Hygrothermal performance of paper plaster: influence of different types of paper and production methods on moisture buffering

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Abstract. Paper as a material needs a lot of input energy. Many measures have been suggested to recycle paper, but still a huge amount of it ends in landfills. Hereby, one possibility for recycling paper - making paper plaster and putting it into service in indoor environment - is introduced. The study focuses on the moisture buffering properties of paper plaster. Two questions are under consideration in this article. Firstly, how paper type and production method influence the properties (dry density, drying shrinkage) of paper plaster, and secondly, what the material moisture buffering properties of paper plaster are. The plasters for testing were made from four types of paper (printer paper, glossy paper, newsprint and book paper). The production methods used were rumpling, grinding with a shredder or special crusher (prepared for the study) and soaking the paper after that. The dry density of groups varied from approx. 240 kg/m³ to 400 kg/m³. The shrinkage properties were from 3% to 10% in diameter. To evaluate the moisture buffering ability of paper plaster, the methodology introduced in the Nordtest protocol was used. Paper plaster is an outstanding water vapour buffering material \[\text{MBV}=2.23-3.91 \text{ g/(m}^2\cdot\%\text{RH)}\] belonging to the moisture buffering class "excellent" defined by Rode [15]. From the production methods rumpling gave the best value while printer paper showed the best values from the chosen materials. The tests with glossy paper resulted in modest values. To conclude, all the paper materials and preparation methods introduced in this study can be used to make paper plaster

1 Introduction

Paper production is a huge branch of industry, and paper recycling and reuse is an area of industry as well. Paper could be recycled several times as paper or carton [1]. A remarkable amount of paper is just burned for heat production [2].

In building material industry paper is used in many ways for example in cellulose insulation [3] and gypsum boards [2]. One way of recycling paper, which is not very commonly used, is making paper plaster [4-6]. Plaster made from paper can be used as an indoor finishing material and here a question arises why paper should be considered from that point of view.

Today we have to build energy efficient houses [7]. Optimal relative humidity and safe hygrothermal conditions on the surface and in the boarders are concerns in all types of buildings [8]. Ensuring good indoor climate may include additional costs and a material with good buffering ability helps to balance moisture fluctuations [9-11].

Paper is a hygroscopic material which has an influence on indoor relative humidity [12]. Measurable parameters like moisture effusivity \(b_m\) [15] and hygroscopic inertia \(I_h,d\) [16] of the room are the parameters which help to evaluate paper plaster.

\[\text{MBV}_{\text{practical}}\] describes the changes in moisture content in (MC) real situations in rooms with human occupants. The cycle 8/16h between relative humidity range \(\text{RH}=33-75\%\) has been described by Rode and others [13, 15] in the Nordtest protocol. Also, penetration depth and therefore effective thickness [17] of the material are important aspects.

Paper plaster could be prepared in different ways. Everybody can collect waste paper while rumpling and soaking processes are quite easily performed in domestic conditions. Also, production could be mechanized or even industrial if people want to use paper plaster because of its properties and buying a pre-prepared material not getting involved in making the plaster themselves could be an option.
2 Materials and methods

2.1 Paper type and plaster production methods

In the study different types of papers were used: printer paper, glossy paper, newsprint and book paper. Three production methods were tested - rumpling, grinding with a special crusher (Fig.1, 2a) (prepared for the study) or shredder (Fig. 2b) and finally soaking.

A simple recipe was used for plaster: pre-processed paper with a glue solution (ca 500 g paper + 1 l water + 20-25 g starch) added.

The specimens moulded in a cylinder (a 110 mm plastic pipe with the inside diameter of 103 mm and 25 mm high) were grouped as follows and left to dry (Fig.3): rumpled printer paper – group 1 (PPR); rumpled book paper – 2 (BPR); shredded printer paper – 3 (PPS); shredded book paper (Fig. 2b) - 4 (BPS); rumpled glossy paper – 5 (GPR); printer paper grinded with a crusher (Fig. 1, 2a ) – 6 (PPC); glossy paper grinded with a crusher - 7 (GPC); book paper grinded with a crusher – 8 (BPC); newsprint grinded with a crusher - 9 (NPC); shredded glossy paper -10 (GPS).

2.2 Sorption test

Hygroscopic sorption properties were determined by following the principle of the standards EVS-EN ISO 12570:2000 [18] and EVS-EN ISO 12571:2013 [19]. Four different RH levels were tested: 30%, 50%, 75% and 95%, at temp (23 ± 0.5) °C and according to standard ranges (RH=30-95%). A plastic film and silicon hermetic were used for tightening. Only one side was exposed to environment to present the situation in real plaster and only one-dimensional moisture transport was enabled. Weighing was carried out with a 24-hour interval until the stabilization of weight (weight gain or release <0.1%). At each RH level during the first six hours the weighing was carried out more frequently (with a 2 h interval).

2.3 Moisture buffering with the Nordtest methodology

Moisture buffering properties were determined by following the principle of the Nordtest method [13]. The same specimens were used again. Initially, the specimens were acclimatised at RH = 50% and 23 °C. After that relative humidity was raised to RH = 75% for 8 h and during that the specimens were weighed with a 2-hour interval. Then relative humidity was lowered to RH = 33% for 16 h, and the specimens were weighed once in 2 hours after lowering the RH once. No weighing took place during the last 14 hours. The total study cycle was 24 hours - 8/16 h.

The formula for MBV_{8h} [g/(m²·%RH)] calculations (Formula 1)[9] could be used:

\[
MBV_{8h} = \frac{m_{\text{max}} - m_{\text{min}}}{A (\phi_{\text{high}} - \phi_{\text{low}})}
\]

where \(m_{\text{min/}}\text{max}\) is moisture mass (min and max) in the finished sample (g or kg), \(A\) – exposed area m²; \(\phi_{\text{high/low}}\) - high/low RH (%) levels. Using the moisture buffering values [g/(m²·%RH) 8/16h] materials can be classified as follows: negligible (0-0.2), limited (0.2-0.5), moderate (0.5-1.0) good (1.0-2.0), excellent (2.0-).
2.4 Water vapour permeability

Water vapour transmission properties were estimated by using wet cup method condition C (air temperature 23°C, RH 50/93%) (EVS-EN ISO 12572:2016) [20]. Weighing interval was 24 h which was performed until stabilisation.

2.5 Hygroscopic inertia and moisture effusivity

Using the parameters gathered in the previous tests some calculations were made.

Daily hygroscopic inertia index, \( I_{h,d} \), \( g/(m^3 \%RH) \) was defined by Ramos and others [12,16] as a function of MBV taking ventilation and time (Formula 2) into account

\[
I_{h,d} = \frac{\sum_i^{MBV_i} S_i + \sum_j^{MBV_{obj}}}{ach \cdot V \cdot t_g}, \quad (2)
\]

where MBV_{obj}, MBV_i – the moisture buffering value of objects and elements, \( S_i \) – the surface of an element \( i \) in \( m^2 \) ach- air exchange rate \( h^{-1} \), \( V \) – room volume \( m^3 \), \( t_g \) – vapour production period, \( h \).

When we take an example room (only its wall area) with measurements 3 x 4 x 2.6 m (windows and doors approx. 4 m²), where the ventilation rate is 0.42 l/(sm²) [21] according to the energy efficiency requirements, it is possible to calculate (by using Formula 2) the daily hygroscopic inertia index of the room. To describe the effect the hygroscopic inertia an alternative calculation was made with ventilation rate 0.15 l/(sm²).

Also, calculations were made with the case when only one wall was covered with paper plaster.

Moisture effusivity \( b_m \) \( [kg/(m^2 Pa^{1/2})] \) was determined with Formula 3 introduced by Rode and others [15] and was based on material properties measured under steady state and equilibrium conditions.

\[
b_m = \sqrt{\frac{\phi \cdot p_s \cdot \delta_p}{\rho_0 \cdot u}}, \quad (3)
\]

where \( \delta_p \) \( [kg/(m-s-Pa)] \) is water vapour permeability, \( \rho_0 \) \( [kg/m^3] \) dry density of the material, \( u \) \( [kg/kg] \) moisture content, \( \phi \) [-] relative humidity, and \( p_s \) \( [Pa] \) saturation vapour pressure. Apart from \( p_s \), which is given by the test conditions, the other parameters in the definition of \( b_m \) are all standard material properties estimated in the study.

3 Results

3.1 Density and shrinkage of specimens

The data of dried specimen groups are presented in Table 1. The highest shrinkage was observed in group 5 - rumpled glossy paper (shrinkage 9.7%) and group 10 - shredded glossy paper. Group 8 - crushed book paper kept its form the best (shrinkage 2.7%). Glossy paper had the highest dry density (rumpled - 5 and shredded - 10) – 400.0 and 377.1 kg/m³ accordingly. The density of newsprint was 240.0 kg/m³. In general, it can be concluded that glossy paper had the highest density while book and printer paper were quite similar. If production technology was under consideration, it seemed that rumpling gave the highest density, all in all, the density values indicated that paper plaster is a lightweight material compared with gypsum [22] or clay plaster [23, 24].

Table 1. The data of dried specimens: diameter (d, mm), thickness (h, mm), dry density (\( \rho_0 \), kg/m³)

| Group | d, mm | h, mm | \( \rho_0 \), kg/m³ |
|-------|-------|-------|------------------|
| 1 – PPR | 95.19 | 21.93 | 345.5 |
| 2 – BPR | 94.71 | 24.02 | 336.6 |
| 3 – PPS | 98.15 | 23.65 | 291.2 |
| 4 – BPS | 98.01 | 23.33 | 294.0 |
| 5 – GPR | 92.99 | 19.67 | 400.0 |
| 6 – PPC | 96.69 | 21.96 | 312.7 |
| 7 – GPC | 96.63 | 21.12 | 342.6 |
| 8 – BPC | 100.21 | 23.81 | 262.8 |
| 9 – NPC | 97.70 | 22.27 | 240.0 |
| 10 – GPS | 93.79 | 20.65 | 377.1 |

3.2 Sorption properties

The weight gain was more intensive within the first hours (Fig. 4) and half of water vapour uptake was gained within the first day, while whole stabilisation was recorded after 216 hours (at RH=75-95%) or 144 hours (RH=95-75%).

![Fig. 4. weight gain of 1 - PPR specimens at RH=75-95% and RH=95-75%](image-url)
to MC=18% at RH=95%. The second and third (at RH=95%) moisture content values were observed with rumpled printer paper (1–PPR, MC=16%) and rumpled book paper (2–BPR, MC=15.9%). At 50% and 75% of RH the book paper crushed (8–BPC) had higher moisture content values MC=4.4% (RH=50%), MC=7.7% (RH=75%), MC=9.1% (RH=75%), MC=5.5% (RH=50%).

The lowest MC values at all RH levels were offered by rumpled glossy paper (5–GPR):

MC=3.2% (RH=50%),
MC=5.9% (RH=75%),
MC=12.9% (RH=95%),
MC=7.9% (RH=75%),
MC=4.1% (RH=50%).

Comparing paper types, printer paper and book paper had higher performance in moisture content. Comparing technologies, it could be seen that on average rumpling gave higher moisture content values.

### 3.3 Moisture buffering

To describe the moisture buffering fluctuation, moisture content in specimens (g) was measured with regular weighing (Fig. 7). Water vapour uptake and release were higher strictly after changing the RH level (Fig. 8).

Moisture buffering (plaster thickness 2.0-2.4 cm) was calculated (Formula 1) for every cycle (Fig.9, Table 2). It can be seen that one day was different. On March 1st weighing was performed by another person and the difference in data showed how sensitive testing process was if automation was not used. These values (from March 1st) were excluded from the calculation of average results. Rumpled printer paper (1 - PPR and 2 – BPR) showed higher MBV values [3.91 and 3.31 g/(m²·%RH)]. Shredded and crushed glossy paper [2.20 and 2.33 g/(m²·%RH)] resulted in modest values.
3.4 Water vapour permeability

Testing of water vapour permeability needs more space in climate chamber than sorption and moisture buffering tests because of the size of the testing cups. Therefore, only 8 types of specimens were tested. Newsprint and shredded glossy paper were excluded. Water vapour permeability was estimated with the wet cup method and the results can be seen in Table 2.

The water vapour resistance factor varied from $\mu = 3.0-5.1$ ($S_d = 0.07-0.11$ m, thickness 2.0-2.4 cm). Printer paper rumpled (1 - PPR) and book paper rumpled (2 - BPR) which had the highest MBV and MC as well showed the highest resistance. Other specimens acted quite uniformly ($\mu = 3.0-3.8$).

Table 2. MC at RH=50%, RH=95%, water vapour resistance factor $\mu$, water vapour diffusion-equivalent thickness $S_d$, m (2-2.4 cm plaster), MBV$_{8/16}$, g/(m$^2$·%RH).

| Group | MC at RH50% | MC at RH95% | $\mu/S_d$ | MBV$_{8/16}$ (ads) |
|-------|-------------|-------------|-----------|-------------------|
| 1 - PPR | 3.8         | 16.0        | 4.6/0.10  | 3.91              |
| 2 - BPR | 3.8         | 15.9        | 5.1/0.11  | 3.31              |
| 3 - PPS | 3.9         | 14.8        | 3.4/0.07  | 2.91              |
| 4 - BPS | 3.9         | 14.1        | 3.2/0.07  | 2.82              |
| 5 - GPR | 3.2         | 12.9        | 3.3/0.07  | 2.48              |
| 6 - PPC | 3.8         | 14.3        | 3.8/0.07  | 2.76              |
| 7 - GPC | 3.6         | 13.0        | 3.0/0.08  | 2.33              |
| 8 - BPC | 4.4         | 15.2        | 3.1/0.07  | 2.41              |
| 9 - NPC | 5.0         | 18.0        | N/A       | 2.36              |
| 10 - GPS | 3.5         | 13.8        | N/A       | 2.20              |

3.5 Hygroscopic inertia and moisture effusivity

Table 3 presents the calculated parameters: hygroscopic inertia $I_{h,d}$ at three cases and moisture effusivity $b_m$.

Hygroscopic inertia was calculated (Formula 2) in four example cases. The highest values (1.38-2.45) were obtained when all the walls (32.4 m$^2$) were plastered and the ventilation rate was 0.15 l/(sm$^2$) which is minimum for the ventilation rate in dwellings with demand-based ventilation [21]. A remarkable effect could be observed even when only one wall (4 x 2.6 m) was plastered and the ventilation rate was minimum [0.48-0.79 g/(m$^2$·%RH)] – class IV according to Ramos and Freitas [16].

If materials and technologies are compared, the lining was the same as for MBV, because of the nature of the Formula.

The moisture effusivity $b_m$ was $5.56 \times 10^{-7} - 6.88 \times 10^{-7}$ kg/(m$^2$ Pa s$^{0.5}$). In general, the values for moisture buffering of paper plaster were comparable with sprayed hemp concrete [25] and cellulose insulation being clearly higher than concrete (2-3 times), wood (2-3 times) expanded polystyrene or mineral wool (at least 10 times) found by Rode and others [26].

Table 3. Hygroscopic inertia $H_{h,d}$ [g/(m$^3$·%RH)] and moisture effusivity $b_m$ [kg/(m$^2$ Pa s$^{0.5}$)].

| Group   | $I_{h,d}$ walls are plastered | $I_{h,d}$ one wall is plastered (4x2.6 m) | $b_m$   |
|---------|-------------------------------|-----------------------------------------|--------|
|         | l/(sm$^2$)                     | l/(sm$^2$)                               | kg/(m$^2$ Pa s$^{0.5}$) |
| 1-PPR   | 0.42                          | 0.15                                     | 0.42   |
| 2-BPR   | 0.87                          | 2.45                                     | 0.28   |
| 3-PPS   | 0.74                          | 2.07                                     | 0.24   |
| 4-BPS   | 0.65                          | 1.82                                     | 0.21   |
| 5-GPR   | 0.63                          | 1.76                                     | 0.20   |
| 6-PPC   | 0.55                          | 1.55                                     | 0.18   |
| 7-GPC   | 0.52                          | 1.46                                     | 0.17   |
| 8-BPC   | 0.54                          | 1.51                                     | 0.17   |
| 9-NPC   | 0.53                          | 1.47                                     | 0.17   |
| 10GPS   | 0.49                          | 1.38                                     | 0.16   |

4 Discussion and conclusions

There are several ways how paper plaster can be produced, and everybody can choose a suitable solution. There is a slight difference in hygrothermal properties when different production methods or paper types are used – water vapour permeability ($\mu = 3.0-5.1$), sorption (MC=12.9-18% at RH=95%), moisture buffering properties [MBV$_{8/16}$ = 2.2-3.9 g/(m$^3$·%RH)] but in general the material has excellent hygrothermal properties and everybody can use the way which suits them best to make paper plaster. Also, there is no need to plaster the whole room because every square meter covered with paper plaster has a significant influence on the hygroscopic inertia of the room.

The question of the study was to find out which production method gives the “best” material. In general, it is possible to produce plaster at home using waste paper or buy pre-prepared material. There are a few ideas how to produce paper plaster:

1) Gather paper waste from the household and get a “homemade product” by rumpling and soaking the paper.
2) Another way is to collect paper and use a shredder or crusher (which could be borrowed).
3) The easiest way is to buy grinded paper and after soaking it for a while receive a usable product.

A rough calculation shows that for covering 1m$^2$ of wall with a 2-cm-thick plaster, 16-17 newspapers or one pack of printer paper is needed.

Compared with clay or other mineral plasters paper plaster is remarkably lighter (240-400 kg/m$^3$ vs 1360-1900 kg/m$^3$) [23, 23].
Air quality aspects were not studied in the current research but knowledge about any emissions is important and needs further investigation. Also the physical properties could change when components imparting fire resistance are added.

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