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Hygrothermal assessment of wind-driven rain as a risk for internal insulation retrofit of traditional buildings

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SUMMARY:

This paper describes a study in which the hygrothermal performance of a traditional Scottish sandstone wall, which is highly exposed to wind-driven rain and had been internally insulated, was monitored and modelled using the simulation software WUFI 2D. Internal and external temperatures and relative humidities and the external solar gain and wind-driven rain load have been recorded from April 2012 to November 2013. Also recorded were temperatures and humidities and the moisture content of timber blocks within the wall. The monitoring results indicate that, despite the concerns that have been expressed about the consequences of applying internal insulation to traditionally constructed masonry walls, no problems have become apparent in this case.

Modelling the wall, using the measured data as boundary conditions, demonstrates the importance of choosing material properties appropriate to the structure under investigation. Three types of sandstone were modelled, with different moisture transport properties, giving very different moisture contents. The modelled temperatures at the interface between the stonework and internal insulation agreed closely with the measured values. The relative humidities measured at the same point followed the same general trend as those calculated using the least porous of the three modelled sandstones, although the values did not agree closely.

1. Introduction

Building regulations in the United Kingdom recommend that the risks of interstitial condensation should be addressed by following the guidance in British Standard BS 5250:2011. This specifies that, when internal insulation is added to a stone wall, a highly air and vapour resistant membrane, an air and vapour control layer (AVCL), should be included on the warm side of the insulation. It is recommended that the risk is assessed with a calculation using the *Glaser method*, specified in EN ISO 13788:2012. However, this 'conventional' assessment method completely ignores liquid moisture transport, for example as a result of wind-driven rain (WDR). Concerns have been raised, especially by heritage professionals, that an AVCL may make conditions within the wall worse by inhibiting evaporation to the inside (Hermann 2013, Little & Ferraro 2014, Rye & May 2012). More advanced methods for hygrothermal assessment, by *numerical simulation*, are now available, taking liquid transport into account. They are based on procedures set out in EN 15026:2007, and software packages for such advanced assessment are available, for example Delphin, MOIST and WUFI.

To provide further information, a sandstone wall in a traditional tenement flat in Glasgow, insulated internally and highly exposed to WDR, has been monitored in detail for 18 months, and hygrothermal conditions have been simulated using the simulation software WUFI 2D 3.3, developed by the Fraunhofer Institute for Building Physics. The simulations were carried out using the measured internal and external temperatures and relative humidities (RH) and the solar radiation and WDR load measured on the outside wall face. The properties for the materials present were taken from the WUFI database, which contains properties of nine sandstone types: eight from Germany and one from India. As it is not known which of these corresponds most closely to the sandstone used in the Glasgow tenement, the simulations were run with three of these sandstones covering the range of properties in the database.

2. Field measurements

2.1 Location

The monitoring was carried out as part of a retrofit project by Glasgow City Council and Historic Scotland in a top floor corner flat with south and west facing elevations and a fairly open aspect to the west (Figure 1). The building is located near the south bank of the river Clyde in Govan, a suburb of Glasgow. The monitored wall was ca. 600 mm thick and made of sandstone, bedded in mortar. The wall was finished internally with plasterboard which contained a 12.5 mm extruded polystyrene (XPS) insulation backing. This internal finish was presumably installed during the 1980s. The plasterboard was fixed to timber studs, forming a cavity of ca. 90 mm between the stone face and the XPS. This cavity was filled in April 2012 with Knauf Supafil 34, a blown glass fibre mineral wool insulation.

FIG 1. The wall being monitored is the west facing wall of the top floor corner flat with a fairly open aspect and with monitoring equipment installed to the left of the bay window.

The west facing wall was monitored after the retrofit. Climate sensors were installed on the external wall face, primarily to assess the impact of WDR on moisture transport through the wall and its effect (if any) on the risk of moisture problems due to the addition of higher levels of internal insulation. The risk of moisture problems is greatest at the interface between the stonework and the insulation: humidity, temperature and moisture sensors were installed at five locations on the west facing wall. Novel moisture measuring equipment, using the time domain reflectometry (TDR) technique (Philipson 2011), was employed both internally and externally.

This paper covers the monitoring from April 2012 to November 2013. The flat was occupied as of August 2012. The measured TDR data was not yet available at the time of writing of this paper.

Before the retrofit, in situ U-value measurements, carried out during March 2012 at three locations on the west facing elevation, gave an average U-value of 0.77 ±0.03 W/(m^2·K). Measurements on the south elevation after the retrofit gave an improved average U-value of 0.23 ± 0.03 W/(m^2·K). (Measuring on the west elevation was, unfortunately, not possible at the time.)

2.2 Monitoring procedures

Before filling the cavity with insulation, sensors were installed internally in five locations, fixed to the stone surface on the west facing wall (Figure 3). Temperature, relative humidity and wood block moisture content (WBMC) sensors were installed in all five locations, and TDR probes with 75 mm probe length were inserted from the internal stone face at four positions. A combined temperature and relative humidity sensor was also installed to measure the room conditions.

The electrical resistance of the wood blocks was measured and converted into timber moisture contents. The generally recognised safe threshold for timber moisture content is 18%.

FIG 3. Interior sensor locations on west facing wall: temperature, relative humidity and moisture sensors are fixed to the internal stone face in the five locations where plasterboard has been cut away.

The following sensors were mounted on the external west facing elevation (Figure 4):

- combined temperature and relative humidity sensor enclosed in radiation shield
- solarimeter measuring global and diffuse solar radiation incident on the vertical surface
- anemometer (wind speed)
- rain gauge mounted vertically, which senses water hitting its outside surface using infrared light (The gauge can be set up to give a pulse output, emulating a tipping bucket rain gauge.)
- two TDR probes with 75 mm probe length inserted into stonework

Logging commenced on 20th April 2012. Data were logged at 1 minute intervals and stored at 10 minute intervals for all sensors, except for the TDR probes which were recorded hourly.

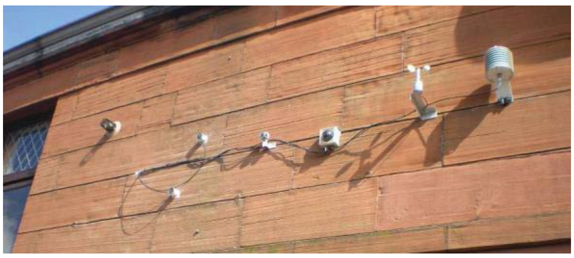

FIG 4. Instrumentation on external wall from left to right: two TDR moisture probes, vertical rain gauge, solarimeter, anemometer and combined temperature and relative humidity sensor in radiation shield. (Note that the item to the very left, mounted at slightly higher level, is an existing boiler flue.)

2.3 Monitoring results

Figure 5 shows the monthly total solar radiation, measured in the vertical plane, and the total rainfall incident, both on the west facing wall. Figure 6 shows the monthly average relative humidities and WBMCs. Figure 7 shows the temperatures.

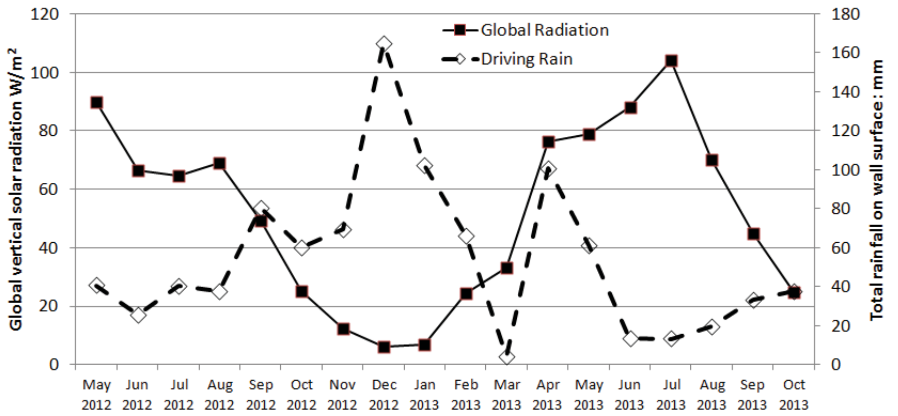

FIG 5. Monthly total solar radiation measured in the vertical plane of the west (facing) wall and total rainfall incident on the same wall

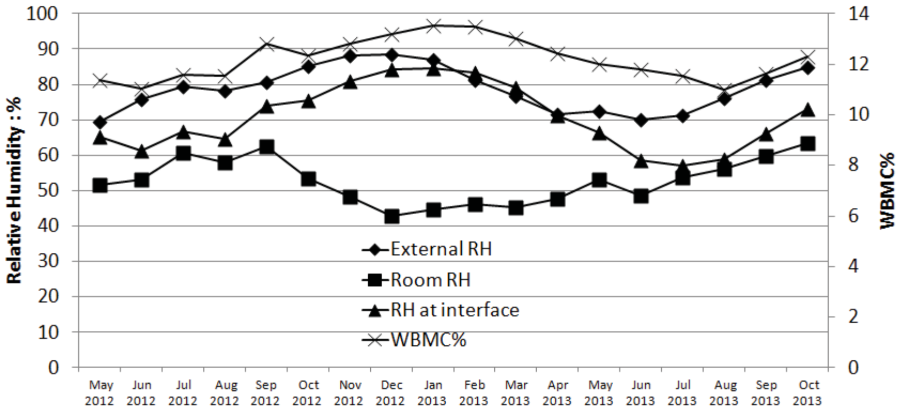

FIG 6. Relative humidities measured externally, within the flat and at interface stonework / insulation (average of 5 measurements); WBMCs measured at the same interface (average of 5 measurements)

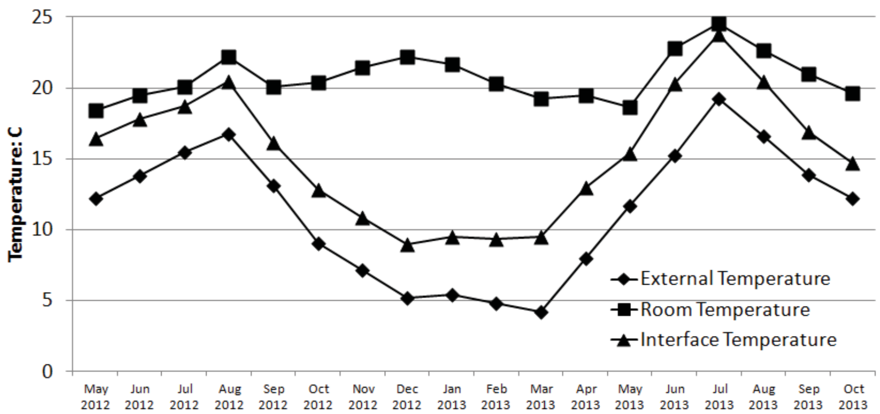

FIG 7. Temperatures measured externally, within the flat and at the interface between the stonework and the insulation (average of 5 measurements)

Figure 6 shows that WBMC follows the change in relative humidity at the interface between the stonework and the insulation. The maximum WBMC is approximately 14%, which indicates low risk of moisture problems so far. Both the WBMC and the relative humidity at the interface generally follow the change in external humidity as well as a seasonal pattern, rising in the winter and falling in the summer.

There is no significant evidence that the amount of rainfall received at the external wall face has an impact on the humidity and WBMC at the interface between the stonework and the insulation. The effect of wind and solar radiation may be sufficient to evaporate moisture from the external wall face and prevent rainwater penetration. Analysis of the TDR data, once available, should clarify the effect of rainfall, wind and solar on the moisture content of the wall.

3. WUFI 2D modelling

3.1 Simulation model

The WUFI software, which complies with EN 15026, was used to develop a model of the wall that had been monitored. Traditionally constructed stone walls in Scotland consist of layers of stones either side, bound together by a mix of smaller stones and mortar, which is likely to contain many air voids. Even if the contents could be defined exactly, it would be impossible to represent them in WUFI. Therefore, a simplified model of homogenous stonework with one horizontal mortar joint was developed using WUFI 2D 3.3, a two dimensional version of the WUFI software family. As no information on the properties of the materials used in the wall was available, the model was run with three German sandstones, representing the range of those available in the material database of WUFI. Table 1 summarises their moisture transport properties.

TABLE 1- Moisture transport properties of the sandstones used in the WUFI model

Sandstone type	Density [kg/m^3]	Porosity	Diffusion resistance factor [-]	Moisture storage at 99% RH [kg/m^3]	Liquid transport coefficient at $50kg/m^3$ [m^2/s]
Baumberger	1980	0.23	20.0	115.5	3.9×10^{-9}
Obernkirchner	2150	0.14	32.0	9.4	2×10^{-8}
Zeitzer	2300	0.05	70.0	26	1.0×10^{-8}

The relatively porous Baumberger sandstone has a high moisture storage capacity, but a low liquid transport coefficient, compared to the denser Zeitzer sandstone.

The measured internal and external temperatures and relative humidities and the solar radiation and WDR incident on the external surface were used as the boundary conditions.

3.2 Results

The figures below show the daily means from the hourly data calculated by WUFI. Figure 8 shows the moisture content of the three sandstones modelled, which is very different for the three cases. Figure 9 shows the moisture content of the mineral wool insulation. The high level of liquid transport in Obernkirchner sandstone allows more of the water hitting the outer face of the wall to pass into the mineral wool. It is worth noting, however, that even the highest calculated moisture content (~11 kg/m^3) is well below the level where the thermal conductivity rises (50 – 100 kg/m^3). Figure 10 shows the temperature at the interface between the stonework and the insulation, together with the data measured at this point. There is little difference between the three stone types, and the agreement with measured data is good.

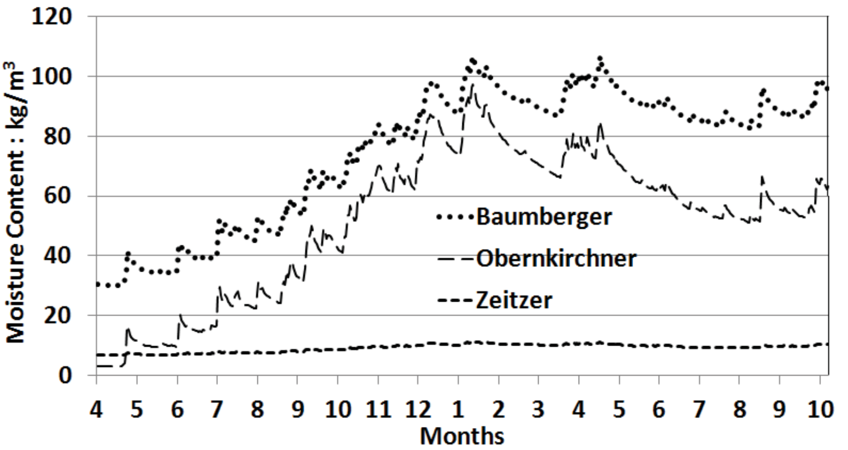

FIG 8. Overall stone moisture content

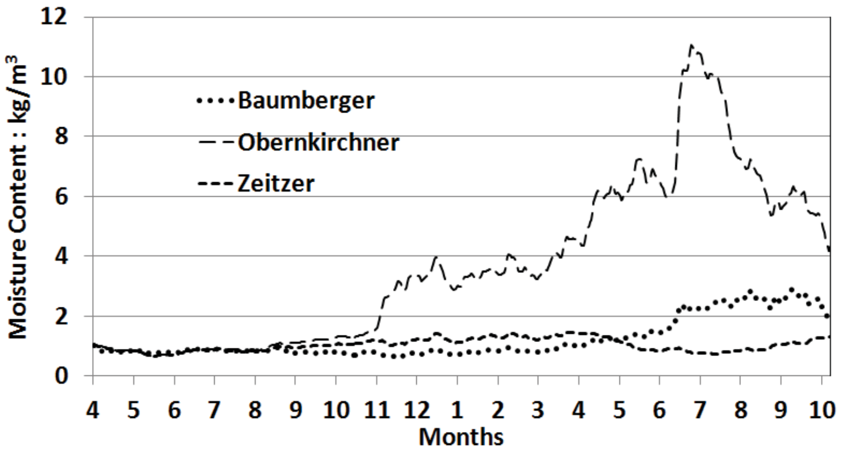

FIG 9. Overall moisture content of the mineral wool insulation

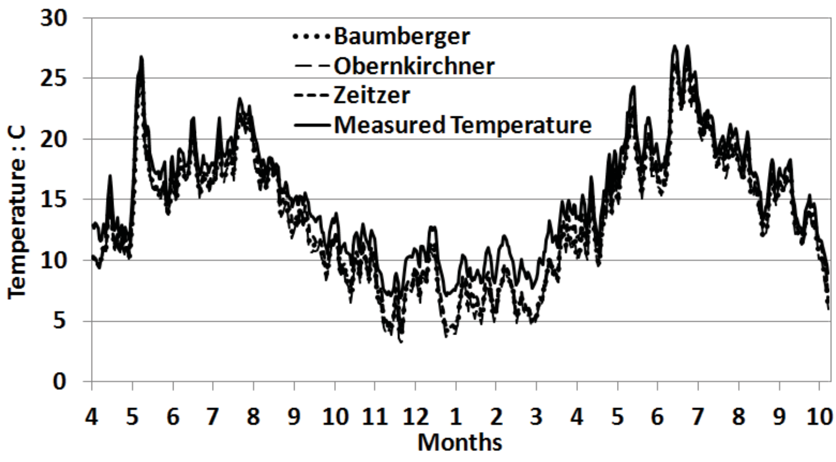

FIG 10. Temperature in the outer 1 mm of the mineral wool insulation (i.e. near interface of stonework and insulation) with the measured data

Figure 11 shows the relative humidity at the same point and measured data. There is considerable variation between the calculated data from the three sandstone types, with that from the Zeitzer sandstone agreeing with the measured data most closely. The simulated RH values for Baumberger and Zeitzer sandstones exceed the measured values continuously as of month 8 of the first measurement year (i.e. December 2013) and Obernkirchner sandstone as of month 2 of the second year (i.e. February 2013). It is worth noting that the simulated humidity levels of all stone types exceed temporarily RH values of 80%, the generally accepted threshold for mould growth; the values for Baumberger and Zeitzer sandstones remain continuously above this threshold after month 10 of the first measurement year (i.e. February 2013). These simulated results would be cause for concern in situation where the 80% threshold is exceeded for prolonged periods of time. Fortunately, the measured results show that the RH levels only exceed the threshold for suitably short periods of time, followed by period with RH levels substantially below the threshold.

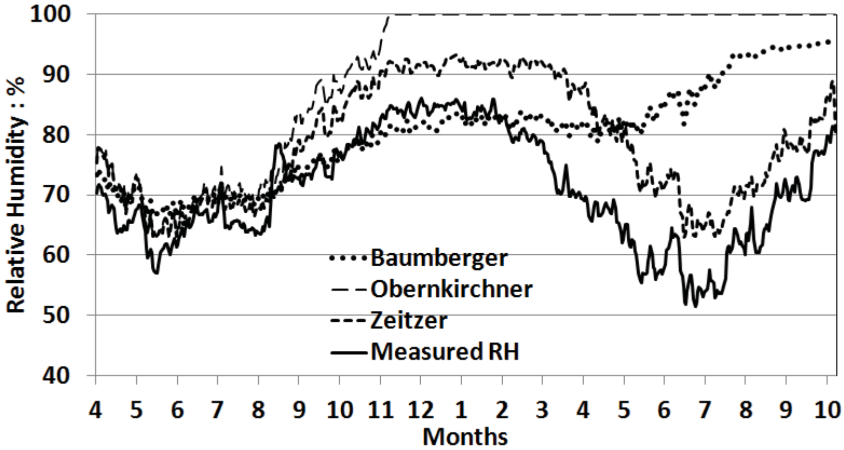

FIG 11. Relative humidities in the outer 1 mm of mineral wool insulation (i.e. near interface of stonework and insulation) with the measured data

4. Discussion

The results from the monitoring and modelling described in this report have indicated that, despite the concerns that have been expressed about the consequences of applying internal insulation to traditional masonry walls, no problems have become apparent in this case. There is no significant evidence that the amount of rainfall received at the external wall face has an impact on the humidity and timber moisture content at the interface between the stonework and the insulation. The effect of wind and solar radiation may be sufficient to evaporate moisture from the external wall face and prevent rainwater penetration. Analysis of the TDR data, once available, should clarify the effect of rainfall, wind and solar radiation on the moisture content of the wall.

Modelling the wall with WUFI 2D, using the measured temperature, humidity, solar and WDR data as boundary conditions, demonstrates the importance of choosing material properties appropriate to the structure under investigation. The three types of sandstone modelled, with different porosities, moisture storage capacities and liquid water transport coefficients, gave very different calculated moisture contents of the sandstone and the mineral wool insulation. It is worth noting, however, that the predicted moisture content of the mineral wool remained well below the levels that have any effect on its thermal conductivity.

The modelled temperatures at the interface between the stonework and the insulation agreed closely with the measured values. Relative humidities measured at the same point followed the same general trend as those calculated using the least porous sandstone, Baumberger sandstone, although the values did not agree closely. This is not surprising, given the great simplification of the model, with one mortar joint in stone, compared to the complex matrix of stone and mortar in reality. Once the TDR data have been analysed, it will be possible to make a more detailed comparison between the measured and calculated moisture contents. It is worth noting that the simulated humidity levels of all stone types exceed, either temporarily or continuously, RH values of 80%, the generally accepted threshold for mould growth. These simulated results would be cause for concern in situation where the 80% threshold is exceed for prolonged periods of time. Fortunately, the measured results show that the RH levels only exceed the threshold for suitably short periods of time.

It is clear that, if advanced hygrothermal models in accordance with EN 15026:2007, such as WUFI, are to be used to carry out routine assessments of moisture conditions in building structures, considerably more data on the properties of the materials used must be available to achieve realistic simulation results.

5. Acknowledgements

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