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A review on the buffering capacity of earth building materials

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Unfired clay building materials are recognised for their ability to regulate indoor humidity levels through their moisture buffering capacity. Research is being conducted on the moisture buffering capacity of a variety of building materials with natural materials, such as clay, and organic materials, such as hemp or straw, presenting a greater potential to regulate indoor humidity than industrial building materials. Due to their high affinity to water, which is usually regarded as detrimental, clay materials present complex hygrothermal coupling phenomena, which are still under investigation. This paper summarises some recent investigations into the dynamic water adsorption process within clay materials in relation to their ability to regulate indoor air humidity levels. First, a review of the experimental methods to characterise this behaviour is provided. A review of experimentally measured results on the material scale using compressed earth block, rammed earth or plaster samples is then provided, followed by some larger and whole building measurements.

1. Introduction

Earth materials are used in various ways in buildings and this includes rammed earth, compressed earth blocks (CEB), earth plasters and cob. Such buildings must have the ability to cope with materials that are very sensitive to water in both liquid and vapour phases. This hydrophilic behaviour leads to a variety of interactions between the building material and water present inside or outside the building (Houben and Guillaud, 1994; Minke, 2012; Schroeder, 2010; Walker *et al.*, 2005), leading to complex building response.

These interactions can be detrimental to the mechanical properties of raw earth as the strength of unstabilised earth materials decreases with increasing water content (Champiré *et al.*, 2015; Heath *et al.*, 2009; Morel *et al.*, 2007); this has resulted in a number of studies on stabilising raw earth to make it less sensitive to the effects of water (Maskell *et al.*, 2014; Oti *et al.*, 2009a, 2009b; Venkatarama Reddy, 2012). However, in many situations where these materials are used with appropriate building techniques and applications, the integrity of the buildings can be preserved without stabilisers. The moisture content of the raw earth also influences its thermal properties. In particular, the thermal conductivity and apparent heat capacity tend to increase with the amount of water within the material (Allinson and Hall, 2010; Hall and Allinson, 2009b, 2010); this can affect energy performance of the building, which can have either positive or negative consequences.

The hygroscopicity of raw earth drives the material to achieve equilibrium with the vapour pressure in its environment.

Excess moisture loads are adsorbed by the material and are released during low moisture load phases (e.g. empty building). Adsorbed water is weakly bonded to the surface of the particles, whereas absorbed water is loose water held within the porous structure of the material. The term absorbed is often used as a generic word instead of adsorbed in the literature. In the context of moisture buffering, water is adsorbed. In the indoor environment where relative humidity (RH, ratio between vapour pressure and the saturation vapour pressure) levels are fluctuating due to internal moisture loads, the raw earth can act as a passive buffering material. This allows smoothening moisture level peaks and stabilising RH levels. Indoor air quality is closely linked to indoor RH levels (Arundel *et al.*, 1986) and therefore moisture buffering could be beneficial for the health and well-being of the occupants. Furthermore, the sorption–desorption of water molecules induces latent heat that can significantly impact the thermal behaviour of the material. It follows a complex hygrothermal behaviour that can lead to a higher thermal performance than expected from the sole knowledge of the thermal characteristics of the material (thermal conductivity and heat capacity) (Soudani *et al.*, 2015).

Historically, the industrial revolution led to new materials and new building methods and much of the vernacular relation between outdoor climate, building materials and architecture was lost. A corresponding mechanised approach to control indoor climate was adopted and existing passive methods were discarded in much of modern architecture (Mahdavi and Kumar, 1996).

Mahdavi and Kumar (1996) critically discuss the mechanically controlled environment, the viability and consistence of a believed ideal indoor environment regardless of the exterior climate and human adaptability. From their conclusion, the use of mechanical heating, ventilation and air conditioning systems is unsatisfactory in many respects. The technology at the time was nearly exclusively focused on thermal control and the systems were often unreliable and failed to deliver the set of environmental conditions they were designed for. The systems demanded regular maintenance, which is not systematically done, therefore creating poor performance (Mahdavi and Kumar, 1996). While more modern systems can include both temperature and RH control, RH control through ventilation only is governed by external RH levels, which may not be optimal and reliance on active mechanical dehumidification can be energy intensive. On the contrary, passive control does not depend on energy input and human supervision; it therefore represents a more resilient and sustainable option in many situations as the energy consumption of ventilation systems and dehumidifiers can be reduced (Woloszyn *et al.*, 2009).

To obtain passive control of temperature and humidity, the nature of building materials is of major importance. Earth building materials are widely perceived to be excellent passive humidity regulating materials and this paper aims to summarise experimental evidence that characterises the buffering behaviour of earth building materials.

2. The moisture buffering concept

This section presents a review of the available methods and protocols that have been used around the world to characterise the dynamic water vapour sorption properties of building materials. The reviewed methods generally follow the principle of step response, which subjects a material to a change in environmental conditions (typically change in RH) and monitors its gravimetric response (mass change with change in RH). A diagram of the typical set-up for this test is given in Figure 1. The measured value is the variation of the mass of the sample but results are usually presented in g/m^2 (mass variation per exposed surface area).

The details of the most common test procedures are presented in Tables 1 and 2. Table 1 presents the sample size, thickness and sealing method used by the different methods, while Table 2 describes the environmental test conditions used.

2.1 Step-response test protocols

The step-response method was first used at the Fraunhofer Institute for Building Physics in Germany (Fraunhofer IBP) and at Lund University in Sweden. A review was written by Svennberg *et al.* (2007) on experiments undertaken between 1960 and 2000 which included five papers. In Germany, the tested materials included wall materials, wood, carpets and curtains. Results were either expressed as 'moisture absorption' (g/m^2) plotted against time or as 'absorption coefficient' expressed in g/m^2 √h. Typical results for plasters (lime plaster, lime cement plaster and cement plaster) from the work undertaken in Germany varied between 35 and 55 g/m^2 after 8 h. The 'absorption coefficients' were the strongest for natural fibre carpets with 30–36 g/m^2 √h. Similar experiments were conducted at Lund University on the typical building and furnishing materials used in Scandinavian houses between 1980 and 2000 (Svennberg *et al.*, 2007).

In addition to the more general material tests, a German industry norm (DIN 18947 (DIN, 2013)) was created especially for earth plasters (DIN, 2013). This norm includes a description of a test method to characterise the water vapour adsorption capacity of the plaster under a 50% RH/80% RH step. The test uses the method proposed by Kunzel (1965) as described by Svennberg *et al.* (2007). However, there is no mention of the effect of air convection on the adsorption properties during the test compared with other standards. Indeed, the air convection above the samples is an important parameter in these tests, which can influence the results by 20%, and this can be expressed by the surface air film resistance to

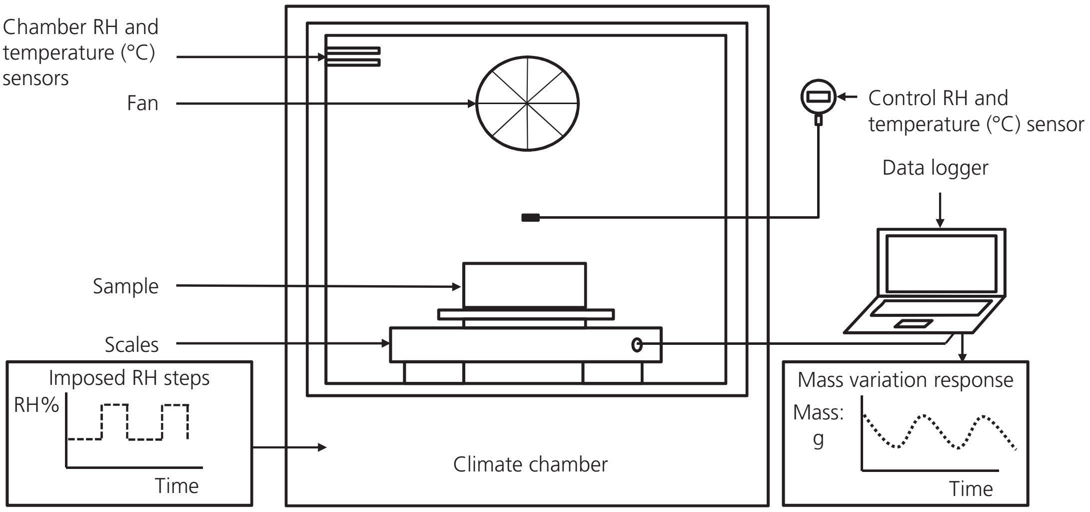

Figure 1. Diagram of the step-response method's typical experimental set-up

	Fraunhofer IBP	Lund University	DIN standard	JIS	Nordtest project	ISO standard
Sample dimensions	15 × 15 cm, 25 × 25 cm, 25 × 40 cm, 40 × 40 cm	Not specified	Min. 1000 cm^2	Min. 100 cm^2	Min. 100 cm^2	Min. 100 cm^2
Sample thickness	Real thickness	Not specified	0·15 cm	Real thickness	Real thickness or at least the penetration depth	Real thickness
Sample seal	Paraffin on five sides	Not specified	One side open metal form	Aluminium tape on five sides	Aluminium tape on five sides	Aluminium tape on five sides

Table 1. Sample dimensions

the transfer of water vapour. In this method, results are expressed in g/m^2 and a first classification is proposed (Table 3).

Only a few research publications can be found that use this test (Lima and Faria, 2013, 2014); it seems to be mainly used by the German earth building industry to characterise their products.

A moisture buffering test was proposed under a project initiated by Nordic countries and was intended to become a Nordtest method. The Nordtest project chose boundary conditions relevant to the use of a bedroom or office to quantify the moisture sorption performance of the building material. A round robin test was performed by several universities using this test method and the results were all comparable even with varying experimental set-ups (Rode *et al.*, 2005). In general, there is a good agreement between the results, but it is clear that particular attention needs to be given to the experimental set-up. The Nordtest proposes a unique value, the moisture buffering value (MBV), which offers a simple method of rating the moisture buffering properties of materials. The Nordtest method is currently the most commonly used, especially for earth building materials (Allinson and Hall, 2012; Collet *et al.*, 2008; Dubois *et al.*, 2014; Liuzzi *et al.*, 2012; McGregor *et al.*, 2012, 2014a, 2014b; Wilkinson, 2009).

A Japanese Industrial Standard (JIS-A1470 (JIS, 2002)) was proposed based on the same principle of the step-response method. A comparison of this test with the method of the Nordtest was

	Fraunhofer IBP	Lund University	DIN standard	JIS	Nordtest project	ISO standard
Preconditioning	40% and 20°C	Not specified	50% at 23°C	43, 63 or 83% (depending on the test conditions) at 23°C	50% at 23°C	43, 63 or 83% (depending on the test conditions) at 23°C
Temperature	20°C	Not specified	23°C	23°C	23°C	23°C
Low/high humidity steps	40%/80%	33%/75% (with intermediary stages of 44 and 54%)	50%/80%	30%/55%, 50%/75% or 70%/95%	33%/75%	30%/55%, 50%/75% or 70%/95%
High/low time steps	24/24 h	3/3, 6/6, 11/11, 48/48, 96/96 h	12 h adsorption	12/12 h	8/16 h	12/12 h
Humidity control method	Climate chamber	Chamber with humidifier and salt solutions	Not specified	Not specified	Climate chamber or salt solutions	Not specified
Number of scientific publications (before September 2015)	2	2	<5	<10	>20	<10

Table 2. Test conditions

Adsorption class	0·5 h: g/m²	1 h: g/m²	3 h: g/m²	6 h: g/m²	12 h: g/m²
WS 1	≥3·5	≥7·0	≥13·5	≥20·0	≥35·0
WS 2	≥5·0	≥10·0	≥30·0	≥30·0	≥47·5
WS 3	≥6·5	≥13·0	≥26·5	≥40·0	≥60·0

Table 3. German classification of moisture adsorption capacity of earth plasters

performed by Roels and Janssen (2006). There is mention of the surface film resistance in the JIS, which should be set to a value of $4{\cdot}8 \times 10^7 \pm 10\%$ m^2 s Pa/kg. This standard is not extensively referred to in research publications in English.

An International Standards Organization (ISO) protocol was published in 2008 (ISO-24353 (ISO, 2008)). The protocol is nearly identical to the JIS. Scientific publications using this protocol are limited, with only a few authors using the standard as a reference protocol.

2.2 Limitation of step-response tests

A limitation of the step-response methods is that they do not represent an intrinsic material property. The results are dependent on the chosen RH and time cycles and also on the experimental set-up; therefore, comparison between the different test set-ups is limited and it is difficult to compare results for different materials if the tests were undertaken using different methods.

The step-response test provides an indication of the material performance and allows a comparison with other building materials if the same test was used; however, the results from such dynamic tests cannot be directly used to estimate the whole building performance. At present, modelling of the buffering behaviour through a numerical calculation can be used with steady-state hygric properties, the determination of these under isothermal conditions from the step-response method is achievable (Abadie and Mendonça, 2009; Dubois *et al.*, 2014; Hall and Allinson, 2009a; Liuzzi *et al.*, 2012). A whole building situation requires the use of equations that represent the coupled heat and moisture transfer in the porous media (Soudani *et al.*, 2015; Woloszyn *et al.*, 2009) and the existing coupled models fail to model correctly the complex behaviour of unfired clay materials which could affect the outcomes (Kwiatkowski *et al.*, 2009; Soudani *et al.*, 2014; Woloszyn *et al.*, 2015).

3. Experimental work

In view of the variety of test conditions that have been used to characterise the buffering behaviour in laboratory tests it is difficult to extract values that can be compared from the literature. To obtain a better comparison of the data, the values of adsorption will always be expressed in g/m^2 and preferably for an 8 h time step at high humidity levels. For earth blocks (adobe)/CEB and rammed earth, work reviewed includes the thesis of Lustig-Rössler (1992) published in Germany and the work by Allinson and Hall (2012). For earth plasters, work by Eckermann and Ziegert (unpublished, 2006), Lima and Faria (2013) and Thomson *et al.* (2015) are reviewed. In both cases, the results are compared with recent work by the authors (Dubois *et al.*, 2014; McGregor, *et al.*, 2014a, 2014b).

3.1 Earth blocks/rammed earth

Experimental work characterising the dynamic adsorption of raw earth building materials using a similar step-response method used by the Nordtest method was first started in Germany (Lustig-Rössler, 1992) and this work is partially presented in the publication by Minke (2012). In this work, water vapour permeability, sorption isotherms and dynamic adsorption of three different soil compositions were measured. The three tested soils were as follow

- *mortar clay*: 14% clay, 24% silt, 57% sand and 5% gravel
- *silt clay*: 12% clay, 75% silt, 11% sand and 2% gravel
- *fat clay*: 28% clay, 33% silt, 37% sand and 3% gravel.

The dynamic moisture buffering test consisted of stabilising the samples for about 8 weeks at 35% RH in a climate chamber until the samples had reached equilibrium moisture content. The RH in the chamber was then increased to 75% RH and lowered back down to 35% RH with both a 24 h cycle and an 8 h cycle. Tests were then run for eight consecutive cycles. The results are presented as the final mass change in g/m^2 after each 24 or 8 h period.

During this study, these three soils were used as a baseline to further investigate different sample thicknesses of 1, 2, 3 and 4 cm, different waterproofing coats and different plaster formulations. Soil samples were also compared with other building materials such as gypsum, lime, cement plasters or treated and untreated wood. The samples were prepared as 100 × 100 mm cubes and five faces were sealed for the moisture buffering test with chlorinated rubber paint and paraffin, leading to one-dimensional moisture movement.

The average moisture uptake for 8 h periods for materials at 10 mm thickness varied between 45 and 65 g/m^2 for all earth materials and for fired brick and plasterboard the moisture uptake is no more than 1 g/m^2, whereas wood showed a slightly better adsorption of 25 g/m^2. Neither the experimental set-up for the moisture buffering test nor the sample preparation was described. There was no mention of surface film resistance or air velocity in the climate chamber.

Experimental measurement of moisture buffering was performed on stabilised rammed earth (SRE) by Allinson and Hall (2012). Three different particle size distributions were tested, the proportions are given per dry mass and no information on clay mineralogy was provided.

- '613 mix', which represents a mixture of 60% sand, 10% gravel and 30% silt and clay.
- '433 mix', 40% sand, 30% gravel and 30% silt and clay.
- '703 mix', 70% sand, 0% gravel and 30% silt and clay.

These mixes were stabilised with 10% per dry mass of Portland cement. The MBV was obtained from the 33%/75% cycles used in the Nordtest project with time periods of 8 and 16 h. The MBV practical varied between 0·68 and 1·29 g/(m^2 % RH) with the highest value for the 703 mix with no gravel. This is equivalent to moisture sorption values of 29 and 54 g/m^2.

In a more recent study by the present authors, more than 100 samples of CEB were tested, unstabilised and stabilised. Samples were prepared with different types of clay minerals (kaolinite and montmorillonite), and variable clay content. Density, initial water content (water content during compaction), stabiliser content and particle size distribution were also investigated. In addition, two commercial earth plasters were tested with and without the final coating (McGregor *et al.*, 2014b). Figure 2 shows the moisture buffering results according to the Nordtest method, with RH variation between 33 and 75%. In this figure, soils were all prepared as CEB and samples had an average dry density of 1863 kg/m^3 with a range between 1712 and 1961 kg/m^3; the content of silt and clay was considerably higher than in other studies; these ranged between 26 and 96% with highest content for the 'Ch' sample with the highest adsorption properties. The results illustrate the great variation of moisture sorption that is obtained when different types of soils are used. Furthermore, the study has shown that clay mineralogy and clay content are the main parameters defining moisture buffering, whereas material properties such as density only had a limited influence.

The calculated 'penetration depth', depth in the sample at which the humidity variation is <1/*e*% (or 1% depending on the convention, *e* is the Euler's number) of the surface variation, was shown to be lower than 10 mm for all samples, including earth plasters with lower densities. This was partially confirmed by experimental results where no difference could be observed in 3, 5 and 7 cm thick CEB. Equally no difference was observed between 1·2 and 2 cm thick earth plasters.

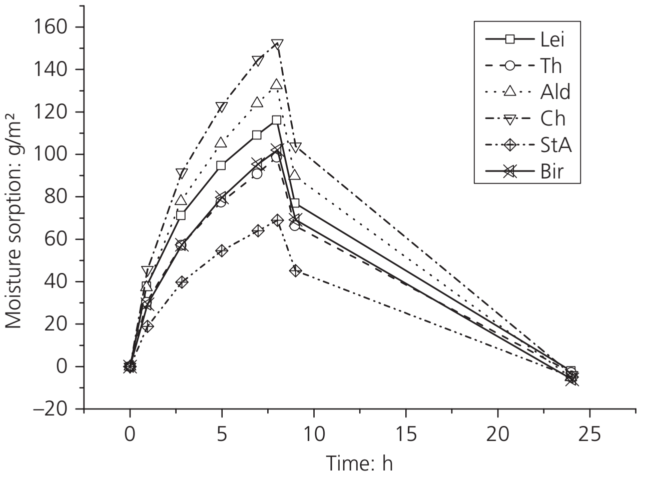

Figure 2. Dynamic moisture adsorption for various brick soils (soils used for fired brick manufacturing, Lei, Th, Ald, Ch, Bir correspond to the initials of their origin) and one soil that has been used for a rammed earth building (StA) (McGregor *et al.*, 2014b)

3.2 Earth plasters

On the basis of existing studies, earth plasters have generally a lower adsorption capacity than earth blocks, yet have higher MBVs than existing results on rammed earth and this is probably because rammed earth generally has a low clay content and low shrinkage (low expansive clay content) compared with earth blocks and plasters. This low clay content in rammed earth is largely because it is necessary for rammed earth to dry and shrink in situ after construction, while individual earth blocks can largely dry and shrink before wall construction. A study by Eckermann and Ziegert (unpublished, 2006) shows the adsorption results of earth plasters and common surface materials (Figure 3). Earth plasters largely exceed the adsorption capacities of common building materials. The strong adsorbing plaster reaches values close to 55 g/m^2 at 8 h adsorption. These results on earth plaster agree with other results from the literature (Lima and Faria, 2013), where the average moisture sorption at 8 h reaches values close to 55 g/m^2. These values are close to the least adsorbing CEB in Figure 2.

More earth plasters were tested at the University of Bath (McGregor, 2014) and show similar results. Two commercial plasters (Pla1 and Pla2) were tested at 12 and 20 mm thicknesses with and without a finishing coat of 3 mm. The finishing coats used were from the same manufacturers as the plasters. Neither the thickness nor the finishing coat had a decisive influence on moisture adsorption, as shown in Figure 4. Both plasters have similar adsorption capacity with a MBV close to 1·3–1·4 $g/(m^2\ \%\ RH)$. The test shows good repeatability, with all Pla1 samples having a moisture sorption around 55 g/m^2, whereas Pla2 has a moisture sorption slightly above 60 g/m^2.

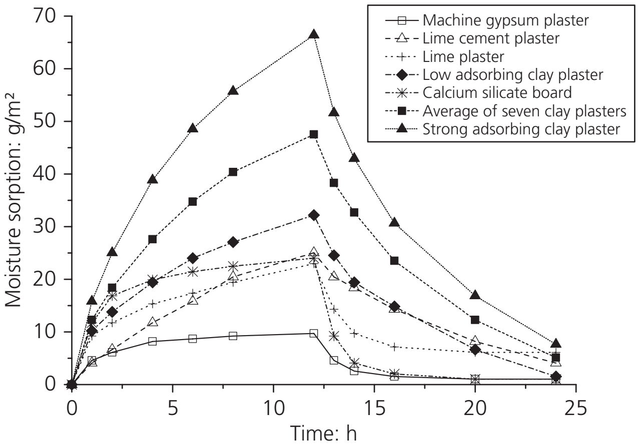

Figure 3. Adsorption data for 12 h cycles modified from Eckermann and Ziegert (unpublished, 2006)

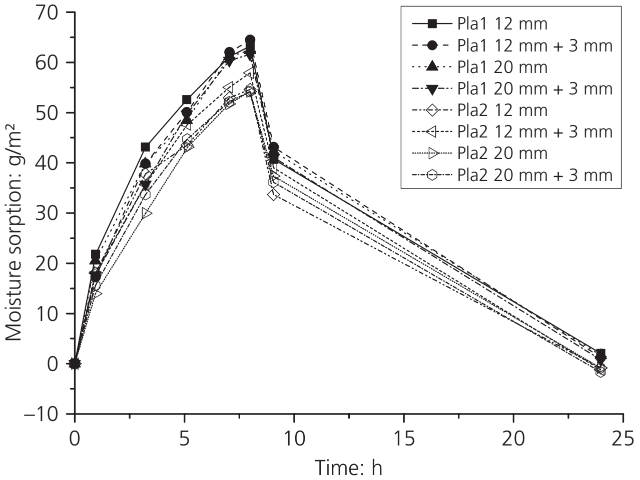

Figure 4. Moisture sorption of commercial earth plasters (McGregor *et al.*, 2014b)

3.3 Improving the adsorption capacity

The improvement of the hygrothermal properties of existing commercial clay plasters was investigated by Thomson *et al.* (2015). Novel clay coatings, which incorporate different mineral and organic aggregates as a substitution of equivalent-sized aggregates, ensured a consistent grain curve. In Germany, the common definition of clay plasters and mortars, as set out in DIN 18947 (DIN, 2013), provided the basis for this work. DIN 18947 (DIN, 2013) allows for flexibility in the use of novel aggregate additions as described below.

Mineral aggregates permitted in clay plasters

- all natural grains of sand and gravel
- brick dust; untreated/non-processed, without mortar
- natural lightweight filler – for example, perlite, expanded clay, natural pumice.

Organic aggregates permitted in clay plasters

- all plant parts and plant fibres
- animal hair
- chipped or cut wood; untreated, non-processed wood-based products.

The two novel mixes consisted of pumice and cellulose fibre additions of 35 and <1%, respectively. These were compared with two commercially available clay plasters used as a base coat and finishing coat. For reference, the novel mixes are termed 'pumice' and 'hemp', while the two standard mixes are termed 'top coat' and 'base coat'. The top-coat plaster is a clay and sand mix and the base-coat plaster is a clay, sand and flax fibre mix.

The moisture buffering properties were determined in accordance with ISO 24353 (ISO, 2008). Four cycles of the following conditions are run while the mass of the specimen is continuously recorded.

- Step 1: 12 h, RH of 75% and temperature of 23°C.
- Step 2: 12 h, RH of 50% and temperature of 23°C.

The introduction of novel plant and mineral aggregates had a positive effect on the moisture buffering capacity of clay plasters. The use of hemp shiv and fibres yielded a moisture buffering capacity 54% greater than that for the reference base-coat plaster. The use of pumice aggregate also gave a higher performance when compared with the standard base-coat plaster. However, unlike the hemp mix, the pumice mix has shown an almost equal level of performance with the standard top-coat plaster. The top-coat plaster incorporated flax fibres and a higher proportion of fines, which may, in part, give the 29% improvement over the base coat.

The rate of moisture adsorption and desorption is an important property to consider if an internal coating plaster is to be effective. The use of hemp shiv and fibre aggregates in clay plaster was found to increase significantly the initial rate of moisture adsorption and desorption when compared with the standard clay mixes. Both adsorption and desorption rates were more than 60% greater than for the standard base-coat plaster. The values at 12 h for a 50–75% cycle varied between 35 and 54 g/m^2.

A study by Stahl *et al.* (2013) investigated the improvement of the buffering capacity of plasters. Two clay plasters were included as reference in the study ('Lehmputz 1' and 'Lehmputzt 2'); following the Nordtest procedure the plasters were measured and showed moisture adsorption at 8 h of 59 and 53 g/m^2. In this study, a plaster was designed specifically to have a strong adsorption capacity, the measured adsorption capacity reached 90 g/m^2.

4. Full-scale buffering experimentation and in situ measurement

In situ observations are important to validate the experimental findings. Several larger-scale experimental tests have been undertaken utilising raw earth as a construction material and in situ observations such as the evolution of the indoor environment were monitored.

The large-scale tests reviewed include experiments conducted by Padfield (1998), a whole room experiment undertaken by Allinson and Hall (2010) with an SRE building and a monitored house by Morton (2010).

Padfield (1998) measured the influence of a material buffering capacity on the RH inside a flux chamber. The flux chamber was designed specifically to measure the buffering behaviour of building materials and had a volume of 500 l. This test used a controlled environment similar to the step-response test but it measured the influence of the material on the RH rather than the influence of the RH on the material. Padfield did demonstrate the high buffering capacity of clay materials through this experiment. The experience showed that end-grain wood has the best buffering performance followed by the unfired clay brick. In his thesis, Padfield specially developed a mixture of bentonite clay, perlite and straw as a buffering material. He recommends this material as having the 'best all-round performance'. Through his observations of buffering materials employed in a real building situation he concluded that buffering materials are efficient over variations of a few days, but 'even the best buffer, the lightweight bentonite/perlite mixture, cannot long prevent the indoor dryness that comes with the onset of the heating season in cold and temperate climates'. He noted that the buffering potential of the material has to be related to weight in a real building situation with the ventilation used. The experience through museum or archive storage, where the environment has to be controlled to avoid damage to any stored art works, shows that mechanical control of the climate without buffering material is only as reliable as the operator's vigilance. The use of buffering material allows a more resilient system where passive control can reduce fluctuations in RH and reduce energy costs.

A small rammed earth shed was monitored by Allinson and Hall (2010) and was used as a case study to compare simulation results compiled using the building simulation software Wufi. The buffering capacity of the exposed earth wall was compared with various surface coatings such as plasterboard, painted plasterboard and a vapour-permeable foil using the simulation tool. The weather data used in the simulation were collected close to the site and the material properties used in the software were determined by the authors. Results of this numerical investigation showed that SRE wall shows considerably lower RH fluctuation than cases with additional surface coatings.

This study determined the number of hours per day for each material where the RH inside the building was outside the given RH ranges. The climatic conditions were for winter months with a temperature variation between 2 and 12°C; therefore, high RH levels prevailed. However, only the painted plasterboard and foil had very high humidity levels above 80% during the whole day, which makes these conditions prone for mould growth.

In the case study of an inhabited house, Morton (2010) collected the results from a monitored bathroom with earth masonry walls. The variation of the RH remained within a range of 40–60% over a whole year, it is normally expected that higher humidity levels will be found in a bathroom. This range is considered as ideal for the health of occupants (Arundel *et al*., 1986).

These larger-scale experiments or monitoring show that clay materials can have a positive influence on the interior climate, and this relates to their dynamic response to the change in environmental conditions which has been described through the experimental work in the previous chapter.

5. Summary and discussion

Even though the experimental conditions of the step-response test described in Section 3 vary considerably, similar results can be observed and Figure 5 represents the different values of moisture adsorption measured at 8 h of adsorption. The type of material is described in the chart along with the low and high humidity levels used. The range is given as the minimum and maximum values in the literature regardless of the number of samples tested. The effect of experimental set-ups and air velocity is disregarded as these details are not always provided in the literature. Most have used the 33%/75% cycle; only two references have used higher values of 80%. Increasing the maximum value will have more influence on the results than the minimum as it corresponds to the sorption isotherm (curves describing the equilibrium moisture contents depending on RH level) where there usually is a sharp increase in equilibrium moisture content.

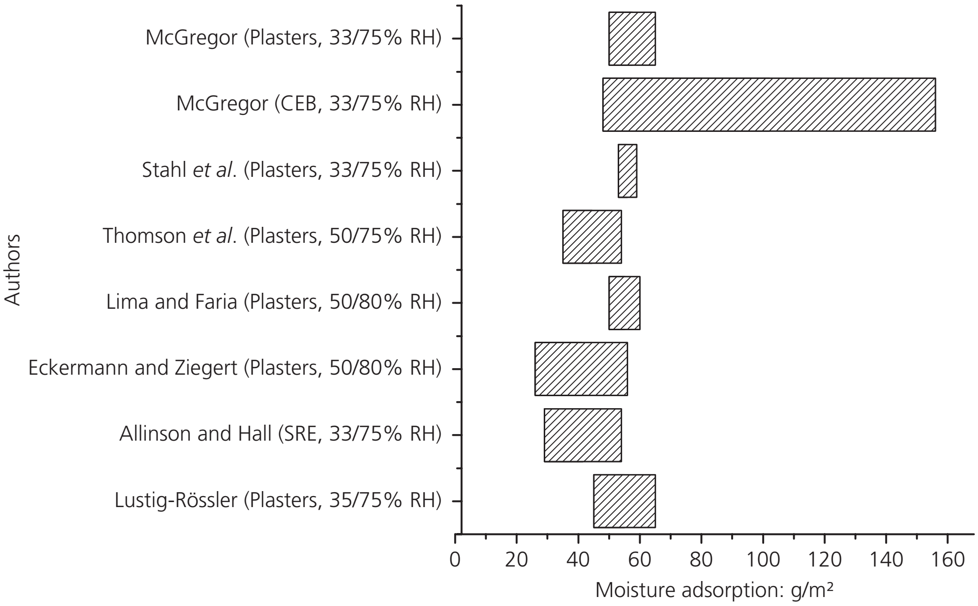

Figure 5. Ranges of measured moisture adsorption in g/m^2 at 8 h for CEB, SRE, adobe (non-compressed fibre/earth block) and plaster (fine-grained earth for surface rendering)

The observations made by Padfield (1998) through on-site investigation demonstrate that the behaviour of moisture buffering materials is highly variable; each situation may be unique due to parameters as variable as building design and climatic conditions. The experiment of the flux chamber seems complex to replicate by other laboratories and obtain repeatable results. The step-response method is simpler and therefore probably preferable to obtain standard measurements.

Very few in situ measurements of the effect of moisture buffering in earth buildings are available. The building monitored by Allinson and Hall (2010, 2012) was compared with other cases with a simulation tool. The house monitored by Morton (2010) showed good humidity conditions over a whole year; yet this also depends on other conditions such as the behaviour of occupants, the rate of ventilation and so on. The results could not be compared with another reference building.

The modelling of whole buildings under real conditions, and in particular the effect that the coupling of moisture uptake and temperature has on the material and building performance is still not well understood. Although theoretical models for this coupled hygrothermal behaviour do exist, the non-linear and hysteretic moisture buffering of earth building materials complicates the analysis. Experimental validation has not demonstrated the accuracy of coupled hygrothermal models for earth materials.

6. Conclusion

Earth building materials present a large variability by their nature, composition and physico-chemical properties and this variability is reflected in their hygroscopic properties. The test conditions from study to study also vary; therefore, the values obtained must be used and compared with caution and only data with the same test conditions can truly be compared. Only a few papers have investigated the dynamic adsorption characteristics of earth building materials, yet similar results can be seen. Earth plasters have a moisture uptake after 8 h that ranges from 30 to 70 g/m^2, and their performance could potentially be improved with the addition of organic and mineral aggregates such as hemp shiv, pumice or perlite. CEB can perform considerably better than plasters as their performance ranges at 8 h from 60 to 160 g/m^2, this is partially explained by the higher amount of clay and silt content that can be used for their manufacture and greater tolerance to the use of swelling clays. The soils used for clay plasters must have a minimum of shrinkage (retraction of the material after drying) to avoid any formation of cracks. Few data are currently available for rammed earth materials, so any conclusions regarding its relative performance compared with CEB or plasters would be premature.

Larger-scale experiments show that the dynamic adsorption capacity that can be measured through the step-response method influences indoor air quality. Whole building simulation tools now take into account the buffering potential of the building's envelope, but most of these rely on static data (mainly the vapour permeability and the moisture capacity) and those material properties are difficult and time-consuming to obtain and are often unreliable. The coupling of thermal and moisture models is not as advanced and is difficult to validate. The information from the reviewed papers clearly shows a lack of consensus on the method for characterising the buffering capacity, but the Nordtest does appear to lead in terms of publications.

While only a few case studies of earth buildings could be found in the literature, there is a growing interest in passive climate control and further case studies of monitored earth buildings along with material characterisation would bring valuable information to the scientific community, creating the potential for improved modelling which would in turn enable construction of healthier and lower-energy buildings. However, results clearly indicate that the use of earth is beneficial for humidity buffering compared with conventional industrial materials, offering a range of benefits, including low embodied and operational energy and improvements in health and wellbeing.

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