THE USE OF POROUS BUILDING MATERIALS TO PROVIDE A STABLE RELATIVE HUMIDITY

Bent Eshøj and Tim Padfield

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This is a digital version of the article first published as: Bent Eshøj and Tim Padfield, 'The use of porous building materials to provide a stable relative humidity, Preprints of the ICOM-CC (International Council of Museums - Conservation Committee) Conference, Washington DC, 1993, pp 605-9.

The use of porous building materials to provide a stable relative humidity

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Abstract

A study of the walls of a medieval church shows that porous, water absorbent materials such as lime plaster and porous limestone, will provide effective short and medium term humidity buffering in a room with about one third of an air change per hour. The church also has natural humidification. The source of the water vapour is probably ground water evaporating from the saturated lower part of the wall. The porous brick floor also contributes to the humidification. Architects can adapt some aspects of church architecture to improve climate stability in museums.

Introduction

This is a study of the stabilising effect on relative humidity (RH) of porous walls and porous surfaces within buildings. Our inspiration and our evidence comes from a study of the microclimate in a church at Gundsømagle, near Copenhagen (See fig. 1). The church and its wall paintings are described in another article in these preprints (1). Here we tell only enough about the church to explain our argument that porous, hygroscopic wall surfaces are a valuable, though seldom used, aid to climatic stability in museums.

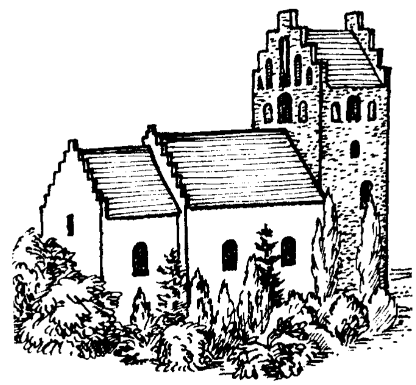

Fig. 1. Gundsømagle church, near Copenhagen.

The church also enjoys passive humidification during the winter. The church is heated to 12°C but still maintains over 60% RH inside at times when the expected value, based on the water content of the outside air, would be about 30%. The source of this humidity is probably the saturated lower part of the wall but there is a contribution from the porous brick floor.

The structure

Gundsømagle church was built soon after 1100 (2). The walls are 0.8 m thick, made from blocks of a very porous calcareous tufa. The surface coating on the outside is a thin layer of hydraulic lime mortar covered with limewash. The inside is mostly covered by medieval lime plaster, between 3 and 12 mm thick. There is also much modern plaster of the same approximate composition: 3 parts quartz sand and one part calcium carbonate. The ceiling vaults are of brick coated on the underside with lime mortar. Most of the floor area is new porous brick, laid over a porous base of lime mortar and insulating mineral pellets. This layer permits water vapour transport from the earth below.

The church interior

The volume of the church is 535 m^3. The wall and vault area is 215 m^2. The wooden furniture is mainly painted but the underneath surface of the seats is bare wood and the floor under the seats is of wood treated with calcium soap to reduce its porosity and uptake of dirt. In winter the church is warmed to 12°C by electric heaters under the seats. For church services the temperature is rapidly raised to about 20°C. One other piece of information that we need is the air exchange rate. This is about 0.3 air changes per hour. It was measured over a five week period, using fluorinated tracer gases.

Hygrometric properties of the materials

One can regard the church as basically a box made of porous inorganic materials resting on bare earth. The main materials, lime mortar, limestone and brick have a rather small absorption of water at moderate relative humidity, compared with wood (See fig. 2) or silica gel but, as we shall see, their exposed area and their bulk compensate for the small buffer capacity. The main hindrance to free movement of water is probably the hydraulic mortar on the outside of the wall.

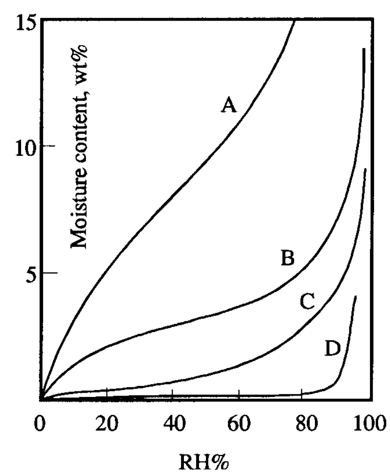

Fig. 2. Absorption isotherms of materials mentioned in the text. A:Wood. B:Lightweight concrete. C:.Medieval lime mortar. D:Calcareous tufa

The permeable wall is a distinguishing feature of Danish churches, although most churches are of porous medieval brick rather than the rare lime tufa of Gundsømagle. Secular buildings of such permeability to water vapour are now rare. Limewash (a brushed on suspension of calcium hydroxide in water, that dries to a thin layer of calcium carbonate) is still a common exterior finish for old buildings in northern Europe but the inside wall surface is very often painted with relatively impermeable modern acrylic or oil paint. Modern building practice has moved towards totally impermeable walls with a polyethylene air barrier close to the interior surface.

The main point of interest in this article is how well the simple, ancient, porous wall performs, in contrast to the many failures of complicated modern walls with air barriers (3). It is true that these failures occur in warmer buildings than the church we describe here but we think that the concept of the homogeneous, hygroscopic wall is worth re-evaluating for museum structures.

We have been fortunate in the choice of Gundsømagle church for our experimental work. The original objective was to study the effect of the heating system on the stability of the wall paintings. The heating system, with its sharp changes of temperature before and after church services, has proved ideal for studying the various factors affecting the microclimate, whatever it may do to the wall paintings.

Moisture buffering by the walls

We explain how the church walls control the RH by following the climate on one day, April 14, 1991, when the church was warmed, for the comfort of the congregation, from the background 12°C to about 18°C. We start by predicting what the RH would be if all the church walls and furniture were entirely unabsorbent. The dotted RH curve in figure 3 is a calculated value derived from the water content of the inside air just before the temperature rise, combined with the actual temperature throughout the day (lower line on the graph) to give the expected RH assuming no absorption or desorption of water vapour.

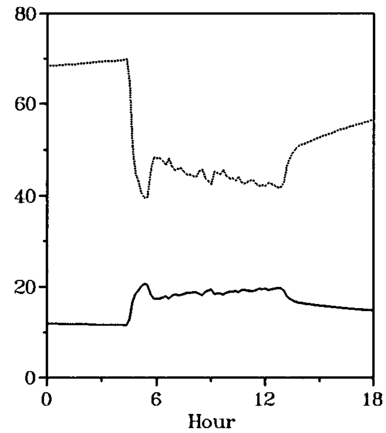

Fig. 3. Actual temperature (solid line) and expected relative humidity (dotted line) in the church, 14 April 1991. The RH is calculated from the water vapour content of the air before warming, acted upon by the actual temperature through the day. This corresponds to the RH expected in a building entirely unreactive to atmospheric water vapour.

What actually happened to the RH that day is shown by the top line in figure 4. The relative humidity dropped, but less than half way towards the calculated value, shown as a dotted line. This phenomenon is quite general in churches (4,5). It appears that the RH is being buffered to some extent, moderating but not preventing the expected fall in RH.

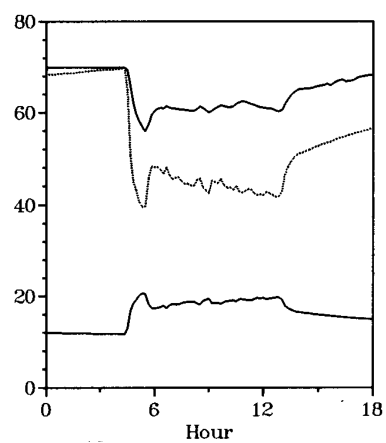

Fig. 4. The same data as in figure 3 with the measured RH added (solid line). Note that the fall in RH during the warm period is only a third of that expected for an inert room.

We believe that the RH is actually being perfectly buffered, but at the wall surface temperature. Figure 5 shows the calculated relative humidity at the wall surface, as a dotted line. This cannot be measured directly because the cool boundary layer of air is only about one millimetre thick. The surface RH is derived by first calculating the water vapour content of the air from the measured RH and air temperature in the church. This value for water vapour content is combined with the wall surface temperature (lower dotted line) to give the RH at the surface (top dotted line). The RH thus calculated holds remarkably steady throughout the warming period. This can be interpreted as a coincidence or as evidence that the wall is buffering the RH of the thin layer of air close to its surface. This air then moves away and mixes with the warmer room air, so the RH drops.

This argument is rather indirect, so we confirmed the validity of our theory by measuring the RH in a chamber sealed against the wall. This chamber is shown in figure 6. It was set on the wall, two metres above the floor. The RH sensor in the chamber is well outside the boundary layer of cool air and is at the same temperature as the air in the church. The observed RH in the chamber is shown as a dotted line in figure 7, together with the RH measured in the choir (solid line). The two curves almost coincide, showing that the cup is acting like a miniature model of the church, confirming that the observed RH in the church is defined by RH buffering at the wall.

This evidence for buffering against the RH change caused by sudden temperature change is supported by evidence for buffering against the RH change caused by ventilation. After the service the church is usually ventilated thoroughly. Figure 8 shows such an event. The two lower curves in this figure show the dew point of outside (dotted line) and of inside air (lower solid line). These become nearly equal at one point, indicating total replacement of the inside air by outside air. When the door is closed the RH (top line) rapidly returns to its original value.

This is our evidence for rapid and effective buffering of the interior RH by the large expanse of porous wall. It is probable that the brick vaults also contribute to the buffering.

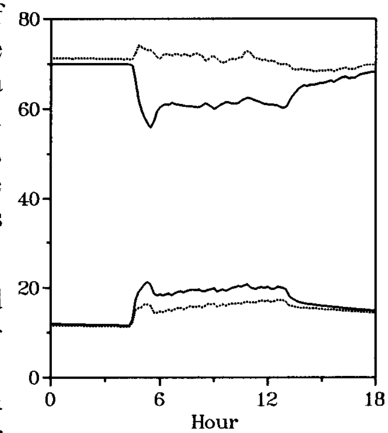

Fig. 5. The calculated RH at the wall surface (top dotted line). This is derived from the measured wall surface temperature (bottom dotted line) and the water vapour concentration derived from the measured RH and temperature in the church (solid lines). The steadiness of the wall surface RH indicates perfect buffering in the boundary layer of air at the wall surface.

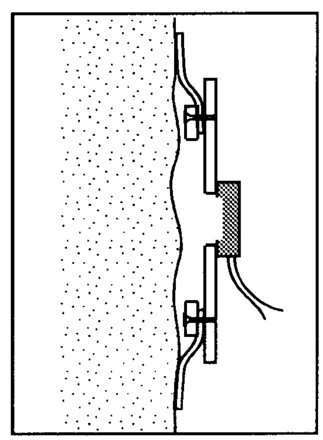

Fig. 6. Cross section of the chamber used to measure the microclimate in equilibrium with the wall. The area of wall exposed within the chamber is 0.07 square meters. The RH sensor (grey) is within the chamber but at room temperature.

Long term humidity buffering by the walls

Figure 9 shows the inside (solid) and outside (dotted) temperature and relative humidity for a period of one week in summer. The stabilisation of the interior climate is impressive. Our case for the use of porous walls for humidity stabilisation is complete. Limestone tufa is a rare material in most parts of the world but lightweight concrete is a good substitute. It has a rather steep absorption curve (See fig. 2). Bare concrete is regarded with disfavour in museums because of its tendency to release alkaline particles into the air. Fully reacted concrete does not effloresce in this way, besides the surface can be covered with porous wallpaper, distemper paint (pigment in a base of chalk powder with glue or carboxymethylcellulose binder) or simply lime plaster. These alkaline materials give the bonus of absorbing the predominantly acid gases that pollute the atmosphere of museums. There are traditional materials with significant buffer function. Mud is good. Wood is excellent as a buffer but it emits acetic acid vapour and it is flammable.

Humidification by porous walls and floors

Gundsømagle church enjoys a moist as well as a stable microclimate. Figure 10 shows a typical week's climate in winter. The RH stability is impressive but the inside RH is consistently higher than that attained by warming outside air to the inside temperature (dotted line). There must be some continuous source of water.

One source can be identified by a glance at the lower part of the wall inside the church: it is green with algae! The wall is saturated to about 300 mm above the floor. Water vapour also comes through the porous floor. When we put the chamber, shown in figure 6, on the floor, the RH within it rose to 100%, indicating that the floor acts as a water vapour source, not as a buffer. The process was however very slow. We assume that the lower wall is the source for most of the water. The observed RH is the equilibrium resulting from competition between evaporation from the walls and air leakage from the church, with the upper parts of the walls providing buffering. The amount of water added to the church air is about 15 kg per day in winter.

There is one other possibility. There may be a transfer of the outside RH, which averages about 90% in winter, through the porous wall. In climate engineering textbooks it is stated that water vapour will move through a porous wall in the direction that tends to equalise the water vapour pressure inside and outside, not the relative humidity. This generalisation, however, only applies to large holes and to pores which do not react to water vapour in any way. Porous limestone does absorb water vapour according to the local RH, a process that is only slightly affected by temperature. It can therefore be regarded as a relative humidity transmitter: water vapour moves through in the direction that tends to equalise RH within and without. The process is probably rather slow, because the RH in the chamber sealed to the wall is only slightly higher than that in the church. It seems likely that the rising damp in the walls is the main source of water vapour. Only measurements of the water vapour flux through the various surfaces can confirm our theory. We have not yet succeeded in doing this and would welcome suggestions.

The wall seems to be performing a double function: evaporation from the lower part and RH buffering higher up. We have tested this theory by measuring the capacity of the wall to absorb water vapour at different heights. To do this we set a damp cloth in an insulated cup and pressed the cup against the wall with a small air gap between cloth and wall (fig. 11). The temperature difference established between cloth and wall is a measure of the rate of water absorption: evaporation from the cloth withdraws heat from the surroundings (just like a psychrometer's wet bulb), absorption by the wall releases heat. The rate of water absorption by the wall was zero at 300 mm from the floor

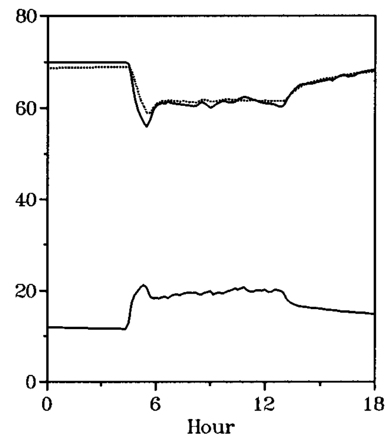

Fig. 7. The RH measured in the chamber sealed against the wall (dotted line), compared with the RH measured in the free air in the church (upper solid line). The close coincidence of these values supports the theory that the RH in the church is buffered by the walls.

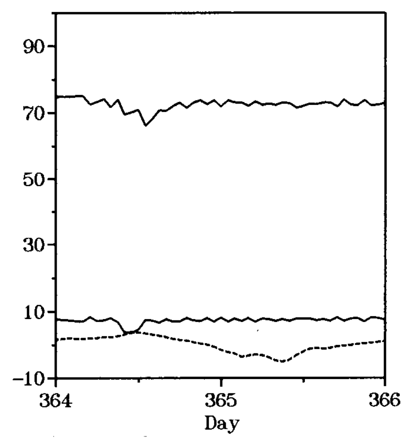

Fig. 8. Evidence for RH buffering after a complete filling of the church with fresh air. When the door is opened at 364.4 the dew point of the inside air (lower solid line) drops to the dew point outside (lowest line). When the door is closed the RH (upper solid line) returns rapidly to its earlier value.

but increased up the wall, confirming that the wall is actually functioning in two separate ways.

Fortunately, the remains of the wall paintings, whose preservation provided the impetus for this investigation, are high on the wall, above the zone of evaporation. Indeed it is possible that the water evaporating from the bottom of the wall is re-absorbed higher up, providing the ideal condition that salts will tend to move away from the painted surface. Unfortunately this free source of humidification from the rising ground water also draws salts up from the ground, so it cannot be regarded as the ultimate solution. The floor construction, with its capillary breaking, but permeable structure, seems a more elegant solution to humidification of the church but it does not work fast enough.

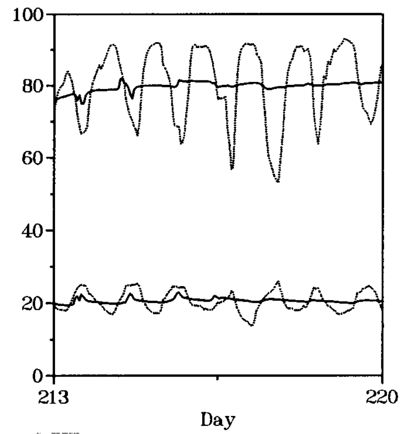

Fig. 9. Buffering of the church interior RH over a week in summer. Outside (dotted) and inside RH and temperature are shown.

Conclusions

A study of the microclimate in Gundsømagle church has revealed that the porous lime plaster of the walls provides a perfect buffering of the relative humidity in the air next to the walls during periods when the church is rapidly warmed for a service, though the temperature difference between wall and air results in a dip in the RH measured in the church. The plaster and the porous limestone walls effectively buffer the inner climate against variation in outside relative humidity, in spite of the 0.3 air changes per hour in the church. The church also humidifies itself in winter, probably through evaporation of water from the saturated lower part of the walls. The wall functions as a source of water in its lower part and as a buffer for relative humidity higher up.

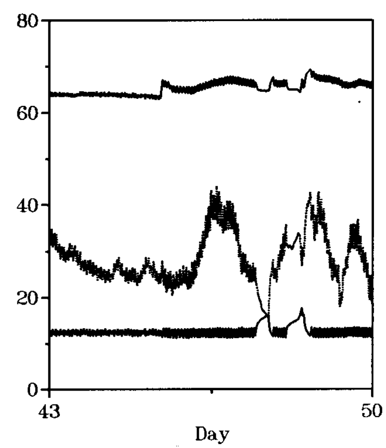

Fig. 10. Buffering and natural humidification in winter. RH and temperature inside (solid lines) are shown. The center dotted line is the RH expected inside in the absence of humidification and buffering. It is calculated from the water content of the outside air at the inside temperature.

The RH stabilisation provided by porous walls can surely be used in museum architecture. Lightweight concrete's steep absorption isotherm (fig.2) indicates that it will buffer RH even more effectively than the limestone walls described in this article. Internal walls will buffer perfectly because there will not be a significant temperature difference between wall surface and air.

Architects could also explore the possibility of free humidification by allowing water vapour to diffuse through porous floors with a rubble layer beneath to break capillary movement and thus prevent the efflorescence of salts on the floor.

All these processes for stabilising RH and for humidifying are most effective when the air exchange rate is fairly slow, about 0.3 air changes per hour. Massive absorbent walls can buffer both the heat and the water vapour from visitors. The only problem is to avoid carbon dioxide poisoning. Ventilation systems that provide the minimum air exchange that gives an acceptable carbon dioxide concentration are becoming more common in museums, so there is some scope for a hybrid technology that takes these natural passive processes and combines them with cunning technology to make more economical, and maybe more congenial museum design.

Porous outside walls are currently unfashionable in new buildings. The universal trend for buildings in a cool climate is to incorporate an air barrier close to the inner side of the wall, to prevent warm humidified air from moving outwards, cooling and depositing dew within the outer wall, with consequent corrosion and frost damage. Such a barrier is necessary in walls with porous, non-hygroscopic insulation, such as glass fibre and rockwool. We suggest that a re-evaluation of the advantages of homogeneous, hygroscopic and porous walls might well lead to cheaper and more durable museum buildings.

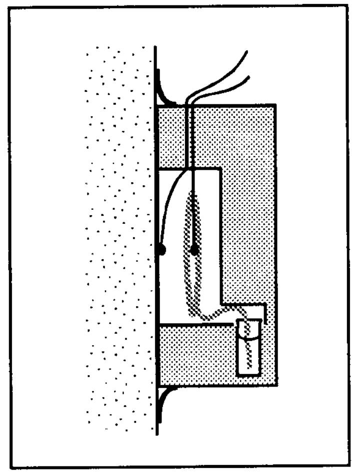

Fig. 11. Apparatus used to measure the ability of the wall to absorb water vapour. An insulated chamber is sealed against the wall. In the chamber is a flat bag of wet cotton cloth containing a thermocouple. The cotton is provided with a wick which dips into a small vial of water. A second thermocouple touches the wall surface. The temperature difference, combined with the thermal resistance of the air between cloth and wall, allows measurement of the rate of water absorption by the wall.

Acknowledgements

We thank Peder Bøllingtoft, wall painting conservator in the Conservation Department of the National Museum, for his help in many aspects of this work. Prof. Anders Nielsen of Denmark's Technical University measured the absorption isotherms of the materials of the church. Niels Bergsøe of the Danish Building Research Institute measured the air exchange rate. Funds for the investigation came from the research fund of the National Museum's Conservation Department and from the Conservation School of the Royal Danish Academy of Arts.

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