5

COMPARING MODEL WITH MEASUREMENT

Definitions

Two material constants are needed for the calculation of the buffering effect of absorbent materials: The *water capacity* as a function of relative humidity and the *water vapour permeability*. One other constant is required: the *boundary layer permeability*, which depends on the air speed over the wall surface and the roughness of the surface.

Water capacity

The water capacity is mainly dependent on relative humidity with a slight temperature dependency. The water capacity is usually given in the form of a sorption curve, because it varies a lot with relative humidity. However, in the RH range of interest in this enquiry the curve can be simplified to a straight line, without significant inaccuracy. This is illustrated by the isotherm for bentonite shown below.
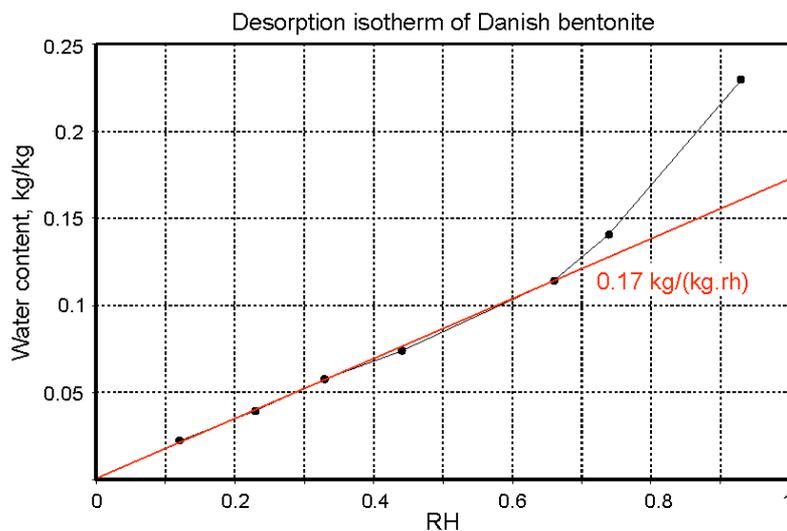

Figure 5.1 The sorption isotherm for sodium-bentonite from Rødby, Denmark.

The graph is usually drawn with weight percent against RH percent. In this chapter the water content is given in kg/kg and the RH is expressed as a fraction, instead of the percent used in the previous chapter.

For bentonite the curve is almost straight in the region between 0.4 and 0.65 RH, which is the region of interest for indoor climate.

There is one important complication with the sorption curve: it takes a different route according to whether the material is being dried or wetted. The route also depends on the starting point. This variation, known as hysteresis, can be quite significant when the RH cycle is wide, as can be seen from the curves for wool and paper insulation in figure 5.2
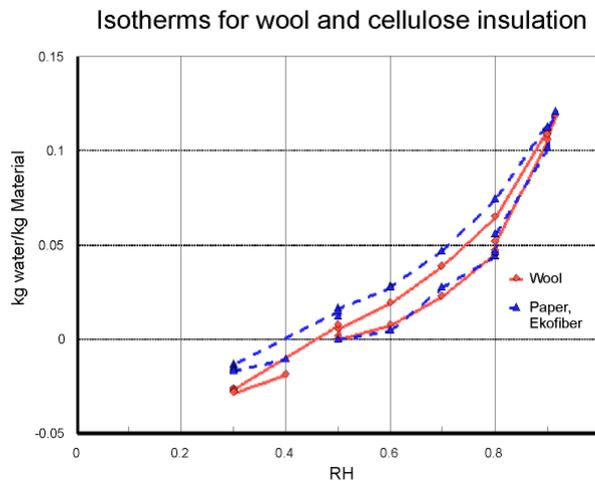
Figure 5.2 Sorption curves for wool (solid line) and for paper fibre insulation. The cycle starts at about 0.5 RH and goes up.

If the cycle is between narrower limits the RH follows a shallower slope. The slope used as the moisture capacity should therefore vary according to the recent history of RH change. In this model the problem is sidestepped by measuring the slope of the sorption line when the materials are cycled repeatedly between 0.4 and 0.65 RH, representing the region in which they cycled in most of the experiments reported in chapter 4. The values are shown graphically in figure 5.3
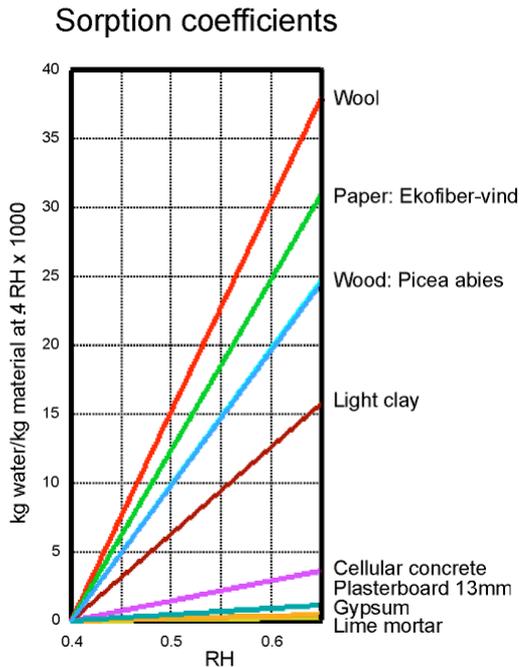

Figure 5.3 Sorption of water by various materials as a function of relative humidity. The RH is cycled between 0.4 and 0.65. The materials will not actually follow the lines shown on the diagram but will trace out a narrow elipse with sharp limits, as in figure 5.2. The slopes of these lines give values for the water capacity which is used in the computer simulations.

The materials shown in figure 5.3 can be grouped into three types.

An organic group is represented by wool and cellulose. These materials have very high water capacity, attributable to hydrogen bonding sites on the polymer molecules.

The clay and the cellular concrete represent silicates with a large surface area per kg. Here the water is also bound to hydrogen bonding sites but because they are only on the surface the water sorption is moderate to poor.

The final group, represented by lime and gypsum plaster, contains coarse grained mineral aggregates which are wettable by water but which have very little capacity for absorbing water at moderate RH.

There is one group which is not represented in the diagram. This is materials which are naturally water repellent or are treated with chemicals to make them water repellent. Examples are perlite insulation and Leca pellets, both of which are treated with silicone to make them water repellent and therefore useful in places where water would otherwise be drawn into structures by capillary suction.

The water vapour permeability

The water vapour permeability is quoted as weight of water transmitted per second through a metre cube of material with a vapour pressure difference of one Pascal across it The unit is kg/(Pa·m·s). This is a very small number which is usually multiplied by 10^{12} for visual clarity.

The water vapour permeability is dependent on the prevailing relative humidity and generally changes rapidly at high RH. However, in the RH range of these experiments the permeabilty can be considered constant, an assertion that was tested by measuring several of the materials at several gradients: 0 - 0.5 RH, 0.5 - 0.76 RH. The difference for wool insulation, for example, is 6 percent.

The water absorption coefficient and the water vapour permeability are not well defined for commercial building materials because of variations in composition and in production technique. The density also varies considerably. The relevant properties, in the relevant RH range, were therefore measured for nearly all the materials used in these experiments. A summary of the values is given in table 5.1.

The permeability of wood in a tangential/radial direction was taken from Kumaran (22). The values for Falkenlowe brick are from Poul Klenz Larsen (22a). This brick is made with a traditional slow firing, which gives it an unusually low moisture absorption.

The water capacity of the bentonite - perlite mixture is much lower than that of the pure bentonite, although perlite contributes almost nothing to the density of the product, and should therefore not influence the value, because it is itself non-absorbent. There is certainly scope for improving the moisture absorption of light clay mixtures by using different fillers and maybe different mixing techniques.

Material	Water capacity kg/(kg.rh) x 10³	Diff. coeff. kg/(Pa.m.s)x10¹²	Density kg/m³	Remarks
Wool insulation	152.0	140 (.5-.76)	19	Scandan
Wood, radial/tangential	98.0	2	384	Picea abies
Wood, longitudinal	98.0	88 (.5-.76)	384	Picea abies
Light clay mix	63.0	22 (.5-.76)	876	Bentonite/perlite
Cellular concrete	14.0	32(.5-.76), 22(0-.5)	782	
Gypsum board	4.8	30(.5-.76), 16(0-.5)	685	
Gypsum, cast	1.6	32	1235	
Lime mortar	0.4	18(.5-.76), 15(0-.5)	1818	1:3 sand
Brick, Falkenløwe	0.6	13	1725	From ref. 22a
Vapour retarder	120	0.03(0-.5)	400	Miljøisolering B2

Table 5.1 The essential properties for modelling the behaviour of the materials used in the experiments.

Water vapour transport through the wall surface

The other constant used in the modelling is the diffusion across the boundary layer of air at the surface of the wall. This constant depends on the air speed and on surface texture. The various experimental values have been reviewed by Wadso (14). At 0.2 m/s, which is just a breath away from still air as we understand it in everyday life, the boundary layer thickness is changing rapidly with air speed, so the moisture transfer rate is not well defined. Extrapolations from curves made at higher velocities suggest a value of $4 \cdot 10^{-8}$ kg/(Pa·m²·s). The results of the buffer calculations are not strongly influenced by variation in this number. Notice that the unit is different from the material diffusion constant described above, having square metres in the denominator. This is because the boundary layer thickness is hard to define and is therefore removed from the unit.

In the model, the wall surface slice uses this value, which is a property of the room, to calculate the water streaming into it, without invoking its own thickness at all. This is permissible because the slice is made very thin. The danger then is that the surface slice absorbs so much water into its tiny volume during a single iteration that it attains an unreasonably high RH. This approximation therefore forces a rapid cycle time.

Scaling the dimensions

The free space in the chamber is taken as a constant 0.5 m³. It varies a little with the thickness of the individual test walls. This volume was measured with a wall of about 50 mm thickness and 0.5 m² area. The wall area did vary somewhat because of the different natural sizes of the various tiles under investigation.

The program assumes one square metre of wall in a room which is a long square prism, one square metre at the end, extending in depth to give the correct ratio of volume to wall area. The flux cycle was usually of 4.8 g half amplitude for the 24 hour cycle, changing proportionately for longer or shorter cycles, so that the steepest rate of change of flux on the sine curve was always about the same. This flux was divided by the wall area before insertion into the simulation program.

Simulation of the performance of the lightweight clay tile wall

The four day cycle for the lightweight clay tile wall is taken as an example for detailed analysis, because it shows a reasonable cyclic variation from all sensors.

The starting data for the simulation are listed here:

Wall area 0.325 m^2
Volume corresponding to one square metre: 1.54
Actual flux: 0.0192 kg half amplitude, corresponding to 0.0592 kg at 1.54 m^3
The wall thickness, 40 mm., is divided into slices: 0.5 mm, 0.5, 1, 2, 2, 3, **3**, 5, 8, 9, **6,** (0.1 impermeable back). The bold numbers mark the slices which will be compared with the data from the buried RH sensors.
Diffusion rate through the surface: 40,000 x 10^{-12} kg/(Pa.m^2.s)
Diffusion coefficient of the wall 22 x 10^{-12} kg/(Pa.m.s)
Water capacity of the wall 0.063 kg/(kg.rh)
Density of the wall 876 kg/m^3

Comparison of model with experiment

The static data does not match the experimental data. The two graphs are shown side by side below.
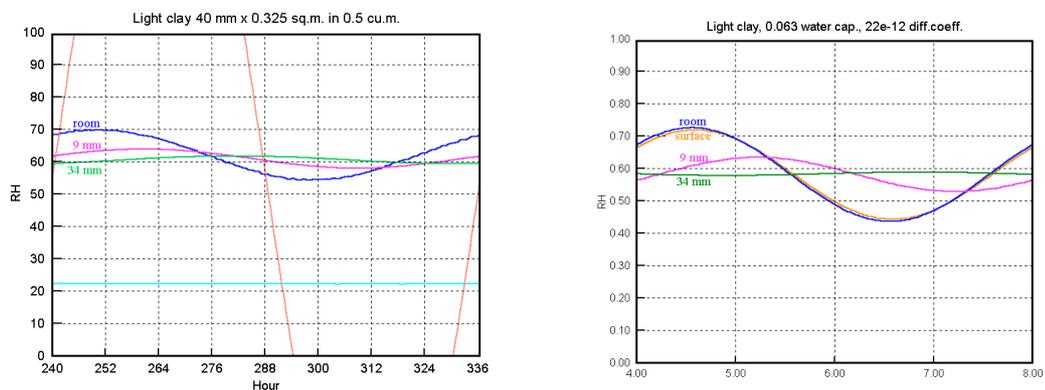

Figure 5.4 On the left is the measured performance of the lightweight clay tile wall over a four day flux cycle. On the right is the performance calculated according to the statically measured values for water capacity and diffusion coefficient. The very steep curve on the left graph is the 'inert' RH for the empty chamber.

The model seems to give the clay too small a water capacity, because the room and the 9 mm curves are swinging more than the measured values. The diffusion coefficient also appears to be too low, because the RH at 34 mm has a smaller amplitude, and a much more delayed phase, than the measured curve.

The diffusion through the boundary layer is not an important influence, as indicated by the closeness of the curves for the room RH and for that in the surface layer of the wall.

The next two graphs show attempts to get a better match by changing the two material constants.
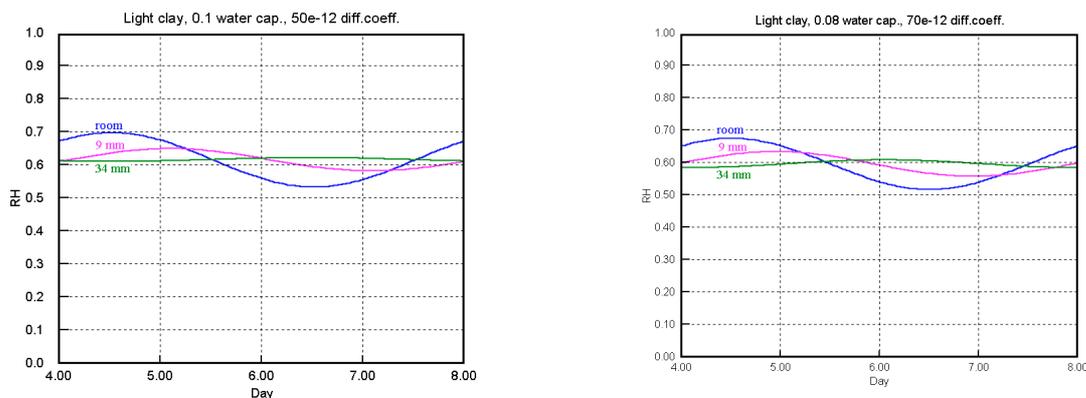

Figure 5.5 A: On the left: both water capacity and diffusion coefficient have been increased over the statically measured values. The fit to the measurements is better but the phase shift is too great in the RH cycles within the wall.

The best match is obtained with a slightly raised water capacity and a much greater diffusion coefficient. Even then the observed phase shift in the deeper layers of the wall is somewhat greater than the observed values.

The greater diffusion coefficient is not unexpected. The static measurements were made on a perfect, crack free specimen, whereas the tiles had many shrinkage cracks and had air channels through and alongside the straw reinforcement. The real wall would certainly have a higher permeability but the three times higher value is unlikely.

There is one assumption in the program which seems to be questionable. The program assumes instant equilibrium with the water diffusing through. This seems unlikely when one looks at the microphotographs of the clay tile structure. There are large voids with clumps of much more finely grained material. One can speculate that water vapour travels easily through the net of large pores, losing, or gaining only a little water by interaction with the tightly packed clay particles which are the real absorption sites. Full equilibrium with the interior of the tight packed zones would come more slowly and only approximate to the model prediction deep in the interior where everything happens very slowly.

Another possibility is air flow within the wall, driven by the slight density difference of the air at different RH at different depths and also by the turbulent air movement within the chamber.

The revised set of basic constants was then applied to the one day cycle and compared with the experimental data.
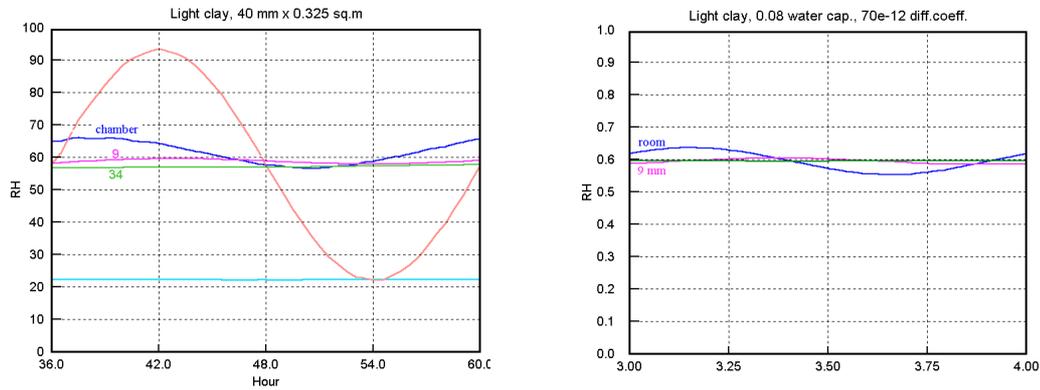
Figure 5.6 A: On the left is the measured performance of the test wall under a daily flux cycle. B: On the right is the modelled performance, which shows a slightly too good stabilisation of the climate.

The one day cycle shows good agreement between model and reality. The model predicts a slightly smaller than measured RH cycle in the chamber. The RH cycles within the specimen are now very flat and cannot be interpreted quantitatively.

Any delay in the sorption process will have more effect at this short time scale so the direction of the error is consistent with this hypothesis. The data, particularly the depth of the measurements within the tiles, are not well enough defined to allow a more profound analysis of these results. The RH sensors are physically large relative to the thickness of the wall and the wall itself is not homogeneous enough to allow one to assume that one sensor can give a true account of the state of the material at a given depth.

Extension of the model to longer climate cycles

The next section extrapolates these short measurement times to years. The purpose is to examine the feasibility of using clay walls as stabilisers for the climate in houses, with their moderate air exchange rate and in museum stores and archives, with a very small air exchange rate. The model is not intended to be a quantitative design tool but to illustrate the decisive influence of ventilation rate on the performance of absorbent walls.

Houses typically have at least one quarter of an air change per hour. The next diagram shows the performance of a house with light clay walls 400 mm thick, sealed on the outside so that the weather has no influence except through the air exchange.

The RH outside is set to 0.2, which is typical for the winter air, brought to the indoor temperature. This graph therefore represents the resistance of the house to drying at the onset of winter. There are no indoor water sources to resist the drying process, which is unrealistic for an occupied house. The rather impressive buffering performance must therefore be regarded as quite realisable in practice.

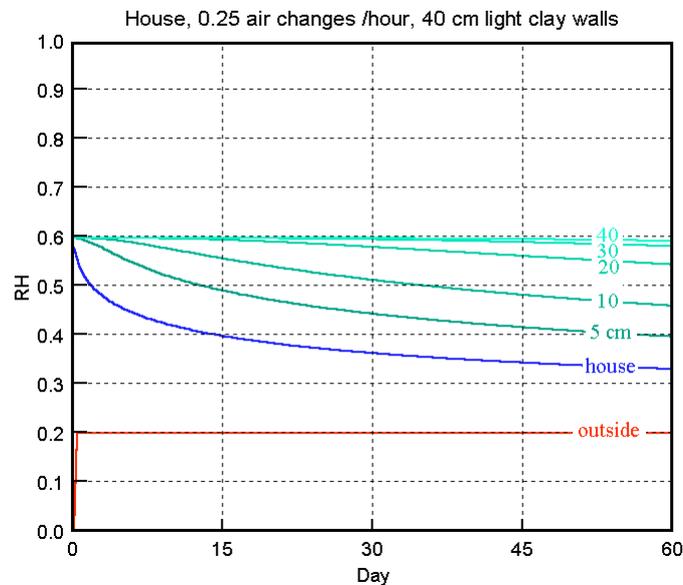House, 0.25 air changes /hour, 40 cm light clay walls

Figure 5.7 The climate in a house with one quarter of an air change per hour, 400 mm thick walls of lightweight clay mix, sealed on the outside. There is one square metre of wall to one cubic metre of room volume. The outdoor climate is set at 0.2 RH to imitate the RH of winter air brought up to the constant 22.6°C of the house.

The performance is quite impressive. It suggests that modern houses, which are sealed only to reduce heat loss, would benefit from humidity buffering by porous walls.

The wall thickness is a little excessive, from the point of view of humidity control, because by the time the surface has half lost the battle with ventilation and has let the room descend to 0.4 RH, after about two weeks, the deepest layers of the wall have hardly released any water at all. The optimum thickness for humidity buffering is about 20 cm.

If the outer wall were not sealed on the outside orthodox wisdom would suggest that it will lose water to the outside, diminishing its effectiveness in buffering the interior. This is probably not so: there should be a movement of water vapour through to the interior, reinforcing the good performance shown in the diagram. This matter is discussed further in a later section, where a model is used which includes the effect of a temperature gradient through the wall.

At this ventilation rate the annual climatic cycle overwhelms the buffering effect of the wall, regardless of its thickness. The simulation is shown in the next diagram, with the warning that this is an extreme extrapolation of a four day measurement and must not be taken as more than an order of magnitude calculation.
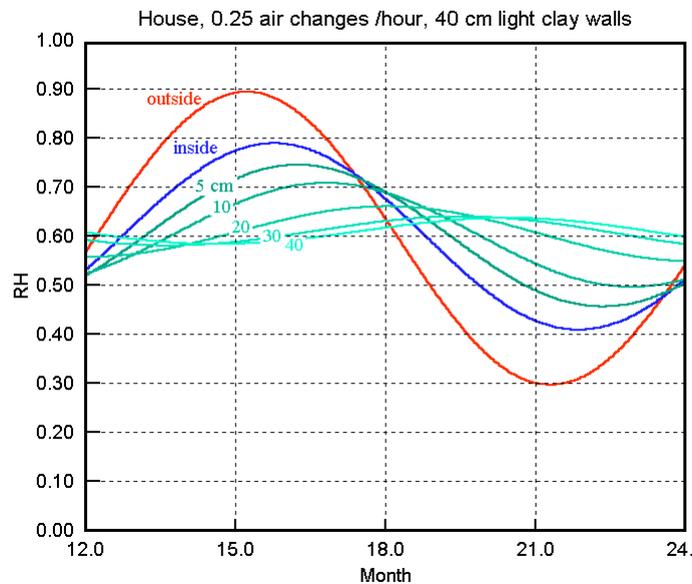
Figure 5.8 One year's climate in a house with one quarter of an air change per hour, 400 mm thick walls of lightweight clay mix, sealed on the outside. There is one square metre of wall to one cubic metre of room volume. The outdoor climate is varied from 0.3 to 0.9 RH to imitate the RH of the outside air brought up, or down, to the constant 22.6°C of the house.

Humidity buffering in archives and stores

Buildings, or rooms, that do not have permanent residents do not need a quarter of an air change per hour. The practical limit for air change that is achievable without building a house like an aeroplane is one air change per day. Christoffersen reports one air change in 20 hours for the State archive in Schleswig, which he investigated rather thoroughly (4).

Christoffersen's measurements established that an archive full of papers will easily buffer the yearly cycle of the climate to an acceptably low amplitude among the archive boxes. His data are given in the next chapter. There is no need for a mud wall in the Schleswig archives. But suppose that the archive contains only metal, like the Smithsonian collection of patent models. Can the walls provide stability through the year?
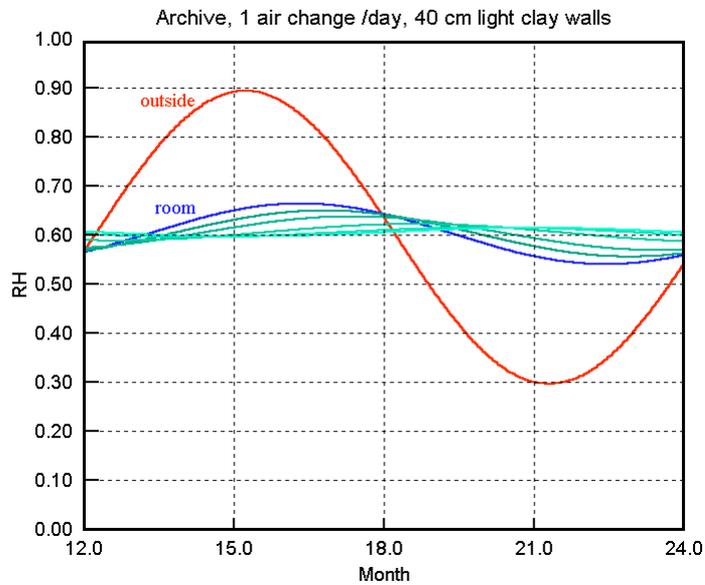
Figure 5.9 The annual climate in an empty archive, or a store with unabsorbent material. The air exchange rate is once per day.

No problem! Notice that at this long cycle time and low exchange rate the full 400 mm thickness of the wall is involved in the buffering. A thicker wall would not, however, significantly increase the stability, which is already very good indeed.

Let us now consider a historic collection of steam locomotives. Can these be safely exhibited in a building made of lightweight mud?
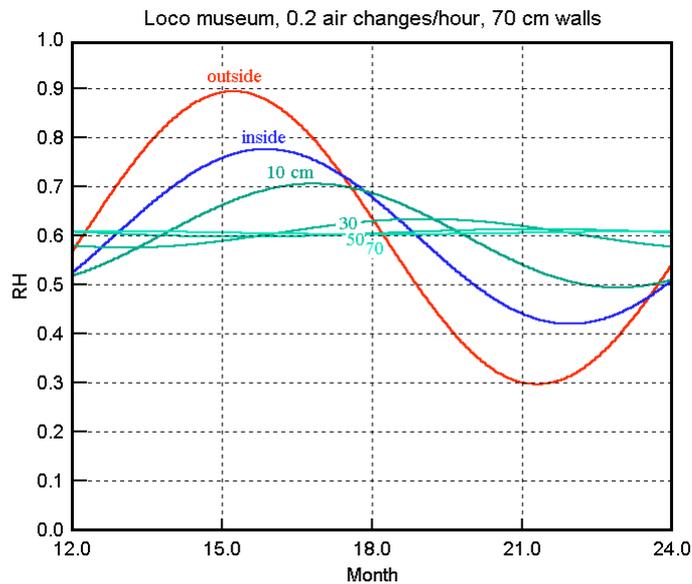

Figure 5.10 The railway museum with earth walls.

The ventilation rate has been set at 0.2 changes per hour because there is public access but the building is vast, so that this exchange rate provides ample cubic metres of fresh air per person, as required by the regulations.

The buffer will certainly protect against short periods of unusually wet weather, and winter dryness is no problem in a museum devoted to metallic machinery. A combination of passive buffering by absorbent walls with dehumidification at a steady rate during the summer would certainly provide an excellent climate for the machinery.

These modelled results are an extreme extrapolation from the original experiments in a half cubic metre steel box with slabs of dried mud stacked up inside. I emphasise that they are shown here to demonstrate the potential of the concept of buffering with absorbent walls.

Adding the temperature gradient through outer walls

The experiments and the model runs have been made with equipment and program code that works at a constant temperature. This is fine for walls used as separators within a house but the outer walls represent a considerable fraction of the wall area which is controlling the inside climate. The effect of a temperature gradient through these walls cannot really be imitated by putting in an unrealistically low outside RH to imitate cold air brought up to the indoor temperature. There is an interaction between heat and moisture flow which needs to be modelled to give a complete impression of the various effects that contribute to the buffering of the indoor climate.

What is the driving force for moisture movement?

The additional calculations needed when modelling the effect of temperature on moisture movement through outer walls have been summarised in the last section of chapter 3. A consequence of these calculations is that moisture should flow through a porous, absorbent wall driven by the relative humidity gradient, rather than by the concentration gradient.

In a temperate climate the relative humidity gradient is usually inwards during the winter and spring, changing to a weaker reverse gradient during the summer. If water diffuses through the wall under the influence of the RH gradient the indoor relative humidity will be higher than that calculated for outside air brought directly in and warmed to the indoor temperature. Consequently, the water vapour concentration is higher than that outside. Water movement through definite cracks in the structure will, on the other hand, tend to even out the water vapour concentration. This competing process tends to reduce the inside RH.

The purpose of the next computer simulation is to evaluate the relative magnitudes of these two processes. If the water pumped in by the RH gradient is very small compared to that lost by ventilation then the question of which gradient, RH or concentration, should apply is of only academic interest. If the two processes are of similar magnitude then it is important to test the program against an experiment, because clarification of this mechanism is an important issue in the design of walls containing absorbent materials, or in walls designed deliberately to use absorbent materials to move water against the vapour pressure gradient.

The mechanism invoked to move water against the concentration gradient in the market leaders in computer simulation of moisture movement, WUFI and MATCH, is capillary movement of liquid water.

Another way of looking at the matter is to ignore the possible mechanism and concentrate instead on the measured fact that the sorption isotherms for absorbent materials lie close together, if relative humidity is used as the controlling variable (see cotton as an example, in figure 1.8). A logical consequence of this is that if there is a temperature gradient across an enclosed mass of absorbent material the RH should be almost the same at both surfaces. If the RH at the cold side is increased, then there will be movement of water towards the hot side, even though the water vapour concentration is higher at the hot side. Water is being pumped against the concentration gradient, while the heat flows the other way.
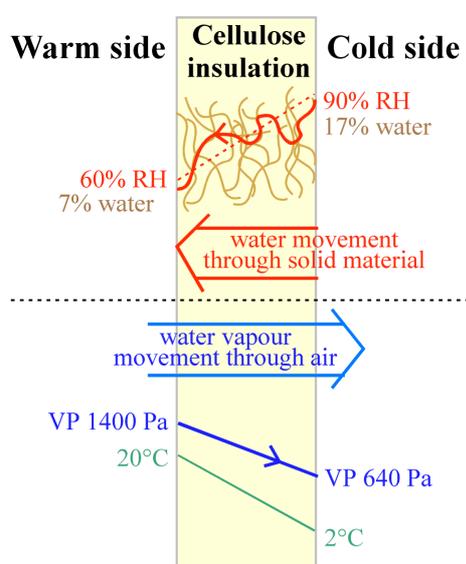

Figure 5.11 The two mechanisms by which water vapour can move through an absorbent, porous material. At the top: molecular movement through the material. At the bottom: diffusion through the pore spaces, driven by the concentration gradient.

This mechanism allows transfer of water against the concentration gradient at all values of RH, whereas the other programs put a stop to the process at a middling RH, so that the water gets trapped in a sort of whirlpool between the limit for capillary movement and the high RH side of the wall, usually the outside. Here the water moves as far as it can inwards by capillarity, then gets caught up in the outward moving vapour stream in the pore space.

It is quite likely that the two processes leading to outward and inward movement respectively occur together in walls that combine absorbent materials with unabsorbent insulation, for example.

The RH driven mechanism requires that the material in the wall be hygroscopic right through. This is far from the case in modern buildings. Most building materials are nonabsorbent, even if they are porous: gypsum, mineral fibre and brick have very little absorption at the 60% RH that is typical of the indoor climate. Cellular concrete is the only commonly used materials which is both porous and absorbent at moderate RH. Wood and concrete are absorbent but not very permeable. It is therefore not surprising that condensation is often encountered in modern buildings, because there is no absorbent material available to pump back the water that enters the wall from the inside of the building. There is abundant evidence that most of the water in walls gets there by flow of air through openings in the construction, or by flow of liquid water from the outside, so the question of which *diffusive* transport mechanism dominates is not yet decided (31).

Moisture movement in a wooden hut

The first diagram, 5.12, shows the climate in a room lined with wooden panelling. All parts are at the same temperature. The diagram shows the good stabilisation provided by the wooden panelling.

Figure 5.13, on the next page, shows the same room, but now the wooden panelling is also the outside wall, subjected to a temperature gradient.
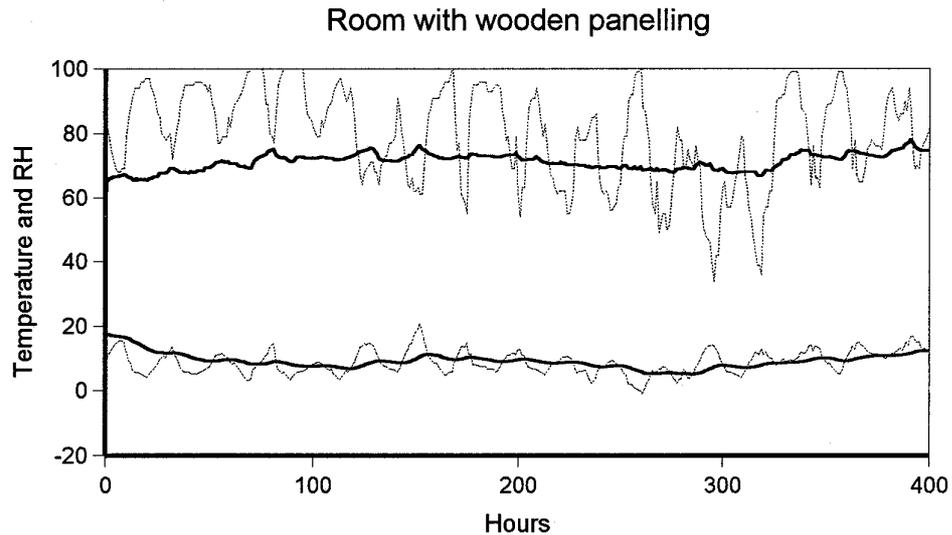

Figure 5.12 The climate over 12 days inside a room 10 x 10 x 2 m high with all surfaces faced with unvarnished wood, 0.1 m thick, sealed at the back. The air exchange rate is 0.2 per hour. The outside climate (dotted) is typical for Danish weather in April. The room (bold) is unheated so the temperature and the RH follow the outside (dotted) values.
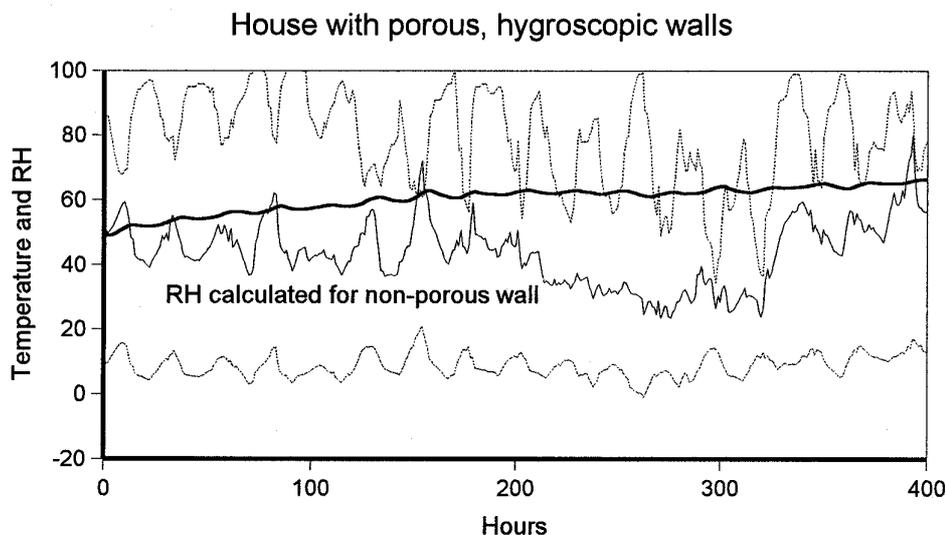
House with porous, hygroscopic walls

Figure 5.13 The climate in a wooden hut of the same dimensions as in figure 5.12, with walls 0.1 m thick, porous right through. The air exchange rate is now 0.1 per hour and the room is warmed to a constant 18°C. The wood has the longitudinal direction oriented through the wall, to increase the diffusion rate of water vapour.

The upper dotted curve is the outside RH and the lower dotted curve is the outside temperature. The middle fine curve is the inside RH calculated for air at the inside temperature with the outside water content. The smoother, bold line is the inside RH, calculated on the assumption that water is diffusing through the wall driven by the RH gradient.

It is immediately apparent from this second diagram that water diffusion through walls as a result of a relative humidity gradient is comparable with the rate at which water leaves through cracks in the structure. It must be acknowledged that end-grain wood is an unusual building material, but the results of this theoretical exercise are interesting and provocative.

The only experiments that I know which support the assertion that the RH gradient is the driving force for diffusion across a temperature gradient were made by Martin Krus (12, pp 54-55) and by Siau and coworkers (31). Krus set a 16 mm slice of particle board, presumably pressed wood shavings, over a cooled bath of a saturated salt solution. The temperature was 13°C below, and 23°C above the board. He measured the RH below and above the board. The actual value of the RH is not stated but he quotes a dew point excess above the board of between 1 and 2 degrees.

This result is so important to the understanding of moisture movement through porous walls that it needs to be confirmed and quantified for several materials. Krus' explanation is that water flows along the walls of capillaries against the vapour flow through the centre. A chemist's explanation might be that water moves from absorption site to absorption site according to the vacancy density, which is greater at a lower RH but is hardly affected by temperature. If one thinks of RH as a chemical potential and the movement of water molecules as a reversible reaction with receptive sites on the

stationary phase it is not hard to believe in RH as the driving potential. Siau invokes a thermodynamic explanation for his experiments on diffusion through solid wooden blocks.

Summary of chapter 5

This chapter begins with a comparison of the measured and the modelled moisture exchange between air and a clay mixed with lightweight filler. Agreement between theory and measurement for the dynamic experiment can only be attained by tripling the statically measured diffusion coefficient. This is a large discrepancy. However, the model, once modified, predicts the observed RH at 24 and at 96 hour cycles with reasonable agreement.

The model parameters were then applied to a house with a leak to the outside air. The predicted buffering against two weeks of cold, dry (in kg/m^3) air infiltrating at 0.25 changes per hour was quite impressive and suggests that the concept of moderating climate against short periods of unusual weather is well worth investigating on a larger scale.

Buffering of specialised buildings which can be run with very low air exchange rates, such as museum stores and archives, is impressive. A significant flattening of the yearly cycle of RH can be achieved by a wall of 70 cm thickness, provided the air volume to wall area volume is about one to one.

The flux through a wooden wall which is porous right through and subjected to both a RH and a temperature gradient is modelled to show that the theoretically predicted pumping of water against the concentration gradient is of comparable magnitude to the exchange of water vapour through leaks. This is a theoretical exercise which certainly needs experimental verification.

Taken as a whole, the evidence and arguments presented in this chapter suggest that humidity buffering by porous walls is a significant unused potential in common building materials.