Hygrothermal performance of internally insulated masonry walls with embedded wooden beam heads: a field study on the impact of hydrophobisation

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Abstract. Internal insulation remains often the only option to thermally upgrade massive masonry. Unfortunately, internal insulation can significantly change the wall’s hygrothermal performance, resulting in a higher risk on frost damage, wood rot of embedded beam heads, etc. The application of hydrophobisation is often put forward as a potential measure to avoid moisture problems, though more research on the impact of hydrophobisation is still required. Thereto, the current paper presents the results of a field study on the hygrothermal performance of internally insulated masonry with embedded wooden beam heads, exposed to wind-driven rain. Both a vapour open capillary active and a vapour tight insulation system are studied. Mainly the moisture conditions near the back of the wooden beam head are found to be influenced by hydrophobisation, which lowers the relative humidity. Closer to the masonry’s interior surface, the choice of the insulation system also influences the results. In case of a well-applied hydrophobisation, overall, the vapour tight system shows a better performance than the capillary active vapour open system. An exception to this is found for the first months after applying the hydrophobisation and the insulation system, where a longer drying period is needed in case of the vapour tight system.

1. Introduction

To reach the 2030 energy targets, a thermal upgrade of our built heritage is necessary. When dealing with existing buildings, three post-insulation techniques could be applied to thermally upgrade the walls, i.e. cavity wall insulation, external insulation or internal insulation. From a building physics point of view, internal insulation is the most risky, as this technique can lead to a higher moisture level and a colder temperature in the wall [1]. For massive walls in an urban context or with a valuable exterior facade, however, internal insulation remains as the only option. Hence, potential measures to diminish or to avoid the risk on frost damage, wood rot of embedded beams and other damage patterns have been put forward [2,3]. One of these measures is the application of a hydrophobic treatment. In recent years, a few field studies including hydrophobised walls with internal insulation have been set up [2,4,5]; though a full understanding of the moisture behaviour of hydrophobised walls is still lacking. Additional field studies for different wall configurations or boundary conditions can help to obtain a better view on the physical phenomena and to check and improve numerical models. Therefore, this paper shows the results of a field study on the hygrothermal performance of a typical Belgian masonry wall with embedded wooden beam heads, exposed to wind-driven rain. Both walls with a vapour tight and with a vapour open capillary active insulation system have been studied, and the impact of a hydrophobic
treatment is evaluated. Additionally, non-insulated and non-hydrophobised walls are analysed as a reference.

2. Field test setup

2.1. Test walls
To study the impact of a hydrophobic treatment on internally insulated walls, six 1½ stone thick masonry test walls, approximately 32 cm thick, 0.6 m wide and 2.7 m high were constructed in two south-west oriented wall frames of the VLIET test building of KU Leuven (Figure 1a). The masonry assemblies were masoned by use of Vandersanden Robusta bricks ($A_{\text{cap}} \approx 0.61 \text{ kg/(m}^2\cdot\text{s}^{0.5})$) and lime mortar (ratio: 12.5 kg Saint-Astier NHL3.5, 50 kg River sand 0/2, 10 litres water; $A_{\text{cap}} \approx 0.26 \text{ kg/(m}^2\cdot\text{s}^{0.5})$ for mould cured mortar). Between the different test walls, a barrier was provided, such that the hygrothermal behaviour of the test walls was not affected by the adjacent test walls. The construction of the test walls was finalised by the end of August 2017, after which a drying period took place. On October 23th 2018, three of the six test walls were hydrophobised by use of Silres® BS SMK 2100 from Wacker Chemie AG, which is a solventless silicone micro-emulsion concentrate based on silanes and siloxanes [6]. An impregnation depth of 3 cm in the bricks was pursued, for which per m$^2$ wall 6.9 litres of a 10 vol% hydrophobic agent solution was applied by spraying. During the application of the hydrophobisation, the other test walls were protected, as shown in Figure 1b.

![Figure 1](image1.png)

**Figure 1.** Outside view of the field test setup: (a) south-west oriented side of the VLIET-test building with hydrophobised and non-hydrophobised test walls, (b) spraying of the hydrophobic agent.

In the study, the impact of two types of interior insulation was analysed: (1) a vapour tight system and (2) a vapour open capillary active system. Thereto, on the inside, two walls, of which one hydrophobised (H) and one non-hydrophobised (NH), were provided with a vapour tight XPS-insulation system, while two other test walls where internally insulated with calcium silicate (CaSi), see Figure 2a. Both systems were composed of a 10 cm thick insulation board which was fully adhered to the masonry by use of a product-specific glue mortar. Such a fully adhered application avoids air rotation behind the insulation system, and is thus preferential for the wall’s hygrothermal performance. The interior insulation systems were adhered to the masonry in the second half of December 2018. As an interior finish, the XPS- and CaSi-system were provided with a gypsum board and plaster layer, respectively. The remaining two test walls were left uninsulated (Non), and thus acted as reference walls. Hence, six different wall compositions were obtained: NH-XPS, NH-CaSi, NH-Non, H-XPS, H-CaSi and H-Non.

In each of the test walls, two wooden beam heads were embedded in the masonry (Figure 2a). The upper wooden beam heads were in contact with a mortar layer (Figure 2b), whereas for the lower wooden beam heads an air gap was present between wooden beam and masonry, and this at all sides except for the bottom of the wooden beam head (Figure 2c). This way, two extreme situations in respect to the ease with which moisture from an outdoor moisture source could reach the wooden beam were analysed. To prevent convective moisture transport and the associated enlarged moisture risk, an airtight connection between wooden beam and test wall was provided as discussed by Vereecken and Roels [7]. Thereto, if
present, the gap between wooden beam and masonry was sprayed up with flexible PUR-foam and the connection between wooden beam and masonry surface was sealed with an airtight tape. Idem, the gap between beam and insulation system was sprayed up and the connection between wooden beam heads and interior finish was sealed. To prevent vapour diffusion via the longitudinal wood direction, the end of the wooden beams positioned toward the room side were covered with bituminous paint.

Figure 2. Inside view of the field test setup: (a) six test walls with wooden beam heads, (b) upper wooden beam head in contact with mortar, (c) lower wooden beam head in contact with an air gap.

2.2. Climatic boundary conditions

The exterior climatic boundary conditions, i.e. temperature, relative humidity, wind speed, wind direction, rainfall on a horizontal plain and solar irradiation were recorded by two weather stations, of which one was located above the test building and one was located in the open field in front of the test building. Additionally, the wind-driven rain (WDR) load exposed to the test walls was measured via wall-mounted WDR gauges. Initially, two wall-mounted WDR gauges were positioned between the hydrophobised and non-hydrophobised test walls. In December 2019, two additional wall-mounted WDR gauges were positioned at half height of the test wall (Figure 1a). The four WDR gauges had a collection area of 0.2 m x 0.2 m, as used by Blocken and Carmeliet [8]. Figure 3 shows the WDR load measured by three of the four WDR gauges.

Figure 3. Wind-driven rain load as measured by the wall-mounted WDR gauges (the lowest WDR gauge showed some malfunctioning and is therefore omitted).

Inside the test building, temperature and relative humidity were logged. As shown in Figure 4, the indoor climate during the first measured winter period (2018-2019) can be classified as indoor humidity class 1. This low moisture load was attributed to a malfunctioning of the humidifier in the test building. In the second winter period of the measurement campaign (2019-2020), an elevated indoor moisture load which corresponds to humidity class 3 was exposed. In the third (still ongoing) winter period (2020-2021), presented by the blue unfilled markers, both days with a higher moisture load (ICC 4) and a lower moisture load (ICC 1) occurred.
2.3. Measurement techniques
The hygrothermal performance of the test walls was measured by use of a series of sensors (Figure 5). The temperature and the relative humidity in the test walls and of the indoor air were measured by use of in-house calibrated Thermo Electric Type 1 (class 1) thermocouples and Honeywell HH-4021 humidity sensors, with an accuracy of +/- 0.2°C and +/- 2% RH. Relative humidity sensors that had to measure the relative humidity in the (glue) mortar were protected by use of nylon and/or wrapped beforehand with the respective (glue) mortar. As such, sensors that showed some malfunctioning after a first contact with wet (glue) mortar could still be replaced.

Figure 4. Daily mean difference between indoor and outdoor vapour pressure as a function of the daily mean outdoor temperature, together with the boundaries specifying the internal humidity classes (ICC) [9].

Figure 5. Schematic view of one of the test walls with an indication of the position of the thermocouples, relative humidity sensors, heat flux sensors and moisture pins.

Apart from the sensitivity of the relative humidity sensors in case of contact with mortar, the relative humidity sensors are less accurate in the high moisture range and can stop working correctly. Therefore, in addition to humidity sensors, in-house made moisture pins, measuring the electrical resistance, were embedded in the test walls to analyse the moisture conditions at the back of the wooden beam heads, in the mortar in the masonry, in the glue mortar and in the calcium silicate. The electrical resistance of the material depends on the material’s moisture content, given the good electrical conductivity of moisture. The higher the materials’ moisture content, the lower the electrical resistance measured in the material. The electrical resistance method is mainly intended to be used in the high moisture range. For a more in depth description on the electrical resistance method, the reader is referred to specialised literature [10]. Furthermore, at half height of the test walls, a heat flux sensor was glued at the warm side of the masonry.
3. Results

The next sections show a selection of the measurement results of the field study. The focus is put on the relative humidity in the 1D-part (middle of the wall) and near the wooden beam heads. Hourly-averaged data are presented. At the beginning of the measurement campaign, the walls were non-hydrophobised and non-insulated. In the legend of the graphs, however, these walls are indicated from the start by their final state of hydrophobisation and interior insulation system.

3.1. Relative humidity in the 1D-masonry part

3.1.1. Position 5 - In the masonry wall. Figure 6 shows the relative humidity measured at Position 5 (see Figure 5). At the beginning of the measurement campaign a similar relative humidity is found for the six (at that moment still non-hydrophobised and non-insulated) test walls. When applying the hydrophobisation (at the end of October 2018), a steep increase in relative humidity can be observed (see the pink rectangle). Although an impregnation depth of 3 cm was pursued for the hydrophobic treatment, by spraying the water repellent solution, liquid is transported much deeper into the walls. This was also clearly noticed by the moisture pins embedded in the walls, as shown in [11]. In the non-hydrophobised walls the relative humidity remains below 70% during this period.

In December 2018 (yellow rectangle), the sensors were temporarily disconnected in order to apply the interior insulation systems. When reconnecting the sensors, also for the non-hydrophobised walls a relative humidity close to 100% was noticed, which could be attributed to a heavy wind-driven rain load during the past period. In the next months, a drying out can be observed, which is found to occur most easy for the hydrophobised non-insulated wall and the hydrophobised wall with the vapour open capillary active interior insulation system. For the hydrophobised wall with a vapour tight system it takes more than seven months before the relative humidity drops below 80%, which is approximately three months longer than found for the vapour open capillary active system.

From the second winter period onwards, no impact of the moisture deposited by the hydrophobic solution is visible anymore. For the non-hydrophobised walls, the wind-driven rain induces a high relative humidity. For the hydrophobised walls, the relative humidity is much lower and shows a similar trend for the vapour tight and vapour open capillary active insulation system. The hydrophobised non-insulated wall shows the lowest relative humidity.

![Figure 6. Relative humidity at Position 5 of the 1D-masonry part (see Figure 5) together with (in light grey) an indication of the WDR peaks exposed to the wall.](image)

3.1.2. Position 3 - Between masonry wall and interior insulation. The relative humidity measured in the glue mortar between masonry and insulation is shown in Figure 7. The recording starts shortly after applying the interior insulation systems. At the beginning, a high relative humidity is obtained due to the moisture used to prepare the glue mortar. The glue mortar of the vapour open capillary CaSi-system starts drying out right from the start, while for the vapour tight XPS-system a reduction in the relative
humidity is only noticeable more than three months later. The reason for this slower drying process is the vapour tight system that strongly reduces a drying to the indoor room. Furthermore, the decrease in relative humidity occurs later for the vapour tight system applied to the hydrophobised wall, as (1) the moisture deposited by spraying the hydrophobic solution results in a higher moisture level already present in the masonry and (2) the hydrophobic treatment makes a drying out to the exterior more difficult. Later on, for the wall with XPS, the relative humidity in the non-hydrophobised wall is 10% higher than for the hydrophobised wall, as wind-driven rain is absorbed by the non-hydrophobised wall.

For the vapour open capillary active system, a hydrophobic treatment is found to have only a small impact on the relative humidity in the glue mortar. During the heating season, the relative humidity in the glue mortar of the vapour open capillary active system becomes, due to an outward vapour flow, higher than for the vapour tight system. When excluding the first ten months after applying the insulation system, the hydrophobised wall with XPS performs best.

![Figure 7](image1.png)

**Figure 7.** Relative humidity in the glue mortar between the masonry wall and the interior insulation material (Position 3 in Figure 5).

3.2. Relative humidity at the wooden beams

3.2.1. Position 3 - Near the interface between masonry wall and interior insulation. Figure 8 shows the relative humidity at Position 3 (see Figure 5 for the positions) at the upper wooden beam head. The presence of the wooden beam results (compared to the drying observed in Figure 7) in a faster drying of the glue mortar as well as a higher temperature, resulting in a relative humidity lower than 80% shortly after applying the insulation systems. Hence, the lower drying potential of the vapour tight system seems to yield no problem for the durability of the wooden beam heads at this position and, taking into account the results described in section 3.1.2., the hydrophobised wall with XPS performs best.

![Figure 8](image2.png)

**Figure 8.** Relative humidity at Position 3 (see Figure 5) at the upper wooden beam heads.
3.2.2. *Position 5 - Near the back of the wooden beam heads.* Figure 9 shows the relative humidity at the back (Position 5 in Figure 5) of the wooden beam heads as a function of the temperature at this position. To eliminate the moisture behaviour at the start of the measurement campaign, which was influenced by the moisture of the hydrophobic solution, only the data starting from the second winter are plotted. Additionally, Sedlbauer’s isopleths for mould spore germination [12] are shown. A comparison between the non-hydrophobised (1st and 3rd column) and the hydrophobised (2nd and 4th column) shows a clear reduction in relative humidity achieved by applying a hydrophobic treatment. For the wooden beam heads in contact with mortar (1st and 2nd column) embedded in an internally insulated wall, especially during Spring and Summer a reduction in relative humidity is visible. For the wooden beam heads in contact with mortar as well as the wooden beam heads in contact with an air gap, the choice between a vapour open capillary active and a vapour tight interior insulation system seems to be subordinate to the application of a hydrophobic treatment.

In general, the wooden beam heads in contact with mortar show a higher relative humidity than the wooden beam heads surrounded by an air layer (see 1st column versus 3rd column for the non-hydrophobised cases and 2nd column versus 4th column for the hydrophobised cases). For the non-hydrophobised walls, this can be explained by the moisture absorbed during a wind-driven rain load that can be transported more easily to the wooden beam via the mortar. Exception to this behaviour is found for the non-insulated walls and, in less extent, for the hydrophobised wall with CaSi, which show for a wooden beam head in contact with an air gap, a higher relative humidity during winter. Possibly, the absence of an airtight plaster layer at the non-insulated masonry wall or some small air paths inside the masonry make that (internal) convective air flow and moisture transport is not fully excluded. As also shown by Vereecken and Roels [7], a CaSi-system can be more sensitive to such convective air flows than a vapour tight system.

Finally, the relative humidity in the walls with an interior insulation system is much higher than found for the non-insulated walls. Though, when no hydrophobic treatment is present, also for the non-insulated wall the relative humidity often exceeds the lowest isopleth for mould spore germination.

![Figure 9](image_url)  
*Figure 9.* Relative humidity as a function of temperature at Position 5 (see Figure 5) at the wooden beam heads, as measured from December 21\textsuperscript{st} 2019 till January 31\textsuperscript{st} 2021, together with Sedlbauer’s isopleths for mould spore germination (substrate category I).
4. Discussion and conclusions

Results of an ongoing field study on the hygrothermal performance of internally insulated masonry walls and the impact of a hydrophobic treatment are shown. Currently, ca. 2.5 years of data are available. In the first year of the measurement campaign, however, the moisture conditions in the hydrophobised walls were found to be influenced by the moisture deposited by the water repellent solution. After drying of the hydrophobic agent, the presence of a hydrophobic treatment is found to have a positive impact. A hydrophobic treatment lowers the relative humidity. When no hydrophobic treatment is applied, wind-driven rain loads induce an increase in relative humidity. At the wooden beam heads, this increase in relative humidity is especially visible during Spring and (for the wooden beam heads in contact with mortar) Summer. Near the back of the wooden beam heads and for positions closer to the masonry’s exterior surface (not shown), the presence of a hydrophobic treatment has a larger impact than the choice between a vapour tight and vapour open capillary active interior insulation system. Closer to the masonry’s interior surface, the difference in performance between both types of interior insulation system becomes more visible. Overall, based on the measurement results, if a hydrophobic treatment is present, the XPS-system is preferential. Besides, this XPS-system outperforms the thermal performance of the capillary active vapour open system. Further research for more severe boundary conditions and on the sensitivity of the timing for applying the hydrophobic treatment and the insulation system is however desirable before generalising these conclusions.

In the current study, a micro-emulsion based on silanes and siloxanes was applied as a hydrophobic treatment. A large impregnation depth was provided to ensure good practice, as this way the risk on inward moisture transport via cracks and thus on a possibly unfair comparison between the test walls was reduced. A study on the potential problems caused by the combination of a hydrophobic treatment and cracks is beyond the scope of the current field study, as is the impact of the type of hydrophobic agent and the impregnation depth. The data set achieved within the current field study can however be used to further develop numerical simulations of hydrophobised walls, which in a next step could be used to study other boundary conditions and insulation systems.

Acknowledgements

The results within this paper have been partially obtained within the EU Horizon 2020 RiBuild project (Project ID 637268). Evy Vereecken is a postdoctoral fellow of the Research Foundation (FWO) - Flanders, Belgium (FWO project 12J5219N). These financial supports are gratefully acknowledged. The authors are very grateful to Wim Bertels, Patricia Elsen, Bernd Salaets and Jimmy Van Criekingen for their dedicated contributions in realising these measurements in practice.

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