4

EXPERIMENTS IN THE FLUX CHAMBER

Introduction

The flux chamber was used to measure the ability of materials, and combinations of materials, to buffer the relative humidity of an enclosure against the effect of a varying flux of water vapour.

The usual procedure was to evaporate about ten grams of water into the chamber air and then withdraw it again in a sinusoidal cycle of, typically, one day's duration. If the chamber were empty, this flux would cause the relative humidity to cycle between about ten and 90%. An absorbent material within the chamber will diminish the amplitude of the relative humidity cycle because there will be a redistribution of the water between the air space and the material. A material with a steep sorption curve, that is with a rapidly increasing water content with rising RH, will absorb much of the water released into the air and thus prevent the RH from varying much.

The other factor that influences the chamber RH is the permeability of the material: if it is very permeable it will be more effective in buffering the RH as water is injected into the air, because the storage capacity of a greater thickness of material will be available to buffer the RH.

A relatively minor influence on the chamber RH is the resistance to water vapour transfer of the boundary layer of air right at the surface of the wall.

The cyclic variation in RH measured in the chamber during the flux cycle is an expression of the combined porosity and absorptive power of the material, or assembly of materials, in the test wall. These two independent factors can be separated, in principle, by running the experiment with different cycle times, because the absorption curve is independent of time.

A complicating factor is the RH dependence of both the absorption and the permeability. This can in principle be studied by increasing the amplitude of the applied flux cycle or, more simply, by running several successive flux cycles of small amplitude, starting from a higher or lower average RH value.

A further complication is that there is some evidence that the permeability is time dependent when the flux is varying.

There are experimental limitations to the cycle time, the flux amplitude or the mean chamber RH. The flux generator has a limited ability to withdraw water vapour from the chamber. The chamber has a small leak rate to the room which limits the cycle time to about five days. The dew point detector has a 15% RH lower limit and the RH sensors that were embedded in the test walls are imprecise below about 25% RH. Finally, at high RH the surfaces of the walls and equipment in the chamber begin to compete with the absorption by the test wall. These practical limitations are discussed in detail in chapter 2.
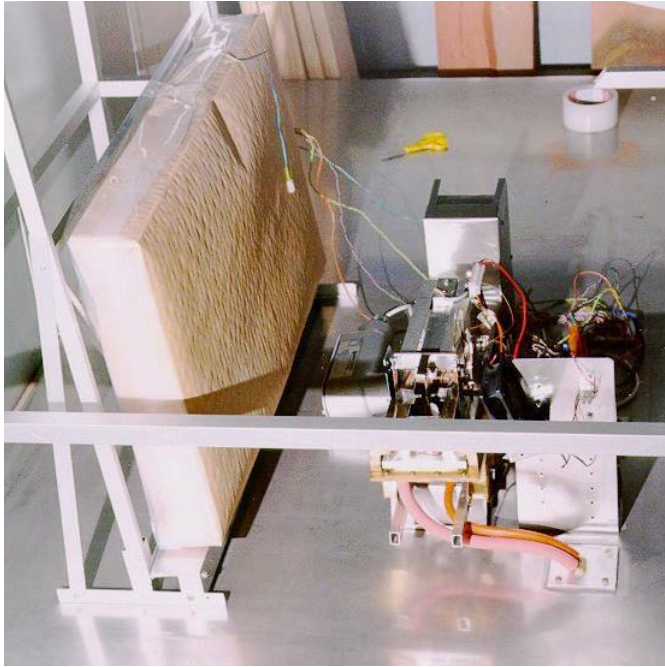
Construction of the test wall

Figure 4.1 The interior of the chamber. The air conditioning assembly is on the right. On the left is the material under test: in this example it is wool insulation faced with vapour retarding paper and backed by aluminium foil and polyethylene film. The wires leading to RH sensors within the wool can be seen entering the far edge of the experimental wall. One of the small resistive sensors is seen dangling in front of the face of the assembly.

All the test materials are put into the chamber as walls, tilted slightly back to allow safe stacking of the individual pieces without any binder.

The ratio of surface area to chamber volume was chosen with care. A vast area of very absorbent material will absorb a large flux without the RH of the chamber changing by an amount that can be measured with precision. A small area of poorly absorbent material, on the other hand, will allow the same water flux to swing the RH to such extreme values that the results will be spoiled by the water absorption of the materials that the chamber itself is built of. A standard flux and exposed area of material would allow rapid visual comparison of the performance of the various materials. Finally the chamber should imitate a plausible combination of material area, air volume and water production in a dwelling, so that the graphs would show instantly if the material were of any significance as a moisture buffer.

The compromise wall area used for nearly all the experiments was about one third of a square metre of exposed surface in the 0.5 cubic metre chamber volume. The ratio was not defined exactly because some test constructions occupy more volume than others.

The back of the wall was sealed by aluminium foil and by thick polyethylene sheet. The experimental setup imitates the performance of the materials when used as interior walls of buildings, in double the quoted thickness. The performance of the outer walls, with their varying temperature gradient, requires much more elaborate equipment. In this dissertation the humidity buffering processes occuring in outer walls are illustrated by case histories from real buildings rather than by laboratory experiments. Some insulating materials were, however, included in the laboratory tests.
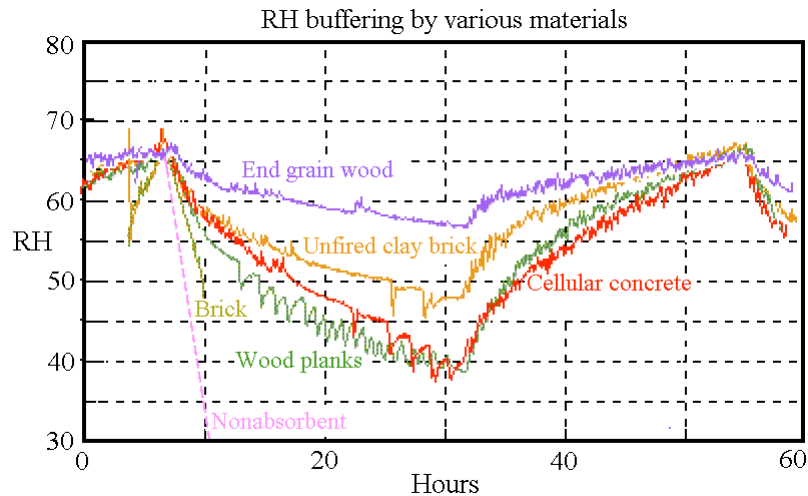
Figure 4.2 A comparison of several building materials, built as walls 0.5 m² by 30 mm thick, sealed on the back. The jagged curves are due to intermittent release of water from a condenser to the weighed water tank in an early version of the flux generator. This fault was corrected in later experiments. The curves are extracted and assembled from a series of experiments in which each material in turn was exposed to repeated cycles in which water was withdrawn at a steady rate for 24 hours and then returned to the air in the chamber at the same rate. The RH change is buffered by desorption and then by re-absorption of water by the materials.

The choice of materials for testing

The first experiments in the chamber were designed to find the order of magnitude of the buffer performance of a range of building materials. Figure 4.2 combines data from five materials, each tested separately. The materials were built as walls, 0.5 m², 30 mm thick and sealed at the back. The starting equilibrium RH for all materials was between 58% and 68%. In the graph the separate experimental curves have been superimposed so that they all start at about 65% RH, for easier comparison.

Water vapour was withdrawn from the chamber at a steady rate that would bring the empty chamber from 100% to 0% RH in twelve hours. The theoretical curve for the empty chamber is shown as the steep dotted line descending at the left. Brick is not much better at giving out moisture to buffer the fall in RH than a totally nonabsorbent material. Brick is quite porous and becomes quite absorbent at high RH but at these moderate values it has hardly any water absorption. Wooden planks are surprisingly bad at buffering the RH. This is because they have a very low permeability to water, though the water capacity is high. Cellular concrete has a moderate buffer capacity. Its permeability is high but its capacity is not great: notice how the curve is straightening out as it crosses the curve for wood towards the end of each leg of the cycle, indicating that its capacity is becoming exhausted, while wood still has a water reserve available which is being drawn out by the high RH gradient at the surface. Unfired clay brick is much superior to burnt brick as a humidity buffer but the best buffer of all is wood cut across the grain so that the high permeability in this direction can release the high water capacity of the wood.

Other materials and combinations were tested in later experiments but the set described above covers the range of observed buffering by massive materials. One absorbent

insulator, wool, was also tested. It has a high permeability and high water capacity per kilo but the density of wool insulation is so low that it has a limited buffer capacity in practice.

In real life the surfaces of these materials exposed to an inhabited room would be decorated and protected against becoming dirty unreasonably quickly. These finishes increase the surface resistance to moisture movement and suppress expression of the behaviour of the material behind. The use of moisture barriers or retarders in outer walls also prevents absorbent materials from influencing the indoor climate. The performance of lime and gypsum plaster and vapour retarding paper was studied but paint was not included in this study.

Reporting the results

The experimental settings changed according to the material. In particular the position of RH sensors within the material varied from wall to wall, according to thickness and layer structure. For this reason I have abandoned the traditional separation of experimental results from discussion of their significance. The structure, behaviour and performance of each material or assemblage is discussed in turn, in a qualitative way, at the point where the experimental curves are shown. Then there is a page summarising the test results for all the single materials, exposed to a daily cycle. In the next chapter selected data from this catalogue of buffer materials are discussed in more detail. Exact values of sorption and diffusion coefficients are given. Finally the experimental results are compared with results from computer models.

The typical flux cycle

The left half of the graphs in figure 4.2 shows the course of the climate within the chamber during a linear withdrawal of water vapour into the water tank, while the second half shows a corresponding return of water vapour to the chamber air. Most of the graphs reported in this chapter were, however, obtained with a sinusoidal variation in flux.
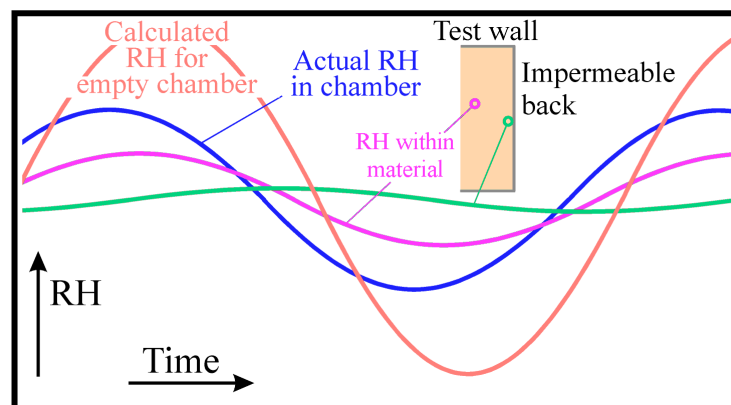

Figure 4.3 An explanation of the typical appearance of the graphs in this chapter. The widest cycle is the RH calculated from the flux acting in the empty chamber. The next curve is the measured RH. The shallower curves show the RH in cavities hollowed out in the experimental wall.

This provides data that can be studied by models based on an electrical analogy. On a more mundane level, it is much easier to control a sinusoidal variation in flux than the sharp change of flux at the points of a triangular waveform.

The flux cycle imposed on the chamber was usually chosen to give a nearly 100% RH swing over one day in the empty chamber. This basic daily cycle imitates the daily rhythm of both climate and human activity, but runs were also made with longer and shorter cycles to provide data for the computer simulations designed to separate the influences of absorption and diffusion. In these runs the flux was usually adjusted so that the maximum rate was the same, regardless of cycle time.
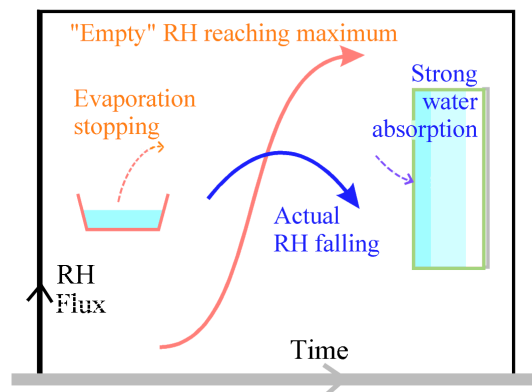
Figure 4.4 An explanation of why the buffered chamber RH cycles up and down in advance of the RH calculated for the empty chamber. In the diagram the cycle of the chamber climate has been frozen just as the weight of the water reservoir reaches its mimimum. This, in the empty chamber, would coincide with the maximum RH. However, the flux has been slackening for some time before the peak RH is reached, while the absorption of water vapour into the test wall is still strong, because of the still relatively high, though diminishing, RH in the chamber. The absorption rate into the material exceeds the slackening flux well before the top of the "empty" RH curve, so the buffered RH is already on the way down before the calculated "empty" RH reaches its peak.

The RH measured within the material lags behind the chamber RH, as expected, because of the relatively slow diffusion of water into the depths of the wall.

In nearly all the graphs in this chapter the imposed flux cycle is presented in the form of the expected RH in the empty chamber. It is always the most extreme fluctuation. The observed, buffered RH in the chamber is the next in amplitude. A comparison of these two curves gives an immediate visual impression of the ability of materials to moderate relative humidity. The RH at various depths within the test wall is often shown in other, shallower, curves. Without exception the deepest RH shows the smallest amplitude.

Most of the graphs show just one daily cycle, after the system has settled to a steady rhythm. Sometimes, however, the approach to the steady cycle reveals interesting details of the process, in which case more cycles are shown. Usually the hours elapsed from the beginning of the experiment are shown on the horizontal axis, even though only one day's data is shown.

The daily cycle is the most relevant. Passive humidity buffering by wall materials in ventilated buildings cannot overcome the influence of the outside climate in the long run, which means about a week. The response of materials to two and four day cycles is, however, displayed in some graphs in this chapter, because it shows up the different performance of materials according to whether they have a high water capacity or a high permeability.

Accuracy and precision of the measurements

Contrary to received wisdom, the dew point sensor that measured the chamber RH was less reliable than the resistive RH sensors embedded in the materials under test. Wood products, in particular, release easily condensable vapours that deposit on the cold, damp mirror of the dew point sensor. The indicated RH could rise by 4 percent over the two or three weeks required to make a test in the sealed chamber. The mirror was cleaned and the calibration checked each time the chamber was opened. Even so, a detailed comparison of the chamber RH with the RH within the material is not really possible. This experimental problem points to a fundamental problem with the use of building materials to moderate indoor relative humidity: the slow ventilation rate that is necessary for them to function increases the concentration of pollutants outgassed from the materials. This is a serious problem in museums as well as in climate chambers, because the water soluble materials that cause a high indicated dew point on the chilled mirror are precisely the chemicals that absorb water and facilitate the corrosion of metals.

Fortunately, the resistive RH sensors used within the test material, and sometimes as a check on the dew point drift, proved very robust and extremely sensitive to small changes in RH, which is all that ever happens inside good moisture buffers. The combination of the accuracy of the clean mirror dew point measurement with the reliability and sensitivity of the resistive sensors ensures the overall good accuracy of the data.

The sensors buried within the wall occupy a space about 10 x 15 x 5 mm deep. The cavities enhance the diffusion of water vapour while the sensors obstruct it. The sealing in of the sensors also leaves cracks and inhomogeneities that are not typical of the material as a whole. The signals from these sensors cannot therefore be assigned to a precisely defined depth in the specimen.

The assumption of constant temperature is not quite true. Rapid changes of flux cause warming, or cooling, of the experimental materials through the heat of vaporisation of water. Temperature changes of up to half a degree were measured in some experiments deliberately run with high flux. These small, temporary temperature differences account for some anomalies in the fine structure of the observed RH within specimens, but the assumption of constant temperature does not introduce significant errors in interpretation.

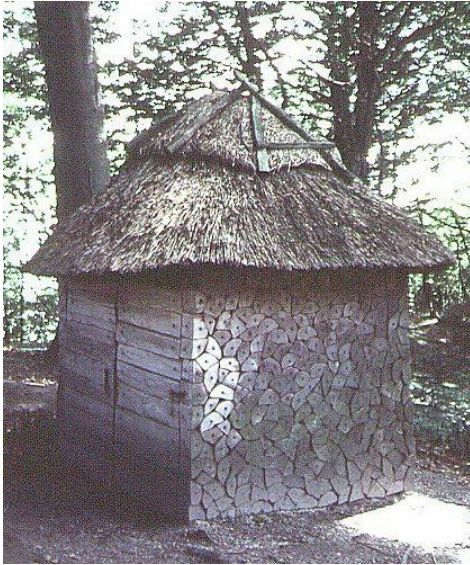**The buffer performance of wood cut across the grain**

Figure 4.5 A small shed in the eighteenth century pleasure garden at Liselund on the Danish island of Møn. Sadly, the end-grain wooden wall is a sham: thin slices are nailed onto planks.

The catalogue begins with tests on wood used in an unusual way, emphasising the unused potential in common materials.

A panel was made of many blocks sawn from a plank of Norway Spruce, *Picea abies*. These were stacked with the cross section facing into the chamber. The exposed area was 0.33 m^2 and the depth was 30 mm.

Figure 4.6 A block of end grain wood with a thin slice removed so that a small RH sensor could be placed in a cavity in the wood.

One block had a 3 mm slice sawn off it. Under this a hole was bored to take a small RH sensor. The slice was replaced over the sensor and the block was then glued in a group of seven blocks, one of which had a similar hole bored in the back. In this way the RH was measured at approximately 3 mm below the surface and at the back, about 20 mm behind the surface. The blocks rested against a plate of aluminium.
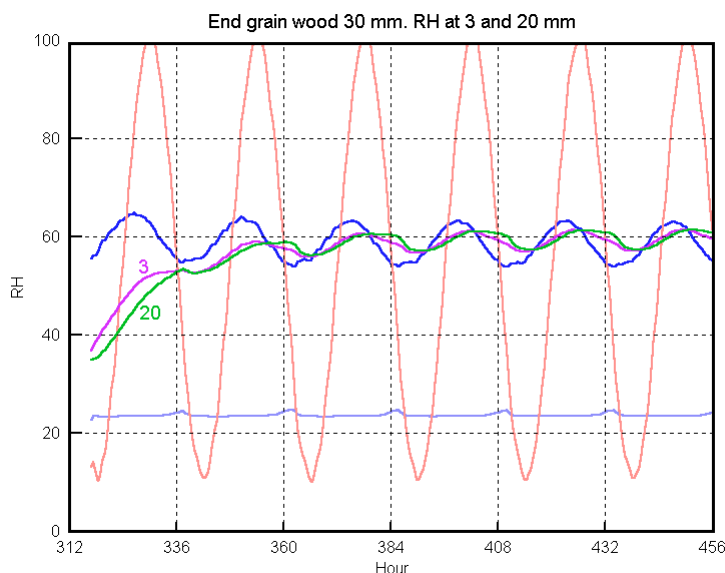
Figure 4.7 The approach to equilibrium of end grain wood blocks, 30 mm thick. The RH at 3 mm below the surface and at 20 mm rises steeply from the initial wood equilibrium at about 38% RH. The chamber RH is correspondingly dragged down a little as it loses water to the wood.

Figure 4.7 shows the first six daily cycles for the panel. The good stabilisation of the relative humidity is immediately noticeable. The 90% RH swing of the empty chamber is reduced to 10%. The curves for 3 and 20 mm behind the surface are delayed and of lower amplitude but are close to each other. This pattern cannot be exactly reproduced by a model based on Fick's law, however much one varies the three parameters: sorption, diffusion and surface resistance. The matter is taken up in the next chapter.

Note that the chamber RH is the result of the interaction of wood and air. The RH cycle shows a descending tendency because the wood withdraws water until the two phases, wood and air, are in equilibrium, averaged over several cycles. This is the important difference between the flux chamber and the usual environmental chamber which controls the RH. It is important to bear in mind that the RH cycle is not controlling the moisture absorption of the wood: the chamber space and the wood are exchanging water in an attempt to come to equilibrium with each other. The flux cycle forces a continual disturbance of this equilibrium by supplying water to the air, or by withdrawing water.

The curves for the RH within the wood are not truly sinusoidal. This is because of the disturbance in the temperature at times when the flux generator was working hard at condensing water from the air. The heat generated during this process overcame the temperature controller. This fault was corrected in later experiments.
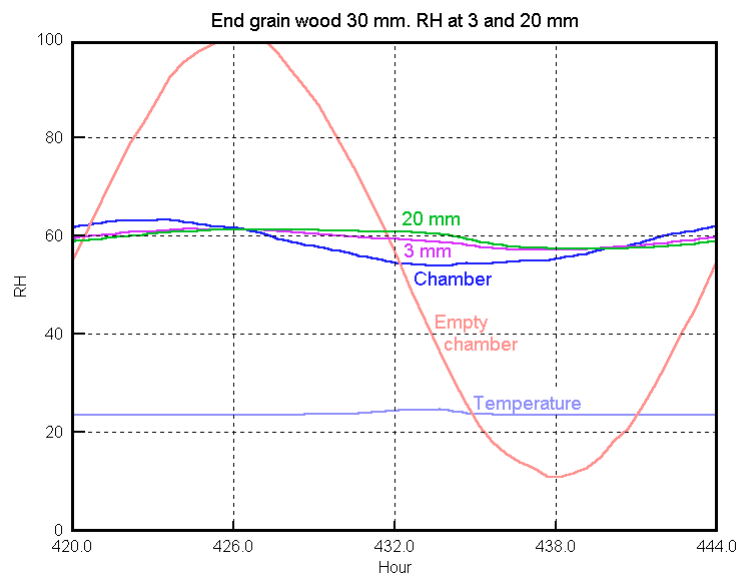

Figure 4.8 A single day cycle for end grain wood.

Figure 4.8 shows a close up of one cycle from fig.4.7. Notice the very good stabilisation of the chamber RH. The wood is exchanging water throughout its entire thickness, as shown by the green curve for the 20 mm RH following closely after the curve for RH at 3 mm. This indicates very fast diffusion of air through the wood. It also hints that absorption of water into the wood substance must be rather slow.

The entire thickness of the wood is in play. The 30 mm thickness of this wooden panel is therefore usefully employed in buffering the daily cycle of humidity in a house. A thicker layer would be even more effective. A ceiling made from tiles of wood cut across the grain would form an excellent humidity buffer. End grain wood is used for flooring but it rapidly clogs with dirt. End grain wood behind a permeable protective coating would also be quite effective.
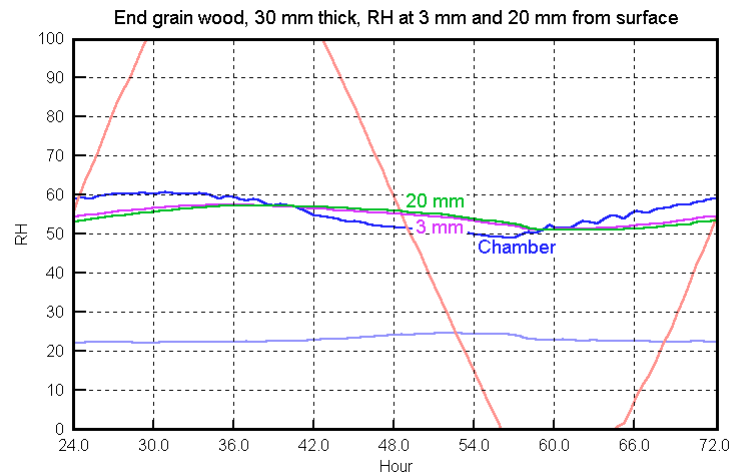

Figure 4.9 A two day cycle with double the flux amplitude.
This flux would cause condensation in the empty box but
the wood buffers the RH very effectively.

A longer cycle with double the flux amplitude would cause the RH in the empty chamber to reach 100%, followed by condensation on the walls. The wood entirely prevents this. Notice that the RH within the wood is uniform from 3 to 20 mm and the amplitude is close to that of the RH in the chamber. The phase delay is about 0.2 cycles. At this cycle time a greater thickness of wood would give better performance. The flux is "seeing through" the wood.

End grain wood is the most effective buffer for relative humidity among the materials tested. It is not, however, without defects. End grain wood panels are physically weak and expand and contract as they exchange water vapour with the air. The wood outgasses numerous organic chemicals. One of the most abundant, acetic acid, is corrosive to the base metals, lead and zinc. The cocktail of chemicals within the wood does, however, make it resistant to fungal growth, so end grain wood would work well in a bathroom to absorb the intermittent flux of steam from the shower. The brief period of raised, but still moderate water content as the wood first absorbs and then releases water vapour will not cause fungal growth, whereas intermittent condensation on non-porous surfaces will eventually result in mould growth.

Wooden planks

A wood surface cut parallel with the cell direction reacts to the water vapour flux much more slowly than does end grain wood. Diffusion across the cell direction is about ten times slower than diffusion along the cell direction. The buffer performance of the wood is now limited by the diffusion rate. Only a thin surface layer is effective in buffering the daily cycle.
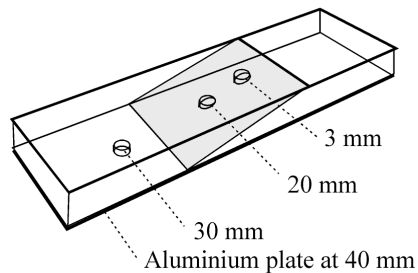

Figure 4.10 The RH sensors within the wooden planks were installed in shallow holes drilled into a very oblique section. The thin wires were led parallel to the surface to the edge of the plank, to minimise movement of air bypassing the hard route through the solid wood.
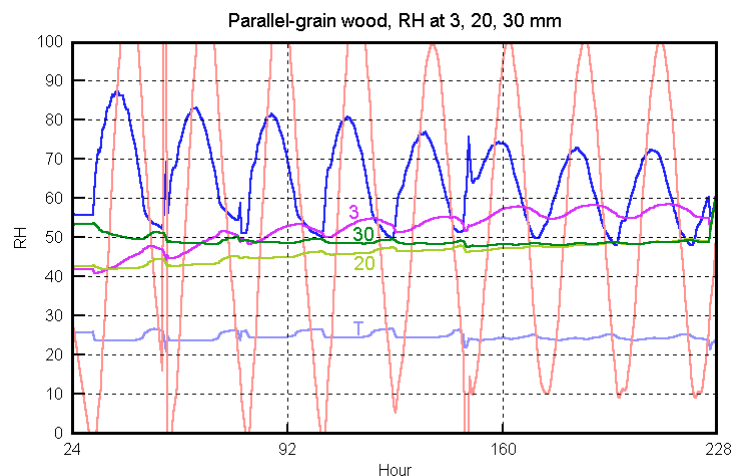
Figure 4.11 The initial cycles for wooden planks. The flux amplitude was changed at the fourth cycle.

The messy start to this graph is quite informative. It shows how slowly the inside of the plank reaches equilibrium The sensors inside the plank were installed in a room at about 40% RH. The sensor at the back of the plank, however, was installed at the last minute in the more humid room containing the experimental wall. At the beginning of the run the back sensor slowly fell in RH as it came to equilibrium with the low RH of the middle of the plank. Meanwhile the middle of the plank was slowly absorbing water from the front, exposed to the relatively humid chamber. The sensor at 3 mm took about 8 days to come to equilibrium with the chamber. During this time the chamber RH showed a steady fall in its mean value as it lost moisture to the wood. After 8 days the interior of the wood was still far from equilibrium with the chamber RH.
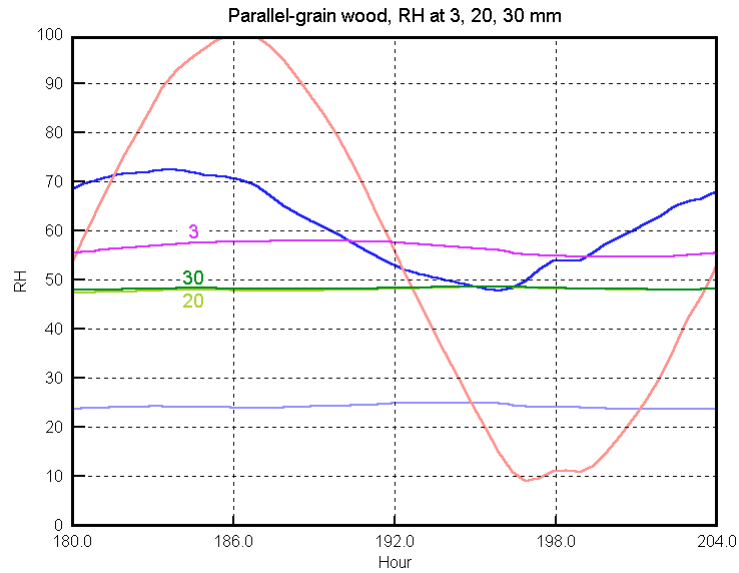
Figure 4.12 A single day extracted from figure 4.10. The interior of the wood is far from equilibrium and not at all affected by the daily flux cycle in the chamber

The contrast with the behaviour of end grain wood is very striking. The buffer capacity is very moderate. The sorption curve is of course exactly the same as that of end grain wood but the diffusion is so slow that only the outer few millimetres are engaged in reacting to the daily flux cycle. The slow diffusion of water vapour through wood means that it actually behaves as a vapour barrier to the daily flux cycle, while allowing the yearly cycle to reach right through it.

Clay tiles

Figure 4.13 Panoramic view of Shibam in Yemen. Unbaked earth bricks are used to build up to eight storeys. Photo: Pia Olsen
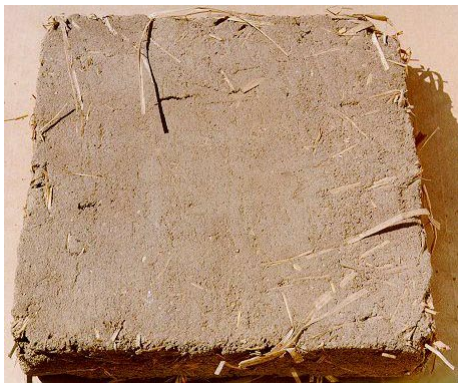
Figure 4.14 Unbaked clay tile made from moraine clay, glacial sand and straw. The clay was pressed into a mould 200 x 200 x 40 mm. The dry tile is approximately 190 mm square.

Sand bound with clay is still the world's commonest building material, but it is not the subject of very much academic research. The tiles made for this experiment were a typical earthy mixture of moraine clay, sharp sand and rounded sand, from Stenlille in Zealand. The clay sand mixture was adjusted to the right consistency for building according to the stickiness as measured by a naked foot stamping the plastic mixture. Straw was added until the mixture became too stiff to mix. It was then pressed into a wooden mould, 200 x 200 x 40 mm (the only precision measurement in the exercise) and turned out to dry in the open for two days before a further maturing period of four weeks indoors. The tiles are a lean mix, coherent enough for building but with less clay than the mixture could hold without excessive shrinkage.
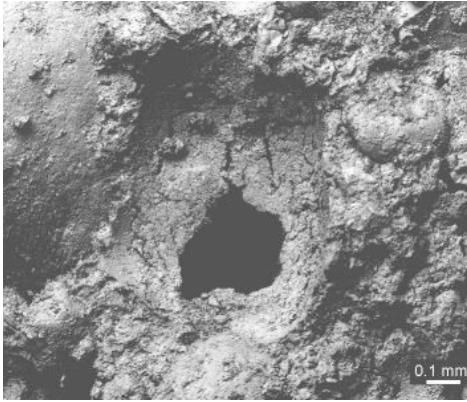
Figure 4.15 SEM picture of a broken surface of a mud brick. In the centre is the smooth depression where a sand grain has pulled out, leaving a thin wedge of clay and a void behind. The shrinkage cracks in the clay give the porosity that allows good humidity buffering. The close contact between sand grains gives good resistance to shrinkage. This is a good building quality but less than ideal as a moisture buffer. Photo: Ulrich Schnell.

Holes were dug in one of the tiles, from the back. RH sensors were inserted and sealed with plugs of nearly dry clay set in a wet clay mortar. This is why the start of the experiment shows very high RH for the enclosed sensors. It takes over a week for these sensors to come to equilibrium, although a minimum of water was used to dampen the tile so that the mortar would seal the cavities well. This hints at a buffer performance
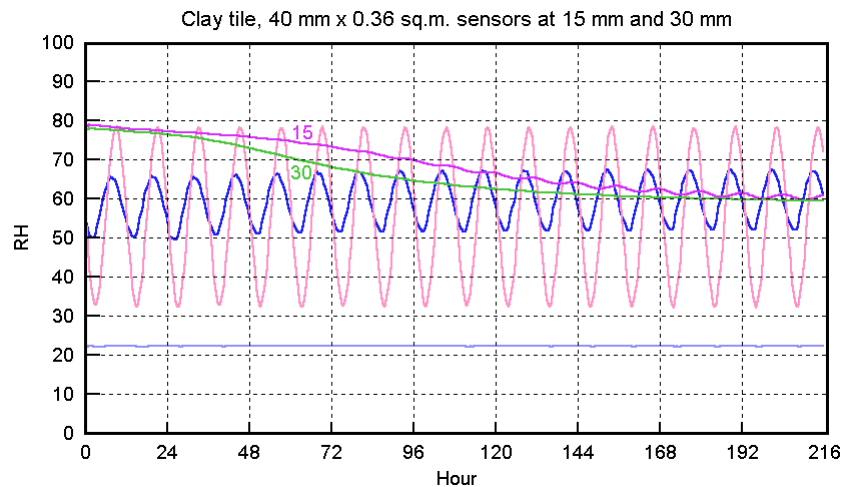
Figure 4.16 The first cycles for clay tile. The cycle time is 12 hours. The built in sensors start at a high RH because a wet creamy clay mortar was used to seal the cavities containing the sensors. The deep sensor comes more quickly to equilibrium because less water was used to install it. Notice how the average chamber RH rises as the clay dries

limited by the permeability of the material. The shallowest sensor is at 15 mm. This is because the coarse structure of the clay would give very untypical results if the sensor were placed at the 3 mm depth used in the experiments on wood.
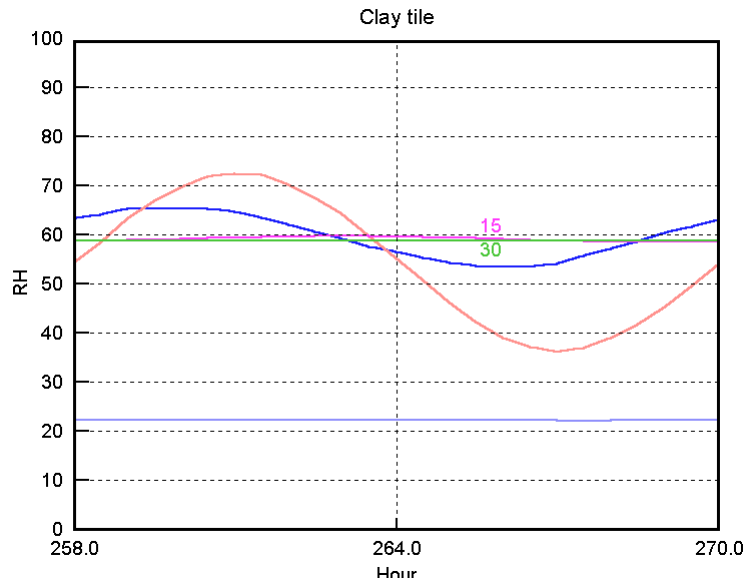
Figure 4.17 A single 12 hour cycle from later in the experimental run whose start is shown in figure 4.16. The buffering is moderate, even though the sensor at 15 mm is scarcely reacting.

The diagram for the single cycle shows that the buffering is moderately good but is only engaging the outer layer of the tile. The sensor at 15 mm is hardly reacting at all to the twelve hour cycle. The efficiency of the buffering at this short cycle time is limited by the resistance of the boundary layer.
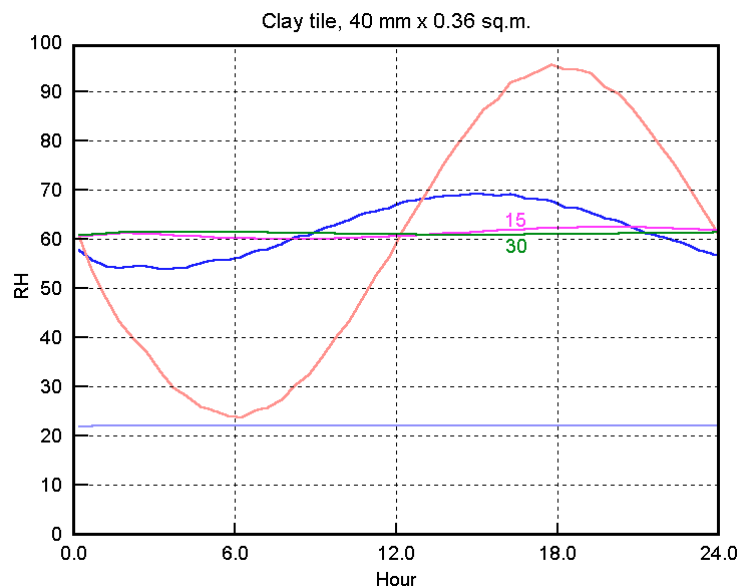

Figure 4.18 The daily cycle for clay tile. The buffering is good, in spite of the very slight engagement of the material in depth.

The daily cycle also hardly stirs the deeper layers, although the buffering is good. The clay performance resembles that of the wood planks: the water reserve is there but it is not readily available to moderate the daily cycle.
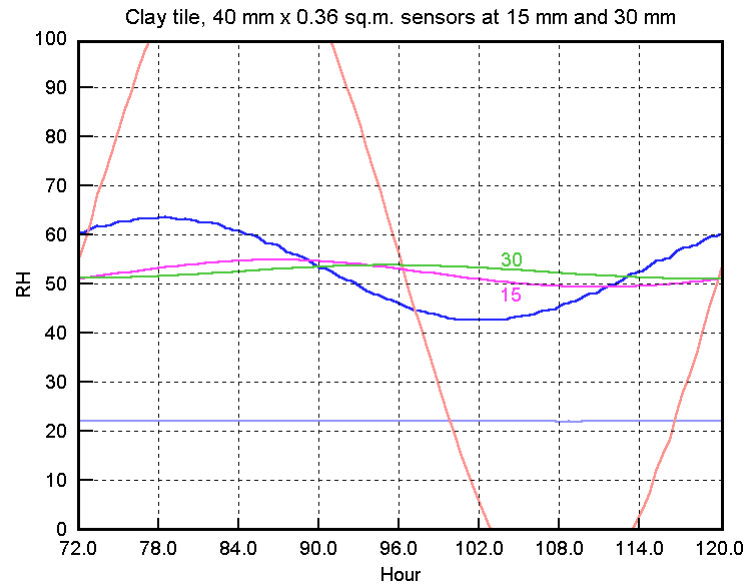
The next diagram shows a two day cycle.

Figure 4.19 A two day cycle does reach down to the back of the clay tile.

The two day flux cycle does stir the deepest layer of the clay tile. The optimum thickness for effective buffering of the daily cycle is about 20 mm. This amount of clay can certainly be used as a plaster over a brick wall, as a substitute for gypsum or lime plaster, which have very little buffer effect, as later graphs will show. The clay tiles used in this experiment were friable and not immediately useful as an interior finish but a combination of clay tile with a thin porous covering of gypsum or lime, maybe in the form of a fresco painting, would be an interesting and practical interior finish.

A clay tile made specially to function as a humidity buffer

The clay tile investigated in the previous section was just a typical clay brick mixture. Mud brick is always a local product. The moraine clay was not analysed, because an exact description of that particular clay would be no help to anyone building anywhere else. Its buffering action was quite good, so it seemed worth investigating the possibility for developing a well defined clay mixture with superior humidity buffering. A 20 mm layer of such a clay could be used as an interior wall finish instead of gypsum or lime plaster, which have very poor buffering properties, as will be shown later in this chapter.

Figure 4.20 Bentonite clay (left) and Perlite grains of up to 2 mm diameter. The bentonite is 80% montmorillonite clay in very finely divided but compact form and is very impermeable indeed. The admixture of perlite opens the structure and makes the resulting tiles dimensionally stable and porous.

A search of the literature suggested that the clay with the best water absorption properties is sodium montmorillonite, in the finely divided form known as bentonite. This is a marine clay formed by the weathering of volcanic rock. Denmark has vast supplies of this clay in a homogeneous deposit extending from Lolland to Fyn.

If one takes the trouble to develop a specialised product as a substitute for an extremely common material it makes sense to look at the other ingredients as well. The requirements for a thin vertical surface layer are rather different from the requirements for a brick. The filler and dimensional stabiliser in mud brick is sand, usually quartz. This is heavy, has no moisture absorption and little thermal resistance. A replacement filler should be light and water absorbent. It should add high porosity to the mixture. One use of bentonite is to waterproof toxic waste dumps and ornamental fountains, so in its pure state it is no good at all for buffering humidity. An effective opening of the structure is essential to change it from a moisture blocker to a moisture buffer. Bentonite also swells enormously when wetted, so the filler should ideally lock its particles together better than sand to withstand the movement of the bentonite.
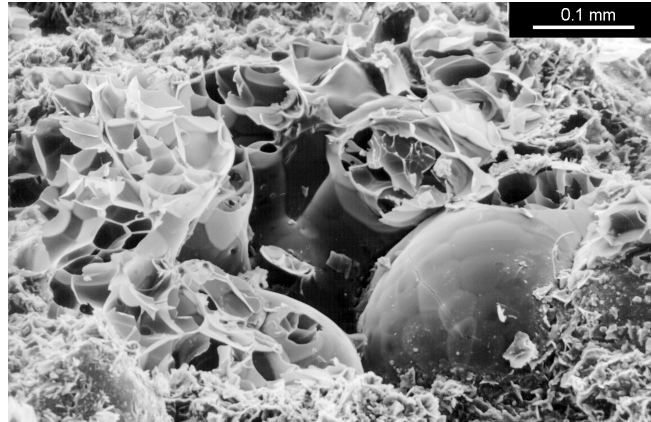
Figure 4.21 SEM picture of an agglommeration of perlite grains in a perlite - bentonite mixture. The view is about 0.6 mm across. Photo: Inger Søndergaard.
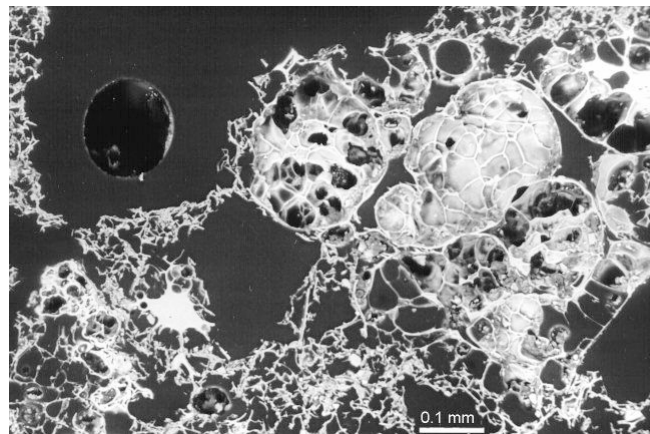

Figure 4.22 SEM image of a polished section of a similar structure to that shown in the previous figure. The clay particles form a filigree between the rounded outlines of the perlite particles. The clay content is only about one tenth of that of perlite by volume. Photo: Inger Søndergaard.

The material chosen as filler has only some of these ideal properties. It is perlite, an artificial glass froth made by heating granules of volcanic glass that contains water that originally was prevented from forming bubbles by the high pressure at the point where the glass solidified within the earth. The crushed glass is blown into a flame in a tall tube. The glass softens and the trapped water expands into steam, blowing the particle up into a frothy sphere.

The bentonite from the clay pit is a scarcely plastic, dense mass. It is first mixed with one and a half volumes of water to reduce it to a creamy consistency which can be mixed with ten parts by volume of perlite. The final mix occupies only five volumes, because the clay fills in the voids in the perlite and the mixing crushes some of the perlite. This mixture has some straw added at the last moment. A good mixer for this combination of materials is a baker's dough mixer. Finally the plastic mix is pressed into moulds and dried. The shrinkage is about 10%.

Figure 4.23 A clay tile, 180 mm square, made from bentonite, perlite and straw. A hole was cast into the tile when it was made and a plug was cast to fit the hole. The RH sensor was placed in the hole and the plug was inserted and sealed with moist clay mortar. The shallow hole is for the sensor at the back of the tile. The entire back and the sides of the tile were finally sealed with aluminium foil and polyethylene foil.

One tile was fitted with sensors at 9 mm and at 34 mm from the surface. The structure is more homogeneous than the ordinary clay tile studied in the previous section, so the sensor could be closer to the surface. This tile was then placed in the middle of a set of nine tiles which were stacked up against an aluminium back plate.

When the tile dries the bentonite component tries to shrink but is restrained by the perlite fragments. The loose glass shards and the partly crushed frothy particles form a very resistant interlocked mass which stops the tile from shrinking. The bentonite is therefore forced to take up an open porous structure, which is very difficult to distinguish from the perlite shards in a SEM picture. The individual clay particles are well below the resolution of the SEM and the chemical signature is rather similar to that of perlite. The section shown in figure 4.22 is chosen to match the structure shown in the broken surface of figure 4.21. Figure 4.24 shows a more typical area at lower magnification. This picture has been manipulated to increase the contrast and to show the solid matter in black. The structure has four components: damaged perlite particles and curved fragments, voids and an open structure of loosely stacked plates of clay particle aggregates. The intact perlite grains have closed pores and are impermeable. The humidity buffering is presumably provided by the mesh of poorly organised plates of montmorillonite.
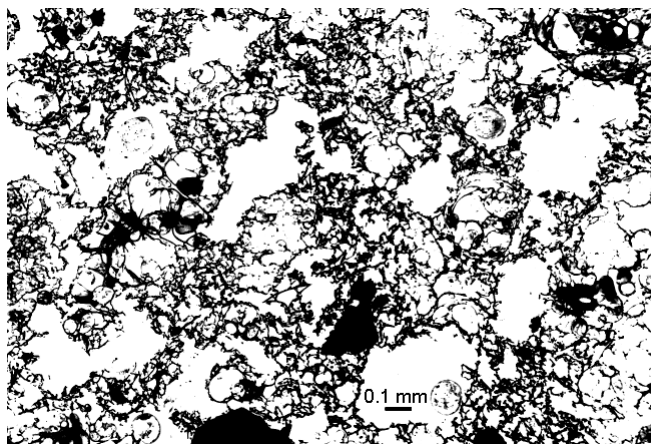

Figure 4.24 A typical section of the clay tile with solid material in black The density of the tile is 740 kg per cubic metre, about the same as cellular concrete.

.

Figure 4.25 The bentonite - perlite mixture shrinks evenly if it is not restrained (bottom). It is therefore suitable for making clay bricks but less suited to cob methods, where the clay is applied in a plastic state. A formulation suitable for plastering walls has yet to be developed.

Bentonite with perlite is not a mixture recommended by earth builders. The exceptional shrinkage of bentonite on drying suggest that it will be difficult to use. The corresponding expansion on rewetting suggests that it will be unstable once the house is built.

The drying shrinkage indicates that building should be done with clay bricks, rather than by the cob technique, where globs of plastic clay are piled up and pressed together to make a wall. The dry stamping technique known as pisé may work but requires that the wet mixture be dried out considerably before stamping begins, introducing an extra, time consuming process.

The lightweight clay tiles are very similar in density to cellular concrete and could be used in much the same way. The compressive strength is quite adequate. The advantages over cellular concrete are that it can be recycled and it can be given great bending strength through incorporating extra, oriented fibres, making it quite suitable for shelving and arches.

The tiles are surprisingly resistant to water spray. The clay at the surface swells and seals off the interior.

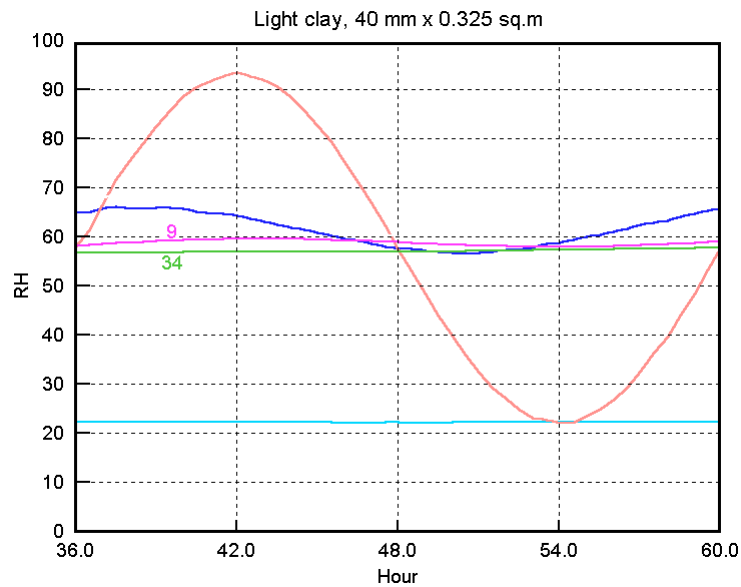**The moisture buffering potential of lightweight clay tile**

Figure 4.26 The daily cycle for lightweight clay tile.

The buffering of the daily cycle is so good that the RH at 9 mm hardly changes at all. The observed RH cycle is largely controlled by diffusion across the boundary layer between air and tile.
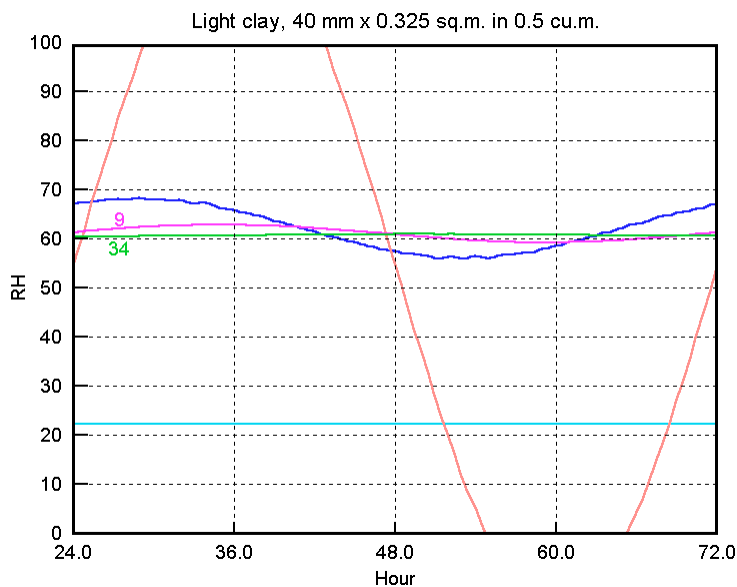

Figure 4.27 The two day cycle for lightweight clay tiles

During the two day cycle the amplitude of the chamber RH is hardly greater than in the one day cycle, in spite of the greater quantity of water injected during the cycle. This suggests that the main factor causing the observed RH swing in the one day cycle is the surface resistance to moisture transfer.

Light clay 40 mm x 0.325 sq.m. in 0.5 cu.m.
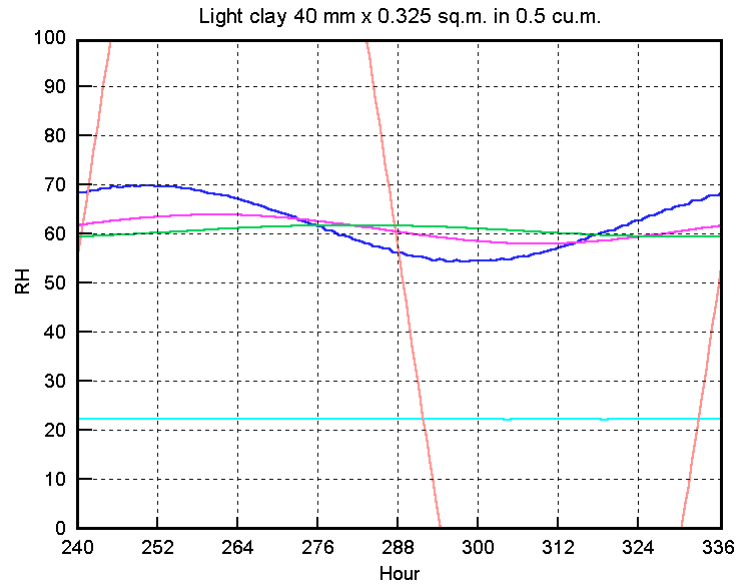
Figure 4.28 Four day cycle for lightweight clay tiles.

The four day cycle at last shows some influence on the deepest layer of the tile. The RH cycle is still within +/- 10% of the mean value, whereas the curve for the empty chamber shows that condensation would otherwise set in at an early stage in the cycle and would continue for many hours.

This last graph shows the exceptional buffer performance of lightweight clay as an interior finish.

Lime plaster

The traditional interior mineral surfaces are lime plaster and gypsum plaster. These have very inferior buffer capacity, compared with clay.
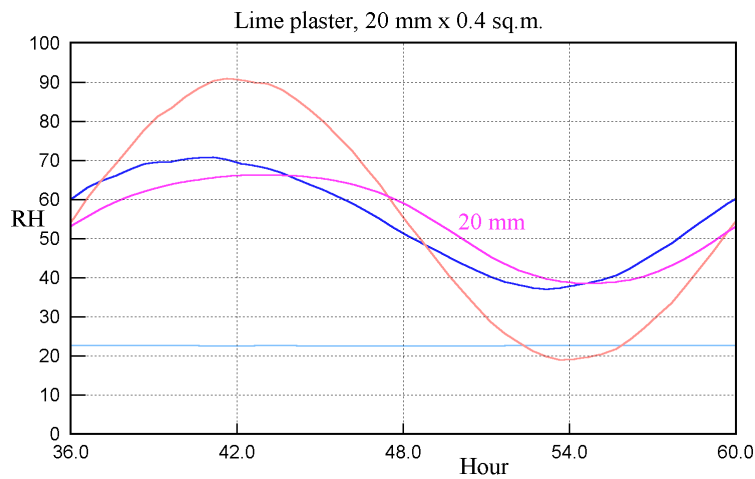
Figure 4.29 The daily cycle for lime plaster, made from approximately one part slaked lime in the form of lime putty, mixed with three parts of sand. The buffering is very poor.

The lime plaster is very porous. The RH at 20 mm follows close behind the RH in the chamber and is of nearly the same amplitude. This indicates that the entire thickness of the plaster is available to react to this daily cycle. The buffering capacity is fully used, and is not very impressive. The "empty" RH is halved by the presence of the plaster.
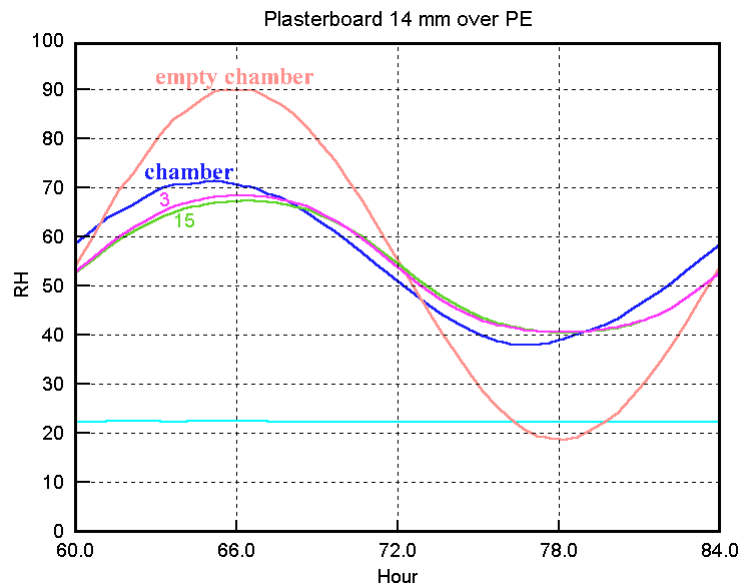
Gypsum plaster

Figure 4.30 Gypsum board, made from two layers of paper with gypsum in between, has a rather similar pattern to lime plaster. The buffering effect is nearly identical. The porosity is difficult to compare because the gypsum board is thinner than the lime plaster. The entire thickness is in play in this daily cycle.

Cellular concrete

The last mineral material in this catalogue of building materials that can function as humidity buffers is cellular concrete. This material is made by mixing silica, calcium oxide, aluminium powder and water. After a few seconds of mixing the slurry is poured into a mould where it froths up as hydrogen is released by the reaction of aluminium with water in alkaline solution. The final product is a mass of interlocking needle crystals of calcium aluminium silicate with some residual silica particles and relatively large voids. The density of cellular concrete depends on the mix but is typically 750 kg/m^3.
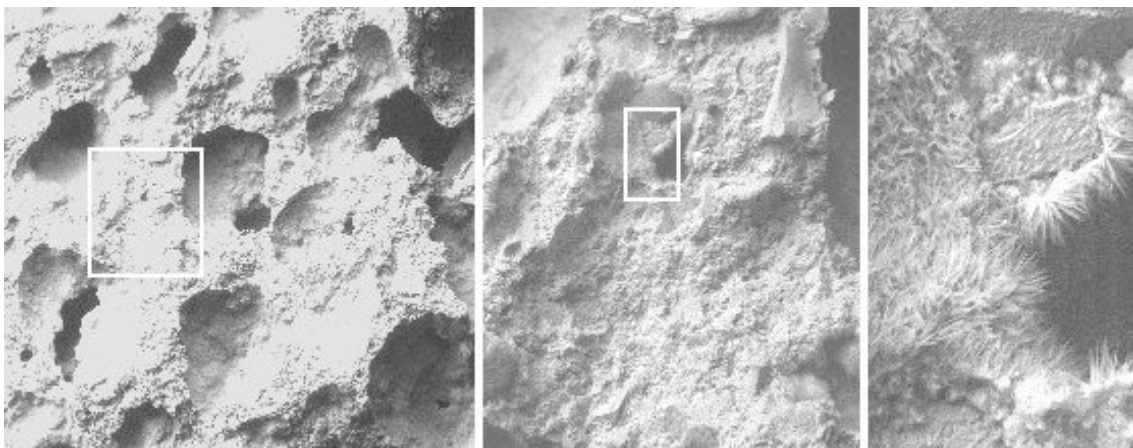

Figure 4.31 SEM images of a broken surface of cellular concrete at three magnifications. The picture on the left is 2 mm across. Photo: Ulrich Schnell.

The enormous surface area gives plenty of sites for water absorption, so cellular concrete is a moderately good buffer, as the next three diagrams show.
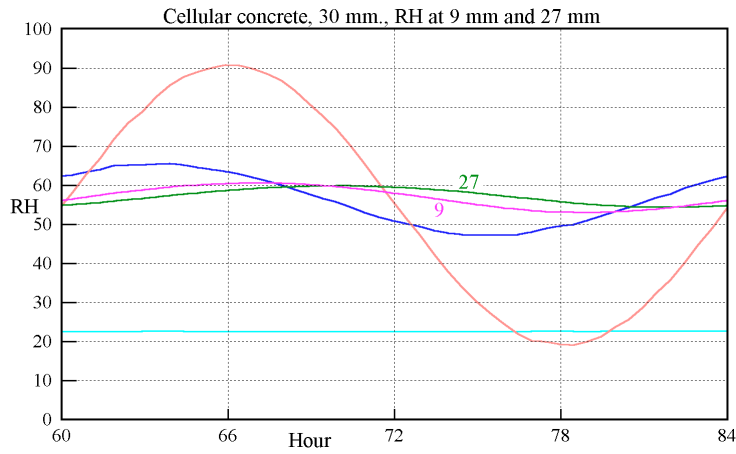

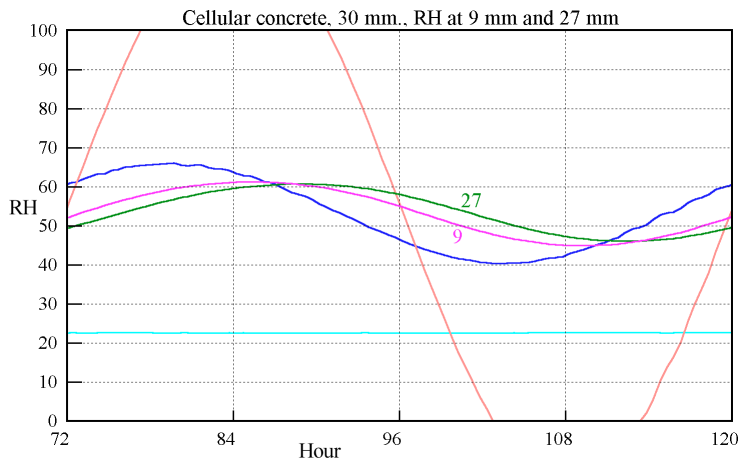*Figure 4.32 Cellular concrete, 24 hour cycle.*

Figure 4.33 Cellular concrete, 48 hour cycle

The entire 30 mm thickness of the cellular concrete is working to buffer the 48 hour cycle. The 24 hour cycle also reaches down to the back of the tile, so this thickness is less than the optimal for buffering the daily cycle.
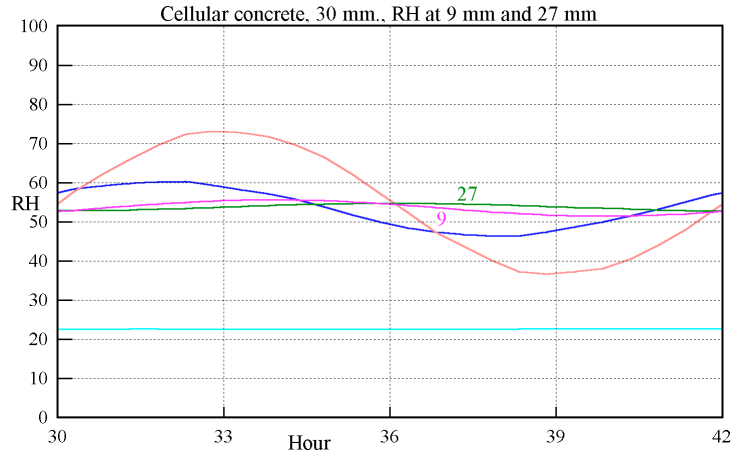
Figure 4.34 Cellular concrete, 12 hour cycle

During a twelve hour cycle the back of the tile does not exchange so much water. Approximately 60 mm of cellular concrete are needed to provide optimal buffering for the daily humidity cycle. This is not a problem because cellular concrete is usually used to build walls at least 100 mm thick. Cellular concrete walls covered thinly with gypsum plaster should give the best moisture buffering of the established industrial building materials and construction methods.

This hypothesis was tested by laying a 15 mm layer of gypsum plaster over the cellular concrete tiles. The tiles were moistened to prevent the tearing of the gypsum during application, through rapid drying by capillary suction. The gypsum was, of course, entirely water saturated at the beginning. The wall was then dried for two weeks in a room at 52% RH. After this the chamber was dropped down over the wall and the flux generator was set to condense water at a steady rate.
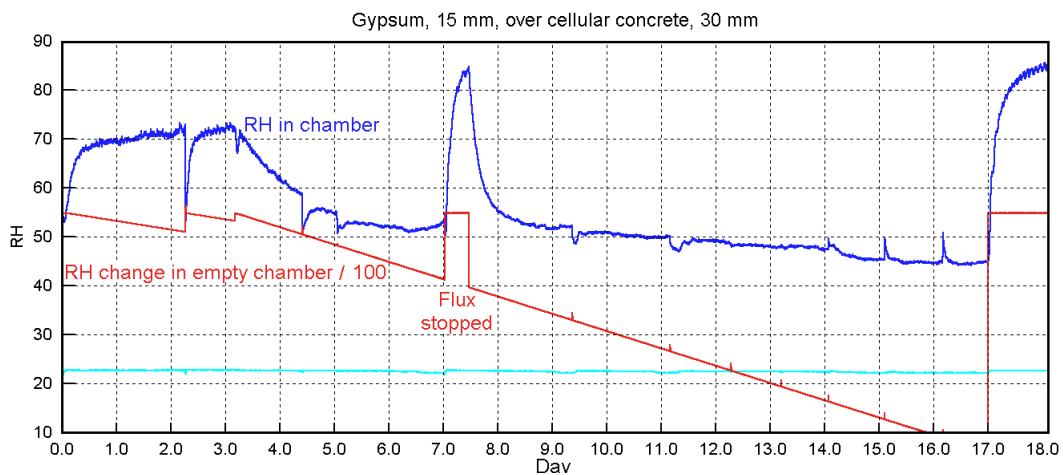

Figure 4.35 The drying of a wall of cellular concrete, 30 mm with a 15 mm gypsum surface layer. In this graph the 'inert' RH is divided by 100. This means that an indicated 1% change would actually be a 100% change in RH

.

The result was surprising. Part of the graph is shown in figure 4.35. A flux of -2 g/hr was applied (that is 2g/hr of water was condensed into the tank). The RH fell quite quickly to about 50% but then continued to decline very slowly while many tankfuls of water were extracted from the wall. Extracting 2g/hr of water would make the RH in the empty chamber drop from 50% to zero in 2.5 hours, yet the RH only fell from about 52% to 48% over a week.

A plausible explanation for this almost constant RH in the chamber is that most of the water from the gypsum was absorbed into the cellular concrete soon after the setting of the plaster. During the initial period of ventilation a relative humidity gradient established itself through the gypsum, with 100% RH at the interface with the cellular concrete and a value at the surface which depends on the flux through the surface. This gradient will remain stable for weeks, while the cellular concrete gives up its stock of capillary moisture. This condition is due to the different pore size in the two materials: the gypsum has coarser pores.
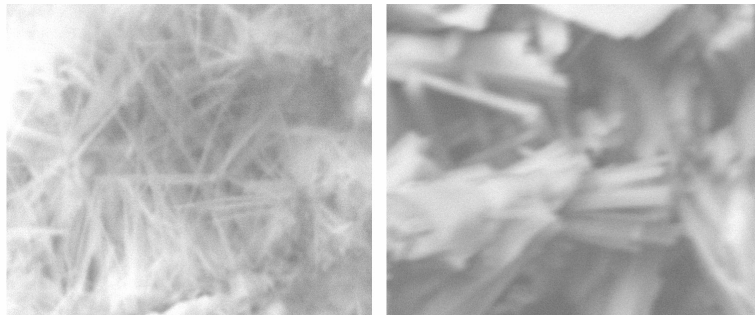

Figure 4.36 SEM pictures of cellular concrete, on the left, and gypsum plaster. Each image is 25 microns across. Photos: Ulrich Schnell.

This unintended experiment demonstrates that humidity buffering at moderate RH by absorbent porous materials is a minor phenomenon compared with the huge quantities of water that can be stored in the capillaries of materials, in a condition where the equilibrium RH remains at 100%, while a large amount of water is released, or absorbed. The significance of this for the indoor climate is that the process by which wet gypsum gives up its capillary water to the cellular concrete is not reversible in the way that buffering by a block of one material is reversible. If a brief episode of condensation in a bathroom, for example, is absorbed into the gypsum, the water will be transferred by a relatively rapid capillary flow to the cellular concrete. The reverse process will be slow because the water changes to vapour at depth within the wall, at the interface of the two materials. There is no air flow to boost evaporation: the water vapour must diffuse to the surface. This assymetry in the speed of wetting and drying can be advantageous if the cellular concrete can evaporate the moisture to the outside of the building.

Wool insulation

The materials discussed so far in this chapter have been stiff, structural materials. The catalogue ends with a soft material: wool.

Absorbent insulators are credited with many virtues and vices, according to which side of the green line one is standing. Advocates of environmentally friendly, organic insulation in houses point to the water absorption of wool as an asset, preventing condensation within walls and moderating the indoor humidity. Opponents from the mineral fibre industry argue that the water absorption allows rotting and encourages insect attack. I will return to this controversy in a later chapter.

Figure 4.37 Wool insulation. This picture shows a 70 mm section of wool insulation. Notice the laminations parallel to the surface of the slab as it would be installed in a wall.

Wool has a steep absorption curve and is therefore a good humidity buffer. Wool insulation, however, has a density of only 300 g per square metre of wall, if it is installed as a layer 200 mm thick. It is, however, very porous, so the entire thickness of the wool is brought into play, even during a daily flux cycle.
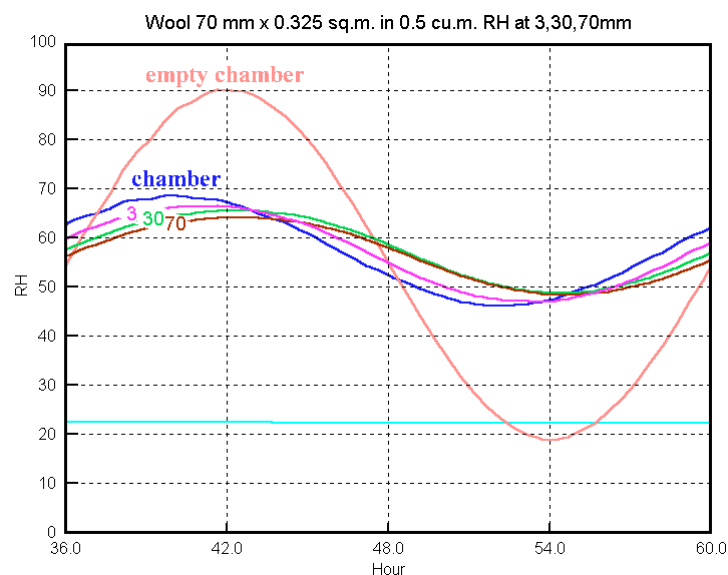

Figure 4.38 The daily cycle for wool. The interior RH cycles cluster closely behind the RH in the chamber. This indicates that the entire thickness of the wool is involved in the daily cycle.

All the RH curves, except the empty box one, are going up and down almost identically, with a small phase delay for the sensors embedded in the wool. The buffering is considerable, but it is also all that the wool can offer: there is no reserve for longer flux cycles.
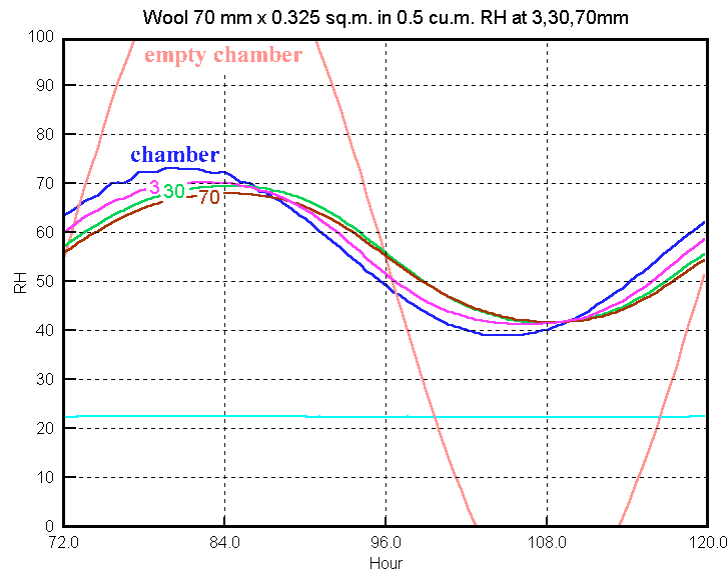

Figure 4.39 Wool insulation: 48 hour cycle

The two day cycle resembles the pattern of the 24 hour cycle with the important difference that the amplitude of the chamber RH is greater.
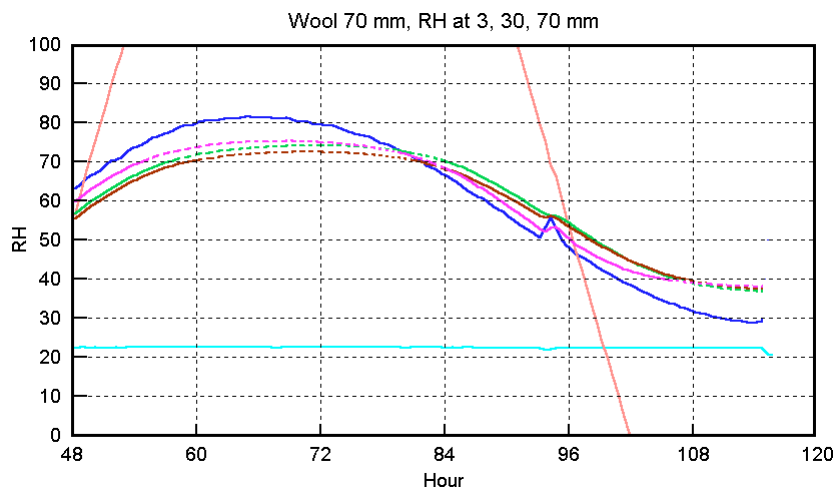

Figure 4.40 Part of a four day cycle with wool insulation. The RH is now swinging with a large oscillation, though there is still no danger of condensation. The curves for the RH inside the wool are flattened at the extremes (dotted lines) and are no longer accurate: the sensors are outside their linear range

The four day cycle shows an even greater swing, but there is still no danger of condensation. The wool is therefore effective as a buffer at any frequency. Its efficiency continues to increase with thickness, because the rate of moisture diffusion is much faster than that for clay or wood planks. Compacting the wool would also work to some extent, though eventually the greater density would affect the permeability.

Wool insulation encapsulated

Figure 4.41 A detail from an 18th century French tapestry in the Royal Palace, Copenhagen. Photo: Roberto Fortuna

Walls of exposed wool are a very presentable form of interior decoration, though expensive. Tapestries have for centuries been regarded as the most prestigious wall covering for a grand house in Europe. Curtains are a more mundane form of wool moisture buffer.

The density *per square metre* of tapestry is not so far from that of wool used as insulation and so its buffer capacity is similar, and very useful because it is immediately available to fight acute water vapour fluxes.

Sheep's wool is one of the insulating materials that is recommended as an environmentally friendly replacement for mineral fibres. Advocates of moisture absorbent insulators, such as paper and other vegetable fibre and wool, assert that these materials give a more pleasant indoor climate, through their moisture buffering action. This effect cannot possibly work if the wall is provided with an impermeable barrier, as is usually recommended to prevent condensation within the wall in heated buildings. A *moisture retarder*, which is moderately permeable to water vapour, is therefore recommended for these insulators.

A typical wall construction would be gypsum board as the interior finish, then a vapour retarder and wool insulation with some permeable outer sheathing to allow ventilation of moisture to the outside.

These materials are examined one by one, and in combination, to see how easily the room can receive the benefit of moisture absorption by the wool.
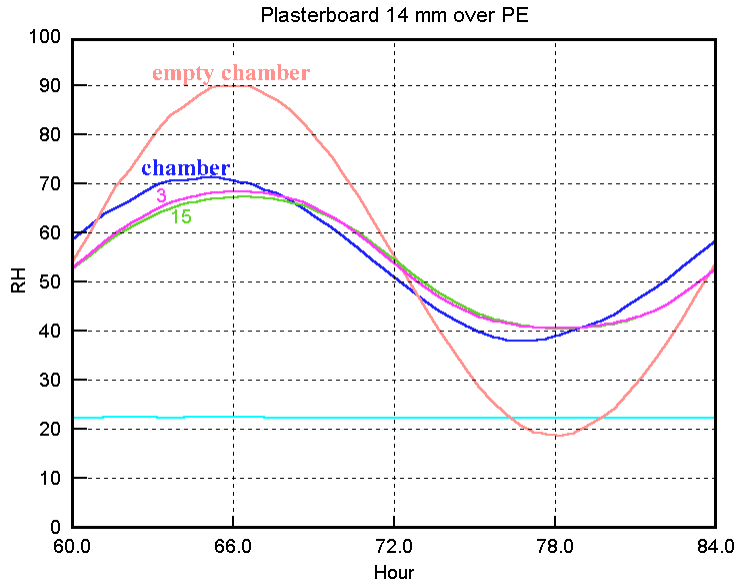
Figure 4.42 Buffer performance of plasterboard alone (a repeat of figure 4.30). Sensors are mounted behind the front layer of paper and behind the second layer, just in front of the polyethylene membrane that seals the back.

Plasterboard alone has a modest buffer capacity, mostly contributed by the layers of paper enclosing the gypsum. If it is unpainted, or painted with a thin paint with water permeable binder, it will perform as shown in the figure. One sensor is placed behind the first layer of paper and another sensor behind the second layer, just in front of the polyethylene film that seals the back. The capacity is modest and the permeability is such that all the buffer capacity is available to the daily cycle.
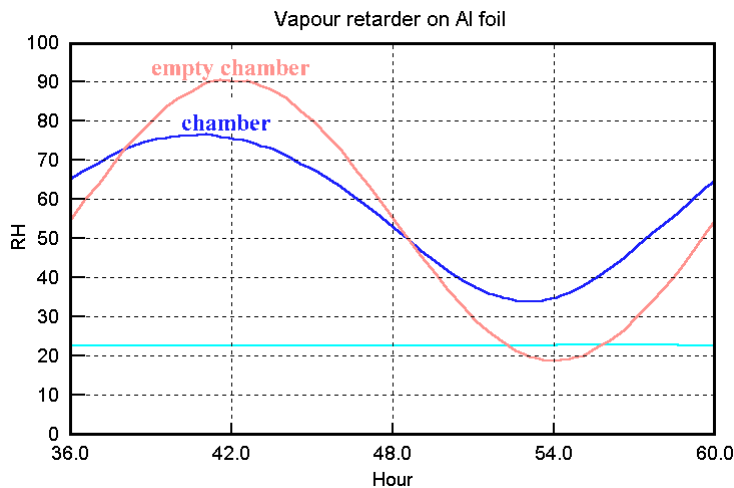

Figure 4.43 Buffer performance of vapour retarder alone

The vapour retarder is made from thick paper with thread reinforcement to limit tears. It also has a noticeable buffer capacity, but less than that of plasterboard.
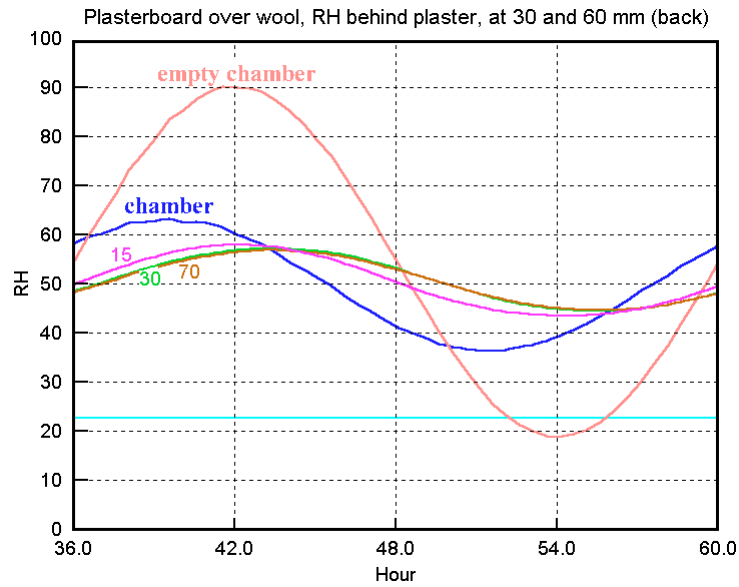
Plasterboard over wool, RH behind plaster, at 30 and 60 mm (back)

Figure 4.44 Plasterboard over wool, sensors behind the plaster, midway through the wool and at the back

Wool behind plasterboard can still influence the indoor climate, but only marginally. The clear swing in RH within the wool is as much due to its low capacity for water as to its buffering of the chamber air.
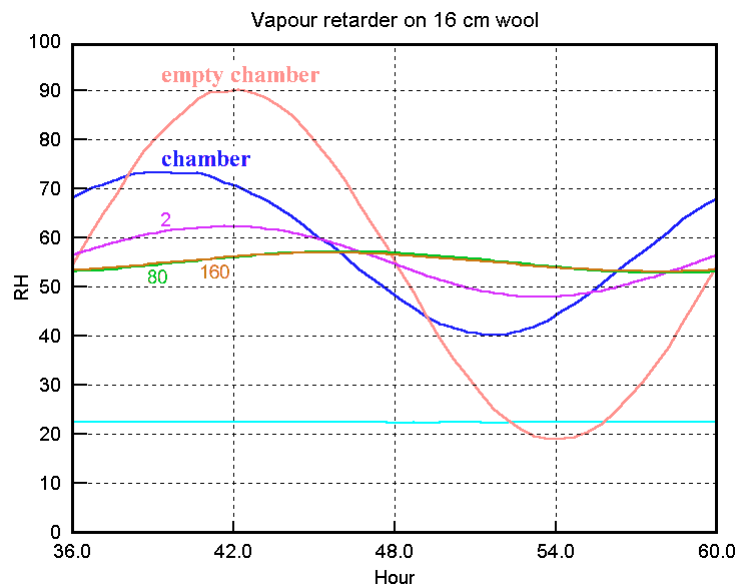
Vapour retarder on 16 cm wool

Figure 4.45 Wool behind vapour retarder. Sensors behind the retarder and within the wool at 7 and 15 cm.

Wool behind the vapour barrier has a negligible effect on the room climate.
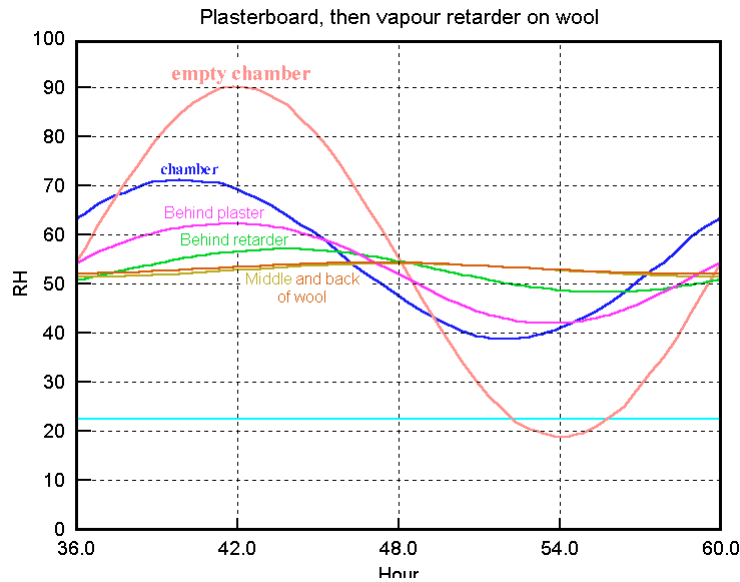
Figure 4.46 Plasterboard, vapour retarder and wool. Sensors behind the plaster, behind the retarder, half way through the wool and at the back.

When the orthodox combination of plasterboard, vapour retarder and wool is examined, the RH within the wool varies by just a few percent, indicating a negligible participation in the moisture exchange. The plasterboard and the vapour barrier provide what humidity buffering there is.

Reaction of a wall to a sudden injection of water vapour

The way in which the various components of such a complex wall react in turn to the flux in the room is rather clearly shown by a different experiment in which a sudden pulse of water vapour was injected. The response of the wall is shown in the diagram below. At about hour 5 in the graph, water is added to send the empty chamber to "200%" RH, which is roughly the same flux as in the 48 hour cycle in earlier diagrams, but added all at once.

The plaster, more particularly its two layers of paper, does most of the moisture buffering in the early hours after the water is injected. Then this water diffuses through to the vapour retarder and eventually to the wool. The peak chamber RH is moderated to 80% from the expected 100% with intense condensation that the empty chamber would experience. At this time the wool has hardly noticed the unexpected moisture. When everything has come to equilibrium after about two days the wool has pulled the chamber RH down to less than 60%. Put rather crudely, the plasterboard has moderated the RH from about "200" to 80% as a quick buffer. Later, all the wall components combine to stabilise the RH at 57%.
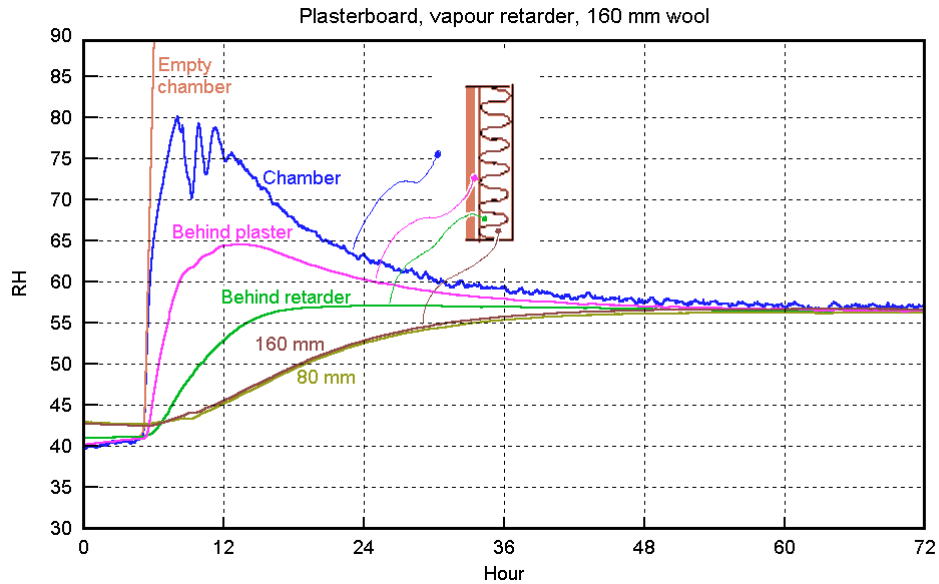
Figure 4.47 The effect of suddenly adding enough water to bring the empty chamber to "200%" RH. The rapid fluctuations at the peak are due to instability of the flux controller. The wall is made of plasterboard, vapour retarder and wool insulation.

Summary of chapter 4

The response to the release of water indoors has been measured for several materials used in buildings. The material is put in a chamber into which water vapour can be injected, and then removed in a continuous cycle. The exposed area of material is about 0.6 m^2 per cubic metre of air. The materials moderate the RH in the chamber, by absorbing the injected water vapour and then by releasing water vapour to compensate for that withdrawn from the chamber. A series of graphs gives a visual impression of the relative efficiency of different materials in moderating swings in indoor relative humidity, by comparing the RH swing in the empty chamber with the actual cycle.

All the materials exert some moderating effect. The least effective was lime plaster, which reduces the swing to about half that in the empty chamber. The most effective RH buffer is more difficult to define, because it depends on the cycle time. End grain wood is very effective at moderating a daily cycle, because of its great porosity. Bentonite clay tile was excellent at all cycle times because of its very high absorption, combined with moderate porosity. Wool insulation has very high absorption per unit weight and very high permeability but when used as insulation its very low density reduces its practical usefulness.

The reaction to the daily cycle by the single materials is collected in a summary diagram in figure 4.48 below. As an aid to translating these sinusoidal curves into the potential of these materials for moderating the indoor climate one can take as an example a house in winter. The house is warmed to 23°C and is by chance at 50% RH. The water content is about 10 g/m^3. The outside air is at 0°C and 100% RH. Its water content is 5 g/m^3. The maximum rate of change of moisture content of the inside air in the diagrams is about 1.6 g/(m^3.hr). This is equivalent to 0.3 air changes per hour. This

is the exchange rate for a fairly well sealed, modern house. It is immediately clear that the RH in the non-absorbent house is going to fall quite rapidly, though exponentially, to the 22% RH which is the RH that the outside air will acquire through warming to the room temperature. The process will be substantially complete within 6 hours, but will be about ten times slower in a house panelled with end grain wood. The winter in the author's latitude is much longer than this, so absorbent walls in houses are strictly for moderating an indoor climate whose average value, measured over a few days, is acceptable. Store houses are another matter: it is quite practical to design them to buffer over the whole year, as reported in a later chapter.
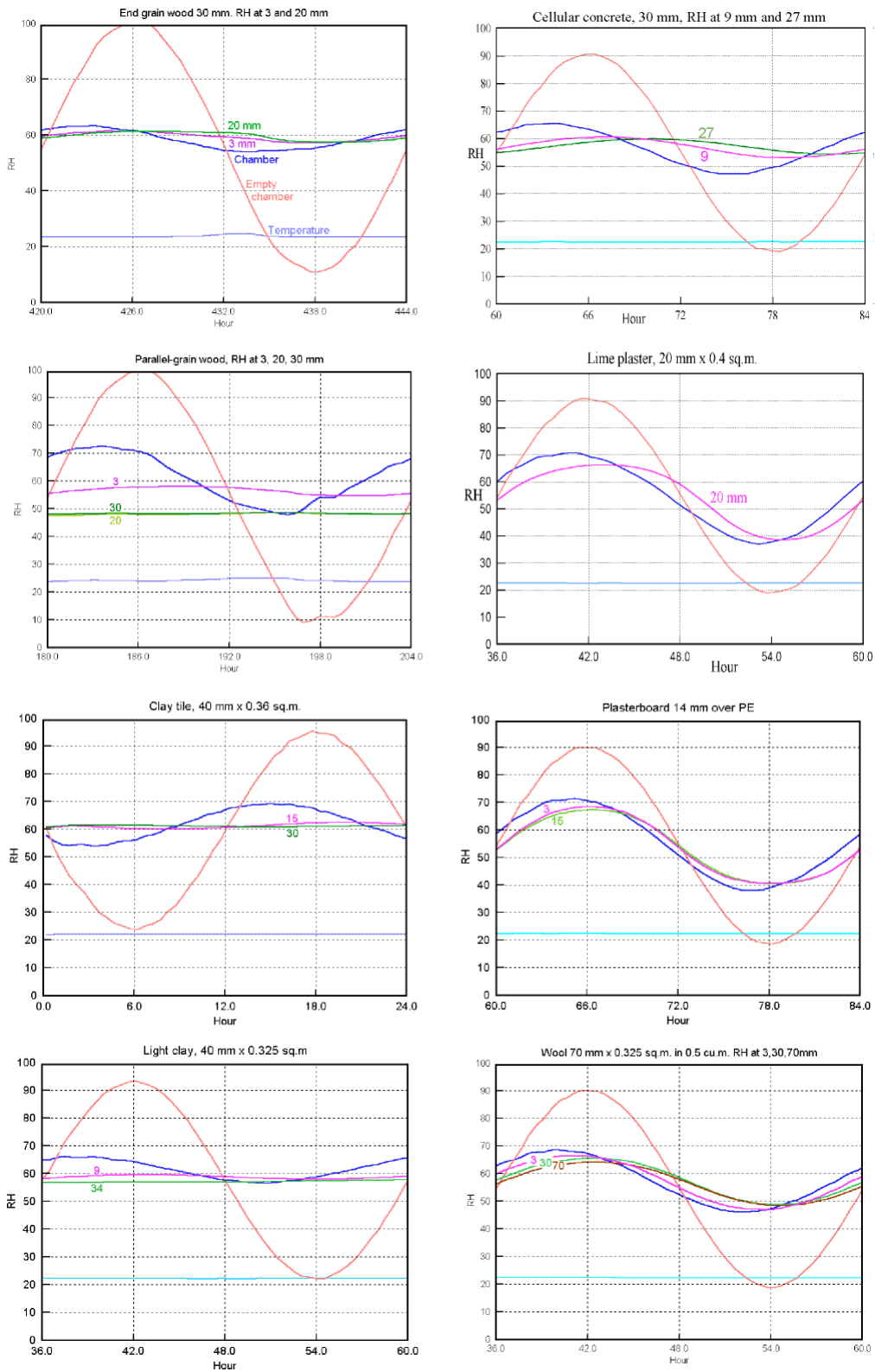
Summary of the performance of the materials

Figure 4.48 A collection of the 24 hour cycles for the simple materials.