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REALISTIC VAPOUR PERMEABILITY VALUES

The concept of 'differential' permeability

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There is presently much discussion of the validity of conventional calculation techniques for predicting interstitial condensation. However, the success of any predictive method depends upon the accuracy of the vapour permeability values used as input data. Considerable information is available from standard tests, but the values quoted are generally unique to the conditions of the test and cannot be extrapolated to other conditions. An alternative approach is therefore suggested here, involving the concept of 'differential' permeability, and a differential permeability curve is generated for exterior quality plywood.

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Il y a à l'heure actuelle de nombreuses discussions sur la validité des techniques de calcul conventionnelles permettant de prévoir la condensation superficielle. Mais, le succès de toute méthode de prévision dépend de l'exactitude des valeurs de la perméabilité à la vapeur utilisées. Or les essais courants donnent d'innombrables renseignements mais qui restent propres à ces essais et non extrapolables. Les auteurs de cet article qui travaillent au département Thermodynamique et Mécanique des Fluides de l'Université de Strathclyde de Glasgow proposent donc une autre méthode mettant en jeu le principe de la perméabilité «différentielle», qui permet d'établir une courbe de perméabilité différentielle pour le contreplaqué qualité extérieur.

Severe condensation affects an estimated 1.5 million dwellings in the United Kingdom and constitutes one of the biggest housing problems of the last thirty years (refs 1 and 2). Condensation can occur superficially on the interior surfaces of a building where it becomes obvious; but it can also form unseen within a structure as 'interstitial' condensation and may ultimately cause failure of the building fabric if it continues unchecked. The introduction of non-traditional methods of building, employing materials which are highly sensitive to the presence of water, has highlighted the importance of avoiding interstitial condensation. In particular, the successful design of timber-framed buildings is dependent upon architects and designers having at their disposal accurate techniques for predicting building performance.

In recent years the accuracy of the BS 5250 method (ref 3) for predicting interstitial condensation has been questioned and shown to produce results which do not agree with experimental observations (ref 4). As a consequence, alternative calculation procedures have been investigated, *eg* the Glazer method (ref 5), and the British Standard is currently being revised to produce a more realistic approach. However, although a great deal of progress is being made in devising a more appropriate calculation method, it must be appreciated that the results obtained from such techniques can only be as accurate as the values of material vapour permeability used as a data base.

THE PERMEABILITY COEFFICIENT

The transfer of moisture through a plane-parallel element of building structure is generally represented for most practical applications (refs 6 and 7) by a form of Fick's law of molecular diffusion

$$\dot{m} = -\mu dp/dx \qquad (1)$$

where

$\dot{m}$ = rate of moisture transmission (in the x direction) per unit area, kg/m^{2}s
dp/dx = vapour pressure gradient, N/m^2/m (Pa/m)
μ = coefficient of permeability, kgm/Ns (kg/msPa)

The above equation is analogous to Fourier's equation for conduction heat transfer and implies that the mass of water vapour transmitted is proportional to the vapour pressure gradient, with permeability a constant characteristic of the material, independent of p and x.

If a material does not sorb water, there is no apparent reason to expect any variation in the permeability through the material, as the transfer process is one of pure diffusion. However, most building materials are hygroscopic and the movement of water vapour through them presents a complex phenomenon (ref 8). The simplicity of equation (1) is therefore misleading; μ is not a constant but is in fact a variable function of the prevailing conditions.

The complexity arises from the interactions between molecules of water and those of the substance through which it is passing, resulting in the sorption of water by the material in quantities which depend upon the relative humidity. Consequently the basic gaseous diffusion process may be combined with other forms of transport, namely,

- a movement through the medium as a polymolecular layer on internal surfaces (adsorbed water)
- a migration in liquid form under conditions where adsorbed layers become thick enough to merge and capillary spaces fill (absorbed water).

It would appear from experimental data that the relative effect of these processes is manifested in certain cases by the identification of two distinct humidity regimes (ref 9):

1. A low relative humidity 'dry' zone in which adsorbed layer movements occur and which is characterised by relatively small variations in permeability with humidity.
2. A high relative humidity 'wet' zone dominated by liquid-type flow and characterised by rapid increases in material moisture content and permeability with increasing humidity.

The transition between the regimes, and indeed their existence as described, depends upon the hygroscopy and pore structure of the material. The more hygroscopic the substance, the lower the relative humidity at which a transition is to be expected. Transition humidities of 70 – 80 percent are commonly quoted in literature, but values as low as 50 percent have also been reported (ref 10).

DIFFERENTIAL AND AVERAGE PERMEABILITIES

It is clear that the coefficient in equation (1) must incorporate the effects of all the mechanisms involved in the vapour transmission process and in practice is likely to vary along the flow path through the material in question; μ can therefore only be regarded as a *'differential'* or *'spot'* permeability.

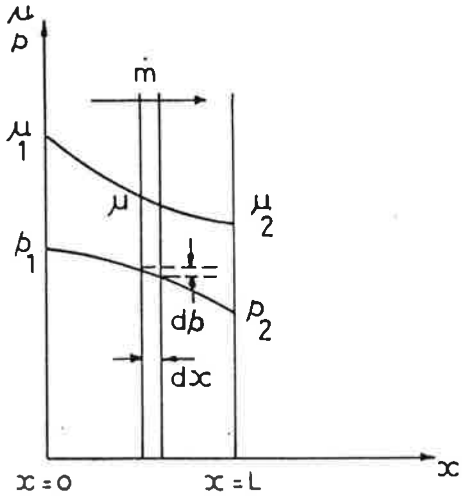

Fig. 1. Vapour transmission through a plane slab

A one-dimensional steady-state transmission through a plane slab of thickness L is represented in figure 1. Substantial simplification is introduced into the analysis if the isothermal condition is considered. Permeability can then be expressed as a function either of vapour pressure or relative humidity for any particular temperature.

Applying the differential equation (1) to an infinitesimal element of slab

$$\dot{m}\,dx = -\mu\,dp \qquad (2)$$

Integrating from x = 0 to x = L

$$\dot{m}L = -\int_{p_1}^{p_2} \mu dp$$

and dividing both sides by the overall vapour pressure difference

$$\frac{\dot{m}L}{p_1 - p_2} = \frac{\int_{p_1}^{p_2} \mu dp}{p_1 - p_2} \qquad (3)$$

This leads to the definition of the *average* permeability $\bar{\mu}$ over the range p_1, p_2

$$\bar{\mu} = \int_{p_1}^{p_2} \mu dp \; / \; (p_1 - p_2) \qquad (4)$$

Thus

$$\dot{m} = \frac{\bar{\mu}\,(p_1 - p_2)}{L} \qquad (5)$$

This equation is the form most commonly applied in calculations; one of the central problems in the study of moisture transmission therefore becomes the prediction of numerical values of $\bar{\mu}$ for a given set of boundary conditions.

PERMEABILITY TEST TECHNIQUES

The permeability of a material is determined by measuring the flow rate of vapour through a sample across which a vapour pressure difference is generated. This can be done by sealing the sample into the mouth of an impermeable 'dish' or 'cup' containing a vapour pressure regulator. The vapour pressure regulator maintains a constant vapour pressure at the inside surface of the sample and may be water, desiccant or a salt solution. The cup is then placed in an environmental chamber with the outside of the sample exposed to a controlled atmosphere (figure 2).

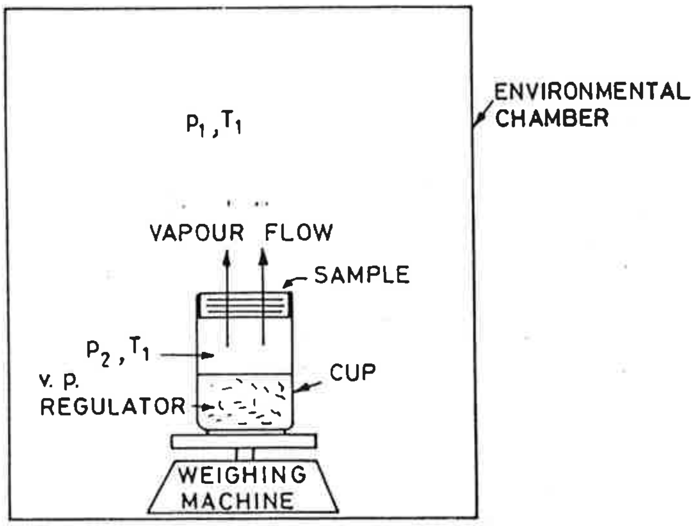

Fig. 2. Permeability test technique

With this arrangement a constant vapour pressure difference is maintained across the material, and the vapour flow rate calculated from the steady decrease (or increase) in cup weight. The permeability $\bar{\mu}$ is then found by application of equation (5).

Most authorities employ this technique of measurement, although differences exist in the cup design, the vapour pressure regulators used, and the recommended chamber conditions. The standards for vapour flow testing adopted by Britain, America and France are outlined in table 1. Two important comments are appropriate.

- Vapour permeability values are normally required for the determination of building performance during the cold winter months. At no time in the UK will there exist temperatures even approaching those suggested, the most reasonable value being the British temperature of 25°C.
- As most building materials are hygroscopic, it might be expected that values of $\bar{\mu}$ obtained from standard test procedures will generally be unique to the conditions of the test and by themselves be insufficient to predict values for other conditions.

AVAILABILITY OF DESIGN INFORMATION

A considerable amount of information on the permeability of materials is available. However, it is interesting to examine the usefulness of this information to a designer and the degree of confidence with which it could be applied. This aspect of the problem can be illustrated by considering plywood as an example of a common component used in modern building structures.

Table 1. Comparison of several test standards

	British BS 4370 Part 2 1973	**American ASTM E96-80 1973**	**French T56-131 1982**
Test cup conditions	1) Dry cup, 0% RH using desiccant	1) Dry cup, 0% RH using desiccant 2) Wet cup, 100% RH using water	1) Dry cup, 0% RH using desiccant
Test chamber conditions	1) 38 ± 0.5°C 88 ± 2% RH 2) 25 ± 0.5°C 75 ± 2% RH	1) 32 ± 0.6°C 50 ± 2% RH 2) 38 ± 0.6°C 90 ± 2% RH	1) 38 ± 0.5°C 88.5 ± 2%
Test cup design	Beaker, 250 ml Ø – 65 mm	Cup of any impermeable non-corroding material. Square samples	Beaker, 250 ml Ø – 65 mm
Presentation of results	Permeability in units μgm/Nh, with test conditions specified	Permeance in perms (grains/ft²h.in.Hg) along with material thickness and test conditions	Index of permeability ICPVE (38) in μ/m²s N.B. No pressure term in this unit. Test conditions must be specified

Table 2. Some quoted permeability values for plywood

Source of information	**Type of plywood**	**Quoted permeability kgm/Ns × 10¹²**	**Test conditions**
Szokolay (ref 11)	not stated	2.0 – 7.0	not stated
ASHRAE (ref 6)	Douglas fir, interior glue	0.7	unclear – stated only as neither wet cup or dry cup
CIBS (ref 7)	not stated	0.3 – 1.0 2.0	not stated
BRE (ref 12) Burberry (ref 13)	not stated	0.17 – 0.67	not stated
Prangnell (ref 14)	not stated	0.17 – 0.67 2.0 – 7.0	not stated

Table 2 is a summary of the information available on plywood from a selection of well-known sources, which might be expected to provide the basis of calculation procedures. The values tabulated have been converted from the original units quoted to SI units.

The uncertainty which a designer would encounter in attempting to apply such data to a given set of conditions is obvious and can be highlighted by the following points:

- The test conditions are not specified in any of the references.
- In several of the references a range of values is given. It is not made clear whether this is a variation for different plywoods in a given test or a variation for a given plywood in different tests.
- The highest value which appears in the table is some 40 times the smallest quoted value.

THE DIFFERENTIAL PERMEABILITY CURVE

The prediction of the average permeability $\bar{\mu}$ for a given set of boundary conditions requires a knowledge of the behaviour of the function $\mu(p)$ over the whole humidity range. This can be obtained by considering the construction of a curve of differential permeability.

The differential permeability μ cannot be measured directly, but it is possible to construct a curve from values of average permeability taken from a series of cup tests on a given material.

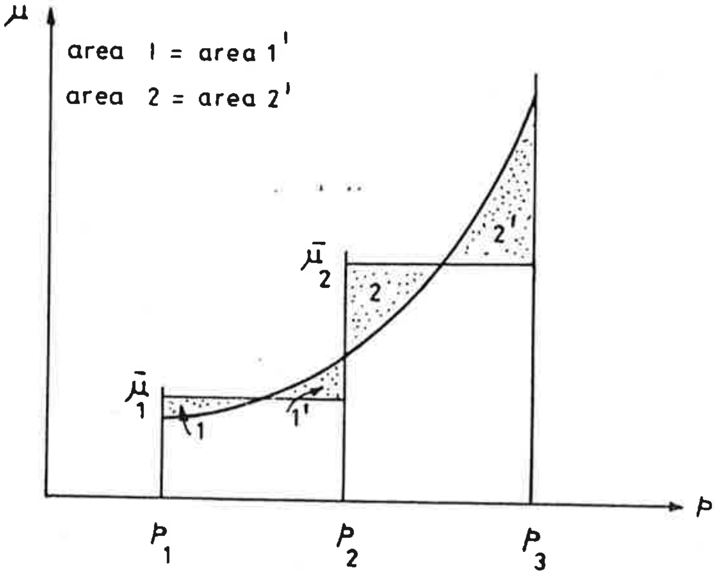

Fig. 3. Relationship between average and differential permeability

From equation (4) it is seen that the differential permeability curve must satisfy the condition, in the case of each test, that the area under the curve between the limits of vapour pressure (or relative humidity) should equal the area under the average permeability line, as determined from the test, between the same limits. This relation between μ and $\bar{\mu}$ over a given range is illustrated in figure 3. Note that the average permeabilities $\bar{\mu}_1$ and $\bar{\mu}_2$ will not generally be equal to the differential permeabilities at the mean pressures $(p_1 + p_2)/2$ and $(p_2 + p_3)/2$.

With the construction of a differential permeability curve it is possible by reversing the procedure to evaluate the average permeability $\bar{\mu}$, for any required limits of humidity, for isothermal conditions at the temperature for which the test data were obtained.

GENERATING A PERMEABILITY CURVE

Work is currently being undertaken at the University of Strathclyde to identify the effect of environmental factors on the permeability of some common building materials. This work is aimed primarily at producing data which can be applied to any set of boundary conditions and which will be usable in standard design calculations. It is also hoped that a modified test procedure will ultimately evolve which will enable such information to be produced as a matter of course.

The initial stage of this research has concentrated on the production of a differential permeability curve for exterior quality plywood at a temperature of 25°C. Although it is well recognised that 25°C is an unreasonably high temperature for winter conditions, it was chosen because it is the lowest recommended temperature given in the current British Standard Test Procedure.

Experimental procedure

A variety of different test cup designs are suggested in the literature. For this investigation standard 250 ml laboratory beakers were used as recommended by the British and French standards. All of the test specimens were cut from the same batch of 5-ply, 12mm thick Brazilian plywood, which is made from Brumasa Madieras wood and bonded using WBP formaldehyde glue. The plywood samples were trimmed to fit tightly into the beakers and sealed in place using plasticised petroleum wax. A metal template was used to provide an accurately defined exposed area on the top surface of the test specimen (figure 4).

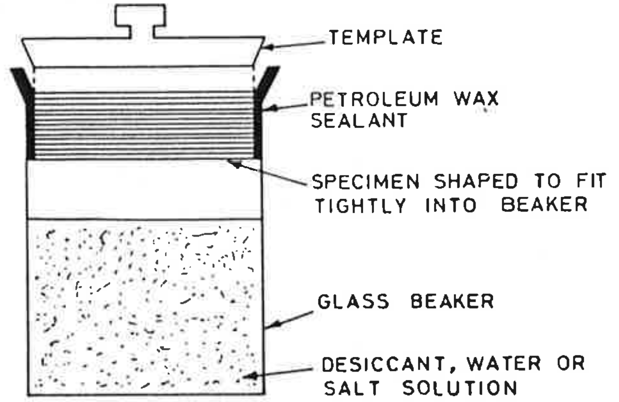

Fig. 4 The British and French standard cup

The British and French procedures refer to a 'dry' cup test only, with desiccant as the cup vapour pressure regulator giving 0 percent relative humidity within the cup. The American standard suggests in addition a 'wet' cup arrangement using water within the dish to generate an internal relative humidity of 100 percent.

It was estimated initially that to generate an accurate differential permeability curve around 10 separate test results would be required. Results from experiments carried out early on in the research indicated that it took between two and three weeks at a temperature of 25°C for results to be obtained for each chamber condition. Thus it was felt that for testing on a regular basis the use of only 'wet' and 'dry' cups along with a variety of chamber conditions could become prohibitive.

With this in mind it was decided to investigate the use of a selection of saturated salt solutions in addition to desiccant and water (table 3).

Table 3. Internal vapour pressure regulators

Cup vapour pressure regulator	**Internal cup RH (%)**
Water (H_20)	100
Ammonium dihydrogen ortaophosphate ($NH_4H_2PO_4$)	93
Ammonium sulphate ($[NH_4]_2SO_4$)	81.1
Ammonium chloride + Potassium acetate ($NH_4Cl + KNO_3$)	71.2
Calcium chloride desiccant ($CaCl_2$)	0.0

A summary of the chamber and corresponding cup test conditions is given in table 4. For each set of conditions quoted a total of four nominally identical cups were used. The weight of each was measured daily, and when equilibrium was attained the average permeability was determined from the gradient of a graph of weight gain/loss against time.

Table 4. Test conditions at 25 ± 0.5°C

Chamber Relative Humidity (%)	**Cup Relative Humidity (%)**
88	0, 71.2, 81.1, 100
80	0, 100
50	0, 71.2, 81.1, 93, 100

Results

The values of $\bar{\mu}$ for each test, taken as the mean of the four cup samples, are given in table 5. An indication of the variation found in individual cup values is also reported in terms of a small-sample standard error.

Table 5. Summary of experimental results

Test cup conditions		Experimental average permeability $\bar{\mu}$ (kgm/Ns × 10^{12})	Standard error
internal	**external**		
0.0	50	0.764	±0.055
71.2	50	1.612	±0.148
81.1	50	1.681	±0.054
93.0	50	3.880	±0.197
100.0	50	6.656	±0.287
0.0	80	1.260	±0.057
100.0	80	14.835	±0.443
0.0	88	3.129	±0.176
71.2	88	6.403	±0.317
81.1	88	7.557	±0.283
100.0	88	21.588	±1.040

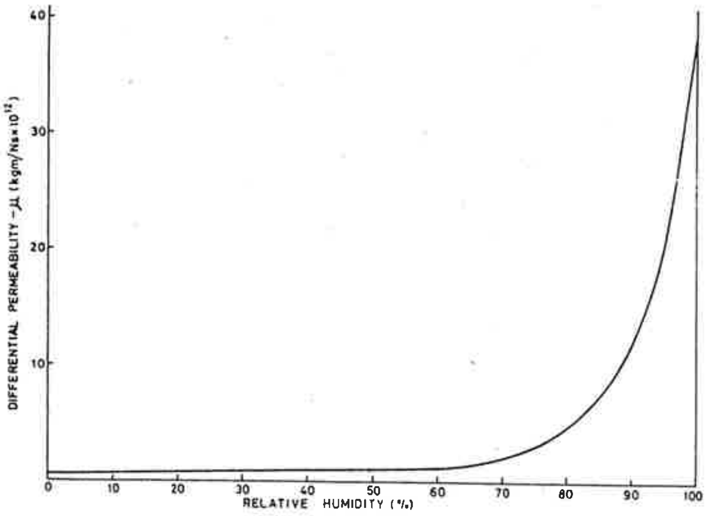

Fig. 5. Differential permeability curve for plywood at 25°C

These average permeability values have been used to construct the curve of differential permeability for plywood shown in figure 5. The construction follows the basis as outlined above and constitutes a 'best-fit' of the experimental values, some of which correspond to overlapping humidity regions.

The correlation between experimental values and the permeability curve is illustrated by figure 6, which plots the experimentally-determined average permeabilities against values predicted from the curve. In most cases the error falls within 10 percent.

OBSERVATIONS AND DISCUSSION

The differential permeability curve clearly shows the extremely large variation in permeability which occurs over the range of relative humidity, with a predicted value at saturation which is some 50 to 60 times the values at low humidity. The shape of this curve reinforces the existence of two humidity regimes, the transition between them occurring at about 60-70 percent RH. Below the transition, values of permeability and changes in permeability are small. Above the transition the permeability increases rapidly with increasing humidity.

This obvious dependence of permeability on humidity demonstrates the uniqueness of permeability test values to the conditions of the test. Values of permeability quoted without reference to test conditions, as shown in table 2, are therefore of little value to a designer.

In many references where test conditions are specified, the permeability values quoted still bear little relation to the permeability associated with the conditions under which the material might be expected to operate in practice.

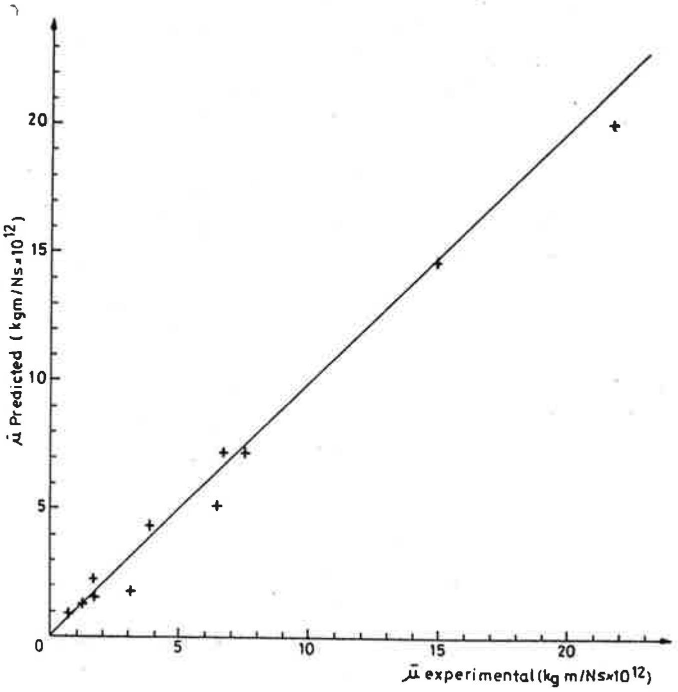

Fig. 6. Experimental against predicted average permeability

Table 6. Comparison between predicted and experimental results

Test conditions	Average permeability in kgm/Ns × 10^{12}		% error
	$\bar{\mu}$ **predicted**	$\bar{\mu}$ **experimental**	
0/50	0.847	0.764	+10.9
71.2/50	1.562	1.612	−3.1
81.1/50	2.207	1.681	+31.3*
93.0/50	4.316	3.880	+11.2
100/50	7.093	6.656	+6.6
0/80	1.275	1.260	+1.2
100/80	14.670	14.835	−1.1
0/88	1.778	3.129	−43.2*
71.2/88	5.144	6.403	−19.7*
81.1/88	7.247	7.557	−4.1
100/88	20.094	21.588	−6.9
*Error > 15%		Total – Average error –	−16.9 −1.54%

For example, an assumed internal relative humidity of 70 percent may not be unrealistic for a building likely to suffer condensation, and external conditions approaching 100 percent RH are common during the winter months. In this situation, for a range of 70 to 100 percent RH, the permeability for plywood predicted from the curve is approximately 11 x 10^{-12} kgm/Ns. This can be compared with the value of 0.9 x 10^{-12} kgm/Ns corresponding to the conditions of the British Standard dry cup test. It is also considerably greater than the highest value which appears in table 2.

CONCLUSION

Where the permeability of a building material varies over a wide range, as is the case with plywood, large errors will be incurred in calculations if this variation is not accounted for, however sophisticated the computing procedures. Designers must therefore have access to accurate values of permeability which are realistic for the conditions to which the material may be exposed.

The present information available on permeability, although voluminous, is deficient in two ways:

(i) The conditions of test are often not quoted, thus rendering the values virtually unusable.

(ii) Even where test conditions are quoted, many of the recommended test conditions are inappropriate.

It is clear from the above that a review of testing procedures is required to produce a standard test which gives realistic results. In addition, further investigation is needed into methods of predicting material behaviour under varying sets of operating conditions.

The curve of differential permeability is a useful way of quantifying material behaviour, although for this to be of practical value the curve must be fitted with a simple mathematical function. This would enable existing computer procedures to incorporate within their database the average permeability as a variable function of prevailing conditions. It is hoped that the research at the University of Strathclyde will eventually provide a practical solution to these problems.

ACKNOWLEDGEMENT

The work being undertaken at the University of Strathclyde is funded by the Building Research Establishment Scottish Laboratory and is a part of their overall programme of research concerned with condensation in buildings.

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