Hygric properties of Cement-Lime Plasters with Incorporated Lightweight Mineral Admixture

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Abstract. Cement-lime plasters are among the most often applied materials for surface finishing of interior and exterior surfaces of buildings. In order to improve their properties, especially the thermal insulation performance, common silica filler is often replaced with lightweight filler. The main positive effect of the thermal insulating plaster is reflected primarily in winter, preventing freezing of water in the masonry porous structure. In this paper, novel cement-lime plasters with lightweight aggregate are studied. In plasters composition, silica sand was replaced with perlite. The replacement ratio was 25 %, 50 %, 75 %, and 100 % by volume. The effect of the sand substitution on plasters structural characteristics, such as bulk density, matrix density, and total porosity, was tested. As one of the plasters functional properties is to protect the masonry from the water penetration, i.e., from the moisture related damage, and at the same time the moisture from the structure must be efficiently drained, determination of their moisture transport parameters is of the particular importance. In this respect, the water vapour transmission rate in the developed materials was characterized by water vapour permeability, water vapour diffusion coefficient, and water vapour resistance factor. For the description of the liquid moisture transport in the studied plasters, a 1-D vertical water uptake experiment was performed. Based on this experiment, moisture profiles that characterize moisture distribution along the sample length at the specific time of water suction were determined. Using inverse analysis of moisture profiles, the moisture dependent moisture diffusivity was calculated. Since the admixed lightweight filler increased the moisture diffusivity of the developed plasters, their samples were in the second set of tests provided with a hydrophobic coating based on silicone oil. This improvement helped to reduce the moisture diffusivity of plasters to the value of the reference mixture. In summary, presented experimental analysis of hydrophobic lightweight plasters proved their increased porosity and reduced moisture diffusivity, which can improve plasters thermal performance and prolong the durability of both the plasters themselves and the masonry they cover.

1. Introduction
Lime, gypsum, and cement plasters have played a major role in protecting the structural elements of buildings for many centuries. Traditional lime plasters excel in their good compatibility with masonry and easy workability. Since the 19th century, their often insufficient mechanical properties have been improved by the addition of a small amount of cement. However, the amount of lime had to prevail over the cement in the mix to maintain positive parameters, such as good plasticity of fresh mortar or high vapour permeability.
The use of lightweight aggregates (LWA) is a known and popular method how to enhance thermal insulation properties of plasters. In addition, LWA significantly reduces the bulk density of the composite so that it does not burden the load-bearing structure too much even when applied in a thicker layer. Their use also guarantees excellent workability. Plasters with incorporated LWA can find use also on curved surfaces and tiny facade elements of historic buildings as well as on modern architecturally designed structures [1].

Another advantage of composites containing LWA is their high porosity, which allows safe accumulation of salts in their structure without causing their destruction. Particularly for plasters designed for rehabilitation of historic facades, their porous structure and ability to drain moisture from construction - drying and vapour permeability - is crucial. Lightweight plasters are often the only possible solution where a typical ETICS (External Thermal Insulation Composite System), including, e.g., polystyrene, cannot be used, where it is desirable to preserve the original appearance of the facade or sufficient diffusion permeability of the cover layer [2].

On the other hand, the high capillary conductivity of the lightweight plasters can lead to unbearable loads from moisture for both the masonry and the plaster itself. This also leads to a significant deterioration of the thermal insulation properties. This negative effect can eliminate application of hydrophobizing agents. However, the inappropriate implementation of hydrophobization can lead to an increase in the level of capillary moisture above the level of newly rendered plasters. Another negative effect of LWA on the properties of the final composite plaster is the decrease in strength. This can prevent either improving the mechanical properties of the binder (addition of cement, metakaolin) or application of dispersed reinforcement, such as cellulose or propylene fibres [3].

Traditionally used lightweight aggregates include perlite, vermiculite, zeolite, pumice, and polystyrene. Newly developed composites contain expanded glass, hollow microspheres or expanded obsidian [4]. Many authors agree that perlite has the most significant effect on the improvement of thermal insulating parameters among commonly used lightweight aggregates [5]. For example, in article [6] authors presented, that a plaster consisting of 25% of vermiculite had a 50% thermal conductivity than a reference one, whereas a plaster consisting of 25% of perlite exhibited decrease in the thermal conductivity of about 70%. In paper [2] authors realized measurements on plaster samples from natural hydraulic lime and cement with different percentage content of perlite. They pointed out that the dependence of the thermal conductivity on the amount of perlite in the plaster mixture is considerably non-linear. Increasing the content of the perlite over 40% of the volume had not a relevant benefit as the thermal conductivity of the resulting material was already slowly approaching the value of the perlite itself. On the other hand, the linear dependence of the bulk density on perlite content in plaster mix was proved. Significant influence of moisture content in the material on the thermal conductivity was underlined. For saturated samples, the thermal conductivity was of about 250% higher than for the completely dried material. Further, in-situ application of the lightweight plaster was carried out. Measurement at real temperature and humidity conditions showed a 30% increase in the thermal conductivity value than for a dried material stored at laboratory conditions. This proves that limiting the moisture penetration could significantly increase the thermal insulation properties of the lightweight plasters.

2. Materials and sampling
The composition of the particular examined plasters is shown in table 1. The binder consisted of lime hydrate produced by lime kiln Čertovy Schody, which is a member of the Lhoist Group, Czech Republic, and Portland cement from cement factory Radotin, Prague, Czech Republic. In all plasters, lime hydrate and cement dosage was at a ratio 1:1 by weight, i.e., a ratio of about 2:1 by volume. In a reference plaster mix, silica sand produced by Filtrační písky Ltd., Chlum u Dokš, Czech Republic, was used as a filler. Three different sand fractions with a particle size of 0.063 / 0.5 mm, 0.08 / 1.0 mm, and 1.0 / 2.0 mm respectively were used. These three sand fractions were mixed in a ratio 1:1:1 by weight to obtain a continuous cumulative particle size distribution curve. For the reference plaster
mix, the binder/filler ratio was 1:4 by weight. As LWA, two different fractions of expanded perlite produced by Perlit Praha, Ltd., were used. Perlite EP 100 with a particle size of 0.005 / 0.5 mm was mixed with PB 150 with a particle size of 0.005 / 2.0 mm in a ratio of 1:4 by volume. In lightweight plasters composition, the mixture of perlite was used as a volume replacement of the silica aggregate. The sand replacement with perlite was 25 %, 50 %, 75 %, and 100 % by volume. Before samples preparation, perlite was immersed in water for 24 h to achieve its saturated state. Subsequently, it was mixed with other dry plaster components and batch water. The dosage of batch water was optimized to achieve similar fresh mixes consistency for all tested mortars. Rod shaped samples with the dimensions of 40 × 40 × 160 mm, and thin circular samples with a radius of 100 mm and a thickness of 20 mm, were casted. After demoulding, samples were left in a highly humidity environment of about 98 % RH until the age of 28 days.

### Table 1. Composition of studied plasters.

| Plaster | Lime hydrate (kg m⁻³) | Portland cement (kg m⁻³) | Silica sand (kg m⁻³) | Perlite EP 100 | Perlite PB 150 | Water (kg m⁻³) |
|---------|-----------------------|--------------------------|----------------------|----------------|----------------|----------------|
| CL R    | 241.9                 | 241.9                    | 3 x 451.6            | -              | -              | 348.3          |
| CL P 25 | 239.9                 | 239.9                    | 3 x 335.9            | 2.4            | 40.8           | 263.9          |
| CL P 50 | 250.4                 | 250.4                    | 3 x 233.8            | 5.0            | 85.6           | 210.3          |
| CL P 75 | 262.2                 | 262.2                    | 3 x 122.3            | 7.3            | 123.8          | 157.3          |
| CL P 100| 274.3                 | 274.3                    | -                    | 9.5            | 173.4          | 98.8           |

### 3. Experimental and computational methods

To obtain basic information about the properties of the tested lightweight plasters, their bulk density, specific density, and total porosity were determined. First, the prepared samples were dried at 105 °C until their constant mass was reached. From the specimen dry mass and volume, its bulk density \( \rho_b \) (kg m⁻³) was calculated. Specific density \( \rho_s \) (kg m⁻³) was obtained by helium pycnometry. This method uses the principle that small molecules of helium fill the entire porous system. From the gained values of bulk density and specific density, the total open porosity of studied plasters \( \psi \) (%) was calculated. The dried plaster specimens were left immersed in water until the saturation of the porous space was completed, and then weighed. The specimen dry mass and the saturated mass were used to determine the saturated moisture content \( w_{sat} \) (kg m⁻³).

Water vapour permeability \( \delta \) (kg m⁻¹ s⁻¹ Pa⁻¹), water vapour diffusion coefficient \( D \) (m² s⁻¹), and water vapour resistance factor \( \mu \) (-) were measured using the wet cup method. Flat circular specimens with a radius of 100 mm and a thickness of approximately 20 mm were placed to a cup above the salt solution providing a RH of (93 ± 5) %. The cups were placed in an air-conditioning chamber with RH of (50 ± 5) % and temperature of (23 ± 1) °C. The water vapour permeability \( \delta \) represents the mass of water vapour transported through a material of defined thickness and area at specified ratio of water vapour pressures and during a given time interval. The water vapour diffusion coefficient \( D \) defines velocity of water vapour transport. The water vapour resistance factor \( \mu \) indicates how much higher is the diffusion resistance of the given material compared to the layer of air of the same thickness and temperature.

To obtain information on the behavior of the tested lightweight plasters in contact with water, 1-D water suction experiment was conducted. First, the specimens with the dimensions of 40 × 40 × 160 mm were insulated on all lateral sides by epoxy resin. Than a water suction experiment was performed in which the foreheads of the specimens were immersed in water to a depth of about 5 mm. After the specified time intervals, the particular specimens were cut into 15 mm thick pieces. For each type of plaster, three samples were exposed to rising water for various time intervals. Immersion times ranged from 0.5 h to 4 h, depending on material performance in contact with water. The particular wet pieces of the rectangular specimens were weighed, dried to steady mass, and then
weighed again. Based on that, the moisture content was calculated using gravimetric method. To obtain moisture profiles, the moisture content values were graphed according to the $\eta$ parameter

$$\eta = \frac{x}{\sqrt{t}},$$

where $x$ (m) is place coordinate and $t$ (s) time of water suction experiment. From the experimentally gained moisture profiles, moisture dependent moisture diffusivity was calculated using their inverse analysis [7]. In the inverse analysis, moisture transport was described by a non-linear diffusion equation

$$\frac{\partial w}{\partial t} = \frac{\partial}{\partial x} \left( \kappa (w) \frac{\partial w}{\partial x} \right),$$

where $\kappa$ (m$^2$/s) is moisture dependent moisture diffusivity, $w$ (m$^3$ m$^{-3}$) is volumetric moisture content, $t$ (s) time of water penetration and $x$ (m) place coordinate. For the calculation, Matano method that consists in an application of Boltzmann transformation was applied, with the following boundary and the initial conditions

$$w(0, t) = w_1, \quad w(l, t) = w_2, \quad w(x, 0) = w_2.$$

Experimentally measured data was smoothed using spline curve and processed by computer code K-spline developed at the Department of Materials Engineering and Chemistry, FCE, CTU in Prague. Details on the mathematical solution of inverse analysis problem can be found in [8].

Not only the total open porosity affects water transport in porous material, but also volumetric representation of pores of specific diameter, shape, and connectivity are parameters driving the water ingress. Therefore, pore size distribution was measured using mercury intrusion porosimeters Pascal 140 and Pascal 440 (Thermo).

4. Results and discussion

The data on basic material parameters is summarized in table 2. The incorporation of pearlite into the plaster mix caused a considerable decrease in plasters bulk density. The mixture with a 100% substitution of sand by lightweight aggregates showed only a one-third of the reference bulk density value. With increasing LWA content in plaster mix, the specific density values also decreased, apparently due to closed micropores in the structure of expanded perlite. With perlite admixing, a significant increase in total open porosity was observed. For the plaster with 100% sand replacement, it was increased to more than twice compared to the reference value. Results of measured saturated moisture content corresponded with the total open porosity data.

| Plaster | $\rho_b$ (kg m$^{-3}$) | $\rho_s$ (kg m$^{-3}$) | $\Psi$ (%) | $w_{sat}$ (kg m$^{-3}$) |
|---------|-----------------------|-----------------------|------------|------------------------|
| CL R    | 1 815                 | 2 525                 | 28,1       | 275                    |
| CL P 25 | 1 536                 | 2 330                 | 34,1       | 338                    |
| CL P 50 | 1 163                 | 2 090                 | 44,4       | 441                    |
| CL P 75 | 908                   | 2 034                 | 55,3       | 544                    |
| CL P 100| 635                   | 1 618                 | 60,8       | 593                    |

Data describing transport of water vapour in the investigated plasters is given in table 3.
Table 3. Water vapour transmission parameters of studied plasters.

| Plaster | δ \times 10^{-12} (kg m^{-1} s^{-1} Pa^{-1}) | D \times 10^{-6} (m^2 s^{-1}) | µ (-) |
|---------|--------------------------------------------|------------------------------|-------|
| CL R    | 9.4                                        | 1.3                          | 21.0  |
| CL P 25 | 11.6                                       | 1.6                          | 17.4  |
| CL P 50 | 15.4                                       | 2.1                          | 12.9  |
| CL P 75 | 19.9                                       | 2.7                          | 9.9   |
| CL P 100 | 21.1                                      | 2.9                          | 9.4   |

As expected, with the increased LWA content in the plaster, and thus increased porosity, the water vapour transmission rate also increased. The rising rate of water vapour transmission was in line with the decreasing water vapour resistance factor. The dependence between the diffusion parameters and the LWA percentage content in plaster is approximately linear up to the 75% replacement of silica sand. On the other hand, the diffusion parameters obtained for CL P 100 were only slightly different from those accessed for CL P 75.

The moisture profiles subjected to inverse analysis are introduced in Figure 1a). Moisture dependent moisture diffusivities of tested plasters are presented in figure 1b).

![Figure 1](image_url)

Figure 1. a) Moisture profiles, b) moisture diffusivity as function of moisture content

The maximum moisture content values were significantly lower compared to the total open porosity and saturated moisture content. This was due to the fact that water penetrates on the capillary principle, which is reduced by gravity. For the increasing LWA content in plaster composition, the moisture content of the foreheads of the samples significantly increased. Another effect, caused by the presence of LWA in the material, was the increase in the moisture diffusivity up to the 75% silica sand replacement with expanded perlite. At first glance, it was surprising that for plaster CL P 100 was the moisture diffusivity lower compared to that of CL P 75. Nevertheless, this effect we attribute to the higher content of capillary mesopores with a radius of 1 - 2 μm in plaster CL P 100, as confirmed by mercury intrusion porosimetry (figure 2). For a larger pore radius, there was a more pronounced effect of gravity, and a slower penetration of moisture into the material.
Increasing the rate of water transport in lightweight plasters was classified as a negative effect because of possible faster degradation of the material in presence of excessive moisture. Therefore, the newly made samples of the tested plasters were provided with a hydrophobic coating of silicone oil. The samples were subjected to 1-D water suction experiment as described above. For these materials, the penetration time ranged from 4 h to 12 h. Moisture profiles and moisture dependent moisture diffusivity for plasters with silicone oil coating are represented in figures 3a, 3b. Application of silicone oil had two effects. Firstly, the moisture content of the foreheads of the samples was slightly reduced for all examined plasters. Secondly, there has been a significant reduction in the moisture diffusivity of all materials. With the increasing LWA content, the decrease in the moisture diffusivity was more pronounced. This was due to the fact that material with greater porosity absorbed more oil.

**5. Conclusions**
Cement-lime plasters containing perlite and in a second step coated with silicone oil were designed and tested. These composites are distinguished by high porosity, high water vapour transmission, and low water transport rate. Based on that, these newly developed materials can find used as a highly thermal-insulating covering layer of masonry with a prolonged service life.

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