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Abstract

Unfired clay brick, wood, and cellular concrete have been evaluated as relative humidity (RH) buffers for indoor spaces. Their response to a cyclic variation of RH has been measured and expressed in a novel unit for describing the buffer capacity, the 'buf' with symbol B. This is defined as the quantity of water vapour exchanged with the material, expressed as the volume of space which will experience the same change in amount of water vapour when exposed to the same RH cycle. One can regard the sum of the buffer values of the wall lining and the furnishing as a virtual (larger) volume to the room, into which water vapour from infiltration and internal generation has to disperse, with a consequently smaller RH variation. The buffer value is dependent on air velocity over the surface and on temperature, as well as on cycle period.

The B–value is approximately equal to the number of air changes needed to exhaust the buffer moisture reserve in a typical room with walls lined with the material. Well ventilated unfired perforated brick, 5 cm thick, has a buffer capacity of 27 m^3 per square metre of surface for a daily RH cycle, providing significant resistance to RH change caused by an air exchange rate of once per hour. Wood cut across the grain was second best in performance, with a value of 15, just ahead of massive unfired brick at 10. Cellular concrete was an unimpressive buffer at 7 but worst of all was fired perforated brick with a buffer value of 3 even for a long RH cycle.

However, even the well ventilated perforated unfired brick reacted slowly to changing RH, having a buffer capacity nearly doubling from a one-day to a four-day humidity cycle then doubling again for a very long cycle, represented by a week at a steady RH. As the cycle lengthens the performance approaches that predicted from sorption measurements made on finely granular samples of the material. For practically useful performance, a wall needs to have a moisture-active surface larger than its area facing the room. The buffer capacity can be considerably increased if deeper layers of the wall are brought into use by convecting, or forcing, air through internal channels. A wall, 106 mm thick, of unfired perforated brick with the channels arranged parallel to the surface and ventilated mechanically, has a B–value of 61.

Introduction

Building physicists have long been concerned with moisture exchange with absorbent materials in the walls and roofs of buildings. Water vapour is generally regarded as a nuisance, causing condensation within walls, with consequent mould growth and corrosion of construction materials. However, the stabilisation of the interior climate by moisture-active building materials and furnishing is of great value in the world of museums and archives. Humidity buffering by absorbent materials has long been used to stabilise the microclimate in showcases and transport boxes. These have a very low air exchange rate, so the rate of moisture exchange between the buffer material and the air in the case is not important.

In this article we explore the potential for extending the benefits of humidity buffering to larger and better ventilated enclosures: stores, archives and even museum galleries. For these large spaces, the buffer material must be cheap and available through large scale production. There are no building materials explicitly formulated to buffer indoor relative humidity (RH) so we have investigated the few materials which have a fairly large water sorption capacity combined with porosity. These are unfired brick, wood and cellular concrete. All these materials are inherently variable in their sorption properties. Brick clays have different sorption according to their mineralogy - kaolin having very little sorption while sodium montmorillonite (bentonite) has such extreme sorption that unfired brick would crack with even a moderate change in RH. Wood species vary somewhat in sorption and cellular concrete is a generic term for many different porous mineral blocks. The one tested here, 'Celcon', is a fibrous aluminosilicate containing no cement.

The computer simulation programs developed for modelling moisture movement in buildings have concentrated on the diffusive movement outward of water molecules through the outer walls and roof, driven by the generally higher water vapour concentration indoors. Even slow outward water movement through the wall can cause serious damage to the building structure if it is blocked by a cold impermeable layer towards the outside of the wall. However, diffusive movement inwards through the outer wall is too slow to influence the interior RH because its effect is much diluted by air exchange through openings and by much larger amounts of moisture injected through human activities.

This leaves just the exchange of water vapour with the inside surface of the wall, and the furnishing of the room as the process which has the promise to moderate the indoor relative humidity.

We know that buildings which are heavily loaded with water absorbent materials keep their internal RH remarkably stable, even over a whole year. Figure 1 shows the Suffolk Record Office in Ipswich UK. Its microclimate has been measured over several years (figure 2). The RH varies between 52% and 58% in a gentle annual cycle. The RH is confined within this moderate range by winter heating alone. This drives the RH down a little in winter, because of the low moisture content of infiltrating cold air. During the summer the infiltrating air would raise the RH but for the buffer effect from the paper. This is shown clearly in the lowest trace, which is the difference

Figure 1: The Suffolk Record Office in Ipswich, UK. Opened in 1990, Architect Henk Pieksma.

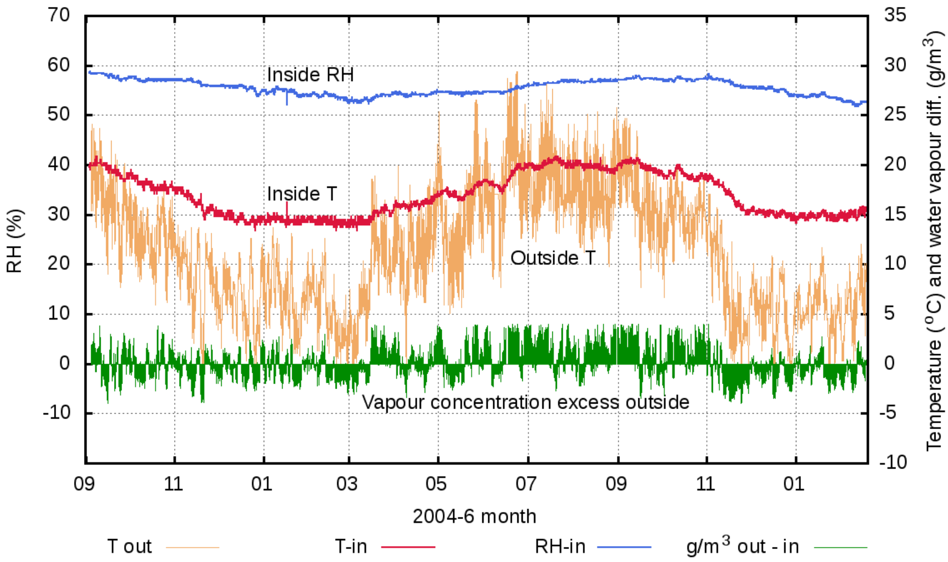

Figure 2: The annual cycle of temperature and relative humidity in the Suffolk Record Office. The lowest trace indicates the difference between the concentration of water vapour inside and outside. During the winter the inside RH is driven down by air exchange; during the summer the outside air has more water vapour, as shown by the lowest trace being mostly above the zero line, but buffering by the archived documents prevents the RH from rising to equivalence with the water vapour concentration outside.

between the outside and inside water vapour concentration. In summer, the concentration is consistently higher outside but the paper holds down the inside concentration. Other museum stores, and particularly museum galleries, have the same need for RH stability, but do not have the buffer capacity provided by densely packed paper records. Can this lack of buffering by the materials within the room be compensated by moisture exchange with active materials in the walls of the room?

The experimental evaluation of the buffer performance of building materials

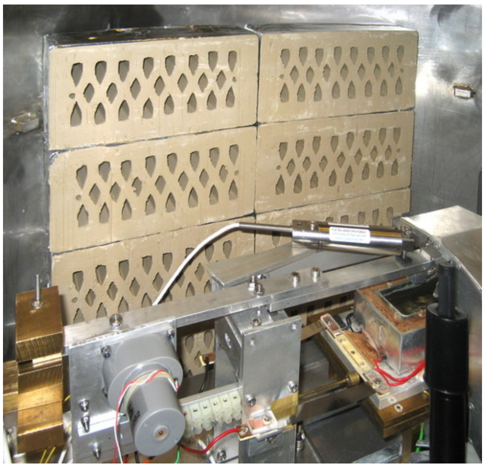

Figure 3: Eight perforated unfired bricks, exposed in the climate chamber. The apparatus controlling the RH and measuring the weight of water moving into the specimen is at the bottom of the picture. The exposed area of the brick wall is 0.2 m^2, its depth is 53 mm. The sides and back are sealed with aluminium foil so the perforations are exposed to the chamber air as blind tubes.

The materials were exposed to a sinusoidal RH variation between 50% and 60% RH. This is the preferred indoor RH and it is also the RH range where materials have a relatively linear relationship between RH and equilibrium water content. At higher RH, which could well occur in a kitchen or bathroom, there is an increase in water vapour sorption per unit increase in RH. This would give an over-optimistic indication of the performance of the material in more moderate indoor conditions.

The exchange of water vapour between the surface of the material and the surrounding space was measured. The experimental technique is described in Padfield et al. [1] and in an appendix to this article. The apparatus, with the perforated brick specimen, is shown in figure 3. The material is exposed in a sealed chamber while the RH follows a cyclic variation controlled by the temperature of water in a weighed reservoir. The temperature is adjusted by a thermoelectric heat pump in the bottom of the reservoir. It is assumed that water lost from the reservoir is largely absorbed in the test material, with small corrections for the sorption by the chamber equipment and for the change in water vapour content of the space. By weighing the water rather

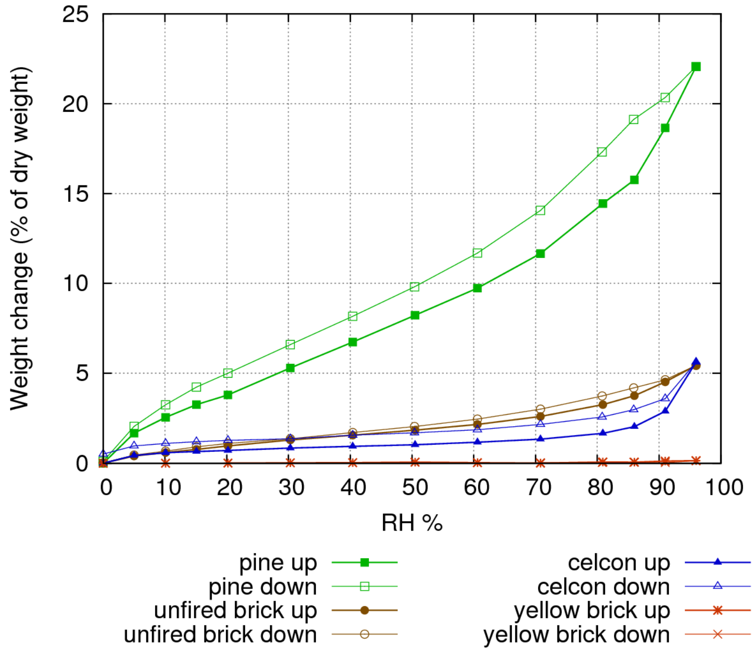

Figure 4: Water vapour sorption curves of the materials. The sorption is expressed conventionally as weight of water per unit weight of material. However, the unfired clay brick is 2.5 times as dense as wood, so its sorption per unit of volume is comparable to that of wood.

than the specimen, specimens of widely different geometry and weight can be tested conveniently.

In a separate experiment the materials were finely divided for measurement of their equilibrium sorption curves. The full sorption curves are given in figure 4.

The sorption curves were also measured over a repeated cycle between 40% and 60% RH to confirm that the hysteresis between absorption and desorption is negigible over the small RH range of our experiment. One can regard the sorption per unit of RH as a constant over this range, regardless of the direction of change of RH. This sorption coefficient also defines the theoretical maximum exchangeable water, given enough time to reach equilibrium, to compare with the measured exchange in the dynamic experiments with cycles far too short for equilibrium to be attained.

The diffusion rate through the specimens was not measured. The standard method measures the vapour transmission through a slab of material exposed to a constant RH difference across it. We regard this number as likely to be different from the dynamic performance of the material, where chemical processes of sorption and desorption delay the response in a way which the static measurement cannot reveal. The dynamic permeability can in principle be studied by analysis of the response of the material at different cycle times. We have not done this, but would welcome a study by a mathematician, based on our data.

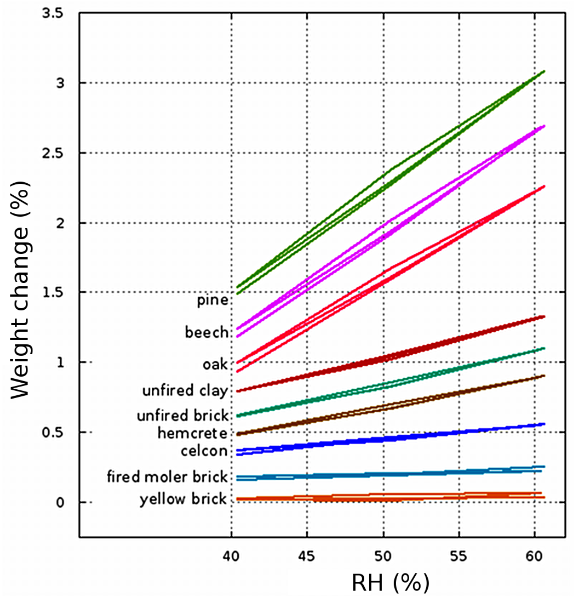

Figure 5: Sorption of water vapour over a limited RH range. The plots show the response to cyclic step changes of RH between 40%, 50% and 60%. The hysteresis loops are insignificant over this moderate RH range. The sorption cycle for each material is offset vertically for clarity. 'Moler' is a clay rich diatomaceous earth quarried in western Denmark. 'Hemcrete' is lime mortar mixed with hemp residues. 'Celcon' is a porous calcium-aluminium silicate block. The clay products are from Wienerberger brickworks in Helsinge, Denmark.

The quantitative description of the buffer performance

The experimental apparatus measures the weight of water transferred between the test object and the reservoir as a consequence of a change of ambient RH applied over a defined cycle time, at a constant temperature. An example of the raw data is shown in figure 6 and the entire data set is shown in the appendix.

Given the diversity of materials and forms which combine to influence the microclimate of the room, we need to find a way of expressing the performance of both the walls and the freestanding content which can be summed conveniently to predict how the room will react to the exchange of water vapour with outside air and the generation of water vapour by human activity within the room.

We transform the measured water exchange of our specimens to the equivalent volume of air (strictly speaking the volume of space) which will experience the same cyclic change in RH with the same water vapour transfer. This concept is illustrated in figure 7. This equivalent volume is labelled the B–value for the material. For construction materials the volume is calculated per square metre of exposed surface, giving it the formal dimension of metres. For irregular shaped buffering objects within the room, such as a sofa, the B–value can be defined as the equivalent air volume for the entire object. For a library, the equivalent air volume per linear metre of shelved books would be appropriate.

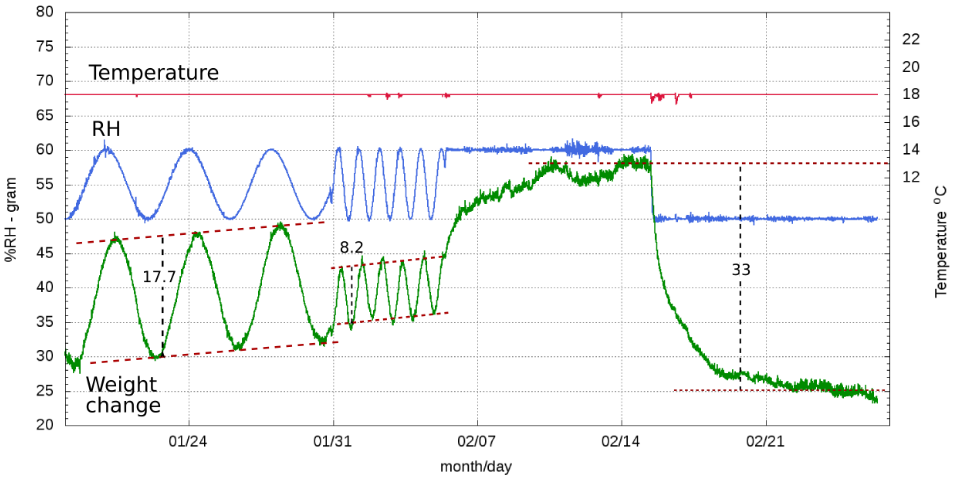

Figure 6: An example of raw data from the experiment. The perforated unfired brick is exposed successively to three 96 hour RH cycles, then 24 hour cycles and finally to steady chamber RH. Parallel lines mark the envelope of the cycles. The numbers indicate the weight of water in grams absorbed through the 0.2 m^2 exposed area of the bricks.

The sum of the B–values for all wall surfaces and all sorptive components within a room, expressed in cubic metres of space, is added to the actual volume of the room to give a larger, virtual volume (figure 8). To calculate the effect on the RH of moisture generation and air exchange, one uses the actual air exchange, and the actual moisture production, but calculates the resulting change of RH caused by these fluxes dispersing into the larger virtual volume. For example, if the total of B–values is 100 m^3, and the actual room volume is 25 m^3, the change of RH in the room will be that calculated for the dispersion of infiltrated air and generated moisture into a moisture-inert room of 125 m^3, so the variation in RH will be reduced to about a fifth of the variation calculated for a moisture-inert room of 25 m^3.

Experimental results

Table 1 shows the B–values for materials expressed in metres (cubic metres per square metre of exposed surface), for a one day sinusoidal cycle, a four day sinusoidal cycle and a long cycle represented by holding the RH steady at each of the extreme values, 50% and 60%, for long enough for the specimen to reach equilibrium, but not longer than two weeks. The last column shows the theoretical B–value on the assumption that all the exchangeable water through the whole thickness of the specimen is available for movement between the material and its surroundings. This value is derived from the equilibrium sorption curves between 40% and 60% RH, which are shown in figure 5.

The measurement precision is such that for the poorly absorbent materials B–values less than 5 are omitted from the table. For more absorbent materials the variation between specimens of different wood species, or dif-

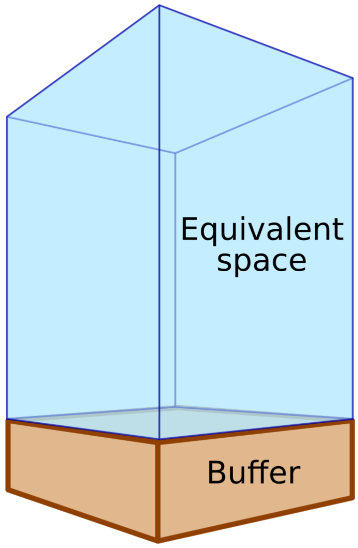

Figure 7: A visual display of the 'equivalent air volume' principle for defining a figure of merit for a buffer material or construction. The horizontal area of the buffer is one square metre. Suppose that the RH is increased by 1%. The buffer material will absorb water vapour through its surface as it moves towards achieving equilibrium at this higher RH. The volume of the column is defined as that volume which will also increase by 1% RH when injected with exactly the same amount of water which enters the buffer. A highly buffering material will absorb a lot of water, so its equivalent air column will be high. This unit of buffer capacity is called the 'buf' (B) with dimension length.

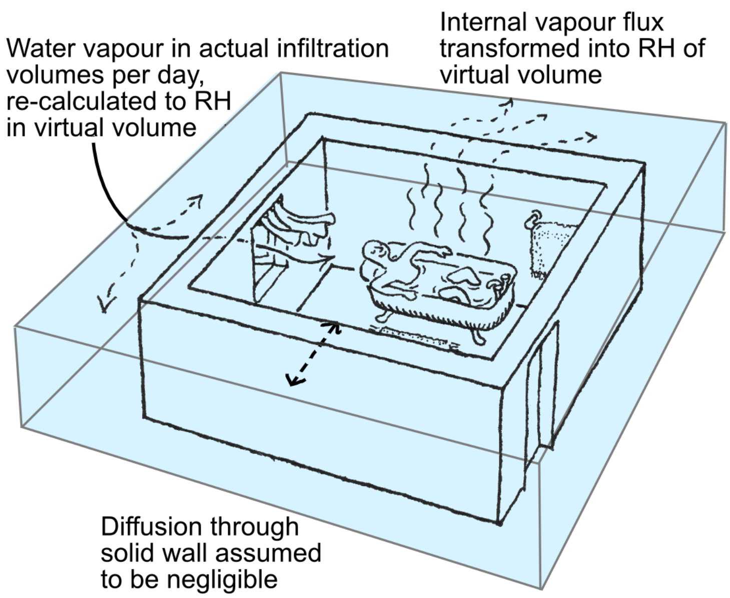

Figure 8: The B–values for all surfaces and furniture, converted to cubic metres, are added to the actual room volume to give a larger, virtual room volume. All water vapour fluxes are led into this volume and then the RH is calculated.

Specimen description	mm	B24	B96	long	static
Unfired massive brick	53	10	21	–	165
Unfired perforated brick	53	27	58	108	136
Unfired perforated brick double depth	106	39	95	196	272
Unfired perforated brick double depth, low airflow	106	10	21	–	272
Unfired perforated brick double depth, paper covered	106	10	26	98	272
Unfired perforated brick fan ventilated	110	61	108	243	271
End-grain wood	40	15	34	–	122
Cellular concrete	50	7	9	–	17
Fired perforated brick	52	–	–	3	12

Table 1: Buffer values, in metres, of building materials at 18°C. The second column is the specimen thickness. The next columns are the B-values for 24 hour, 96 hour and 'long' cycle time (a square wave with minimum 7 days settling time). 'static' is the value calculated for complete moisture equilibrium throughout the thickness of the specimen, based on the measured sorption curve shown in figure 5.

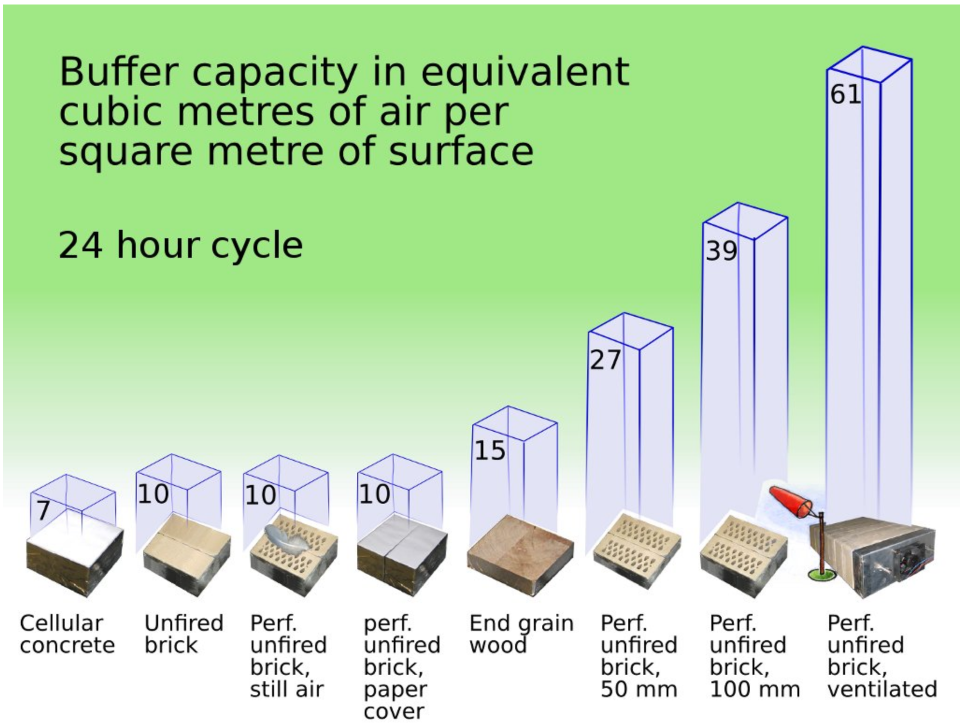

Figure 9: A graphical display of the tabular data for the 24 hour cycle. Notice the large effect of obscuring the perforation in the brick with paper and the much lower B–value of the perforated brick in stagnant air.

ferent clay pits, would be greater than the experimental error. The values given here are therefore indicative rather than exact.

The B–values for the 24 hour cycle are shown graphically in figure 9. This is the set of values of most use in architecture, being relevant to the daily cycle of both human activity and the weather.

The effect of cycle time on the exchangeable water supply

The B–value increases with the RH cycle time because deeper layers of the material become involved in the diffusion process. A 24 hour cycle matches the pattern of human activity, but a longer cycle time would be appropriate for designing an archive, which has a slower air exchange and very little human generated water vapour. The B–values roughly double from the 24 hour to the 96 hour cycle, then double again for the slow cycle. For a very long cycle, such as the annual cycle characteristic of the archive building, experimental patience can confidently be replaced by a calculation which assumes that the entire thickness of buffer material comes to equilibrium with the prevailing RH as described by the sorption curve. This calculated B–value is listed in the last column of table 1.

The effect of air movement on the water exchange through the surface

Most of the experiments were conducted with a high air speed, by indoor standards, between 0.2 and 1.2 m/s. This was chosen to ensure that diffusion through the specimen was the rate determining step, so that the measured B–values would be a material property, undistorted by environmental factors. To compare these optimal results with more realistic domestic air velocities some experiments were conducted at low air velocity - less than 0.1 m/s.

For the perforated specimens, the B–value depends greatly on the air turbulence at the surface. The effect of ventilation vigour on the performance of the perforated brick was checked by exposing the brick in a larger chamber with a much gentler air circulation system, more typical of a dwelling. The B_{24hr} value sank from 39 to 10, illustrating the importance of air circulation around highly absorbent materials. This dependence on air speed was confirmed by adapting the smaller experimental chamber to provide a slow air movement.

The effect of surface coatings on the B–value

To compare the results for bare materials with the same materials with a porous decorative finish, a surface coating of filter paper was laid over the perforations of the unfired clay brick specimen (figure 10). This is a highly permeable surface decoration but it reduced the buffer performance considerably, even though the paper is itself a good humidity buffer.

The effect of temperature on the B–value

The B–value is temperature dependent. This effect has not been measured in this set of experiments. As a general rule, one can expect the B–value for long cycles to double with a ten degree fall in temperature. This is because the buffer material retains almost the same water content for a given RH, independent of temperature, while the water content of space, at constant RH, diminishes considerably with falling temperature. For short cycle times

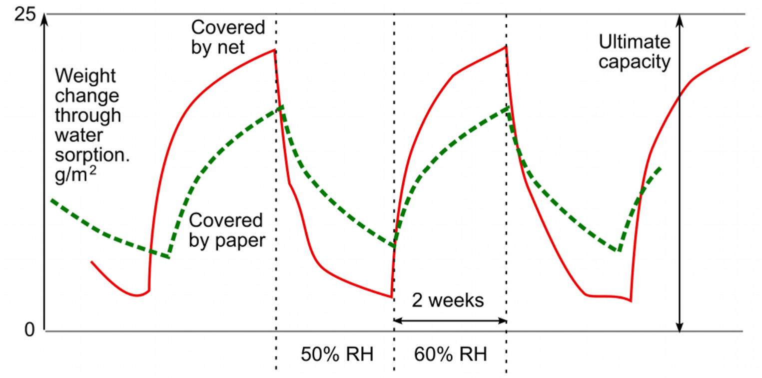

Figure 10: The effect of covering unfired perforated brick with a single layer of filter paper. The response curves to a four week square wave RH cycle are plotted superimposed. The top and bottom boundary lines indicate the ultimate buffer capacity derived from the static sorption measurement. The net had mesh openings 1.2 mm square, the paper was Whatman nr.1, 88 g/m^2.

this effect will be masked to some extent by slower diffusion, so there will be a smaller increase in B–value.

Dimensional change associated with RH buffering

Absorption of water changes the dimensions and other physical properties of materials. Unfired clay brick swells as it absorbs water. The extent of swelling depends on the clay type and on its ratio to the sandy components of the brick. Brickworks must limit the dimensional change with water content of their unfired brick, to ensure a constant size of fired bricks at the end of the manufacturing process. The clay bricks used in this experiment changed size 0.04% for a 40 - 60% RH change. No cracking or surface powdering was observed during our experiments.

Using the B–value in the design process

We don't know of a building that has been deliberately constructed to minimise the variation of RH caused by infiltration and internal generation of water vapour, and whose performance has been measured. We have to resort to simulation based on an existing museum storage building (figure 12) which is currently dehumidified to control its RH. This building, in Ribe, South Denmark, is described by Ryhl-Svendsen et al. [2].

For the simulation we modify the single space of this building to contain three equal rooms, each 14 × 24 × 6.5 m high, lined on all walls with 50 mm unfired perforated brick. We combine this imagined construction with the actual air exchange rate of the Ribe building, 0.03 per hour, and the measured room temperature and outside climate during one year. Using the long period B–value of 100 for the unfired brick, the total B–value for the room is 50,000 m^3, while the room volume is 2184 m^3. The virtual volume is thus 52184 m^3, which is 24 times the actual volume. To calculate the effect of infiltration, we reduce the infiltration rate to 0.03/24 = 0.00125. The

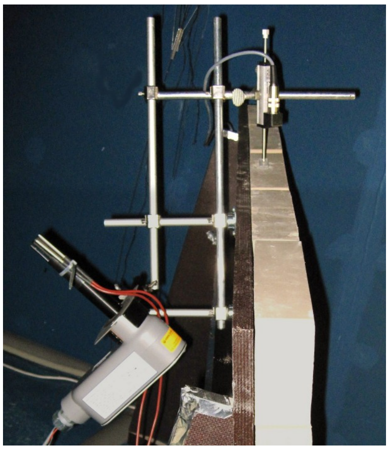

Figure 11: The effect of changing the RH on the size of the unfired brick was measured on a pile of eight bricks set on edge. The dewpoint RH sensor is in the foreground, the displacement sensor is held by an aluminium rod structure. The temperature was constant at 18 °C.

Figure 12: The museum store near Ribe in west Denmark

outside vapour concentration is calculated every hour. This concentration is multiplied by the virtual exchange rate and brought into the interior while an equal volume of internal air is expelled. We assume that there is no internally generated moisture. The new vapour concentration and the interior temperature are used to calculate the interior RH. The slow change of the interior RH predicted in this way retrospectively justifies the choice of the long term B–value for the calculation.

For a typical dwelling or office one can assume a fairly constant temperature through the year. In the case of the Ribe museum store the temperature is uncontrolled and varies in an annual cycle. An extra calculation stage is needed to account for the fact that the water vapour content of the interior varies with temperature, even when the RH remains nearly constant. Consider the case where the temperature declines from hour to hour. The buffer will maintain the RH, but the water vapour concentration in the air space will diminish. Therefore, one calculates from the RH a new water vapour concentration at this lower temperature. This modified concentration is used in the next iteration of the simulation.

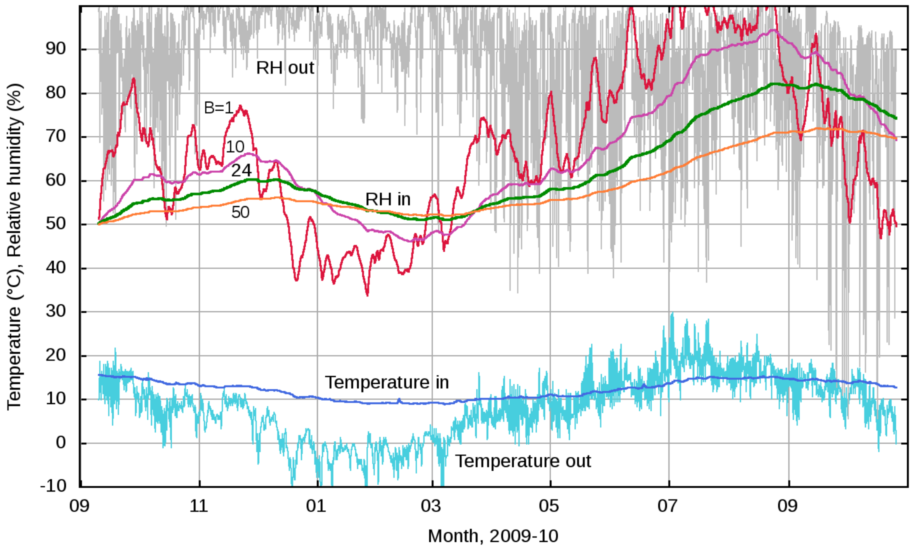

Figure 13: Simulated buffering of the RH in a museum store by lining the walls with unfired brick (trace 24). The interior RH starts arbitrarily at 50%. The trace marked B = 1 shows the course of the RH in a completely water-inert building with an air change rate of 0.03 h^{-1}.

The result of this calculation process is shown in figure 13, which predicts what would happen were the dehumidification stopped. The traces show the subsequent course of the RH in a building with no buffer capacity (B = 1), and in the buffered building (B = 24). The B–value is very dependent on air flow over the surface. In undisturbed interior air the value may be just a fraction of the well-ventilated value. The curve for B = 10 may well be more realistic for a museum store. The calculation predicts that in this specialised application, moisture buffering is very effective and will delay serious consequences of mechanical dehumidification failure for at least two months. Notice that the RH in the unbuffered store reaches 100% in summer, because of temperature buffering by the floor.

The B–value concept, compared with other descriptions of buffer capacity

The buffer capacity test described here is similar to the method defined in the Japanese standard [3] and the proposed Nordtest standard [4]. These methods, which are summarised by Roels and Jannsen [5], use a set series of step RH changes and express the result as the weight of water exchanged through one square metre per percent RH change. All these measuring protocols give a single number for the buffer performance, roughly equivalent to our B_{24} value. This number is not directly usable in heat and moisture diffusion models, which are based on finite element calculations dependent on two material properties, water sorption and diffusion. Janssen and Roels [6] suggest a procedure for combining data from different cycle times into a capacity, an equivalent thickness and a diffusion rate which can be integrated into a finite element program. They demonstrate this by modifying the proposed Nordtest procedure, using the water transferred at an early state of the cycle to represent the performance on a shorter cycle.

The B–value can be considered a lumped vapour capacity which is always in equilibrium with water vapour in the space within the room. In our system, the element of delay caused by diffusion within the material is approximately compensated by choosing a B–value matching the typical cycle of water vapour production. This will be the daily cycle for measuring buffering in a bedroom, to calculate if the sleepers can keep the windows closed without causing condensation on the glass. For kitchens, a lower B–value should be chosen to match the short but more frequent periods of vapour generation.

We present the B–value as suitable for simple calculations to estimate the climate in a room, dependent on moisture movement through gaps in the envelope and internal production but ignoring as relatively negligible the moisture diffusing right through the outer wall. Simonson ([7] page 48) describes significant buffering of intermittent moisture production in a bedroom with permeable walls and an air exchange rate of less than 0.1 per hour, compared with the same room with walls covered by plastic. At 0.5 air changes per hour the difference disappears. It is not clear, given the short period of experimental humidification and the variable outside conditions, whether the good performance is from transmission of moisture right through the wall, or is caused by buffering by the materials close behind the inside surface.

Discussion

The clear winner in buffer performance is unfired perforated brick. This is a material in large scale production as an intermediate stage in the making of brick. The energy used to dry the unfired brick is derived from the waste heat from the firing process. A small proportion of unfired brick can be removed from the production line before firing without disturbing the normal production process or its energy efficiency.

The unfired brick was exposed in several variations. The performance of the perforated brick was instructive because it showed the importance of air flow to the buffer performance. In a real building the airflow is not enough to exploit the extra surface area provided by the perforations. Slow diffusion of moisture from the air to the brick surface severely limits the performance of entirely passive buffer schemes. This is why buffering is effective in archives which have an enormous surface area of paper exposed to the room air and a low air exchange rate.

Measurement of the buffering effect in houses and exhibition spaces is difficult because the air exchange rate must be measured, as well as vapour production by people. Continuous measurement of air exchange requires constant measurement of concentrations of tracer gases emitted at a constant rate into the room air. This makes it a research project rather than a routine measurement to supplement the commonly measured temperature and RH [8]. Carbon dioxide can be used as the tracer gas but its rate of generation by people is inconstant, and requires continuous counting of people in the room. The measurements we do have suggest typical air exchange rates in houses between 0.5 and 1.5 per hour.

The effectiveness of humidity buffering of the indoor climate can be estimated by considering a typical room, with walls lined with perforated unfired brick. A room, 5 x 4 m, has a wall surface to volume ratio of 0.9, but corridors and small rooms bring the ratio to about one for a typical dwelling. Assuming a typical air exchange rate of 1 per hour, a room with internal wall cladding of unfired brick, with a B–value 27 m for the 24 hour RH cycle will have a virtual volume 28 times its actual volume and therefore an effective air change rate of 1/28 per hour, so it will take about a day to equilibrate with the outside water vapour concentration. If there is little convective air circulation, however, it takes only about 10 hours for the RH to approach equilibrium with the outside water vapour concentration. A room with a B–value of 10 will provide significant buffering of the daily production of vapour from within the room and release this through ventilation. Plain surfaces, even of strongly absorbent materials such as wood cut across the fibre direction (B = 15), have poor buffer capacity against a 24 hour RH cycle, so the full wall area needs to be used.

Bathrooms and kitchens are subject to high moisture flux which will cause condensation on non-absorbent surfaces. The unfired brick will absorb the condensate, preventing dripping. The moisture will move rapidly within the brick through capillary processes which are insignificant at the moderate RH of these tests. The performance of unfired brick in kitchens and bathrooms, where transient high RH is likely, will be much better than the B–value predicts. However, a large amount of condensate will damage the clay buffer.

The long period performance will be less sensitive to air movement. This study was undertaken with the hope of improving the performance of museum stores and archives, which have both a low air exchange and little internal moisture generation. The increase in B–value at low temperature makes buffering of cold stores very effective. It also enhances the resistance to RH variation in stores which are only slightly warmed in winter to keep the annual average RH lower than that outside, as illustrated by the Suffolk Record Office.

Over a longer cycle period the B–value increases but the influence of the air exchange rate comes to dominate the indoor water vapour concentration, since the B–value does not increase proportionately with the number of air exchanges. Nevertheless, the Suffolk Record Office needs only a B–value around 200 provided entirely by its content rather than by its structure, assuming an air exchange rate about once per day (this has not been measured and the building is now air conditioned). To provide this degree of stability to a store for large and non-absorbent objects, such as railway engines, is barely practical, since it would require a surface layer of perforated brick 100 mm deep covering about 1 m^2 per cubic metre of volume. However, less effective buffering would still be useful because the influence of infiltrating air can be partly compensated by semi-active climate control: pumping air into the building during periods when, by chance of the weather, the outside vapour concentration is suitable for driving the inside RH towards the set point. This principle has been applied to the Arnemagnæan archive of Copenhagen University. [2]

For museum exhibitions, there is no inherent buffering, because most exhibits are in showcases and exposed exhibits are often varnished. The flux from internal water vapour sources cannot be calculated, without good data for visitor numbers and length of stay. At present therefore, it seems that passive buffering of large and popular exhibition spaces is not practical, but buffering of small galleries with relatively few visitors against the human moisture flux is likely to be effective, preventing a high RH developing over the short period the museum is open.

Hybrid climate control methods

In heavily populated exhibition rooms where mechanical ventilation is necessary to exhaust foul air one can use moisture and heat exchangers in the ducted air flow. These work by moisture diffusing through a porous membrane between opposing streams of air, driven by the concentration difference. In winter this can be advantageous because moisture generated by people can be recycled into the relatively dry incoming air stream simultaneously with the cold outside air being warmed by heat exchange across the same membrane. This will keep the indoor water vapour concentration above that outdoors, which is usually necessary to avoid a low RH. In summer, in a non-air conditioned building there will usually still be an excess of water vapour indoors, because of human activity, so the exchanger will not help. These passive devices equalise the water vapour concentration between air streams. It is however possible to pump water vapour preferentially into or out of a building by using a discontinous process based on the fact that the equilibrium moisture content of materials depends on the surrounding RH nearly independently of the temperature. If moisture is absorbed at low temperature into the material it can be released into a high temperature air stream which is at a lower RH *but at a higher water vapour concentration*, thus drying the material and enabling it to dehydrate the low temperature air stream once it has been cooled back to the lower temperature. Even if the water vapour concentration is always greater in the high temperature air stream, it is still possible to remove water from the low temperature stream.

Low energy climate control of populated exhibition spaces will surely evolve into a combination of methods. Passive buffering will absorb the daily pulse of heat and vapour from visitors but will not have the capacity to keep temperature and RH at the optimum values for long. The push towards the desired climate will come from ventilation when the outside air is at a suitable temperature and water vapour concentration, supplemented by solar powered dehydration or hydration with a daily cycle of operation. Heat pumps will supply the necessary heating and cooling.

Conclusion

The moisture buffer capacity of unfired brick, used as a wall material, or wall cladding, is sufficient to moderate the course of the RH in a house, as it is influenced by water vapour released by humans breathing, cooking and washing and by infiltrating outside air. The resistance to RH change caused by infiltration can be calculated from the air exchange rate, the outside water vapour concentration and the buffer value of the moisture-reactive components of the room walls and furnishing.

For specialised buildings such as archives, there is already evidence from existing buildings that humidity buffering by the stored paper is capable of ensuring a steady RH through the year, provided the air exchange rate is held below about once per day. This allows a considerable simplification of the air conditioning in temperate climates, using winter heating to a fixed temperature. For buildings holding non-absorbent material, wall cladding of unfired brick will not alone ensure a stable RH throughout the year but will be useful when combined with intermittent ventilation with outside air when, by chance, it is of suitable water vapour concentration to drive the inside space towards the set point. One can also envision climate control by solar powered dehumidification during the summer, with the winter climate controlled by buffering of both temperature and RH.

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Appendix A: measured values

The entire sequence of measurements is shown, unedited, in figure 14. Note that the weight is here shown as diminishing with increasing RH. This is because the weight change recorded is that of the water in the reservoir rather than in the specimen.

Figure 14: Unedited climate data from the experiment.

Appendix B: the climate chamber

The climate chamber is shown in figure 15. The annular temperature control system is shown in cutaway in figure 16. The flux control device is shown in figure 17 and explained in figure 18. Normally, the top is closed with an airtight stainless steel lid and covered with 200 mm of wool insulation.

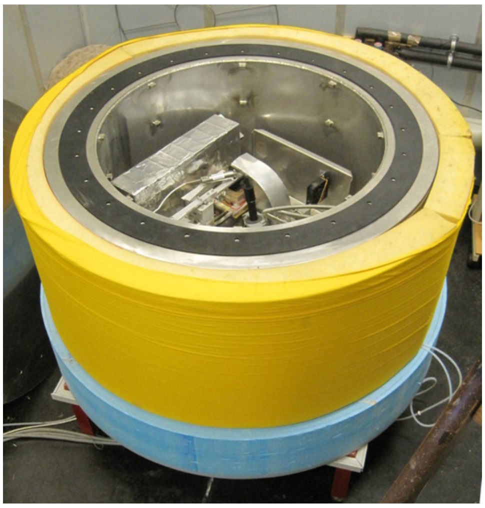

Figure 15: The buffer measurement chamber with lid removed, showing the ventilated brick test specimen and the top of the flux generating apparatus. The inner cylindrical space is 793 mm diameter, 500 mm deep.

The chamber climate is managed and measured through a computer program written in Python, running on a PC with Debian Linux operating system. This program controls a Hewlett Packard programmable data control and acquisition unit which in turns operates various valves and relays to govern the operation of the chamber. For this experiment the chamber had a controlled RH, with feedback from a dew point sensor. The chamber can also operate by controlling the water vapour flux, measuring the RH as a consequential value. It is clear from figure 14 that there was intermittent instability in the RH control.

This is a slightly modified version of the apparatus described in detail by Padfield et al. [1]. The complete description of the apparatus is given in [9]

The sorption experiments were made in an apparatus which mixes a wet and a dry air stream within a chamber held at constant temperature. The specimens are suspended within the chamber on an automatic carousel which drops each specimen in turn onto a hook suspended from an external balance. The chamber need not be opened during the process, so cyclic RH steps can be applied with complete assurance that there is not a moment of exposure to an unregulated RH. The instrument is shown in figure 19.

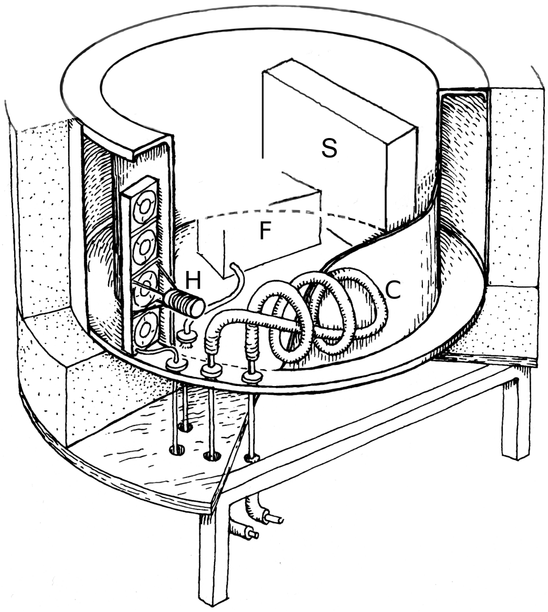

Figure 16: The chamber temperature is controlled by air blowing around the annular space. The electric heating element is marked **H**, the water cooling is marked **C**. Both heating and cooling are switched by the computer program. The flux generator within the inner chamber, **F**, is also supplied with cooling water to its heat exchanger. A fan blows air over the specimen **S**.

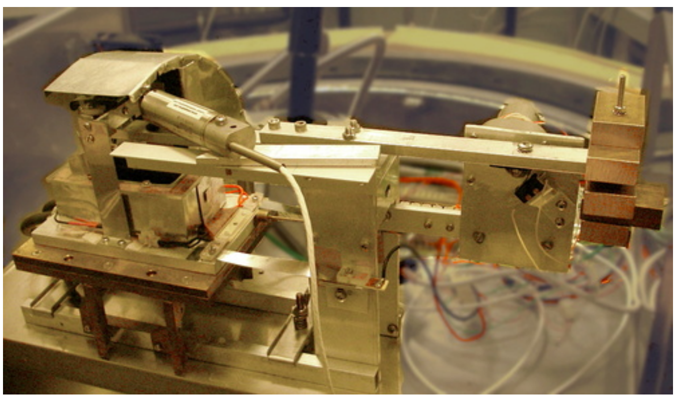

Figure 17: The flux generator. See figure 18 for the explanation.

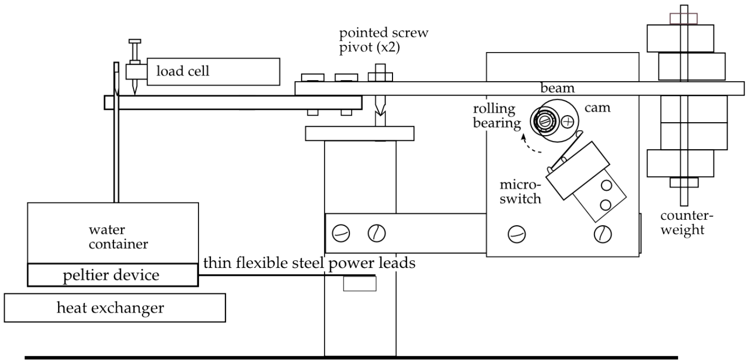

Figure 18: The flux generator heats or cools the water reservoir on the left, alternately evaporating and condensing water. The weight of the full reservoir is just overbalanced by the counterweight at the other end of the beam, which is pivoted in the middle. In normal operation, the raised cam tilts the beam so the reservoir rests on the heat exchanger, which is held at 2 degrees above the chamber dewpoint. At one minute intervals, the chamber fans are stopped and the cam rotates to release the beam to rotate freely up against the load cell which is placed close to the knife edge holding the reservoir. Flexible stainless steel strips supply current to the Peltier elements which control the water temperature in the reservoir. The reservoir is suspended slightly off-centre, so the strips are under slight tension, which keeps the reservoir level during weighing. Various adjustments to the bearing points and to the counterweight blocks allow the beam to be balanced so that the exact tilt has no influence on the weighing process.

Figure 19: The sorption measuring device. Finely divided specimens are loosely packed in polyester mesh bags which are suspended from a carousel which rotates them in turn to be hooked to a rod, connected via a briefly open tube to a balance mounted out of sight above the picture. The climate is controlled by mixing two air streams, one saturated, the other dry. The entire assembly is held at a constant temperature in a double enclosure.