Humidity buffering by absorbent materials

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Abstract

Unfired clay brick, wood, and cellular concrete have been evaluated as relative humidity (RH) buffers for indoor spaces. Their response to a cyclic variation of RH has been measured and expressed in a novel unit for describing the buffer capacity, the 'buf' with symbol B. This is defined as the quantity of water vapour exchanged with the material, expressed as the volume of space which will experience the same change in amount of water vapour when exposed to the same relative humidity (RH) cycle. This number is approximately equal to the number of air changes needed to exhaust the buffer moisture reserve in a typical room with walls lined with the material. Well ventilated unfired perforated brick, 5 cm thick, has a buffer capacity of 27 m^3 per square metre of surface for a daily RH cycle, providing significant resistance to RH change caused by an air exchange rate of once per hour. One can regard the sum of the buffer values of the wall lining and the furnishing as a virtual (larger) volume to the room, into which water vapour from infiltration and internal generation has to disperse, with a consequently lower RH variation. The buffer value is dependent on air velocity over the surface and on temperature.

Wood cut across the grain was second best in performance, with a value of 15, just ahead of massive unfired brick at 10. Cellular concrete was an unimpressive buffer at 7 but worst of all was fired perforated brick with a buffer value of 3 even for a long RH cycle.

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

Introduction

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

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

The computer simulation programs developed for modelling moisture movement in buildings have concentrated on the diffusive movement of water molecules through the outer walls and roof. Even slow water movement through the wall can cause serious damage to the building structure but diffusive movement through the outer wall is too slow to influence the interior RH, compared with the effect of air exchange through openings and moisture injected through human activities.

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

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

Other museum stores, and particularly museum galleries, have the same need for RH stability, but do not have the buffer capacity provided by densely packed paper records. Can this lack of buffering by the materials within the room be compensated by building, or lining the walls, with moisture absorbent materials?

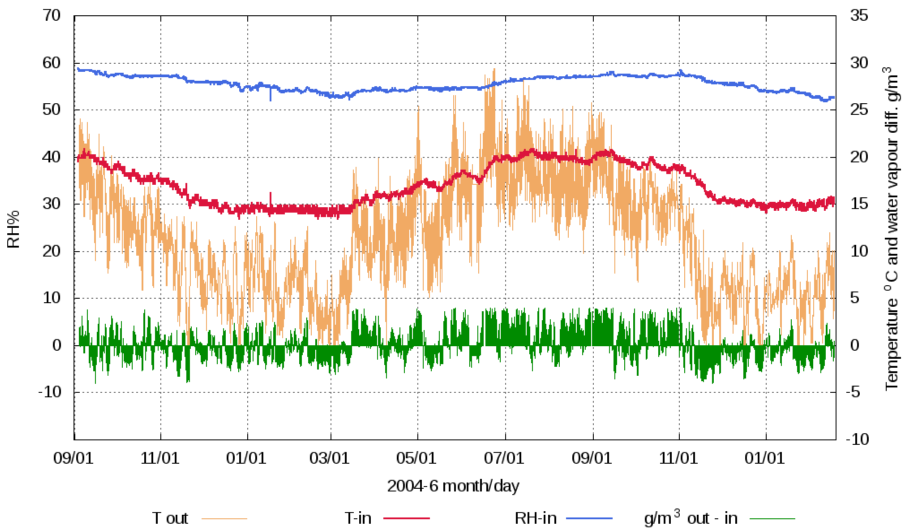

Figure 2: The annual cycle of temperature and relative humidity in the Suffolk Record Office. The lowest trace indicates the difference between the concentration of water vapour inside and outside. During the winter the inside RH is driven down by air exchange; during the summer the outside air has more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

The experimental evaluation of the buffer performance of building materials

The materials were exposed to a cyclic RH variation between 50% and 60% RH. The consequent exchange of water vapour with the surrounding space was measured. The experimental technique is described in detail by Padfield et al. [1]. The apparatus, with the perforated brick specimen, is shown in figure 3. The material is exposed in a sealed chamber while the RH is set to follow a cyclic variation, controlled by the temperature of water in a weighed reservoir. The temperature is adjusted by a thermoelectric heat pump in the bottom of the reservoir. It is assumed that water lost from the reservoir is mostly absorbed in the test material, with a small correction for the sorption by the chamber equipment and for the change in water vapour content of the space. By weighing the water rather than the specimen, specimens of widely different geometry and dry weight can be tested conveniently. The materials were also finely divided for measurement of their equilibrium sorption curves. The sorption curves were also measured over a repeated cycle of 40% to 60% RH, to give the theoretical maximum exchangeable water, to compare with the measured exchange in the dynamic experiment.

The quantitative description of the buffer performance

The experimental apparatus yields a weight of water transferred between the test object and the reservoir as a consequence of a change of ambient RH applied over a defined cycle time, at a constant temperature.

Given the diversity of materials and forms which combine to influence the microclimate of the room, we need to find a way of expressing their performance which can be summed conveniently to predict how the room will react to the exchange of water vapour with outside air and the generation of water vapour

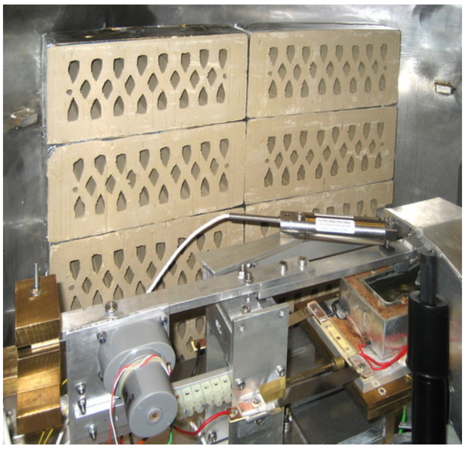

Figure 3: Eight perforated unfired bricks, exposed in the climate chamber. The apparatus controlling the RH and measuring the weight of water moving into the specimen is at the bottom of the picture. The exposed area of the brick wall is 0.2 m^2, its depth is 53 mm. The sides and back are sealed with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

by human activity within the room. We transform the measured water exchange of our specimens to the equivalent volume of air (strictly speaking the volume of space) which will experience the same cyclic change in RH with the same water vapour transfer. This concept is illustrated in figure 4. This equivalent volume is labelled the B–value for the material. For construction materials the volume is calculated per square metre of exposed surface. For irregular shaped buffering objects, such as a sofa, the B–value can be defined as the equivalent air volume for the entire object. For books in a library, a typical weight change per linear metre of shelving would be appropriate.

The sum of the B–values for all wall surfaces and all sorptive components within a room, recalculated to the equivalent cubic metres of space, gives a larger, virtual volume for the room (figure 5). To calculate the effect of moisture generation and air exchange, one uses the actual air exchange, and the actual moisture production, but calculates the resulting change of RH for these fluxes dispersing into the room plus the larger virtual volume. Put simply, if the total of B–values is 100 m^3, and the actual room volume is 25 m^3, the change of RH in the room will be that calculated for the dispersion of infiltrated air and generated moisture into a moisture-inert room of 125 m^3, so the variation in RH will be reduced to about a fifth of the variation for a moisture-inert room of 25 m^3.

The effect of cycle time on the exchangeable water supply

The B–value increases with the RH cycle time because deeper layers of the material become involved in the diffusion process. A 24 hour cycle matches the pattern of human activity, but a longer cycle time would be appropriate for designing an archive, which has a much slower air exchange and very little human generated water vapour. The B–values were measured for a 24 hour and a 96 hour sinusoidal RH variation. The longer term performance was approximated by a longer square wave cycle. The ultimate performance, given infinite time for equilibration, can be calculated from the sorption curve.

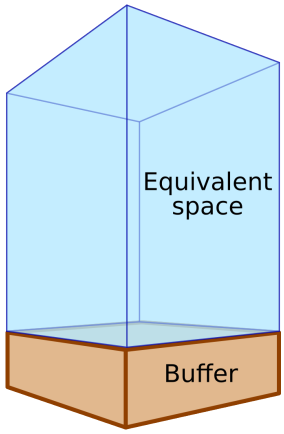

Figure 4: A visual display of the 'equivalent air volume' principle for defining a figure of merit for a buffer material or construction. The horizontal area of the buffer is one square metre. Suppose that the RH is increased by 1%. The buffer material will absorb water vapour through its surface as it moves towards achieving equilibrium at this higher RH. The volume of the column is defined as that volume which will also increase by 1% RH when injected with exactly the same amount of water which enters the buffer. A highly buffering material will absorb a lot of water, so its equivalent air column will be high. This unit of buffer capacity is called the 'buf' (B) with dimension length.

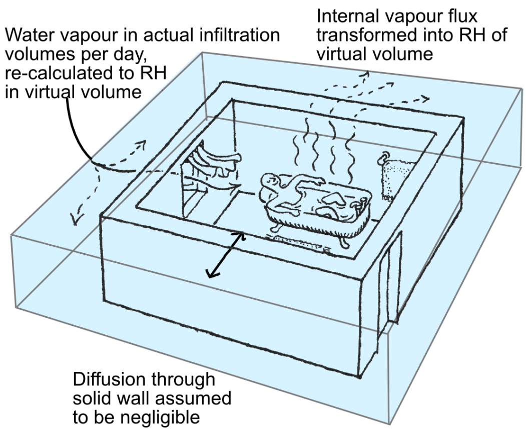

Figure 5: The B–values for all surfaces and furniture, converted to cubic metres, are added to the actual room volume to give a larger, virtual room volume. All water vapour fluxes are led into this volume and then the RH is calculated.

The effect of temperature on the B–value

The B–value is temperature dependent, because although materials have a sorption which is nearly unaffected by temperature, the change in water vapour concentration in space for a given RH change varies strongly with temperature. As a general rule, the B–value will double with a ten degree fall in temperature.

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

Most of the experiments have been conducted with a high air speed, by indoor standards, between 0.2 and 1.2 m/s. This was fast enough to make diffusion through the specimen the rate determining step but not so fast as to be totally

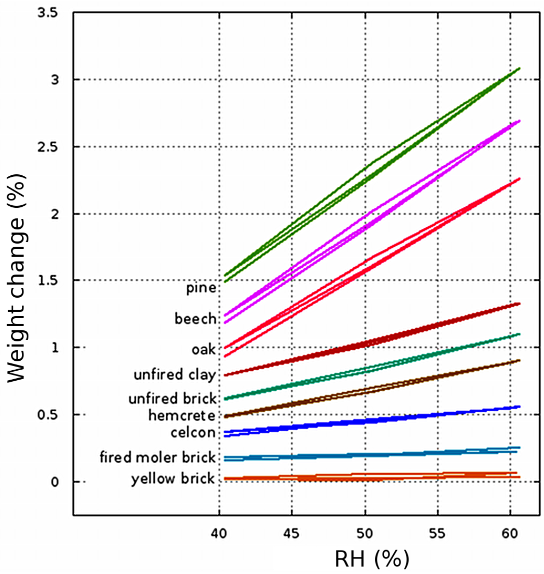

Figure 6: Sorption of water vapour over a limited RH range. The plots show the response to cyclic step changes of RH between 40%, 50% and 60%. The hysteresis loops are insignificant over this moderate RH range. The sorption cycles for each material are offset vertically for clarity. 'Moler' is a clay rich diatomaceous earth quarried in western Denmark. 'Hemcrete' is lime mortar mixed with hemp residues. 'Celcon' is a porous calcium-aluminium silicate block. The clay products are from Wienerberger brickworks in Helsinge, Denmark.

unrealistic. Some experiments were conducted at low air velocity - less than 0.1 m/s, and some experiments were made with a permeable surface coating over the specimen.

Experimental results

Table 1 shows the B–values, expressed in metres, for a one day sinusoidal cycle, then a four day sinusoidal cycle and finally a long cycle represented by holding the RH steady at each of the extreme values, 50% and 60%, for long enough for the specimen to reach equilibrium, but not longer than two weeks. The last column shows the theoretical B–value on the assumption that all the exchangeable water is available for movement between the material and its surroundings. This value is derived from the equilibrium sorption curves between 40% and 60% RH, which are shown in figure 6.

The measurement precision is such that for the poorly absorbent materials B–values less than 5 are omitted from the table. For more absorbent materials the variation between specimens of different wood species, or different clay pits, would be greater than the experimental error. The values given here are therefore indicative rather than exact.

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

Discussion

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

The unfired brick was exposed in several variations: a single thickness of brick with perforations exposed at only one end, a double thickness with perforations aligned, and the double thickness with the surface covered by a single layer of Whatman no. 1 filter paper to restrict air flow into the perforations. The bricks were also set with perforations aligned and air was forcibly blown through the assembly. In this case, all surfaces except the perforations were sealed. This ventilated system, with a B_{24} of 61 should be compared with the value 39 for the 100 mm deep perforated brick exposed passively to the general movement of the chamber air. The single depth brick (50 mm) had a B–value of 27. more than half that of the deeper perforated brick. and not far below equivalence with the thicker specimen which was forcibly ventilated through the perforations. It is not surprising that the deeper recesses of the perforations are not so active in the daily cycle but the effect of closing the perforations to forced air circulations by putting filter paper over the surface is dramatic: the B–value falls to 10. When the air velocity across the face of the uncovered perforated brick was reduced to less than 0.1 m/s, the B–value again dropped to 10. Even the long period performance with good ventilation is notably impaired by the addition of filter paper (figure 7). These large changes in buffer performance emphasise the importance of access of circulating air to an intricately perforated or grooved surface. They also show that increasing the surface area by perforating the material is only advantageous in a strong air flow, such as that from an office fan at about 2 m distance. One must conclude that buffering by absorbent materials in the walls and furnishing of houses is a slow process. Plain surfaces, even of strongly absorbent materials such as wood cut across the fibre direction (B = 15), have poor buffer capacity against a 24 hour RH cycle.

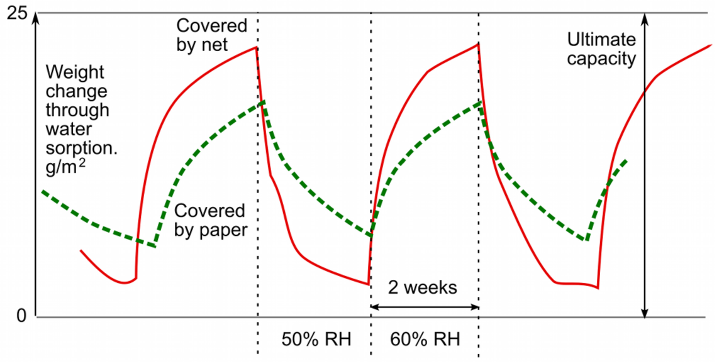

Figure 7: The effect of covering unfired perforated brick with a single layer of filter paper. The response curves to a four week square wave RH cycle are plotted superimposed. The top and bottom boundary lines indicate the ultimate buffer capacity derived from the static sorption measurement. The net had mesh openings 1.2 mm square, the paper was Whatman nr.1, 88 g/m^2.

The effectiveness of humidity buffering of the indoor climate can be estimated by considering a typical room, with walls lined with perforated unfired brick. A room, 5 x 4 m, has a wall surface to volume ratio of 0.9, but corridors and small rooms bring the ratio to about one for a typical dwelling. Assuming a typical air exchange rate of 1 per hour, a room with internal wall cladding of unfired brick, with a B–value 27 m for the 24 hour RH cycle will have a virtual volume 28 times its actual volume and therefore an effective air change rate of 1/28 per hour, so it will take about a day to equilibrate with the outside water vapour concentration. If there is little convective air circulation, however, it takes only about 10 hours for the RH to approach equilibrium with the outside water vapour concentration.

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

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

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

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

The B–value can be considered a lumped vapour capacity which is always in equilibrium with water vapour in the space within the room. The element of delay caused by diffusion within the material is approximately compensated by choosing a B–value matching the typical cycle of water vapour production. This will be the daily cycle for measuring buffering in a bedroom, to see if the sleepers can keep the windows closed without causing condensation on the glass.

For kitchens, a lower B–value should be chosen to match the short but more frequent periods of vapour generation.

We present the B–value as suitable for simple calculations to estimate the environment in a room, dependent on moisture movement through gaps in the envelope and internal production but ignoring as relatively negligible the moisture diffusing through the outer wall. The reverse influence of the room RH on diffusion through the wall is another matter, not considered here. The B–value is strongly influenced by temperature, compared with the exchange measured in kg, because the sorption curves of materials are largely independent of temperature, while the moisture content of space for a given RH varies greatly with temperature. The B–value can be calculated approximately at different temperatures, roughly doubling for a ten degree cooling. This makes buffering of cold stores very effective. It also enhances the resistance to drying of stores which are only slightly warmed in winter to keep the annual average RH lower than that outside, as illustrated by the Suffolk Record Office.

The B–values resulting from these experiments are optimal, requiring an air velocity past the surface which is only attained in rooms with fans. The short cycle performance will be worse in rooms with natural convective air movement but the long period performance will be less sensitive to air movement. This study was designed to improve the performance of museum stores and archives, which have both a low air exchange and little internal moisture generation, but they also have a slow air movement. In an ordinary dwelling, the best material in this study, the perforated unfired brick, will, if used on all walls, give a B–value for the room of around 10, representing a significant buffering of the internal climate on the scale of a day. Notice that these measurements describe buffering within the moderate RH range. Bathrooms are subject to high moisture flux which will cause condensation on non-absorbent surfaces. The unfired brick will absorb the condensate, preventing dripping. The moisture will move rapidly by capillary processes which are insignificant at the moderate RH of these tests. The performance of unfired brick in kitchens and bathrooms, where transient high RH is inevitable, will be much better than the B–value predicts.

Conclusion

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

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

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Specimen description	Depth (mm)	B–24 hour	B–96 hour	B–long	B–static sorption
Unfired massive brick	53	10	21	–	165
Unfired perforated brick	53	27	58	108	136
Unfired perforated brick double depth	106	39	95	196	272
Unfired perforated brick double depth, low airflow	106	10	21	–	272
Unfired perforated brick double depth, paper covered	106	10	26	98	272
Unfired perforated brick fan ventilated	110	61	108	243	271
End-grain wood	40	15	34	–	122
Cellular concrete	50	7	9	–	17
Fired perforated brick	52	–	–	3	12

Table 1: Buffer values of building materials at 18°C for 24 hour, 96 hour and 'long' cycle time (a square wave with minimum 7 days settling time). 'B–static sorption' is the value calculated for complete moisture equilibrium throughout the thickness of the specimen, based on the measured sorption curve shown in figure 6.