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Mechanical, fracture-mechanical, hydric, thermal, and durability properties of lime–metakaolin plasters for renovation of historical buildings

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ABSTRACT

An extensive set of parameters of several lime–metakaolin plasters, including basic material characteristics, mechanical and fracture-mechanical properties, durability characteristics, hydric parameters and thermal properties, is presented. In a comparison with the reference lime plaster without any additives, the experimental results show three- to five-fold increase in strength, about 25% decrease of water vapor diffusion coefficient, 20% decrease of water absorption coefficient and a very high increase of freeze/thaw resistance. Using the lime of very high purity in lime–metakaolin plasters (98.0% of CaO + MgO) is found preferable to lower-purity limes; the main differences are observed in the freeze/thaw resistance, mechanical and fracture-mechanical parameters. A comparison with two commercial renovation plasters shows that the only notable advantage of the best commercial plaster studied over the best lime–metakaolin plaster is in its lower moisture diffusivity but it can be matched relatively easily by using hydrophobization admixtures. Therefore, it can be concluded that the lime–metakaolin plasters can find a wider application range in the renovation of historical buildings in the future and may at least partially replace the current renovation plasters as a cheaper and equally effective solution.

1. Introduction

Portland cement-based mortars were commonly used for restoration purpose over a substantial part of the 20th century. However, during the last decades their application was often criticized. Maravelaki-Kalaitzaki et al. [1] pointed out the limited physico-chemical, mechanical, and esthetic compatibility of cement mortars with the old masonry and architectural surfaces. As a result, advancing of the process of deterioration due to restoration interventions was observed; the harmful byproducts, together with the high stiffness and strength of cement mortar induced severe damage to the adjacent stone blocks [2]. Also, the adhesion of Portland cement-based mortars to the old historic materials was found generally poor, their thermal conductivity was usually higher, and the open porosity lower than of the lime-based ones [3].

Lime mortars produced using the contemporary high-purity limes without any additives, on the other hand, lack the required durability [4] although they certainly have better compatibility with historical constructions. Therefore, renovation renders and systems applied in the current practice of reconstruction of historical buildings are often conceived as lime–cement based, hydrophobized and including admixtures which generate pores during setting and hardening. Ashurst and Ashurst [5] rated a mortar based on the mix of lime and Portland cement in a ratio of 1:1 or 2:1 as acceptable for building conservation. Arioglu and Acun [6] presented an analysis of the restoration of traditional lime mortars and plasters and recommended application of ready-to-use repair mortars. Most commercial producers of renovation mortars followed a similar line.

Another current trend in the preservation of architectural heritage is somewhat stricter. Binda et al. [7] discussed the choice of mortar for the reconstruction of the Cathedral of Noto. They recommended a hydraulic lime for mortar; if a good hydraulic lime was not available the use of hydrated lime and pozzolana was found acceptable. Maravelaki-Kalaitzaki et al. [2] selected natural hydraulic lime with pozzolanic additions as binding material and aggregates of siliceous sand and crushed brick for the design of repair mortars and plasters. van Hees et al. [8] emphasized the compatibility of plasters and renders with salt loaded substrates in historic buildings, aimed at improving the maintenance of monuments by means of a better understanding of the working principles of the plasters and the damage mechanisms induced by salt crystallization.

In the Czech Republic, the supervisory authorities of cultural heritage began to discourage the owners from using the common commercial renovation render systems in historical buildings (and to forbid their use whenever it was within their competence) over the last decade, with an argument on using strictly materials

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which conformed to claims of the care of historical monuments [9,10]. The hydrophobicity of renders was objected to, as well as the small dimensions of aggregate grains. In the first case the main reason was the possible damage of historical masonry due to the accumulation of water in the area close to the render/masonry interface and its freezing in winter period. In the second it was argued that the small size of aggregates affects the optical properties of a façade. In general, mortars based on lime or hydraulic lime, without artificially increased volume of pores and without any cement, were recommended for renewal of historical buildings.

Rendering mortars composed of quicklime and pozzolana fillers such as volcanic ash, tuff and spongilite were used since the times of ancient Rome. The reaction of pozzolana with lime formed hydrated calcium silicates which caused higher durability of the renders. In other parts of the world crushed or ground burnt clays were used with similar result. In the 16th century hydraulic lime was manufactured purposively, which substituted the mixtures of quicklime with hydraulically or pozzolanically reacting admixtures. Due to the higher resistance of these materials to the environment, some original plasters or plaster fragments were conserved up to now. The concept of using lime–pozzolana renders in building renovation is thus feasible as it provides physical, chemical, and esthetic compatibility with the old masonry and sufficient durability at the same time.

Metakaolin is a pozzolana material having a high potential for use in renovation renders as clays and burnt clays were historically used in many countries as additives to lime, whether knowingly or not. However, lime–metakaolin mortars and renders were studied relatively rarely (only about 30–40 references in WoS during the last 30 years). The reaction kinetics of a mixture of lime and metakaolin and its dependence on temperature was studied in [11–13]. Mechanical properties of lime–metakaolin mortars and pastes were the most frequently studied parameters because of their primary importance for lime-based materials [3,14–18]. Fundamental hydric properties were analyzed in [16,17,19], thermal properties in [19], chloride binding in [20–22]. Measurement of durability properties and fracture-mechanical properties of lime–metakaolin renders was not reported yet in common scientific databases.

In this paper, we present an extensive set of parameters of several lime–metakaolin plasters, including basic material characteristics, mechanical and fracture-mechanical properties, durability characteristics, hydric and thermal properties. Experimentally obtained data are compared with the parameters of lime plaster without any additives and two commercial renovation renders. The main target of such extensive measurements is obtaining a representative set of input data for service life assessment studies of renovation render systems suitable for conservation of historical monuments.

2. Materials

The current standard EN 459-1 is not very strict regarding the purity of commercially produced limes. The mass of CaO + MgO in a CL-90 lime hydrate is supposed to be higher than 90%, which means that the impurities in an amount of up to 10% by mass are permitted. For the properties of lime–pozzolana plasters the presence of some impurities in lime does not have to be necessarily harmful. The experience with the historical lime-based plasters gives clear indications in that respect. However, it would not be wise to make any generalizations concerning the positive effects of impurities in lime when one cannot be exactly sure which of them are useful; historical lime plasters with improper additives were obviously not preserved. Therefore, the CL-90 lime hydrates of four different producers were used for the preparation of lime–metakaolin plasters to assess the possible effect of impurities in lime on their properties. The composition of the lime hydrates is given in Table 1. It was determined by X-ray fluorescence analysis; an X-ray spectrometer S4 Pioneer was used.

Finely ground metakaolin Mefisto K05 (D_{50} = 4.82 µm, D_{90} = 9.31 µm, specific surface 13.06 m^2/g) produced by České lupkové závody Inc., Nové Strašecí, was used as the pozzolanic admixture. Its composition, as determined by X-ray fluorescence analysis, is shown in Table 2. The amount of metakaolin in the lime–pozzolana binder was chosen as 20% of the mass of lime hydrate. According to the study presented in [23] this dosage of metakaolin makes possible to achieve significantly better strengths than for pure lime plasters but the water vapor transport properties are not yet negatively influenced by the metakaolin addition.

Table 1
Chemical composition of lime.

Component	Type of lime			
	Vitošov	Mokrá	Štramberk	Čertovy Schody
	Amount (%)			
CaO	95	93.4	95.7	97.4
MgO	0.5	0.4	1.1	0.6
SO_3	0.1	0.2	0.1	0.13
CO_2	3	2	0.9	0.1

Table 2
Chemical composition of metakaolin.

Component	Amount (%)
SiO_2	58.70
Al_2O_3	38.50
Fe_2O_3	0.72
CaO	0.20
MgO	0.38
K_2O	0.85
TiO_2	0.50

The composition of lime–metakaolin plasters is given in Table 3 where the symbol w/ds means the water to dry substances ratio. For a comparison, also a reference lime plaster with the same b/s (binder to sand) ratio as the lime–metakaolin plasters was studied. Two renovation plasters commercially produced in the Czech Republic were analyzed as well, but in this case the exact composition was not known.

3. Experimental methods

3.1. Basic material characteristics

The bulk density ρ_b, open porosity ψ and matrix density ρ_{mat} were determined using the water vacuum saturation method [24]. In the experiment six 50 × 50 × 25 mm samples were used. Characterization of pore structure was performed by mercury intrusion porosimetry. The experiments were carried out using the instruments PASCAL 140 and 440 (Thermo Scientific).

3.2. Mechanical and fracture-mechanical properties

The measurement of bending strength was done on six 40 × 40 × 160 mm prisms. Every specimen was positioned in such a way that the sides that were horizontal during the preparation were in the vertical position during the test. The experiment was performed as a common three-point bending test using the WPM 50 kN device. The distance of the supporting cylinders was 100 mm. The bending strength was calculated according to the standard evaluation procedure. Compressive strength was determined on the halves of the specimens left over after the bending tests. The specimens were placed between the two plates of the WPM 100 kN device in such a way that their lateral sides adjoining during the preparation to the vertical sides of the molds were in contact with the plates. In this way, the imprecision of the geometry on the upper cut off side was not affecting negatively the experiment. The compressive strength was calculated as the ratio of the ultimate force and the load area.

A three-point bending test of a specimen having a central edge notch length a_0 of about 1/3 of the depth of the specimen was used in the measurement of fracture-mechanical parameters. Nominal