Humidity regulation in earth buildings

Dr Paul Jaquin, Ramboll Edinburgh, Visiting Research Fellow, University of Bath

Abstract

Earth buildings (for example sun dried mud bricks, rammed earth and cob) are known to control internal relative humidity. There is an optimum relative humidity range within which humans operate best, if the relative humidity is too high, then a space feels hot and stuffy, if the relative humidity is too low, this tends to dry the eyes and throat. Some benefits of keeping relative humidity within a specific range are given. Museums and art galleries require a constant relative humidity to preserve historic artefacts. This paper defined relative humidity and outlines the mechanisms by which earth buildings regulate relative humidity. Two types of relative humidity regulation are described, balancing and buffering, and a qualitative descriptions of each process discussed. Ongoing research work at the University of Bath is described, which will enable the quantification of these processes such that earth building elements may be designed by engineers to achieve humidity balancing within a building.

Introduction

Earth buildings take many forms around the world. The traditional notion of 'mud hut' hides a plethora of architectural styles and a rich heritage stretching back thousands of years. Modern earth buildings are becoming increasingly popular, requiring much less energy for their construction and maintenance. 20% of UNESCO world heritage sites are constructed for unfired earth, and it is estimated that around 2 billion people live in earth buildings (Houben and Guillaud 1994).

Earth buildings take many forms around the world. In the UK, the placing of damp clayey soil to form walls – known as *cob* is particularly prevalent in Devon, Hampshire, East Anglia and in the Solway Plain (Hurd and Gourley 2000). Moist soil placed between removable formwork boards is called *rammed earth*, and is which is found around the Mediterranean rim, north India and western China (Jaquin, Augarde *et al.* 2008). Sun dried clay bricks, known as *adobe* are common in much of North Africa, historic Persia and many parts of south America. Structures made from woven or laid timber plastered with mud are found through much of Africa and in the UK are known as *wattle and daub*. Most recently, in the UK rammed earth has been promoted as a sustainable building material, able to provide both thermal mass and relative humidity balancing potentially using material available on site (at projects such as WISE at the Centre for Alternative Technology in Wales and the Rivergreen Centre in County Durham). Unfired clay bricks have been developed as an alternative to fired masonry or concrete blockwork, used as infill between timber frames. In Germany, clay plasters are becoming increasingly popular, as they are felt to improve the internal ambience of a building (eg Minke 2007)

Earth buildings provide a pleasant internal environment and tend to provide a constant internal relative humidity. Their ability to do this has been qualitatively shown by a number of authors (Minke 2000; Morton, Stevenson *et al.* 2005) but the mechanism for this were previously unknown. Jaquin, Augarde *et al.* 2009 showed that earth building materials maybe considered using unsaturated soil mechanics principles, with additional bonding between soil particles provided by bridges of water held under surface tension. These water bridges provide additional strength and stiffness to the soil allowing vertical faces to be formed, compared to saturated or completely dry soil which act as purely frictionally, forming slopes at their angle of internal repose. The number and strength of these liquid bridges is a function of the relative humidity of air in the pores between the soil grains, and the relatively open pore structure of earth means that it is able to take in water vapour from the air, allowing the liquid bridges to grow and earth walls to store moisture from the air.

Humans and relative humidity

Relative humidity describes the amount of water vapour in the air, and is given as a percentage, with low relative humidity tending to dry the throat and eyes (aeroplane cabins are held at 20-25% relative humidity to prevent corrosion of exposed aluminium) and high relative humidity tending to cause a space to feel stuffy. The recommended relative humidity for humans comfort is between 30 and 60% (Balaras, Dascalaki *et al.* 2007; Wolkoff and Kjærgaard 2007).

Sporik, Holgate *et al.* (1990) showed a clear link between house dustmite exposure and asthma development in children in the UK. Arlian (1992) showed that allergen production by house dust mites is directly influenced by relative humidity, and that mites feed and multiply more at higher relative humidity. Tetsu, Akio *et al.* (1999) showed that house dust mite concentrations were directly related to relative humidity levels. Therefore, by reducing relative humidity within a building, it may be possible to reduce incidences of asthma development.

Adan (1994) showed that short term peaks in relative humidity, such as through boiling water for cooking, will allow fungal growth, and Straube and DeGraauw (2001) argue that the speed with which a wall can absorb moisture is important for avoiding surface condensation and therefore fungal growth, which may be detrimental to health (Portnoy, Kwak *et al.* 2005)

Relative humidity

A body of water contains water molecules in constant random motion by virtue of their kinetic energy. At the surface of the water body, some molecules gain sufficient momentum to escape from the body of water, and join the water molecules in the air surrounding the water. The water molecules in the air are known as water vapour and are also in random thermal motion, sometimes gaining sufficient momentum to enter the body of water. When the number of leaving molecules is equal to the number of arriving molecules, an equilibrium state is reached. When more molecules are leaving than arriving, the body of water can be seen to be evaporating, and when more molecules are arriving than leaving, the body of water will grow through condensation.

The proportion of water molecules in the air to the maximum possible number of water molecules which could be present is known as the relative humidity. Air containing the maximum number of water molecules possible is termed saturated. The relative humidity can be determined by considering the vapour pressures of the fluids in question. The ratio of actual vapour pressure (p_v) to the saturation vapour pressure (p_0) is known as the relative humidity, RH .

$$RH = \frac{p_v}{p_0}$$

The saturation vapour pressure (p_0) is highly temperature dependent, and so the relative humidity is also highly temperature dependent. For example air at 100% relative humidity at 20°C contains the same mass of water vapour as air at 75% RH and 25°C and 55%RH and 30°C. It is therefore possible for a room to go from stuffy and cool to warm and bearable, by increasing the temperature. The volumes of water involved are however extremely small, with air at 100%RH and 20°C containing around 12.5ml per cubic metre of air. By contrast, typical external air, at 50% RH and 10°C contains 5ml of water per cubic metre of air. It can therefore be appreciated that the water vapour produced in the home through cooking and showering can easily increase the relative humidity of an internal space.

How earth buildings regulate relative humidity

Earth buildings regulate the relative humidity by holding water in the form liquid bridges, and it is these liquid bridges which provide the strength and stiffness of earth bridges. These bridges are stable in pores of radius r which is given by the Equation below

$$r = \frac{2\sigma_t v_w}{RT} \ln(RH)$$

where σ_t is the surface tension, v_w is the specific volume of water, $R$is the universal gas constant, T the temperature in Kelvin and RH the relative humidity. In earth buildings, the pores between the soil particles contain these liquid bridges.

If there is a difference in the relative humidity between that required for a given pore radius (Equation 2) and that of the pore air, then water molecules evaporate from or condense to the liquid bridge, changing its volume. The ability of a mud brick to hold water depends on the volume of these liquid bridges, and various isotherms can be defined for the water content of an earth brick at different relative humidity (for example Heath, Lawrence *et al.* 2009). Where the water vapour has evaporated from the liquid bridges to the pore air, there exists a water vapour pressure gradient between the pore air and the external air. Assuming the relative humidity of the air is higher than the relative humidity of the pore air, this pressure gradient drives water vapour from the air to the wall, reducing the water vapour pressure of the air and increasing the water vapour pressure of the air in the pores of the earth wall. The rate of this transfer is given in very general terms by Ficks law (Fick 1855) given below where J is the diffusion flux (amount of substance per unit time) $D_e$is the effective diffusion coefficient which is a function of the porosity, tortuosity and constricitivity of a porous medium and $\frac{\delta\phi}{\delta x}$ is the one dimensional concentration gradient.

$$J = -D_e \frac{\partial\phi}{\partial x}$$

Earth walls therefore allow transfer water vapour to transfer through them, given a relative humidity and therefore water vapour pressure gradient (relative humidity balancing), or to absorb and emit water vapour for given fluctuations in relative humidity (relative humidity buffering).

Practical applications and examples

This section outlines the practical applications of using earth in the buildings fabric for relative humidity buffering. There are obviously a myriad of possibilities for the placement of earth within a building, from using an unfired earth floor, to clay plasters and unfired clay brick walls or a whole earth structure. This section shows two practical applications, relative humidity balancing and relative humidity buffering.

Relative humidity buffering

Buffering relative humidity inside a building evens out the peaks and troughs of relative humidity produced during the day or year but does not remove any water vapour from the system. Relative humidity buffering is achieved by placing an earth wall within an otherwise vapour impermeable building envelope. Figure 1 shows the plan view of a space with idealised relative humidity buffering for a constant internal temperature. The earth wall, or earth plaster is shown in brown, with the vapour impermeable building fabric shown in grey. The initial conditions are assumed to be a relative humidity of 50% RH in both the internal air and the pores in the earth wall. If a water vapour source is introduced (for example showering, drying washing, boiling a kettle or cooking) then the relative humidity of the space would tend to increase (this is usually seen by as steaming up of mirrors or windows during such activities). If an earth wall is present in the space, then some of the water vapour will be absorbed by the wall, causing an increase in the relative humidity in the pore spaces, therefore the size of the liquid bridges and the water content of the wall. The time taken for this, and the storage capacity of the wall are a function of the area, thickness and pore volume distribution of the earth wall. If the water vapour source is then removed, then the relative humidity of the pore air in the walls is greater than the of the space, so there is a flow of water vapour from the wall to the room, increasing the relative humidity of the room. However, the relative humidity of the whole system is still higher than in the initial case, so an air change is required. Relative humidity buffering can therefore be used to smooth peaks in relative humidity caused by cooking or showering, but is unable to remove water vapour from the system. In most housing applications, the natural response to increases in relative humidity is to open a window to reduce relative humidity. However, this is a huge source of heat loss, and forthcoming building regulations and the Passivhaus standard recommend against using occupier openable windows to allow for better building climate control and a lower energy requirement . Relative humidity buffering allows a smoothing of peaks in relative humidity, while still requiring air changes as specified by the Passivhaus standard.

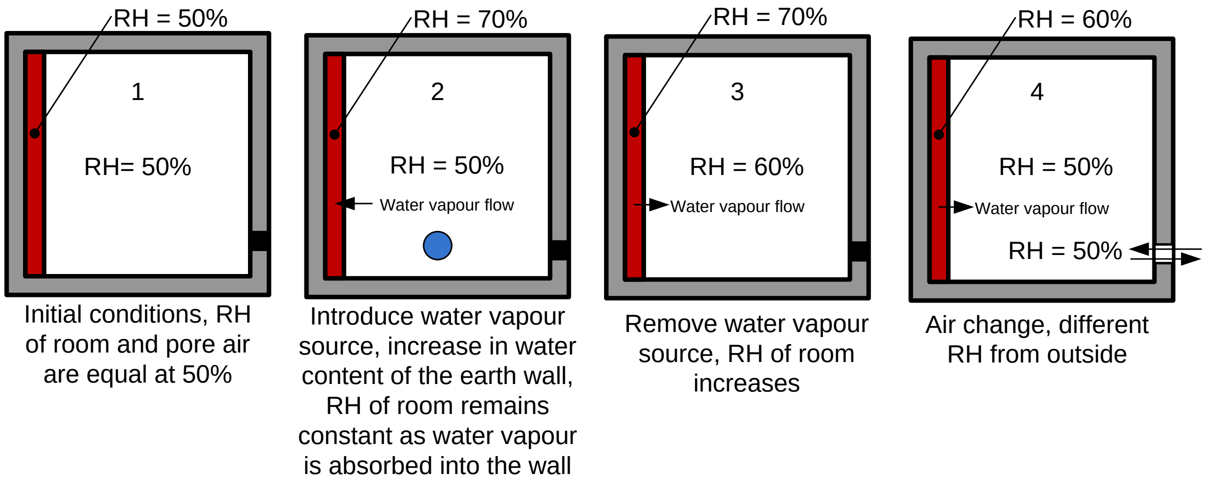

Figure 1 Relative humidity buffering. Values are indicative only. Grey represents an impermeable box, brown an earth wall or plaster.

Relative humidity balancing

Relative humidity balancing occurs where there is a difference in relative humidity between the inside and outside of a building, and the humidity of an internal space follows the moving average o the external relative humidity. In the UK the external relative humidity fluctuates between around 50% and 100%, while the internal relative humidity of building also fluctuates, but generally on a shorter time scale. Figure 2 shows an schematic plan of a building with perimeter earth walls. The external relative humidity will increasing during rainfall, and will change with temperature, with lower night time temperatures meaning that that saturation vapour pressure of water vapour is reduced, thereby increasing the relative humidity. Inside a building, relative humidity peaks occur when water vapour is produced through activities such as showering and cooking. If an earth wall is placed on the perimeter of a building, the internal and external faces are subject to different relative humidity and therefore there is a vapour pressure difference between each face of the wall. This vapour pressure difference means that there is a movement of water vapour through the body of the wall with the pressure gradient. Therefore, for example, if it is raining outside, the vapour pressure gradient means water vapour flows through the wall, increasing the internal relative humidity. If there is a source of water vapour inside the building, then water vapour flows through the wall reducing the internal vapour pressure and relative humidity. Over time, the relative humidity of the internal space becomes the moving average of the internal and external relative humidity. The water content of the wall is a function of the relative humidity of the wall pores, which varies through the wall given the relative humidities at each side. Morton, Stevenson *et al.* (2005) showed that the internal relative humidity of a timber framed, unfired clay brick house closely matched the external relative humidity on a 40 day moving average. Relative humidity buffering also occurs during relative humidity balancing, and peaks and troughs of relative humidity are smoothed.

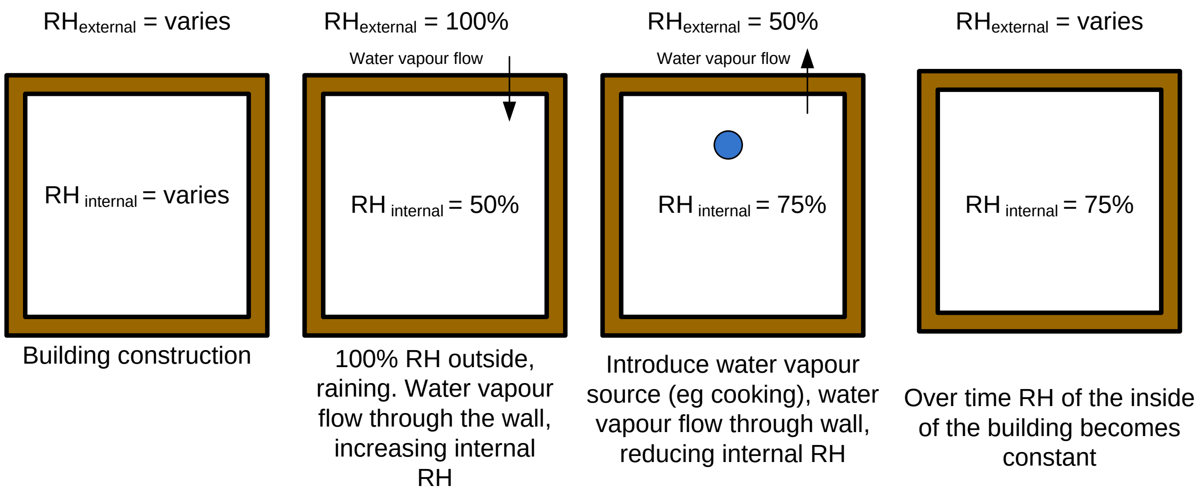

Figure 2 Relative humidity balancing. Values are indicative only

Ongoing research

Research is currently being carried out by the author as part of a Visiting Research Fellowship at the University of Bath to look at the relative magnitudes of these processes. Although the mechanisms as described above are qualitatively understood, and there are studies which investigate building scale processes, it is still difficult to determine the area or volume of earth wall required to buffer or balance a given relative humidity. Further work planned involves experimentally determining the effective diffusion coefficient D_e for specific earth building materials, thereby allowing design of relative humidity buffering and balancing systems. It may be possible to buffer humidity within a building using a 20mm thick clay plaster on internal surfaces, or this may require mass rammed earth walling though the centre of the building. With a quantitative understanding of the processes, it will be possible to actively design surfaces and building elements for a constant internal relative humidity for zero energy input.

Concluding remarks

This paper has presented the basic principles of relative humidity buffering as provided by earth building materials. The constant relative humidity inside earth buildings has frequently been presented as beneficial to health and a reason to use earth as a construction material. This paper has outlined the concepts of relative humidity balancing and buffering, and described the processes qualitatively. Further research will determine the magnitudes of these processes, allowing the design of humidity balancing systems. The dependence of relative humidity on temperature was outlined above, and the role temperature plays in balancing humidity is also under investigation. Earth building materials can be used to regulate humidity within a building, but the rate at which this is achieved is not yet fully understood.

Control of the relative humidity is currently not generally considered in building design, however the benefits of keeping relative humidity within limits outlined above mean that it should be considered in future design. Where HVAC systems are used to control internal relative humidity, earth walls reduce the need for their operation and provide an energy free method of regulating relative humidity.

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