position in the construction

Moisture assessment

Moisture damage on the surface (reduction of heating energy losses):

Minimum energy performance
(External wall, DIN 4108-2)

$$R_{min} = 1{,}2\, m^2 \cdot K/W \leq R = \sum_{i=1}^{n} \frac{\lambda_i}{s_i}$$

Microclimate on the inner surface
(DIN 4108-2, DIN EN ISO 13788)

$$f_{Rsi} = \frac{\theta_{si} - \theta_e}{\theta_i - \theta_e} \geq 0{,}7$$

Moisture damage in the structure:

Evaporation of condensation water
(DIN 4108-3, DIN EN ISO 13788)

$$m_{W,T} \leq m_{W,V}$$

Limiting the amount of condensation water*
(DIN 4108-3, DIN 68800-2)

$$m_{W,T} \leq ...kg/m^2$$

* Limit depends on the type and capillarity of the material

Moisture assessment

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Minimum energy performance / heating energy losses
(Exterior walls, DIN 4108-2)

$$R_{min} = 1{,}2\,m^2 \cdot K/W \;\leq\; R = \sum_{i=1}^{n} \frac{\lambda_i}{s_i}$$

Steady-state

λ - Thermal conductivity
s - Thickness of layer

$$R_{min} = 1{,}2\,m^2 \cdot K/W \;\leq\; R_{trans} = \frac{\overline{q_{si,HP}}}{\overline{\theta_{i,HP}} - \overline{\theta_{e,HP}}}$$

Non-steady state

trans – transient (non-steady state)
HP - Heating period
q - Heat flux
si - Internal temperature
q - Temperature

For simulation: definition of the outdoor climate

Definition of the indoor climate,
(possibly evolved from the outside climate < EN 15026)

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Moisture assessment

Minimum energy performance / heating energy losses
(Exterior walls, DIN 4108-2)

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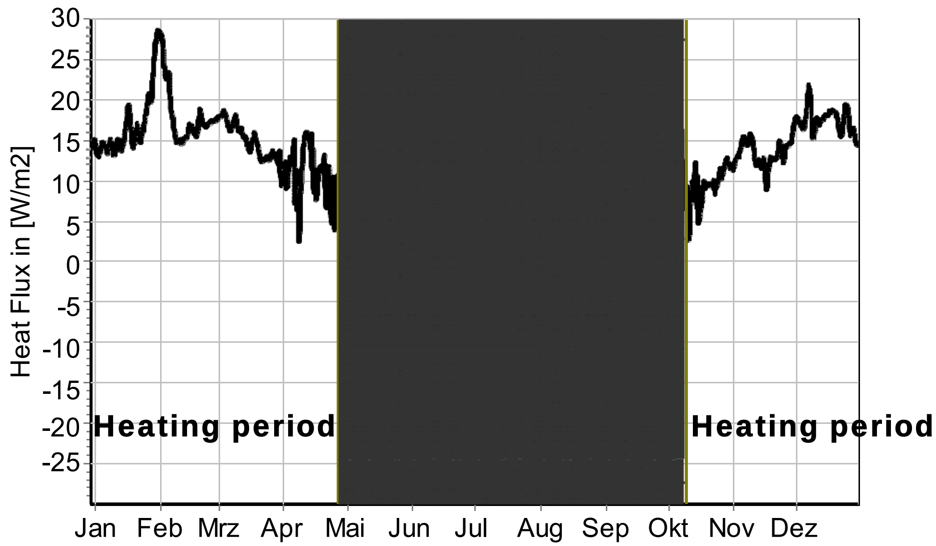
trans - Transient
HP - Heating period
q - Heat flux
si - Indoor temperature
q - Temperature



Moisture assessment

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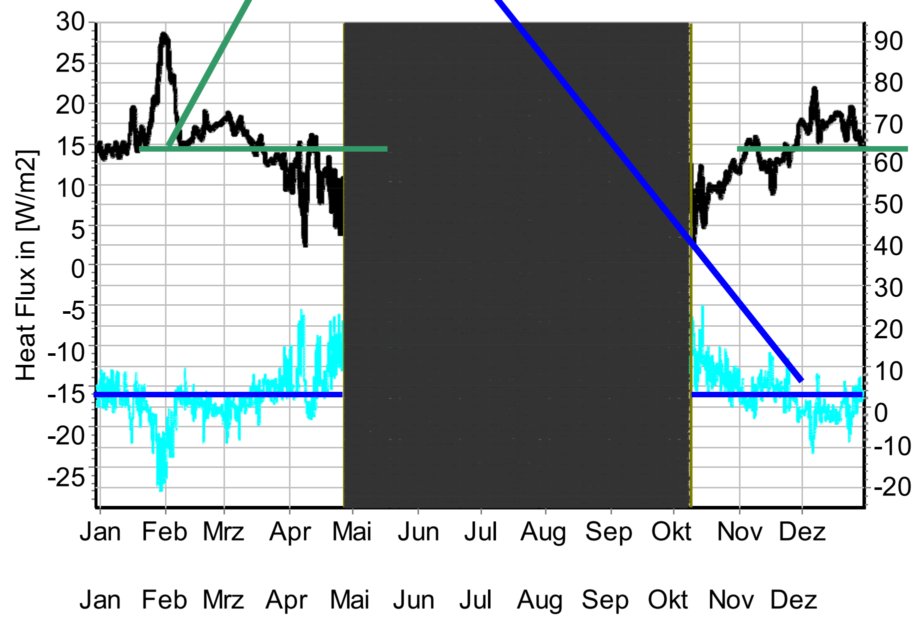

Surface effects

Relative humidity at surface

Relative humidity at construction surface – steady state

Surface temperature

$$q = \frac{\theta_i - \theta_e}{R_{ges.}} = \frac{\theta_i - \theta_{oi}}{\frac{1}{\alpha_i}} \Rightarrow \theta_{oi} = \theta_i - \frac{\theta_i - \theta_e}{R_{ges.} \cdot \alpha_i}$$

Surface vapor pressure

If $(r_{v,ges} \cdot \beta_i) >> 1$

$$g_v = \frac{p_{vi} - p_{ve}}{r_{v,ges.}} = \frac{p_{vi} - p_{voi}}{\frac{1}{\beta_i}} \Rightarrow p_{voi} = p_{vi} - \frac{p_{vi} - p_{ve}}{r_{v,ges.} \cdot \beta_i}$$

$$p_{voi} \approx p_{vi}$$

Surface relative humidity

$$\boxed{\varphi_{oi} = \frac{p_{voi}}{p_s(\theta_{oi})} = \varphi_i \frac{p_s(\theta_i)}{p_s(\theta_{oi})}}$$

Moisture assessment - Mould

Micro climate at inner surface

Moisture assessment - Mould

Robert-Sterl-Haus, Naundorf / Pirna

Moisture assessment - Mould

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Health hazards due to mould:

- Allergy
  - Proof is complex (prick test)
  - Tests shows that 5% of the german population has antibodies against mould (contact)
- Toxic effects
  - Some metabolites of mould can be toxic (Myco toxine, Glucans) or carcinogenic (Ochratoxin, Aflatoxine)
  - Plays normally no role for indoor air pollution (more in case of food and work places with high loads)
- Infections
  - Is possible in case of immunodeficient persons
  - Plays normally no role for indoor air pollution (maybe for hospitals)
- Odour nuisance
  - Negative effect on quality of life
  - Sometimes used as proof for mould growth.

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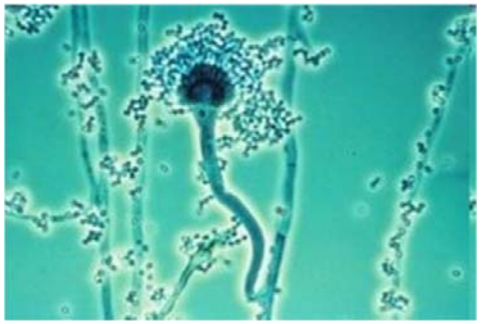
Moisture assessment - Mould

Especially proplematic kinds of mould:

- Increase of risk for allergies with high spore formation (Penicillium marneffei, Aspergillus fumigatus)
- Infectios must likely from Aspergillus fumigatus, Aspergillus flavus, Cladophialophora bantiana
- Stachybotrys chartarum can emit a toxin (seldom and very demanding)



Aspergillus fumigatus

Stachybotrys chartarum

Mould and bacteria

- It can be assumed that a greater growth of bacteria exists if the conditions are favourable for mould growth
- Studies have shown that, especially for high relative humidities, bacteria can growth also without visible mould growth
- Health risks are possible – up to now not studies about this topic exist.

Moisture assessment - Mould

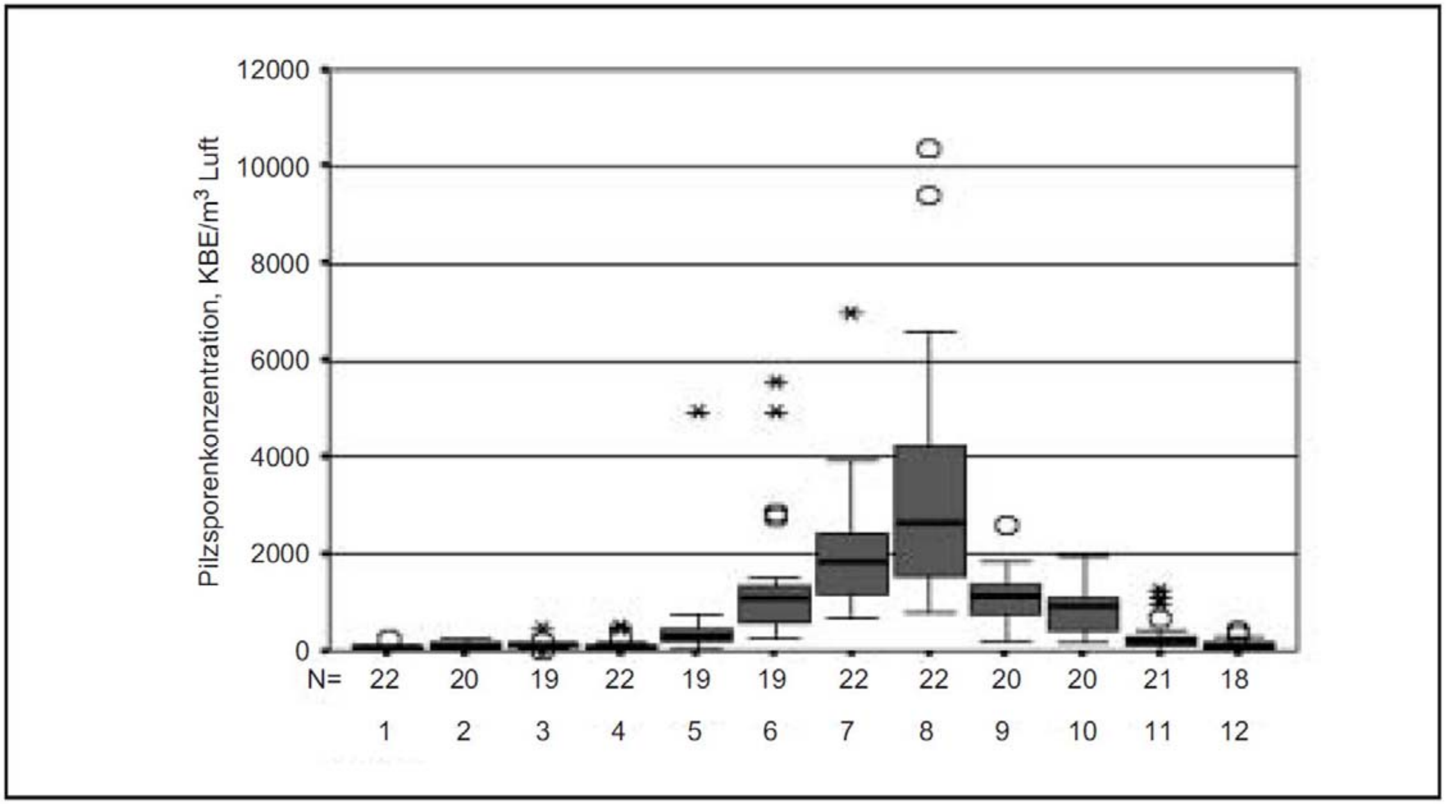
Micro climate at the inner surface

Mould growth depends on the following factors:

- Combination of temperature and relative humuidity
  - Germination and growth happens only for specific limit values
  - Isoplethes are lines of same growth in a $\varphi(\theta)$-diagram (time dependend)
- Nutrient content
  - Isoplethen differs according nutrient content
  - Mould cannot growth without nutrients
- pH-value
  - Optimal for mould growth around 5 – 7
  - Tolerated from 2 to 11
  - Especially alkaline surfaces can supress mould growth

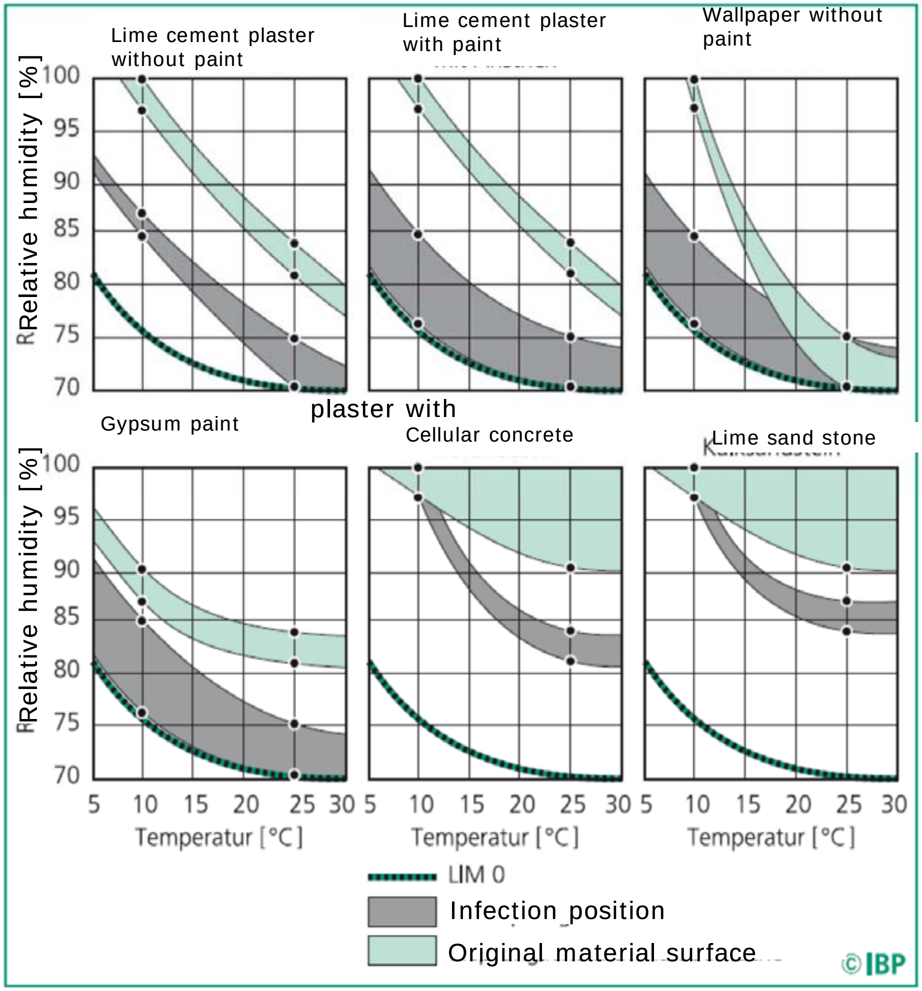
Moisture assessment - Mould

Spore concentration in outer air over a year



Quelle: Koch, A., K.J., Heilemann, J., Heinrich, H.E., Wichmann; W., Bischof (2000): Indoor viable mold spores – a comparison between two cities, Erfurt (Eastern Germany) and Hamburg (Western Germany). Allergy 55: 176-180

Moisture assessment - Mould



Isoplethes for different types of materials and surfaces.

Differences between infection postion and normal material surface.

Source: IBP Mitteilung 457, 32 (2005)

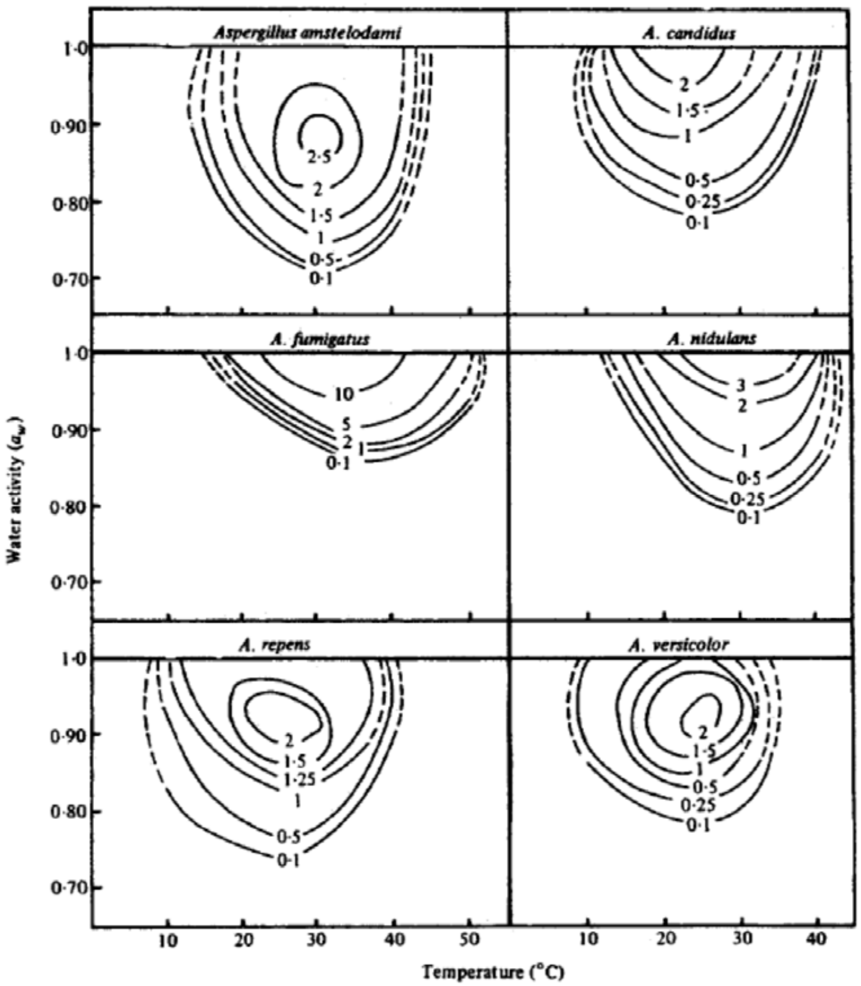
Moisture assessment - Mould

Minimum, optimum and maximum growth requirements of different mould species for temperature, relative humidity and pH according germination and mycelial growth for different risk classes.

Species	Risk class	Growth requirements												
		Temperature [°C]						Rel. Humidity {%]				pH [-]		
		Germination			Mycelial growth			Germination		Mycelial growth				
		min	opt	max	min	opt	max	min	opt	min	opt	min	opt	max
Asp. Flavus	A	10	30	45	6	40	45	80	100	78	98	2.5	7.5	>10
Asp. Fumigatus	A	10	40	50	10	43	57	80	97	82	97	3	6.5	8
Asp. Nidulans	A	10	37	50	6	40	48	75	95	78	97			
Asp. Niger	A	10	35	50	6	37	47	77	98	76	98	1.5		9.8
Asp. Penicillioides	A				5	25	37							
Asp. Versicolor	A	8	30	42	4	30	40	74	91	75	95			
Stachybotris atra	A	5	25	40	2	23	37	85	97	89	98			
Risk class A	A	5	33	50	2	40	57	74	96	75	97	2	7	10

Source: Dissertation Dipl.-Ing. Klaus Sedlbauer, Universität Stuttgart

Moisture assessment - Mould



Isoplethes for different species of Aspergillus on optimal nutrients.

Quelle: Nielsen, K. F.; Nielsen, P. A.; Holm, G.:

Growth of moulds on building materials under different humidities.

Proceedings of Healthy Buildings (2000), Vol.

3, S. 283 - 288

Moisture assessment - Mould

Micro climate at inner suface:

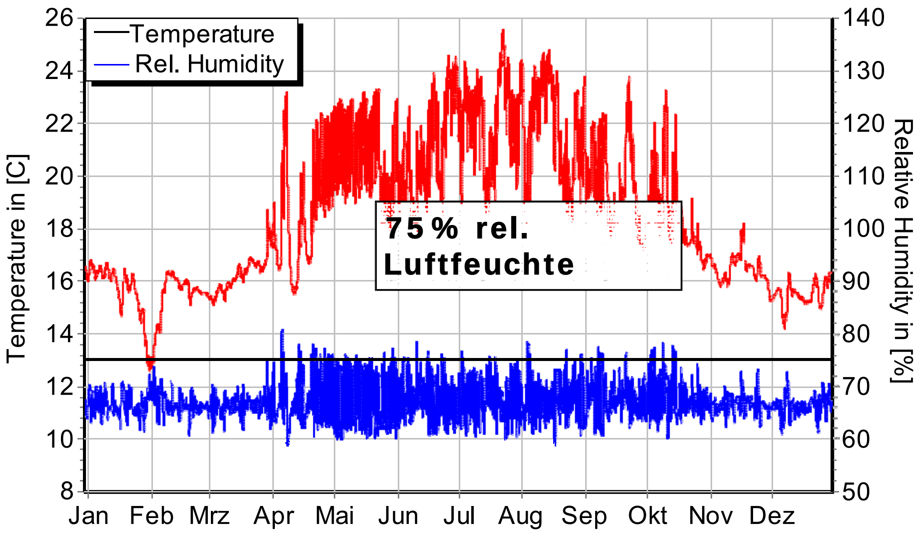
Temperature factor f_{Rsi} (according DIN 4108-3 S. 17f)

$$f_{Rsi} = \frac{\theta_{si} - \theta_e}{\theta_i - \theta_e} \geq 0{,}7$$

Corresponds for θ_i=20°C and θ_e=-5°C → $\theta_{si} > 12{,}5°C$

This corresponds to φ_i=50% → φ_{si}≈80%

Mould growth:
Under very favourable conditions from 75% rel. humidity



Moisture assessment - Mould

Micro climate at inner suface:

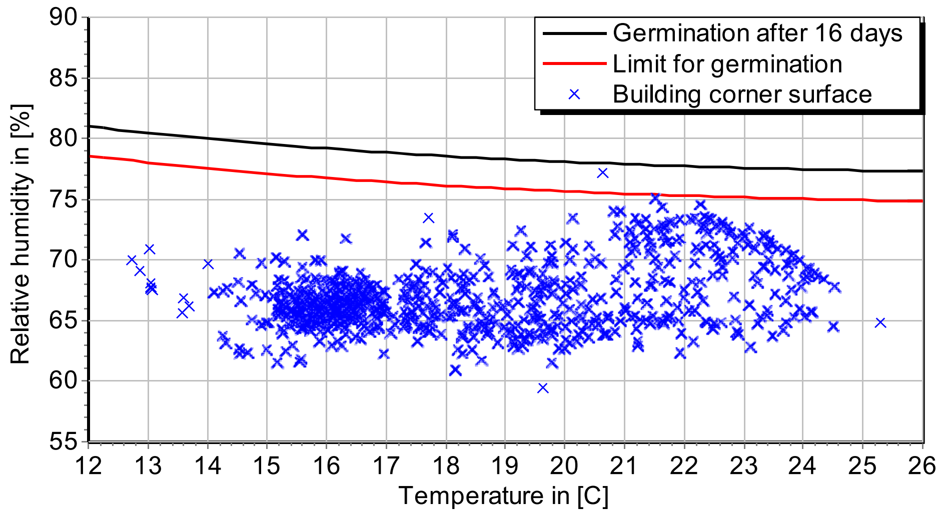
Mould growth prediction

→ Isopleth-model (Sedlbauer, WTA-Merkblatt 6-3-05)

→ Viitanen et al. (dynamic model)

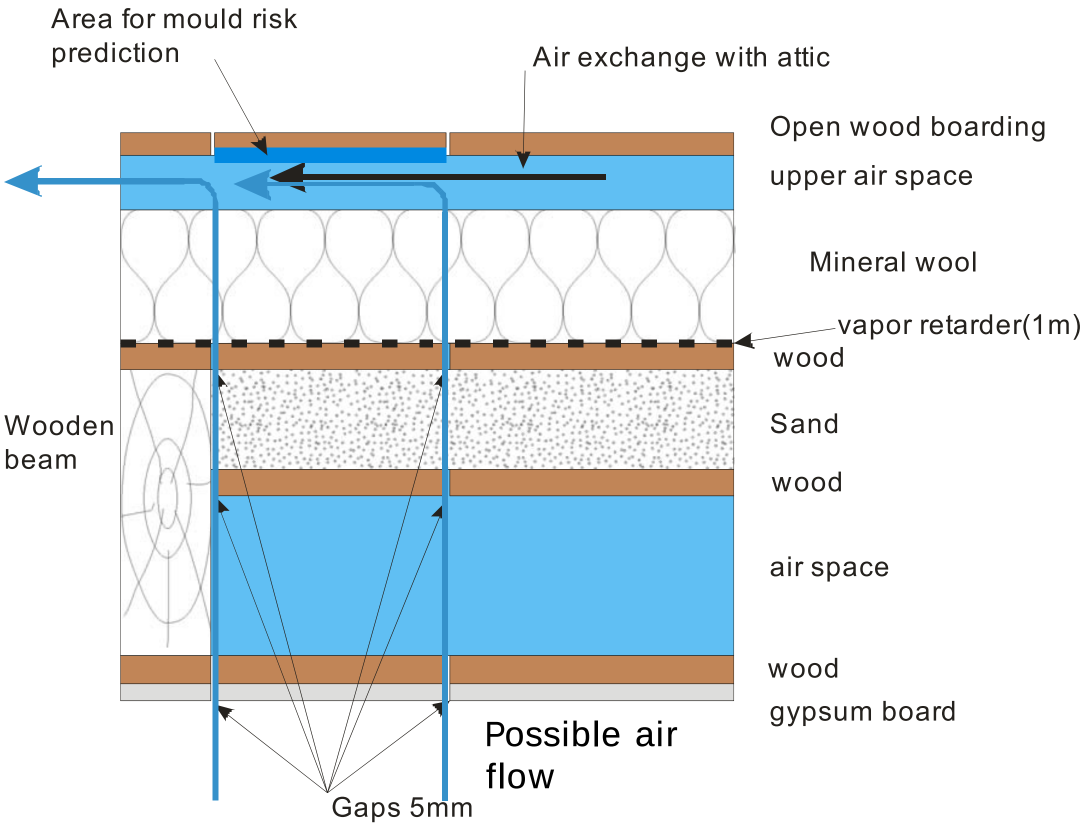
(e.g. 1997. Modelling the time factor in the development
of mould fungi in wood—The effect of critical humidity and temperature conditions.
Holzforschung 51(1):6–14.)

Isoplethes for spore germination (lines) with averaged data φ(θ) at a inner surface of a building corner



Example

Example – storey ceiling between normal room and unheated attic

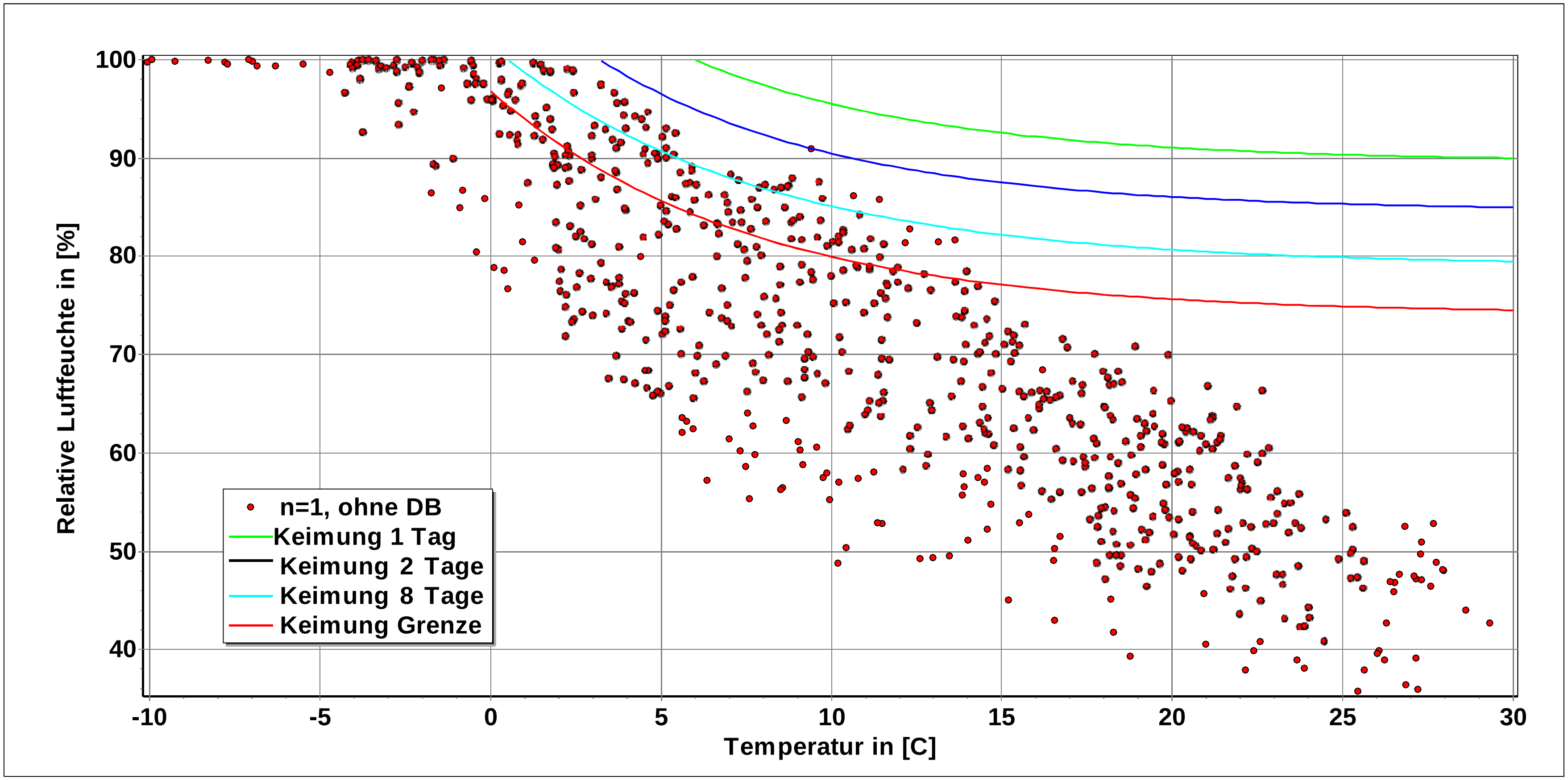


Construction

This construction is calculated with Delphin in different variants /with and without air flow through the construction)

Example

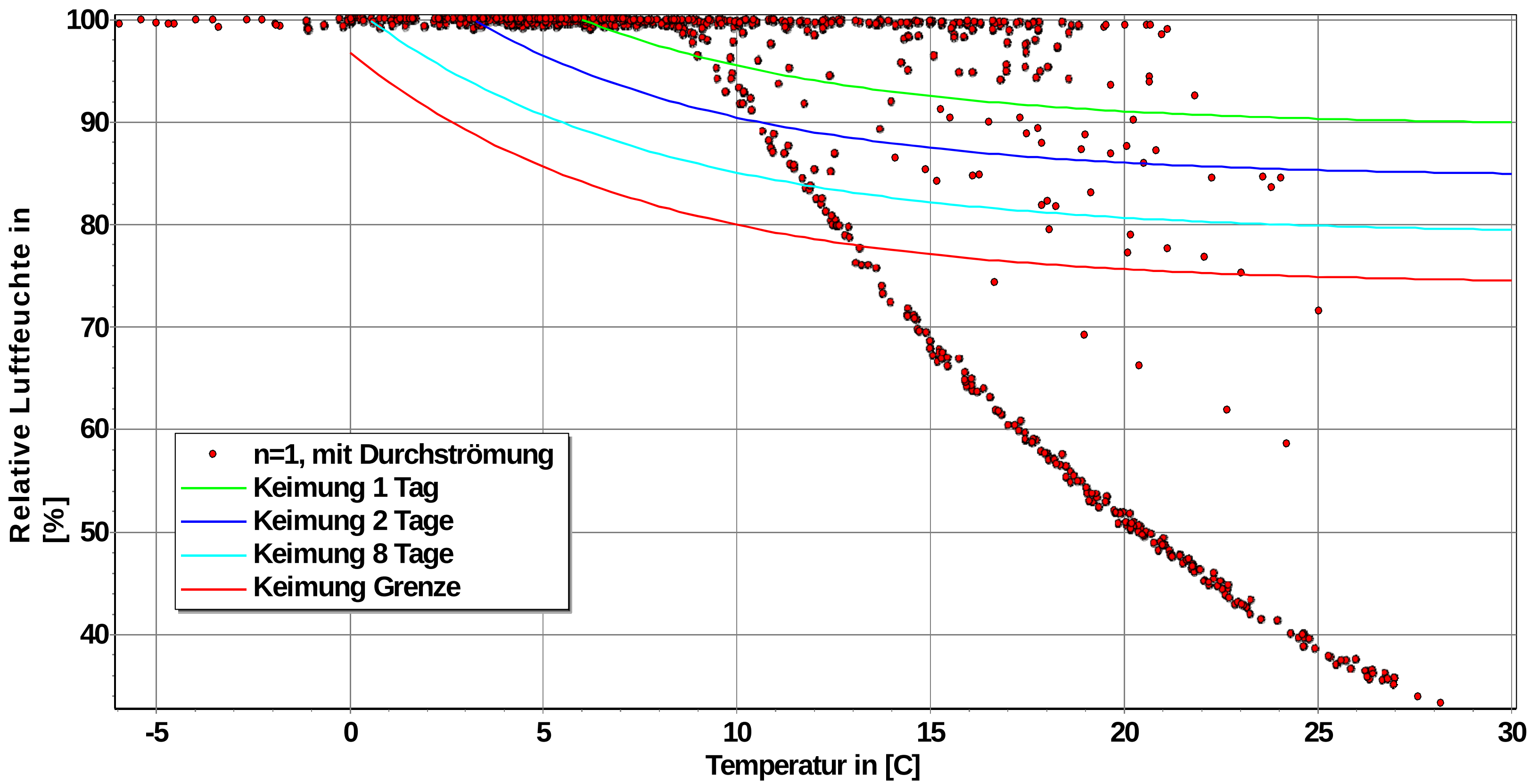
Example – storey ceiling between normal room and unheated attic



Isopleth diagram, without vapor retarder, airtight construction

Example

Example – storey ceiling between normal room and unheated attic



Isopleth diagram, without vapor retarder, with airflow

Mould

- The mould prediction model from Viitanen is an empirical dynamic modell
- Basis for calculation are the hourly values of temperature and relative humidity at the building surface
- Calculation procedure:
  - control of temperature limits (between 0 and 50°C)
  - Calculation of critical relative humidity for germination
  - If humidity is higher – calculation of mould growth intensity (depends on temperature, moisture, material, surface)
  - From this calculation of a cumulative mould index
  - If humidity falls below the critical value – calculaion of a declining intensity
    - *Will be subtracted from mould index*
- Result is a time depending mould index

Mould

Mould index	Growth	Description
0	No growth	Spores not activated
1	Small amount of mould on surface (microscop)	Initial stages of growth
2	<10% coverage (microscop)	-
3	<10% coverage (visual)	New spores produced
4	10-50% coverage (visual)	Moderate growth
5	>50% coverage (visual)	Plenty of growth
6	100% coverage (visual)	Very heavy and tight growth

Mould

Calculation approach

critical relative humidity:

$$RH_{crit} = \begin{cases} T > 20 \rightarrow -0.00267 \cdot T^{3} + 0.16 \cdot T^{2} - 3.13 \cdot T + 100.0 \\ T \le 20 \rightarrow 80\% \end{cases}$$

Mould growth intensity ($\varphi > RH_{crit}$):

$$\frac{dM}{dt} = \frac{1}{7 \cdot \exp\left(-0.68 \ln(T) - 13.9 \ln(RH) + 0.14 W - 0.33 Q + 66.02\right)} \cdot k_1 \cdot k_2$$

M – Mould index

Q – Surface quality factor

W – Material factor

k_1, k_2 – correction coefficients

Mould

Calculation approach

Correction factor 1:

$$k_1 = \begin{cases} M < 1 \rightarrow 1.0 \\ M > 1 \rightarrow \dfrac{2}{t_v / t_m - 1} \end{cases}$$

t_v – time for germination until the first visible appearance
t_m – time for germination

$$t_m = \exp\left(-0.68 \ln(T) - 13.9 \ln(RH) + 0.14 W - 0.33 Q + 66.02\right)$$

$$t_v = \exp\left(-0.74 \ln(T) - 12.72 \ln(RH) + 0.06 W + 61.5\right)$$

Correction factor 2:

$$k_2 = 1 - \exp\left(2.3\left(M - M_{max}\right)\right)$$

M_{max} – biggest possible mould index under given conditions

$$M_{max} = 1 + 7\frac{RH_{crit} - RH}{RH_{crit} - 100} - 2\left(\frac{RH_{crit} - RH}{RH_{crit} - 100}\right)^2$$

Mould

Calculation approach

Declining rate:

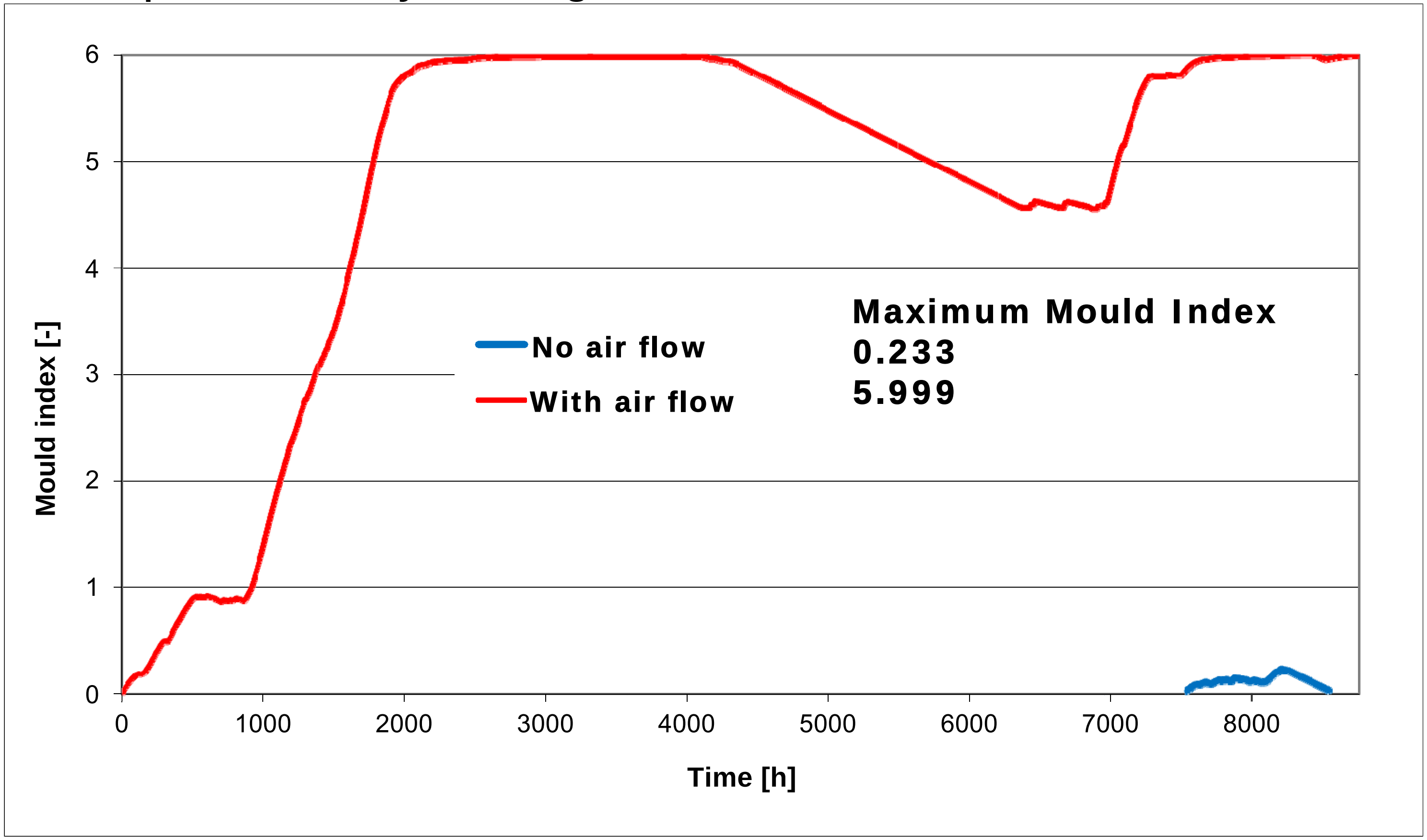
$$\frac{dM}{dt} = \begin{cases} t - t_1 \leq 6h & -0.032 \\ 6h \leq t - t_1 \leq 24h & 0.0 \\ t - t_1 > 24h & -0.016 \end{cases}$$

t-t_1- Lenght of dry period

These value will be added to the mould index and can diminish this under poor conditions.

Mould

Example – storey ceiling between normal room and unheated attic



Mould index acc. Viitanen, without vapor retarder, with and without air flow

Algae

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Algae growth at outer building surfaces

Up to now no model exists for algae growth at building surfaces.

Algae

View of a facade retrofitted with a insulation composite system.
The differences of algae growth is related to thermal bridges from mounting elements.

Source: Helmut Künzel, Angewandte Ökologie, ARCONIS 2/03

Algae

Algae growth at outer building surfaces

Up to now no model exists which can be used for calulating algae growth based on hygrothermal state variables like the mould models.

Temperature and (high) relative humidities are the dominating factors

Possible model:

→ yearly period with moisture content near condensation

$t_{cond,e}$: (> 98% r.L.) <u>and</u> temperatures over 0°C at the outer surface

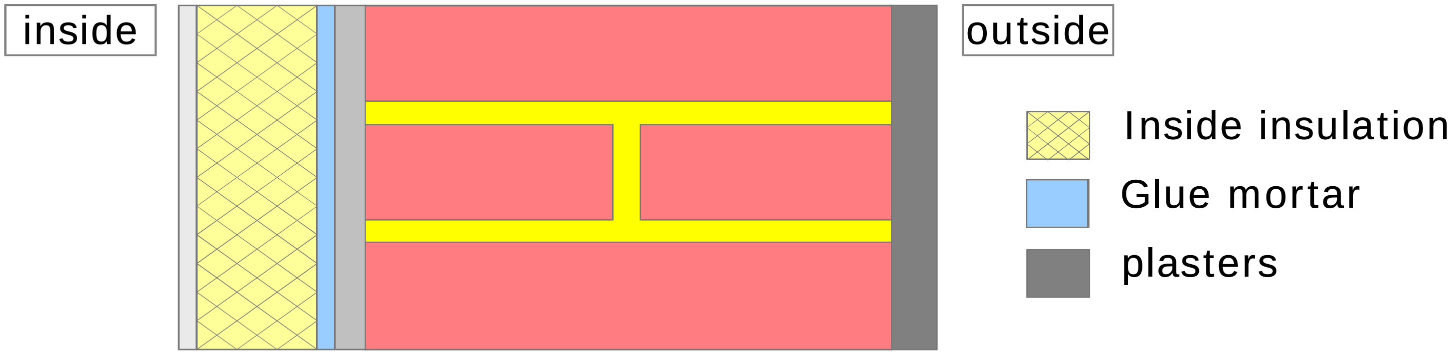
Moisture inside construction

Moisture assessment - Condensation

Condensation: DIN 4108-3 (*Glaser-Method*),
DIN EN ISO 13788

Limits:

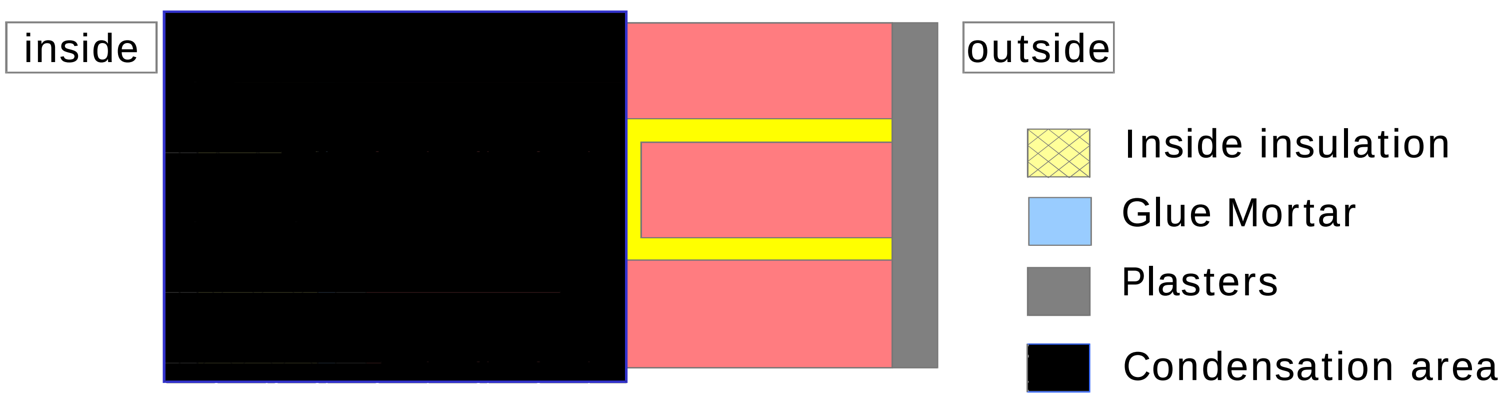
- Only heat and vapor transport, no moisture storage,
- (constant climate conditions,
- Material properties constant (not mousture or temperature dependend),...



Moisture assessment - Condensation

Condensation : Calculation with sophisticated methods

- "Reale" climate,
- Moisture storage,
- Vapor and liquid water transport,
- Material properties as functions of moisture content,...



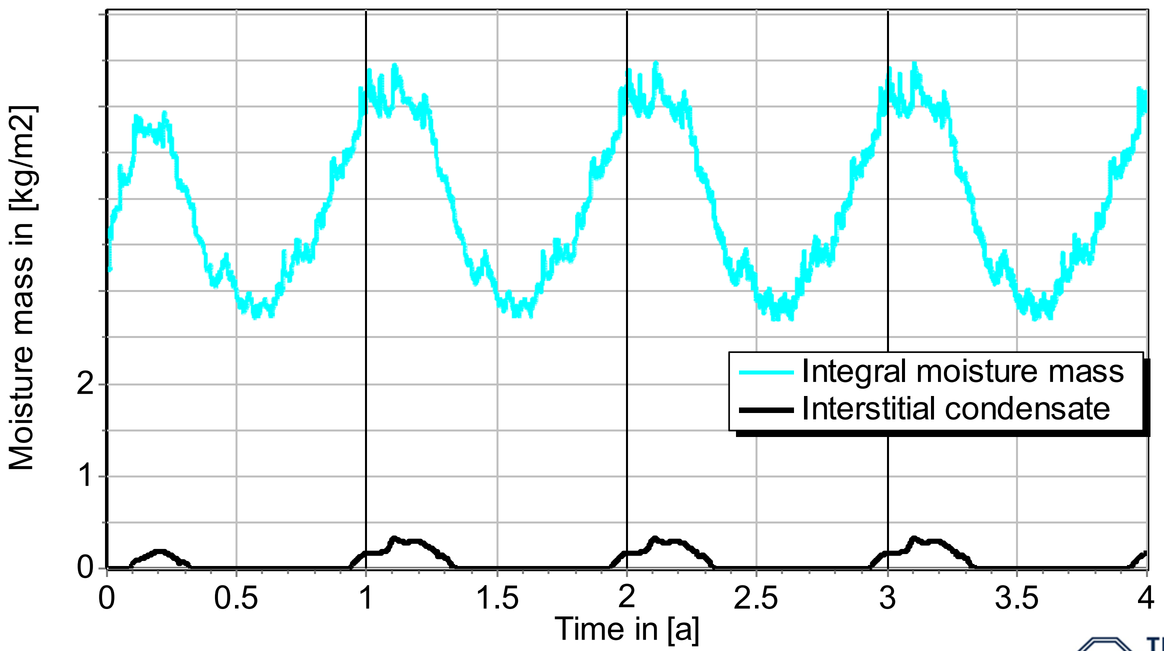
→ No rain, no condensation at outer surface

→ Comparison with standard: Only condensation at inside insulation and inner half of wall

Moisture assessment - Condensation

Condensation : Calculation with sophisticated method

- "Reale" climate,
- Moisture storage,
- Vapor and liquid water transport,
- Material properties as functions of moisture content,...



Moisture assessment - Condensation

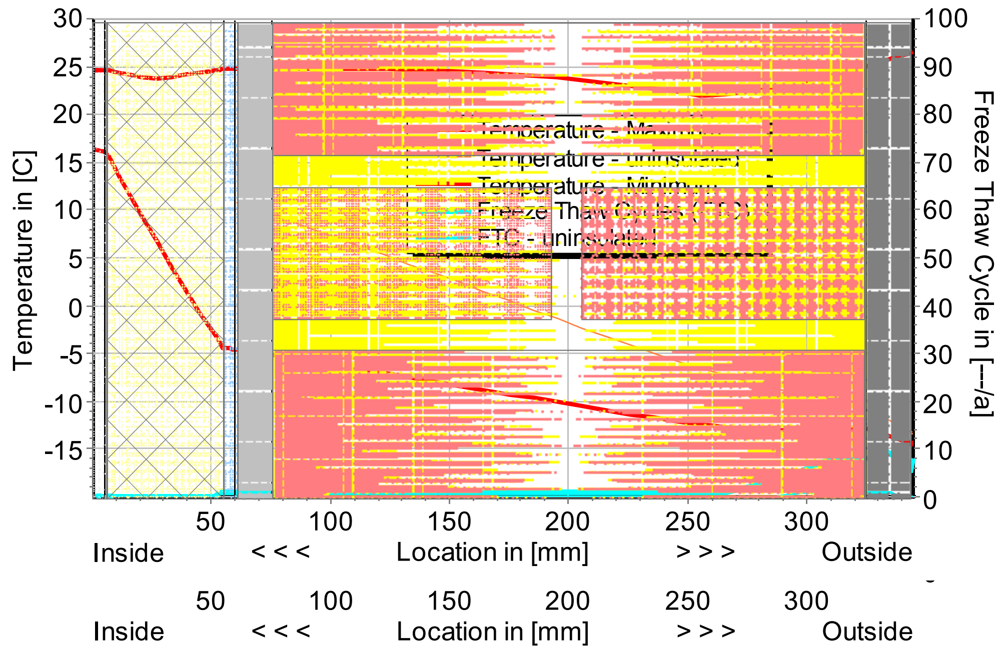
Hygrothermal load indicators

- Freeze/Thaw-cycles (Temperature and moisture profile)
- Biological vermin growth inside the construction
- Weathering load can lead to hygrothermal induced damages (swelling, shrinking)

Moisture assessment - Condensation

Freeze / Thaw-cycles: Modell is based on thermo dynamical considerations: Freeze/Thaw-Cycle (TTC) = f(w,θ) (Xu 1996)

inside



outside

Temperature and Freeze/Thaw-Cacle profiles
(rated risk of FTW, no real damages)

Modell from: P. Häupl, Y. Xu; Numerical Simulation of Freezing and Melting in Porous Materials under the Consideration of the Coupled Heat and Moisture Transport, Thermal Envelope & Building Science, Volume 25 No 1, July 2001, pp. 4-31)

Moisture assessment - Condensation

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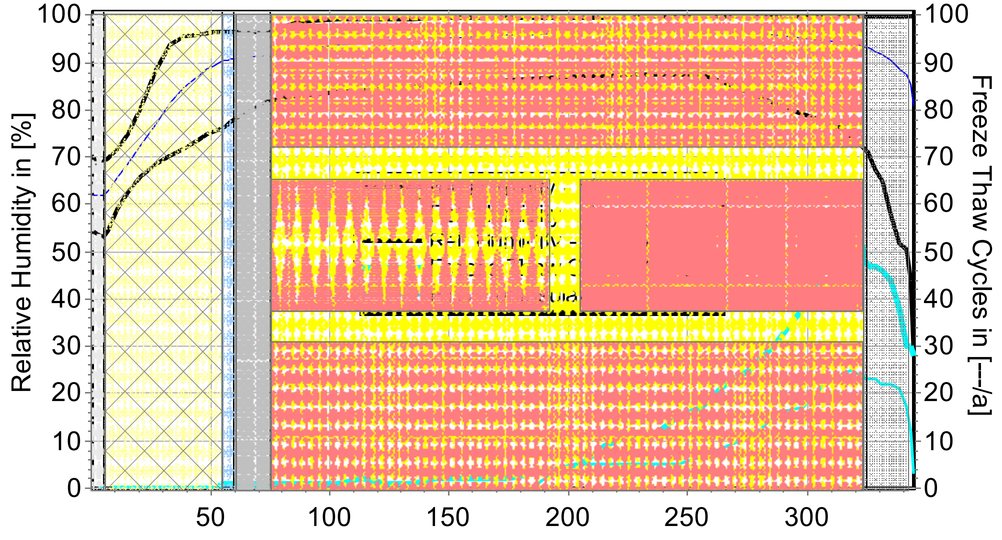
innen



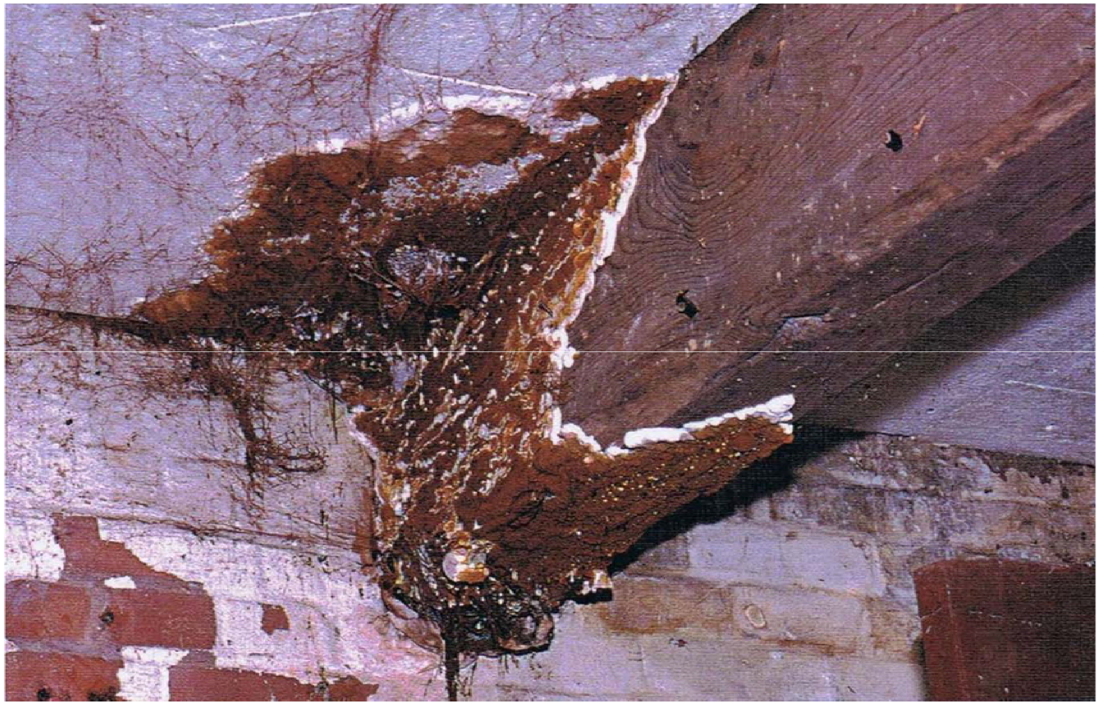
außen

Charakteristische Profile der relativen Luftfeuchte und Frost-Tau Wechsel
(bewerten Risiko von FTW, nicht tatsächlich zu erwartende Schäden)

Moisture assessment - Fungi

Vermin growth inside the construction

Aims to common and dangerous biological wood pests: Dry rot (*serpula lacrymans*)



Moisture assessment - Fungi

Historical building in Luckau

Moisture assessment - Fungi

Vermin growth inside the construction

Aims to common and dangerous biological wood pests:
Dry rot (*serpula lacrymans*)

Standard (DIN 68800-1): Moisture content > 20 M% only "for short times"

Limiting factors:

- *Temperature*: Germination begins at 3-5°C
- *Germination*: From fibre saturation: 27-30 M% (Spruce)
- *Growth*: From 20 M% only, if fugi has ist own „water supply"

→ Long continually periods with high humidity is positive!

Moisture assessment - Fungi

Vermin growth inside the construction

Aims to common and dangerous biological wood pests:
Dry rot (*serpula lacrymans*)

$t_{PGV,20/26}$ Yearly time period with temperatures higher than 2°C and moisture content >20 or 26 M%

$t_{PGV,20/26,max}$: longest continually time period with temperatures higher than 2°C and moisture content >20 or 26 M% (Unit: d)

PGV – Possible Growth of Vermin

Wood damage

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- Wood-destroying fungi (dry rot, brown cellar rot)
- Fresh wood insects (bark beetle, shipyard beetle)
- Dry wood insects (old house borer [xylophages], gnawing beetle or wood worm)
- Wood dwelling but not destroying fungi (mould or blue stain fungi)
- Loss of strength of the wood if moisture content is high, for all kinds of strenght; if moisture content is higher than 18M% strenght should be attenuated by 1/6.

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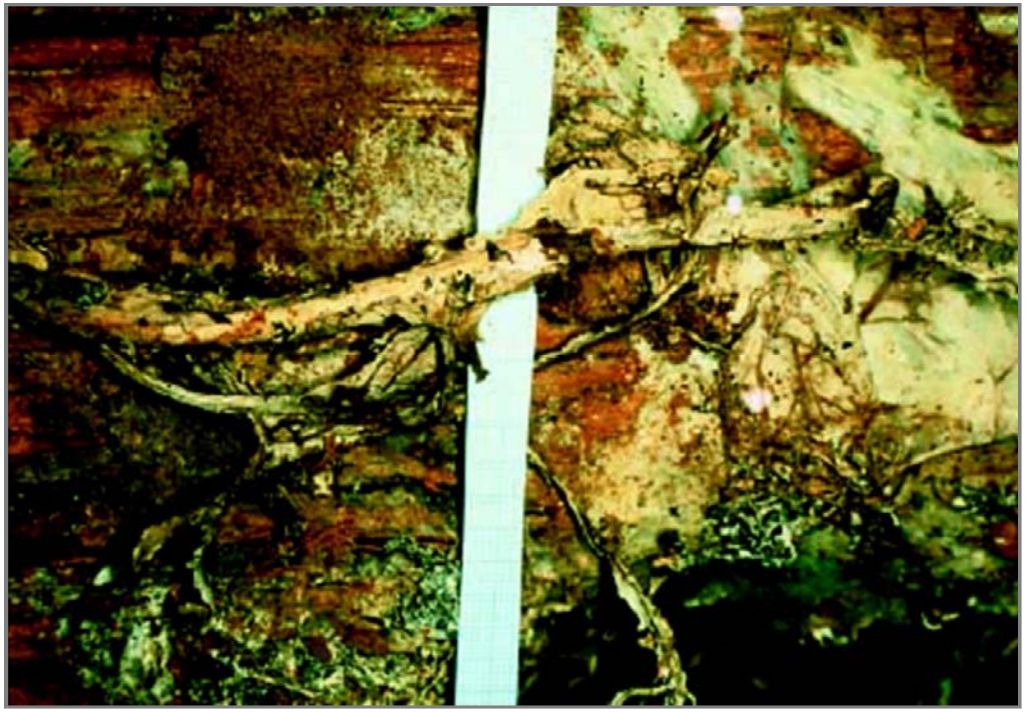
Wood damage

- Wood-destroying fungi (dry rot, brown cellar rot)

Fruiting body of dry rot

Wood damage

- Wood-destroying fungi (dry rot, brown cellar rot)



Mycelium of dry rot

Wood damage

- Wood-destroying fungi (dry rot, brown cellar rot)

Blight – caused by dry rot or brown cellar rot

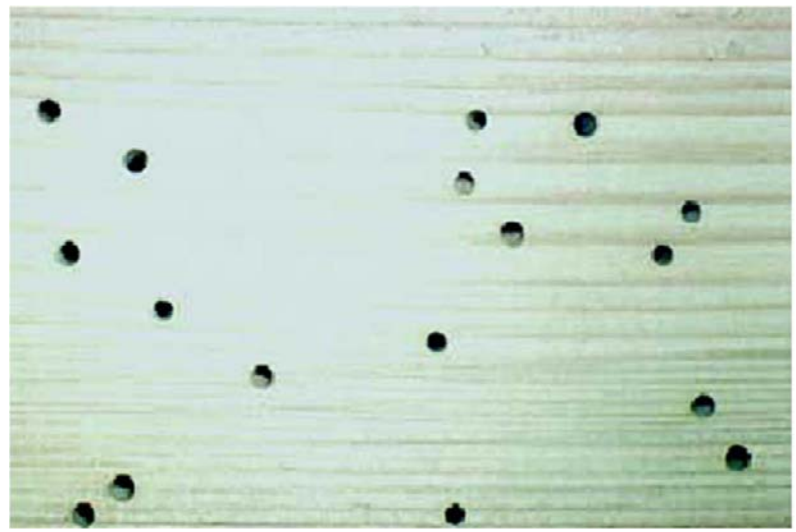
Wood damage

- Wood-destroying fungi (dry rot, brown cellar rot)

Fruiting body of brown cellar rot

Wood damage

- Fresh wood insects (bark beetle, shipyard beetle)



Ate holes made by shipyard beetle

Wood damage

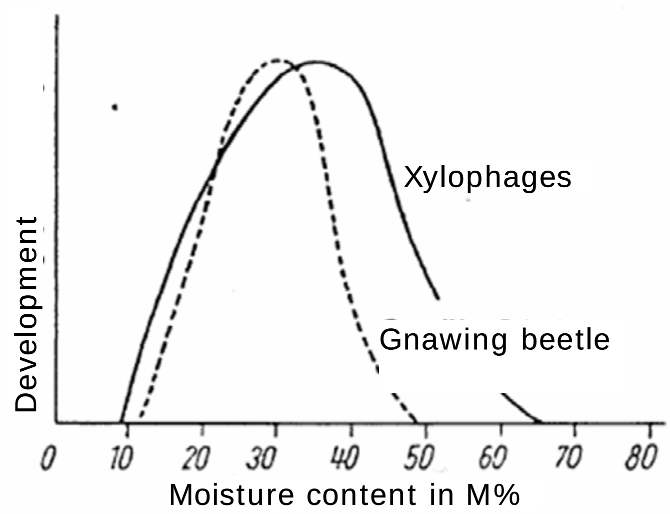
- Dry wood insects (xylophages, gnawing beetle or wood worm)

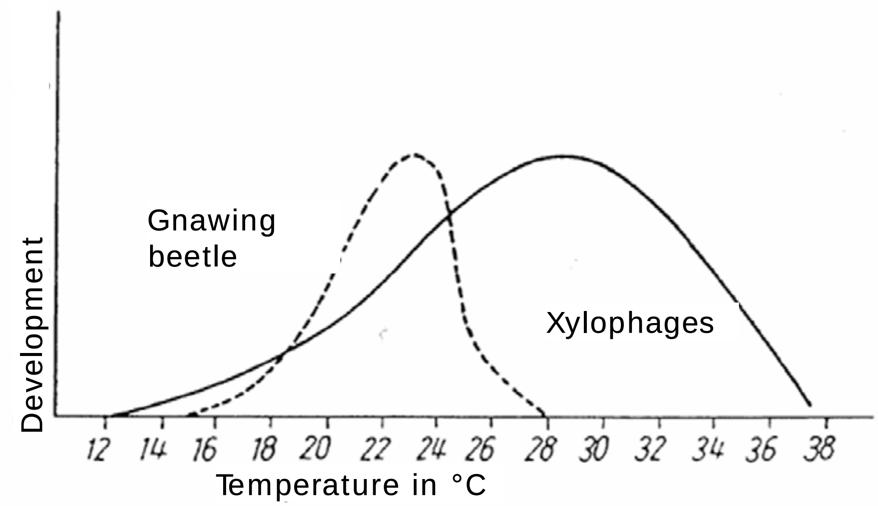
Common gnawing beetle
(larvae are known as wood worms)

Xylophagae

Wood damage

Dry wood insects (xylophages, gnawing beetle or wood worm)





Influence of temperature and moisture content of wood on development of larvae according Becker (from Kempe, K., Holzschädlinge)

For common gnawing beetle:

- Optimum of development around 30M%
- Minimum moisture content 10 – 12M% - below – no development of larvae

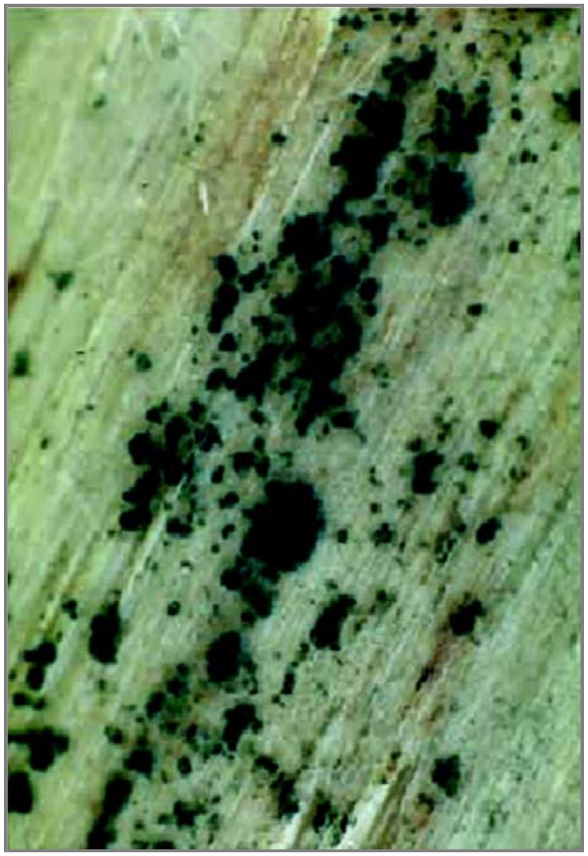
Wood damage

Damage on wooden beam ends by the dead watch beetle (Anobium puncatum)

Source: U. Müller, "Holzbalkenköpfe in historischen Mauerwerk", presentation at the 2nd international "HolzBauPhysik Kongress" in Leipzig, Feb. 2011

Wood damage

- Wood living but non-destructive mould fungus or blue stain



Mould fungus on wood

Moisture assessment

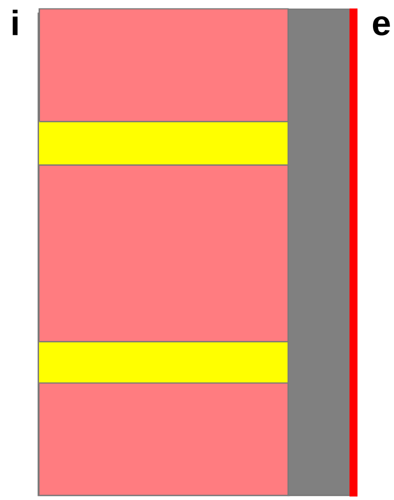
Hygrothermal damages induced by weathering load

Moisture and temperature differences at the building surface can lead to stress and cracks

Moisture and temperature differences between building surface and deeper layers can lead to shear stress → Spalling (flaking, chipping)

Moisture assessment – swelling, shrinking

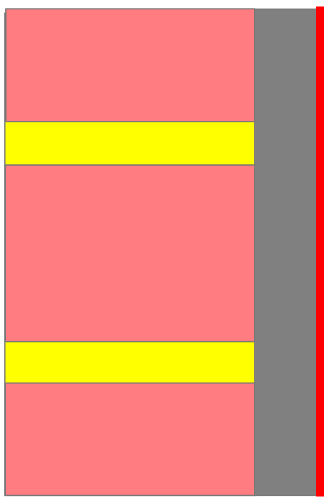
Hygrothermal damages induced by weathering load

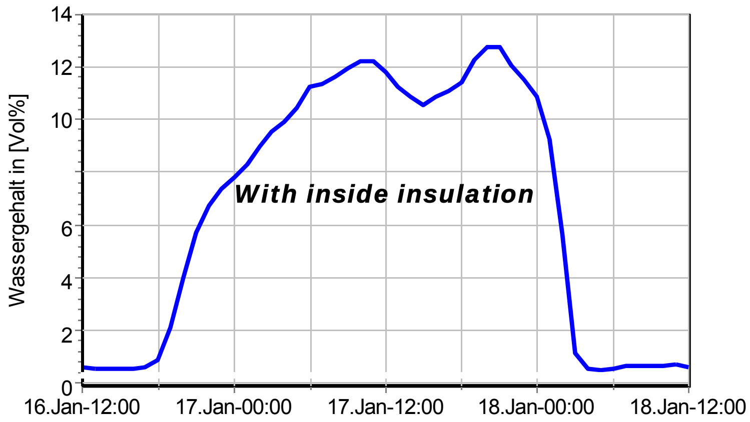


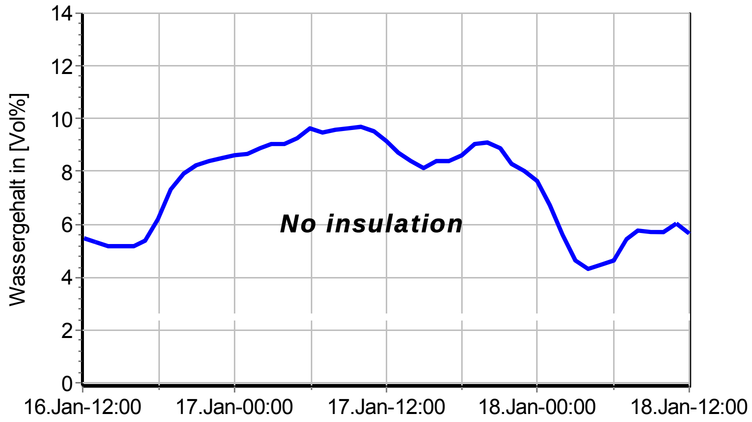
Moisture and temperature differences at the building surface → Cracks

Moisture assessment – swelling, shrinking

Hygrothermal damages induced by weathering load

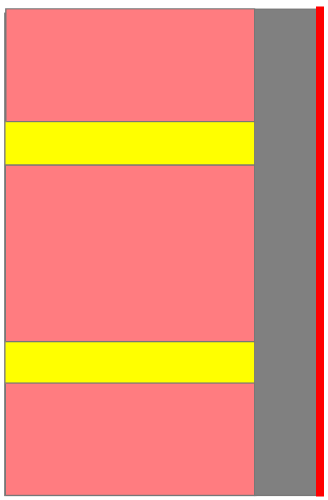


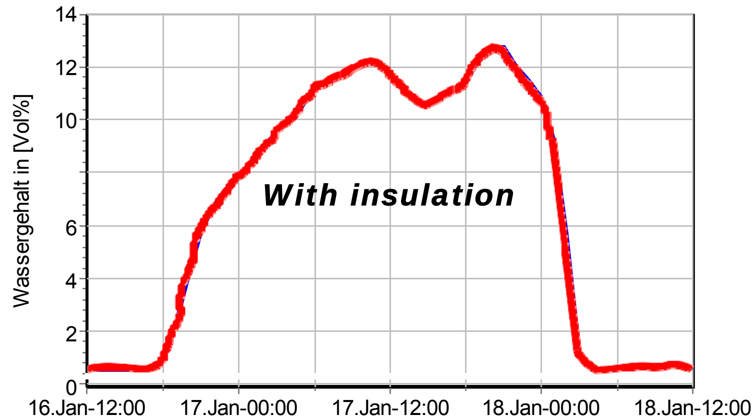


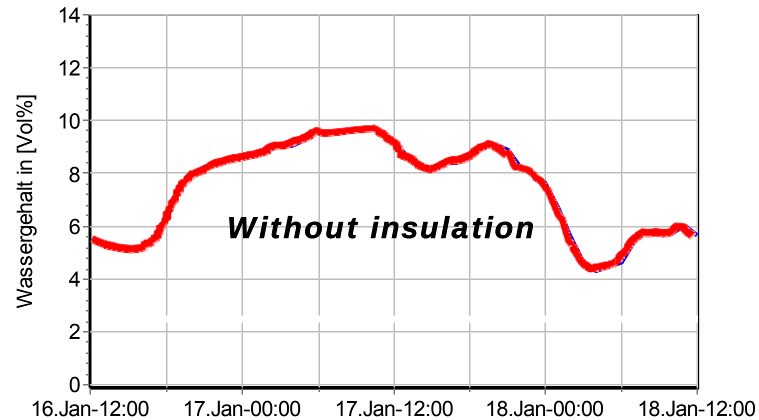


Moisture assessment – swelling, shrinking

Hygrothermal damages induced by weathering load







here: $WL_{w,\text{with ID}} > WL_{w,\text{without ID}}$

WL_w: Weathering load related to moisture