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Utilization of hydrophilic cellulose fibers for preparation of plaster with enhanced moisture control capability

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Abstract. The relative humidity is one of the most important parameters having a substantial impact on ambient climate comfort. The negative effects induced by undesired levels of relative humidity in building interiors are related not only to a deterioration of materials but also to a potential health risk for building occupants. In the recent paper, a traditional lime plaster is modified by biomass fly ash and hydrophilic cellulose fiber admixture to improve material durability and provide material with enhanced capability for the moderation of ambient relative humidity. Within the experimental analysis, the basic material properties, as well as mechanical strength of designed plaster, is determined. The moisture buffer potential of all designed plasters is evaluated according to the Nordtest test procedure. Obtained results show that the application of cellulose fibers has a synergic effect on both improvements of the potential of studied plaster for passive adjustment of interior relative humidity and mechanical strength.

1. Introduction

In the recent period, several concerns related to the maintenance of the ambient environment can be distinguished. Besides the issues associated with insufficient thermal performance, problems connected with indoor humidity management represent a substantial task for materials engineers and architects. Maintaining the optimal level of relative humidity is related not only to buildings with specific environmental condition requirements such as museums or galleries, but also the indoor air quality of residential buildings need to be secured. In light of the recent findings, the unsatisfactory level of relative humidity in modern passive houses can be responsible for various health problems [1]. A limited response of used building materials to outside weather variations has a negative effect on respiratory discomfort, eye and skin irritation, allergies. Moreover, the condensation of water within the building structure was identified as one of main triggers for degradation of interior materials and furniture [2].

To avoid the problems mentioned above, additional HVAC devices are usually employed, especially in the case of rooms with special requirements on environmental conditions. However, the application of such devices is connected with increased energy consumption and substantial economic costs. In order to overcome the moisture related issues and maintain an optimal range for indoor relative humidity level, the development and application of moisture responsive materials became an important task [3]. The modification of commonly applied building materials can substantially improve the interaction between seasonal or diurnal relative humidity fluctuations and thus improve



the quality of indoor air. The characterization of building materials to modulate the interior climate in terms of adjustment of humidity in the room was described by Rode and Grau [4] who introduced moisture buffer value as the integrated indicator.

The modification of the porous space was found as an efficient way to promote passive, moderation of indoor RH. Across the literature is possible to distinguish several attempt aimed at fulfillment of this task, for example by application of light-weighted admixtures such as perlite, charcoal or vermiculite; use of porogene substances (aluminum powder) or utilization of superabsorbent polymers used for control of hydration heat and shrinkage of concrete mixtures [5-7]. However, most of the performed research concluded that incorporation of particular admixtures could provide only limited success due to an adverse effect of applied admixture to material durability. Some drawbacks by the meaning of the loss of workability, shrinkage, and segregation were also observed [8].

An elegant solution for overcoming of described issues can be found in the utilization of natural hydrophilic cellulose fibers. Additionally, the application of such material meets with the requirements associated with the renovation of historical objects. Incorporating natural fibers can significantly improve both the moisture buffering and mechanical strength [5], however application of hydrophobized cellulose fibers resulted in the improvement of mechanical parameters, and more favorable results can be achieved by application of hydrophilic fibers.

In the performed study, the moisture buffering potential of plasters modified by hydrophilic cellulose fibers is studied. The moisture buffering is evaluated according to the Nordtest method in order to access material response to diurnal relative humidity fluctuations. Obtained results from dynamic loading of tested plasters are compared with moisture buffer value (MBV_{ideal}) calculated from steady-state values.

2. Materials and methods

2.1. Materials

The biomass fly ash (BFA) together with cellulose fibers as a hygroscopic material were used to increase the functionality of studied plasters. The BFA was originated during the combustion of biomass in the electricity plant. The chemical composition of BFA given by X-ray fluorescence analysis is shown in Table 1. A substantial part of BFA is formed by SiO_2 (51.3 %), CaO , (15.4 %) and Al_2O_3 (14 %), while the rest is composed by Fe_2O_3 , MgO , K_2O , Cl^- , SO_4^{2-} and P_2O_5 .

Hydrophilic cellulose fibers with length ranging between 2 and 4 mm were incorporated for reinforcing of a plaster structure. Hydrated lime CL 90-S (Mokrá Plant of Carmeuse Czech Republic) was used as a base binder for plaster design. In order to improve the durability of plasters, the BFA was used as 20% replacement of lime. The amount of applied cellulose fibers varied from 1 to 4 %. In order to provide a material with the same workability, the flow table test was carried out. Water/binder ratio was modified according to the results of the flow table test. The detailed composition of the designed plasters is shown in Table 1.

Table 1. Composition of designed plasters.

Mixture	Lime (kg)	Aggregate (kg)	Cellulose (kg)	BFA (kg)	Water (kg)
RP	3	9	-	0.9	3.20
CBP1	3	9	0.036	0.9	3.25
CBP2	3	9	0.072	0.9	3.30
CBP3	3	9	0.108	0.9	3.40
CBP4	3	9	0.144	0.9	3.50

2.2. Experimental methods

2.2.1. Basic physical properties

Basic physical properties of studied plasters were characterized by measurements of the bulk density, matrix density, and total open porosity. Performed measurement of the bulk density was done on five cubic samples of 50 mm side and determined from the measurement of sample sizes (using digital caliper) and its dry mass. The matrix density was accessed by helium pycnometry using apparatus Pycnomatic ATC (Thermo Scientific).

2.2.2. Mechanical properties

Compressive strength (MPa) and flexural strength (MPa) as the main mechanical parameters were determined by employment the device VEB WPM Leipzig having a stiff loading frame with the capacity of 3000 kN. The strength was determined for 28-days cured samples.

2.2.3. Moisture buffering

The experimental determination of moisture buffer values using the step-response method when the sample with the known exposed area is continuously weighting during the exposure to various relative humidity levels. For this purpose, DVS (Dynamic Vapor Sorption Device) was used to maintain cycles of 8 hours at high RH (70%) and 16 hours at low RH (30%). The sample mass was recorded for 4 cycles in order to reach a dynamic equilibrium where the final mass at the end of the cycle and initial mass vary by less than 5%. The practical Moisture Buffering Value (MBV_{practical}) was consequently calculated by taking into consideration the maximum moisture uptake after 8 hours of adsorption phase according to used the RH levels. Here, the procedure presented by McGregor et al. [9] was adopted. Employment of this methods is beneficial for determination of material response to diurnal relative humidity fluctuation and can be viewed as an indicator of material suitability for application in specific indoor climate conditions.

The moisture buffer capacity of materials is described on the basis of the heat-mass transfer analogy. The moisture effusivity is derived from the thermal effusivity, by a description of the material ability to absorb and release moisture as is given in Eq. 1.

$$b_m = \sqrt{\frac{\delta_p \cdot \rho_0 \cdot \frac{\partial u}{\partial \varphi}}{p_s}} \quad (1)$$

where δ_p (kg/msPa) is the water vapor permeability, ρ_0 (kg/m³) the dry density of the material, u (kg/kg) the moisture content, φ (-) the relative humidity, and p_s (Pa) the saturation vapor pressure at a temperature of the experiment.

Ideal moisture buffer value (MBV_{ideal}) was obtained from the theory of moisture transport; the estimation of surface moisture flux over time related to sample exposure to relative humidity variations. The accumulated moisture uptake $G(t)$ (kg/m²), respectively the moisture release that both happen within the time period t_p , can be described by integrating the moisture flux over the surface $g(t)$ as in Eq. (2)

$$G(t) = \int_0^t g(t) dt = b_m \cdot \Delta p \cdot h(\alpha) \sqrt{\frac{t_p}{\pi}} \quad (2)$$

where

$$h(\alpha) = \frac{2}{\pi} \sum_{n=1}^{\infty} \frac{\sin^2(n\pi\alpha)}{n^{3/2}} \approx 2.252[\alpha(1-\alpha)]^{0.535} \quad (3)$$

where α (-) is the fraction of the time period where the humidity level is high. For the 8/16 hours scheme, $\alpha=1/3$, which makes $h(\alpha)=1.007$, the accumulated moisture uptake can be given in a simplified form:

$$G(t) \approx 0.568 \cdot b_m \cdot \Delta p \cdot \sqrt{t_p} . \quad (4)$$

MBV (g/m^2 %RH) can be expressed by normalization of accumulated moisture uptake by the change in surface relative humidity. Therefore, the moisture buffer value is proportional to the moisture effusivity b_m times the square root of the time period, $t_p^{1/2}$ ($\text{s}^{1/2}$). The MBV can be therefore defined as follows:

$$MBV_{ideal} \approx \frac{G(t)}{\Delta RH} \approx 0.00568 \cdot p_s \cdot b_m \cdot \sqrt{t_p} . \quad (5)$$

Based on the described experimental arrangement, the moisture effusivity can be determined from the steady-state experiments. On the other hand, the moisture buffer value represents a dynamic characteristic. Additionally, the ideal conditions can be barely maintained, so Eq. (4) represents an approximation, and $MBV_{practical}$ (g/m^2 %RH) was calculated from the DVS experiment.

3. Results and discussion

3.1. Basic physical properties

Determined basic physical properties of studied plasters are given in Table 2. Looking at the results, one can see a gradual increase in the total open porosity induced by a decrease in the bulk density in line with the increasing amount of applied cellulose fibers. Namely, the total open porosity of RP about 37.6 % were shifted up to almost 41 % for CBP4 mixture. This factor represents important information since the materials with a higher level of porosity were found as more perspective in the sense of moisture buffering.

Table 2. Basic physical properties of studied materials.

Mixture	Bulk density (kg/m^3)	Matrix density (kg/m^3)	Total open porosity (%)
RP	1596.7	2558.6	37.6
CBP1	1578.0	2571.9	38.6
CBP2	1562.3	2566.8	39.1
CBP3	1548.1	2549.0	39.3
CBP4	1518.1	2572.1	40.9

3.2. Mechanical properties

Results of mechanical properties are given in Table 3. Here, despite the increase in the total open porosity, application of cellulose fibers was found as beneficial for strength development. Obtained results of compressive strength were improved from initial 1.76 MPa for RP to 2.19 MPa for CBP4. The flexural strength was shifted even more significantly from initial 0.73 to 1.35 MPa. Revealed findings point to successful incorporation of applied fibers which reinforced the plaster matrix thanks to the synergy between the structure of the material matrix, tensile strength of cellulose fibers and created bonds between fibers and material matrix.

Table 3. Strength of studied materials.

Mixture	Compressive strength (MPa)	Flexural strength (MPa)
RP	1.76	0.73
CBP1	1.86	0.79
CBP2	1.99	0.89
CBP3	2.13	1.11
CBP4	2.19	1.35

3.3. Moisture buffering

The record of moisture buffer measurement given in Fig. 1 proved a beneficial influence of applied cellulose fibers in designed plasters. As one can see, a higher content of cellulose fibers shifted absorption capability of studied plasters during moisture loading (represented by dotted line). Despite the minor changes in material porosity, plotted curves of samples mass record revealed distinct differences which can be assigned to the hygroscopicity of applied cellulose fibers. Looking at the results given in Table 4, MBV_{ideal} was found as slightly lower compared to $MBV_{practical}$. Thus the calculation of moisture buffering from the steady-state experiment can be viewed as satisfactory. Calculated $MBV_{practical}$ from the performed dynamic moisture buffering experiment was only about 5 % higher on average. Namely, $MBV_{practical}$ was gradually shifted in line with increased cellulose fiber dosage from initial RP was about 1.44 obtained for RP to 2.13 for SBC4. The achieved improvement can be partially assigned to changes in porosity, but more significant influence can be assigned to a higher amount of applied hydrophilic cellulose fibers with a great moisture absorbability.

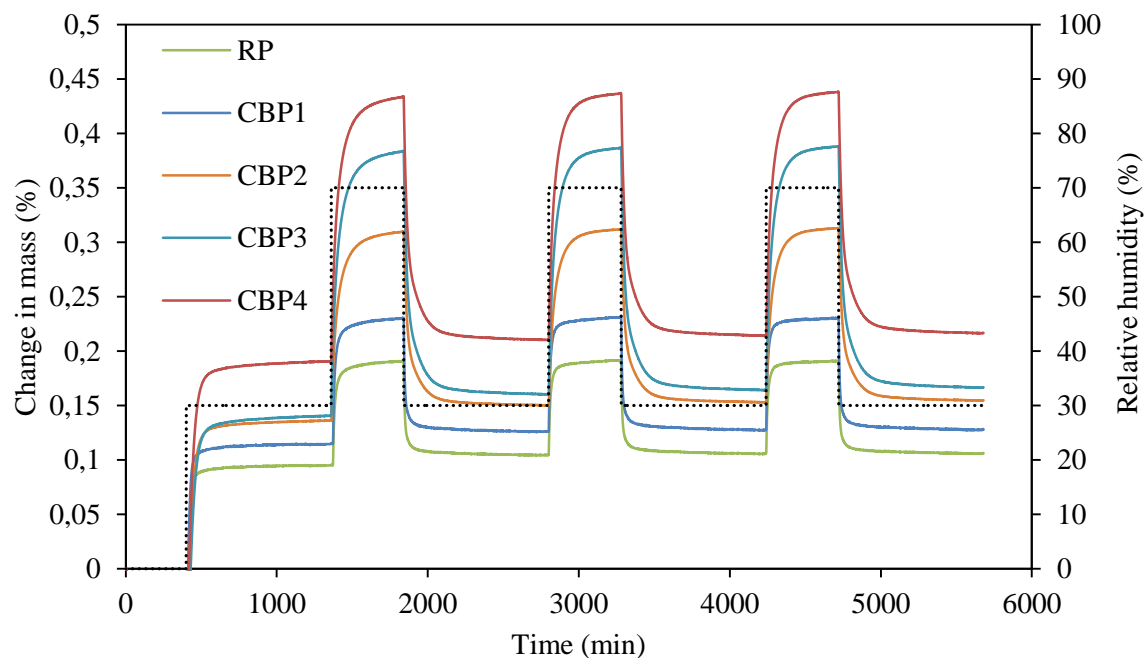
**Figure 1.** Record of MBV measurement.

Table 4. Moisture buffer values of studied materials.

Mixture	MBV_{ideal}	$MBV_{practical}$
RP	1.28	1.44
SBC1	1.31	1.37
SBC2	1.58	1.68
SBC3	1.76	1.91
SBC4	2.01	2.13

4. Conclusions

In the present study, the moisture control capability of modified plasters by cellulose fibers was studied. At first, the designed plasters were characterized by the meaning of determination of the bulk and matrix density, and porosity. The effect of incorporated hydrophilic cellulose fibers resulted in a slight increase in the total open porosity assigned to a loss of bulk density. This finding was not accompanied by a decrease in strength, and both compressive and flexural strength was improved thanks to the reinforcing the effect of applied cellulose fibers. The main aim of the performed work consisted of the determination of moisture buffering of modified plaster according to the Nordtest protocol by 16/8 h loading schema at 70/30 %RH. Obtained findings point out the synergic effect of applied cellulose fibers which substantially increased the moisture buffer value. Considering the classification of building materials introduced by Rode and Grau [4], SBC4 plaster can be labeled as excellent moisture buffering material while RP, SBC1, SBC2, and SBC3 was found as good moisture buffering material. The mixture SBC4 with the highest content of cellulose fibers enhanced moisture buffering about 70 % which substantially increased moisture control capability in case of varying conditions. Such material can be effectively employed in interiors to mitigate a negative effect of undesirable humidity level and improvement of ambient air quality. Comparison between the calculation of MBV_{ideal} given by steady-state experiment and $MBV_{practical}$ from the dynamic experiment revealed only minor differences and proved the applicability of both approaches. Nevertheless, further research focused on the moisture penetration depth and subjecting of materials to testing in varying weather conditions should be done in order to determine the potential impacts of hygroscopic materials on energy consumption related to the building's maintenance.

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