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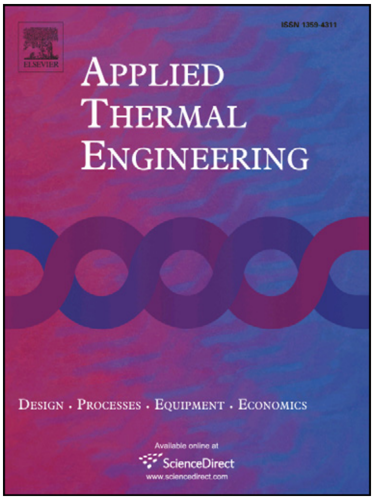

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Hygrothermal Performance Study of an Innovative Interior Thermal Insulation System

Abbreviated title: **Innovative Interior Thermal Insulation**

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Abstract

An innovative interior thermal insulation system on the basis of hydrophilic mineral wool which can serve as an alternative solution to the commonly used systems with water vapor barrier is presented in the paper. At first, the process of materials design is described. Then, the hygrothermal performance of the designed insulation system is tested in the difference climate conditions that correspond to the winter climate in Middle Europe. In the experiment, the profiles of temperature, relative humidity and liquid moisture content are monitored. Measured temperature profiles demonstrate the proper thermal insulation function of the system. The hygric function can also be considered very good as no water condensation during the whole testing period of five months appears in the insulation layer. Therefore, the basic requirements for the successful application of the system in building practice are met.

Keywords: interior thermal insulation system, hydrophilic mineral wool, water vapor retarder, hygrothermal performance

1. Introduction

Energy crisis in 1973 has claimed attention of building physicists, designers and building materials producers. Since that time, it was not able to construct buildings fulfilling mainly static function and forming interior space. For energy savings reasons, the indoor quality, thermal performance of buildings and hygienic requirements became suddenly focus of designers and investors. The hygienic quality of indoor space was until this time provided by natural infiltration of exterior air through building envelopes structures (above all trough the windows joints) and the thermal losses were fully compensated by heating systems [1]. However, this state was not sustainable. Because of rapid increase of heating expenses, it was necessary to solve the problem of thermal insulation of newly developed as well as of existing buildings.

The contemporary progress in material base of building materials is characteristic by rapid development of new thermal insulation materials and design of new structural and technological solutions. The progress is aimed at lower thermal losses of buildings, and answers the strict requirements of thermal technical standards. Various thermal insulation systems taking advantages of different types of thermal insulation materials on both organic (expanded plastics, wood wool, cork, straw, technical hemp) and inorganic basis (foamed glass, glass and mineral fibers) are being designed and tested, and new methods for analyzing the properties of both insulation materials and insulation systems are being devised [2]-[18]. The particular products differ in their shape, flammability, composition and structure, what in a relation to designers' requirements assigns the possibilities of their application in building practice.

2. Exterior and interior thermal insulation systems

For thermal insulation of existing and newly built structures, exterior thermal insulation systems are the most frequently applied. They are capable of formation of compact insulation layers; herewith the possible thermal bridges that can lead in specific cases to significant increase of thermal losses are easily eliminated. Application of exterior thermal insulation systems also reduces the thermal loading of envelope structures (especially of their joints) that are usually exposed to the negative effects of temperature and weather changes. The exterior insulation can be realized in the form of a contact system or with air gap. The contact insulation systems form compact structure. The thermal insulation plays here also the bearing role for surface layers. The facade surfaces are made mostly of plasters and sometimes of glued facings. In the case of systems with air gap the thermal insulation layer is fixed between the parts of bearing grid that supports the facade elements. These can be formed by glass, metal, wood, cement composites, ceramic materials, etc.

On the other hand, the interior thermal insulation systems can be found in building practice relatively rarely. The main reason for the less common usage of interior systems is that their application brings many problems from the view of building physics that must be taken into account and solved in advance. Nevertheless, sometimes there is no other reasonable chance than the application of the interior thermal insulation systems. A typical example is historical buildings where the preservation of original architectonical view of facades is one of the top interests of conservationists. The interior systems can also find use in buildings having complex facade surfaces.

The most obvious problems of interior insulation systems present thermal bridges that can not be fully eliminated. Another problem is the temperature differences in envelope walls that are not protected against external environment, thus the masonry can be faster deteriorated. The low heat accumulation in envelope structures and reduction of indoor space notably limit the possibilities of interior insulation systems as well.

Probably the most serious problem typical for interior thermal insulation systems is the risk of water vapor condensation in the thermal insulation layer. It can be prevented in two basic ways. A standard solution to this problem consists in application of vapor barrier (e.g. on polyethylene foil principle) under the internal plaster on the surface of the insulation layer, so that both the insulation layer and the load bearing structure are protected against water vapor. The risk of this construction solution consists in fact that the foil vapor tight barrier can be mechanically damaged. Afterwards, the vapor condensation can occur and the thermal insulation function will be reduced. In addition, even in the case that the barrier would perform without mechanical damage, the absence of water vapor removal from the interior through the envelope in the winter period, when the air ventilation in the interior is usually limited, can lead to an undesirable increase of relative humidity in the interior and to the worsening of the internal microclimate.

The second possible solution of the risk of water vapor condensation in the interior thermal insulation is utilization of capillary active or hydrophilic thermal insulation materials. The first steps in that direction were done during the last couple of years [19, 20]. The basic idea of the interior thermal insulation system designed in [19] consisted in the change of usually employed composition of the building envelope formed from the exterior to the interior by load bearing structure, thermal insulation, vapor tight layer and interior plaster by the following: load bearing structure, water vapor retarder having exactly specified water vapor diffusion resistance factor (allowing only such amount of water vapor to transfer which could not condensate in the load bearing structure), hydrophilic thermal insulation (special type of mineral wool) and water vapor permeable plaster. The system was proved to be effective in several specific cases. However, a universal solution valid for arbitrary load bearing structure was not found yet.

In this paper, the work done in [19], [20] is continued with new materials and new ideas for the solution of water vapor transport and water condensation problems typical for interior thermal insulation systems. The methods of directed design are applied to the materials of the chosen interior thermal insulation system; they consist of a combination of computational simulation techniques, laboratory experimental work aimed at the hygric and thermal properties of the studied materials and semi-scale experimental verification of the functionality of the system in the conditions of difference climate.

The materials of the thermal insulation system resulting from this type of design should be applicable universally, without restricting requirements and presumptions as for the material of load bearing structure.

3. Materials design of the innovative interior thermal insulation system

In the process of materials design, a detailed computational analysis of the studied problem was performed at first. A special attention was paid to the hygric and thermal transport and storage properties of hydrophilic thermal insulation material and water vapour retarder. Contrary to the previous investigations which were done in [19], [20], an additional condition was imposed that the resulting interior thermal insulation system should be independent of the material of the load bearing structure. The computational simulations were performed using the TRANSMAT computer simulation tool [21] where the model of coupled heat and moisture transport in multi-layered building envelope systems formulated by Künzel [22] was used. The parameter data for the materials of load bearing structure (ceramic brick, sandstone, argillite, granite, concrete) were taken from the TRANSMAT material database. The data for hydrophilic thermal insulation material and water vapour retarder were the free parameters in the computations.

The data of heat and moisture transport and storage properties of hydrophilic thermal insulation material and water vapour retarder which in computational simulations led to the proper hygrothermal performance of the system were passed to the material producers and were taken into account in the materials' manufacturing. The producers then delivered the following materials which were supposed to conform to the requirements given by the computational analysis: hydrophilic mineral wool Dachrock (Rockwool, Inc.), water vapor retarder SM-T FLT – a material on flexible cement glue basis (Mamut-Therm, Ltd.), and interior plaster SM-TJ VJ (Mamut-Therm, Ltd.) on lime basis.

In the further step of the materials design procedure, the measurement of basic parameters of manufactured materials was done. The reason for doing these experiments was to verify whether the requirements on material properties identified in the computational design were really met. The measured material parameters which are shown in Table 1 (ρ is the bulk density, c specific heat capacity, κ moisture diffusivity, μ water vapor diffusion resistance factor, λ_{dry} thermal conductivity in dry state, λ_{sat} thermal conductivity in water saturated state, θ_{sat} saturation moisture content and θ_{hyg} hygroscopic moisture content) were then used as input data for the final computational testing of the hygrothermal performance of the system.

A comparison of the properties of the new hydrophilic mineral wool Dachrock with the other types of mineral wool which were analyzed before in [23] showed that the moisture diffusivity of Dachrock was four to five orders of magnitude higher than moisture diffusivity of common mineral wools and even one to two orders of magnitude higher than for the previous types of hydrophilic mineral wool. This was the key factor for the successful use of Dachrock in the innovated interior thermal insulation system. The extremely high value of moisture diffusivity was achieved by a combination of two modes of liquid water transport in the material. The first was the surface transport of water along the fibers provided by hydrophilic surface treatment. The second was capillary water transport in the pores which were smaller than in previous types of hydrophilic mineral wool due to the higher density of Dachrock; this led to a substantial magnification of capillary effects.

The computational simulations with the real data for thermal and hygric parameters of the materials of the interior thermal insulation system confirmed the proper hygrothermal function of the system in several modifications as for the load bearing structure [24]. It was shown that the condensate annual balance of the structure was negative in the first year. The load-bearing structure was dried-out during the first summer after the application of the interior thermal insulation system. In the subsequent four years, no overhygroscopic moisture appeared in the whole structure. Based on the promising results of the computational simulations, an experimental hygrothermal performance study of the whole system in the conditions close to reality on building site could be done as the final step of the design process.

4. Experimental setup for the hygrothermal performance study

The hygrothermal performance study was performed for the interior thermal insulation system described in the previous section which was applied on the 300 mm thick brick wall (Fig. 1). The tested structure was exposed to the difference climate conditions corresponding to the typical winter period, which is the most critical part of the year from the point of view of water condensation in building structures. On the exterior side, climatic hourly data for the time interval of November 1 to March 27 were simulated according to the test reference year (TRY) data for Prague obtained by meteorological measurements. On the interior side, the wall was exposed to natural climatic conditions in the testing laboratory which corresponded to the values typically observed in residential houses in Czech Republic (relative humidity 20-60%, temperature 20-26°C).

The experiment was performed using the measuring and simulation system NONSTAT (Fig. 2, see [25] for details). The system consisted of a climatic chamber for simulation of external climatic conditions which was connected to an external tunnel provided with thermally insulated walls. The analyzed specimen was placed inside the tunnel. In order to ensure 1-D heat and moisture transport conditions, the specimen was water- and vaporproof insulated on all lateral sides and the space between the specimen and the walls of the tunnel was filled with foamed polyurethane. The external face of the tunnel with the specimen was exposed to the laboratory environment. In the tested structure, the monitoring of liquid moisture content, relative humidity and temperature was performed. The liquid moisture content was measured using a time-domain reflectometry (TDR) device by Easy Test, Ltd. TDR is a microwave moisture measurement method based on relative permittivity assessment. The particular device used in the experiment works in the frequency range of 50 MHz to 2 GHz [26]. The accuracy of moisture content measurement given by the producer is ± 2% in the water saturation range of 0-100%. For monitoring relative humidity and temperature, commercially produced combined sensors by Ahlborn were employed. The accuracy was as follows: capacitive humidity sensors were applicable in the humidity range of 5-98% with the accuracy of ± 2%, resistance thermometers had the accuracy of ± 0.4°C in the temperature range of -20°C to 0°C, and

± 0.1°C in the temperature range of 0°C to 70°C. The positioning of the particular sensors is shown in Fig. 3.

5. Experimental results and discussion

Fig. 4 presents temperature profiles in the insulated brick wall which clearly demonstrate the proper thermal insulation function of the system. Also, the temperatures of the interior surface are typically higher than 20°C what ensures the quality of indoor climate from the point of view of well-being of building occupants. These temperatures also reduce the risk of biological pollution of indoor climate as well as of the interior surface. Although one of the main disadvantages of interior thermal insulation systems in general is the exposure of exterior side of the load-bearing structure to the climatic loading without any insulation, in the investigated case the brick wall temperatures only rarely decreased deeper under the water freezing point. This finding which reflects the relatively mild weather conditions in Middle Europe is very positive, particularly regarding the durability of exterior surface layers.

The relative humidity profiles are given in Fig. 5. In the brick masonry, rather high relative humidity values were observed which corresponded with the measured liquid moisture profiles (Fig. 6). The content of liquid moisture was typically between 3 and 5%. The presence of this kind of moisture in the wall is a result of wetting of the studied structure during the specimen preparation. It did not evaporate until the end of the experiment because of applied winter climatic conditions which were chosen on purpose as the worst-case scenario. Nevertheless, we have good reason for conclusion that the liquid water is supposed to evaporate during the next summer period as it was proved in computational simulations.

In the whole thickness of the thermal insulation board, the relative humidity values were lower than maximum hygroscopic moisture content and the liquid moisture content was equal to zero. So, no water vapor condensation in the insulation layer or on its surface appeared during the whole winter period. This was an apparent consequence of the very high values of water transport parameters of the hydrophilic mineral wool used in the insulation system.

6. Conclusions

The hygrothermal performance study presented in this paper can be considered as further step towards routine application of interior thermal insulation systems without water vapour barrier in building practice. Contrary to the previous work which was done with this type of insulation systems in the past ([19], [20]), the proposed innovative solution does not depend on the type of load bearing structure. This was achieved mainly due to the remarkable improvement of water transport properties of the advanced types of hydrophilic mineral wool which lowered the significance of the properties of water vapour retarder for the proper function of the insulation system.

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Table 1 Basic parameters of the materials designed for the innovated interior thermal insulation system

Parameter	ρ [kg/m^3]	c [J/kgK]	κ [m^2/s]	μ [-]	λ_{dry} [W/mK]	λ_{sat} [W/mK]	θ_{sat} [Vol %]	θ_{hyg} [Vol %]
Plaster - SM-T VCJ	1490	1000	8.0 e-9	18	0.50	1.53	42	9.5
Water vapour retarder SM-T FLT	1390	1050	2.5 e-10	12	0.61	1.70	44	1.0
Hydrophilic mineral wool Dachrock	170	800	4.84 e-5	7.1	0.047	0.72	93	0.21

Figure captions

Figure 1 Scheme of the studied structure

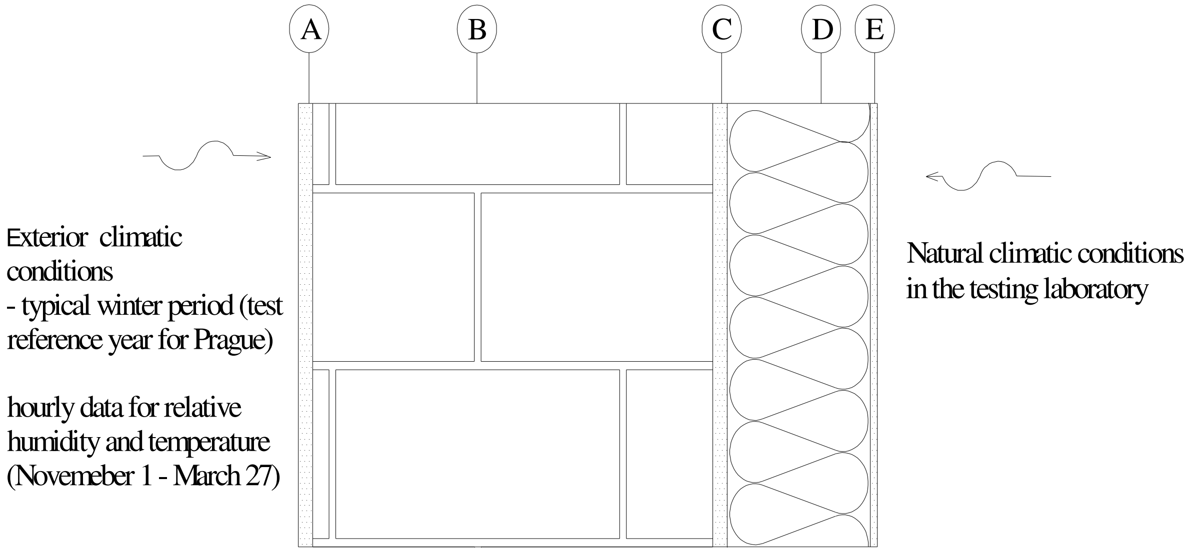
Figure 2 Scheme of the measuring and simulation system NONSTAT

Figure 3 Sensors positioning in the investigated structure

Figure 4 Temperature profiles in the insulated brick wall

Figure 5 Relative humidity profiles in the insulated brick wall

Figure 6 Liquid moisture profiles in the insulated brick wall



Exterior climatic conditions
- typical winter period (test reference year for Prague)

hourly data for relative humidity and temperature (Novemeber 1 - March 27)

Natural climatic conditions in the testing laboratory

A lime plaster SM - T VJ, Mamut-Therm, 10 mm
B brick wall, 300 mm
C retarder - cement glue SM - T FLT, Mamut-Therm, 3 - 10 mm
D mineral wool Dachrock, Rockwool, 100 mm
E lime plaster SM - T VJ, Mamut-Therm, 5 mm, reinforcing plastic net

Figure 1

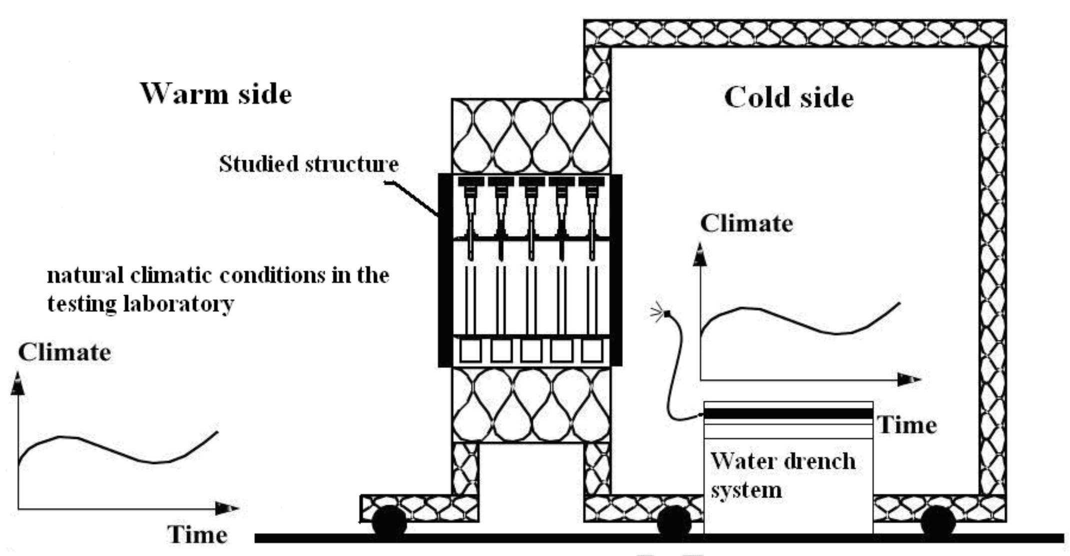
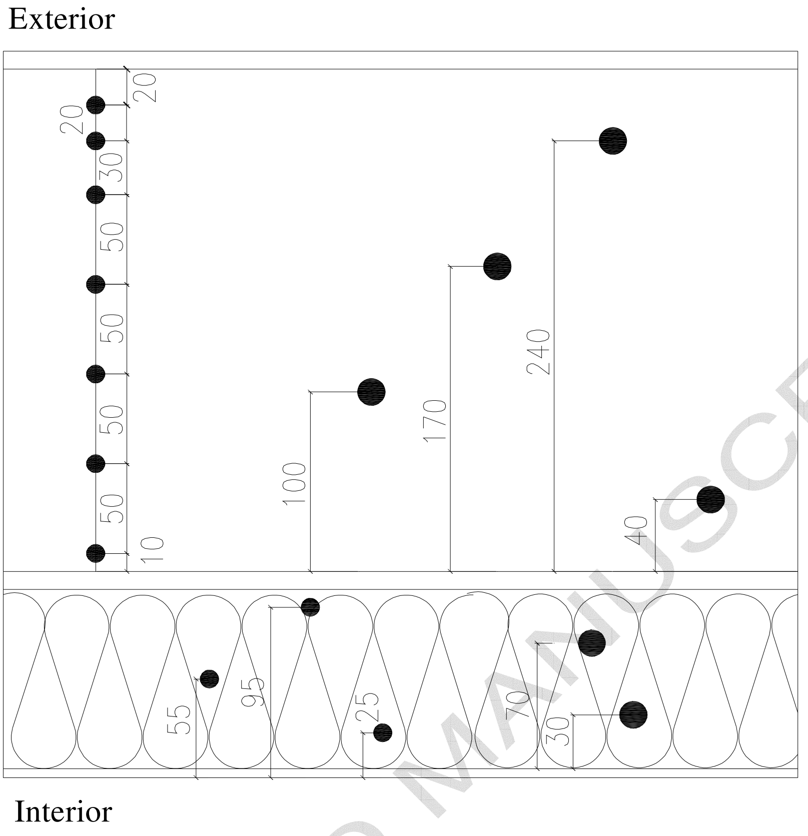

Warm side
Cold side
Studied structure
natural climatic conditions in the testing laboratory
Climate
Time
Climate
Time
Water drench system

Figure 2



• combined Ahlborn sensors - relative humidity, temperature

● Easy Test (TDR) sensors- liquid moisture measurement

Figure 3

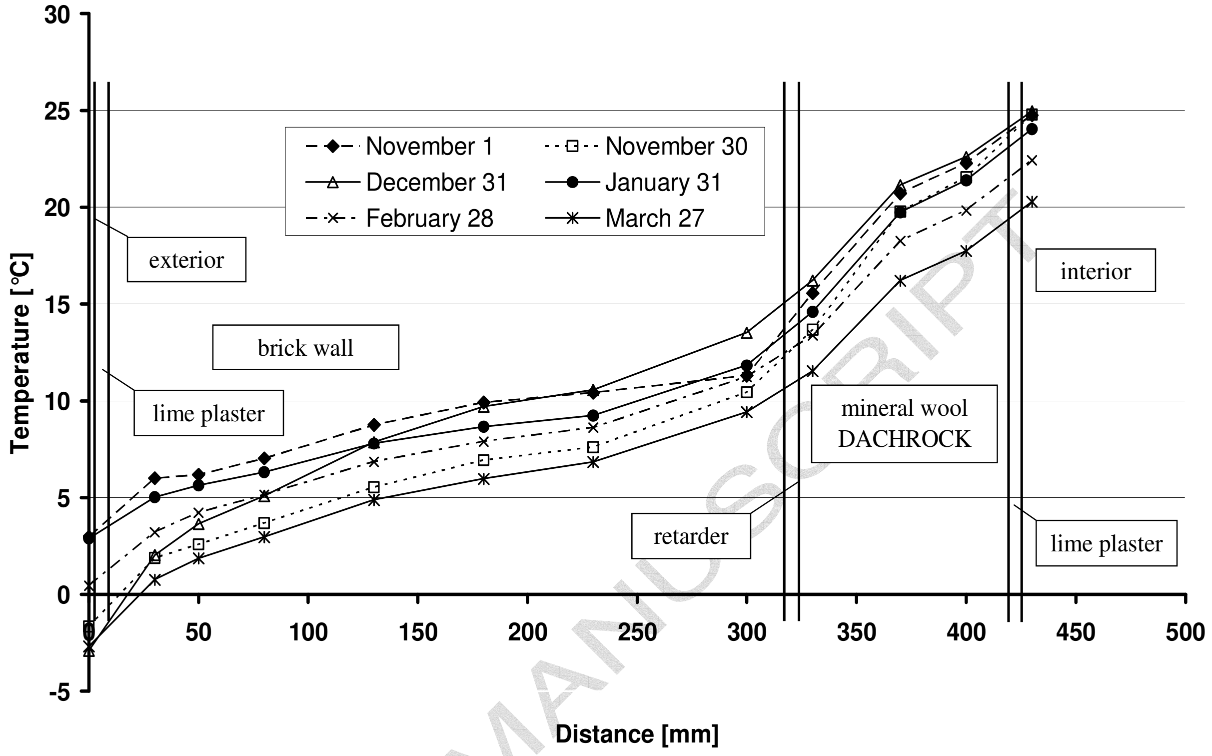

Temperature [°C]
Distance [mm]
30
25
20
15
10
5
0
-5
50
100
150
200
250
300
350
400
450
500
November 1
November 30
December 31
January 31
February 28
March 27
exterior
brick wall
lime plaster
retarder
mineral wool DACHROCK
interior
lime plaster

Figure 4

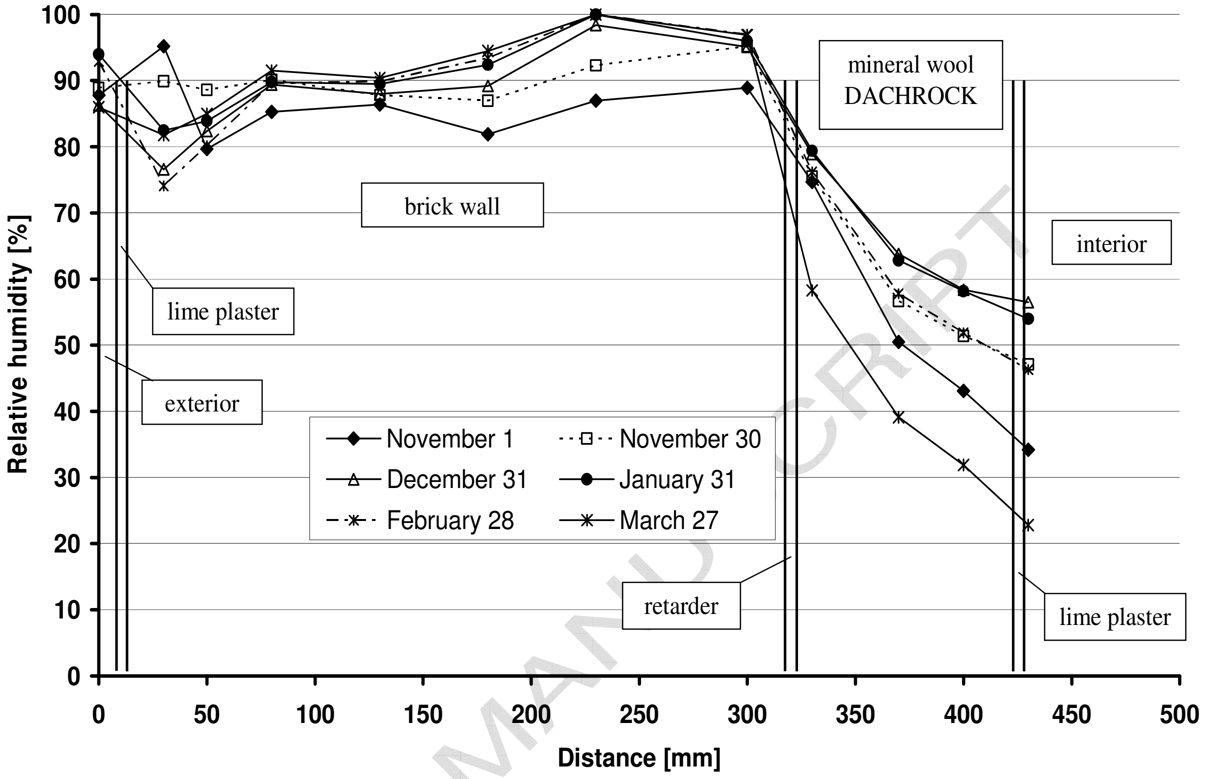

Relative humidity [%]
100
90
80
70
60
50
40
30
20
10
0
Distance [mm]
0
50
100
150
200
250
300
350
400
450
500
mineral wool DACHROCK
brick wall
interior
lime plaster
exterior
retarder
lime plaster
November 1
November 30
December 31
January 31
February 28
March 27

Figure 5

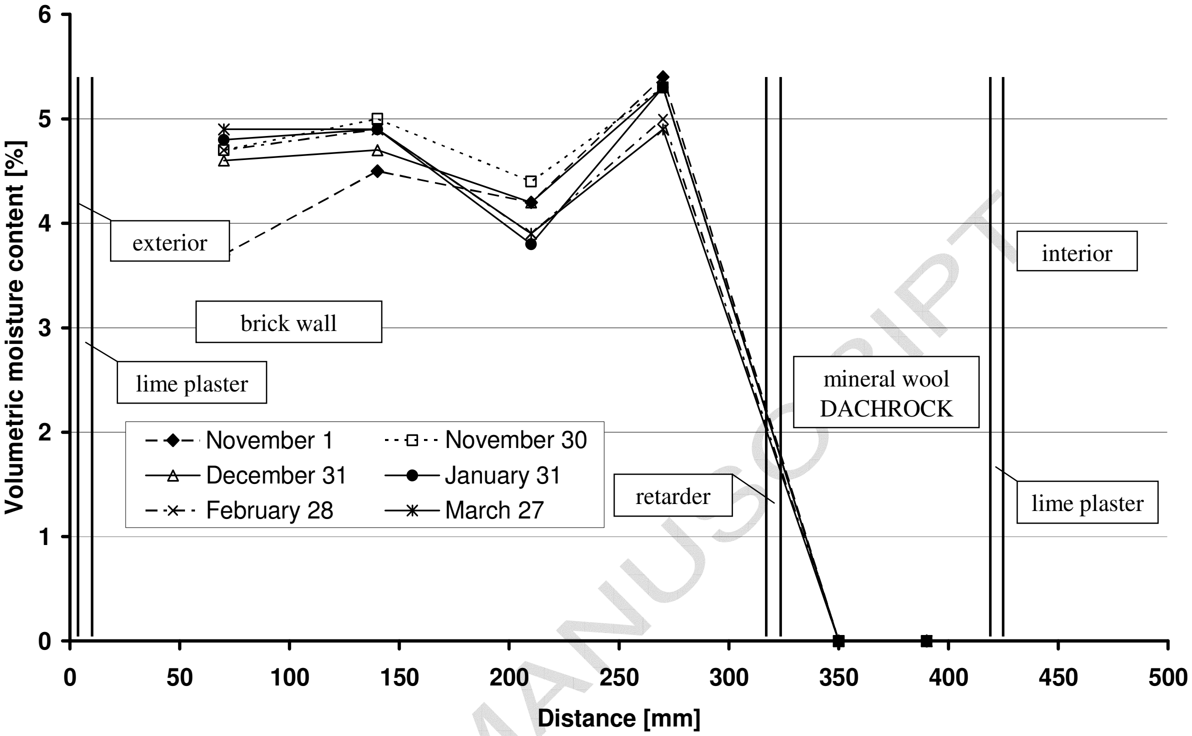

Volumetric moisture content [%]
Distance [mm]
0
1
2
3
4
5
6
0
50
100
150
200
250
300
350
400
450
500
exterior
brick wall
lime plaster
November 1
November 30
December 31
January 31
February 28
March 27
retarder
mineral wool DACHROCK
interior
lime plaster

Figure 6