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Summary An experimental study of the heat and moisture transfer processes in an insulated cavity wall was carried out under controlled steady-state winter conditions applicable to the UK, in a wall laboratory at Salford University. The overall test area of each wall, between the indoor and outdoor climatic chambers was 3 m × 3 m. The principal objective was to study the thermal performance of the wall and the effect of moisture. Other objectives were to locate regions of interstitial condensation and compare with theoretical predictions, and to compare the actual performance with that predicted. In the cavity wall filled with mineral fibre, moisture was found to have a negligible effect on the thermal conductivity of the insulant and a small but predictable effect on the concrete block inner leaf. The variations in thermal conductivity of the concrete could be explained in terms of the moisture content profile, which in turn could be explained, to a large extent, by the hygroscopic moisture present under the prevailing relative humidity distribution. Under 'wet' conditions, where interstitial condensation is predicted to occur, saturation conditions were detected and these were found to be restricted to the brick/insulant. The measurements support the current theory that condensation tends to be restricted to the interface. Measurements of relative humidity in the cavity were broadly in line with those predicted by current theoretical models. The overall measured thermal performance was in line with normally accepted values.

Mineral fibre filled cavity wall: Hygrothermal properties

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1 Introduction

Many walls are permeable to water vapour, and under winter conditions in occupied buildings vapour is driven through the wall from inside to outside. Simple steady-state calculations indicate that under certain conditions, condensation is likely to occur in the region of the brick/cavity interface of a cavity wall. When the cavity is filled with insulation the temperature of the outer leaf is reduced, and the rate of interstitial condensation is predicted to increase. Steady-state measurements carried out by the authors in an earlier study sponsored by the Science and Engineering Research Council (SERC) indicated that expanded polystyrene bead and ureaformaldehyde foam filled walls exposed to condensation conditions for long periods, experienced only a small increase in the thermal conductivity of the insulation adjacent to the brick leaf, and negligible accumulation of moisture in the insulant[1–3], although liquid water was found on the brick face. At present there is no conclusive evidence that interstitial condensation reduces the thermal effectiveness of the insulation.

For some time it has been common practice to use simple steady-state models (e.g. *BS 5250:1975*[4]) which predict 'zones of condensation' within structures i.e. condensation is predicted to occur extensively within the insulation and brick outer leaf of an insulated cavity wall. In recent years this concept has been questioned, particularly in 'breathing' structures. Johnson[5], for example, presents a theoretical argument supported by limited experimental results which predicts that interstitial condensation is restricted to the interfaces on the cold side of relatively low vapour resistance material. In the case of a filled cavity wall, the most vulnerable position would be the insulation/brick interface. This model has been incorporated, as a standard calculation method, into *CIBSE Guide* Section A10 1986[6] and the recently revised version of *BS 5250:1989*[7]. Earlier work at Salford has tended to support these ideas, although it has been limited to polymer insulation fills.

Mineral fibre cavity fill, a class of insulation widely used in the building industry, has not been included in any of the previous investigations at Salford described above. Its thermal conductivity is a little greater than that of the polymers whilst its permeability to water vapour is also larger. Consequently its performance in saturated regions should be compared with that of polymers, and this has recently been carried out as part of an experimental study sponsored by SERC.

The principal objective of this study was to investigate the thermal performance, under controlled steady-state conditions, through mineral fibre insulations within the cavity wall, and to study the moisture diffusion processes and their effects on thermal conductivity. Other objectives were to locate regions of interstitial condensation and compare with theoretical predictions, and to compare the actual performance of the whole wall with that predicted.

2 Test rig and measurements

The wall was studied under steady-state, controlled environmental conditions, in a specially built highly insulated test rig. In order to achieve one-dimensional heat flow over a reasonably large area, the wall under investigation was about 3 m × 3 m. Both the temperature and humidity were controlled to ±0.3°C and ±2% RH, in chambers on either side of the wall to simulate external and internal environmental conditions. A schematic diagram of the wall laboratory is shown in Figure 1. It should be noted that the external climatic chamber is separated from a refrigeration chamber by an aluminium sheet partition. The purpose of the partition is to prevent the refrigeration coils 'icing' under high external humidity conditions, whilst allowing sufficient heat transfer between the rooms to cool the external chamber to low temperatures.

† Now retired.

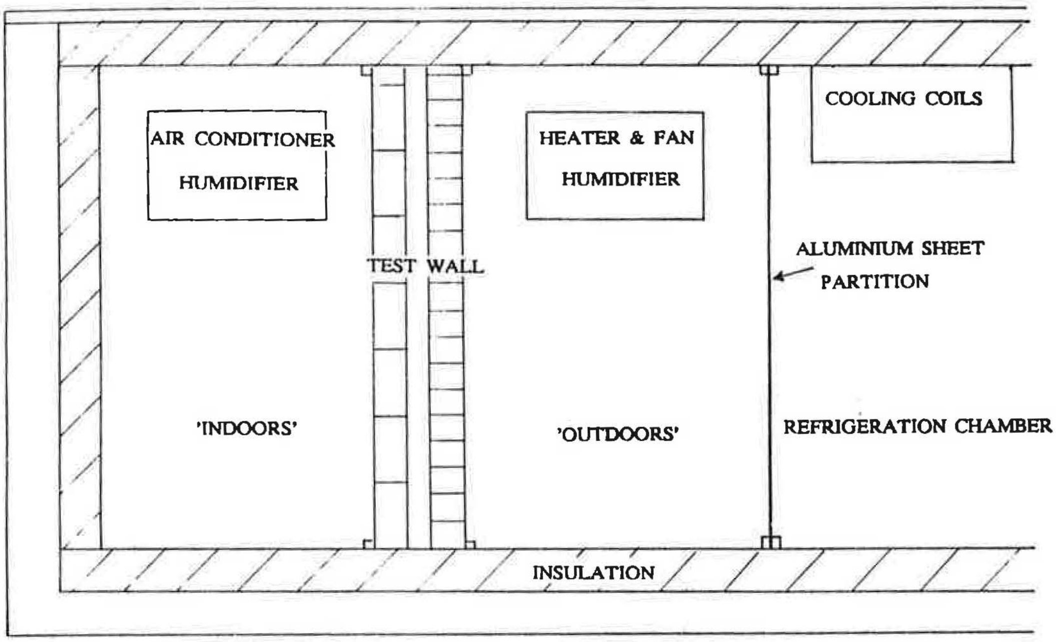

Figure 1 Schematic diagram of wall laboratory

The investigation was carried out on a cavity wall construction, monitored under previous experiments reported by the authors in References 1–3. It was considered advantageous to make maximum use of the existing masonry elements since a great deal of useful information had been obtained on the thermal/moisture performance of these materials which could be related to subsidiary thermal conductivity measurements.

The wall consisted of plaster, aerated concrete (of density 642 kg m^{-3}), cavity and common Fletton brick. Care was taken to ensure that the cavity was air-tight by sealing the periphery of the wall with a mastic sealant and covering with aluminium tape. For the latter part of the experiment the wall was filled by machine-blowing loose fill mineral fibre of nominal density 30 kg m^{-3} into the cavity.

Heat flux through the central area of the wall was measured with a heat flow meter buried in the plaster lining and the temperature on each surface and at eight points through the structure was monitored with thermocouples, as shown in Figure 2. The heat flow meter, made by TNO Delft, was

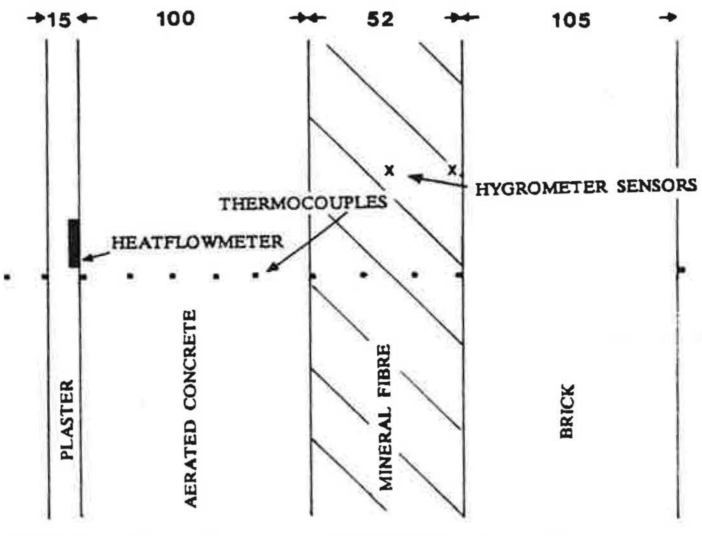

Figure 2 Schematic diagram of cavity filled wall showing position of sensors (dimensions in mm)

100 mm in diameter and 3 mm thick and consisted of copper/constantan thermocouples embedded in polyvinylchloride filling material. This was calibrated in a NAMAS approved guarded hot plate against a reference material of known thermal conductivity, before and after the experiments.

By using a special technique the manufacturers of the heat flow meters were able to accommodate a large number of differential thermocouples per unit area, resulting in a sensitive heat flow meter having an output of about 0.2 mW per Wm^{-2}. Thermocouples for measuring wall temperatures were constructed in the laboratory by arc welding 0.2 mm diameter chromel/alumel wire (40 μVK^{-1}) in an argon atmosphere. Although the wire conforms to NBS standards up to 500°C, separate calibrations were made over the range −30°C to 90°C on thermocouples made from the same batch of wire, at the National Physical Laboratory. In addition the working thermocouples were calibrated against each other before experiments, in order to identify faulty junctions. Experience has shown that chromel/alumel thermocouples made in this way are self-consistent and stable when used under built environment conditions. The wires were covered in glass-fibre sleeving to give an overall diameter of 1 mm. When installed in the wall the thermocouple junctions were sited along a line perpendicular to the surface of the wall, the line being slightly offset from the perimeter of the heat flow meter to ensure that local heat flux perturbations, due to the presence of the meter, did not interfere with thermocouple readings. The thermocouples were spaced equally at intervals of 20 mm in the concrete and 17 mm in the cavity, in order to determine local variations of thermal conductivity under different conditions.

The relative humidity within the mineral fibre was also monitored using the two specially modified Kane and May hygrometers, installed in the cavity just before filling. In order to minimise distortions in the heat flux, the humidity sensors (5 mm long, 3 mm wide and 1 mm thick) were separated from the much larger main body of the probe. Each sensor was protected from dust and direct contact with surrounding materials by a wire mesh guard 6 mm in diameter and 25 mm long. The sensors were positioned with their axes perpendicular to the direction of heat flow, at distances of 3 mm and 26 mm from the cavity/brick surface,

Table 1 Summary of average and incremental thermal conductivity data for each element at the end of each exposure cycle

Element	Thermal conductivity ($Wm^{-1}K^{-1}$)									
	Before cavity filling		20 days after cavity filling		200 days at 20°C, 44% indoors		180 days at 20°C, 60% indoors		60 days at 20°C, 75% indoors	
	0.173		0.167		0.164		0.165		0.165	
100 mm aerated	0.176		0.168		0.166		0.166		0.166	
concrete	0.186	0.182†	0.169	0.168†	0.167	0.166†	0.166	0.166†	0.167	0.167
block	0.189		0.169		0.167		0.166		0.167	
	0.189		0.167		0.167		0.165		0.168	
			0.048		0.047		0.046		0.045	
52 mm cavity	0.279		0.047	0.047†	0.047	0.047†	0.046	0.046†	0.045	0.046
	Resistance		0.047		0.047		0.047		0.046	
	$-0.186\ m^2\ KW^{-1}$									
105 mm bricks	0.69		0.80		0.61		0.67		0.68	

† Average value for whole element

and offset 150 mm from the monitoring axis of the heat flow meter. The hygrometers are claimed by the manufacturers to be accurate to ±2% at relative humidities up to 97%, the resolution of the direct reading instrument being 1%. In addition there was an uncertainty in the position of the sensor in the cavity of ±1 mm, giving an overall uncertainty about ±3%. Calibration of the sensors was carried out before and after the experiments against standard relative humidities of 0 and 75%, and only small changes were observed within the limits of claimed accuracy.

In order to facilitate the measurement of time dependent effects and thereby obtain useful information about moisture processes, the temperature and heat flow were logged every hour of each day using a Hewlett Packard 3947A data acquisition/control unit, and the information stored and processed on a microcomputer. The resolution of the voltmeter was 1 μV, which is equivalent to 0.025°C for temperature measurement. Uncertainties associated with the thermocouple reference junctions in the data logger increased the absolute accuracy of temperature measurement to ±0.1°C. However this was not as important as temperature difference measurements and the accuracy here was certainly better, being about ±0.05°C. The voltmeter was checked regularly using an NPL calibrated DC voltage generator.

3 Results and discussion

Initially the cavity was unfilled and the wall had been conditioned to thermal and moisture equilibrium under nominally 'dry' conditions of 20°C, 44% RH indoors and 0°C, 90% RH outdoors for 125 days. The wall was then filled by machine blowing mineral fibre into the cavity. The environmental conditions were maintained at the above levels for 200 days, until a new thermal and moisture equilibrium state had been reached. After this the relative humidity was increased to 60% at 20°C indoors for a further 180 days, followed by a period of 60 days with the indoor humidity raised to 75% at 20°C.

3.1 Unfilled wall

The thermal conductivities of the wall components, including values for the five 20 mm, and three 17 mm incremental positions in the block and cavity respectively (see Figure 2) are summarised in Table 1, in which the entries in descending order show the thermal conductivity of each element going from indoors (hot) to outdoors (cold). A single thermal conductivity value and the equivalent thermal resistance are given for the empty cavity (i.e. before filling). In view of the small changes observed the results have not been plotted graphically as a function of time.

Before filling, under 'dry' conditions, the thermal resistance of the air cavity was $0.186\ m^2\ K\ W^{-1}$, and the thermal conductivity of the brickwork was $0.69\ W\ m^{-1}\ K^{-1}$, in line with normally accepted values. The thermal conductivity of the aerated concrete blocks ranged from $0.173\ W\ m^{-1}\ K^{-1}$ on the warm side to $0.189\ W\ m^{-1}\ K^{-1}$ on the cold side adjacent to the cavity. This distribution was to be expected, in view of the moisture content variation in the block (determined by the dust drilling method[8]) which increased progressively from 1.5% by volume, on the warm side, to 4% on the cold side, as shown in Figure 3. Also included in figure 3 is a plot of the distribution of thermal conductivity through the block.

Subsidiary measurements of thermal conductivity (λ) as a function of moisture content, using a guarded hotplate to *BS 874*[9], were carried out on samples of aerated concrete cut from the same batch of blocks. The results, reported by Stuckes and Simpson[10], show that the relationship between λ and moisture content for the aerated concrete used ($\rho = 652\ kg\ m^{-3}$) is

$$\lambda = 0.164 - 9.84 \times 10^{-4} m + 1.968 \times 10^{-3} m^2 \quad (1)$$

where m is the percentage moisture content by volume.

The theoretical curves given in Figure 3 are those predicted by the empirical equation 1 for the moisture content distribution shown in the lower half of the diagram. Allowing for an uncertainty of up to 4% in the λ-value measurements, it is clear that there is very good agreement between the predicted and the *in situ* results from the wall structure. This would seem to verify the heat flow meter measuring technique used in these studies.

To a large extent, the moisture content profile in the aerated concrete blocks can be explained in terms of hygroscopic moisture present under the long-term prevailing relative humidity distribution. The humidity can be derived from calculated vapour and saturated vapour pressure gradients,

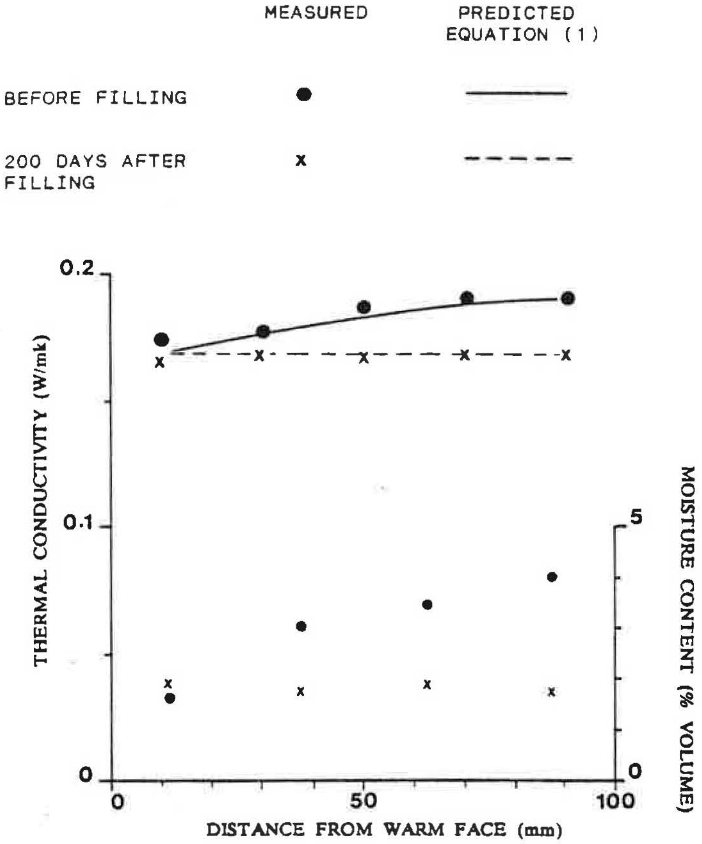

Figure 3 Distribution of thermal conductivity and moisture content in aerated concrete block before and after filling the cavity with insulation

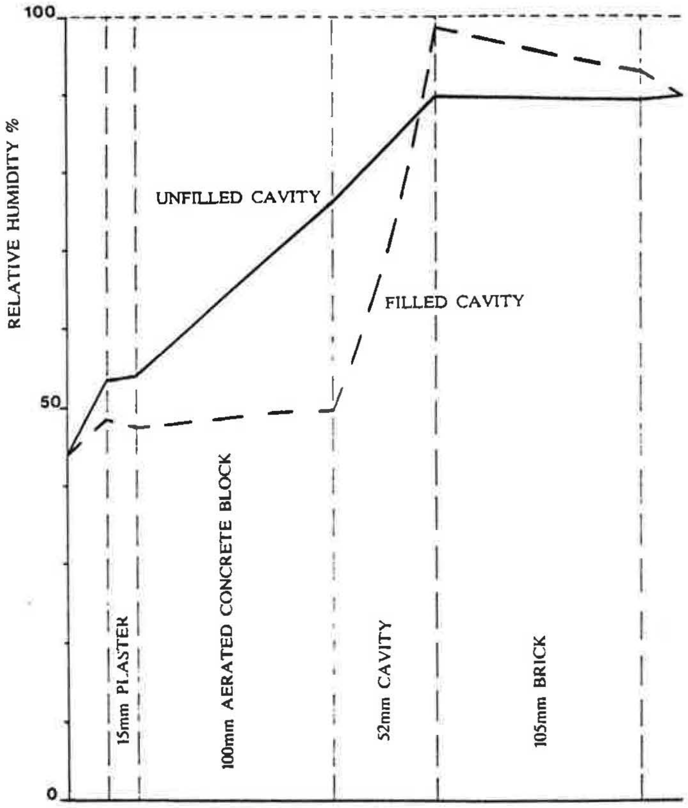

Figure 4 Predicted relative humidity through cavity wall 20°C, 44% indoors/0°C, 90% outdoors

using standard methods [6,7], given the values of vapour resistance of the elements. The vapour resistances of the concrete blocks and brickwork were obtained from subsidiary measurements based on conditions laid down in *BS 4370*[11] applied to specimens measuring 210 × 145 × 100 mm thick, whilst the resistance of the other elements was obtained from standard sources, see Table 2. The thermal resistance data given in Table 2 are experimental data from the wall.

The relative humidity distribution for the unfilled wall in Figure 4, has been calculated for indoor conditions of 44%, 20°C (1028 Nm^{-2} vapour pressure) and outdoor conditions of 90%, 0°C (550 Nm^{-2}). Under these conditions no part of the wall is predicted to have reached saturation levels, the maximum humidity occuring at the cavity/brick interface. The humidity level in the aerated concrete block ranges from 54% to 76% and from this some prediction of the

Table 2 Measured thermal and vapour resistance values for wall elements

Element	Thermal resistance (m^2KW^{-1})	Vapour resistance ($Ns\ kg^{-1}$)
Indoor surface	0.196	2.6×10^8†
15 mm plaster	0.081	1.1×10^9†
100 mm aerated concrete	As calculated from Table 1	3.5×10^9
52 mm cavity	As calculated from Table 1	4.10×10^8†
105 mm brick	As calculated from Table 1	1.70×10^9
Outdoor surface	0.028	2.6×10^8†

† Published general data

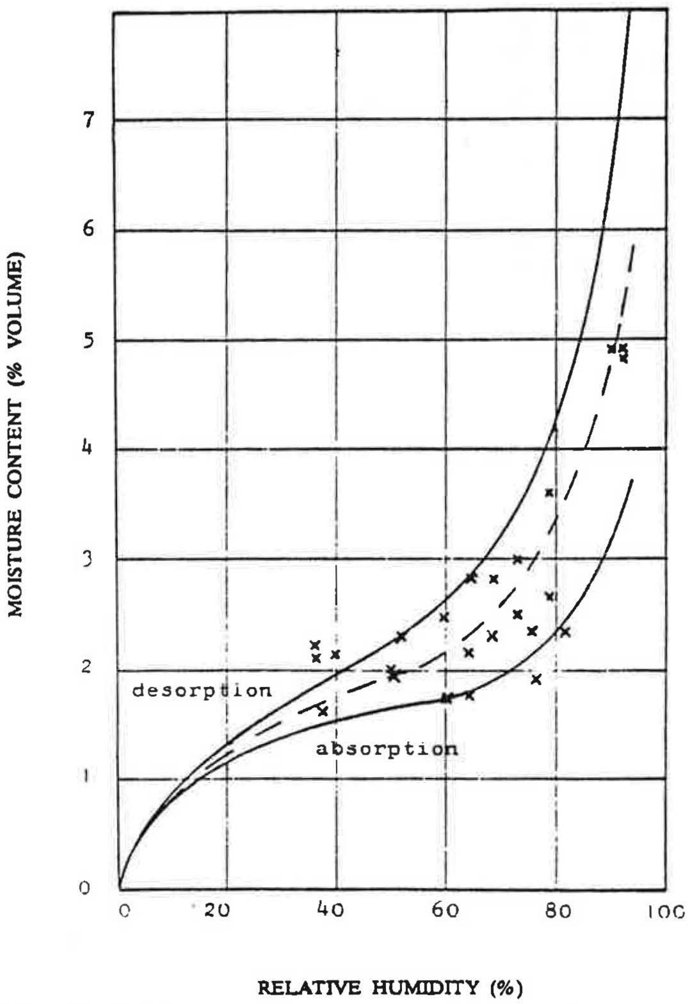

Figure 5 Relationship between relative humidity and moisture content for aerated concrete of density 510 kg m^{-3} (reproduced from Reference 12)

moisture content can be made using hygroscopic curves such as those shown in Figure 5, reproduced from Ahlgren[12], for aerated concrete of density 510 kg m^{-3}. Although there is a large scatter in the experimental data points, predicted absorption and desorption curves are included.

Generally, published data on hygroscopic properties of aerated concrete give only a single curve which does not take into account the hysteresis effect arising from moisture absorption/desorption cycles. The desorption curve in Figure 5 has been chosen as the most appropriate as the experimental wall initially contained a high level of construction moisture and had dried to an equilibrium level under test conditions. From this the moisture content in the aerated concrete is predicted to range from 2.5% to 3.7% by volume, which partly explains the measured moisture content profile in the blocks shown in Figure 3. Although the predicted mean moisture content of 3.1% is similar to that measured (3%), the driest region of the block was found to contain only about 1.6%, significantly less than that predicted above. It should be remembered that the dust drilling technique for moisture determination, is subject to experimental error, particularly at low moisture contents, where localised heating due to drilling can be important. Steps were taken to minimise this by hand drilling, and regularly cooling the drill in alcohol.

3.2 Filled wall

After filling the cavity with mineral fibre the average temperature of the block increased from 12°C to 16°C, and the concrete rapidly dried out and, after 20 days the conductivity had fallen to 0.168 W m^{-1} K^{-1}. The mineral fibre had an average thermal conductivity of 0.047 W m^{-1} K^{-1}, and there was no significant variation within the insulant. Subsidiary hot plate measurements of the conductivity of a sample of the loose fibre at a density of 30 kg m^{-3}, showed that its conductivity was significantly lower at 0.042 W m^{-1} K^{-1}. This suggests that the density of the fill in the monitoring area of the wall is less than the above figure and, possibly additional effects due to the transfer of water vapour drying from the blocks and through the fibre. The thermal conductivity of mineral fibre (Stuckes[1]) increases by about 10% for a very small moisture content of 0.1% by volume. It was not possible however, to determine the moisture content of the mineral fibre in the wall.

Maintaining the indoor conditions at 20°C, 44% RH for 200 days, and then raising the humidity to 60% and 75% for 180 days and 60 days respectively, resulted in very little change in the thermal performance of the aerated concrete or the mineral fibre. The changes in thermal conductivity given in Table 1 cannot be seen as anything more than variations due to experimental error. After 200 days at 44% RH indoors, a significant reduction in the moisture content of the concrete was measured, down to a uniformly distributed level of 1.8% from a mean pre-fill value of 3%. This suggests that the average rate of drying from the block over this period was about 6 g m^{-2} per day. The thermal conductivity predicted by equation 1 for the drier level is 0.168 W m^{-1} K^{-1}, which is in very good agreement with the wall measurements shown in Figure 3. The uniform distribution of conductivity and moisture is in accord with the flat relative humidity profiles predicted in Figure 4. The hygroscopic curve (Figure 5) indicates a moisture level about 2.2%, somewhat higher than the measured value.

By increasing the indoor humidity to 60% and 75%, condensation is predicted to occur on the brick/mineral fibre

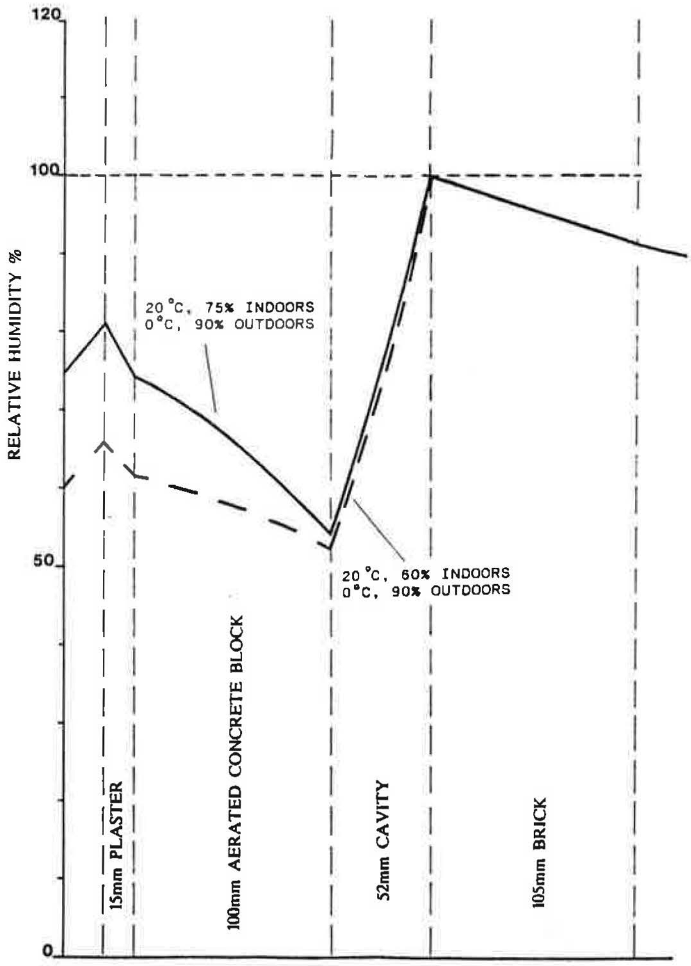

Figure 6 Predicted relative humidity through cavity wall using revised *BS 5250* calculation method

interface (Figure 6). Small droplets of water were seen to be present on the interface, when viewed through an observation hole. It is surprising that the thermal conductivity of the blocks was virtually unaffected under the 75% RH regime, as the local humidity levels were substantially increased. It is thought that 60 days of exposure to these conditions was not sufficient time for hygroscopic moisture equilibrium to be re-established in the blocks. In retrospect, it is unfortunate that the moisture content of the blocks was not measured in order to substantiate this explanation. Although saturation conditions were located on the brick face, this had no detrimental effect on the thermal performance of the mineral fibre. By comparing Figures 4 and 6, it is clear that the predicted average humidity in the fibre under these 'set' conditions is not much greater than that under 'dry' conditions. Consequently the mean hygroscopic moisture content, which influences the thermal conductivity of the insulant, was probably unaffected.

An interesting aspect of the insulated cavity wall was that the thermal conductivity of the bricks (Table 1) increased markedly to 0.8 W m^{-1} K^{-1}, shortly after filling, and then declined to, and maintained, values similar to pre-fill conditions for all the remaining exposure cycles. Clearly under steady-state conditions the conductivity of the bricks was not affected significantly, even though the mean relative humidity within the brickwork was predicted to have increased from 90% to 96% over the whole test period. However, filling the cavity gave rise to a short-term increase

Table 3 Predicted and measured relative humidity in filled cavity

Conditions	RH% 26 mm from bricks			RH% 3 mm from bricks		
	Measured	Predicted		Measured	Predicted	
		Old *BS 5250*	Revised *BS 5250*		Old *BS 5250*	Revised *BS 5250*
44%, 20°C indoors 90%, 0°C outdoors	69	69.7	69.7	97	95.1	95.1
60%, 20°C indoors 90%, 0°C outdoors	73	80.9	71.7	98	109.4	96.2
75%, 20°C indoors 90%, 0°C outdoors	77	91.4	73.0	100	122.9	96.4

in conductivity, as measured 20 days later, suggesting that additional moisture had temporarily transferred from the inner leaf across to the brickwork.

The overall thermal transmittance (U-value) was also determined experimentally by measuring the heat flow per unit area per unit difference between the air temperatures in the indoor and outdoor climatic chambers. The U-values, determined this way (i.e. 0.86 W m^{-2}K^{-1} for the unfilled wall and 0.47 W m^{-2}K^{-1} for the filled wall), are in accordance with generally accepted values for these wall systems.

3.3 *Relative humidity measurements*

The data presented in Table 3 summarise the relative humidity measurements made, at the end of each exposure cycle, for the two positions in the mineral fibre filled cavity i.e. one near the centre of the cavity and one adjacent to the brick leaf. In addition, the predicted humidity levels are included for:

(*a*) the 'old' *BS 5250* method[4] which allows zones of condensation and therefore humidities in excess of 100%;

(*b*) the 'revised' *BS 5250* method[7] which fixes condensation to a plane at the nearest interface and does not allow the relative humidity to exceed 100%.

For method (*b*) a computer program was developed and validated against that used by Johnson[5], using vapour and thermal resistance data given earlier.

Allowing for measurement uncertainties and inhomogeneous insulation fill, the measured values are in reasonable agreement with those predicted by the 'revised' method. Clearly the 'old' method gives erroneous results when condensation occurs. This and the appearance of water droplets on the brick face, with no accumulation of moisture in the insulant (also observed in polystyrene bead and ureaformaldehyde foam filled cavities[1-3]), lends strong support to the notion that condensation tends to be restricted to interfaces.

4 Conclusion

An experimental study of the heat and moisture transfer processes in a cavity wall containing blown-in mineral fibre has been carried out under prolonged steady-state winter conditions. In general the measured thermal conductivity of the wall components, except for the cavity insulation, corresponded closely with subsidiary small-scale hot plate measurements and standard values. The *in situ* conductivity of the mineral fibre was some 7% higher than that determined by subsidiary measurements. This is mainly attributed to local variation in the density of the insulation from the overall fill density of 30 kg m^{-3}.

The introduction of cavity insulation into the wall resulted in an increase in temperature and drying of the aerated concrete block inner leaf. The effect of moisture drying out was noted in the brickwork, as the conductivity increased initially, and then declined to the original value. In the aerated concrete the change and distribution of thermal conductivity could be explained in terms of the measured moisture content profile, which in turn was determined, to a large extent, by the predicted hygroscopic moisture present under the prevailing relative humidity distribution. Experiments indicate that it takes months rather than days to drive water back from the inner leaf to the outer leaf (the normal escape route), and for a moisture equilibrium to be re-established under steady-state conditions.

Under 'wet' conditions, where interstitial condensation is predicted to occur, saturation conditions were located on the insulant/brick interface, and these had no detrimental effect on the thermal performance of the wall components, including the mineral fibre. Generally, relative humidity measurements in the filled cavity were broadly in line with those predicted by current theoretical models. The measurements, and the presence of liquid water on the brick face, lend strong support to the notion that condensation in 'breathing' insulated cavity walls is restricted to the brick/insulant interface, which is the basis of current predictive techniques.

The filling of the cavity wall reduced the heat loss through it by over 45%, and the measured thermal transmittance was in accordance with generally accepted values.

Acknowledgements

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