Mechanical and hygric properties of lime plasters modified by biomass fly ash

Jan Fořt*, Monika Čáchová, Eva Vejmelková and Robert Černý

Czech Technical University in Prague, Thákurova 7, Prague 6, 166 29, Czech Republic

E-mail: *jan.fort@fsv.cvut.cz

Abstract. Utilisation of waste industrial products together with the modification and replacement of tradition binders represent an important discipline within the new material design. Since lime plasters are not suitable for many applications due to the poor durability and resistance against environmental deterioration and cement sometimes cannot be used because of its incompatibility with the historical buildings, the application of pozzolan admixtures poses an efficient way for plaster improvements. Moreover, in terms of the sustainable development, the utilisation of various environmentally friendly materials as a lime replacement represents an important advance for the low-carbon industry. On this account, the fly ash generated during wood combustion in a biomass power plant is employed as a promising pozzolanic material for the modification of lime plasters. Within the experimental investigations of the composed plasters with lime replacement up to 50 mass% the influence of waste wood fly ash (WWFA) on the basic material characteristics, mechanical and hygric properties is analysed. Experimental results show that WWFA dosage up to 50 mass% significantly improved the compressive and flexural strength while liquid transport properties were maintained on the same level. Therefore, the modified lime-pozzolan plasters reveal a good potential for the application in surface layer of buildings.

1. Introduction

Utilization of biomass for electric power generation can be perceived as world widely growing in order to abandon fossil fuels and converge energy production to use of renewable sources. This alternative induced that about more than 90 % of global bioenergy is produced by combustion of biomass [1]. Moreover, according to the low carbon economy targets aimed at mitigation of combustion of fossil fuels, a further increase of biomass consumed for energy production can be expected. Nowadays, around 2 billion tons of biomass is used in European Union for energy production and about 480 million tons of waste ash is produced every year. The European Union Directions are currently aimed at substantial mitigation and abatement of the amount of landfilling and seek to promote alternative ways of dealing with waste.

The second important factor which plays an important role in the utilization of pozzolanic materials for design of building materials is modification of contemporary binders in order to reach desired material properties [1–5]. This perspective can be employed for design of renovation plasters where the usage of cement is strongly unfavorable due to historical relevance. However, an application of the pure lime binder is deficient thanks to the different manufacturing processes of currently produced lime. Thus, the application of various admixtures can be perceived as a step towards improved material durability and resistance against negative environmental influences. Moreover, the utilization of such materials exhibits a good compatibility with historical constructions [6]. The big challenge consists of renovation of the old, damped and salted masonries where the main problem is caused by disintegration of the original materials and plasters in particular. The utilization of materials such as zeolites was found by Barnat-Hunek et al. [7] as an efficient way to design a plaster with suitable features and convenient compatibility with the original masonry. The incorporation of zeolite particle promoted the migration of water from the applied plaster and improved hardening of the plaster [8]. The other way was introduced by Nunes and Slížková [5], who employed metakaolin to prepare freeze/thaw resistant lime plaster for historical building renovation. The utilization of the waste paper sludge ash as a waste industrial material studied by Ferrándiz-Mas et al. [9] was found as useful for a preparation of renders and plasters. Based on the experimentally accessed results, the incorporation of admixtures with suitable chemical composition represents an efficient way to design a plaster with not only a good compatibility with historical structures bur also with improved resistance to weathering damage in a comparison with pure lime plasters [10-13].

The aim of this study is determination of the influence of biomass fly ash on lime plaster material properties. Within the study, the lime binder is replaced up to 50 mass% by fly ash gathered from wood combustion and new types of plasters are designed.

2. Materials and methods

2.1. Used materials

The fly ash gathered from a biomass electricity plant is intended as lime replacement due to its suitable chemical composition and good compatibility with traditionally used binders. The fuel base of the electricity plant is composed of waste wood which cannot be utilized for another purpose and its combustion can be perceived as the most suitable waste treatment. The chemical composition of the studied waste wooden fly ash (WWFA) was determined by X-ray fluorescence (XRF) analysis. The chemical composition of the fly ash powder is given in Table 1. According to the given results, the major part of the fly ash was formed by SiO_2 (approx. 51.3 mass%), CaO (approx. 15.4 mass%) and Al_2O_3 (14 mass%). The share of residual carbon content was negligible.

Table 1. Chemical composition of WWFA

Compound	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	Cl	SO_3	P_2O_5
Share in mass%	51.3	14.0	4.0	15.4	2.4	1.0	4.4	0.2	3.3	2.0

The particle size distribution was measured by Analysette 22 Micro Tec plus (Fritsch) laser diffraction device with the measuring range up to 2 mm. The obtained results revealed a main peak on the distribution curve close to 50 μm which can be considered as a suitable finesse of a material which does not require additional milling. The results are showed in Figure 1.

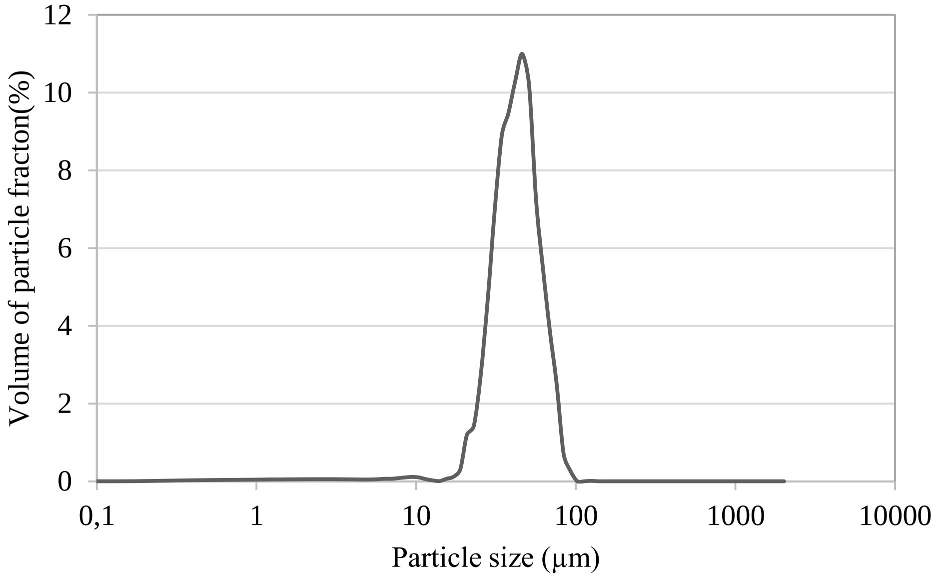

Figure 1. Particle size distribution of WWFA

Hydrated lime CL-90-S (Mokrá, Czech Republic) was used for the preparation of testing samples. During the preparation of the modified plasters lime binder was replaced by WWFA up to 50 mass%. Three grades of quartz sand were used as aggregate. Water/binder ratio was kept at 0.5 for all composed plaster mixtures. The detailed composition of plaster mixtures is given in Table 2. Casted prisms with the dimensions of 160 x 40 x 40 mm were stored in a highly humid environment during the curing period.

Table 2. Composition of the studied plasters

Mixture	Lime (kg)	WWFA (kg)	Quartz sand fraction (kg)			Water/binder ratio
			0.3 - 0.8	0.6 - 1.2	1.0 - 4.0	
PLR	2.25	0	2.25	2.25	2.25	0.5
PL10	2.025	0.225	2.25	2.25	2.25	0.5
PL20	1.8	0.45	2.25	2.25	2.25	0.5
PL30	1.575	0.675	2.25	2.25	2.25	0.5
PL40	1.35	0.9	2.25	2.25	2.25	0.5
PL50	1.125	1.125	2.25	2.25	2.25	0.5

2.2. Measuring methods

The basic physical properties of studied pastes, the bulk density, matrix density and open porosity were measured to investigate the basic impact of applied WWFA on material characteristics. The bulk density was determined by weighing the samples with known volume which was obtained using a digital caliper. The matrix density was measured by a helium pycnometer Pycnomatic ATC (Thermo Scientific). The total open porosity was calculated on the basis of the knowledge of bulk- and matrix density.

A hydraulic testing device VEB WPM Leipzig having a stiff loading frame with the capacity of 3000 kN was employed for the measurement of compressive and bending strength. Mechanical properties of the studied plasters were determined after 28 and 90 days.

The cup method in dry-cup arrangement was employed in the characterization of water vapor transport. It was based on measuring the diffusion water vapor flux through the specimen and partial water vapor pressure in the air under and above specific specimen surface. Water vapor transmission properties of a studied material were found by placing a specimen of the material on the top of a stainless-steel cup, whereas the specimen was in contact with the cup sealed by technical plasticine. For the measurement 5 samples with dimensions of 100 x 100 mm and 50 mm thickness were used. The cup contained a sorption material, namely silica gel. Measuring cups were placed in a controlled climate chamber and weighed periodically. The steady state values of mass gain were utilized for the determination of water vapor transport properties.

The ability of designed plasters to transport liquid water was described by the measurement of water absorption coefficient which was defined as

$$i = A \cdot t^{1/2} \quad (1)$$

where i (kg/m^2) is the cumulative mass of water, A (kg/m^{2}s$^{1/2}$) the water absorption coefficient and t the time (s). The water sorptivity test [14] was used in the experiments.

3. Results and discussion

3.1. Basic physical properties

The obtained basic physical properties of designed plasters are given in Table 3. The achieved results did not exhibit significant changes in the bulk or matrix density. Thus, the total open porosity of all designed mixtures reached similar values close to 33 % . This finding can be assigned to the suitable particle size of the WWFA which allowed a successful replacement of the lime binder.

Table 3. Basic physical properties of designed mixtures

Mixture	Bulk density (kg/m^3)	Matrix density (kg/m^3)	Total open porosity (-)
PLR	1755.5	2615.2	0.33
PL10	1724.9	2593.9	0.32
PL20	1734.8	2577.2	0.32
PL30	1753.8	2591.8	0.32
PL40	1741.6	2596.8	0.33
PL50	1742.5	2606.7	0.33

3.2. Mechanical properties

The comparison of the compressive and flexural strength determined after 28 and 90 days of curing is given in Figures 2 and 3. Despite of limited changes in the plasters basic physical properties, the mechanical parameters were significantly improved. While the compressive strength of the reference plaster after 28 days achieved about 0.91 MPa, the plaster with 50 mass% replacement reached 3 MPa. Similar results were obtained also for flexural strength when from the initial strength about 0.4 MPa for the reference plaster an increase up to 1.1 MPa was found. The evaluation of mechanical properties after 90 days pointed at further improvements. The change of mechanical properties of studied plasters could be assigned partially to the carbonation of calcium hydroxide in a contact with the carbon dioxide in the air and partially to the pozzolanic reaction when the pozzolanic compound reacted with the unreacted calcium hydroxide to form C-S-H and C-A-H gels [15]. As the threshold amount of WWFA, 30 mass% replacement of lime binder could be perceived, when both compressive strength and flexural strength were significantly improved.

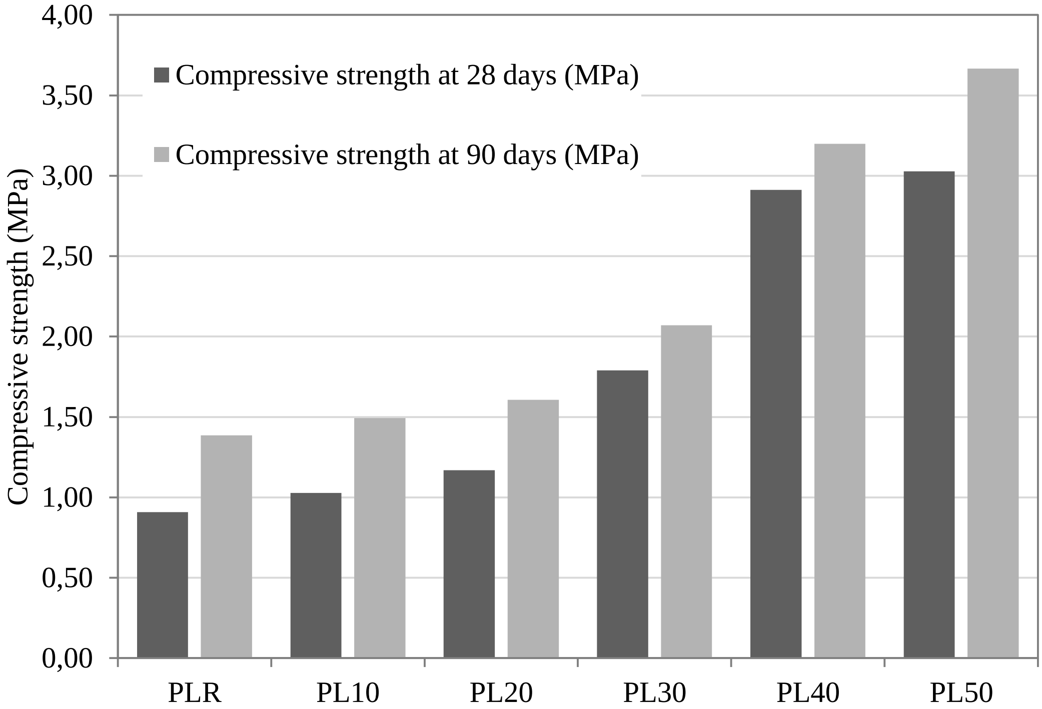

Figure 2. Compressive strength of modified plasters after 28 and 90 days

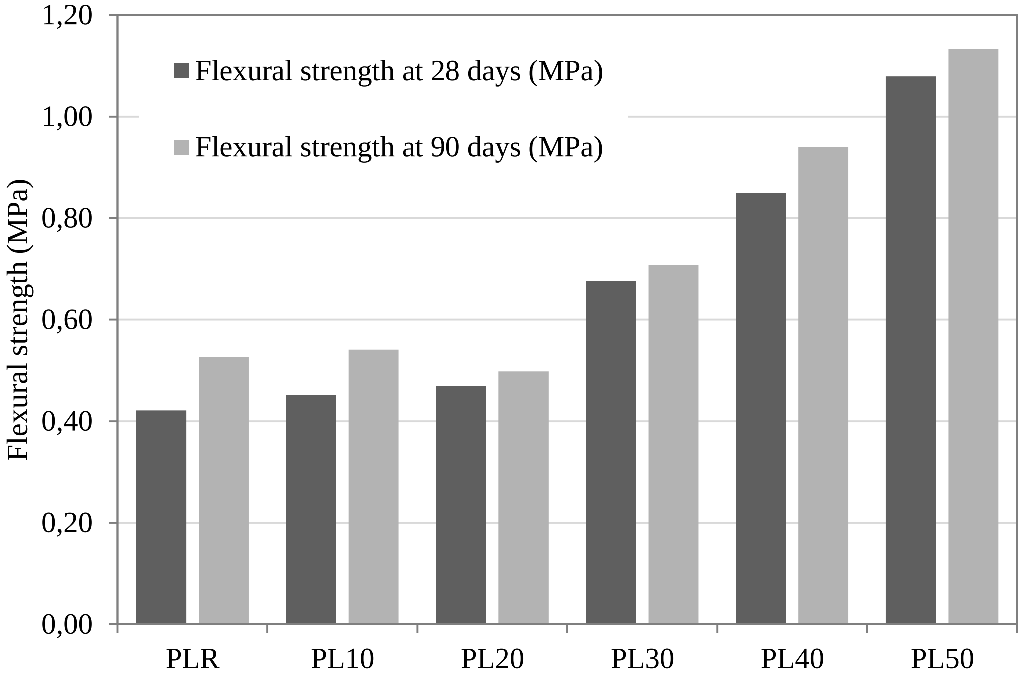

Figure 3. Flexural strength of modified plasters after 28 and 90 days

3.3. Hygric properties

The water vapor transmission abilities of modified plasters (Table 4) decreased with the increasing content of applied WWFA. The water vapor diffusion resistance factor was changed from initial 10.28 to 14.72. The most significantly the water vapor transmission properties were influenced when 40 and 50 mass% of lime were replaced by the WWFA. These findings are probably related to the appearance of C-S-H and C-A-H gels in the studied plasters which have a fine pore structure. The obtained results are still satisfactory and do not exceed common values for building plasters.

Table 4. Water vapor transmission properties of modified plasters

Mixture	Dry cup		
	δ (s)	D (m^2s^{-1})	μ (-)
PLR	1.63E-11	2.24E-06	10.28
PL10	1.48E-11	2.04E-06	11.30
PL20	1.46E-11	2.01E-06	11.45
PL30	1.43E-11	1.96E-06	11.72
PL40	1.24E-11	1.71E-06	13.50
PL50	1.14E-11	1.57E-06	14.72

The liquid water transport parameters were influenced only slightly (Table 5). The water absorption coefficient of 0.175 $kg/m^2s^{1/2}$ for the reference plaster was only about 5% higher than for the plaster modified by 50 mass% of WWFA. The effect of C-S-H and C-A-H gels was thus here not so pronounced as for the other parameters.

Table 5. Liquid water transport parameters of modified plasters

Mixture	A ($kg/m^2s^{1/2}$)
PLR	0.175
PL10	0.176
PL20	0.173
PL30	0.170
PL40	0.168
PL50	0.167

4. Conclusions

The experimental analysis of the basic physical, mechanical and hygric properties of lime plasters modified by WWFA revealed a promising potential of such materials for the building practice. The appropriate dimensions of WWFA particles and their suitable chemical composition with dominant share of SiO_2, CaO and Al_2O_3 made good prerequisites for their compatibility with traditional binders, such as lime or cement. The application of the WWFA as a lime replacement up to 50 mass% did not affect significantly the basic material properties; the total open porosity was almost the same. On the other hand, the values of both compressive and flexural strength of modified plasters revealed an overall positive effect of increased WWFA dosage; the mechanical parameters were improved almost three times. The water vapor transmission abilities of modified plasters decreased by almost 50% with the increase of WWFA dosage, contrary to the liquid water absorption coefficient which decreased only slightly. The obtained results thus showed that waste wooden fly ash can be successfully utilized for plaster modification by replacing lime in the amount of up to 50 mass%.

Acknowledgment

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