NET-ZERO ENERGY PASSIVE HOUSE AND TIMBER LOAM CONSTRUCTION FOR HEALTHY INDOOR CLIMATE: PILOT PROJECT "AKTIVHAUS“-RESIDENTIAL ESTATE IN KRAMSACH, AUSTRIA

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ABSTRACT

The project “Aktivhaus“-residential estate in Kramsach focuses on (1) energetic aspects and measures to reach the “net-zero-energy-building” and (2) avoidance of low indoor air humidity in winter by using the moisture buffer capacity of loam. The latter is discussed in this paper and results are presented.

This investigation includes laboratory measurements on material scale for the characterization of the used loam (sorption isotherm, diffusion resistance). Cross-validation of the building simulation model Dynbil with its hygrothermal wall model is conducted. Furthermore, the hygrothermal wall model is calibrated using laboratory experiments on component scale (hygrothermal behaviour of components in climate chambers).

The building simulation results are compared with measured temperature and relative humidity of the one-year on-site monitoring campaign in the terraced houses. Conclusions about the potential enhancement of the indoor climate are drawn depending on the area weighted moisture retention potential. An optimization with regard to loam formulation, loam area and thickness is conducted by means of simulation.

DESCRIPTION OF THE RESIDENTIAL ESTATE

In Kramsach, Austria, the new housing estate with passive house apartments in timber-loam-construction with on-site energy production consists of three apartment houses and 15 terraced houses with in total 46 apartments with 4400 m living area.

Compact devices (with ventilation and integrated ground sourced heat pump) are producing the remaining heat demand of the terraced houses (60 m of borehole heat exchanger per terraced house). Each of the three apartment houses is supplied by a central heat pump with 5 boreholes heat exchanger with 90 to 100 m length each. All houses and flats have well dimensioned floor heating systems. Due to the four-pipe distribution system and fresh water modules it is possible to operate the system at a relatively low temperature level and to distribute the heat efficiently inside the building. The semi-central ventilation system is equipped with an energy-efficient heat recovery unit. The planed photovoltaic panels should not only produce the electric power demand for heating but also the electricity demand of an apartment (net-zero: balanced over the year).

One further aspect of the “Aktivhaus“-residential estate in Kramsach is to provide a healthy indoor climate. Due to an innovative timber-loam construction parts of the structures have sufficient energy and moisture storage capacities. This is supporting a healthy living comfort. Focus was further drawn on the strict control of chemicals in the used materials resulting in an indoor climate without pollutants.

PASSIVE HOUSE IN TIMBER-LOAM-CONSTRUCTION

On the concrete cellar of the terraced houses two floors with load-bearing wooden construction and load-bearing, cross-braced internal walls (plywood elements) are mounted. External panelling of the wooden construction is done with a timbering or a plastered wooden soft fibre board. Inside screed of cement as floor and gypsum boards as ceiling liners are used. The walls are covered inside with loam plaster or prefabricated loam boards. The layers of the external wall construction are shown in figure 1. The load-bearing part with cellulose insulation (dark hatching) and the plaster-base sheeting outside are prefabricated in the factory. The upcoming loads are borne by vertical TJI-structures in combination with diagonal planks mounted on both sides. The internal part of the wall is constructed with some layers of loam undercoat and fine loam plaster. The loam is spattered wet on-site on a rush mat, which is fixed on vertical wooden board. The total thickness of the loam construction is between 4 and 5 cm. All of the external walls of the terraced houses with the exception of the walls in bathroom and kitchen and the seperation walls to the neightbour were built in this way (see fig. 4).

The load-bearing internal wall (see fig. 2) is plastered on-site with loam with a thickness of 2 to 2.5 cm. In case of the non load-bearing internal wall (see fig. 3) prefabricated loam boards were nailed on a timber frame on both sides and plastered with fine loam plaster. In total a thickness between 5 and 5.5 cm was reached. Several other construction variants were tested regarding technical and economical optimization.

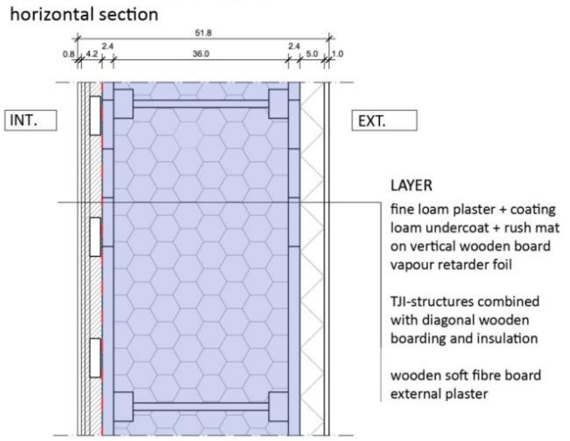

Figure 1 Detail of external wall

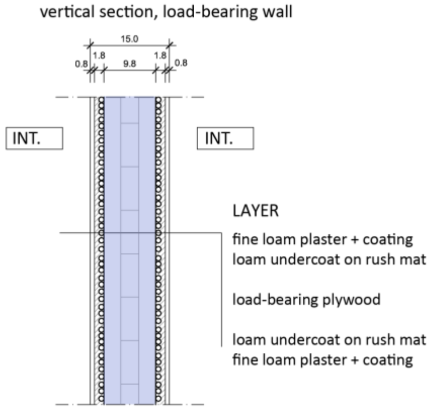

Figure 2 Detail of load-bearing internal wall

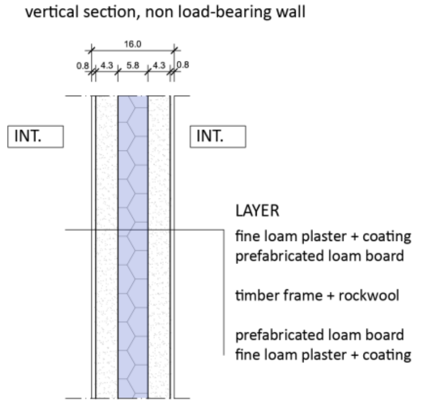

Figure 3 Detail of non-load-bearing internal wall

At the separation wall between the terraced houses gypsum boards are mounted on both sides due to noise protection. The end-terraced houses in each block of 5 houses have such walls only at one side of the flat and therefore more wall area is covered with loam (see fig. 4).

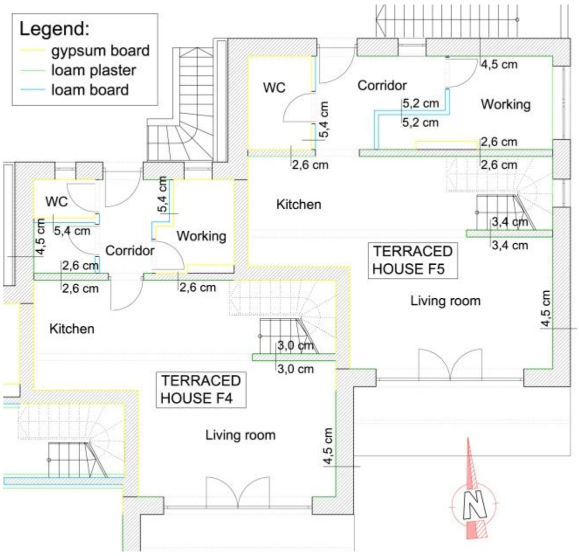

Figure 4 Ground floor of terraced house F5 and F4 with thickness of loam layer

In table 1 the loam areas in the end-terraced houses F1 and F5 and the centre house F3 are compared. The total area (A_t) includes walls, windows, ceiling and floor). The aspect ratio (area/volume) of the two different typologies is the same. The treated area and thus, the volume of the centre-houses is somewhat smaller. Taking to account that the thickness of the loam layer of an external wall (4.3 cm) is relatively high compared to the internal walls, a much higher amount of loam is attached in the end terraced houses than in the centre ones. Therefore, it was decided that main part of the sensors for the monitoring are installed in the end-terraced houses and in the centre terraced houses a reduced monitoring is installed for comparison (see next chapter).

Table 1

Comparison of area and aspect (area/volume) ratio of the end-terraced houses F1, F5 and the centre house F3, l: loam, w: wall, t: total

	WALL AREA		**TOTAL AREA**	**ASPECT (A/V) RATIO**		
Flat	A_l	A_w	A_t	A_l/ V	A_w/V	A_t/V
	[m]	[m]	[m]	[1/m]	[1/m]	[1/m]
F1	211.4	313.1	567.0	0.6	0.9	1.7
F3	170.7	305.2	526.1	0.6	1.0	1.8
F5	228.8	331.0	584.3	0.7	1.0	1.8

MONITORING AND EVALUATION

Monitoring System

Two different types of measurement equipment were installed for the monitoring of the terraced houses in Kramsach. Datalogger with integrated sensors to detect the indoor climate (temperature and relative humidity) later called room sensor and datalogger with external sensors were installed in the loam layer of the walls (wall sensor), see figure 5 and 6. In seven monitored centre-terraced houses and in each of the six end-terraced houses two room sensors were installed in the supply air duct and extract air duct of the ventilation system (compact device). In each of the six end-terraced houses additionally four room sensors were put in the kitchen, the living room in the ground floor and in two rooms (sleeping room, children) in the first floor. As shown in fig 6 the wall sensor was installed in the loam layer of the internal wall close to the stairs in the ground floor and two in internal walls in the same sleeping rooms as the room sensors.

In total, this amounts to 18 wall sensors and 50 room sensors that were installed in the terraced houses for the 18 month monitoring campaign. In addition, a weather station to monitor the ambient conditions (temperature, humidity, global radiation) was mounted on the roof of one terraced house. All measurement equipment were calibrated before and after the monitoring in climatic chambers.

Figure 5 Installation of data logger (room sensor) to detect the indoor climate

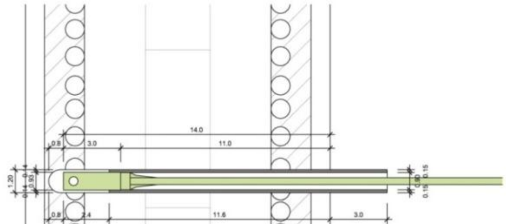

Figure 6 Detail of the installation of the wall sensor, vertical section, load-bearing wall

Evaluation of the monitoring

In the upper diagram in figure 7 the moisture content calculated from the temperature and humidity measurement of the extract air is shown. The black bold line illustrates the mean value of all measured terraced houses and shows the lowest values in winter with around 5 gram water per kilogram air and the highest values around 12 g/kg in summer. The grey area (fluctuation range) mainly represents the influence of the behaviour of occupants. Caused by daily activities such as cocking, showering or drying the laundry depending on the habits of the occupants, at different times different amount of humidity sources occur. Due to that and the different occupancies of the flats as well as due to different window ventilation behaviour the fluctuation can be explained. The difference value shown in the lower diagram (difference between the minimal and maximal value of all flats at each point of time) is fluctuating during the whole year in average around 2 g/kg and with a peak in summer about 4 g/kg.

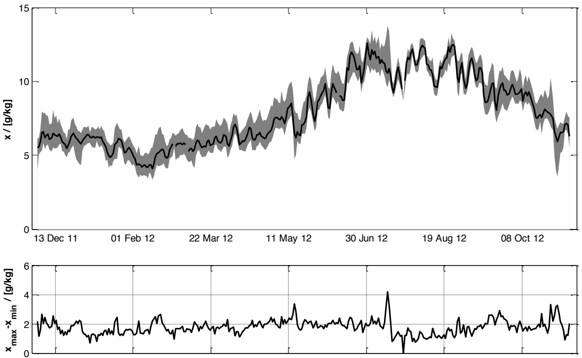

Figure 7 ***Upper diagram:*** *comparison daily mean values of moisture content of extract air in different terraced houses with mean value of all houses in the timeline from Nov. 2011 to Nov. 2012;* ***Lower diagram:*** *difference of maximum and minimum value of moisture content of all flats at the same timeline*

Despite of the occupant behaviour influence on the moisture content in each terraced house the flats are comparable. This applies in particular to the seasonal course which is in the focus of this paper. The influence of the external climate is much higher than the influence of the occupant behaviour. In the annual development of the moisture content there is a difference of about 7 g/kg between summer and winter, whereas daily fluctuation are in the range of 2 g/kg.

For the analysis of the indoor climate in the terraced houses, the calculated moisture content of the houses D5, E1, E5 and F5 is displayed in the same way in figure 8 and 9. The course of the mean value (black bold line) of the absolute humidity of living rooms and sleeping rooms in the four flats is similar to the one of the extract air (compare fig. 7 with fig. 8 and fig. 9). The deviations of the indoor air (living room and sleeping room) are lower compared to the deviations of the extract air. One reason besides the smaller sample number is that a high amount of the humidity is produced in extract air rooms (kitchen, bathroom) which directly leaves the house through the ventilation system. Therefore, this humidity is neither available in the living or sleeping room nor for moisture storage in the loam construction. The indoor climate is mainly influenced by the ambient climate and less by the occupants' behaviour.

In the living room in winter, the deviations are almost negligible. The higher deviations in the sleeping rooms might be explained by different ventilation behaviour of the occupants. According to the information of one inhabitant, the sleeping room in one house is ventilated also with windows throughout the year. Thus, in winter this leads to a reduction of the air humidity in the sleeping room and thus to higher deviations.

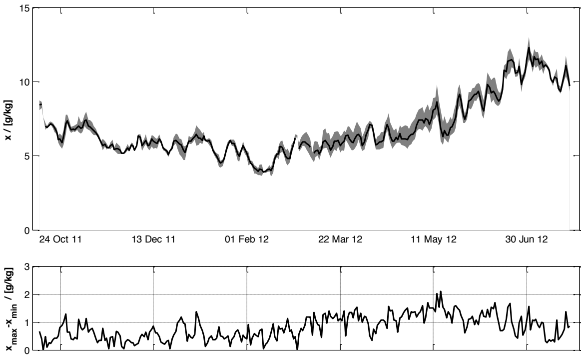

Figure 8 ***Upper diagram:*** *comparison of daily mean values of moisture content in the living room in different terraced houses with mean value of all houses in the timeline from Oct. 2011 to July 2012;* ***Lower diagram:*** *corresponding difference of maximum and minimum value of moisture content*

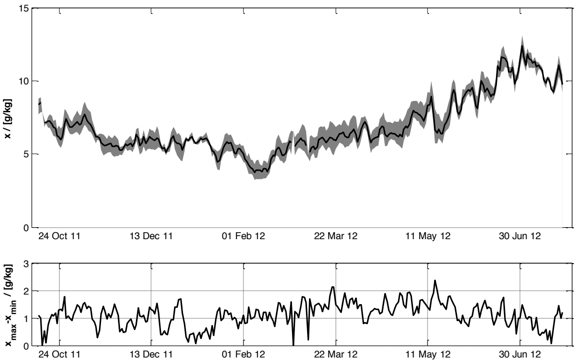

Figure 9 ***Upper diagram:*** *comparison of daily mean values of moisture content in the sleeping room in different terraced houses with mean value of all houses in the timeline from Oct. 2011 to July 2012;* ***Lower diagram:*** *corresponding difference of maximum and minimum value of moisture content*

SIMULATION OF A END-TERRACE HOUSE IN KRAMSACH

The simulation model represents an end-terraced house in Kramsach. This end-terrace house is modelled with the building simulation programme Dynbil as 4-zone model with as realistic as possible wall constructions. The neighbouring building is considered as a fifth zone. Thermal losses to the unheated cellar and to the naturally ventilated attic are considered by means of so called reservoirs. The model contains 12 different constructions for walls, ceilings and basements (66 components).

Dynbil is a 2*multi-zone transient building model (Feist, 1994) which was later extended by a moisture transfer model based on the method of (WUFi, 2013) with some minor simplifications in order to increase simulation performance (Schnieders, 2008). The heat and moisture transport model was cross-validated against a hygrothermal in Delphin (Delphin 2013) and against a Matlab model developed by the authors (Janetti et al. 2011, see also next section).

As information about the user behaviour (presence, window ventilation, door position and so on) are not available standard occupation and load profiles on hourly basis are employed (see Rojas et al. 2012). Weekdays and weekends are distinguished but there is no seasonal distinction (such as summer-winter or vacancies). In addition to the constant air change rate of 120 m /h (with heat recovery), temperature dependent window ventilation is considered in summer. Moreover, in summer temporary shading depends on the solar radiation. Occupation profiles and ventilation rates are varied to investigate their influence.

The seasonal development of the measured indoor moisture content (see section monitoring above) shows relative good agreement with the simulated indoor moisture content based on measured outdoor humidity, as is shown in fig. 10. However, there are periods in summer as well as in winter where the deviations are with 0.5 g/kg to 1 g/kg relatively high. A better agreement could not be achieved neither by changing ventilation rates nor by changing presence profiles.

The relative high deviations in summer may be explained partly by the fact that the humidity of the supply air is assumed to be equal to ambient air humidity. In reality, in summer, condensation occurs due to cooling of the ambient air with brine-to-air heat exchanger if the heat pump (compact unit with heat pump with vertical ground heat exchanger) is in operation (see general description of the project above).

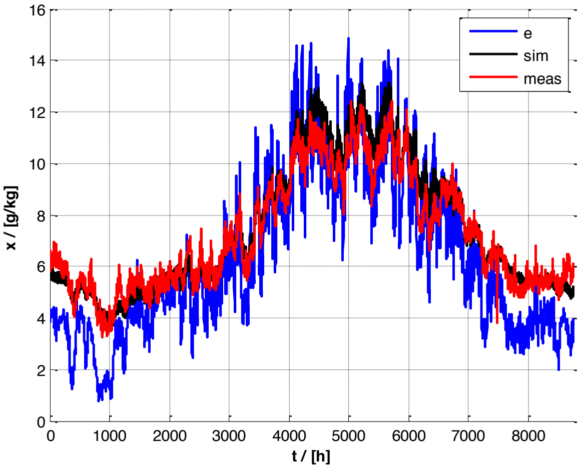

Figure 10 Measured ambient moisture content (e) and measured indoor moisture content (meas) as well as simulated moisture content (sim)

A good agreement on daily or even on hourly basis cannot be achieved without knowledge of the user behaviour. Better seasonal agreement may be achieved by seasonal distinction of the load profiles and ventilation rates.

Four different construction variants have been considered to investigate the influence of the loam on the indoor humidity compared to other wall construction: besides the existing timber frame construction with loam coating, a variant with gypsum board and two massive construction variants (concrete and brick) have been implemented in the simulation model.

The influence of the different constructions on the indoor moisture content is hardly recognisable. Moisture peaks in summer are slightly damped in case of loam (a) compared to gypsum board (b). However, the effect is of the same order of magnitude as for the massive constructions (c, d). The effect on the low moisture contents in winter is even less and compared to the deviations between simulation results and measurement not significant. Nevertheless, a trend can be derived. The number of hours below 4.5 g/kg are reduced and, additionally, the minimum value is increased, see Fig. 12.

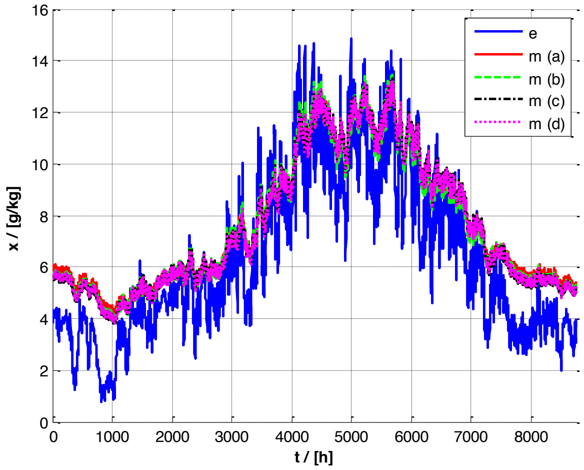

Figure 11 Ambient moisture content (e) and simulated mean indoor moisture content for the existing loam construction (a) for a gypsum board construction (b),a concrete wall with plaster (c) and brick with plaster (d)

GENERAL INVESTIGATION OF THE SEASONAL MOISTURE BUFFER POTENTIAL

The moisture buffer potential is significantly influenced by the following parameters:

- Loam quality (moisture retention curve and water vapour diffusion resistance number)
- Loam thickness d
- Effective loam area related to the enclosed volume A/V (see tab. 1)
- Specific moisture sources S_v/V

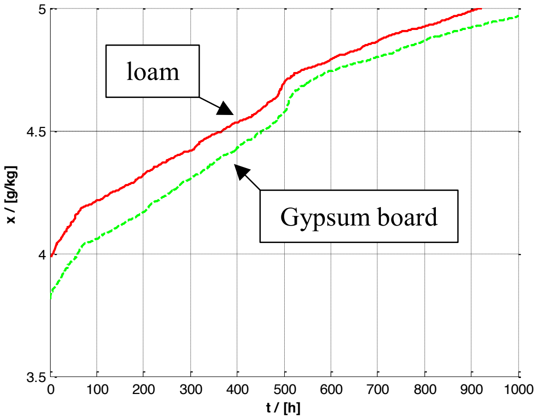

Figure 12 Sorted simulated mean indoor moisture content for the existing loam construction (a) and for the same construction with gypsum board instead of loam (b)

The influence of these parameters is investigated by means of multi-anual simulation with a simple 1*-1 zone room model with a hygrothermal wall implemented with the Matlab pdepe solver.

The balance equations for the heat and moisture transfer are

$$\frac{\partial u}{\partial \phi}\frac{\partial \phi}{\partial t}+\frac{\partial}{\partial x}\left(-D_{m,\phi}\frac{\partial \phi}{\partial x}-D_{m,T}\frac{\partial T}{\partial x}\right)=0 \qquad (1)$$

and

$$\frac{\partial h}{\partial T}\frac{\partial T}{\partial t}+\frac{\partial h}{\partial \phi}\frac{\partial \phi}{\partial t}+\frac{\partial}{\partial x}\left(-D_{e,T}\frac{\partial T}{\partial x}-D_{e,\phi}\frac{\partial \phi}{\partial x}\right)=0 \qquad (2)$$

The system of equations (1) and (2) can be solved with Matlab using the pdepe solver. Temperature T and relative humidity ϕ represent the dependent variables whereas position x and time t are the independent variables of the problem.

The second term in eqution 2 can be neglected in most cases $\frac{\partial h}{\partial \phi}\frac{\partial \phi}{\partial t} \approx 0$. $D_{m,\phi}$, $D_{m,T}$, $D_{e,T}$ and $D_{e,\phi}$ are material specific diffusion coefficients that are described by the following equations:

$$D_{m,\phi}=\frac{p_s D_v}{\mu R_v T}-K_l\frac{\partial p_c}{\partial \phi} \qquad (4)$$

$$D_{m,T}=\frac{\phi D_v}{\mu R_v T}\frac{dp_s}{dT} \qquad (5)$$

$$D_{e,T}=\lambda+\left(h_{lv}+c_{p,v}T\right)\frac{\phi D_v}{\mu R_v T}\frac{dp_s}{dT} \qquad (6)$$

$$D_{e,\phi}=\left(h_{lv}+c_{p,v}T\right)\frac{p_s D_v}{\mu R_v T} \qquad (7)$$

Equation (8) gives the relation between the vapour density ρ_v, the relative humidity ϕ and the saturation vapour density ρ_s, which is a function of the temperature:

$$\rho_v=\phi\rho_s(T) \qquad (8)$$

The system of equations (1) and (2) is coupled with the the moisture balance equation for the room:

$$\rho_{v,i} = \frac{\dot{S}_v/V + n \cdot \rho_{v,e} + \beta \cdot A/V \cdot R_v \cdot T_s \cdot \rho_{v,s}}{n + \beta \cdot \frac{A}{V} \cdot R_v \cdot T_\mathrm{i}} + \left(\rho_{v,t-1} - \frac{\dot{S}_v/V + n \cdot \rho_{v,e} + \beta \cdot A/V \cdot R_v \cdot T_s \cdot \rho_{v,s}}{n + \beta \cdot A/V \cdot R_v \cdot T_\mathrm{i}}\right) \cdot exp(-(n + \beta \cdot A/V \cdot R_v \cdot T_\mathrm{i}) \cdot \Delta t) \qquad (9)$$

The moisture balance for the room is solved for each time step (Δt), iteratively to calculate the moisture density $\rho_{v,i}$ as a function of the moisture source S_v, the ventilation rate n, the A/V ratio, the moisture density of the wall surface $\rho_{v,s}(t)$ and the moisture density of the previous time step $\rho_{v,t-1}$. For the sake of simplicity, the room is considered isothermal with $T_i = 20$ °C.

For these investigations four loam qualities taken from the Delphin Database (Delphin, 2013) and are compared with three types of measured loam qualities, see Fig. 13.

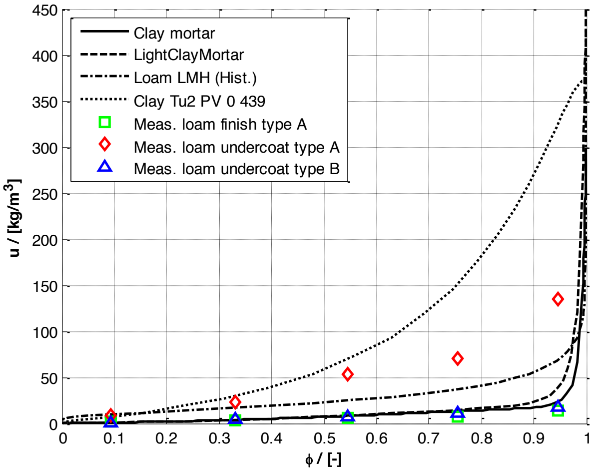

Figure 13 Moisture retention curve of four different loam qualities taken from Delphin Database (clay mortar μ = 12, LightClayMortar μ = 30; Loam LMH (Hist.) μ = 10.58, Clay Tu2 PV 0 439 μ = 10) and measured sorption isotherm of loam finish (μ = 13) and loam undercoat of two types of loam (μ = 10).

Significant differences can be recognised. The measured moisture retention curve of loam undercoat type B, which is used in the houses in Kramsach, is only slightly better than loam finish of type A and is in the range the loam quality clay mortar or "LightClayMortar". The equilibrium moisture content u of loam undercoat type A is - in the interesting range between 20 % and 80 % relative humidity - about 50 % to 100 % higher than the loam quality "Loam LMH (Hist.)" of the Delphin database. The loam "Clay Tu2 PV 0 439" of the Delphin Database may represent the maximum possible limit, as it is a soil (and not a construction material). For the investigations three qualities are compared "clay mortar", "Loam LMH (Hist.)" and "Clay Tu2 PV 0 439".

Liquid transport is not considered as in the interesting range of the relative humidity of the indoor air the influence is negligible.

For each loam quality three loam thicknesses are considered (d = 2 cm, d = 5 cm und d = 10 cm) and 3 different aspect ratios (surface-to-volume ratio A/V = 0.5 1/m, A/V = 1.0 1/m and A/V = 1.5 1/m). Moisture sources are kept constant with 330 g/h, the air change rate is varied with n = 0.2 1/h, n = 0.3 1/h and n = 0.4 1/h. The ambient moisture content is approximated with a periodic function such that the maximum sommer and minimum winter moisture contents are matched. The monolithic loam walls are considered as internal walls (20 °C at both sides). Vapour transfer occurs only on the internal side of the walls (external vapour tight walls). The moisture transfer coefficient is assumed to be constant with β = 2.1e-8 kg/(m s Pa).

The transient response of the indoor relative humidity of the different loam qualities with the three wall thicknesses shows significantly different behaviour, see fig. 14. For the low (clay mortar) and the average (Loam LMH (Hist.)) loam quality– independent of the loam thickness and the aspect ratio – quasi steady state is reached within 2 to 3 years. Contrariwise, it takes more than five years for the high loam quality (Clay Tu2 PV 0 439) with a thickness of 10 cm to reach steady state. Even for an aspect ratio of A/V = 0.5/m with a loam thickness of 10 cm the duration to reach quasi steady state is about 4 years.

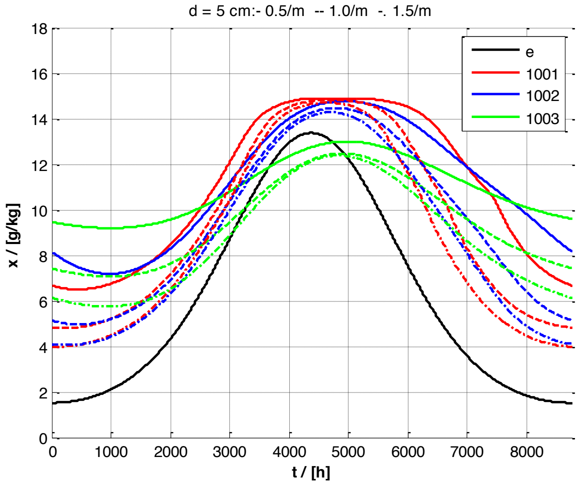

Figure 14: Development of the indoor air moisture content with time (quasi steady state) for the 9 cases: 3 qualities (1001 = clay mortar, 1002 = Loam LMH, 1003 = Clay Tu2 PV 0 439) and 3 aspect ratios (0.5/m, 1.0/m and 1.5/m) for the thicknesses of 5 cm for a periodic approximation of the ambient moisture content (e)

In fig. 15 for the three loam qualities and the three loam thicknesses the minimal values of the indoor moisture content (for quasi steady state conditions) are plotted vs. the aspect ratio and in fig. 16 vs. the ventilation rate.

The relative change with regard to the minimum value (A/V = 0.5/m, d = 2 cm, low loam quality) has to be taken for evaluation (the absolute values are less meaningful due to the simplification regarding the model and the boundary conditions).

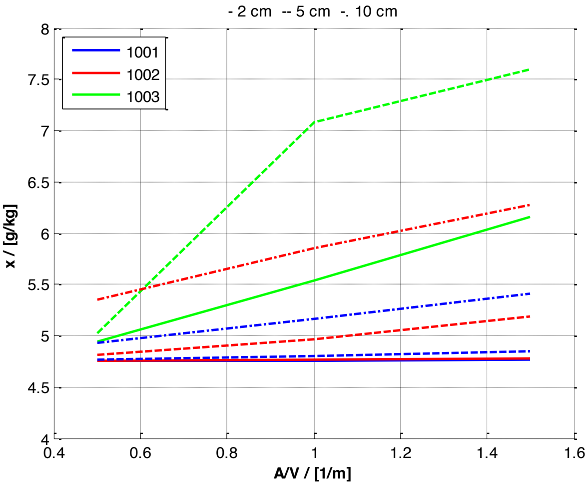

Figure 15: Minimal values of the indoor moisture content as a function of the aspect ratio for the three loam qualities with the thickness as parameter and a ventilation rate of n = 0.3/h

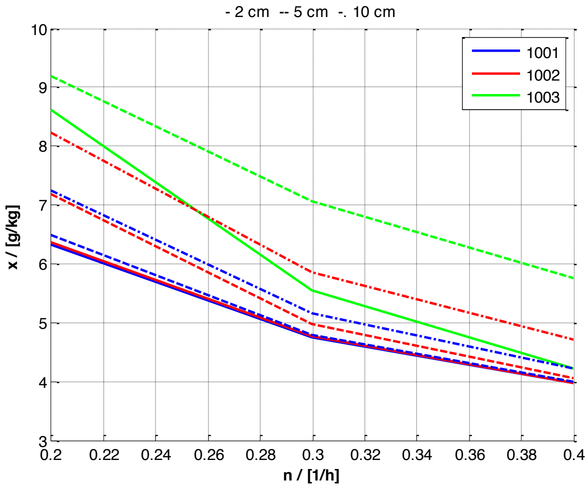

Figure 16: Minimal values of the indoor moisture content as a function of the ventilation rate for the three loam qualities with the thickness as parameter and an aspect ratio of A/V = 1.0/m

For the seasonal moisture storage potential, supposed there are sufficient usable moisture sources, besides the aspect ratio and the thickness, the loam quality is of prior importance. Whereas low loam quality cannot or only hardly be compensated by means of wall area and loam thickness, the influence of loam quality can be recognised already in case of relatively small areas (A/V = 0.5/m) and loam thickness (d = 2 cm).

In case of the lowest loam quality a significant influence of the aspect ratio is only recognisable for a loam thickness of 10 cm. For the average loam quality at least 5 cm are necessary to achieve an increase of the minimum value of the indoor relative humidity with increasing aspect ratio. However, with the good loam quality remarkable results (5.0 g/kg instead of 4.75 g/kg) can be obtained even if only 2 cm of loam is used in a room with an A/V-ratio of 0.5/m. The positive effect increases significantly with increasing loam thickness and aspect ratio (here 7.75 g/kg instead of 5.25 g/kg).

Generally, the influence is higher in summer with the high moisture contents (peak shaving) than for the low moisture contents in winter. For real wall constructions (in contrast to the monolithic walls used in this simulation study) and real boundary conditions (instead of the periodic ones and the isothermal room) the seasonal moisture buffer should have minor effect, but still enough to reduce the problem of the low indoor humidity in winter.

CONCLUSION

The influence of the moisture buffer potential of loam on the indoor air humidity was investigated by means of laboratory experiments, by means of monitoring and by means of building simulation coupled with heat and moisture transfer models (Dynbil, Matlab).

Two types of loam have been investigated by laboratory experiments (on material and on component level). Loam quality in terms of moisture retention and water vapour diffusion resistance can differ significantly.

With the monitoring as well as with the simulation results of the terraced houses in Kramsach a significant reduction of the low indoor humidity in winter could not be observed. The influence of the user is at least in the same range than the influence of different constructions.

However, as could be proved by means of a more general investigation applying a simplified room model with different loam qualities, different loam thicknesses and A/V-ratios, a significant reduction of the low indoor moisture content can be achieved with appropriate loam quality (in terms of moisture retention and moisture diffusion resistance). In contrast, with poor or average loam quality even with large areas and high loam thickness positive effects may not be obtained. Thus, future work should concentrate on the improvement of loam formulations. Then, in addition to other advantages of loam such as thermal mass, short time moisture buffering, sound absorption, absorption of VOC (Darling et al. 2012) as well as low environmental impact, the seasonal moisture buffer potential of loam may contribute to the reduction of the low indoor humidity in winter.

NOMENCLATURE

Latin

A	$[m^2]$	*Area*
c	$[J/(kg\ K)]$	*heat capacity*
$D_{m,\varphi}$	$[kg/(m\ s)]$	*Transport Coefficients*
$D_{m,T}$	$[kg/(m\ s\ K)]$	
$D_{e,\varphi}$	$[W/m]$	
$D_{e,T}$	$[W/(m\ K)]$	
h	$[J/m^3]$	*Volumetric enthalpy*
n	$[1/s]$	*Air change rate*
p	$[Pa]$	*Pressure*
R_v	$[J/(kg\ K)]$	*Gas constant of vapour*
t	$[s]$	*Time*
T	$[K]$	*Temperature*
u	$[kg/m^3]$	*Volum. water content*
V	$[m^3]$	*Volume*
x	$[g/kg^3]$	*Moisture content*
x	$[m]$	*position*

Greek

β	$[s/m]$	*Mass transfer coefficient*
ρ	$[kg/m^3]$	*Density*
ϕ	$[\%]$	*Relative humidity*
λ	$[W/(m\ K)]$	*Thermal Conductivity*
μ	$[-]$	*water vapour diffusion resistance number*

Subscripts

e	*external*
i	*internal*
l	*liquid*
l	*loam*
s	*surface*
s	*saturation*
t-1	*last time step*
tot	*total*
w	*wall*
v	*vapour*

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