Performance of internal wall insulation systems - experimental test for the validation of a hygrothermal simulation tool

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SUMMARY: *In the UK, transient models of heat, air and moisture transport (HAMT) are common tools used by building practitioners to better understand moisture movement within building elements and construction systems. Enforced by BS 5250:2011, hygrothermal simulations are also used for condensation risk analysis and to estimate the likelihood of mould growth and fabric decay. This paper describes the methodology applied in the validation of a hygrothermal-modelling tool used in the evaluation of internal wall insulation. Wall assemblies typically constructed for internal insulation were exposed to transient boundary conditions derived from vapour pressure profiles and their response to step changes and fluctuations were analysed. The wall assemblies were constructed using one wall substrate (aerated clay blocks and gypsum plaster) and eight commonly used internal insulation systems. Relative humidity and temperature levels measured at the interface between the wall substrate and each insulation system were used to assess the hygrothermal performance of each insulation system. As a result, the wall assemblies were clustered in three subgroups; dense capillary-active insulation, lightweight vapour-permeable insulation and synthetic vapour-closed insulation, and the hygrothermal performance of the proposed clusters compared with the results provided by the simulation tool. It was found that simulated assemblies have similar hygrothermal performance as those monitored.*

1 Introduction

In England, approximately 6.5 million homes are built of solid wall – 31% of the total housing stock, of which around 60% have been built before 1920. Solid wall dwellings are considered “hard-to-treat-homes”, since they cannot be upgraded with easy or cost-effective fabric energy efficiency measures (BRE, 2008). Improving the energy efficiency of these dwellings becomes even harder in conservation areas, listed buildings, or building with decorative façades where the only feasible solution is internal wall insulation (IWI); planning permission for external wall insulation (EWI) is often denied. However, the installation of IWI may affect the interstitial temperature and vapour permeability of the building envelope leading to moisture accumulation and the reduction of the building durability; high interstitial relative humidity is ideal for mould growth and timber decay.

This paper describes the experimental test carried out for the validation of a numerical tool for heat, air and moisture transport. The experiment was designed to help understand the hygrothermal behaviour of internal wall insulation exposed to transient boundary conditions of relative humidity and temperature, and to validate a simulation tool commonly used to estimate moisture movement within building elements and the likelihood of mould growth and fabric decay in buildings. Two walk-in environmental chambers are utilised for the experiment; wall samples were exposed to climate conditions set independently in each chamber.

2 Methodology

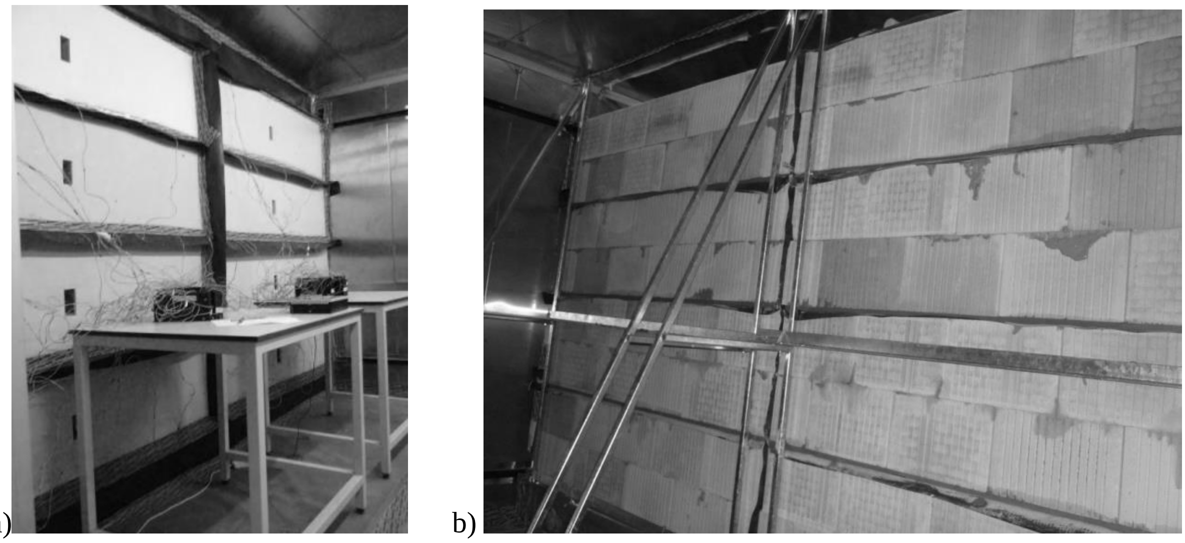
2.1 Experimental method

Eight internal wall insulation systems were built and assessed under transient boundary conditions of temperature and relative humidity; these were controlled to define specific vapour pressure levels, to trigger vapour diffusion (varying direction and magnitude) and enhance moisture transfer within the construction assemblies. Similar methodologies have been used for the analysis of the hygrothermal behaviour of internal wall insulation systems exposed to a winter condition, combined with X-ray tomography on moisture distribution in samples (Vereecken and Roels 2011) and for the analysis of timber frame wall samples under external vapour pressure excess (Carmeliet and Derome 2012).

Temperature and relative humidity at the critical interface between the masonry substrate and the insulation system were measured and the data were used in the validation of a numerical tool for the evaluation of capillary active internal wall insulation.

2.1.1 Wall assembly

A partition wall between the two environmental chambers was constructed considering assemblies of one wall substrate and eight different internal insulation systems (Figure 1). The wall substrate consisted of 175mm-thick aerated clay block and 10mm-thick gypsum plaster (outside to inside). The eight wall samples are described in Figures 2-3 and considered capillary active and conventional insulation technologies. The assemblies were constructed as individual units to avoid moisture movement between them; each side of the assemblies was sealed using a polyethylene membrane, leaving only the surface of the aerated clay block and the surfaces of each insulation system in contact to the set exterior and interior climate conditions.



a) b)

FIG 1. Test wall built between the environmental chambers a) view of eight insulation systems exposed to internal boundary conditions b) view of clay block wall exposed to external boundary conditions

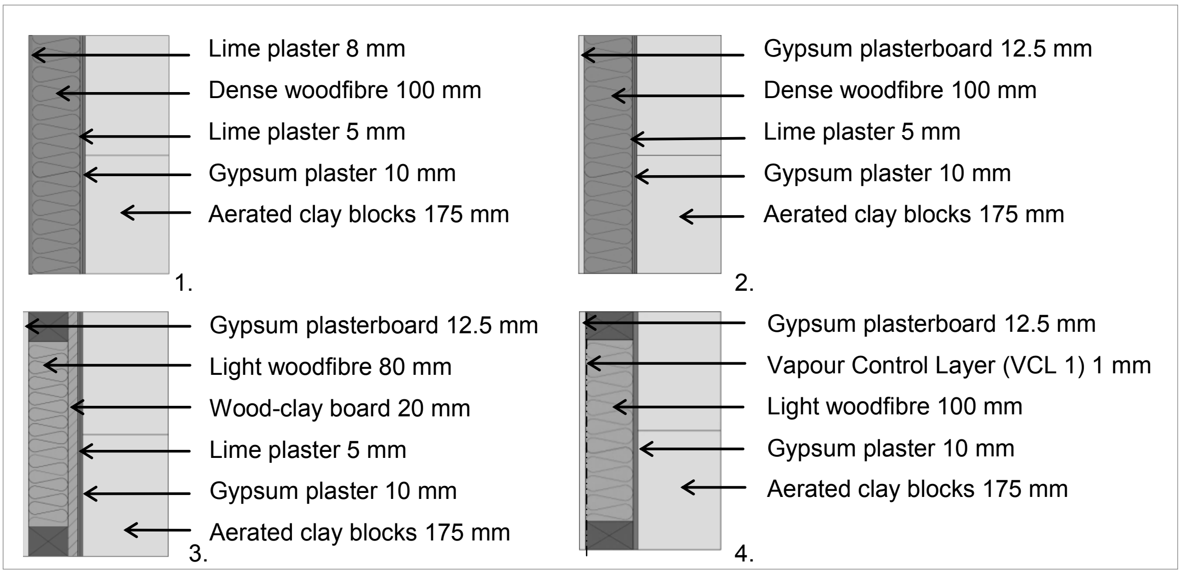


FIG 2. Construction assemblies of the capillary active insulation systems, samples 1 to 4

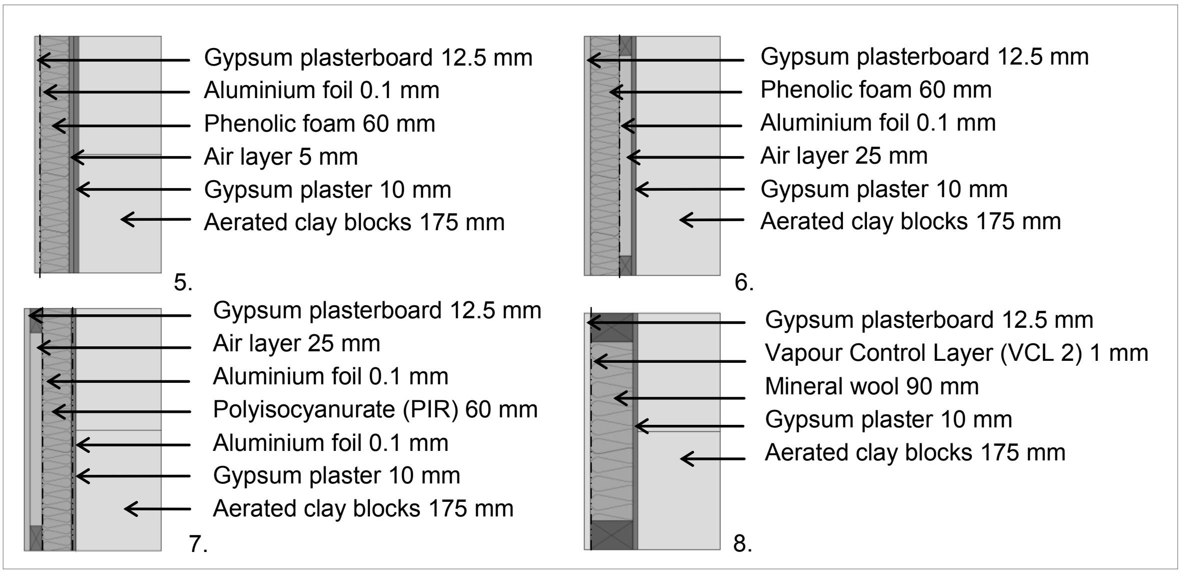


FIG 3. *Construction assemblies of the conventional insulation systems, samples 5 to 8*

2.1.2 Boundary conditions

Profiles of temperature and relative humidity (Table 1) were used to create two vapour pressure gradients between the environmental chambers and within the insulation samples. The first set of boundary conditions (Set 2) considered an internal vapour pressure excess of 400 Pa ($p_{v,int} - p_{v,ext}$ = 400 Pa), while the second set (Set 3) an external vapour pressure excess of 400 Pa,($p_{v,ext} - p_{v,int}$ = 400 Pa). Vapour pressure p_v (Pa), was calculated using equation 1, where T and ϕ represent temperature (°C) and relative humidity (%) respectively.

$$p_v=\phi \cdot exp\left(22.565-\frac{2377.1}{T}-\frac{33623}{T^{1.5}}\right) \qquad (1)$$

Hygrothermal equilibrium within the wall was achieved by setting similar profiles of temperature and relative humidity (initial conditions) in both chambers. Samples were exposed to T=15 °C and ϕ=80 % for a period of 30 days and to Set 2 and Set 3 for 30 days and 13 days respectively.

TABLE 1.Boundary conditions for experimental test

	Internal T (°C)	ϕ (%)	$p_{v, int}$ (Pa)	External T (°C)	ϕ (%)	$p_{v, ext}$ (Pa)	Average $\Delta p_v = p_{v,int} - p_{v,ext}$ (Pa)
Set 1 (initial conditions)	15	80	1364	15	80	1364	0
Set 2	18.4 ± 1.5	58 ± 2	1228 ± 158	6.6 ±1.9	85	828±109	400
Set 3	18.4 ± 1.5	29 ± 5	614 ± 164	11.1 ± 3.7	75	991 ± 245	-377

2.1.3 Monitoring

The relative humidity at the interface between the insulation and the substrate wall was monitored using six temperature and relative humidity sensors applied to the gypsum plaster and subsequently covered by the insulation system (total of 96 sensors). Thermocouples and capacitive sensors were used for temperature and relative humidity respectively. Also, room temperature and relative humidity were monitored in each environmental chamber. Data were collected every 5 minutes, for 43 days, and averaged every hour. The collected data were then used as the boundary conditions input in the simulations for the tool validation.

2.2 Simulation method

The paper presents a validation of a heat, air and moisture transport (HAMT) tool; the tool used for the one-dimensional hygrothermal simulations is WUFI® Pro, developed at Fraunhofer IBP and compliant with EN 15026:2007. The material properties, boundary conditions and method of simulation are described below.

2.2.1 Wall assembly

The wall samples analysed in the experiment were reproduced in the simulation tool using material data provided by the respective manufacturers and properties taken from the simulation tool database (Table 2).

TABLE 2. Material properties for simulation

	ρ (kg/m^3)	ψ_o (m^3/m^3)	C_p (J/kg K)	λ (W/mK) at 0% RH	μ (-) at 0% RH
Aerated clay block	1400	0.74	850	0.58	10
Gypsum	850	0.65	850	0.2	8.3
Lime	1600	0.3	850	0.7	7
Dense woodfibre	155	0.981	2000	0.042	3 (1.5 at 60%RH)
Light woodfibre	53	0.96	2100	0.039	1.35 (1.58 at 72%RH)
VCL 1	130	0.001	2300	2.3	3500
VCL 2	130	0.001	2300	2.3	100000
Air	1.3	0.999	1000	0.155	0.51
Aluminium foil	130	0.001	2300	2.3	1500000
Phenolic Foam	43	0.95	1500	0.04	30

2.2.2 Boundary conditions

The boundary conditions considered in the simulation were those monitored in the experimental test and differed slightly from those set in the experiment. Boundary conditions used in the simulation are described in Table 3.

Initial conditions used in the simulation were those measured at the interface between the insulation systems and the wall substrate when the samples were in equilibrium and Set 2 was introduced (time t = 0) as shown in Table 4.

TABLE 3. Boundary conditions for simulation

	Internal			External			Average $\Delta p_v = p_{v,int} - p_{v,ext}$ (Pa)
	T (°C)	ϕ(%)	p_v (Pa)	T (°C)	ϕ (%)	p_v (Pa)	
Set 1 (initial conditions)	15	80	1364	15	80	1364	0
Set 2	17 ± 1.5	60 ± 2	1163 ± 150	6.9 ± 1.9	81 ± 5	806 ± 156	357
Set 3	17 ± 1.5	31 ± 4	601 ± 135	10.8 ± 3.4	76 ± 1	984 ± 237	-383

TABLE 4. Interstitial initial conditions for simulation

	T (°C)	ϕ (%)
Sample 1	15.5	83.8
Sample 4	15.5	74.36
Sample 5	15.7	84.11
Sample 6	15.5	86

2.2.3 Monitoring methodology

Similar to the experimental test, the simulation was set to last for around 42 days. Temperature and relative humidity levels were monitored using virtual monitoring sensors positioned between the wall substrate and the insulation, in the layer representing gypsum plaster.

3 Results and discussion

The experimental test was designed to generate data for the validation of the heat, air and moisture transport model as well as to understand the effect of environmental conditions on the moisture levels at the interface between wall substrate and insulation. The relative humidity at the substrate-insulation interface of 8 internal wall insulation systems was measured and analysed considering the level of humidity and the fluctuation amplitude of the humidity curves after the steps change between the two sets of boundary conditions.

An increase in the relative humidity of sample 5, sample 8 and capillary active insulation systems, ($\Delta\phi/\Delta t$ = 0.283 to 0.779 %/h) was observed in the first 12-hour period after the step change between Set 2 and Set 3. On the other hand, the variation of relative humidity in sample 6 and sample 7 was found to be minimal ($\Delta\phi/\Delta t$ = 0.049 and -0.108 %/h respectively). Similar results were observed after the step change between Set 2 and Set 3; the relative humidity of capillary active systems, sample 5 and sample 8 decreased with a rate of $\Delta\phi/\Delta t$ = -0.124 to -0.048 %/h, whereas sample 6 and sample 7 show negligible variations ($\Delta\phi/\Delta t$ = -0.007 and 0.015 %/h).

Samples 1, 2, 3, 6, 7 showed a daily fluctuation of negligible amplitude. Sample 5 on the other hand, showed a small fluctuation under Set 2, more visible during Set 3. Samples 4 and 8 presented visible fluctuations throughout the test.

TABLE 5. Results

	Set 2		Set 3	
	Δϕ/Δt (%/h)	Peak-to-peak amplitude (%)	Δϕ/Δt (%/h)	Peak-to-peak amplitude (%)
Sample 1	0.283	0.48	-0.105	0.39
Sample 2	0.309	0.32	-0.065	0.46
Sample 3	0.308	0.40	-0.048	0.42
Sample 4	0.613	1.18	-0.199	1.34
Sample 5	0.291	0.76	-0.078	1.06
Sample 6	0.049	0.32	-0.007	0.48
Sample 7	-0.108	0.55	0.015	0.42
Sample 8	0.779	1.78	-0.124	1.53

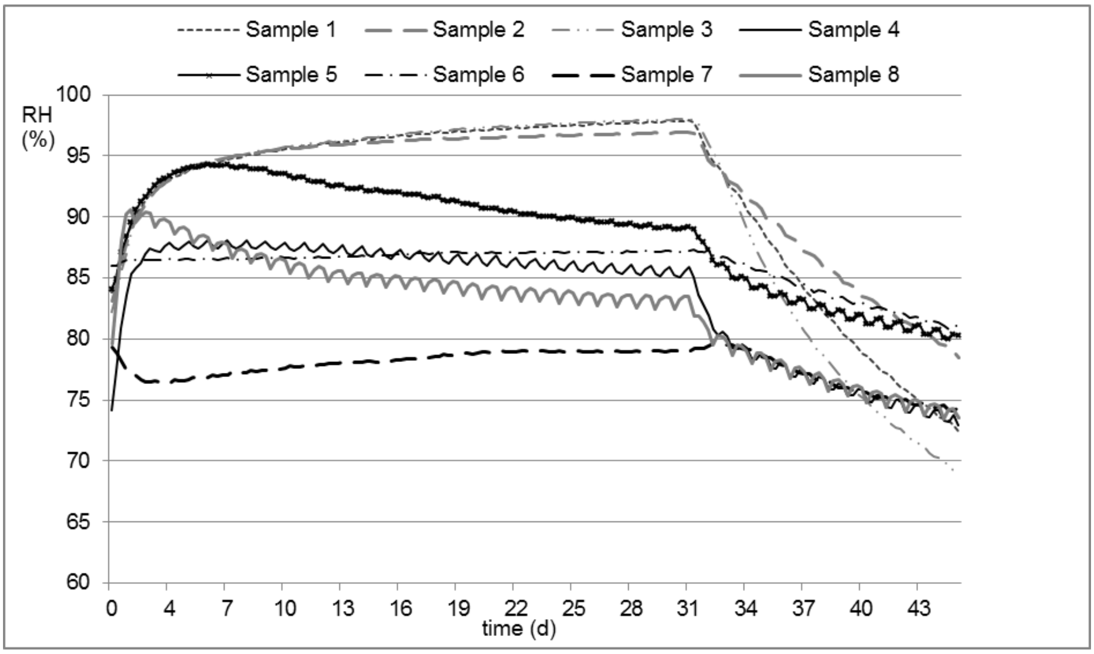


FIG 4. Hygrothermal response to a step change

The results showed that the hygrothermal performance of the insulation systems does not relate exclusively to their generic materials (e.g. wood). For instance, samples 1, 2, 3 – all based on woodfibre – show a comparable hygrothermal performance, while samples 4 and 8 have a similar performance but different materials (woodfibre and mineral wool respectively). For this reason, the samples were clustered in three groups according to their hygrothermal behaviour: Cluster A (samples 1, 2, 3) included samples largely affected by the step change between boundary conditions but showing a negligible amplitude of the daily fluctuations; these samples feature woodfibre-based dense boards with low vapour diffusion resistance coefficients. Cluster B (sample 4 and sample 8) included samples affected by the step changes and with significant daily variations; these samples are made of lightweight fibrous material (light woodfibre batt and mineral wool respectively) and feature a vapour control layer with low to medium vapour diffusion resistances (s_d=3.5 m and s_d=100 m are the respective equivalent air layer thicknesses). Cluster C (sample 6 and sample 7) included samples which presented minor correlations between boundary conditions and interstitial relative humidity; common characteristics of these samples are the presence of foam insulation (preventing moisture movement) and the use of a highly resistant vapour barrier, with μ=1500000. Sample 5, which has similar material properties to sample 6 (see Figure 3), presented a hygrothermal behaviour comparable to samples 4 and 8; this is due to undesired air convection occurring in the sample.

A comparison between the experimental test and the simulations was carried out taking into account the measured and calculated profiles of relative humidity. A sample of each cluster was selected and simulated. Results of the hygrothermal tool were considered acceptable if the profile of predicted relative humidity fell within the data intervals monitored, including a variation/error (ε_{ϕ}) in the measured relative humidity of ± 3.5 %. Sample 1, sample 4 and sample 6 were used as representative of Cluster A, Cluster B and Cluster C respectively. Sample 5 was also simulated and compared to the measured data.

Results of the simulations showed that the predicted profiles of relative humidity were most of the time in agreement with the measured data. Relative humidities of sample 6, fell the entire period within the range of measured data, whereas relative humidities of samples1 and 4 were at times slightly off from the range of the monitored data, yet following a similar trend. It might be possible that there was a higher actual error of the measured relative humidity; at low temperatures the error (ε_{ϕ}) of the relative humidity sensors could be as high as ± 30 % (Fossa and Petagna, 2004). In contrast, the trend and the levels of the relative humidity modelled for sample 5 were completely different to the monitored data. These results suggest a likely inaccuracy when constructing the sample; samples 5 and 6 have similar materials and construction assembly, yet dissimilar measured and modelled data.

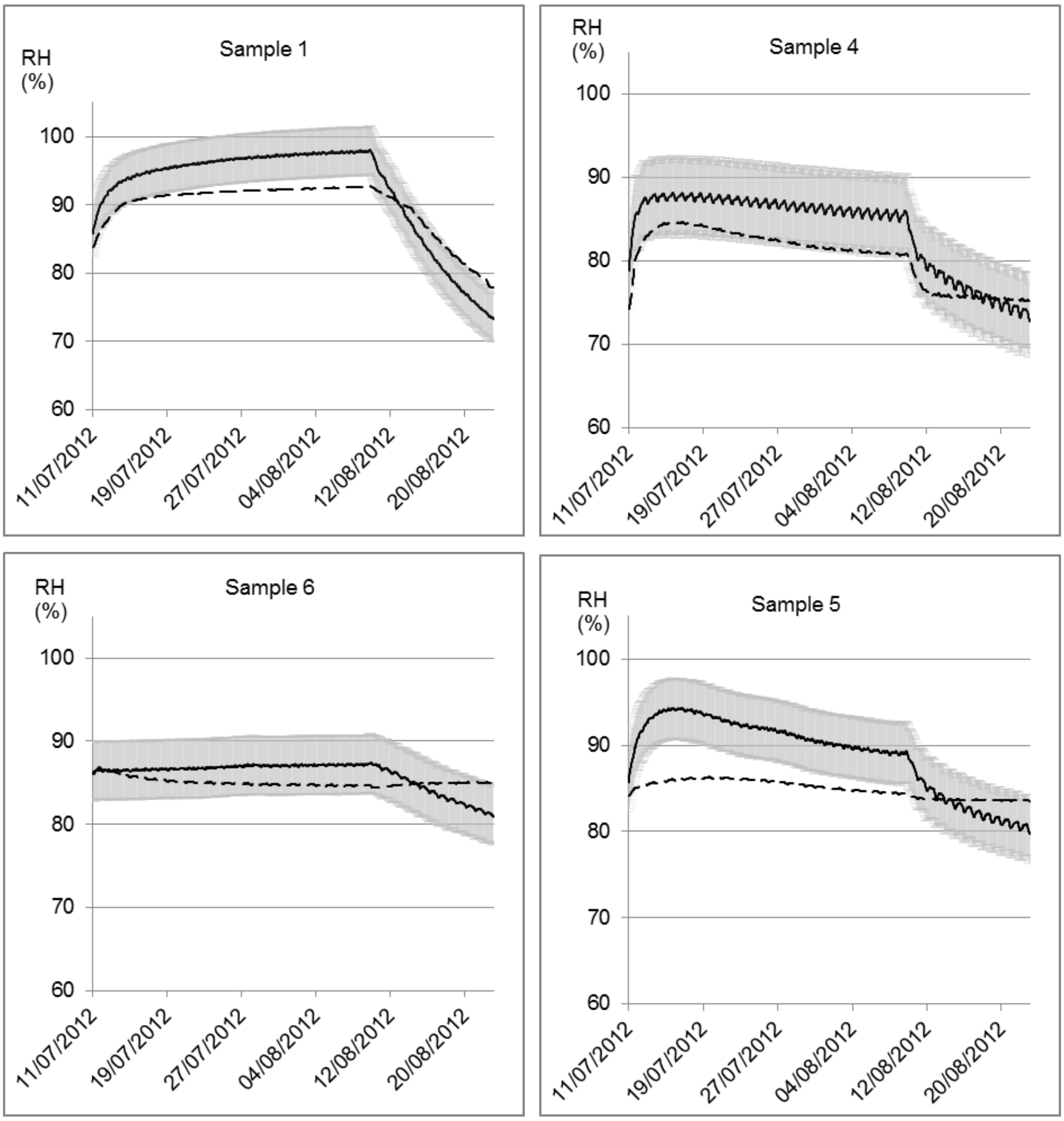


FIG 5. Comparison between experimental data (solid line) and simulation results (dashed line).

4 Conclusion

For certain building typologies, internal wall insulation is the most likely measure for increasing the walls thermal resistance. However, it may have other effects; internal wall insulation may as well help to reduce the temperatures and increase the vapour diffusion resistance of the retrofitted walls, raising the relative humidity at the existing wall-insulation interface, therefore increasing the risk of mould growth and timber decay.

This paper has presented the methodology and results of a test developed to help understand the hygrothermal behaviour of internal wall insulation and to provide data for the validation of numerical simulation tools. The hygrothermal behaviour of eight internal wall insulation assemblies exposed to transient boundary conditions of relative humidity and temperature were analysed by measuring the temperature and relative humidity at the interface between the masonry substrate and the insulation systems. Results of the experimental work showed that the insulation systems had a different response to same boundary conditions and the interstitial relative humidity varied considerably. The difference in hygrothermal behaviour was not only related to the generic materials used in the insulation assemblies, but to the specific properties of the insulation system. Similar differences were observed when the assemblies were modelled and the hygrothermal simulation tool validated.

Acknowledgments

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