Indoor Air Quality and Hygroscopically Active Materials

By: J.F. Straube, Ph.D [1] and J.P. deGraauw[2]

Indoor air quality is an important issue from both a social and economic point of view. There are several design strategies that can be used to deliver good IAQ. Controlled ventilation, proper design, and the use of appropriate healthy building materials can provide good indoor air quality if used in as part of a holistic design approach (one that emphasizes the importance of the whole and the interdependence of the parts. As part of a complete IAQ design strategy, hygroscopically active materials (so-called breathing walls) can help moderate indoor humidity and thereby reduce the potential for fungal growth on building surfaces.

This paper discusses the three basic design strategies for IAQ, and the role of breathing walls. The physics of breathing walls are discussed, and the ways in which such walls can improve IAQ are outlined. A research program directed at exploring the properties of CBWF, a low-density cement-bonded wood fibre is described. The research included material tests, field monitoring of full-scale walls, and computer modelling. Some results of this research are presented and discussed.

Supported by calculations and field data, it is concluded that IAQ can be greatly improved by using a holistic approach to building design. Breathing walls made of vapour permeable and highly hygroscopic materials can enhance IAQ when used in conjunction with other strategies.

Keywords: moisture, air quality, health, sustainable

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Introduction

In industrialised countries most people spend more than 90% of their lives inside buildings. During this time the nature of the enclosed environment directly affects the health, quality of life, and productivity of the occupants.

Modern buildings, however, clearly have a problem providing a healthy or even appropriate indoor environment. The US Environmental Protection Agency (EPA) concedes that about 30% of new or renovated buildings have serious indoor air quality problems (IAQ), and ranks IAQ as our most prominent environmental problem (Roodman and Lenssen, 1995). In fact, recent estimates place the direct health care costs of poor IAQ in the US at $30 billion, with sick leave and productivity losses adding another almost $100 billion annually (Fisk and Rosenfeld, 1997).

Extensive measurements by numerous agencies have shown that the typical modern home contains a chemical soup of volatile organic compounds (VOC's) like formaldehyde, xylene, isobutylaldehyde, vinyl chloride monomer, and other organochlorides, aldehydes and phenols from all kinds of manufactured wood products, paints, carpets, and synthetic textiles including furniture and carpets, plastics, foam, tile and carpet glue, etc. (Rousseau 1995, van Vliet 1995)   New building materials and HVAC systems are demanded to reduce the effects of these pollutants.

Radon from the soil, ozone from some electrical appliances, and micron-sized particles from many sources add to the health risk. The EPA and Surgeon General estimate between 5000 and 20 000 deaths per year can be attributed to radon gas in the US, where it is the second leading cause of lung cancer (Marinelli and Bierman-Lyle 1995).

Airborne particulates, especially those less than about ten microns in diameter, can seriously damage the lung. Small particles can penetrate deeper into the lung, while larger particles are filtered out by the body's natural defences.

A major concern in many cold-climate countries is the growing number of studies that link allergies, immuno-depression, and illness to the amount and type of fungal growth in a building (e.g., see Health and Welfare Canada 1987, Scanada 1995). By avoiding surface relative humidities in excess of about 80% RH fungal spores, unavoidable in all buildings, will be starved of the moisture they need to survive. Mould growth within the building envelope can also affect health if an interior air barrier is not present.

Design Strategies for Indoor Air Quality

Several basic strategies can be employed in the design, construction, and operation of buildings to dramatically reduce the presence and concentrations of indoor air pollutants.

Avoidance

As mentioned in the introduction, it is widely known that organic vapours are unhealthy (Levin 1989, Denis 1994, EPA 1995, Molhave 1990) and surveys have shown that they are present in potentially dangerous concentrations in many modern buildings (Dumont 1992, Piersol 1997). The first line of attack should therefore be the avoidance of products that contain solvents, glues and plastics that release potentially unhealthy organic vapours -- even natural products can off-gas. There is an increasing number of commercial sources of paints, glues, materials, and systems that can be economically substituted for building materials which release large quantities of various VOC's, e.g., particle board, waferboard, carpet, foams, paint (Bower 1993, Pearson 1994, Baggs 1996). The use of natural (and unpainted) lime-cement plasters and solid wood as wall finishes, and concrete, linoleum, solid wood, and ceramic tiles for floor finishes can reduce total VOC concentrations by an order of magnitude. Occupants and maintenance staff should also avoid the use of materials and products that might affect IAQ.

Avoiding fungal growth can be difficult if the surface humidity is over about 80% (IEA 1991); the paper facing of drywall is an ideal mould growing substrate, and even ceramic tiles will allow mould growth if soap and skin residue remain on their surface. Maintaining a high, and uniform, wall temperature will ensure that the surface relative humidity remains only slightly above the interior humidity. Thermal bridging at framing members, especially steel studs, can result in dramatically lower surface temperatures and much higher surface humidities. Moderating variations in indoor relative humidity through the liberal use of hygroscopic and "breathable" materials can virtually eliminate the potential for fungal growth. A complementary approach is the use of finishes which do not provide food for fungi and/or have a high pH; virtually no fungi can survive on surfaces with a pH over about 10.

Removal

The second step in improving IAQ is pollutant removal. A building should be designed to remove pollutants down to at least the level of the outdoor air and perhaps lower. This involves increased volumes of, and more controllable, ventilation, porous adsorbers, and plants. Hygroscopic materials moderate RH and can permanently adsorb some VOC's. Plants such as Devil's Claw and spider plants may improve IAQ by filtering and humidifying the air while consuming CO_2. Any falling or running water will also act as a powerful particulate filter by trapping particles.

Studies have shown that 75% of all damaging airborne particulates originate in the exterior air. The proportion is likely higher in healthy homes, which should produce fewer particulates. A combination of an airtight building enclosure and high quality filtration of ventilation air, by mechanical or natural means, can be used to greatly reduce the number of particulates.

Exclusion

Exclusion is the third principle of good IAQ design. Radon control, for example, requires an airtight floor and/or basement system. Exclusion of radon from the interior environment must be an important design consideration because of the serious consequences of exposure. Ventilation of living areas (i.e., removal) does aid radon control, but it is imperative to first design and build the ground floor or basement as airtight as possible to avoid penetration into the building.

Exclusion of outdoor particulates requires an airtight above-grade building envelope. If the air barrier system is applied to the interior side it can control off-gasing, particulates, and mould spores from within the enclosure system.

Research Program

The hygrothermal performance of several different enclosure wall systems was studied in some depth with the support of a consortium of seven building product manufacturers (Straube and Burnett 1997). The study involved theoretical investigations, laboratory tests, and the monitoring of moisture and temperature conditions within 26 full-scale test walls. The test walls were instrumented, mounted in the University of Waterloo's natural exposure and test building, and monitored for two years at 5 minute intervals while exposed to the natural environment of South-western Ontario.

A manufacturer of a proprietary low-density insulating concrete form made from CBWF was part of this research consortium. This company has been producing cement-bonded wood-fibre based building products around the world for more than 50 years. As part of the larger study, this manufacturer was interested in the reasons for the healthy performance of their products and how the properties of cement-bonded wood fibre composites provided this performance. An additional objective was an explanation of the long history of satisfactory performance of walls made with CBWF insulating layers even when no polyethylene vapour retarder was installed. The moisture-related performance of the CBWF material was examined and several test walls made of CBWF panels and the insulated concrete form system. Some of the results of this investigation are presented in this paper.

Cement-bonded wood fibre building products have been used for years because of their beneficial impact on a healthy indoor climate. For example, the Norwegian firm Cobolt Architects uses CBWF for entire wall and roof constructions, often cladding the inside and out with ventilated wood boards [Pearson 1994]. Strawbales have similar hygrothermal properties, and have also been used in Norway by Dag Roalkvam of Gaia Architects [Lacinski 1996] and have been built by the thousands in North America

(Elizabeth and Adams 2000). Dale Bates, an architect specialising in healthy housing, has used cement-bonded wood-fibre based insulated concrete forms in several dozen homes.

Material Properties

CBWF is a composition of only natural raw materials in most formulations; specially-graded recycled wood particles are neutralised and mineralised before being bonded together with cement. It can be moulded to form any shape and compressed to provide a range of mechanical and thermal properties. Hardened CBWF is lightweight, porous, insulating [NRCC 1975], exceptionally fire-resistant [ULC 1974], termite proof [Takeo 1960], and very durable, even under harsh environmental conditions [Dietikon 1956]. CBWF with a dry density of 500 kg/m^3 (30 pcf) has a thermal resistance of about RSI12.1 per m, (R1.75 per inch)

Healthy Properties

Since CBWF is made of inert and natural materials it does not off gas dangerous vapours.

The cement used in CBWF results in a very high initial pH that reduces the potential for fungal growth on its surface. Based on lab tests the pH is approximately 10 (e.g. it is alkaline) after reaction with atmospheric carbon dioxide (e.g. about 3 months old). Upon delivery, the pH is higher since the blocks are new, so the alkalinity is highest when the product is still wet from production and construction. This level of alkalinity makes the growth of fungi and even viruses very difficult. It is for this same reason that lime was historically used to whitewash buildings and stables. (In fact, this practice continues today in dairy barns and other installations where good hygiene is critical).

The same reasoning applies to interior finishes. Lime and cement-based plasters are alkaline enough that mould growth is stymied, and their breathable properties reduce the likelihood that sufficient moisture will be available for growth in any event. CBWF is also an ideal substrate for plasters, often eliminating the need for wire mesh or laths with paper backings.

Moisture Properties

The moisture transport and storage properties of CBWF are an interesting and unique mix of vapour permeability and vapour storage capacity. The only other "structural" material which behaves in a similar manner is compacted straw, although straw, unlike CBWF, has potential fire, moisture, and insect problems. When compared to other common building materials (Figure 1) the vapour permeability (i.e., the permeance per unit thickness of material) is clearly much higher.

The sorption isotherm of some common building materials is plotted in Figure 2 [IEA 1997, Kuenzel 1997]. The sorption isotherm, a plot of the equilibrium moisture content of a material versus the relative humidity, is a direct measure of the hygroscopic nature of a material. Again, CBWF behaves in a different manner than many materials. As the humidity climbs from 30% (relatively dry air) to over 70% (a high value), CBWF adsorbs more than 7% of its dry mass in water vapour. Strawbale walls are expected to behave in a similar manner because of their similar cellulosic base..

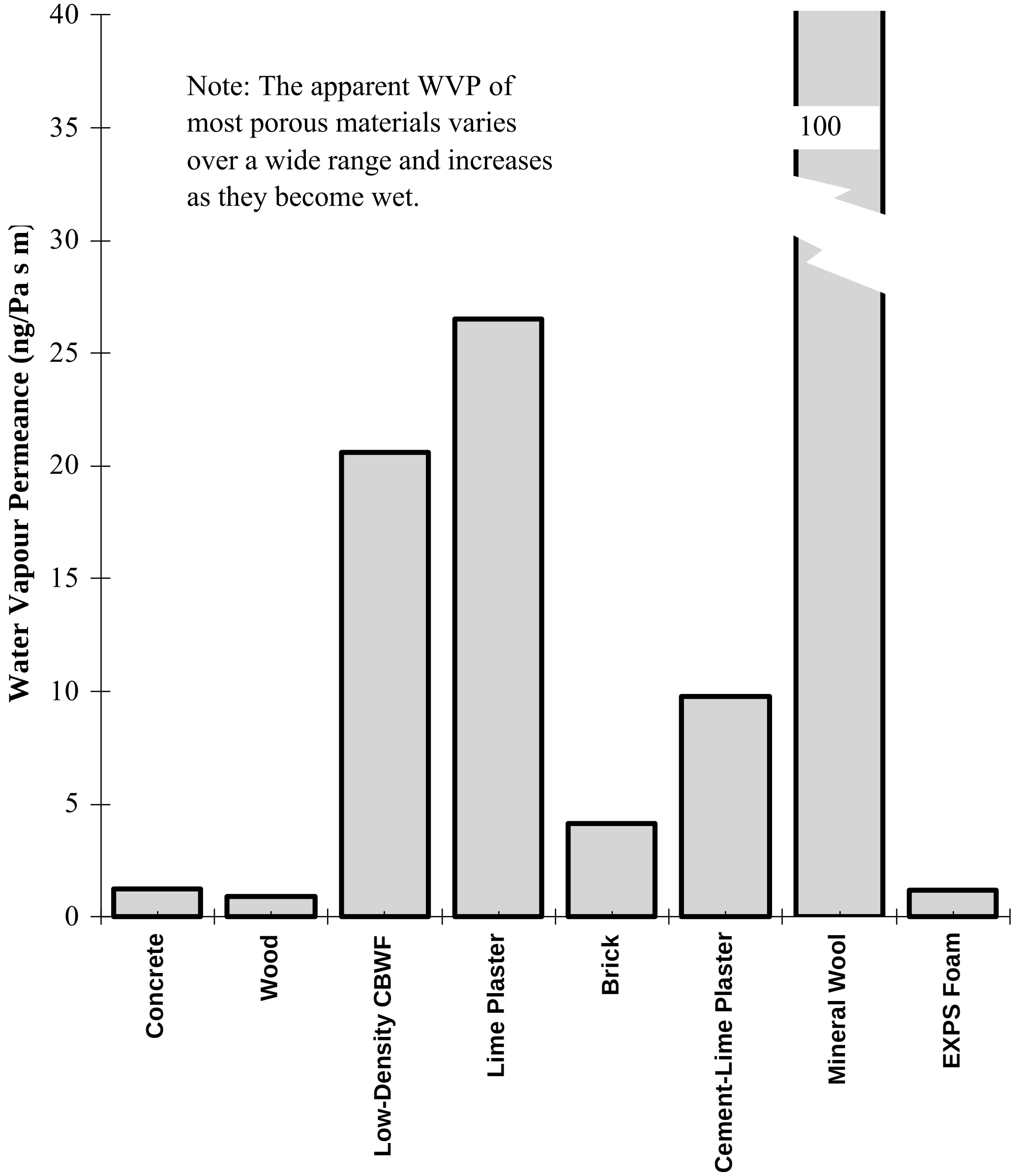


Figure 1: Water Vapour Permeance of Various Building Materials

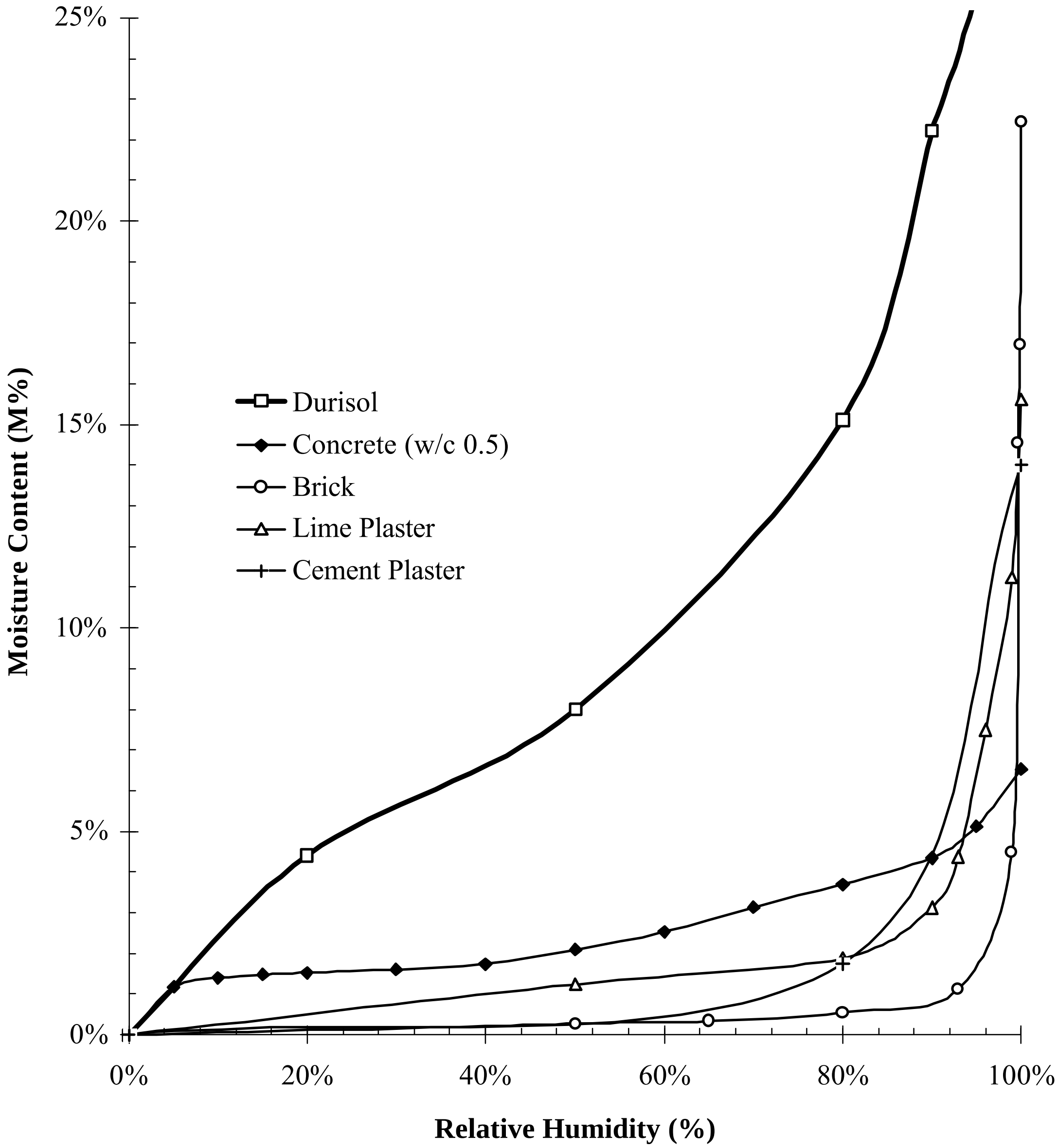


Figure 2: Sorption Isotherm for Various Building Materials

Dynamic Hygric Response

A recent multi-year study concluded that short-term RH peaks of a building's air can support fungal growth, even though the average conditions are well below the threshold for fungal growth, e.g., 70 to 80% RH (Adan 1994). For example, the simple act of boiling water for cooking creates a significant short-term rise in humidity near the kitchen.

After the interior RH has dropped, the fungi can continue to grow for some time using moisture stored within the fungi.

The speed with which a wall surface can absorb moisture is important for avoiding surface condensation and surface relative humidities required to support fungal growth. Materials with a combination of the properties of vapour permeability and high hygroscopicity allow that material to quickly moderate humidity variations by storing or releasing significant quantities of water vapour. A vapour tight finish on walls allows the surface relative humidity to climb to the level where fungal growth can be sustained.

If a material can quickly adsorb moisture from the air, this material will maintain the RH at its surface at a lower and more stable level while also moderating short-term interior air humidity variations. The dynamic hygric response of several wall systems was studied with the aid of computer modelling and field measurements. The results are presented below.

Modelling Hygric Response

Using a sophisticated computerised finite element hygrothermal computer simulation program (developed and validated by Kuenzel, 1997) the amount of moisture released into a room by several different wall systems was calculated. The program is sophisticated in that it considers different moisture diffusivities for suction and redistribution, surface diffusion, capillarity, vapour diffusion, etc.

Each of the assemblies modelled comprised a 200 mm layer of each material. The results showed that the effect of material thickness was not very significant over more than about 40 to 60 mm, much less in the case of relatively vapour impermeable materials. This justified the simplification of the wall systems into one-dimensional constructions. Some of the walls were finished with lime plaster, others with gypsum drywall and various paints. Material properties were taken from manufacturer’s data and various sources (ASHRAE 1997, IEA 1997). The most important material properties (sorption isotherm and vapour permeance) are shown in Figure 1 and Figure 2. The vapour permeance values for the most common finishes are listed in Table 1. The simulation considered a wall and room initially at 30%RH followed by an instantaneous rise in room air moisture content to 80%RH. Over the period of a week the simulation calculated the water vapour balance every 15 minutes.

Material Layer	**Permeance (ng/Pa s m^2)**
Lime Plaster (12.5 mm)	2000
Lime Plaster (25 mm)	1000
Primer + 2 coats latex paint	200
Cement Plaster (25 mm)	70
Vinyl Wall Paper	5

Table 1: Vapour Permeance of Various Finishes used in Simulations [IEA 1997, Kuenzel 1997, ASHRAE 1997, Straube 2000]

Figure 3 plots the moisture adsorption of four walls for the first 24 hours. All of the systems responded in a similar manner, but the speed of response differed considerably. The initial response was fast, followed by a slow exponentially decaying period. Because the shape of the response curves are similar, the results can be usefully summarised and wall systems approximately ranked: see Table 2.

Table 2 shows that there is a large difference between the behaviour of some common wall systems. The plastered CBWF insulated concrete form system and strawbale wall provide about 8 times more vapour control to the indoor environment than the walls used in a typical modern home, and 25 times that of a modern motel room with vinyl wall paper. While the above results do not attempt to exhaustively rate each assembly (the more complex discussions and calculations necessary for this are beyond the scope of this paper), it does provide a relative ranking which clearly shows the problems associated with the use of the most common modern building systems.

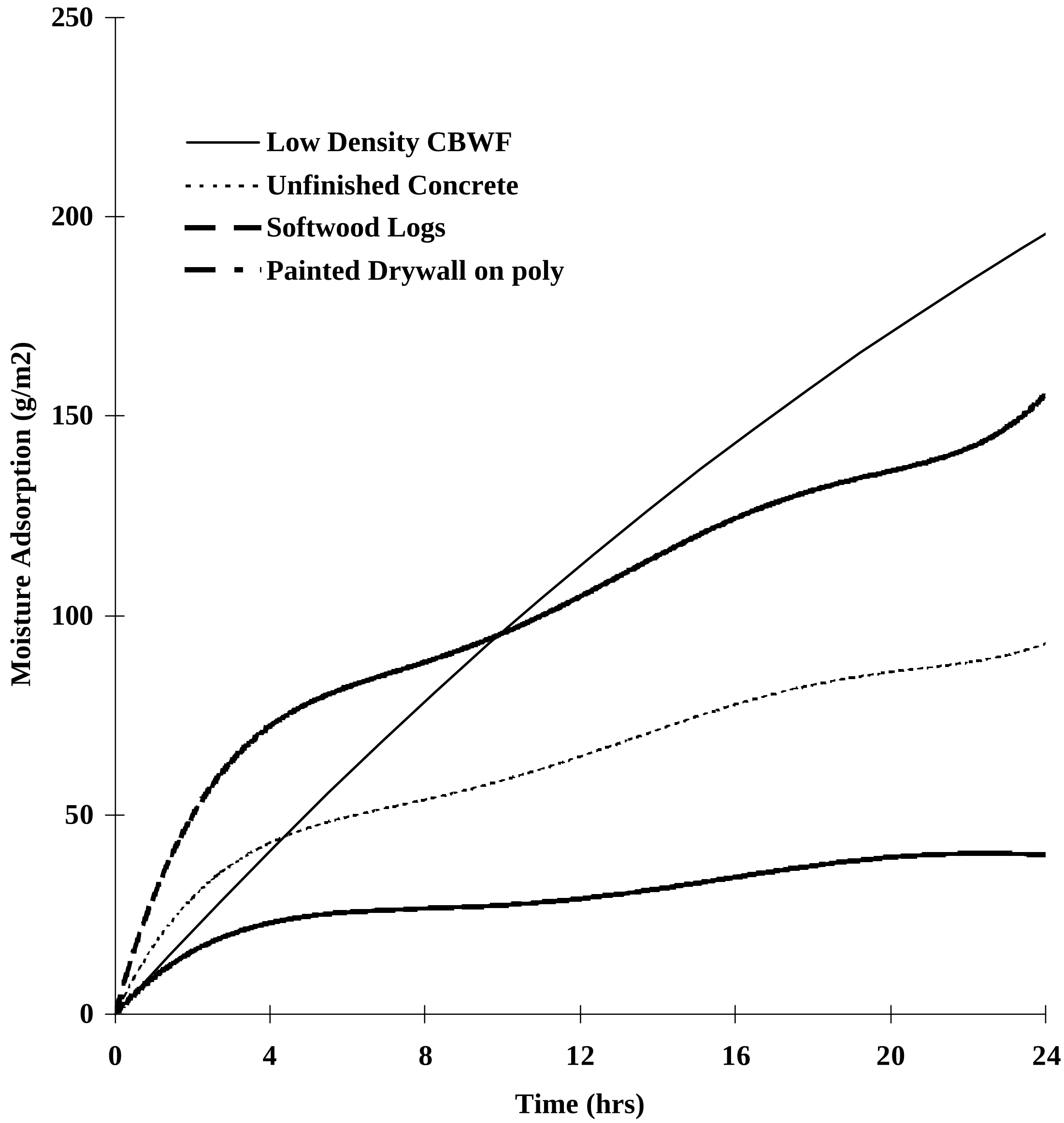


Figure 3: Calculated hygric response of four wall systems to a 50%RH change

The simulation results also showed the clear superiority of lime-based plasters over pure cement-based plaster. The hygroscopic and highly vapour permeable nature of lime plaster provides a very fast response (i.e., several minutes) to changes in the vapour content of the interior air. Substrates like CBWF, strawbales, and brick provide much more moisture storage, storage which participates at longer time scales (i.e., several hours). The worst possible finish is a high-grade vinyl wall, which not only off-gases VOC's but also returns vapour adsorption values of less than about 10.

Rating [g/m^2]	Assembly Description
<10	Any system with vapour retarding paint (including oil based) or "high-quality" vinyl wall paper
40	Painted gypsum drywall on poly on wood frame, primer + 2 coats latex
90	Concrete, unfinished
110	Extruded clay brick, unfinished
150	Softwood logs, unfinished
240	Strawbale wall with 1" lime plaster
250	CBWF WallForm 20 System, finished with 12.5 mm lime plaster

Table 2: Water vapour absorbed in 24 hours by walls exposed to a 50%RH change

To assess the implications of the influence of hygroscopic walls on interior humidity levels, consider a 3 x 5 meter room with 20 m^2 of exterior walls and a 37.5 m^3 volume. Air at 20 ºC and 50%RH contains about 8.7 g/m^3. If 200 g of water (about 6.75 fluid ounces) were to be injected into the air, by human metabolism, cooking, etc., the moisture content of the air would rise by 200 g / 37.5 m^3 = 5.3 g/m^3 and the humidity of the air would rise to above 80%RH. If the source of vapour is cooking or a shower, the water would be quickly injected into the air, and the RH at the surface of any cool exterior wall (in this case any surface cooler than 16 ºC) would reach 100%. If the exterior walls of a room were able to absorb this moisture, i.e., 200 g / 20 m^2 = 10 g/m^2 of wall area, the RH within the room would be maintained, and the surface RH would remain below the threshold for fungal growth. This amount of moisture adsorption is easily and quickly (less than one hour) possible for walls rated over about 150 in Table 1; it is not possible for walls rated less than about 50. If all of the room's walls (e.g,, all 40 m^2) were hygroscopic, the response would be even faster and more powerful.

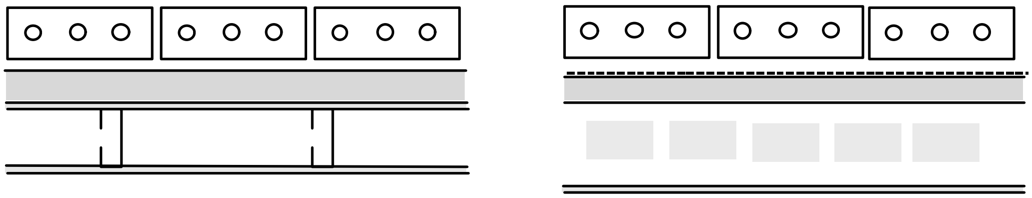
Outdoor air at 80%RH and 0 ºC contains about 3.9 g/m^3. If the room in the previous example were ventilated at one air change per hour with outdoor air, approximately 37.5 m^3 x (8.7 - 3.9) = 180 g of moisture would be removed by ventilation. Thus, ventilation is just as powerful a means of controlling indoor air moisture content as "breathable" or hygroscopic walls. In buildings made with vapour tight walls, ventilation becomes the most important means of vapour control. Ventilation, however, cannot always guarantee moisture removal in the corners of rooms, behind furniture, etc. Ventilation is always necessary because it aids in the removal of other pollutants and delivers oxygen to a room faster than diffusion. Unfortunately, controlling ventilation requires mechanisms (electronics and fans) and/or proper occupant control.

Hygroscopic, walls (sometimes called "breathable" by laymen, but it is unclear exactly what is meant by the term) operate automatically, require no energy and cannot break down. Such walls can also react much more quickly than normal levels of ventilation to moderate humidity, but ventilation is always required to remove it. Hence, ventilation and breathing walls are thus likely best used as complementary techniques for ensuring IAQ. Numerous studies have been conducted on walls through which air is drawn, a completely different form of so-called "breathing" walls (Levon 1986, Taylor 1997, Timusk, 1987), most with the intent of reducing energy consumption.

Field Measurements of Hygric Response

Although computer modelling can be a powerful tool, field measurements are always the best and most reliable means of testing theory. A total of ten different wall types were part of the research program. Space limitations allow for the comparison of only two -- the CBWF Insulated Concrete Form system and a well-built, highly insulated steel stud wall system, both clad with brick veneer. Simplified horizontal sections of the walls are shown in Figure 4.

Wall B clearly contains more thermal mass and a large amount of vapour storage. However, another major difference was the use of a vapour barrier. Wall A used a sheet of 6 mil polyethylene (0.06 US perms, 3.4 ng/Pa/s/m^2) behind the drywall finish. Wall B used an unpainted sheet of drywall only -- unpainted drywall is very vapour permeable (over 20 US perms or 2000 ng/Pa/s/m^2). Although the 51 mm of extruded polystyrene insulation placed outside of Wall B increases the temperature of the CBWF material, it is also reasonably vapour resistant and the drywall was left unpainted to "trap" vapour in the wall. Vapour permeable plasters or recycled rockwool insulation is typically recommended outside of CBWF walls, or thicker, more highly insulated forms are specified.



10 mm air space
75 mm mineral fiber board
insulation gypsum sheathing
w/sealed joints
Steel studs with batt insulation
Painted Drywall on Poly

Wall A

30 mm air space
sheathing paper
50 mm extruded polystyrene
200 mm CBWF ICF
Drywall - unpainted

Wall B

Figure 4: Horizontal section of test walls (schematic)

Figures 5 and 6 plot the relative humidity measured in the middle of the batt space and the middle of the CBWF of Wall A and B respectively over the winter period (from 961031 to 970331). The maximum and the minimum 15 minute average values for each day have been plotted from the data collected at 5 minute intervals. The interior of the test house was carefully maintained at 21 ºC ±1 ºC and 50% ±5%RH over the entire period. This is a higher RH than most houses but is representative of many commercial building environments.

A comparison of the two plots clearly shows the humidity moderating effect within the CBWF material of Wall B. Over the entire heating period, the daily RH variation (i.e., maximum less minimum) was 15.3% for Wall A and only 2.6% for Wall B.

An inspection of the relative humidity measurements in Wall B also shows that they never approached levels at which condensation might occur, even though there was no vapour retarder on the warm side of the wall, and despite a relatively impermeable outer sheathing. This data was collected over a winter in which the outdoor temperature dropped below -20 ºC (-4 ºF) several times. In fact, Wall A with a polyethylene retarder exhibited far more chance of condensation than Wall B. If the drywall had been painted, the CBWF plastered, or the EXPS sheathing replaced with a more vapour permeable material, the RH in Wall B would have been even lower.

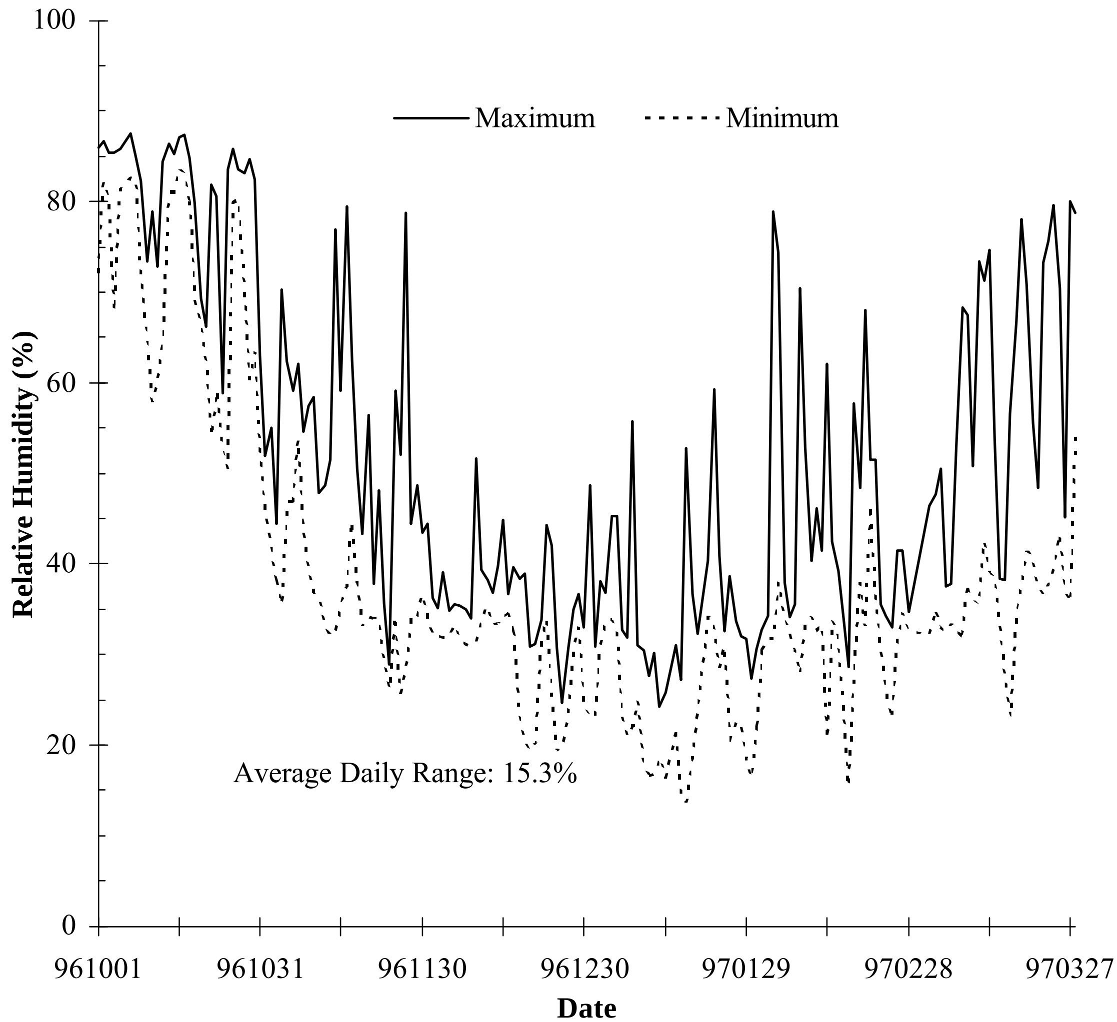


Figure 5: Maximum and minimum relative humidity in Wall A

Wall A also exhibited much higher summertime RH's because of vapour flow from the outdoors to the indoors. The polyethylene trapped this vapour within Wall A. These inward vapour drives have been found to be a problem in many walls, especially in climates similar to or warmer than South-western Ontario (Straube and Burnett 1995).

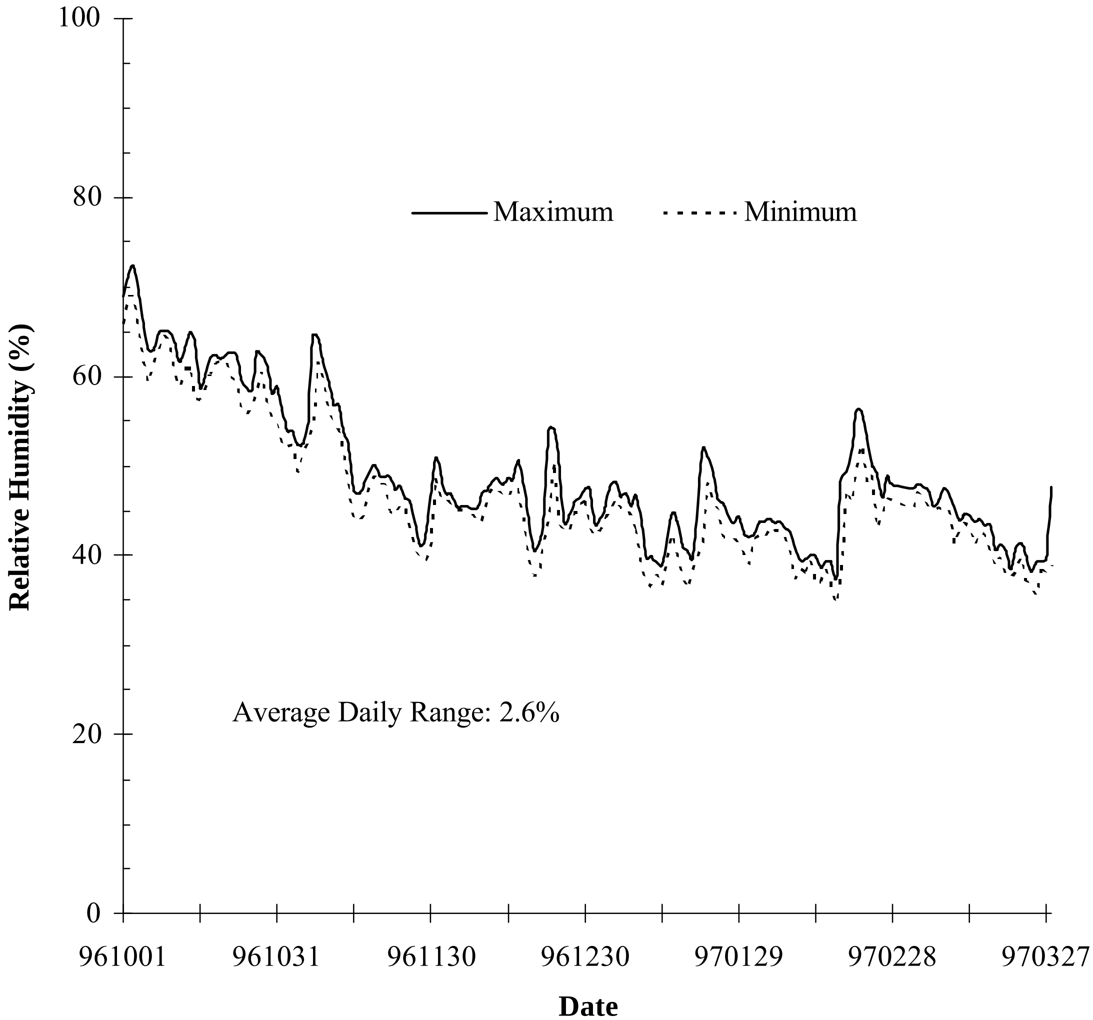


Figure 6: Maximum and minimum relative humidity in Wall B

Conclusions

The indoor air quality of a building directly impacts the health and productivity of its occupants. There are several design strategies that can be used to deliver good IAQ. Controlled ventilation, proper design, occupant behaviour, and the use of appropriate healthy building materials within a holistic design approach can provide good indoor air quality. As part of a complete IAQ design strategy, so-called breathing walls can moderate indoor humidity and practically eliminate the potential for fungal growth on building surfaces.

The properties of the CBWF cement-bonded wood fibre material, like strawbale, are ideal for use in breathing walls because of their combination of vapour permeable and hygroscopic properties.

The results from the field monitoring demonstrated both the humidity moderating effect and the fact that no polyethylene vapour barrier is required in such walls.

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