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NUMERICAL SIMULATION OF DYNAMIC MOISTURE SPREAD IN COMPACT FLAT ROOFS

Martin Haladej

ABSTRACT

The contribution is focused on the numerical verification of the correct design of compact flat wooden roofs in the external boundary conditions of Central Europe (Vienna – Bratislava); the internal boundary conditions of the analysis met the requirements for human habitation. Using the WUFI 2D software, the compositions of compact flat roofs were analyzed using a vapor barrier and a variable vapor retarder with a low dispersion of diffusion thickness values and a variable vapor retarder with a high dispersion of diffusion thickness values. Each of these three compositions was assessed in versions without shading and with shading of the surface (by graveling the roof covering from the exterior side). The length of the analyzed period was 5 years. The main goal was to verify the accumulation of moisture in layers of the structure and whether critical moisture conditions suitable for the formation of molds and fungi causing rot will be reached in any of the compositions. The measurement results showed the different functioning of compact flat wooden roofs depending on the shading, as well as other conclusions for the design and realization of the composition of compact flat wooden roofs.

Keywords: dynamic evaluation; compact flat roof; moisture content; WUFI 2D software.

INTRODUCTION

When designing compact flat wooden roofs with a classic order of layers of overheated spaces, it is essential to design roof construction in such a way as to prevent excessive transport of moisture from the interior to the roof structure and to prevent moisture accumulation in the roof structure. The influence of humidity and temperature on the thermal conductivity of building materials was investigated by Wang *et al.* (2022). Björk and Enochsson (2009) investigated the change in the properties of thermal insulation materials due to changes in the environment; the work published by Kontoleon and Giarma (2016) verified the Dynamic thermal response of layers of building materials in terms of their moisture. The effect of the vapor barrier in an airtight compact flat roof was investigated by Nusser *et al.* (2010). Langerock *et al.* (2017) investigated the limited drying potential of a compact flat roof with in-situ measurements and its sensitivity to moisture penetration and verified the real impact of smart vapor barriers and the color of the waterproofing membrane on the hydrothermal properties of the structure under the conditions of the Belgian climate and exterior boundary conditions. The effect of an unventilated air cavity on the cold side of the insulation in unshielded wooden compact flat roofs was verified by Bachinger *et al.* (2016). The susceptibility of wood and wood-based building materials to attack by molds and wood-destroying fungi causing rot was verified by Vidholdova *et al.* (2016). Suitable conditions for the formation of molds and fungi on wood and wood-based materials were investigated by Viitanen and Ritschkoff (1991), Wang and Morris (2010) and Alev and Kalamees (2016).

In the currently valid Slovak and European technical standards STN 73 0540-2+Z1+Z2 and EN322, the moisture spread is most often evaluated according to a simplified graphic method – Glaser's method (Glaser, 1959). The method describes the spread of moisture through the structure only as the spread of water vapor through the structure depending on one material characteristic, diffusion resistance factor μ [-]. The spread of moisture in the structure depending on only one material characteristic of the built-in materials is reasonable only if we consider the spread of moisture only as the spread of water vapor through the structure and if the boundary conditions (partial pressures of water vapor on the interior and exterior sides of the structure) are constant. In fact, the spread of moisture is affected by variable boundary conditions, and therefore, moisture accumulation also occurs in constructions. The amount of accumulated moisture is described by a curve called equilibrium moisture or sorption isotherm (Mrlik, 1985). In porous materials, which are the majority of building materials (wood, concrete, various of thermal insulation), liquid moisture also spreads due to capillary forces (Krus, 1996). The variable temperature and relative humidity of the exterior and interior air are not the only factors affecting the spread of moisture in structures. This spread of moisture is influenced by e.g., also precipitation that falls on the outer surface of the structure, but also the influence of solar and long-wave radiation.

Since the 1950s, several physical models of the mutual propagation of heat and moisture in porous materials have appeared worldwide. Hill (2003) compared 45 different calculation programs predicting the spread of heat and moisture through construction structures to select suitable calculation programs that can be used in the design of structures from the point of view of moisture spread. Two computational numerical models, MATCH and WUFI, were recommended to assess of the spread of moisture and heat through packaging structures. WUFI software (Warme und Feuchte instationär) – dynamic evaluation method was created based on the dissertation by Künzel (1995) and is based on the following system of differential equations.

$$\frac{dH}{dT} \cdot \frac{\partial T}{\partial t} = \nabla \cdot (\lambda \nabla T) + h_v \nabla \cdot (\delta_p \nabla(\varphi\, p_{sat})) \quad (1)$$

$$\frac{dw}{d\varphi} \cdot \frac{\partial \varphi}{\partial t} = \nabla \cdot (D_\varphi \nabla \varphi + \delta_p \nabla(\varphi\, p_{sat})) \quad (2)$$

Where: dH/dT heat accumulation in wet materials [J/(m^3·K)],
dw/dφ moisture accumulation in materials [kg/m^3],
λ coefficient of thermal conductivity of wet material [W/(m·K)],
D_φ moisture capillary transport coeafficient [kg/(m·s)],
δ_p coefficient of diffusion permeability of the material [kg/(m·s·Pa)],
h_v specific heat of the group [J/kg],
p_{sat} partial pressure of saturated water vapour [Pa],
T temperature [K],
φ relative humidity [%].

Temperature and relative humidity re the unknowns in the aforementioned Künzel system of differential equations. Individual equations (1) and (2) are interconnected, i.e., the partial pressure of water vapor depends on the instantaneous temperature across the structure, the coefficient of thermal conductivity depends on the current moisture content of the material, and the thermal mass depends on the amount of moisture present across the structure. Künzel's numerical model provides the possibility to more accurately model transport phenomena (heat, moisture, energy) and, in contrast to the stationary standard calculation procedures specified in the set of technical standards STN 73 0540, allows for the modeling of heat and moisture propagation through the structure to include physical phenomena in the calculation as a dynamic simulation of heat propagation and moisture in the building structure with any time step, rotation of the structure with respect to the cardinal points and with respect to the horizontal plane, the influence of solar and long-wave radiation on the spread of heat and moisture in the structure, the influence of the color of the outer surface of the building structure on the spread of heat, accumulation of heat and moisture in individual layers structures, the dependence of the coefficient of thermal conductivity of the material on the amount of moisture in the materials, the dependence of the value of the diffusion resistance factor on the amount of moisture in the materials, the spread of liquid moisture in porous materials, the absorption of driven rain on the outer surface of the building structure. Among the most significant influences that Künzel's model does not include are hysteresis (accumulation of moisture depending on time), airflow through the structure, the salinity of the environment or the effect of snow cover.

From the above information, it follows that the procedures according to the mentioned currently valid technical standards for thermal and moisture assessment of building structures are simplified and do not correspond to the latest knowledge from the world of building physics and can thus lead to distorted conclusions. The aim of the theoretical analysis of the dynamic spread of moisture in compact flat roof constructions is to apply a more accurate method for evaluating the spread of moisture in structures and to verify the correctness of the design of compact flat roofs with a wood-based construction and to more comprehensively analyze the effect of using a vapor barrier, or vapor barriers with a variable value of the diffusion thickness S_d and a layer of gravel to spread moisture in the constructions.

Our research focuses on the dynamic spread of moisture in compact flat roofs. We aim to develop a more precise method for evaluating moisture spread in structures. This will help us confirm the accuracy of the design of compact flat roofs with wood-based construction, mainly when using vapor barriers with varying diffusion thickness S_d and a layer of gravel.

MATERIALS AND METHODS

Analyzed constructions of compact flat roof

During the analysis of the moisture properties of compact flat roofs based on wood, six types of structure compositions were created. Different types of a vapor barrier or vapor retarder (vapor barrier with high diffusion thickness (S_d= 300 m), vapor retarder with variable diffusion thickness with an extensive range (S_d = 0.5-30 m), or vapor retarder with variable diffusion thickness with a small range (S_d = 0.3-5m)), while each of these versions were considered in two variants. The first variant is with gravel backfill, and the second is without a layer of gravel backfill. The most crucial step was selecting assemblies commonly used in national conditions for compact flat roofs based on wood. The structural and material design of the individual assemblies S1A-S1C and S2A-S2C used to determine the moisture behavior is shown in Fig. 1 and Fig. 2 (mPVC – a waterproofing film made of softened polyvinyl chloride, EPS – expanded polystyrene, OSB – oriented strand board, SDK –

plasterboard). For the numerical analysis in the WUFI program, a model of those mentioned above compact flat roofs with a length of 1500 mm was modeled in the "Geometry" section.

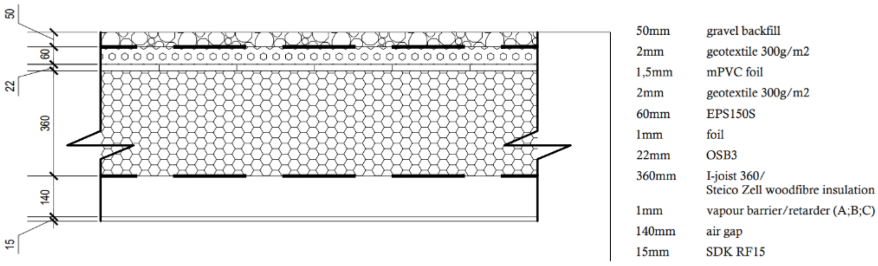

Fig. 1 Structure composition of wood-based compact flat roof with gravel backfill, versions S1A-C (version A – vapour barier S_d=300m; version B – vapour retarder S_d=0.3-5m; version C – vapour retarder S_d=0.5-30m)(author).

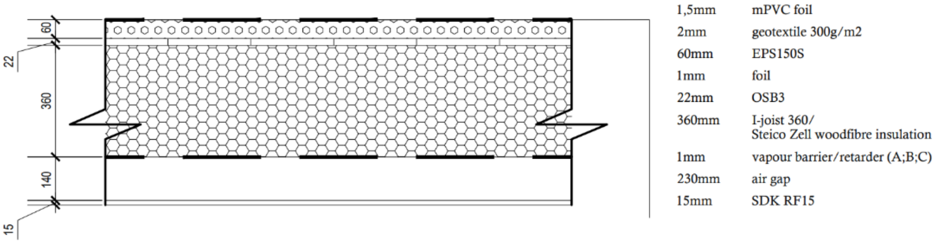

Fig. 2 Structure composition of wood-based compact flat roof without gravel backfill, versions S2A-C (version A – vapour barier S_d=300m; version B – vapour retarder S_d=0.3-5m; version C – vapour retarder S_d=0.5-30m)(author).

Internal boundary conditions

For internal boundary conditions, the sinusoid shown in Fig. 3 was used for temperature and relative humidity to oscillate between 20°C (winter) and 22°C (summer), the average internal temperature is 21°C. The relative humidity varies between 40% (winter) and 60% (summer), the average relative humidity is 50%. These internal boundary conditions are anchored in technical standard EN 15026 and WTA Guideline 6-2 and are recommended for hygrothermal simulations (Künzel, 2014).

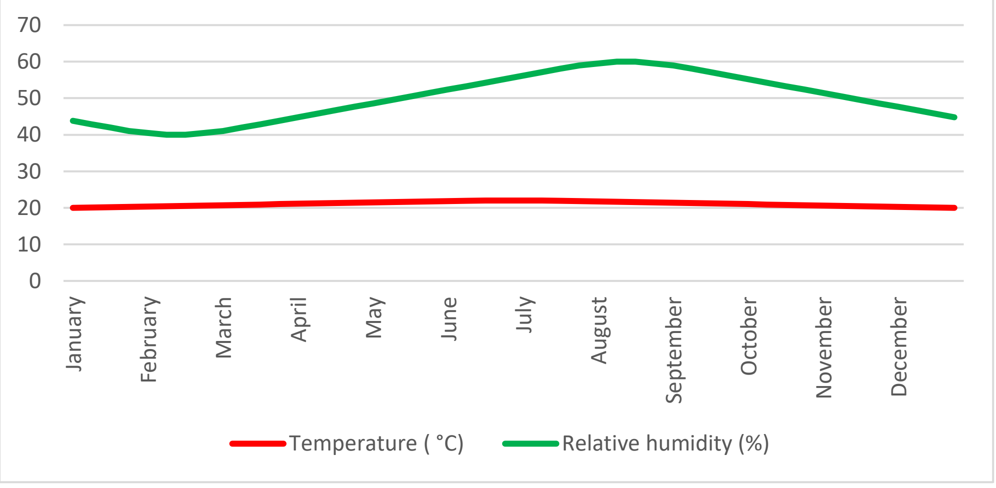

Fig. 3 Boundary conditions on the interior side of the structure during year.

External boundary conditions

For the external boundary conditions, the Vienna area was chosen because it is the closest location that contains hourly data collection for temperature, relative humidity and solar radiation Fig. 4. For the external boundary conditions, the measured hourly values of the following quantities were used: temperature, relative humidity, amount of precipitation, direction and wind power, shortwave and longwave radiation.

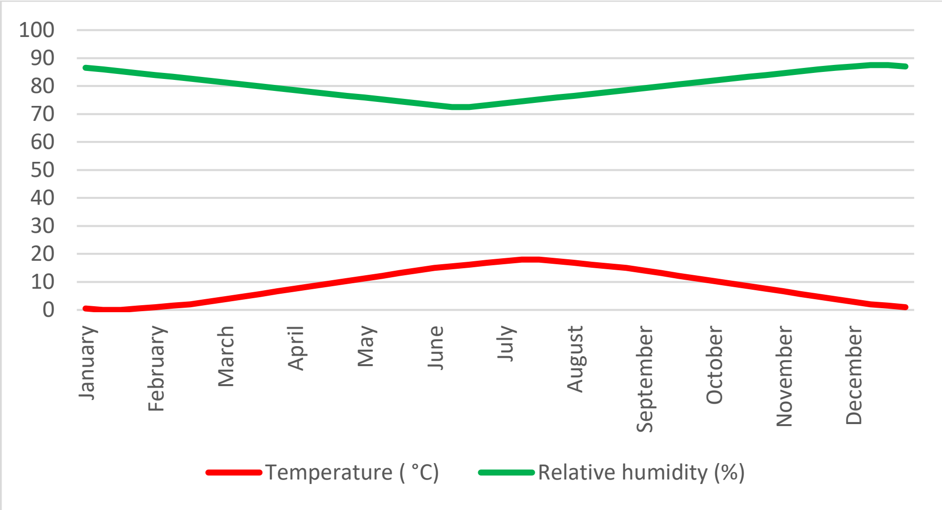

Fig. 4 Boundary conditions on the exterior side of the structure during year.

Setting up numerical analysis in the WUFI program

After modeling the geometry of fragments of compact flat roofs and determining the individual materials in their compositions, the data for the computational network was entered into the calculation. The modeled fragment was divided into 20 elements along the width (axis X) and 30 elements along the height (axis Y), with the fact that each layer of the composition, even the thinnest one (vapor barrier or vapor retarder), consists of at least two units. Data from the WUFI database were determined as initial conditions for individual materials. Table 1 contains data on temperature (°C), water content in materials (kg/m3) and relative humidity (%).

Tab. 1 Initial conditions of materials (WUFI Database – Fraunhofer IBP)

Material	Temperature (°C)	Moisture content (kg/m^3)	Relative humidity (%)
Gypsum board – SDK	20	6.3	80
Air layer 140 mm	20	1.88	80
Vapor barrier/retarder	20	0	80
Wood-fiber insulation	20	5.9	80
OSB3	20	90	80
PE-membrane	20	0	80
EPS 150S	20	1.8	80
Geotextille 300g/m2	20	5.9	80
SIKA Sikaplan G-15	20	0	80

In the calculation parameters, 43,800-time steps (hours) were entered corresponding to five years with a start date of October 1. The calculation was intentionally started before the winter season given the more demanding external boundary conditions exposed to the fragment during the winter period. Subsequently, the numerical analysis began.

Requirements for compact flat roof constructions from the point of view of moisture diffusion

In the numerical analysis, other requirements were chosen for evaluating the moisture spread in the roof sheathing than the current requirements stated in the standard STN 73 0540-2+Z1+Z2. The author evaluates the following requirements because he considers them sufficient for determining the long-term life of the roof sheathing from the point of view of moisture and its spread.

1. There must be no accumulation of moisture in the entire roof covering during the mentioned period.
2. There must be no accumulation of moisture in any layer of the roof covering during the mentioned period.
3. In wood-based layers, the critical moisture content of the material exceeding 20% will not be reached from the point of view of the risk of biodegradation by molds and wood-destroying fungi causing rot.

RESULTS AND DISCUSSION

Before evaluating the numerical analysis, the following hypotheses are considered:

1. In the compositions of compact flat roof structures using vapor barrier S1A, S2A, there will be the slightest moisture change in the structures during the annual cycles, and OSB and Zell will have the least moisture compared to the vapor retarder structure compositions S1B; S2B; S1C and S2C.

2. In compositions using a vapor retarder with a variable value of S_d, without gravel backfill S2B and S2C, sufficient overheating of the structure will occur during summer days. The moisture in the individual layers will rise slightly in the constructions during the colder months (October – April) but decrease significantly during the warmer months (May – September) and thus, there will be no accumulation of moisture in the constructions.

3. In compositions using a vapor barrier with a variable value of S_d and with gravel backfill S1B and S1C, there will not be sufficient overheating of the structure. The moisture in the individual layers will increase in the construction during the colder months (October – April) and decrease slightly during the warmer months (May – September). In structures with vapor retarder foils and gravel, sufficient overheating may not occur during the warmer months, which may result in the accumulation of moisture in these structures during the observed annual cycles.

The values of the outdoor air temperature and relative air humidity were entered into the numerical calculation as shown in Fig. 4. The indoor air temperature was 21 ± 1 °C and the relative air humidity was 50 ± 10%; the conditions corresponded to human occupancy in accordance with the European standards and WTA Guidelines, as shown in Fig. 3.

The analyzed structures of compact flat roofs were assessed from the point of view of the requirements determined by the author for the correct functionality of the structures. According to Fig. 5, it can be seen that the first requirement determined by the author, namely that moisture must not accumulate in the entire roof shell, is met by all assessed compositions of flat compact roof structures. There is no accumulation of moisture in any of the evaluated construction compositions. With repeating annual cycles, the compositions dry out over time. Compositions of constructions with gravel backfill (S1A; S1B and S1C) will reach the state of humidity after only two years. Compositions without graveling and with a vapor retarder film of variable diffusion thickness dry out significantly in the first years. Still, even after five years, these compositions do not reach a state of moisture balance, and the volume of moisture decreases further every year. The most significant amount of moisture and thus the risk with the greatest probability of biodegradation is concentrated in the oriented strand board – OSB and wood fiber thermal insulation Steico Zell, which can be seen in Table 2. Therefore, the results will deal with the analysis of moisture in these layers (oriented strand board – OSB and wood fiber insulation) in more detail. In Fig. 8 and Fig. 9, we can observe the course of moisture volume in individual compositions in the thermal insulation Zell and in the OSB board – the materials most stressed by moisture in the analyzed structure.

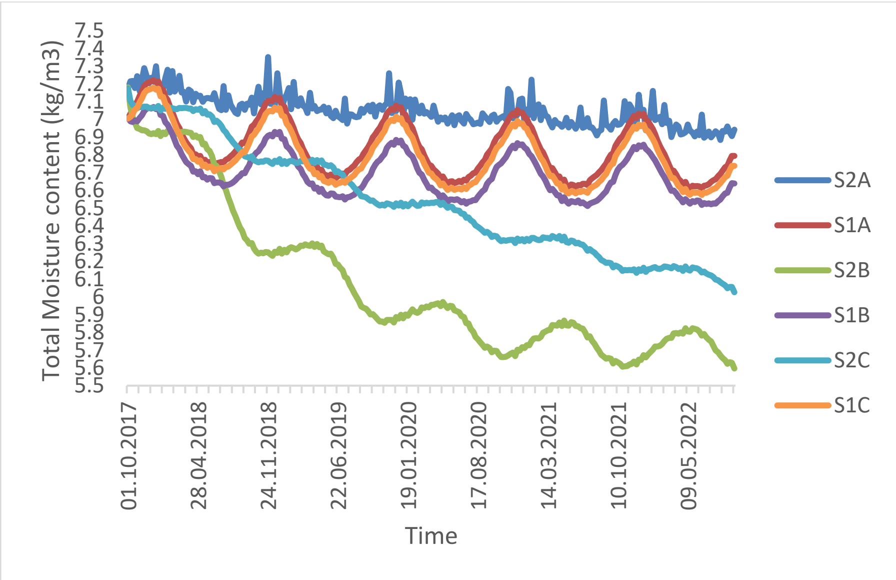

Fig. 5 Total moisture content in fragments of compact flat roof [kg/m^3].

Tab. 2 Total moisture content [M -%] after 1 year (WUFI2DMotion).

Layer	Gypsum board	Vapor barrier/ retarder	Steico Zell insulation	OSB	EPS
Sample	Moisture Content M [%]				
S1A	0.50	0.001	13.49	16.12	5.41
S1B	0.50	2.93	12.81	15.97	5.40
S1C	0.50	0.001	13.28	16.08	5.41
S2A	0.50	0.001	15.66	14.00	4.11
S2B	0.50	2.95	11.16	15.42	4.09
S2C	0.50	0.001	13.05	15.60	4.10

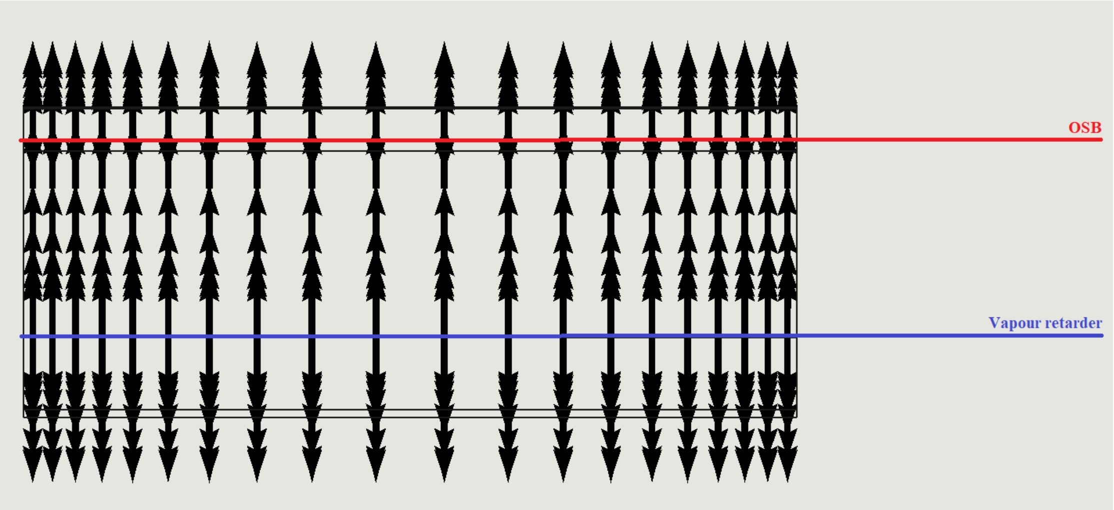

Fig. 6 Diffusion flux direction S2C in November – from ZELL to OSB (WUFI2DMotion).

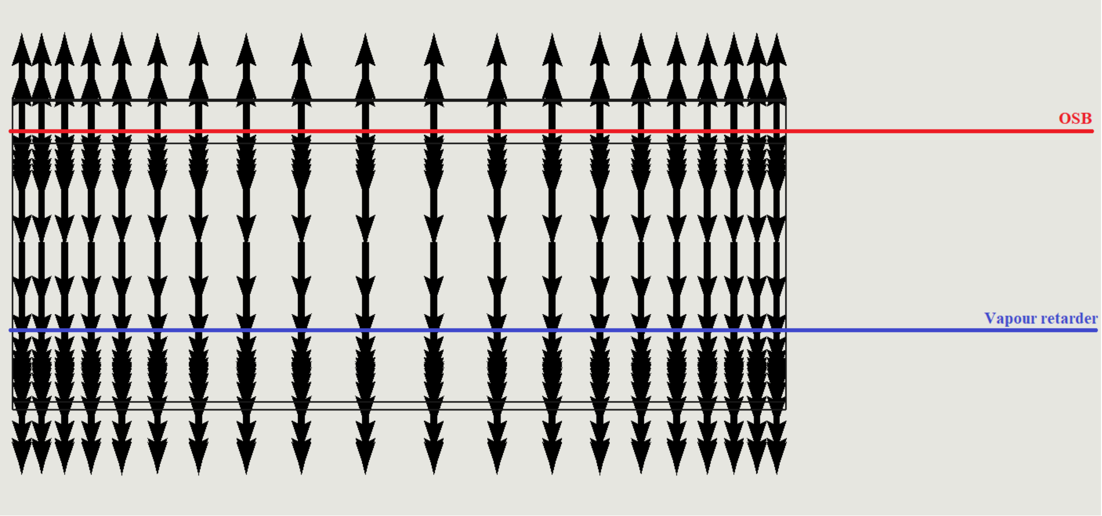

Fig. 7 Diffusion flux direction S2C in May – from OSB to ZELL (WUFI2DMotion).

Tab. 3 Average moisture content in OSB in the observed time period [M -%].

	S2A	S1A	S2B	S1B	S2C	S1C
	Moisture Content M [%]					
1st year	14.57	16.12	15.82	16.09	15.95	16.09
2nd year	14.17	16.26	15.46	16.11	15.88	16.22
3rd year	14.09	16.23	15.17	16.08	15.66	16.18
4th year	14.03	16.20	15.33	16.06	15.48	16.15
5th year	13.98	16.19	15.30	16.06	15.34	16.14

Tab. 4 Average moisture content in ZELL in the observed time period [M -%].

	S2A	S1A	S2B	S1B	S2C	S1C
	Moisture Content M [%]					
1st year	15.17	13.59	12.78	13.10	13.54	13.45
2nd year	15.47	13.12	10.75	12.55	12.56	12.94
3rd year	15.41	12.99	9.72	12.44	11.83	12.80
4th year	15.31	12.92	9.06	12.40	11.21	12.74
5th year	15.22	12.88	8.92	12.38	10.68	12.70

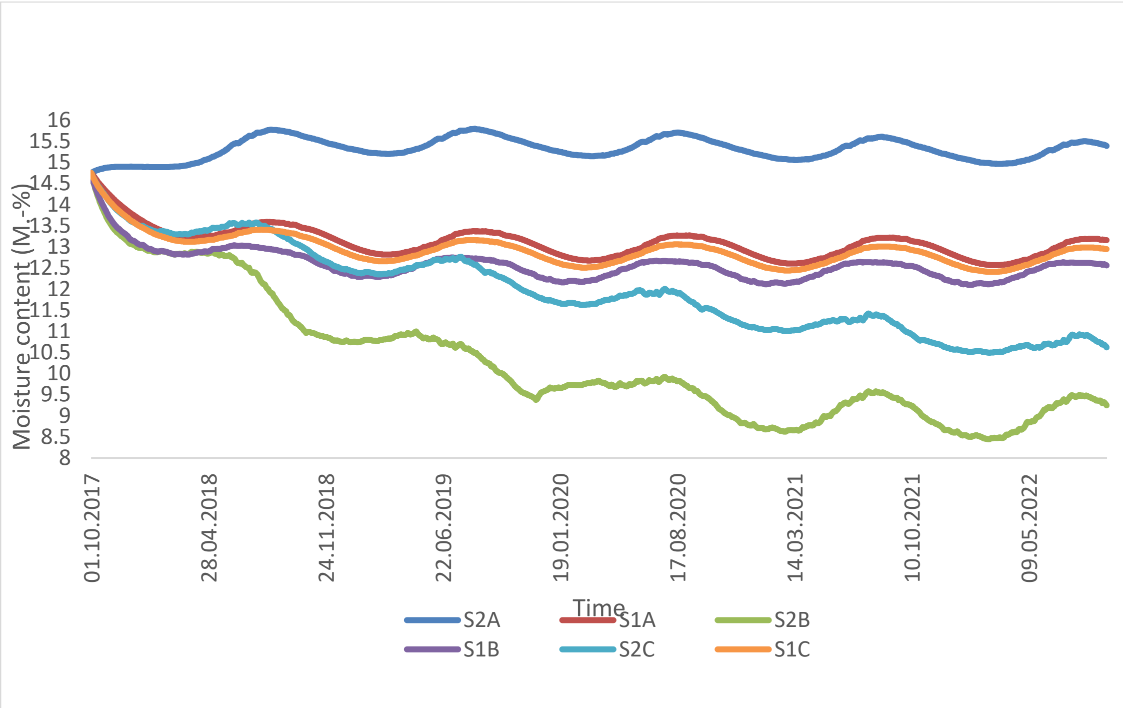

Fig. 8 The moisture content of Wood fiber insulation ZELL.

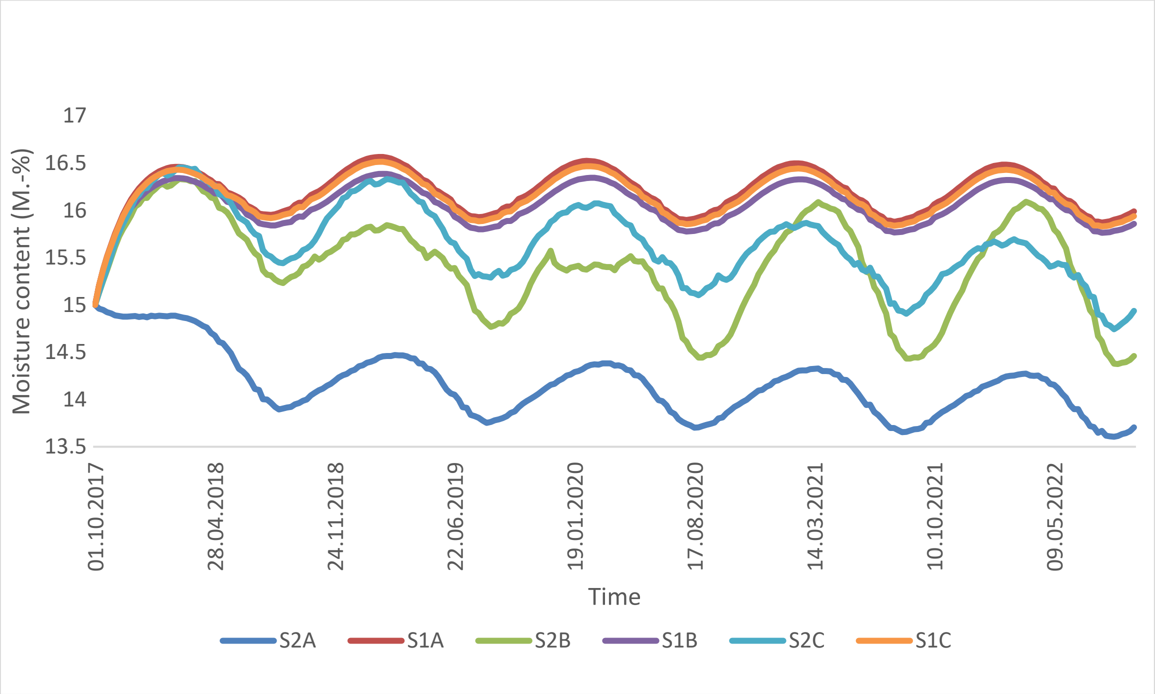

Fig. 9 The moisture content of the OSB – oriented strand board.

From these images, it is evident that the influence of roofing on the moisture behavior of the structure is comparable to the effect of shading on moisture properties (Nusser *et al.* 2010, Bachinger *et al.* 2016). Tracks with gravel backfill S1A, S1B, and S1C reached moisture balance during the first year of the calculation, and the moisture content of the most stressed materials varies in annual intervals without much change. In the compositions without gravel backfill S2A, S2B and S2C there is more overheating of the structure during the summer months. The consequence of this overheating of the structure is the rotation of the diffusion flow of moisture in the structure in the area of the OSB and the vapor barrier or vapor retarder shown in Fig. 6, Fig. 7. In the case of using a vapor retarder (S2B, S2C), compared to the use of a vapor barrier (S2A), there is a reduction in the moisture of wood fiber insulation Zell – drying. The drying in the thermal insulation layer is most pronounced in the case of S2B constructions, where a vapor retarder film with a variable diffusion thickness is used with a low dispersion of the values (0.3 – 3m). The differences can be compared with "on-site measurements" (Langerock *et al.* 2017).

In Table 3, we can see that the average moisture of OSB decreases over time in all compositions. Table 4 shows a significant decrease in the average moisture of wood fibre insulation Zell. After five modeled years, the highest moisture is in the compositions with the use of a vapor barrier S1A and S2A.

From the results of the modeling and analysis of moisture in wood fiber thermal insulation Zell in Fig. 9 and OSB in Fig. 8, it is possible to evaluate the author's second and third requirements for moisture propagation in a compact flat roof. No moisture is accumulated in any version of the construction tracks or in any layer of these tracks. At the same time, in any layer of a compact flat roof, the moisture will not reach a critical value exceeding 20%. This did not meet any requirements for the risk of biodegradation by molds and wood-decay fungi (Viitanen and Ritschkoff 1991, Venäläinen *et al.* 2003, Wang and Morris 2010, Alev and Kalamees 2016).

The first hypothesis that in the composition of constructions with the use of vapor barrier S1A and S2A, there will be the smallest change in moisture and the layers of OSB and Zell will be the driest compared to other analyzed compositions, is partially refuted by the analysis. We can completely refute it in Fig. 9, where we can see that wood fiber insulation Zell has the highest moisture in constructions with the use of a vapor barrier S1A, S2A. This is due to the fact that during the summer period, when, according to Fig. 7, the diffuse flow of moisture is reversed from the OSB through Zell to the vapor barrier, the moisture stops on the vapor barriers and accumulates there. When using a vapor retarder, this moisture is released to a certain extent. When evaluating OSB moisture, the first hypothesis is partially disproved. In the composition with gravel backfill S1A, OSB has the highest moisture content of the analyzed compositions, but in versions without gravel backfill S2A, OSB has the lowest moisture content.

The second hypothesis suggested that in compositions using a vapor retarder with a variable value of Sd (diffuse thickness) without gravel backfill S2B and S2C, the moisture in the individual layers of the structures would increase more during the colder months (October – April) than in a structure with a vapor barrier, but decrease more significantly during the warmer months (May – September), thereby preventing moisture accumulation, is confirmed by our analysis. Fig. 9 and Fig. 8 provide strong evidence that there is no moisture accumulation in annual cycles during the analyzed period of five years. However, the variance of moisture between summer and winter is the highest, a key finding that supports our second hypothesis.

The third hypothesis, which anticipated that in compositions using a vapor retarder with a variable value of S_d and with gravel backfill S1B and S1C, there would not be sufficient overheating of the structure, the moisture in the individual layers would increase during the colder months (October – April), and decrease slightly during the warmer months (May – September), is partially confirmed by our analysis. In structures with vapor retarders and gravel backfill S1B and S1C, sufficient overheating may not occur during the warmer months, potentially leading to moisture accumulation in these structures during the observed annual cycles. It is important to note that sufficient overheating was not the focus of this analysis. However, according to Fig. 9 and Fig. 8, we can confirm that moisture accumulation does not occur in structures S1B and S1C during the observed five annual cycles, a significant finding that supports our third hypothesis.

CONCLUSION

Based on the objective of the contribution to compare functionality when using different types of vapor barriers and shadowing compact flat roofs the following results can be presented:

- The built-in moisture in the structures during construction is decisive for the roof's moisture functioning. If the structure gets wet during construction, the risk of mold formation and its spores and fungi causing rotting increases significantly.
- With the correct implementation of the vapor barrier in the compositions S1A and S2A and the vapor retarder in the compositions S1B, S1C, S2B and S2C, the analyzed compositions of compact flat roofs are safe from the point of view of moisture. The choice of materials and the arrangement of layers in the analyzed compositions do not show an increased risk from the point of view of thermal moisture properties. When using a vapor barrier, the importance of the correct vapor barrier layer is the most important, since the ability of the structure to dry with the use of a feather barrier is the lowest.

- It has been shown that in the case of using vapor retarder foils with a variable S_d value, compact flat roofs without graveling can dry out more significantly during the summer season and thus prevent the formation of molds and fungi.
- The WUFI analysis showed that the effect of graveling a compact flat roof, or its shading is significant from the point of view of the flow of moisture in the structures. Versions without gravel backfill show, after five annual cycles, lower moisture in the most moisture-exposed insulation materials Zell and OSB compared to the same construction compositions that were gravelled.
- Numerical analysis of selected compositions of compact flat roof constructions showed the fact that in the analyzed compositions the graveling of the roof or other shading of the exterior surface of the roof (green roof, photovoltaic panels, solar system, air-conditioning technology, etc.) affects the moisture regime of a compact flat roof more than the choice of vapor barrier layer (foil), whether vapor barrier or vapor retarder with variable diffusion thickness, and therefore it is necessary to in the proposals, focus on the fact whether the roof will be gravelled, or whether it will be shaded in another way mentioned above.

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AUTHORS' ADDRESSES

Ing. Martin Haladej
Technical University in Zvolen
Faculty of Wood Sciences and Technology
Department of Wooden Constructions
T. G. Masaryka 24
960 01 Zvolen
Slovakia
xhaladejm@is.tuzvo.sk
haladej.martin20@gmail.com

M-House, s.r.o.
Hranicna 18
825 05 Bratislava
Slovakia
haladej@mhouse.sk