Breathability: The Key to Building Performance

Introduction

Breathability is a misleading term, but it has now become firmly embedded in the vocabulary of building technology. It does at least indicate that the issue is one of importance - if we cease to breathe, we die. It also indicates not only a physical and a dynamic process but also a biological one. In the human body breathing is vital to many physical, chemical and biological processes, and in this context it is the most common and most significant interaction between the self and the world. As such the use of the term breathability to describe the interaction between water and buildings is appropriate. It is one of the most important relationships between the building and the world and it affects almost everything to do with the building health and performance.

Breathability in buildings is not really about air[1]. It is about water: water as a gas and water as a liquid; water inside the building, water outside the building, and water in the walls, floors and roofs themselves (though not about water in pipes!). It is not only about how water moves through structures (water vapour permeability), but also about the ability of materials to absorb and release water as vapour (hygroscopicity) and about the ability of materials to absorb and release water as liquid (capillarity). Water affects everything in building from the health or decay of building fabric, through to the thermal performance of the building and to the health of occupants. Particularly as we try to increase the airtightness, thermal performance and indoor air quality of our buildings, breathability has become a critical issue, affecting all areas both of new build and of renovation.

Our strategy for dealing with water in the air and in the fabric is therefore central to the success or failure of the building as a structure that endures, performs, nurtures and protects – ie the main functions of buildings. If we do not have a strategy, or if we are reliant on unconnected, bolt on solutions to a variety of different problems, then the health of that building will be at risk. Buildings, like people, need to be healthy in themselves, reliant on their own material structures with plenty of excess resource and robustness, rather than dependent on fragile stick on plasters, applied chemicals and mechanical breathing apparatus. Healthy, durable, working buildings can only be brought about by designing with a full understanding of breathability, which is the key to assessing whether or not a building design and construction is successful or not.

This paper will therefore examine first the various types and mechanisms of breathability, and how different materials perform in different ways. We will then examine materials in particular common situations and the consequences of breathability for the main areas affected by water: water on the outside of buildings (rainwater penetration), water in the structure (thermal performance and interstitial conditions), surface condensation and indoor air quality. We will then consider 4 basic principles for the successful design and construction of breathable buildings: compatibility between elements, making the fabric do the work, building in safety margins, and whole house design. Finally we will draw some conclusions about the science of breathability and the future of construction.

---

[1] Actually VOCs and CO_2 do diffuse through walls in considerable quantities, but for the purposes of this article we will only really be considering water.

Types of breathability and material properties

There are 3 main concepts that have to be understood and applied if the effect of water on buildings is to be fully comprehended. These are:

- Vapour permeability
- Hygroscopicity
- Capillarity

Briefly capillarity refers to the absorption/ desorption of water as liquid, whereas hygroscopicity refers to the absorption/ desorption of water as vapour (as relative humidities change), and vapour permeability refers to the ability of a material to allow water vapour to pass through it

Vapour Permeability

In the context of breathability vapour permeability is the rate of passage of water vapour through solid materials[2]. Water molecules as vapour (which is gas below boiling point) will pass through a variety of materials at different rates according to the pore size and thickness of the materials. The issue really is the rate at which they do this. This is what resistance is really about.

In all building situations however, the significance of water vapour transmission through materials is relative to ventilation and air leakage. It is also relative to the hygroscopic capacity of materials in the building. These issues will be discussed below. The fact is however that even small incidents of high relative humidity can cause considerable damage to structures and to human health through the development of moulds and bacteria. High moisture levels also adversely affect building thermal performance. On the other hand buildings with designed and built in vapour openness can help to transport excess moisture away from the indoor environment and can ensure the long term health of the fabric itself. From all points of view therefore the water vapour permeability of materials and structures is important.

The transport of water vapour through structures is driven partially by differential vapour pressure. Vapour pressure arises from the amount of water gas molecules in the air. If there is a difference in the amount of molecules between two areas adjacent to each other there will be a pressure differential, and the water molecules will move to equalise the pressure. This will usually be from the inside of a building to the outside because of the higher production of moisture in a house. The rate of transmission will depend on the pressure difference, the vapour

---

[2] As stated above we are only concerned with water in this article. However the issue of vapour permeability of materials to other gases is also highly important. Water molecules (H_2O) are relatively small compared to other common molecules in the air such as Oxygen (O_2), or Carbon Dioxide (CO_2), but generally the size of the molecules is not significant in relation to the pore size of materials. It is only with materials like paint and certain plastics that the molecule size becomes critical to rate of transfer and where water can sometimes pass easily through materials when these larger molecules cannot. The passage of these larger molecules is sometimes highly important for the building structure itself. In the case of lime and cement mortars the transmission of CO_2 into all the mortar can make significant difference to the strength and durability of the mortar and thus the wall. However, as with water vapour transmission, in most buildings the significance of vapour transmission of O_2 or CO_2 through the wall itself is only relative to other methods of ventilation and to faults such as air leakage through joints and junctions.

permeability of the boundary between the two areas (ie wall, roof) and the thickness of this boundary. Reverse vapour transmission is possible however in certain circumstances. [3]

Vapour permeability is related to the pore structure of a material or of a set of materials in the case of a wall, floor or roof build up and the size and weight of the gaseous water molecule. The permeability of each material can be measured as the resistance to moisture movement. This resistivity is usually measured as r in GNs/kgm (giga Newton seconds per kilogram metre) or MNs/gm (mega Newton seconds per gram metre). r is a material quality, not dependant on size, thickness, shape etc. Many bulk building materials, such as lightweight concrete, bricks, mineral plasters or plasterboard are around 50. Most solid timber is around 200. Still air is 5.

Another way of measuring resistivity is as a ratio of the resistivity of still air. This factor is called μ[4]. This is the common way of measuring resistivity in Germany and elsewhere on the continent

Vapour resistance, as a construction property is measured as G which is r x thickness (in metres), measured as GNs/kg or MNs/g. (Again on the continent this is measured as sd value, which is μ x metres.)[5] Thus a paint may have a high r value, but because it is only microns thick on a wall, it may have a low G value. Conversely concrete blocks may have a relatively low r value but a high G value because of being 100mm wide.

Below is a table of some common r and G values. Please note that many of these are variable, and the second column is therefore a range of resistivity for some common materials. The third column is a typical thickness for that material as used commonly in construction, in order to allow a construction resistance calculation G :

Material	**Range of resistivity r MNs/gm**	**Typical resistivity r MNs/gm**	**Thickness of the layer mm**	**Construction resistance (at typical resistivity) G MNs/g**
Air	5	5	1000	5
Cement plaster	75 -200	100	20	2
Lime plaster	45-200	75	20	1.5
Clay plaster	30-50	40	20	0.8
Gypsum plaster	30-60	50	20	1
Synthetic top coat plasters	1000-5000	1500	3	4.5
Cast concrete under 1000kg/m3	15-35	25	100	2.5
Cast concrete between 1000kg/m3 and 1900kg/m3	30-80	60	100	6
Cast concrete over 1900kg/m3	115-1000	500	100	50
Foamed concrete	25-50	35	100	3.5

[3] Relative humidity (RH) is also very important. This varies according to the temperature and is expressed as a percentage of total capacity, which is when saturation point is reached and no more water vapour can be absorbed by the air. Higher temperatures allow more water vapour before saturation is reached. The higher the RH the less evaporation of water into the air is possible.
[4] Therefore still air has a μ of 1. Since still air has an r of 5 MNs/gm, this means that to obtain the μ of all other materials, their resistance (r) is divided by 5.
[5] being 1/5th of G

Clinker blocks	50-400	150	100	15
Bricks	25-70	50	100	5
Gypsum boards plain	40-70	60	12.5	0.75
Gypsum boards foil backed	4000 -5000	4800	12.5	60
Clay boards (from Claytec)	90	90	20	1.8
Expanded polystyrene	100-750	150	50	7.5
Extruded polystyrene	600-1500	1000	50	50
Polyurethane foam	115-1000	300	50	15
Polyurethane foam with foil	c.10,000	10,000	50	500
Polyisocyanate plastic insulation with foil	40,000 – 50,000	43,000	50	2150
Mineral wool, flax, sheepswool insulations	5-7	6	100	0.6
Woodfibre insulation boards,	25	25	100	2.5
Cellulose insulation (blown)	40-50	45	100	4.5
Spruce, pine, fir	45-1850	200	20	4
Oak, ash, beech	200-1850	400	20	8
Hard board	150-1000	200	8	1.6
Plywood	150-6000	500	9	4.5
OSB	100-300	216	9	1.95
Metals and metal cladding, some plastics and asphalts	250,000 - ∞	1,000,000	2	2000
Emulsion paints for indoor use	1000-7500	1,500	100 µm	0.15
Emulsion paints for outdoor use	10,000-25,000	15,000	120 µm	1.8
Silicate paints	250-350	300	100 µm	0.03
5 coatings with pure limewash	250	250	100 µm	0.025
Solvent based glosses	15,000-25,000	20,000	120 µm	2.4
Alkyd varnishes	60,000-100,000	80,000	120 µm	9.6
Coatings, based on epoxy resins	175,000-250000	200,000	120 µm	24
Coatings, based on chlorinated rubber	350,000	350,000	120 µm	42

<u>sources:</u> Bablick, Federl (1997): Fachwissen für Maler und Lackierer, Stamm Verlag, Köln
CIBSE 1999 Guide A: Environmental Design
Product technical sheets: Various

Hygroscopicity

Hygroscopicity is the capacity of a material to absorb and release water as a gas (water vapour) from and to the air as the relative humidity of the air changes. The effect of materials with good hygroscopic capacity can be to stabilise indoor air humidity, to reduce surface condensation and, in certain situations, to absorb moisture interstitially (depending on where in the structure the hygroscopic materials are situated). The consequences of this for design of insulation, vapour control and ventilation in both new build and in refurbishment are potentially huge.

The hygroscopic capacity of most materials, like the vapour permeability and the capillary capacity, is mainly related to the physical micro-porous structure. Different size and volume of micro-pores gives different hygroscopic and capillary qualities. In a comparison of fired clay bricks and calcium silicate bricks[6] it has been clearly shown that the different pore sizes and distribution have a very marked effect on material qualities of each product. Fired clay bricks have a very large capillary quality but almost no hygroscopic capacity, whereas calcium silicate bricks have less capillary quality, and a high hygroscopic capacity. The pores of fired clay bricks are all of a similar large size, while the Calcium Silicate bricks have a wide distribution of pore sizes. Another example is wood: in wood the moisture adsorbed from air is mainly held in the cell walls. It is not mainly held in the cell lumens, which is where most of the water is held before the timber has been seasoned or dried. It is only held in cell lumens if the seasoned wood has a moisture content of over 30% which is only possible if the wood is in an ambient atmosphere of 100% relative humidity, ie liquid water. Thus in timber the passage of water as a liquid (the capillary mechanism via cell lumens) is mainly through a different pore structure to that of the absorption of water as a vapour (the hygroscopic mechanism via cell walls).[7]

The hygroscopic capacity of a material is related to its equilibrium moisture content. Equilibrium moisture content (EMC) means the moisture content of a material at a fixed temperature and at a fixed humidity of the ambient air, assuming that the material is given sufficient time to reach a stable state. The hygroscopic mechanism is understood to operate only up to 95% humidity. At levels of humidity higher than this capillary mechanisms start to operate as water vapour starts to become liquid firstly in the finer pores and then in larger ones.

Nearly all materials will absorb and desorb water vapour as humidity and temperature change and so adjust their moisture content. These materials have hygroscopic qualities. Some materials will only adjust their moisture content minutely and for the practicality of buildings these are not hygroscopic. In addition it should be noted that some materials absorb and desorb quickly and others relatively slowly. Furthermore the mass of a material will affect the amount of moisture that can be held in a material. The combination of change in equilibrium moisture content, speed of uptake and mass of a material therefore are the three key factors to understanding the effect of a material in a building.

It is useful to look at the relative effects of changes in temperature and humidity on the equilibrium moisture content of timber, as laid out in the following table.

---

[6] ref Description of the moisture capacity of building materials by Carmeliet and Roels at the 6th Nordic Symposium on Building Physics 2002 (www.kuleuven.ac.be/bwf/common/data/JP_2002_JTEBS_Carmeliet_1.pdf),

[7] There may well be other mechanisms acting on hygroscopic capacity and rate of absorption. One suggested mechanism is electrostatic charge, which may well be influential in the hygroscopic capacity of unfired clay. As with all these issues however the main point is really what happens in practice. It is more important to know how materials act than why.

Table of Equilibrium Moisture Content of timber at different humidities and temperatures.

Relative Humidity	**Ambient Temperature**			
0%	**-1°C**	**10°C**	**21°C**	**32°C**
10%	2.6	2.6	2.5	2.3
20%	4.6	4.6	4.5	4.3
30%	6.3	6.3	6.2	5.9
40%	7.9	7.9	7.7	7.4
50%	9.5	9.5	9.2	8.9
60%	11.3	11.2	11.0	10.5
70%	13.5	13.4	13.1	12.6
80%	16.5	16.4	16.0	15.4
90%	21.0	20.9	20.5	19.8
98%	26.9	26.9	26.6	26.0

Temperature is therefore much less important than relative humidity in determining equilibrium moisture content, and effectively the activity of hygroscopic materials. Where temperature may be critical is in situations such as old churches, which are only occasionally heated, or in uninsulated roof spaces , and where humidity levels are high.

However in most situations temperature is not so critical. For this reason in many tables of the relative equilibrium moisture content of materials, temperature is ignored (or assumed at say 20º C), and only changes in relative humidity are variable. For example the following table shows the relative equilibrium moisture content of brick, concrete and wood against changing relative humidity. This is also known as “the moisture capacity” of a material (as expressed by the gradient of the sorption isotherm).

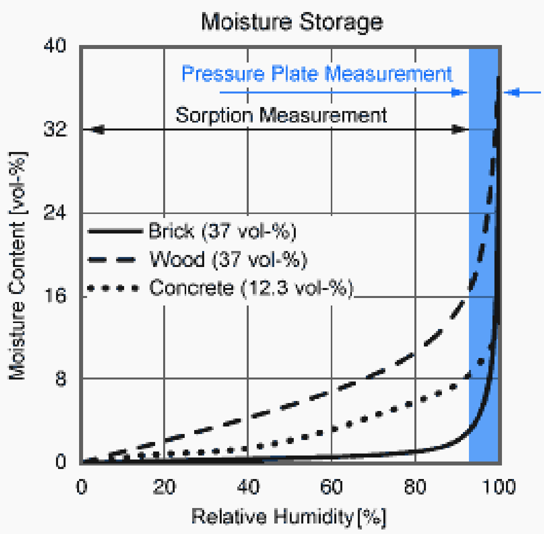


Fig. 3: Typical moisture storage functions for weakly (brick), moderately (concrete) and strongly (wood) hygroscopic building materials. The free saturation of each material is indicated in parentheses. It lies in the capillary moisture region and is thus independent of sorption.

In this chart the blue area at over 95% RH indicates the effect of water transported by capillary condensation. This in itself is also different from capillary transport of water as a liquid, which occurs in different sized pores and is a different mechanism altogether (see footnote 13). The hygroscopic capacity (measured as the change in equilibrium moisture content at different humidities) is here shown to operate only up to around 90 - 95% depending on the materials.[9]

Equilibrium moisture content determines the adjustment of a material to changes in humidity over an unlimited period as required for it to reach a steady state. It does not however indicate the rate of adjustment. This is critical to the buffering of peak humidities in households as regards indoor air quality, condensation and moisture transfer through structures. The much greater speed with which some materials such as unfired clay, end grain wood or certain natural fibre products, can absorb water vapour means that mould growths which can form even within 45 minutes in some locations (such as on tiled surfaces in kitchens and bathrooms), can be avoided (or so it is claimed by advocates of hygroscopic materials), provided of course that the moisture can get to these materials and is not blocked by other building materials and finishes.[10]

In order to measure the speed of absorption there are various standard tests. For example Minke uses a procedure where by materials are placed in a humidity chamber at a constant temperature of 21° C and a relative humidity of 50%. Once they have stabilised they are weighed. The

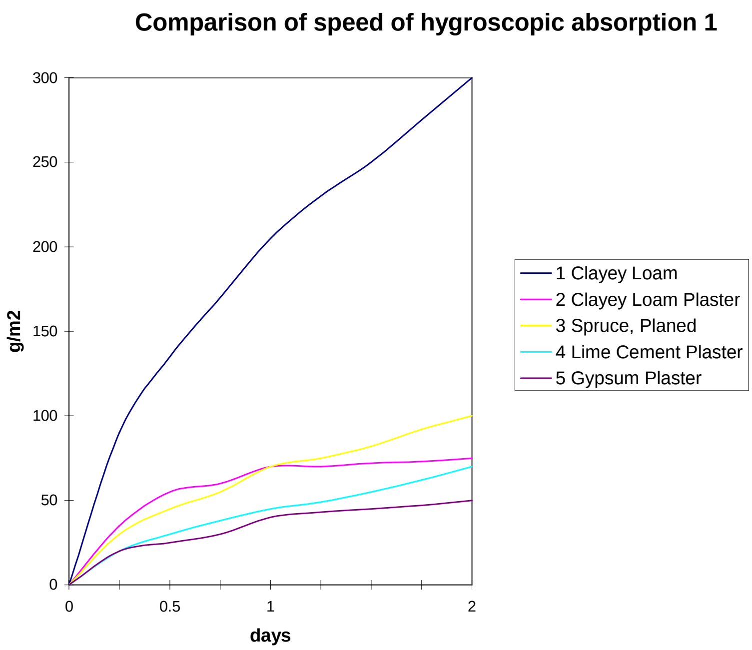
---

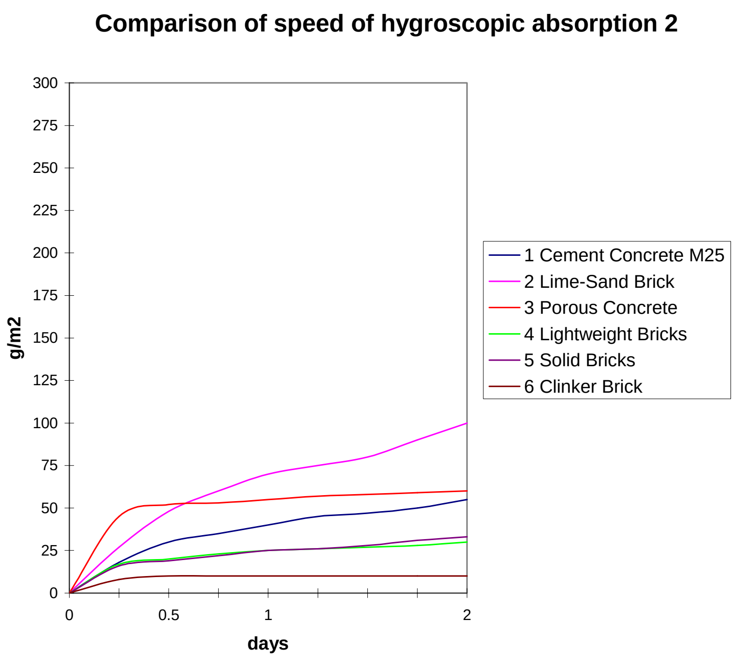
[8] Moisture Transport in Buildings www.hoki.ibp.fraunhofer.de/wufi/grundl_ueberblick_e.html

[9] This chart also has moisture absorption by volume rather than weight. However the basic principles of the chart are correct and clear. Different materials will have different curves according to their changing equilibrium moisture content at different humidities.

[10] It has also been shown by T. Padfield that certain materials can eliminate the need for moisture extraction and ventilation systems in sensitive locations such as museums, providing that air changes can be kept low.
http://www.padfield.org/tim/cfys/phd/phd-indx.php

humidity is then increased to 80%, and the materials are weighed at various intervals to see how much moisture they have absorbed. This gives the following kind of tables[11]:





These tables are interesting in that they indicate how materials vary hugely in speed of absorption over a relatively short period. This is critical to understanding the practical effect of building

[11] Earth Construction Handbook by Gernot Minke WIT press 2000 page 16

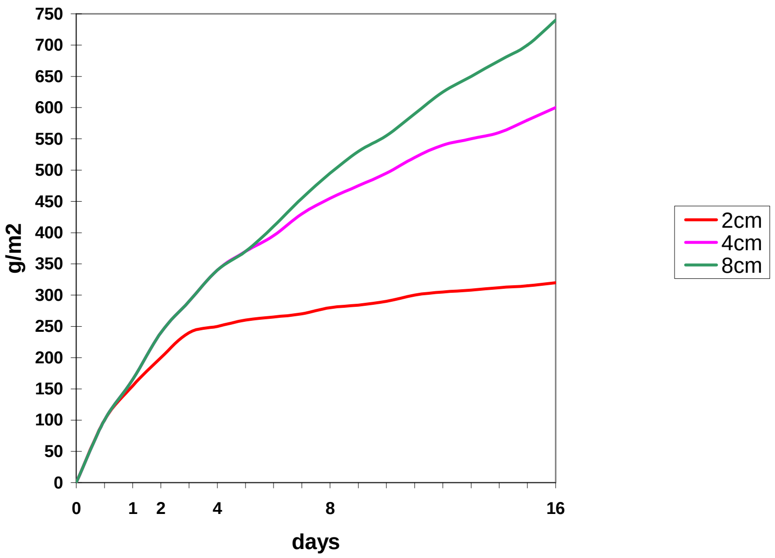
materials in providing moisture buffering in building design. Timber for example has a huge hygroscopic capacity over a long period. Over 12 hours however planed timber is less effective than porous concrete. End grain timber and woodfibre boards are however almost as good as clay, but are not often close to the surface of a room, and therefore will not have the same effect as a plaster or exposed blockwork.

One factor which influences the performance of a material in this matter is the total holding capacity of a material. A loose natural fibre like wool or hemp might absorb water vapour quickly, but it quickly also reaches its moisture holding capacity because of its low density. Mass is therefore an important figure particularly when one is looking at hygroscopic buffering of high humidity for more than 24 hours. This is why for some materials, particularly those with varying density the hygroscopic capacity is measured as a percentage of weight not of volume.

The ability of materials to take up moisture over time depends also on “Penetration Depth”, which relates to the depth of the material which is actively working to buffer humidity. This buffering action will only take place in internal walls or ceilings which are not connected to the outside, or in external walls and ceilings where the outside is vapour impermeable; in external walls and soffits where the outside *is* sufficiently vapour permeable, then the partial vapour pressure differential between inside and outside will mean that most of the moisture which is stored is released to the outside rather than back inside. Penetration depth therefore relates to thickness, density, equilibrium moisture content and the position of the material in the building.

It is interesting in the following table of Minke[12] to see how the thickness of a clay wall absorbs moisture over time. The outer 20mm of the wall starts to loose its rapid rate of absorption within the first day and reaches its capacity about 3 days. It is only as the rate tails off that the next 20mm starts to have a significant additional buffering effect. This effect is only significant however if long term buffering is required.

Effect of the thickness of loam layers at a temp. of 21 deg C on their rate of absorption after a sudden rise in humidity from 50-80%



[12] Earth Construction Handbook by Gernot Minke WIT press 2000 page 17

The combination of density, change in equilibrium moisture content and speed of absorption give the following type of table which compares some different building materials. This table is made up from various sources, some vague and some contradictory, and is intended to be indicative of the kind of comparison that might be made and is not an exact assessement or tool.[13]

Material	Density Kg/m3	EMC at 50% RH (at 20º C)	EMC at 85% RH (at 20º C)	Hygroscopicity (increase in moisture/mass at 20º C from an RH of 50% to 85%)	Hygroscopic capacity Density x Increase Kg/m3	Speed of hygroscopic take up
Cement render	2000	0.5%	2.5%	2%	40	Slow
Lime render (hydraulic)	1600	1.25	3%	1.75%	28	Slow/medium?
Gypsum plaster	850	0.4%	1%	0.6%	5.1	Medium
Concrete	2000	0.5%?	2.5%?	2%?	40?	Slow
Aerated concrete	600	0.9%	2.5%	1.6%	9.6	Medium
Fired Clay Brick	1700	0.1	0.2	0.1%	1.7	Medium
Unfired Clay Brick	1700	4	7	3%	52	Very Fast
Spruce transverse	600	9	18	9%	54	Slow
Spruce end grain	600	9	18	9%	54	Fast
Plywood	500	9	18	9%	47	Very Slow
Mineral wool insulation	10	1.3	2.3	1%	0.1	Medium
All plastic insulations	15	0	0	0%	0	N/A
Woodfibre board insulation	200	8	17	9%	18	Fast
Cellulose insulation blown	45	8	17	9%	4	Fast
Flax/ hemp/ sheepswool insulation	25	8	17	9%	2.25	Fast
All paints	0.1 – 0.3	N/A	N/A	0%	0	N/A

In regard to the actual use and relevance of hygroscopic materials it must be noted however that hygroscopic buffering is only important when the ventilation rate is small. The higher the ventilation rate (assuming effective ventilation of whole room spaces) the less significant is the effect and importance of hygroscopic buffering. It may even be that ventilation and certainly air conditioning work against hygroscopic buffering in that they can dry the internal air in buildings too far, making them unhealthy because of too little moisture, and negating any balancing effect hygroscopic materials might have on indoor air quality. This is discussed further below, in reference to Indoor Air Quality.

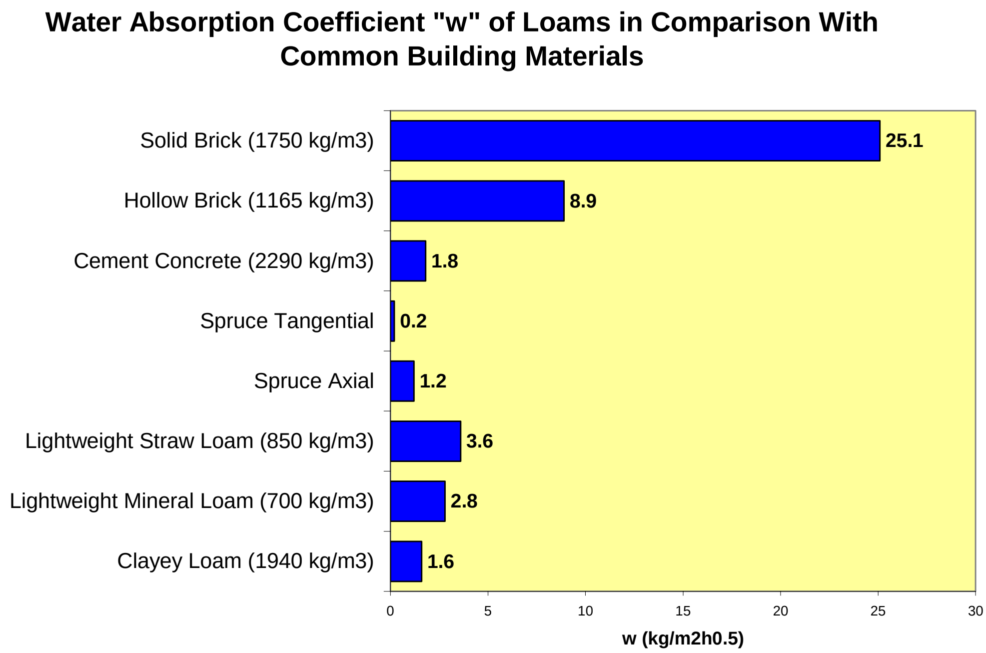
[13] The information in the table is taken from a variety of sources, and is of very varying quality. Where there are question marks, there is greatest uncertainty.

Capillarity

Capillarity refers to the absorption/ desorption of water as liquid. For most practical purposes, materials have a hygroscopicity from 0%RH to 90%RH, they have a permeability to water vapour and they have a capillary absorption from liquid water.[14]

As stated above capillarity, like hygroscopicity, is a function of pore structure. These are much larger sized pores to those used in hygroscopic activity or as regards vapour permeability. Obviously capillarity can be altered by coatings and additives and many of these act as hydrophobic agents by blocking these larger pores, but still allowing the smaller pores to remain open. In this way the pore structure may be kept open for hygroscopic and vapour permeable transfer of moisture but closed to capillary transfer of moisture. On the other hand coatings and additives which physically block all sizes of pores in a material can close off all 3 modes of water transfer.

Capillarity is measured by placing a standard cube of material in water, with all sides sealed except the bottom. The weight of the material is then measured from time to time and this is expressed as a co-efficient w in $kg/m^2h^{0.5}$. The following table compares some materials measured by this method.[15]



---

[14] It is also possible to have capillary condensation at RH of over 90% and under 100% (liquid water). This occurs in micro pore structures of the same size as those in hygroscopic mechanisms. It can affect condensation of materials in dewpoint situations, and cannot be blocked simply by hydrophobic measures.

[15] Earth Construction Handbook by Gernot Minke WIT press 2000 page 28

Another factor however which must be taken account of again is the rate of absorption and the rate of desorption. As with hygroscopic performance, these are not always the same.

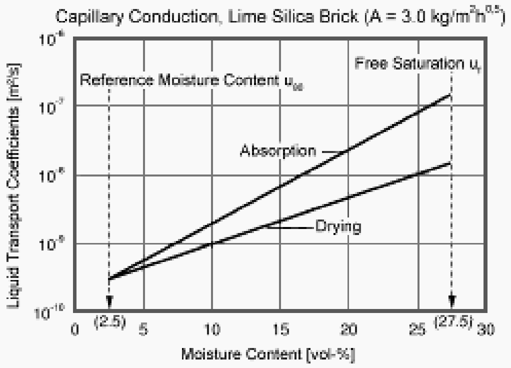


Fig. 5: Liquid transport coefficients for absorption by capillary suction as well as drying and redistribution without wetted surface, estimated from the A-value with WUFI's approximation method. The coefficients increase exponentially with the water content. In most building materials no appreciable liquid transport occurs below the reference moisture content.

[16]

The consequence of differential absorption and drying can be critical in certain materials particularly in the course of construction, or where there is a building defect or change in the intended performance of a building (ie from one that allowed moisture movement to where this has been impaired by the introduction of incompatible materials).

Some observations on the different qualities of different materials:

All this may seem rather complicated. However it is not so important to designers and architects to understand the mechanisms as the actual performance of different materials and the impact on the whole building. Understanding the difference between vapour permeability, hygroscopicity and capillarity is very important as claims are often made about materials being "breathable" which are confused and misleading. This applies to both natural and synthetic materials as well as to many traditional materials.

[16] Moisture Transport in Buildings www.hoki.ibp.fraunhofer.de/wufi/grundl_ueberblick_e.html

The following table gives some examples of material differences in the different categories. Again this table is only indicative, and there are a number of uncertainties about specific material qualitities.

Material	Vapour Permeability (r)	Hygroscopicity (increase in moisture/mass at 20º C from an RH of 50% to 85%)	Hygroscopic capacity Density x Increase Kg/m3	Speed of hygroscopic take up	Capillarity w $kg/m^2h^{0.5}$
Cement plaster	100	2	40	Slow	1?
Lime plaster	75	1.75	28	Medium	1?
Clay plaster	40	3	36	Fast	2?
Gypsum plaster	50	0.5	5	medium	5?
Concrete	500	2%?	40?	Slow	1.8
Fired Clay Brick	50	0.1%	1.7	Medium	25.1
Unfired Clay Brick	40	3%	52	Very Fast	2
Spruce transverse	200	9%	54	Slow	0.2
Spruce end grain	200	9%	54	Fast	1.2
Plywood	500	9%?	54	Slow	0.1?
Mineral wool insulation	5	1%	0.1	Medium	0.1?
Expanded polystyrene insulation	150	0%	0	N/A	0.2?
Polyisocyanate Insulation	43,000	0%	0	N/A	0
Woodfibre insulation	25	9%	18	Fast	0.5 – 2
Cellulose insulation	25	9%	4	Fast	>10
Flax/ hemp/ sheepswool insulation	5	9%	2.25	Fast	1 - 2
Indoor emulsion paint	1,500	N/A	0	N/A	0.2?
Casein paint, pure limewash	250	N/A	0	N/A	> 1
Silicate masonry paint	300	N/A	0	N/A	0.08
Masonry paint	15,000	N/A	0	N/A	0.05?
Rubberised coating	350,000	0	0	N/A	0

[17]

So, for example, a material such as mineral wool insulation is indeed very vapour open compared to plastic insulations, particularly closed cell insulations such as polyisocyanate boards. It is not

[17] Again this table is taken from a variety of sources which may not be reliable or compatible. The idea however is to see how different materials can be in different ways.

however "breathable" in the same way as timber or clay, or indeed as natural fibre insulations. Indeed its qualities are quite different. Mineral wool is, indeed, very vapour open, but has very little hygroscopic capacity. It also has very limited capillarity (and consequently if it does get wet through it dries very slowly, mainly when it can through gravity). By contrast all natural fibre insulations, including woodfibre insulation, not only have a high degree of vapour permeability (flax, hemp and sheepswool insulation having the same vapour permeability as mineral wool), but have excellent hygroscopic qualities and high capillary openness (though, in the case of woodfibre this is reduced to some extent by the addition of 0.5% paraffin as a hydrophobic agent in most proprietary boards). All natural fibre insulations dry quickly, because of the better capillary mechanisms. Natural fibre insulations therefore are quite different in terms of moisture performance from both mineral wool and plastic insulations. All three of the "breathability" qualities make a significant difference to the performance and therefore the design of insulation in timber frames and roofs, and also in the renovation of buildings, all of which will be discussed later.

Another field where there is a lot of confusion about breathability is that of finishes, whether paint or plasters and renders. People assume traditional paints are all "breathable". Some of them, such as pure limewash and distemper are extremely vapour open (as paints go), while others such as linseed oil based finishes, and linseed or tallow improved limewash can be very vapour impermeable, much more so than many modern standard matt emulsions. On the other hand many traditional wall finishes such as lime wash, casein paint, and distemper have very high capillarity. This is mainly due to the weak binders or the low binder to pigment ratio. It means that when condensation or water as a liquid touches them they absorb this immediately. Often this involves a change of colour (usually a darkening), which changes back when the paint dries again. This quality is indicative of the vapour permeability of a paint only because it indicates a very weak, or a low level of binder. It does not mean however that a paint that does not have this quality of capillary openness is not vapour open. Indeed the Beeck Silicate paint Beeckosil, like the Keim Granital silicate paint, has a vapour permeability similar to pure limewash, but is capillary closed, due to the addition of a hydrophobic agent.

As regards hygroscopic qualities, these are not really relevant as regards the paints themselves as they are so thin. However it is assumed by many people that a paint's vapour permeability seriously affects the hygroscopic performance of the rest of the wall. In practice this may not actually the case. This was the surprising result that Minke obtained, when he was looking at how finishes affected the hygroscopicity of an unfired clay wall[18]. He tested a number of finishes including standard emulsions and distempers. The only products that significantly reduced the hygroscopic performance were double boiled linseed oil and pure latex. These both have an extremely high vapour resistance. Most standard wall paints, according to this research will, therefore, have relatively little effect on substrate hygroscopic performance. However these results are countered elsewhere, and this is one area that certainly requires further research.

As regards plasters and renders, there is often an assumption that lime plasters are the most "breathable" products around. As anyone experienced with plasters knows, however, there are many different types of lime, and of lime plasters and renders. Many of them are no more vapour open, hygroscopic, or capillary open than many lime cement, or even pure cement or even some acrylic plasters. In fact many strongly hydraulic plasters are less vapour open than weak cement plasters. Most types of lime plaster also have very low hygroscopic qualities, compared to gypsum and clay plasters. Of all materials investigated by Tim Padfield for buffering humidity in museums, lime plasters were the worst[19]- although it is not entirely clear what sort of lime

[18] see table 1.4-7 in Earth Construction Handbook by G Minke WIT Press 2000
[19] Tim Padfield PhD thesis 1999 www.natmus.dk/cons/tp/tp.htm

plasters were tested and there does seem to be evidence elsewhere that haired fat lime plasters have a reasonably good hygroscopic capacity. As regards capillarity, this is partly dependent on the degree and strength of binder and partly on additives. Many proprietary renders for external use are very vapour open, but, like external silicate paints, have added hydrophobic agents to stop capillary absorption of rain. This is often a desirable quality, although not always on historic buildings with complex facades, particularly on traditional exposed timber frames (see below).

Thus it can be seen that understanding the different types of breathability is vital to understanding the function of a material and the successful design of structures. This will hopefully become apparent in the following sections on applications.

Some notes on water transport

It is important to note that by far the most significant transport of water vapour is by air, either through purposeful ventilation, or through air leakage in the shell of the building. Water vapour movement through walls is mainly by entrainment in air flowing through the wall under wind pressure or thermal expansion pressure. Diffusion plays a relatively little part until the water vapour is within a homogeneous material, like a wall plaster for example.

For this reason the airtightness of a building is critical both in controlling vapour movement and also in attempts to use the hygroscopic and vapour permeability qualities of building materials in a positive and designed way (see below).

Another important influence in certain constructions is gravity. In vertical mineral wool insulation, condensed water falls by gravity. In natural fibre insulations the water is absorbed and the effect of this will depend on the structure and mass of the insulation and the amount of water being condensed. In most situations natural fibre insulation is amply able to cope with large amounts of condensation.

Gravity is also the major factor with water transport as a liquid, and obviously rainfall is the major factor in water penetration of buildings and of building failure through water.

Consequences for buildings:

It has been estimated that 75% of building failures are due to water. These occur mainly in rain water penetration, but also due to interstitial moisture condensation. In addition inner surface condensation affects building finishes.

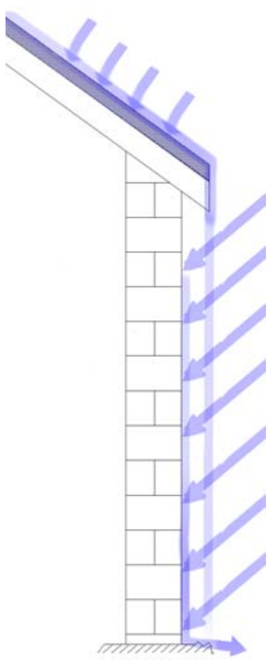
Water also affects the performance of the building in other ways, particularly in terms of thermal performance and the effect on human health. For example damp external walls can have considerably lowered thermal resistance, while surface condensation on the inside of houses causes moulds which are injurious to human health.

We therefore have 4 basic areas where the effect of water on building performance is considerable.

1. On the outer surface: Rain penetration and other external conditions
2. In the middle: building thermal performance and interstitial conditions
3. On the inner surface: surface condensation
4. Inside the building: indoor air quality

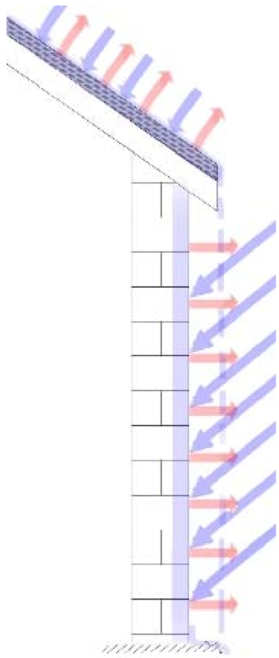
Rain penetration and other external conditions

While it may seem obvious that rain water should be kept out of buildings, there are actually two ways of doing this. The first is to have a capillary block on the materials, so that no water penetrates the fabric at all, and the second is to allow water in a certain distance, but to ensure that it will get out again mainly through drying processes, which involves water both as a liquid and as a gas[20]



Capillary Closed Surface A1

Heavv run off



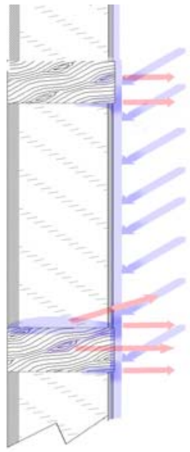
More Capillary Open Surface A2

Reduced run off

[20] ***The colour code for this and following diagrams is that blue indicates water as a liquid. Red indicates water movement as vapour. Green indicates water movement through hygroscopic mechanisms***

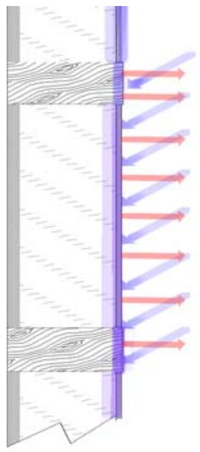
.

In the first instance water is kept out by materials such as glazed tiles, metal roofs, or hydrophobic renders and/or paints. The consequence of this complete non-absorption is that run off is increased, and absolute care has to be taken to ensure that no weakness occurs in this impermeable layer. In the case of a render for example it would be foolish to put a hydrophobic render on infill panels in a traditional timber frame construction, because it would increase the amount of water shed from the panels and this would all end up in the timber frame itself. Although the render might be vapour permeable, this will only help in a small way compared to the capillary draw that a soft lime, clay or other traditional finish might have when next to the timbers.



Exposed traditional timber frame with capillary closed render or paint on the outside.

Water run off is increased, making junctions and timber much more vulnerable, thereby increasing the risk of water penetration into the building and consequent fabric damage and decay.



Exposed traditional timber frame with capillary open render or paint on the outside.

Water is absorbed more evenly over the whole wall, reducing the concentration of water in vulnerable places. Water evaporates evenly from the surface of the wall.

Similarly in a modern building context most of the external wall render systems use capillary closed render and paint systems. This is fine so long as the render remains without cracks, and has proper detailing around plinths, windows etc. However if the render cracks or if detailing is poor, then water may penetrate the building in certain situations, causing moulds and loss of thermal resistance. In addition the render may also start to fail, because of the effect of frost on trapped liquid water held in or behind the render in winter. The fact that an external render may be vapour permeable may not be sufficient to deal with the extreme build-ups of water that can occur in certain situations. Also the degree of vapour permeability is obviously significant to the rate of drying out. It should be remembered at all times that capillary absorption and desorption is far quicker and will on the whole involve far larger quantities of water than vapour absorption and desorption.

In the second instance (as in diagram A2), the use of capillary open materials like most facing bricks or stone, (or non-hydrophobic lime or lime cement renders) means that water will be absorbed by the surfaces, run off will be decreased, and with air movement and warmth, the masonry will again dry out, both by capillary and vapour permeability mechanisms. For this reason it is important that the mortar in these walls is as capillary open, or even more so than the masonry. It will ensure that water doesn't sit in the face of the masonry unnecessarily and it will wick away moisture where there is excess. The pointing may suffer in the long term, but the brick or stone faces will be preserved. This is obviously the better solution from both a structural and a cost point of view.

The danger of using capillary open materials in exposed conditions is that actually too much water penetrates too far into the external surface and then gets transmitted to the internal walls. This situation is made worse in cavity walls if the cavity is not sufficiently wide and is filled entirely with insulation. The insulation ensures that the cavity cannot dry out and also increases the transport of water across wall ties. In addition the insulation loses much of its thermal resistance thus increasing the coldness of the wall and encouraging moulds on the now damp internal walls. For this reason many councils in exposed areas have now put a stop to full fill cavity wall insulation.

As regards timber cladding or roofing, it is important to understand that timber has far greater capillary absorption through end grain than with the grain. For this reason cedar or oak shingles which are hewn (and thus go with the grain) have a life expectancy at least three times that of untreated oak or cedar shingles which are sawn. However in all timber situations it is also important that drying can occur on both sides of the timber, as some capillary absorption will always occur. The capillaries can be largely blocked with paint or oils on the outer side, and when this occurs the ventilation of the space behind the cladding is even more important.

It is also important to understand the external skin of the building in relation to the substrate. This is particularly the case with renders. There has to be compatibility between the substrate and the render. This is not only in terms of the breathability, but also thermally and structurally. Many render systems fail because of this incompatibility. In thermal terms, there have to be similar thermal properties (ie a lightweight insulating render onto insulation blocks) or else the render will shell away as the two layers will move in different ways in hot and cold conditions. In moisture terms compatibility is just as important. For example, the capillary absorption, and even hygroscopicity of a substrate really affects the way a render performs in the long term. When a render goes onto a capillary open material such as soft brickwork, and water for some reason penetrates that render, the soft brickwork will diffuse the water and relieve the pressure on the render, ensuring that there is no frost damage, or separation of render from substrate. When a render goes onto dense concrete, or plywood, or polystyrene, this is not the case, and the render is more vulnerable if there are any cracks in the surface, as the amount of water it has to deal with is far greater. The hygroscopicity of a material may also help to relieve pressure on renders, as many are vapour open but capillary closed. Mineral renders are hygroscopic and this means that they will absorb moisture hygroscopically when relative humidity is high outside. This could increase the chance of moulds on the render surfaces. However if the substrate is also hygroscopic (as in the case of woodfibre boards as an external insulation system) this risk will be reduced.[22]

In conclusion therefore it is vital that the different aspects and mechanisms of breathability are fully understood along side the thermal compatibility and weathering detailing in the successful specification and construction of the external shell of the building.

Building thermal performance and interstitial conditions

It is not often appreciated what a significant effect moisture has on thermal performance. The following diagram gives a very noticable change to thermal resistance of some common materials. Effectively this means that if mineral wool or cellular concrete get wet either by liquid or gaseous water their thermal resistance is considerably reduced. It is however highly unlikely that this situation could occur except by water penetration into the structure. It will not happen by hygroscopic mechanisms.

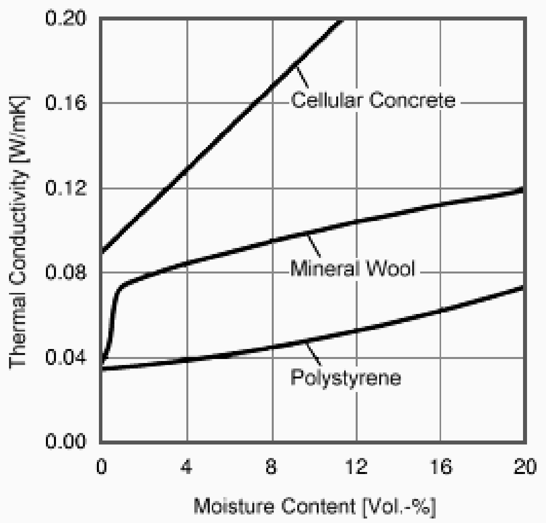


Fig. 1: The effect of moisture on the measured thermal conductivity of building materials

[23]

However the effects on thermal performance of moisture in buildings is not just down to the effect of moisture on the insulation materials. Neither is the effect as simple as this. The

---

[22] There are a number of Fraunhofer institute articles on how woodfibre insulation reduces the risk of moulds from dew formation (see articles by Krus and Sedlbauer). This is mainly because of the thermal mass of woodfibre, which keeps the render surface warm. However the hygroscopic qualities of the board may also contribute to overall moisture reduction in the render in a variety of conditions.

[23] Moisture Transport in Buildings www.hoki.ibp.fraunhofer.de/wufi/grundl_ueberblick_e.html.

resistance has to be considered over time as well. Furthermore the degree and type of breathability of most materials in the external shell of a building will also affect overall thermal performance of the structure sometimes in a dramatic way.

Insulation performance

As illustrated above the effect of moisture on insulation materials can be considerable. This is because in effect the water molecules form a cold bridge, filling up the insulating air voids, and thus reducing thermal resistance. This moisture can accumulate in the insulation either because materials get wet with liquid water, or because they absorb it hygroscopically. It is for this reason that in many European countries now the calculation for thermal performance of a material has to take into account not only the laboratory value of thermal resistance, but also the effect of moisture (commonly measured at RH of 80%) plus a safety factor for poor site practice. In many materials this may mean an addition of over 5% to the conductivity.

It might be thought therefore that having good hygroscopic properties might be disadvantageous to a materials thermal resistance. This is particularly the case with natural fibre insulations which will actively absorb up to 10% of their mass volume as water in changing humidities. This compares with only 1% with mineral wool insulation, and none with plastic insulations of any sort. Indeed many legislative bodies have decided indeed to lower the designed values of natural fibre insulations because of the testing that has been done, showing a drop in thermal resistance in these materials at 80% RH. However as this is a static test, the overall resistance of the insulation materials over time is not being calculated. Interestingly the Fraunhofer institute has shown that over varying humidities the latent heat stored in the material as it absorbs moisture is released on drying and this compensates for the loss of resistance when humidity is high[24]. This research is also borne out by research in the UK recently carried out in a controlled situation where mineral wool was compared with flax insulation. The resistance of the flax varied far more than the mineral wool but was overall about 10% better than the mineral wool for the same designed resistance[25].

What is much more significant possibly is the effect of water in construction, particularly related to rates of desorption. This will depend partly on material qualities and partly on the wall build up. For example if mineral wool gets wet in a cavity during construction, how long will it take to dry out? It has been estimated that much masonry put up in the UK may take as long as 3 years to dry out. During that time how dry is the mineral wool? How long does cellular concrete take to dry out? This is also a function of the rate of capillary desorption and the presence or not of vapour permeable materials adjacent to the insulating blocks.[26] This brings me to the effect of breathability on a number of building situations

---

[24] Fraunhofer institute report Hygrothermal Properties of Ecological Insulation Materials – a closer look by Krus and Sedlbauer

[25] Research carried out by Cardiff University

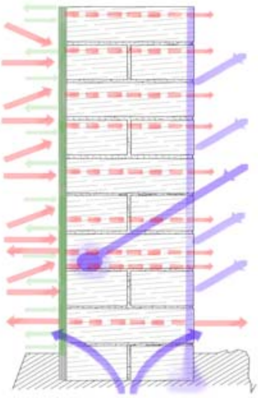
[26] In past times new houses were rented out for the first two years or so to the poor, because they were known to be unhealthy because the construction was still drying out. Nowadays there are more impervious materials than ever before covering wet construction materials and yet people move in before the paint is dry. In some situations such as concrete screeds with vinyl flooring, it is hard to see the materials ever drying out. What is certain however is that moulds will flourish and the indoor air quality will be very poor, even dangerous.

External wall insulation

We have already spoken about external walls insulation as regards rain penetration and hygroscopic substrates. In regard to the effect on thermal performance there are also some serious issues as regards the breathability of the materials.

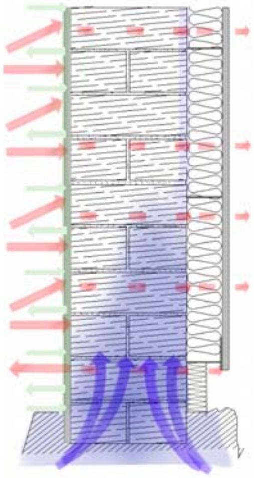
The web site www.dimagb.de is full of case studies from Germany, Switzerland and Scandinavia illustrating the under-performance and health problems of External Wall Insulation systems utilising polystyrene. The performance of many of the buildings is usually at least 30% worse than the designed (theoretical) thermal performance. This is due to several factors including bad application (incomplete insulation, cold bridging etc). However the main cause is identified as being due to the fact that the polystyrene and render systems are relatively vapour impermeable and thus increase the amount of moisture in the original solid masonry. This is particularly critical in the ground floors of solid wall buildings without damp proof courses. This moisture is also trapped because the effect of the sun and wind in drying the outer face of the masonry is also eliminated. The consequence is that the thermal resistance of the masonry reduces, giving an overall reduction in the wall U value. Combined as EWI often is, with new windows and draught proofing, there is the consequence that moulds also grow on the inside of the now damp wall.

Vapour permeability in EWI systems is thus an important factor to be considered, particularly on older buildings where effective ventilation systems are not installed. In addition the hygroscopic qualities of some external wall insulations should also be considered. The only hygroscopic material commonly used in EWI is woodfibre insulation. The result of using woodfibre insulation as EWI may be that moisture in the brickwork is actively drawn into the woodfibre, and then released into the external environment. The external insulation in this case has an actively positive effect both on thermal performance and on internal surface condensation and thus indoor air quality.



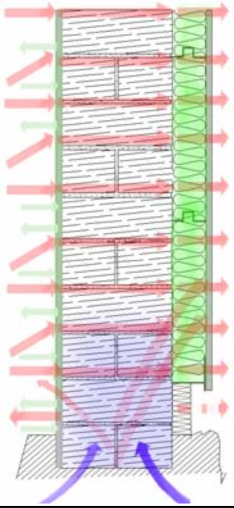
Victorian Solid 9” brick wall with limeplaster and distemper internally

The wall is in equilibrium. Moisture penetration into the centre of the wall by rising damp, or for example defective guttering or pointing can be dispersed. Moisture can easily pass into and through the wall from inside to outside.



Polystyrene EWI system onto Victorian wall

This system traps rising damp and inhibits vapour dispersion through the wall, thus making the wall damper and lowering its thermal resistance. Internally humidity levels can increase, due to decreased vapour permeability of the external surface. Moulds may form particularly at the lower level of the wall, if there is no effective dampcourse.



Woodfibre EWI system onto Victorian Wall

This system allows rising damp to be dispersed and keeps internal humidity low and the wall dry by the vapour open and hygroscopic external board and render.

Cavity wall insulation:

Issues of both thermal performance and building fabric health are raised again when the relationship of water to cavity wall insulation systems are examined. As already explained in the earlier section on insulation performance, the thermal resistance of insulation materials and masonry is reduced when wet. This wetting is a common occurrence during the construction process, either due to rain, or to other construction moisture from mortars and plasters. However in buildings in exposed locations, or with porous masonry or renders, or with building faults such as a lack of mortar in perpends, this can continue to be a problem. The problem is exacerbated if the cavity wall is poorly constructed and there is debris in the cavity and on wall ties. Unfortunately this is often the case. For this reason, amongst others many cavity walls never meet anything like their designed thermal performance. Furthermore the cavity and the inner leaf become damp and can cause moulds.

There is also an additional problem which has arisen with the increased use of close cell insulations, which have very high vapour resistance. This type of insulation is increasingly used in cavities to increase designed thermal performance while keeping the walls slim. However the use of what is effectively a vapour barrier on the cavity side of the inner masonry means that the inner leaf, if wet because of construction processes, will take a very long time to dry out, as it can only dry through itself to the inside. Furthermore it is highly likely that the insulation will not be put in without gaps and at these gaps there will be both cold bridging and condensation. In both cases then the trapped moisture will lower thermal resistance and also possibly cause moulds on the inside of the wall, if there is excess moisture over a long period. In addition the idea of vapour transmission through the wall, as a mechanism for ensuring balanced internal humidity, is now not possible.

Timber frame and roof construction:

Modern timber frame and roof construction is, in the opinion of many building experts, a nightmare which is happening now. Very few people seem to understand the physics of moisture or the biology of timber in the industry[27]. Furthermore no one is taking into account the vulnerability of design to poor site practice and post occupancy activity, such as DIY electrics and carpentry, and by ventilation system failures.[28]

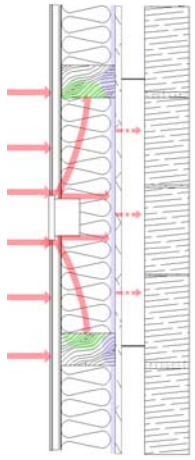
UK Timber frame design and practice:

Standard UK timber frame design has a vapour barrier on the inside of the frame, behind the plasterboard, and the racking board on the outside of the frame. Inside, as standard, is mineral wool insulation. This works in theory, so long as the vapour barrier is complete, and remains complete for the life of the building. It has to be installed while the timber is absolutely dry. In practice however, particularly with UK site practice, this is impossible to attain. If the timber is wet in construction or if moisture gets past the vapour barrier, it cannot get past the OSB, which has a vapour resistivity of 216 GNs/kgm[29], and it cannot get back out internally because vapour resistance of the vapour barrier is high, the vapour gradient is usually inside to outside and the leakage is relatively small. Furthermore the moisture will not be taken up by the mineral insulation, which is vapour permeable but not at all hygroscopic, so it will be diffuse into the timber studs themselves, and will accumulate there until the moisture content of the timber reaches equilibrium. When this is around 18% the timber will then start to decay, if untreated. Even if treated however there will be moulds developed which will eventually affect both the structure and the health of the inhabitants.

[27] For example, when I recently tried to get an exact figure for the vapour resistance of 9mm OSB, none of the main suppliers could tell me, and it took BRE 3 weeks to find the data, which they had certified some years before.

[28] Unfortunately it is common for both mechanical ventilation mechanisms such as extract fans, and passive mechanisms such as trickle vents to be disabled by building occupants very soon after occupation.

[29] This is the figure given for the only test carried out recently by the BRE. In data from Finland the resistivity of OSB is given as between 200 and 700GNs/kgm

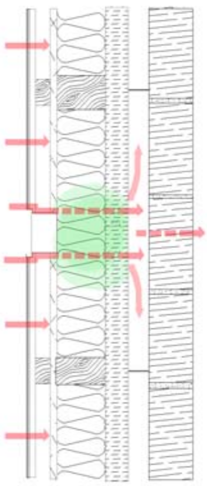


Standard timber frame construction with OSB on the outside of the frame and polythene vapour barrier and plasterboard on the inside. Internally full filled with mineral wool insulation

Water penetration through punctured membrane (ie socket) leads to hygroscopic take up of water by timber and condensation on the cold side, eventually leading to timber decay of the frame

The fact is that with current practice timber gets wet on site, and even if it does not, vapour barriers are not put in correctly, they are punctured by electricians, plumbers and carpenters, and then later punctured by maintenance, DIY and the knocks and cuts that a plasterboard wall will have to withstand in its life time. This is probably most critical in areas of high humidity such as bathrooms and kitchens. The undeniable problem is that the design is not robust. It should be changed as a matter of urgency. This indeed is the one of the main conclusions reached by a number of studies into the massive failures in timber frame construction in Canada, which caused one of the largest building insurers to go bust. Building insurers in the UK should take note.

Alternative designs for timber frame:



Breathing timber frame with OSB on the inside of the frame and woodfibre sarking board on the outside. Internally full filled with a natural fibre insulation.

Water vapour penetration is more difficult due to service void, but if a penetration is achieved through OSB (ie socket) this will lead to take up of vapour by hygroscopic insulation and transmittance through structure by the hygroscopic and vapour open sarking board. There is no risk of timber decay.

It is a simple step to put the OSB on the inside and then put a vapour open board or membrane on the outside, which is indeed what TRADA suggested 20 years ago and which is common practice abroad. The advantage of an insulating woodfibre board is that it is both warm, thus preventing cold bridging and moving the dew point to the outside of the frame and also hygroscopic so that if there is moisture in the frame it will be actively drawn outwards. It is further my opinion that the infill insulation should also be hygroscopic, in order to have full compatibility and long term protection of the structure; the whole wall then works together and remains healthy (as proven with traditional timber frame buildings throughout the ages).

Roofs:

In roofs the principle of vapour openness on the outer layer has been well established over the past 10 years, to the extent that people believe that you can put almost anything in between rafters without having to worry about moisture. However putting a vapour barrier between rafters is not a good idea and will lead to rot. This is effectively what is being done by the use of close cell plastic insulations in roof build ups, particularly where there is a room in the roof, as is most common nowadays. For example Polyisocyanate and Polyurethane foil backed insulations may have G values in a standard 150mm roof rafter build up of over 1000GNs/kg (the figures given in the technical sheets of some of these products are vague, others indicate resistances of over 2000GNs/kg) . This compares with a G value of 0.9 GNs/kg for fibre insulations or 6.7 GNs/kg for cellulose insulation. Again the fault is partly in the design and partly in the practice.

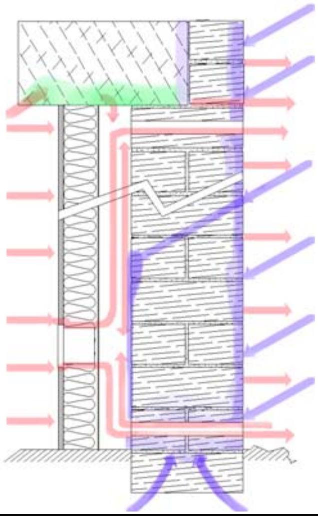
If close cell insulation is inserted between rafters, the timber is not only a cold bridge, but is the only vapour permeable and hygroscopic material in between the plasterboard and the outer membrane. Moisture will be concentrated in areas particularly where there is air or moisture leakage through the usually foil backed plasterboard. Once the moisture is in the timber the only way it can get out is through the timber. This is usually 150mm deep, and for moisture to pass through this will take a considerable time. The time is enough for the moisture content to reach 18% and for decay to be a risk. It is highly debatable therefore whether close cell insulation is compatible at all with timber structures, particularly between timbers, either in roofs or walls.

The answer again has to be vapour open insulations, and preferably hygroscopic insulations, particularly on the outside of the roof, just as in the case of timber frame walls.

Internal wall insulation for solid walls:

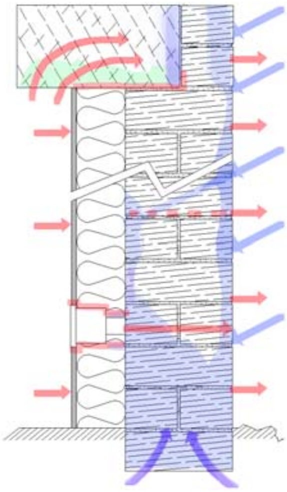
Internal wall insulation is becoming more common as solutions are required for buildings where it is not possible or acceptable for External Wall Insulation or Cavity Insulation to be applied. Traditionally this was undertaken by dry lining walls. This involves battening out the walls and then putting a plastic vapour barrier behind a layer of polystyrene and plasterboard. The cavity behind the vapour barrier should be ventilated (although it usually is not). More recently unventilated systems without cavities are being marketed by large drylining manufacturers. These rely on membranes or vapour impermeable insulation materials. Finally there are also systems being proposed by natural insulation manufacturers which are unvented and without cavities, but which are vapour open and utilise the hygroscopic capacity of the materials as a moisture sink to ensure no build up of interstitial condensation.

The three systems are illustrated in the diagrams below:



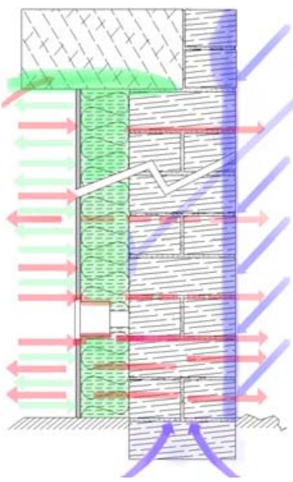
Drylining with vented cavity. E1

Vapour penetrations through punctured membrane (ie sockets) is dispersed through vented cavity as is rising damp and rain penetration. If cavity is not vented properly situation will be the same as E2. No hygroscopic buffering internally so the amount of water vapour internally increases, as does pressure on joists in walls



Solid internal insulation with vapour impermeable barrier or insulation. E2

Vapour penetrations through punctured membrane (ie sockets) will form condensation on wall and make the wall damp. Rising damp and rainwater penetration will only be dispersed slowly to outside. Floor joists in wall will be particularly vulnerable. All joists in wall will absorb excess internal vapour which will lead to very high equilibrium moisture content and will act as cold bridges leading to condensation at cold joist ends, both of these eventually leading to timber decay.



Solid internal insulation with vapour open hygroscopic insulation.

Vapour penetrations through punctured membrane (ie sockets) will be held hygroscopically and dispersed either inwards or through wall. Rising damp and rainwater penetration, as well as moisture in joist ends will be drawn hygroscopically into woodfibre and dispersed inwards or outwards through vapour open materials. The internal lining acts hygroscopically to buffer humidity internally thus reducing the vapour diffusion into joist ends and giving good internal air quality.

The problem in the first system is that actually it is very difficult to provide a ventilation gap in many situations, and if possible it is expensive. Furthermore it effectively means that the only material between the inside of the room and the outside is the plasterboard and the thin amount of insulation. In the case of thin insulation layers, this may be no better than the masonry, if the masonry is dry. (Of course dry lining is often undertaken because of dampness rather than for added insulation and this may be a good solution in such situations.) If the gap is not vented, as it often is not, then potentially there will be both interstitial condensation and (depending on the exposure of the wall) dampness from rainwater penetration. In older buildings there may also be rising damp, because of a lack of DPC. It is estimated that about 25% of the building stock in the UK is solid wall, and in a great many of these there is no damp proof course (and neither is one necessary in their original form of use).

In both the case of unvented drylining and of the second system the threat of dampness from rainwater penetration or rising damp is increased by the application of the internal lining, because there is less heat on the inner surface of the wall, helping to dry the wall, and also there is no ventialtion or vapour permeability, allowing moisture out of the wall. These together will reduce the thermal resistance in the masonry, thus counterbalancing the effect of the actual insulation layer. The result is potentially also a mouldy micro climate, which will affect both building and human health.

The difference between an unvented cavity and the second option is that there is less space for a micro climate or for actual droplets to form in the second option. However there is just as great a risk of damp transmission to the inside if the wall is not entirely sealed by the membrane and insulation. This could be concentrated in places where it is not possible to seal entirely, particularly at internal wall and floor junctions. This can lead to structural failure as well as moulds which will affect indoor air quality.

This problem is made much worse by the potential in both the unvented drylining and the second system by the migration of moisture from the inside of the building into the fabric. This is far harder to address than rising damp or rain penetration. Again it arises where floors, ceilings and internal walls meet the outside wall. In older buildings the joists and internal walls are physically keyed into the outer walls, so it is not possible to insert a membrane or insulation behind them. The internal linings not only make the cold bridging of these elements worse, but also reduce the amount of hygroscopic buffering and vapour transmission in the room. Both these factors thus increase the chance of condensation, mould and, in the case of the floor/ceiling joist, structural failure, where the dry lining is unable to reach. There are some very good examples of this in recently renovated Victorian Hospitals, which now have serious outbreaks of dry rot in joist ends, where none existed 5 years ago.[30]

The solution proposed by NBT and others in the natural building materials market, is to use a board such as the woodfibre board, in an unvented system. This works because it is both vapour permeable, and highly hygroscopic. The moisture in the room is still able to pass through the insulation into the brickwork and then out to the outside. There is no condensation at this interface because of the vapour permeability of the construction and the hygroscopic capacity of the woodfibre board. For example if there was no hyroscopic buffering, and 100mm of insulation were used on the inner face of a 9” solid brick wall (giving a U value of 0.36 as opposed to 2.3 uninsulated), then the maximum amount of moisture over 1 m2 over 60 days in winter conditions would be 0.21kg or 0.21 litres. This moisture would anyway be wicked away by the brickwork, with its high capillary absorption, and would be released into the outside. However this moisture

[30] From Robert Demaus, building pathologist involved in assessing these building problems, in conversation

calculation also does not take into account the hygroscopic capacity of the woodfibre board, which will absorb approximately 10% additional moisture as a percentage of its weight when relative humidity increases from 50% to 90%. This means that with a density of 200kg/m3 a board 100mm thick will absorb 2kg or 2 litres per m2 when RH increases to the point of condensation (ie 100% RH). Thus there is a safety net factor of 10 times the amount of moisture generated over 60 days in worst conditions. As the insulation has the ability to dry out to the inside and the outside this will ensure that the woodfibre does not accumulate moisture, and that the wall remains dry. The hygroscopic capacity of the woodfibre, along with its vapour permeability (and its high thermal mass) will also ensure that the wall itself is also kept dry, thus reducing the risk of a drop in thermal performance of the masonry, as is likely with the other non-vented internal insulation systems.

Inner surface condensation: Warmth and capillary openness.

Condensation on the inner surface of buildings occurs where there are cold surfaces and capillary closed materials. Both are required for condensation to form as droplets; if the surface is cold, then as the warm moist air hits the surface the energy of the vapour is transferred into the cold surface and so the water vapour molecules become less energetic and start to bond, becoming liquid water. However the water droplets will only form on the surface if they are not absorbed by the surface. If the surface is capillary open then any vapour that is converted to water will be immediately absorbed by the surface and be dispersed.

One solution to surface condensation therefore is the use of capillary open paints and plasters. This is a solution that has worked for centuries in old cold buildings alongside plenty of ventilation and lower levels of heating and moisture producing activities. It is still an appropriate solution for buildings such as old churches which are infrequently used, and where large numbers of people can suddenly produce lots of moisture. In this however it is important that the materials do not contain organic materials as far as possible, as the amount of water passing into these surfaces can be quite high. Capillary open mineral paints and plasters are therefore recommended onto substrates which, if possible, allow moisture to be diffused, through capillary openness, deep into the fabric.

Another situation where the use of capillary open materials may be appropriate is in renovated houses where there is still unavoidable cold bridging or situations where ventilation is difficult to install. There are a lot of cases in Germany of people using unfired clay plasters in bathrooms to reduce or eliminate condensation on tiles and other impermeable surfaces. This works not only because the unfired clay is very hygroscopic, but because it is capillary open, ensuring that water as liquid is also absorbed and held by the surface and the substrate. There are also cases in Germany of concrete tower block apartments being sprayed internally throughout, to alleviate condensation and high humidity problems.[31]

Indeed it could be said that all housing could benefit from this approach. The difficulty however with capillary open surfaces is that they absorb dirt as well as water vapour, and can mark very easily. This requires careful planning, and possibly a return to the deep skirtings, panelling and dado rails of former times, which were there for this very reason.

---

[31] Many of the clay plaster suppliers give examples of clay plasters in bathrooms, often their own. As regards spraying concrete tower blocks, this is undertaken by a company set up by G Minke, as reported to me by Tim Padfield in conversation.

Indoor air quality:

Perhaps the area where breathability matters most obviously to many people is as regards Indoor Air Quality (IAQ) and the effect on human health. This issue becomes absolutely critical as we strive to make our buildings more energy efficient by airtight design.

Airtight design is not about unventilated design. It is about ensuring no unplanned air leakage through the fabric. Without a degree of airtightness the insulation of most buildings is pointless. As we try to reduce heat loss through buildings to a greater and greater extent, the issue of airtightness becomes more and more important.

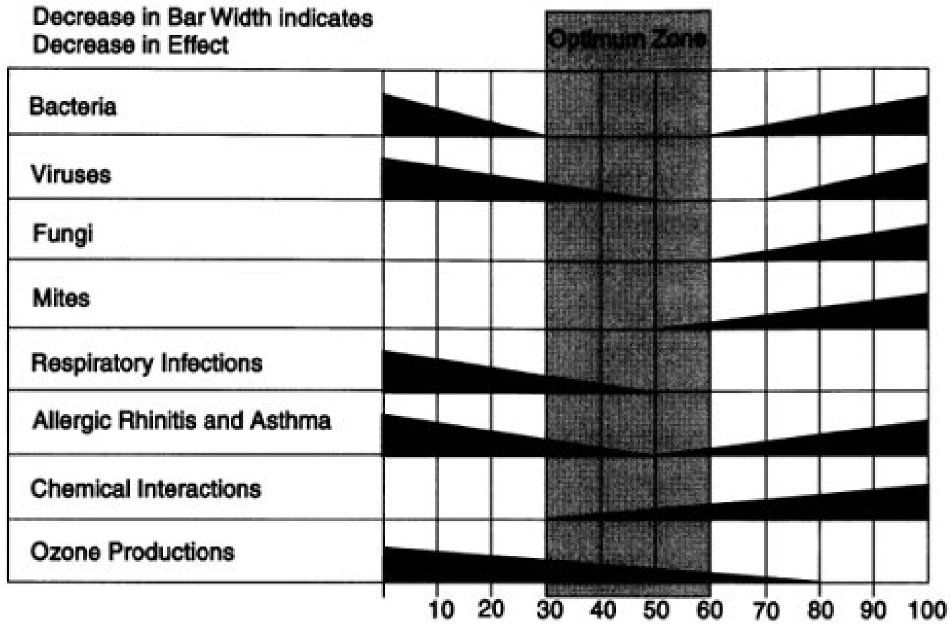
Airtightness is not only about heat loss. It is also about the migration of moisture into the fabric of buildings, and potentially about loss of thermal performance and interstitial condensation. The consequences of this for vapour closed constructions have been identified above for many different construction types. Airtightness however also has a huge potential effect on indoor air quality.

Indoor air quality is usually dealt with in building design by ventilation. Good ventilation design, construction and maintenance can, in the main, deal with the issues raised by air tight construction.[32] However the question needs to be asked as to how easy it is in reality to achieve good design and construction and what are the longer term issues of reliance solely on a ventilation systems for the quality of the indoor atmosphere. If we are to construct buildings which have a design life of more than 10 years, and perhaps as much as several hundred years, then we need to think clearly about how we can ensure moisture control within the building structure itself, and not simply rely on mechanical apparatus, which requires maintenance, repair and eventual replacement.

The main issues which need to be dealt with as regards indoor health relate to moisture, toxins (including VOCs) and odours. There is a relationship between these areas, as even VOCs are more dangerous with levels of humidity outside the magic box of 40 – 60%. In fact getting humidity levels to around 50% for most of the time will deal with most indoor air quality issues, providing that toxic materials are avoided as far as possible (and not only in building work but in all purchases, packaging, and household cleaning materials). This is shown in the chart below:

[32] It is however the opinion of some experts that the designed air exchange rate is nowadays so low that the indoor RH must rise unless there is a high level of mechanical ventilation. To make this economic also means a heat exchanger.

Figure 18-1: The Sterling bar graph



[33]

This particular graph is produced by the American Heating Ventilating and Air Conditioning industry, and has a lower optimum zone than is reasonable, particularly as Relative Humidities under 40% can cause severe health problems[34]. There are also considerable effects on static at levels below 35% RH.[35] I would therefore suggest an optimum zone of 40 – 60% RH

Of course keeping humidity under 60% also protects the fabric of the building from moulds in organic materials. Humidities under 40% can start to effect timber and fabrics by reducing the equilibrium moisture content too far and cause shrinkage and introduce brittleness. Interestingly, according to this chart, certain bacteria also thrive at lower humidities and these may also cause building decay. These however are very rare compared to those which thrive at higher humidities.

The consequences of trapped moisture in airtight buildings, both in the building fabric and in fittings and furnishings, is now linked directly to allergic reactions (particularly as regards asthma) and other auto-immune diseases. The UK has a particularly poor record in this area, with the largest incidence of asthma in the world (now running at about 20% of the population, with up to 40% among teenagers in parts of the UK). We also have a very moist climate and some of the worst built housing in the Western world. There is now substantial evidence linking this epidemic

---

[33] http://www.ptg.org/caut/Kissmann.htm

[34] This is backed up by a large amount of research including laboratory data on animals. "Using the care of rats, cats and rabbits for laboratory uses as an example, we find that these animals should be kept at humidity levels between 40% and 60%. This is noted in the CIBSE Guide "Installation and Equipment Data". In the case of rats this is perfectly reasonable when you consider that at humidity levels below 40% they can develop a disease which causes their tails to drop off leading to death" P4 of Master Class in Humidification by R Palamarczuk July 2004.
http://www.feta.co.uk/humidity/Master%20Class%20Why%20Humidify%20-%20Jul%202004.pdf

[35] Palamarczuk also notes (page 10) that at humidities under 35% static charges are massively increased, owing to loss of microscopic moisture coatings: "Walking over a nylon carpet, wearing man made soled shoes could generate a static charge of 35,000 volts in a dry atmosphere. Raising the humidity [to above 35%RH] would reduce the charge to about 1500 volts".

with trapped moisture in housing in the UK.[36] This link is due to the biological fact that dust mites only thrive in relative humidities of over 70%. At this level there is which is sufficient moisture in the dead skin on which dust mites live, to enable the dust mites to digest the skin. At levels lower than this dust mites cannot thrive and will remain below levels at which they produce sufficient faeces to provoke allergic reactions. As RH levels increase the numbers of dust mites also increase in a hyperbolic relation. However the conditions which produce outbreaks of dust mites are exactly the same as though which produce outbreaks of mould growths, of which there are many serious side effects.

Part of the interest in this field is driven by insurance claims. There have been a number of recent successful claims in the US against landlords and contractors for the presence of the mould Stachybotyrs chartarum in dwellings which has been shown to have been contributory to a wide number of auto-immune diseases. One claimant was even paid $20 million for the death of his dog as a result of this mould, even though the scientific case still has to be fully proven.[37] As a result of this the RICS in the UK commissioned a report from a specialist company, Fugenex, to survey buildings in the UK and determine the incidence just of this one mould in housing here. It was found in 25% of houses, and most frequently in bedrooms and in "higher quality" newer housing. The cause was attributed as "trapped moisture". Interestingly this news appeared mainly in the financial sections of newspapers, because of the insurance implications.[38]

In the work by Howieson and others on housing the main method of improving housing conditions and of removing the threats to health caused by high levels of relative humidity have been to introduce mechanical ventilations systems, usually with heat recovery (MVHR). In the short term, in the houses where this has been studied, this approach has been very successful at least in controlling dust mite populations.

However there are in many peoples minds considerable concerns about relying entirely on mechanical or even passive systems of ventilation. There are risks that the systems are not designed properly in the first instance, so that not everywhere is properly ventilated. There is also the risk that systems will be blocked up (as is common with trickle vents) or will break down (as is common with mechanical systems) or will become dirty and start working against clean indoor air (if ducts are dirty, or if filters are not changed). I have been at talks by people working in Housing Associations who now refuse to put in electrically operated systems for ventilation in their houses because they are vandalised or blocked within months of occupation. For these and many other people a passive approach which is not entirely reliant on ventilation alone is required.

An alternative approach: moisture control by hygroscopic buffering:

There are many cases of earth buildings where moisture levels are kept constant around 50% RH for years on end.[39] In the work of Tim Padfield this approach was tested in museum situations, where moisture levels are critical to the preservation of exhibits. Padfield found that it was possible to keep RH fairly constant indefinitely by the extensive use of hygroscopic materials such as unfired clay and end grain timber. In sufficient quantities these act to buffer RH levels from the normal peaks and troughs , resulting in a fairly constant RH equivalent to the average

---

[36] See Housing and Asthma by S. Howieson, Spon Press, 2005.
[37] See article by Anthony Montanaro MD on www.hobb.org
[38] This first appeared in papers such as the Independent on 27/08/03. It has now been taken up by solicitors expert in housing and health claims such as Reynolds Porter Chamberlain. See their note on Stachybotyrs Charterum on www.rpc.co.uk
[39] Earth Construction Handbook by Gernot Minke WIT press 2000

RH for that area over the season or year (depending on the degree of buffering). However a critical factor was also that air changes were kept at a very low level.[40] This is an obvious point in many ways, as the RH of many north European countries is around 70% for much of the year. The more frequent the air changes the more this outside RH will affect the indoor atmosphere.

The point is that hygroscopic buffering requires low air changes. Increased airtightness in buildings actually makes this easier to achieve. The issue is how much buffering, and where. This is not an issue for this paper, except that it is evident that by far the most effective buffering for indoor air quality *over a 24 hour cycle* comes in the first 10mm of the surface of a wall. So this should be the first area to concentrate on. As regards how much buffering should be installed, it is our opinion that there is no down side to this, so put as much in as you can, not only to assist in balancing moisture levels in buildings, but also to relieve pressure on interstitial moisture levels. This will help not only with reducing peaks of moisture but also with re-humidifying buildings which are too dry. This is a problem with just as great health risks, which should not be ignored in the rush to reduce excess moisture.

The integration of hygroscopic buffering with airtightness and controlled ventilation is an important design approach which could give a safety net to the indoor air quality of house while actively improving the overall moisture control and hence building performance and robustness throughout the structure.

Principles of design:

Having outlined what I see as just some of the building situations where the issues of "breathability" are important to building performance, building health and human health (as well as environmental impact because of energy use and fabric decay), I would like to finish this rather long but necessarily sketchy polemic with some basic principles of design which, in my opinion, arise naturally from this study.

The four principles which I would like to emphasise are

1. Compatibility of building elements
2. Make the structure do the work
3. Safety nets
4. Whole house design

Compatibility of building elements:

By this I mean that materials in many wall roof and floor build ups should have similar "breathable qualities" (vapour permeability, hygroscopicity and capillarity) in order to avoid interfaces where moisture or thermal conflict emerges, and to spread moisture load away from vulnerable areas. I am thinking particularly of timber frame and roof situations, but this also applies to masonry and to the renovation of traditional buildings. In some countries in Europe (Denmark and Austria) there have been strong moves against the use of plastic and even mineral wool insulation in timber frame structures. This is largely because of incompatibility.

---

[40] Tim Padfield PhD thesis 1999 www.natmus.dk/cons/tp/tp.htm. See also Hansen and Hansen confirming this work. http://www.ivt.ntnu.no/bat/bm/buildphys/proceedings/74_Hansen.pdf

Compatibility means that certain design details become less critical. The sealing of vapour barriers is an obvious example of where an incompatible element becomes critical. The failure to have entirely sealed barriers exposes timber frames and roof structures to considerable risk. There is no need to expose our buildings to these risks when a better design would give a better performance, help reduce moisture build up and improve indoor air quality, while at the same time making application easier.

Make the structure do the work

By this I mean that the structure should do the work not only of overcoming interstitial moisture problems and of assisting indoor air quality, but that by understanding the effect of moisture on thermal performance in particular, the structure can do all of its work more effectively. In my opinion passive house design is where design should be heading. For passive design to work properly this needs to take account not only of energy but also of moisture.

In fact the more one concentrates on the building structure as the method of achieving the full aims of the building (in enduring, performing, nurturing and protecting), the easier it becomes to achieve passive design cost effectively. If breathing walls roofs and floors/ceilings can do all the thermal, acoustic, moisture and other functions of the house, then service installation costs, and maintenance and repair costs can be dramatically cut.

Safety nets

The other reason for moving towards a fully breathing design is that it provides safety nets, particularly for bad application in construction, but also for bad alteration work in the future and for failure of other systems or parts of the fabric.

This returns me to the original metaphor of the house as a body. Our health cannot be reliant on everything only just working. The knocks and viruses, the strains and stresses of living, and our own specific genetic make up all require that we have self healing mechanisms and reserves to draw upon. In a similar way we need to build buildings with plenty of excess capacity. In my mind this refers particularly to very open vapour permeable construction, and to masses of hygroscopic buffering both internally and interstitially. I do not believe that this will add significant cost to any project. What it does add is significant robustness and for the designer, builder and occupier, significant peace of mind.

In this way we can start designing houses with over a hundred years life expectancy. Indeed I would go further and push for people to design for 300 years expectancy or more. We know how traditional buildings (both timber and masonry) survived this timespan, and we should start to apply these principles to modern highly energy efficient buildings and to the renovation strategies of older buildings.

Whole house design:

Having ensured that building elements are constructed from compatible materials, and that the structure does the majority of the work with plenty of safety nets, we finally need to ensure that all these elements are understood within whole house design. Passive house design is largely about whole house design, but I am not convinced as yet that the issues of air tightness, ventilation, and hygroscopic buffering have been properly integrated. I am also not sure, particularly in renovation, that the external wall and roof elements, the windows and openings, and the internal walls and floors are integrated, and that these are really understood in the context of the actual, rather than assumed air tightness of the structure.

We really need to start with whole house design and understanding, rather than finishing with it. It should inform everything that is done, from choosing flooring and heating systems to layout of bathrooms and bedrooms. It does however require that we start by understanding the biology as well as the physics of buildings. Like a good doctor we need to see the person as a whole, not only as made up of unconnected organs and limbs.

Conclusion: a new understanding and a new way of building

Until we integrate this biological and physical understanding of water in buildings and its effects on performance and health, we are in danger of designing, constructing and repairing buildings which are going to fail in some, if not many, ways. This issue becomes more acute the more we try to make our buildings perform better from an energy point of view (and indeed from an acoustic point of view).

At first glance it may all seem unbelievably complicated and probably very expensive. However this is not actually the case. It is very simple. Building technology doesn't need to find space age solutions to most building problems. Human beings and trees were not born in space, and are not designed to live in alien surroundings. The materials which are the most natural and most ancient in our buildings are the materials which we have evolved with and which are the best for us and for construction. Just because we want more energy efficient buildings for couch potatoes, this doesn't mean that the basic biology of human beings and of trees has changed.

New buildings and renovated buildings need to be built from low energy, minimally processed bulk natural materials. Materials such as timber, earth, stone, straw and other natural fibres are not only the best materials from an environmental point of view. They are also the best materials from a performance point of view. Understood properly they can and do provide houses which are simple to design, simple to build, simple to maintain, and which give health and satisfaction to those who live in them. This is not a step back to a pre-modern era. It is taking our modern understanding of material science and combining it with modern production techniques and modern designs, to make appropriate buildings for the 21st century.

Breathability is a key to understanding not only building performance, but how we should design, build and renovate our buildings from now on.

Neil May 16/04/05

Acknowledgements: I am extremely grateful to Dr Tim Padfield for his extensive comments and encouragement. I am also grateful to Richard Oxley, Peter Warm, Nick Grant, Phil Allen and Gary Newman for their comments and interest in this article. Any errors are entirely my own responsibility.