Chapter 32
The Relevance of Earthen Plasters for Eco Innovative, Cost-Efficient and Healthy Construction—Results from the EU-Funded Research Project [H]house

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32.1 Introduction

In mostly industrialised countries and first of all in cold climates, where people spend the majority of their time in buildings, occupant's health, well-being and productivity are relying heavily on the indoor environmental quality (IEQ) of buildings. In Europe, more stringent energy efficiency standards led to increased airtightness levels of buildings and reduced air exchange rates, which in turn entail the application of mechanical ventilation in residential buildings to address unforeseen shortcomings with regard to increased relative humidity levels and higher concentration of airborne pollutants, which occur mainly during the winter period. Recent studies (Quinn and Shaman 2017) and experimental data (Klinge 2013), however, induce concerns amongst experts as increasingly drier internal relative humidity (RH) levels can be observed. The approach to introduce active systems in dwellings is discussed more and more controversially as a variety of negative side effects such as com-

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promised occupant's health and well-being, system inefficiencies, etc. are becoming increasingly important in light of a holistic approach. However, common practice is to install mechanical ventilation systems despite associated constraints, such as additional space requirements, increased construction and maintenance cost as well as compromised occupant comfort and control. The main criteria for ventilation can be summarised as follows:

- Control of indoor air humidity
- Flash off of harmful substances
- Provision of fresh air.

It is assumed that through the application of appropriate materials the above-listed requirements can be satisfied so that such an approach can reduce the need for active systems and promote natural ventilation.

The EU-funded project [H]house aimed to develop alternative, sustainable and affordable solutions for widespread application in residential buildings (new construction and renovation) that follow a low-tech rather than a high-tech approach. The project investigated materials with regard to their hygrothermal and air-purifying properties and developed innovative systems for internal partition wall application. Natural building materials were compared to conventional materials in order to identify their potential to improve the indoor air, while limiting the use of technology. A special focus was placed on earthen materials with regard to moisture buffering and air-purifying properties. Sorption velocity and also maximum uptake were investigated in greater detail.

Comprehensive experiments at material and component level have been undertaken to provide a database for the numerical prediction of appropriate material combinations that are able to react to different scenarios, since available surface area, occupation density, air volumes but also the construction of the building envelope might differ significantly between projects.

Accompanying experiments with regard to the emissions of the materials as well as to their potential adsorption of airborne pollutants have been conducted to identify materials that generate the most positive effects on the living environment.

In addition, experimental data coming from a monitoring of dwellings in Berlin fitted out with either earth plasters or conventional materials have been evaluated in relation to indoor air temperatures and relative humidity levels.

To assess the overall cost of the developed solutions and not only capital cost, a comprehensive life-cycle costing (LCC) analysis has been carried out.

Table 32.1 Extract of investigated materials in [H]house

Function	Material	Thickness [mm]
Finishing materials	Marble powder paint, casein primer, dispersion paint, deep sealer and joint filler	0.5–2
Render	EPFF (Earth plaster fine, final coat), EPRF (Earth plaster with straw, final coat)	3–10
Reinforcement	Flax fibre reinforcement, glass fibre reinforcement	0.5
Adhesive	Earth adhesive	2–3
Wall lining boards	Earth dry board, wood fibreboard with integrated earth plaster, wood fibreboard, gypsum fibreboard and gypsum plasterboard	12.5–31
Insulation	Wood fibre insulation boards and mats, mineral wool (eco), mineral wool	40–80
Internal partition walls	Non-load bearing, dry lining walls based on wall lining boards and insulation materials listed above	75–126

32.2 Materials and Test Methods

32.2.1 Material Selection

The material selection was based on an in-depth market analysis focused on natural building materials for internal partition walls, characterised through hygroscopic properties. In addition, natural building materials with no or limited data collection were shortlisted to close a scientific gap. However, special emphasis was placed on earth materials. Acoustic properties, although not presented in this contribution but equally important for the design of innovative partition walls, have been investigated and were taken into consideration for the proposed solutions. For benchmarking purposes, also conventional construction materials have been included. In total a selection of approx. 100 materials, grouped into their function of assembly, has been investigated. Table 32.1 provides an extract of materials that are relevant to this study.

32.2.2 Water Vapour Sorption Tests

To identify the capacity of earth plasters to adsorb moisture from the air via the specimen's surface within set time intervals a voluntary test procedure, determined in DIN 18947 (2013) was applied. The test requires to precondition three material samples (50 cm × 20 cm × 1.5 cm) in a climate chamber at a temperature of (23 ± 1) °C and (50 ± 5) % relative humidity (RH) until constant weight is achieved. The RH level is then increased to 80% and the weight of the samples is measured at specific time intervals (0.5, 1, 3, 6 and 12 h). Based on the results, the water vapour adsorption class of plasters is determined. For entire wall build-ups, the test has been modified in such way that five adsorption/desorption cycles were conducted and sorption was enabled from both sides of the specimen in order to take into account the increased thickness of the elements.

32.2.3 Emission Tests

The materials listed in Table 32.1 were screened for potential emissions prior to the standard tests to estimate the compounds to be expected. Final emission tests ((S)VOCs, radon) for single materials (nine types) and 13 combinations of them were carried out in specially designed test chambers over a testing period of 28 days. The tests were conducted following the requirements of EN 16516 (2015) and evaluated against the German AgBB scheme (2015), in the absence of harmonised evaluation procedures. Formaldehyde and VOC-analyses were carried out according to ISO 16000-3 (2011) and ISO 16000-6 (2011) and radon measurements in accordance with a procedure developed by Richter et al. (2013).

32.2.4 Adsorption of Indoor Pollutants

For adsorption tests according to ISO 16000-24 (2009), the chamber supply air was spiked with 1- pentanol, hexanal, butyl acetate, *n*-decane and α-pinene representing important indoor air contaminants. The test gas mixture was generated with a gas mixing device published by Richter et al. (2013). Concentrations ranged between 200 and 500 $\mu g/m^3$ and were specified of being higher than usually measured in indoor air to ensure a distinct determination of the reduction of the test chamber air concentration caused by the material. The air-purifying performance of the material was determined by monitoring the difference of the inlet and outlet concentration of the test chamber. Tests were carried out for more than nine materials (six single earth plasters with and without additions, three multi-layer specimens composed of different materials).

32.2.5 Monitoring

Monitoring data has been obtained from two different flats located in Berlin from August 2012 to September 2012 (summer period) and from November 2012 to January 2013 (winter period). Flat 01 was fitted out with natural materials and naturally ventilated whereas Flat 02 was constructed from conventional building materials and mechanically ventilated. Measurements were carried out with a miniature sensor and data logging system (iButton®) i-buttons, measuring temperatures (internally and externally as well as relative humidity internally and externally) (Klinge 2013).

32.2.6 LCC Analysis

The LCC analysis was carried out for a case study building, consisting of six storeys, where two different scenarios for the internal partition walls were considered, taking into consideration all associated cost. Scenario 1 is based on an interior fit-out with internal partition walls made out of natural building materials including wood fibres and earthen plaster (Fig. 32.2). Exhaust vents are provided for internal bathrooms and the kitchen. Due to the outstanding moisture sorption capacity of this construction, no further ventilation is required. Scenario 2 is based on an interior fit-out with internal partition walls made out of conventional building materials, such as gypsum plasterboard and mineral wool (Fig. 32.2). Exhaust vents are provided for internal bathrooms and the kitchen; however, due to the limited capacity to adsorb moisture, additional ventilation units incorporated into the external façade are anticipated, which does not require additional pipework or ducting though. Both solutions have been planned by a mechanical engineer with the briefing for cost-efficient solutions and assessed with regard to global and cumulated cost, taking into consideration different growth rates for energy prizes and discount rates for market adaptation for innovative materials.

32.3 Results

32.3.1 Water Vapour Sorption Tests

Figure 32.1 shows an extract of experimental results from different specimens that demonstrate common build-ups for wall finishes of internal partition walls. Casein painted earth plasters on top of wall lining boards have been compared with conventional, gypsum-based boards that were painted with the same colour. Results (Fig. 32.1) demonstrate that earth plasters in combination with wood fibre boards are characterised through an outstanding water vapour adsorption capacity, which is up to three times higher in comparison with gypsum plasterboards, as evidenced also in (Minke 2012; Eckerman and Ziegert 2006). Gypsum fibreboards range between earth plasters and gypsum plasterboards. Interestingly, it can also be observed that the casein paint increased the adsorption capacity of the gypsum fibreboard.

Additional tests have been performed at component level, investigating the potential of entire wall build-ups not only for the immediate moisture uptake but also their potential to provide a comfortable and healthy environment due to seasonal changes. An overview of the most relevant results is presented in Fig. 32.2. Materials were

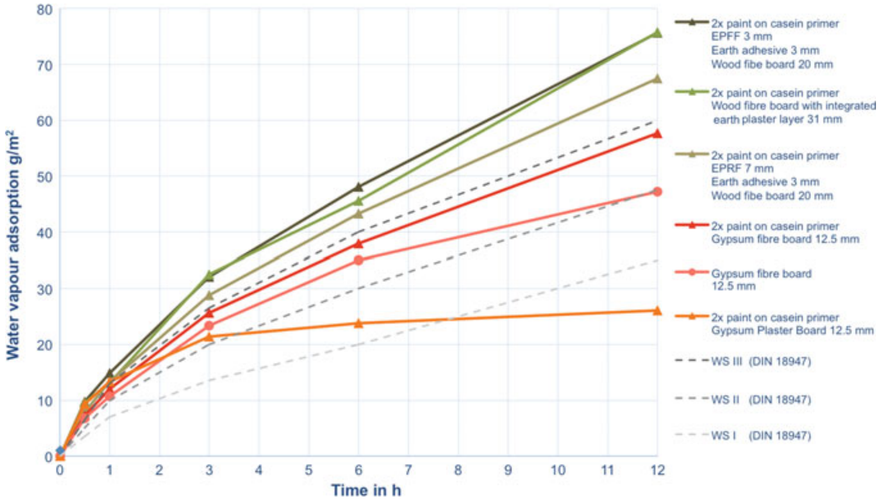

Fig. 32.1 Results of water vapour adsorption test (DIN 18947) of finishing layers of internal partition walls

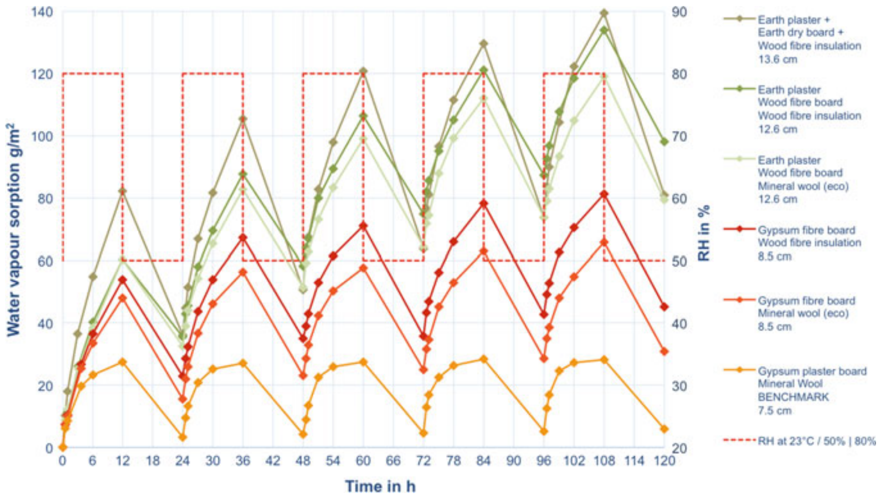

Fig. 32.2 Results of water vapour sorption test (5 adsorption/desorption cycles) of wall build-ups

tested in the most common thickness used for standard partition wall applications and although they differ, a direct comparison of specimens seems useful to identify the most capable materials and their combination.

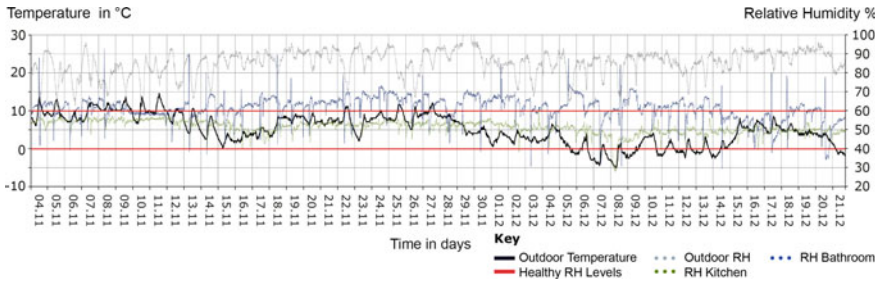

Fig. 32.3 Flat 1 results of monitoring RH (winter, natural building materials + natural ventilation)

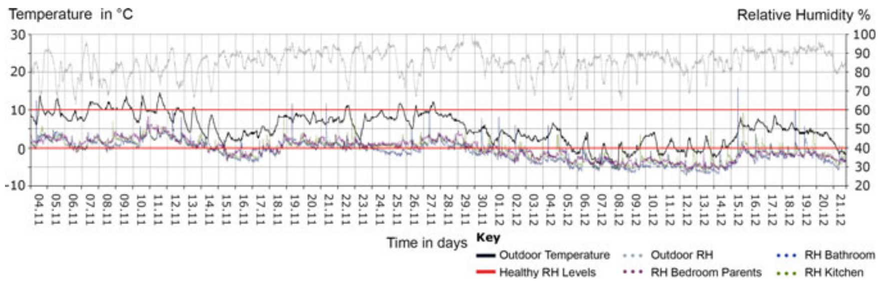

Fig. 32.4 Flat 2 results of monitoring RH (winter, conventional building materials+ mechanical ventilation)

32.3.2 Adsorption of Airborne Pollutants

The results from adsorption tests demonstrated slightly better results for earthen plasters in comparison with wall lining boards specifically designed for the adsorption of airborne pollutants. The best performance was observed for the earth plasters similar to those performing best for the water adsorption behaviour. In general, the polar compounds showed the strongest affinity for all the materials, the nonpolar compounds have hardly attached.

32.3.3 Monitoring

Figures 32.3 and 32.4 show measurements of the relative humidity (RH) of two apartments in Berlin carried out in Berlin in winter 2012–2013. In Flat 1 (natural building materials + naturally ventilation), measurements were taken in the kitchen and bathroom, while in Flat 2 (conventional building materials + mechanically ventilation), measurements were additionally taken in the master bedroom. The measurements show that in Apartment 1 the level of RH remains more stable than in Apartment 2, lying mostly in a healthy and comfortable range of 50–60%. Certain periods

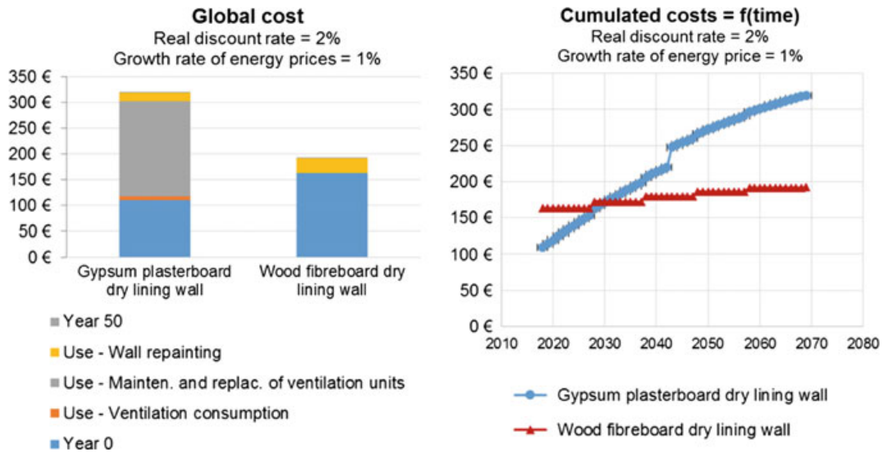

Fig. 32.5 Global costs and cumulated costs = f(time) of the gypsum plasterboard scenario and the wood fibreboard scenario

in the bathroom exceeded, however, 60%, which related to occupant behaviour and insufficient ventilation after showering. After the users were informed and adapted their ventilation behaviour, levels of RH were generally below 60%. In Apartment 2 instead, RH levels are influenced much more by the outdoor condition, which can be seen in the measurements where indoor levels curves outdoor curves. This is caused through the mechanical ventilation system, which takes constantly air in from the outside.

32.3.4 LCC Analysis

Figure 32.5 presents the comparison of the global cost and the cumulated costs = f(time) of both scenarios. It can be observed that, taking into account a real discount rate of 2% and a growth rate of energy price of 1%, the global cost of the gypsum plasterboard construction scenario is higher than the one of the wood fibreboard construction scenarios. More specifically, the investment cost for the wood fibreboard construction is higher than the one for the gypsum plasterboard construction, but this additional cost is compensated by the expenses of the additional ventilation in the conventional scenario. It is worth to note that it is the maintenance of the ventilation units that contribute the most to the global cost, not their energy consumption. The payback time of the investment the wood fibreboard constructions is 13 years.

A sensitivity analysis to both the real discount rate and the growth rate of energy price was carried out. When the discount rate increases, the global cost of the gypsum plasterboard construction scenario decreases. Nevertheless, even taken into account a real discount rate of 4%, the global cost of the gypsum plasterboard construction scenario remains above the one of the innovative partition wall scenarios.

When the growth rate of energy price decreases, the global cost of the gypsum plasterboard construction scenario decreases. Nevertheless, even taken into account a growth rate of energy price of 0%, the global cost of the gypsum plasterboard construction scenario remains above the one of the innovative partition wall scenarios. Taking into account a real discount rate of 4% and a growth rate of energy prices of 0%, the global cost of the gypsum plasterboard construction scenario remains higher than the one of the wood fibreboard construction scenarios and the payback time after investment in the latter is 22 years.

32.4 Discussion

32.4.1 Water Vapour Adsorption Tests

The comparison of the water sorption performance of natural materials in comparison with conventional ones demonstrated the outstanding sorption capacity of the earth plasters in combination with wood fibreboards in comparison with gypsum plaster or gypsum fibreboards. The tests revealed that the performance of the gypsum fibreboard could be increased through a chalk-based paint that was added as a finishing layer. The performance of the earth-based specimen can be attributed in the first instance to the clay minerals, while the qualities of the wood fibreboard lie in the performance of the timber but mainly in the high degree of porosity and therefore the large surface area.

Material investigations at component level demonstrated similar results and showed the superior performance of natural building materials in comparison with conventional wall build-ups. Figure 32.2 demonstrates the impact of earth plasters in combination with wood fibreboards and wood fibre insulation boards in comparison with conventional wall build-ups with gypsum plasterboards and mineral wool. The exact benefit on indoor air quality with regard to seasonal changes has to be determined; however, it can be assumed that buildings fitted out with such walls will benefit from evaporative cooling processes during hot summer months.

32.4.2 Emission Tests

It is important to note that the AgBB criteria were developed for individual building materials, for the analysis of wall systems a different set of criteria would be more appropriate. The results can therefore only have an orienting character. Most of the materials and material combinations that were tested had earth plaster facing surfaces of different thickness. Nevertheless, it can be established that all other tested natural building materials were uncritical with respect to their emission properties, which means that they are suitable for indoor use.

32.4.3 Adsorption of Airborne Pollutants

The adsorption tests revealed that earth plasters have a good adsorption capacity, which was better than that of specifically designed wall lining boards.

32.4.4 Monitoring Results

The results of the monitoring of real spaces (Figs. 32.3 and 32.4) show that the relative humidity of the rooms in the apartment fitted with earth plaster was consistently in the region of 50–60%, which can be attributed to the buffering capacity of the earth, as discussed also in () and (Klinge 2013). The low level of relative humidity of ~30% in Apartment 2 fitted out with conventional building materials can be attributed in part to the mechanical ventilation system that draws in dry air from outdoors all day, and in part to the materials used, that are unable to adsorb significant quantities of moisture arising within the apartment as a result of cooking or showering. It can be stated that in Flat 1 stable RH levels were measured, which ranged between 40 and 60%, which not only increase occupant comfort and health but also do not require mechanical ventilation. In Flat 2, instead unhealthy and uncomfortable values below 35% were measured, in fact, due to the provision of a high-tech approach.

32.4.5 LCC Analysis

An innovative internal partition wall based on earth plasters and other natural building materials (Scenario 1) has been compared to a conventional dry lining wall system based on a gypsum plasterboard and mineral wool (Scenario 2) on their global cost, taking into account 50 years use. The assessment accounted for the fact that additional mechanical ventilation is needed in case the conventional partition wall is used, whereas the innovative partition wall can follow a low-tech approach, based on mainly natural ventilation due to the relatively good humidity buffering capacity.

Taking into account different real discount and growth rates of energy prices, the global cost of the conventional partition wall scenario is always higher to the one of the innovative partition wall scenario. Although the investment cost of the innovative wall is higher than the one of the gypsum plasterboard wall plus ventilation equipment, this additional cost is compensated by the yearly maintenance and replacement expenses of the ventilation units during use (185 actualised € over 50 years of use) taken into account in the conventional scenario. The payback time after investment differs in respect of the assumptions for real discount and growth rates of energy prices. However, the study demonstrates that LCC is a useful to predict more realistic costs for a construction as all associate costs are considered.

32.5 Conclusion and Outlook

The results presented in this study indicate that low emitting, natural building materials with enhanced hygroscopic properties such as earth plasters, wood fibreboards and other natural building materials in combination with natural ventilation offer robust alternatives to mechanical ventilation. Through application of materials able to adsorb airborne pollutants, indoor air quality can be enhanced further. The extract of the LCC analysis demonstrated that such solutions are even more cost-effective than standard construction, if associated costs are considered. This result is especially important and relevant, since constructions based on natural building materials are often not implemented due to cost arguments and a supposedly cheaper option, requiring a high approach.

Although numerical simulations have been undertaken to translate current findings into hygrothermal models for the evaluation of indoor environment quality of residential buildings, additional research is needed as these models still lack an appropriate profile of earthen materials. First of all the adsorption velocity is often not correctly implemented so that results are slightly distorted. Also, the impact of air-purifying materials has to be investigated further.

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