

Direct measurement of effective moisture buffering penetration depths in clay plasters

Introduction

Hygroscopic materials are able to passively regulate the humidity of the indoor environment. The use of these materials can have significant beneficial impacts on internal comfort levels and operational energy use, as well as improvements to the health and wellbeing of occupants. While this effect is observed in a variety of materials, the unique physiochemical properties of clay make it an excellent moisture buffering material. Clay is used as a construction material in a variety of applications, including structurally such as rammed earth or earth masonry, or as a finishing plaster. Consequently, the range in thickness of earth construction exposed to an indoor environment varies from 3 mm of clay plaster, to 400 mm or more for a structural wall. The depth of clay that is able to buffer humidity is considered to be dependent on the internal conditions but also on material properties.

The relative humidity of an indoor environment is closely related to the Indoor Air Quality and together they can have significant health and well being impacts on building occupants. Maintaining RH levels between 40-60% (Rode et al., 2005) is beneficial to the health of building occupants, reducing risks from agents such as bacteria, viruses, chemical reactions, allergies and respiratory infections.

When Relative Humidity (RH) changes the difference in the vapour partial pressure results in the material adsorbing or desorbing moisture in order to reach equilibrium. This dynamic ability is commonly referred to as moisture buffering and can vary greatly in building materials (Rode et al., 2005 and Padfield 1998). The effectiveness of the material is related to the available surface area, porosity and other physiochemical properties of the material.

Padfield (1998) demonstrated the enhanced moisture buffering potential of clay based materials compared to many other conventional materials. McGregor et al., (2015) comment that this is due to the hygroscopicity of the earth due to the unique physio-chemical structure of clay minerals. As seen in Figure 1, clay based plasters have a much greater mass change compared to lime or gypsum when exposed to the same changes in relative humidity.

There has been a growth in research into the moisture buffering properties of materials that would not typically be exposed to the indoor environment. This includes hygrothermal insulative materials such as hemp lime (Collet et al., 2013, Latif et al., 2015) and structural materials such as earth masonry (McGregor et al., 2014 and Ashour et al., 2015). Within a fluctuating RH environment, that is typical of indoor conditions worldwide, the sorption kinetics will mean that moisture can only penetrate to a certain depth during adsorption before desorption begins. While different test methods assume different fluctuations they are based on a 24 hour cyclic period. Therefore, the moisture buffering properties of substrate materials beneath an exposed surface may have negligible effects on indoor relative humidity compared to that of an exposed plaster.

The aim of this paper is to quantify the effective thickness of clay plasters through direct measurement. This has been achieved through an experimental approach of moisture buffering tests on varying thicknesses of clay plaster. In addition to the effective penetration depth of the material being established, the methodology is readily transferable to other materials. The significance of this is the ability to specify the minimum thickness of plaster to result in the maximum effectiveness of humidity regulation.

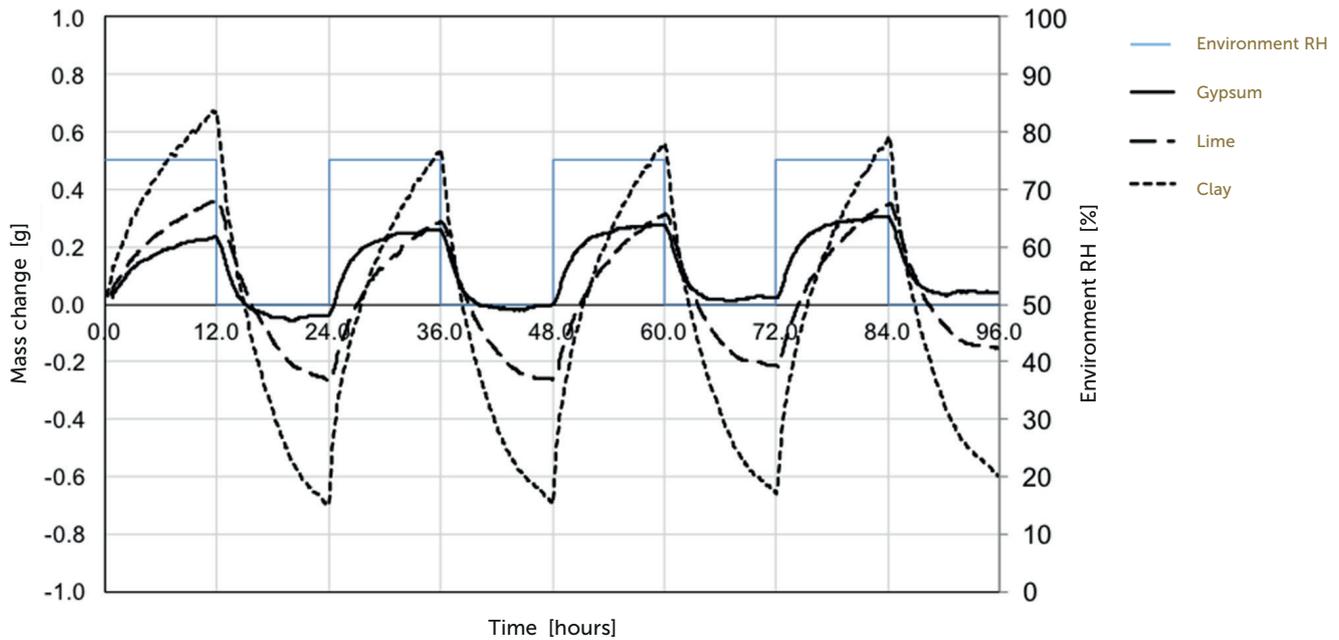


Figure 1 Mass change of plasters when exposed to changing relative humidity

Theoretical Penetration Depth

Whilst the focus of this research is the experimental investigation of the effective penetration depth of clay plasters, the NORD Test (Rode et al., 2005) procedure provides a numerical method of approximation. There are various methods of calculating the theoretical penetration depth (McGregor et al, 2015), with Woods et al., (2013) commenting that there is a difference in approach for short term and long term buffering effects.

The theoretical moisture penetration depth of a sample can be calculated using Kirchoff potentials that describe moisture transport (Rode et al., 2005). The NORD test methodology proposes a simplified method of an approximation based on a sinusoidal variation of the moisture content, u , considering the exponential decrease in amplitude for the surface Δu_s to a depth, dp , and given by Equation 1. The calculated 'penetration depth', is typically determined for a humidity variation that is $<1/e\%$ or 1% of the surface variation (McGregor et al., 2015)

$$\frac{\Delta u_x}{\Delta u_s} = e^{-dp \sqrt{\frac{\pi}{D_w t_p}}} \quad (1)$$

where

Δu_x is the amplitude,

t_p is the cycle time period (s), and

D_w (m^2/s) is the moisture diffusivity

The moisture diffusivity is dependent on the specific moisture capacity and water vapour permeability, which can be determined from two separate test methods. The specific moisture capacity is calculated directly from Dynamic Vapour Sorption (DVS), whereas the water vapour permeability is calculated as part of the determination of the vapour diffusion resistance factor. Additional calculations are subsequently used to give all the required variables for Equation 1. Therefore, a more direct measurement of the effective penetration depth is likely to be favorable compared to inferring it.

Materials and Methods

Materials

Two commercially available clay plasters were selected for the study. These engineered plasters are representative of base and top coat mixes, conforming with the only European standard for clay plasters; DIN 18947. These plasters have subtly different physical and chemical properties, that will result in variable moisture buffering properties.

The research presented in this paper focused on testing two different clay plasters, Figure 2. For reference the two standard mixes will be termed 'Top coat' and 'Base coat'. The Top coat plaster is a clay, sand and flax fibre mix and the Base coat plaster is a clay and sand mix. These plasters can be described as Reddish-Brown sandy SILT with a plasticity index typical

of low plasticity silts, and the engineering properties given in Table 1.

Experimental Methods

The primary aim of this study is the development of the experimental method for the determination of the effective penetration depth of moisture buffering. In addition to the measurement of the moisture buffering properties, mechanical properties were also determined. All the tests were conducted in triplicate 28 days after casting, with all specimens stored at 23C and 50% RH.

Physical and mechanical properties

The bulk density of the hardened mixes was determined in ambient conditions following EN 1015-10

(1999). The flexural and compressive strength was determined in accordance with EN 1015-11 (1999). Specimens were loaded under displacement control at a rate of 0.2 mm/min and 0.5 mm/min for the determination of flexural and compressive strength respectively. The results are presented in Table 1.

Theoretical penetration depth

The theoretical penetration depth is dependent on two independent measurements from isotherms and vapour diffusion experiments. DVS was used to determine the isotherm at 23C temperature and in the relative humidity range 0% to 95%. The vapour diffusion properties were determined according to ISO 12572:2001, investigating both wet and dry cup conditions following the climate chamber method.

Figure 2 Base coat (left) and top coat (right) clay coating specimens



Table 1 Material Characterisation

Properties		Base Coat	Top Coat
Physical Properties			
Liquid Limit	%	14.9	22.1
Plasticity Index	%	1.8	5.7
Linear Shrinkage	%	2.0	4.0
Particle Grading			
Sand	%	69	57
Silt	%	25	37
Clay	%	5	6
Physical Properties			
Bulk Density	kg/m ³	1870	1700
Porosity	%	24.8	30.42
Mechanical Strength			
Compressive Strength	N/mm ²	2.60	2.86
Flexural Strength	N/mm ²	0.97	1.19



Figure 3 Clay moisture buffering specimen

Moisture buffering test method

There are various methods to characterise the moisture buffering effect of a material. In Germany one method for clay plaster is described in DIN 18947, but no Euro-norm exists. The NORD test (Rode et al., 2005) is widely used, with similar methods used by the Japanese standard (JIS A 1470-1, 2002) and the ISO method (ISO 24353:2008). Roels & Jansen (2006) comment that although there is similarity between the test methods, the differences lead to non-comparable results. Of the three standards, the ISO standard test has introduced ranges of RH and time cycles that are most representative of indoor occupancy and is therefore the method adopted in this study.

The cyclic test method for mid-level humidity was adopted. This method required specimens to be pre-conditioned at a relative humidity of 63% and a temperature of 23°C before cyclic climatic variations were started. Four cycles of the following conditions were run whilst the mass of the specimen was logged:

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

Specimens were tested using environmental chambers programmed to subject the specimens to the humidity cycles set out above. Mass balances installed inside the chambers were used to record specimen mass at 5 minute intervals. A screen was

placed around the mass balance to minimize the influence of air movement over the surface of the specimens during testing. An anemometer was used to measure wind speed at the specimen surface and was found to be an average of 0.1 m/s. Fourth cycle moisture adsorption and desorption content values and rates were calculated in accordance with Section 8.3 of ISO 24353:2008.

The three thinnest specimen thicknesses for the moisture buffering tests were prepared in 150 × 150 mm moulds with varying thickness of 2, 4, and 10 mm. The moulds were made from plastic and wrapped in aluminium tape, acting as a permanent formwork. This allowed for thin coating to be accurately achieved while removing the risk of handling damage of the brittle material. The samples of 20 mm and 40 mm thickness were cast within phenolic plywood moulds, removed following 3 days of initial drying after casting. Aluminium tape was used to seal the back and sides of these specimens to ensure vapour exchange only occurred through a single face of the material (Figure 3).

The moisture buffering tests result in the measurement of the amount of moisture absorbed for a given specimen thickness under specific excitation profiles. It was therefore expected that as the specimen thickness increased so would the amount of moisture absorbed. However, this increase was only expected to be up to a certain depth of material, after which no significant gain in moisture would be observed.

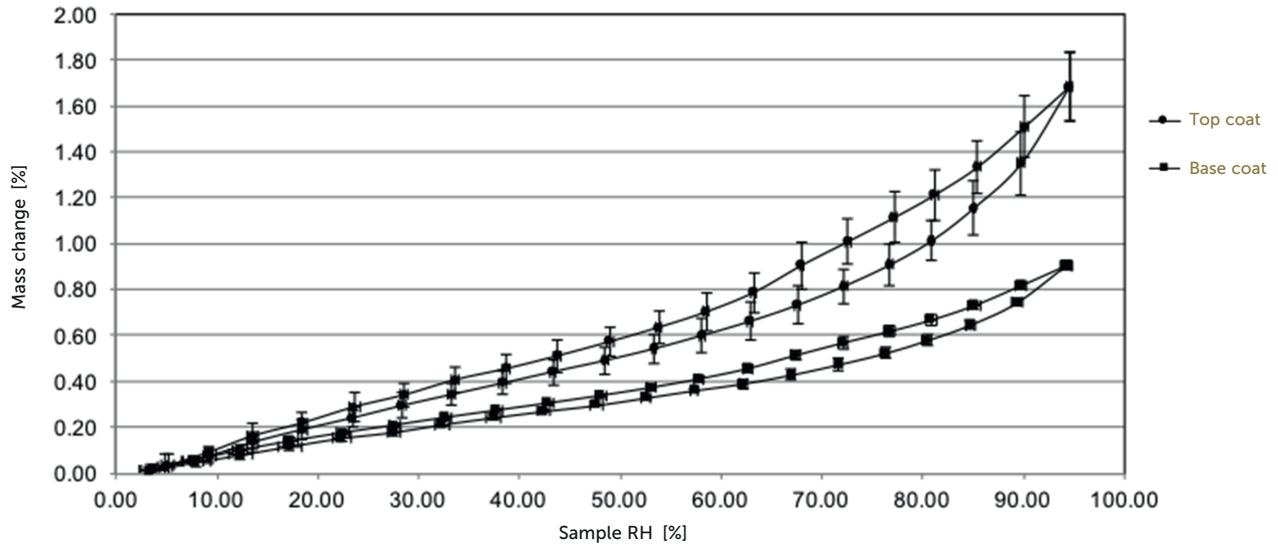


Figure 4 Isotherms for top and base coat

Results and discussion

The results of the DVS and vapour permeability properties are used to estimate a theoretical penetration depth. Whereas the moisture absorption measured from moisture buffering tests on a range of specimen thicknesses can be used to empirically determine the experimental penetration depth.

Calculation of theoretical penetration depth

The theoretical penetration depth based on the isotherms, (Figure 4) and vapour diffusion resistance for the two coatings can be calculated using Equation 1. The mass change in Figure 4 is in agreement to DIN 18947 adsorption and would be defined as class III with up to 65 g/m² adsorption. The calculated moisture diffusivity values for the top and base coat are 3.024 e-9 m²/s and 4.717 e-9 m²/s respectively. Depending on which numerical approximation of the penetration depth is used (1% or 1/e%) the theoretical effective moisture buffering depth can be calculated as given in Table 2.

Experimental penetration depth

A total of 30 specimens were tested for their moisture buffering properties, investigating two clay plas-

ters at 5 thicknesses, all in triplicate. The typical mass change profile (from the Base coat samples) is presented in Figure 5. The ISO standard considers the fourth cycle and calculates the adsorption and desorption mass change per unit of exposed area.

It is clear from Figure 5 that the moisture buffering capacity is capped with thinner layers as the mass change plateaus early into the humidity cycle. Comparing the profiles of the 40 mm and 20 mm negligible differences are observed, indicating that there is no additional buffering achieved through the extra thickness. The adsorption of the fourth cycle of the 30 specimens is presented in Figure 6 with the error bars representing the 95% confidence interval based on 3 specimens.

There is no additional benefit to diurnal moisture buffering beyond a 10 mm thickness of either type of plaster (Figure 6). The best fit lines indicate a bi-linear trend, based on the linear increase in moisture adsorption calculated by the measurements at 2 mm and 4 mm and the mean of the values at 10 mm and greater. The coefficient of determination for both coats is at least 0.98, which indicates the regression is suitable to model the experimental penetration depth. The regression estimates the effective penetration depth for the top and base coat to be 7.1 mm and 7.7 mm respectively, for the tested excitation profile. This indicates that the theoretical methods for the determination of penetration depth overestimate the material required, for typical building occupancy.

Table 2 Theoretical effective moisture buffering depth

Properties	Base Coat mm	Top Coat mm
dp _{1%}	53	42
dp _{1/e%}	11	9

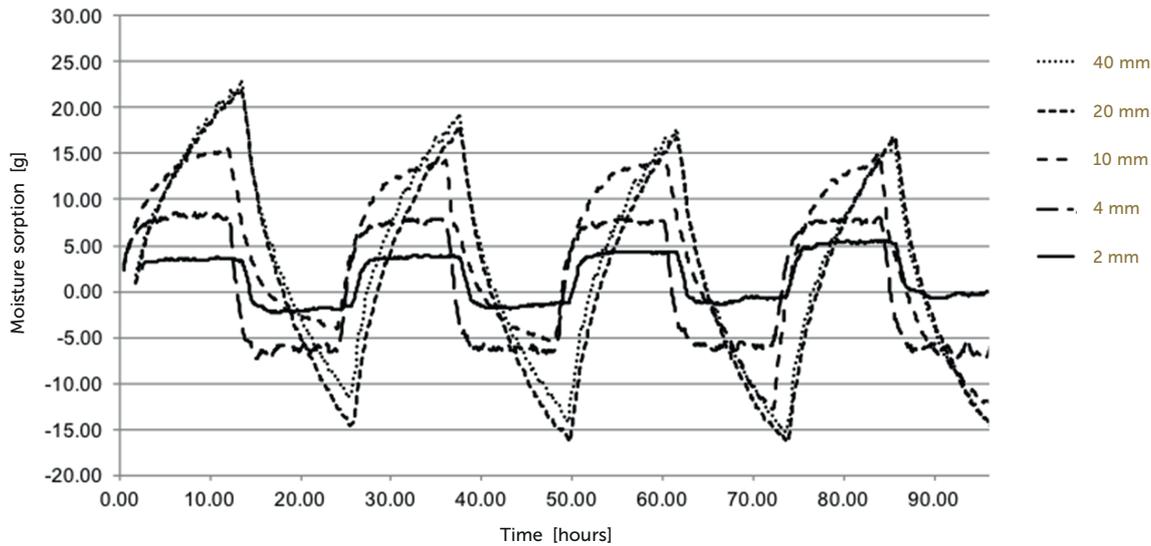


Figure 5 Typical moisture buffering profile

Summary

A method of experimentally determining the effective moisture buffering depth properties of materials has been presented. The method has been developed according to the ISO method, but is applicable to other methods. Two types of clay plaster were investigated, with different physical and chemical properties, that resulted in different moisture buffering properties. A regression model was used to predict the experimental moisture buffering depth that resulted in a lower thickness for each. The significance of directly measuring the moisture buffering penetration depth will result in optimised material use for improved indoor environment quality. Existing methods for calculating optimal moisture buffering depth appear to be overly conservative for typical building occupancy.

Acknowledgements

The research leading to these results has received funding from the European Union’s Seventh Framework Programme (FP7/2007-2013) under grant agreement no 609234.

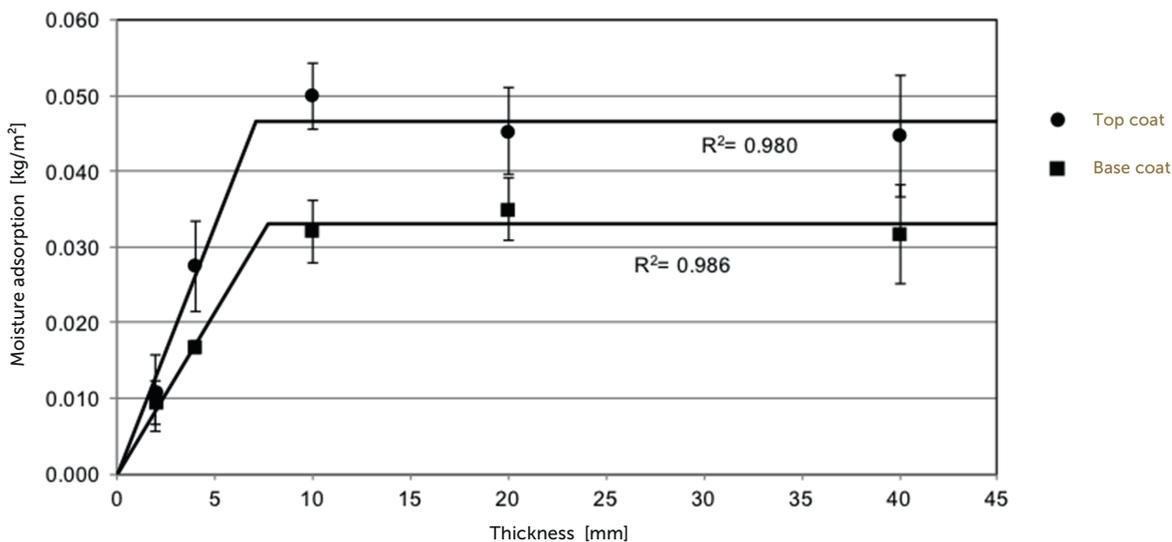
References

Ashour, T., Korjenic, A., & Korjenic, S. (2015). Equilibrium moisture content of earth bricks biocomposites stabilized with cement and gypsum. *Cement and Concrete Composites*, 59, 18-25.

Collet, F., Chamoin, J., Pretot, S., & Lanos, C. (2013). Comparison of the hygric behaviour of three hemp concretes. *Energy and Buildings*, 62, 294-303.

EN 1015-10:1999 Methods of test for mortar for masonry. *Determination of dry bulk density of hardened mortar*. London: BSI.

Figure 6 Variation of moisture adsorption



- EN 1015-11:1999 Methods of test for mortar for masonry. *Determination of flexural and compressive strength of hardened mortar*. London: BSI
- JIS A 1470-1 (2002). Test method of adsorption/desorption efficiency for building materials to regulate an indoor humidity-Part 1: Response method of humidity.
- ISO 8301:1991. Hygrothermal performance of building materials and products — Determination of moisture adsorption/desorption properties in response to humidity variation. International Standardization Organization (ISO).
- ISO 12572:2001. Hygrothermal performance of building materials and products — Determination of water vapour transmission properties. International Standardization Organization (ISO).
- Latif, E., Lawrence, M., Shea, A., & Walker, P. (2015). Moisture buffer potential of experimental wall assemblies incorporating formulated hemp-lime. *Building and Environment*, *93*, 199-209.
- McGregor, F., Heath, A., Shea, A., & Lawrence, M. (2014). The moisture buffering capacity of unfired clay masonry. *Building and Environment*, *82*, 599-607.
- McGregor, F., Heath, A., Maskell, D., Fabbri, A., & Morel, J. C. (2015). A review on the buffering capacity of earth building materials. *Proceedings of the Institution of Civil Engineers-Construction Materials*, 1-11.
- Padfield, T. (1998). The role of absorbent building materials in moderating changes of relative humidity. *Department of Structural Engineering and Materials, Lyngby, Technical University of Denmark*, 150.
- Rode, C., Peuhkuri, R. H., Mortensen, L. H., Hansen, K. K., Time, B., Gustavsen, A., & Harderup, L. E. (2005). *Moisture buffering of building materials*. Technical University of Denmark, Department of Civil Engineering.
- Roels, S., & Janssen, H. (2006). A comparison of the Nordtest and Japanese test methods for the moisture buffering performance of building materials. *Journal of Building Physics*, *30*(2), 137-161.
- Woods, J., Winkler, J., & Christensen, D. (2013). Evaluation of the effective moisture penetration depth model for estimating moisture buffering in buildings. Technical Report NREL/TP-5500-57441

