THE USE OF DIFFERENTIAL PERMEABILTY IN MOISTURE TRANSPORT MODELLING

Graham H Galbraith+
R Craig McLean*
Jiansong Guo+
David Kelly+
Chee-Kong Lee*

+Dept. of Building and Surveying, Glasgow Caledonian University, Cowcaddens Road, Glasgow G4 OBA, UK
*Dept. of Mechanical Engineering, University of Strathclyde, Montrose Street, Glasgow G1 1XJ, UK

ABSTRACT

The successful application of moisture simulation models to building envelopes requires accurate values of material transport properties. Unfortunately, although the presently-available database is reasonably voluminous, much of the information given is of limited use. This paper describes the specification of moisture transport data in terms of the differential permeability function and proposes its most appropriate form.

The use of this function allows the accurate evaluation of permeability and total moisture flux appropriate to the humidity conditions to which a material is subjected in practice. It is also suggested that it allows the separation of the total moisture flux into its vapour and capillary liquid components, which is a prerequisite for the exact solution of the defining transport algorithms. This hypothesis has been tested using a prototype experimental procedure in which permeability measurements are made under different barometric pressures.

INTRODUCTION

It is well-recognised within the building design community that moisture can have devastating effects on building envelopes. High component moisture contents, interstitial condensation and the consequent accumulation of water within a structure, can cause a deterioration in the performance and integrity of building materials and a structural degeneration of the building fabric [1]. In extreme cases, there is even the possibility of a structural failure of the building envelope. Building components with a high moisture content are also susceptible to freezing damage and salt crystallisation, which can result in delamination or defacement. High humidities and condensation on internal surfaces can lead to the spoilage of fittings and fabric and mould infestation, which can present a distinct health risk to occupants [2].

In response to the problems of moisture in buildings and the obvious limitations inherent in the steady-state Glaser-type condensation prediction techniques, a considerable effort has been made over the past decade by the international research community, especially through the auspices of the International Energy Agency Annex 24 and the CIB W40 groups, to provide a more sophisticated approach to the problem. This has resulted in the development of a generation of advanced computer-based transient models which can be used to simulate the hygrothermal performance of building envelopes, with the capability of predicting material moisture content and temperature profiles and the occurrence of interstitial and surface condensation. It is to be anticipated that the application of such models as design decision support tools, for both new and retrofit designs, is likely to become more important in the future, as more innovative constructions, involving novel combinations of materials, are introduced.

While these new models represent a significant advance in the simulation capability available to building professionals, the scope of their application is highly restricted at present. The movement of moisture through porous building materials is a highly complex two-phase phenomenon, with series - parallel capillary transport taking place in both vapour and capillary liquid forms and the associated moisture transport coefficients are highly humidity-dependent. The successful application of any simulation model, which requires the accurate solution of the governing heat and mass transport algorithms, will therefore be critically dependent on the quality of the material transport information used as input data. Unfortunately, this is an area in which progress appears to have lagged well behind that of model development.

THE REQUIREMENTS OF A DATABASE

The integrity of the predictions of simulation models clearly requires the provision of a comprehensive and accurate database of moisture transport properties appropriate to the multiplicity of conditions under which materials might have to operate in practice. It could be asked what are the requirements of such a database and to what extent does the information currently available meet these requirements? Essentially, in order to allow the satisfactory solution of the defining transport algorithms, the material transport data should meet two specific requirements. First, it should be possible to predict values of moisture permeability appropriate to the actual humidity conditions to which a material is subjected, thus allowing a realistic evaluation of the total moisture flux. Second, in order to account for the coupled effect of the heat and mass transfer processes, it should be possible to analytically separate this flux into its individual vapour and liquid components.

The information available at present, although reasonably voluminous, fails to satisfy either of these requirements and thus undermines the applicability of moisture simulation models. In many cases, permeability values are quoted without reference to the conditions of test, thus rendering them, at the very least, extremely unreliable [3]. In other cases, although the test conditions are specified, there is no way of extrapolating the given data to different operating conditions [4]. From studies of different construction types, Lee [5] has shown that the use of inappropriate values of permeability can produce significant effects on even the simplest of prediction models. As regards the second requirement, no information is available. The standard gravimetric 'cup' tests, as adopted in most countries, yield permeability values which relate to the total moisture flux. There is, at present, no accepted experimental method which can identify separately the liquid and vapour fluxes over the range of conditions which correspond to unsaturated liquid flow. Many models therefore assume that, below a critical relative humidity of 98% when the material becomes saturated with liquid water, the total moisture transport is in the form of vapour, even although it is known that the onset of capillary condensation is initiated at humidities well below this value [6]. Other models make arbitrary assumptions as to the relative proportions of liquid and vapour.

This paper proposes a system of data presentation for use in simulation models, which would appear to offer the possibility of satisfying both the database requirements. It also reports briefly on some novel experimental work carried out to investigate the validity of this supposition. The approach used is based on the concept of 'differential permeability', which Galbraith and McLean [7] first described in 1986 and which has been developed since then.

THE DIFFERENTIAL PERMEABILITY FUNCTION

The transport of moisture through a differential thickness of material dx, can be expressed for isothermal conditions as

$$j = - \mu \nabla p_v \qquad (1)$$

where j is the total moisture flux (kg/m^{2}s) and p_v is the local vapour pressure (N/m^2). The differential permeability μ (kgm/Ns) is a function of relative humidity, which for hygroscopic building materials is highly non-linear.

On integration, the total moisture flux through a building envelope component of thickness *l* becomes

$$j = \frac{\overline{m}\,(p_{v1} - p_{v2})}{l} \qquad (2)$$

where p_{v1} and p_{v2} are the boundary vapour pressures and the coefficient $\overline{m}$ is the 'average' moisture permeability pertaining to the varying humidity conditions along the moisture transmission pathway *l*. $\overline{m}$ is related to μ through the relation

$$\overline{m} = \frac{1}{(f_2 - f_1)} \int_{f_1}^{f_2} m(f)\, df \qquad (3)$$

where ϕ_1 and ϕ_2 are the boundary relative humidities.

The prediction of $\overline{m}$ from equation (3) for any imposed set of humidity conditions, requires the full and accurate specification of the functional relationship $\mu(\phi)$. Although the differential permeability cannot be measured directly, such functions can be generated from experimental values of $\overline{m}$ obtained from a series of standard gravimetric cup tests arranged to cover the whole humidity range [6].

The usefulness of presenting material transport performance in terms of differential permeability has become increasingly appreciated by researchers and modellers in recent years [8]. Unfortunately, progress towards the compilation of a rationalised data-base has been inhibited by the fact that a variety of different functional forms have been proposed and used to describe the relation between μ and ϕ [9][10][11]. In order to establish the most appropriate form for the $\mu(\phi)$ function, which would constitute the basis of a consistant mathematical approach, a detailed study was undertaken by the authors in which the efficacy of five different equation types to satisfactorily model actual experimental data was compared. This was done on the basis of measured values of $\overline{m}$ for six materials considered representative of the range of hygroscopy likely to be encountered in practice :- polyurethane insulation, plasterboard, plywood, common brick, aerated concrete and aggregate concrete. The performance of each equation type was assessed according the following stringent criteria:

(a) It should provide a close fit to the experimental data for all materials, as evidenced by coefficients of determination near unity.
(b) The correlation coefficient matrix between the regression parameter estimates should be characterised by values well below unity, thus minimising any possible collinearity effects.
(c) The resulting differential permeability curves should not exhibit any features which contravene the accepted physical principles of moisture transport.

The comparative study and the statistical methods used are fully described in references [12][13][14]. On the basis of the above criteria, it was concluded that the best basis for the description of the differential permeability function was provided by the following mathematical form first proposed by Galbraith [15]

$$\mu = \alpha + \beta\phi^{\gamma} \qquad (4)$$

from which equation (1) becomes

$$j = -(\alpha + \beta\phi^{\gamma})\,\nabla p_v \qquad (5)$$

A sample database of material transport properties based on equation (4) is given in Table 1. Figure 1 shows the resulting differential permeability curves for three of the materials covered.

SEPARATION OF THE TOTAL MOISTURE FLUX

In 1993 Galbraith et al. [16] demonstrated by theoretical reasoning that the total moisture flux could be separated into its vapour and liquid components as

$$j = j_v + j_l = -\left(D_v\, t\left(f\right) + D_l^* f^m\right)\nabla p_v \qquad (6)$$

where $D_v\ \tau(\phi)$ and $D_l^*\ \phi^m$ are the transport coefficients associated with the vapour and liquid fluxes respectively. As specified here, the vapour coefficient will decrease with increasing humidity and liquid water content through the function $\tau(\phi)$, which is an effective vapour transfer area factor. However, it has been shown by Galbraith [15] that the error involved in assigning a value of unity to $\tau(\phi)$, thus effectively taking the vapour coefficient as a constant, is relatively small. Thus, as a good approximation

$$j = j_v + j_l = -\left(D_v + D_l^* f^m\right)\nabla p_v \qquad (7)$$

It is seen that this equation has the same form as equation (5). This implies that the differential permeability expressed as equation (4) not only permits an accurate evaluation of j, but also facilitates the direct separation of j into its two component parts, with $\alpha = D_v$, $\beta = D_l^*$ and $\gamma = m$.

The verification of such a postulate requires an experimental procedure which allows the separate identification of the vapour and liquid fluxes. Such a procedure is currently being developed by the authors as part of a wider investigation into rapid permeability measurement techniques. As in the generation of the $\mu(\phi)$ function, it involves the measurement of values of μ over a range of fixed humidity limits using conventional gravimetric cup tests[6]. However, these tests are now carried out under a range of different barometric pressures, the basic theoretical premise being that the vapour coefficient will be inversely proportional to the barometric pressure p_b, while the liquid coefficient will remain independent of it [15].

Writing D_v as D_v' / p_b and denoting $D_l^* f^m$ simply as D_l, the integrated form of equation (7) can be expressed as

$$j = \overline{m}\frac{\Delta p_v}{l} = \left(\frac{D_v'}{p_b} + \overline{D}_l\right)\frac{\Delta p_v}{l} \qquad (8)$$

where $\overline{D}_l$ is the average liquid coefficient corresponding to the humidity conditions maintained on either side of the test material. This suggests that a graph of $\overline{m}$ plotted against $1/p_b$ should yield a straight line with gradient D_v' and intercept $\overline{D}_l$.

Integrating equation (4), noting that $\alpha = D_v$, gives

$$\overline{m} = a + \frac{b}{\Delta f(g+1)}\left(f_2^{g+1} - f_1^{g+1}\right) = D_v + \overline{D_l}$$

(9)

It can be seen that equations (8) and (9) allow a direct comparison to be made of the values of D_v and $\overline{D_l}$ obtained from the variable barometric pressure tests and those predicted from the differential permeability function which apply to the standard barometric test pressure of 1 bar.

Table 1 Curve Fit Data Based on Equation (4)

Material	**Density** (kg/m^3)	**Thickness** (mm)	**Regression Coefficient** α kgm/Ns x 10^{-11}	β kgm/Ns x 10^{-11}	γ	**Coefficient of Determination** R^2
Expanded Polyurethane	16.6	25	0.350	0.373	4.507	0.982
Common Brick	1676	25	1.114	1.182	6.331	0.931
Facing Brick	2158	12	0.076	0.679	11.922	0.993
Particle Board	589	12	0.355	1.24	8.38	0.965
Pine Wood	388	14	0.123	3.396	4.744	0.993
Spruce Wood	391	15	0.146	3.681	5.687	0.998
External Plywood	604	18	0.139	0.523	5.745	0.994
Plasterboard	700	15	2.030	1.290	1.740	0.907
Aerated Concrete	490	25	2.220	7.230	5.211	0.998
Aggregate Concrete	1327	25	1.167	3.464	10.60	0.904
Dense Aggregate Concrete	3137	25	0.635	3.394	18.14	0.989

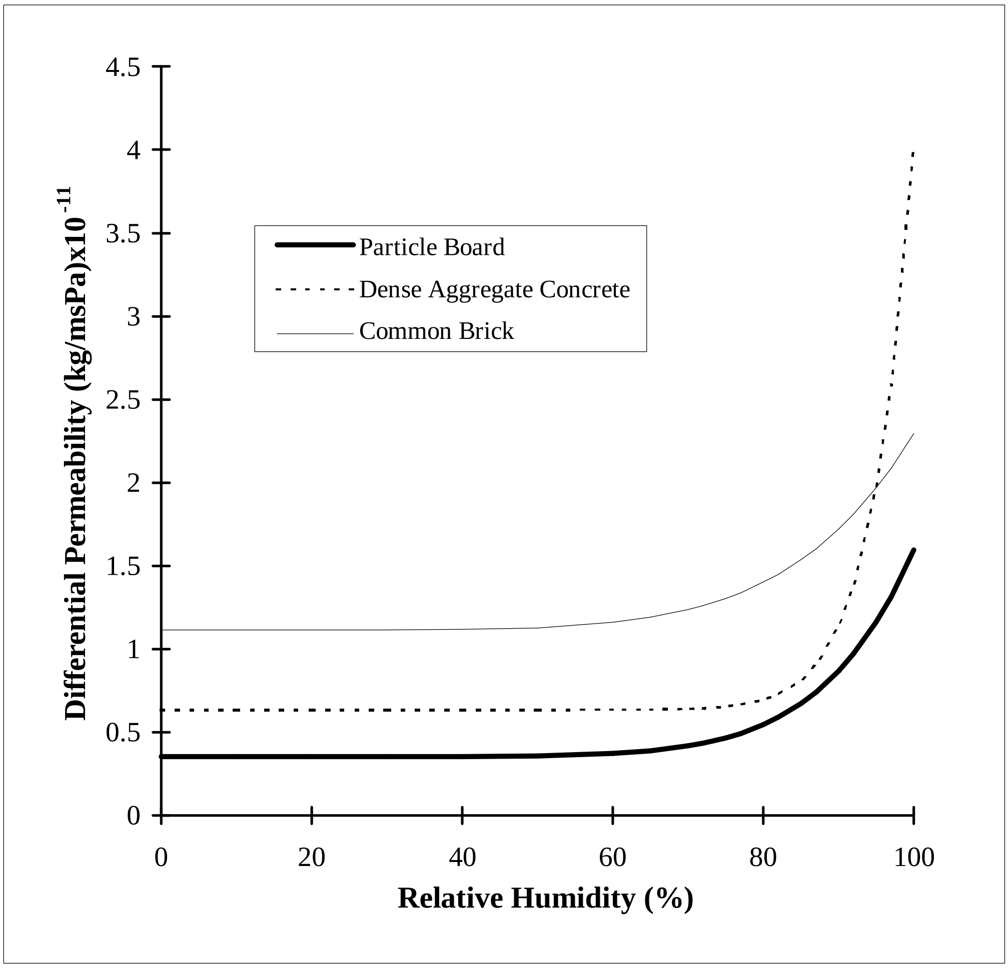

Figure 1 Typical Differential Permeability Curves

PRESSURE TEST RESULTS

The pressure test procedure, details of which are given in reference [17], is still at a prototypal stage and only a limited amount of material testing has taken place. Presented here are the results of tests carried out on particle board. The conditions of test are given in Table 2.

Table 2 Pressure Method Results

Relative Humidity Range (%)	**Test Pressure** (bar)	**Measured Permeability** ($\overline{m}$ x 10^{-11} s)
3-58	0.667 0.811 1.009 1.272	0.495 0.406 0.330 0.262
58-93	0.701 0.814 1.001 1.266	0.622 0.567 0.512 0.440

The measured average permeabilities, also listed in Table 2, are shown plotted against $1/p_b$ in Figure 2.

The best fit lines obtained by regression, together with the associated correlation coefficients, are indicated, from which the coefficients D'_v and $\overline{D}_l$ can be identified. Table 3 compares these with the corresponding values calculated from equation (9) using the values of α, β and γ for the test material given in Table 1. Given the developmental nature of the pressure tests and the inherent uncertainties associated with permeability testing in general [18], it is felt that the results obtained provide a reasonable agreement. In the low humidity range, both methods predict a negligible liquid flux and similar magnitudes of vapour flux.

Table 3 Predicted Transfer Coefficients

	Transfer Coefficients			
Prediction	**RH: 3-58**		**RH: 58-93**	
Method	Vapour $D'_v x10^{-11}$	Liquid $\overline{D}_l x10^{-11}$	Vapour $D'_v x10^{-11}$	Liquid $\overline{D}_l x10^{-11}$
Differential Curve for m	0.355	0.0015	0.355	0.193
Pressure Test	0.325	0.0063	0.281	0.223

Table 3 shows that for the high humidity range, the differential permeability method predicts a j_v/j_l ratio of 1.84, while a ratio of 1.26 is predicted by the pressure method. It should be noted that part of this difference will be due to the assumption of a constant vapour coefficient over the whole 0-100% RH range implicit in the form of this differential permeability equation. Although useful as a simplification in moisture flow analysis [15], this is not strictly correct. As capillary condensation fills an increasing number of pores with increasing humidity, so the area available for vapour transfer and hence the vapour coefficient, will decrease. This physical behaviour is confirmed by Figure 2 which shows the gradient of the high humidity line to be less than that of the low humidity line, indicating that the vapour coefficient reduces slightly with increasing humidity.

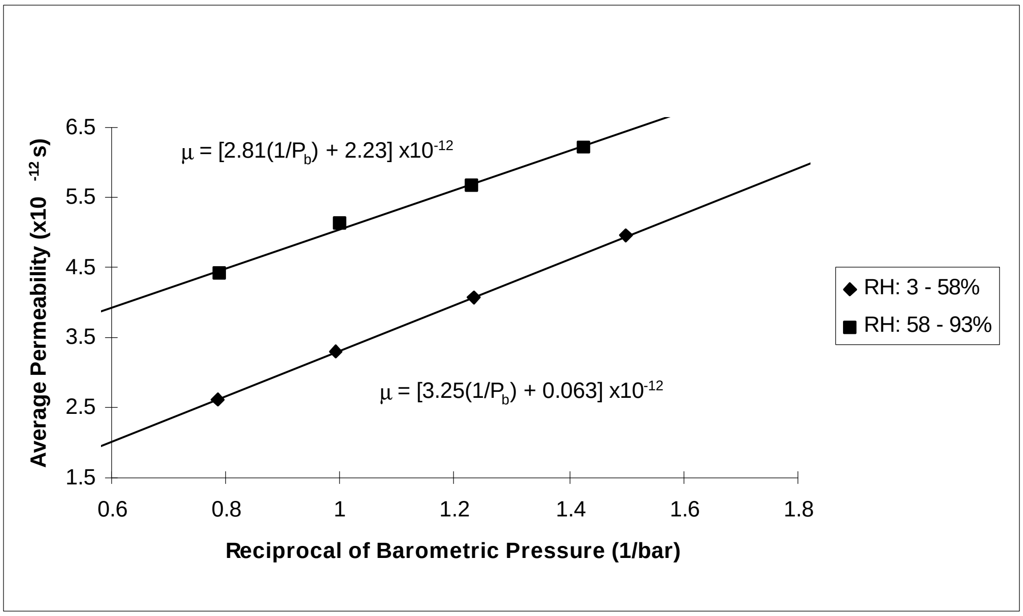

Figure 2 Pressure Test Results for Particle Board

CONCLUSIONS

A significant step towards the generation of a comprehensive database of material transport properties for use in moisture simulation models would be the adoption of a standard functional form for the differential permeability-relative humidity relationship. On the basis of a detailed study comparing different equation types, the most appropriate form for this function has been established. With experimental data expressed in this form, an accurate evaluation can be made of the total moisture flux through a material for any imposed set of humidity conditions. Theoretical analysis suggests that this form of equation might also give a good estimate of the individual vapour and liquid components of the total flux. This hypothesis has been tested using a prototype experimental method which allows the separate identification of the vapour and liquid movements. The results of tests on particle board show a reasonable agreement with the predictions from the differential permeability function and go some way to validating this approach. Development work on the pressure test method is continuing.

REFERENCES

1. Sanders C. Condensation effects on structure durability. Building Services:CIBSE Journal, 1988.
2. Dales RE, Zwanenburg H, Burnett R, Flannigan CA. Respiratory health effects of dampness and moulds among Canadian children. American Journal of Epidemiology, 134,1991.
3. CIBSE Guide Book 1988, vol A, sect 10.
4. ASHRAE Fundamentals Handbook, 1997, chap 24.
5. Lee CK. Unpublished works.
6. McLean RC, Galbraith GH, Sanders CH. Moisture transmission testing of building materials and the presentation of vapour permeability values. Building Research & Practice, 18(2),1992.
7. Galbraith GH, McLean RC. Realistic vapour permeability values. Building Research & Practice, 14(2), 1986.
8. Yik FWH. A differential permeability model for simulating building heat and moisture transfer. CLIMA 2000 Conference, London, 1993.
9. Burch DM, Thomas WC, Fanney AH. Water vapour permeability measurements of common building materials. ASHRAE Transactions, 98(2),1992.
10. International Energy Agency Annex 24, Final Report, 3, 1996.
11. Richards RF, Burch DM, Thomas WC. Water vapour sorption measurements of common building materials. ASHRAE Transactions, 98(2), 1992
12. Galbraith GH, McLean RC, Guo JS. Moisture permeability data presented as a mathematical relationship. Building Research & Information, 26(3),1998.
13. Galbraith GH, McLean RC, Guo JS. Moisture permeability data: mathematical presentation. Building Services Engineering Research & Technology, A, 19(1),1998.
14. Galbraith GH, McLean RC, Guo JS. Moisture permeability data presented as a mathematical function applicable to heat and moisture transport models. BS’97, Vol 1, Prague, 1997.
15. Galbraith GH. PhD Thesis, University of Strathclyde, 1992.
16. Galbraith GH, Tao Z, McLean RC. Separation of moisture flow through porous building materials into vapour and liquid components. Building Services Engineering Research & Technology, A,14(3), 1993.
17. Galbraith GH, McLean RC, Kelly D. Moisture permeability measurements under varying barometric pressure. Building Research & Information, 25(6),1997.
18. Galbraith GH, McLean RC, Tao Z. Vapour permeability: suitability and consistency of current test procedures. Building Services Engineering Research & Technology, 14(3), 1993.