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ARTICLE

Choosing a Plaster Mortar for the Restoration of Cultural Heritage Sites

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ABSTRACT

This article is devoted to a comparative evaluation of mortar compositions intended for the restoration of historic buildings and cultural heritage sites. Eleven plaster mortar compositions were considered, as well as a pure lime-sand mortar and a cement-sand mortar. Tamasli Natural Hydraulic Lime 5 (NHL5) was used as the hydraulic lime. The hydraulic modulus of the lime was M = 2.69. Cement grade CEM I 42.5N was used to prepare the cement-sand mortar. The lime-sand mortar was made from slaked lime (fluff) with an activity of 74%. Highly active metakaolin VMK-45, diatomaceous earth NDP-D-230, and microsilica MK-85 were used as pozzolanic additives in the study. It was found that the addition of pozzolan additives to the formulation of lime mortar increases the compressive strength and adhesion of plaster mortar under air-dry curing conditions, which are 0.79–1.12 MPa and 0.57 MPa, respectively. It was found that the compressive strength of plaster mortars based on artificial hydraulic lime is 1.0 MPa, which meets the requirements of national and international standards (Deutsches Institut für Normung (German Institute for Standardization): DIN 18550). Cement mortars have a more uniform pore size distribution, lower porosity (28%), as well as higher compressive strength (5.3 MPa) and adhesion to the substrate (0.9 MPa). However, due to the lower vapor permeability of the plaster layer, there is a

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possibility of moisture accumulation at the interface with the wall of the object being restored. For reasons of compatibility with old walls being restored and considering the law of structural affinity, there is no need to achieve high strength values. We do not recommend using cement-based plaster for restoration.

Keywords: Restoration Mortars; Lime; Pozzolanic Additives; Strength

1. Introduction

Ensuring the preservation of historical buildings, an urgent task of restoration, requires individual approaches to the choice of materials and technologies for restoration work from a variety of plaster options. When restoring buildings of historical buildings, it is necessary to take into account the features of mortar mixtures for plastering. It is necessary to select solutions that are as close as possible to historical samples in order to achieve a strong connection between modern and original solutions. Taking into account the properties of the ingredients and their interaction with each other is a key factor in ensuring the durability and reliability of restoration. During operation, under the influence of climatic factors, the plaster layer is destroyed: the appearance of cracks, the formation of efflorescences, cracking, and peeling of the plaster solution from the base. When developing a project for a restored object, it is necessary to choose finishing materials compatible in composition with the historical material of the monument. In addition, many buildings are exposed to moisture, and especially the marine environment, which can lead to the destruction of plaster systems. All this together necessitates the selection of suitable solutions for repair work.

Taking into account the basic requirements of restoration intervention, repair mortars should not be stronger than building stones and excessively stronger than the original mortar. In this regard, there is a revival of interest in the use of lime for the restoration of historical buildings and cultural heritage sites due to the vapor permeability of lime mortars, which meet the requirements of preserving architectural heritage well.

Lime mortars, lime-pozzolanic mortars, and mortars based on natural hydraulic lime are widely used for the restoration of historic buildings [1–5]. It is recommended to use mixtures containing lime and metacaolin to restore historical masonry [6,7]. These mortars were used to produce some white plasters in Genoa, Italy. It was found that with an increase in the proportion of metakaolin to the total mass, the pore size decreases—narrow pores (<0.1 μm), and the compressive strength of the solutions increases to 9 MPa. In addition to double combinations (lime → pozzolan), the use of triple systems (lime:pozzolan:cement) proved successful even in the case of lime solutions.

During restoration work in Shanghai and Hangzhou, a natural hydraulic lime (NHL) system, including adhesives and injection mixtures, is used to eliminate detachments on stone, brick and gypsum facades. The key technical parameters of the repair materials are: tensile strength from 0.1 to 1.0 MPa, capillary water absorption of less than 2 $kg/m^2 \cdot h$, vapor permeability coefficient of no more than 100, as well as a consistent coefficient of thermal expansion with limestone within ±50%. There are numerous examples of historic buildings with lime mortars that have been well preserved, demonstrating that lime mortars can be quite durable. Lime, due to its strength properties, which meet the criteria for preserving architectural heritage well, is attracting increasing attention from both restoration projects and researchers. To increase the durability of the finishing layer based on lime mortars, various modifying additives are added to their formulations [8–10].

In addition, factors contributing to an increase in the service life of lime plaster mortar (the use of fine aggregate in plasters, special application methods, for example, for plasters—successive layers with differentiated properties to prevent moisture penetration into the structure, the proportions of the components, the type and size of aggregates) have also been identified [11,12]. The current trend in the field of architectural preservation in Europe is to use hydraulic lime of the natural hydraulic lime (NHL) or hydraulic lime with additives (NHL-Z) categories in accordance with the European Standard EN 459 specification. Mortars based on natural hydraulic lime (NHL) are widely used for restoration work due to their good compatibility with the base material in terms of physical, chemical and mechanical properties. An analysis of the literature data indicates the widespread use of hydraulic lime in the past in the construction and repair of buildings and structures as an independent binder or as an additive to air lime [13]. According to the European standard DIN EN 459 1-2010, NHL hydraulic lime is divided into three classes depending on the compressive strength achieved after 28 days of curing: NHL2, NHL3,5 and NHL5. NHL mortars are highly resistant materials with low shrinkage, capable of good adhesion to masonry elements, having high deformability and vapor permeability, as well as resistant to salt and frost. Hydraulic lime (NHL) is a relatively modern alternative as a binder in restoration, combining well with existing historical masonry. Khabibulina et al. [14] noted that the addition of 10% hydraulic lime significantly increases the physico-mechanical properties of mortars based on air lime, and a mortar containing 100% hydraulic lime showed a higher compressive strength (5.61 MPa).

However, hydraulic lime is currently produced in small quantities. It can be used for the manufacture of building mortars used for masonry and plaster, operated in dry and wet conditions. Meanwhile, as the experience of restoration work shows, hydraulic lime is successfully used in the manufacture of plastering works. The use of hydraulic lime ensures fast setting of mortars, eliminates the risk of damage to plaster coatings by ground and atmospheric moisture, as well as aggressive environmental components. Due to the small production volumes of hydraulic lime, it is relevant to study the potential of using artificial hydraulic lime HL as a substitute for natural NHL in plaster compositions, since artificial lime HL demonstrates characteristics comparable to those of natural hydraulic lime NHL.

The binder system is the most important parameter affecting the long-term strength of lime mortars. Based on this concept, repair materials were developed and applied [15–19]. One of the crucial parameters for the selection of restoration materials is compliance with the basic principles of international restoration practice and the tenets of the International Charter for the Conservation and Restoration of Historical Monuments and Landmarks (Venice Charter of 1964). The selection and use of materials during the restoration project should have theoretical foundations that determine the importance of preserving cultural heritage, as well as take into account the basic principles of restoration. The replacement of the material may be accompanied by the loss of the technological features of the creation of the object, characterizing the authenticity, as well as the uniqueness of the technique and technology of execution. When applying modern plaster, when a partial or complete replacement of the historical layer occurs, the protective effect is manifested only if its pore system is accessible for the penetration of water in liquid and vapor state. The use of modern waterproof plaster on historical masonry creates prerequisites for the formation of a situation characterized by negative phenomena both inside the layer and on its surface. Any impenetrable surface layer will sooner or later crack due to thermal motion, thereby disrupting the continuity of the water barrier. As a result, the plaster will bypass the water spreading in the masonry and accumulate along the boundary of an impermeable layer that prevents evaporation. In addition, due to the obstacle to evaporation, the humidity index in the masonry will reach the highest level in conditions of using modern impermeable plaster under the constant influence of rising moisture. As a result, the internal stress will increase at the interface of the media under the influence of salt crystallization and frost formation.

The development and application of compatible and durable plaster mortars for plaster repair is an urgent scientific and technical task in every restoration project. The compatibility of the applied plaster mortars is achieved due to the functional affinity of the repair mortar with the original, which can be achieved due to comparable porosity, permeability and strength, as well as other important properties. When designing the technology of plastering works during the restoration of buildings of historical buildings, the following rules are followed. The inner layer must have a lower mechanical strength than the base, and each subsequent layer must have a lower strength than the previous one. It follows from these data that the binder system is the most influential parameter affecting the long-term durability of lime mortar mixtures. The development and application of compatible and durable plaster repair mortars is an urgent scientific and technical task in every restoration project.

As a result of the analysis, it was determined that, taking into account the significant amount of scientific and practical work devoted to methods of increasing the durability of lime composites, many aspects of this area remain undisclosed.

It is of interest to examine certain lime mortars intended for restoration plastering. Studies aimed at identifying differences in properties between lime mortars based on artificial hydraulic and natural hydraulic binders will help determine the direction of application of lime mortars of various systems.

The purpose of this article is to compare the compositions of building mixes used for the restoration of historical structures and cultural heritage sites, as well as for the decoration of modern buildings and structures.

2. Materials and Methods

The following research methodology was applied in the work:

1. Comparative assessment of the strength of a solution based on air and hydraulic lime;
2. Evaluation of porosity of solutions based on air and hydraulic lime;
3. Investigation of the adhesion strength of plaster mortar based on air and hydraulic lime;
4. Comparative assessment of vapor permeability and hydrophysical properties of plaster solutions based on air and hydraulic lime;
5. Development of recommendations on the choice of plaster mortar depending on the type of binder.

Eleven plaster mortar compositions were considered, including a pure lime-sand mortar and a cement-sand mortar. Cement grade CEM I 42.5N from Asia Cement LLC was used to prepare the cement-sand mortar. The lime-sand mortar was made using slaked lime (fluff) with an activity of 74% (GOST (Gosudarstvennyy Standart) 9179-18).

For comparison, natural hydraulic lime "Tamasli" NHL3.5 with a hydraulic modulus M = 2.69 and artificial hydraulic lime HL, obtained on the basis of air lime with the use of pozzolanic additives and cement, were used as a binder in the work. The mineralogical composition of hydraulic lime is represented by the manufacturing plant of Interde Lime LLC. Information on the mineralogical composition of hydraulic lime is presented in **Table 1**.

Table 1. Mineralogical composition of hydraulic lime.

Mineral Name	Chemical Formula	Values
Calcium carbonate, not calcined	$CaCO_3$	0.1
Bicalcium silicate	$2CaSiO_2$	48.7
Calcium hydroxide (free slaked hydrated lime)	$Ca(OH)_2$	5.3
Calcium sulfate (gypsum)	$CaSO_4$	35.8
Calcium oxide (quicklime)	CaO	0.6
Magnesium oxide	MgO	1.7
Magnesium-calcium carbonate	$MgCO_3$	1.1
Dolomite	$CaMg(CO_3)_2$	4.7
Tricalcium aluminate	$Ca_3Al_2O_6$	1.5
Calcium alumoferrite (ferrite)	$4CaO·Al_2O_3·Fe_2O_3$	0.5

Highly reactive metacaolin of the VMK-45 brand (specific surface area 1,700 m^2/kg), produced by the company Synergo LLC (Russia), was used for the research. The chemical composition of the material included 53% silicon dioxide and 42% aluminum oxide, while the pozzolanic activity was 1,210 mg/g. As an additional component, microsilicon MK-85 was used, conforming to the GOST R 58894-2020 standard, having a bulk density in the range of 150–399 kg/m^3 and a specific surface area of 12,000 m^2/kg.

White cement PCB 1-500 D0 (GOST 965-89) was also used to develop the artificial hydraulic lime composition. Plaster mortars were made using Sura quartz sand of 0.14–0.315 grade as a filler with a binder:sand ratio of 1:3. The sand density was 1,527 kg/m^3. The same filler was used in all samples, and the ratio of binder to filler remained constant. Microcalcite grade KM2 (GOST 56775–2015) was added to the formulation at a concentration of 25% as a structuring additive.

The water-binding ratio for mortars was 0.65. According to experiments, this amount of water was necessary to achieve a normal consistency and good workability (measured by a spreading test). The samples were cured in air-dry conditions at a relative humidity of 60–70% and a temperature of 20 ℃.

The determination of the plastic strength or the ultimate shear stress of the finishing mixture was carried out using a

KP-3 conical plastometer. To do this, an indenter (cone) was immersed in the test composition and the depth of immersion of the cone was measured under the action of a constant load *P*. When the cone reaches equilibrium, the shear stress τ (Pa) in the composition becomes equal to the yield strength τ_0 (Pa). At this moment, the plastic strength of the finishing compound *n* (Pa) was determined by the formula:

$$\tau = \tau_0 = k\frac{P}{h^2} \tag{1}$$

where τ is shear stress, Pa;

τ_0 is yield strength, Pa;

P is weight of the moving part of the device (load), kg;

h is the depth of immersion of the cone in the mortar mixture, m;

k is a coefficient depending on the value of the vertex angle of the cone. For a metal cone with an angle at the apex of 30°, k = 1,116;

To determine the compressive strength, the IR 5057-50 test complex was used (**Figure 1**). The force measurement range was from 50 to 50,000 N with an accuracy of 1 N (0.1 kgf). The load application rate ranged from 1 to 100 mm/min (in terms of displacement). The values were calculated according to the following expression:

$$R_{om} = \frac{P}{F} \tag{2}$$

where *P* is the destructive force, N;

F is the cross-sectional area of the specimen before testing, m^2.

Figure 1. Apparatus for determining compressive strength.

To assess the uniformity of the strength results obtained, the values of the coefficient of variation were calculated based on the test results of 6 samples using the formula:

$$\vartheta = \frac{\sigma}{\overline{x}} \tag{3}$$

where σ is the standard deviation;

$\overline{x}$ is the average value of compressive strength.

The standard deviation was calculated using the formula:

$$\sigma = \sqrt{\frac{\sum_1^n (x_i - \overline{x})^2}{n-1}} \tag{4}$$

where x_i is the arithmetic mean of the quality index of the *i*-th sample; *n* is the number of samples.

The adhesion strength was determined by the washer separation method. Cylindrical dies with a diameter of 18 mm were used for testing, which were fixed on the prepared surface using epoxy glue (EDP grade corresponding to TU 0751-018-48284381-00). The test sample was positioned horizontally, and the dynamometer was attached to the die. During the experiment, the force required to detach the stamp from the sample surface was measured. When the washer was detached, separation along the contact layer, cohesive and mixed separation were recorded. Only the results of adhesive separation (along the contact layer) were taken into account. The adhesion strength was calculated using the formula:

$$R_d = \frac{P}{F} \tag{5}$$

where *P* is the force required to detach, N;

F is the area of interaction of the stamp with the cover, m^2.

The measured value of the adhesion strength was determined as the arithmetic mean of the values obtained from the three samples.

Ceramic brick was used as a substrate.

The product composition was measured using scanning electron microscopy (SEM).

The properties of the mortar, which determine its resistance to environmental influences, were evaluated by water absorption and water resistance. The samples were dried in an oven at a temperature of 105 °C until a constant mass was reached. The cubes were then immersed in water for 48 h and weighed again. The measured water absorption of each sample was calculated as a percentage of the initial dry weight of the sample. The following formula was used to determine the softening coefficients of mortar samples:

$$K = \frac{R_{wt}}{R_{dry}} \tag{6}$$

where R_{dry} is the dry compressive strength;

R_{wt} is the water-saturated compressive strength.

The determination of the capillary water absorption of plaster coatings was carried out according to the regulations of GOST 31356-2007; the final values were obtained based on the calculation formula provided by this standard:

$$W = k\frac{m_1 - m_2}{S} \tag{7}$$

where m_1 is the dry sample mass, kg;

m_2 is the wet sample mass after 24 h of moisture saturation, kg;

S is the area of the wetted surface of the sample, m^2;

k is the coefficient accounting for the sample saturation time.

The dry weight of each sample was measured using an electronic scale with an accuracy of 0.1 g.

The coefficient of vapor permeability of the coating obtained from the developed dry building mix was determined in accordance with GOST 25898-2012. The technique is based on measuring the flow of water vapor through a unit area (1 cm^2) over a time interval of τ at a temperature regime of 18–20 °C. Calculation of the indicator μ (mg/(m·h·Pa)) was performed according to the formula:

$$\mu = \frac{P\delta}{F(Ee_{60}\tau)} \tag{8}$$

where P is the total mass of water vapor diffused through the coating during the test, mg;

δ is the thickness of the investigated finishing layer, m;

F is the surface area of the finishing layer, m^2;

E is the partial pressure of saturated steam (at 100% humidity), Pa;

e_{60} is the partial pressure of steam at a relative humidity of 60%, Pa;

τ is the test duration, h.

When assessing capillary suction, dry samples were immersed to a depth of 3 ± 1 mm. Samples were taken and weighed at certain intervals: 1, 3, 5, 15, 30, and 60 min. Then the water absorption coefficient was calculated due to the capillary effect.

The depth of carbonation was determined as follows. After hardening in air-dry conditions for some time, the samples were split and the freshly exposed cross-section was sprayed with a 1% alcohol solution of phenolphthalein (ODM 218.2.044–2014). In the plaster layer, which is not affected by carbonation (pH > 9.5), the mortar turns crimson. There is no coloration in the carbonized layer (pH < 9). The depth of carbonization, defined as the distance from the sample surface to the fully carbonized front (100% carbonation), corresponds to the depth of the colorless region. The carbonation rate was determined based on the analysis of changes in the thickness of the formed carbonized layer depending on time.

The porosity of the mortar was determined by the indicators of true and average density according to the formula:

$$\Pi = \left(1 - \frac{\rho_m}{\rho}\right) 100\% \tag{9}$$

where:

Π is total porosity, %;

ρ_m is average density, kg/m^3;

ρ is the true density of the material, kg/m^3.

The structure of the lime composite was studied using a TESCAN MIRA 3 electron microscope at a magnification of 10,000 times.

3. Results and Discussions

Lime dough is a plastic system, the rheological behavior of which is described by the Shvedov-Bingham equation. It has been revealed that mortar mixtures based on artificial hydraulic lime have a faster set of plastic strength. Thus, the plastic strength of the composition based on air lime with the use of metakaolin in an amount of 50% of the lime weight at the age of 6 h from the moment of mixing is 30 kPa, and based on air lime—3 kPa. The plastic strength of a mortar based on natural hydraulic lime at the age of 6 h is 40 kPa (**Figure 2**).

The composition of the mortars and the results of the studies are given in **Table 2**.

An analysis of the research results presented in **Table 1** shows that the introduction of metakaolin VMK (composition 8.9) into the lime mortar formulation significantly increases the compressive strength of the lime mortar under air-dry hardening conditions, amounting to R_{com} = 0.79–1.12 MPa at the age of 28 days, depending on the dosage of metakaolin. A low coefficient of variation indicates stable results. The obtained results are consistent with the literature data [20,21].

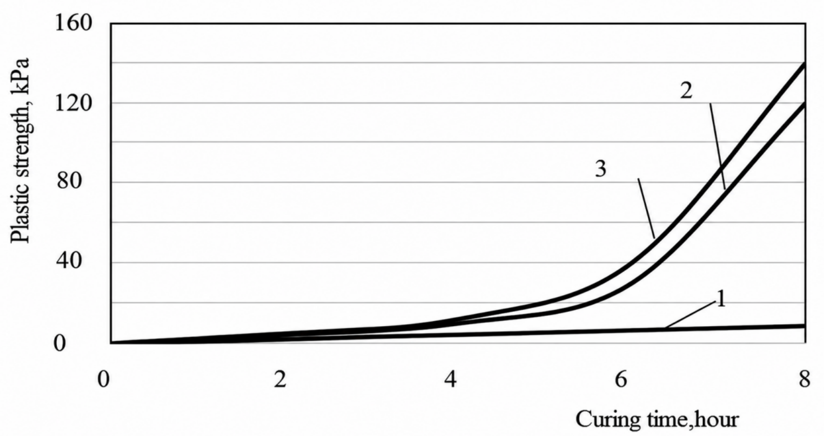


Figure 2. Plastic strength of lime mixture: 1: composition based on air lime binder; 2: composition based on lime binder using metakaolin (artificial hydraulic lime); 3: composition based on natural hydraulic lime.

Table 2. Properties of mortars*.

No.	Type of Binder	Density (kg/m^3)	Compressive Strength (MPa)	Porosity (%)
1	Air lime	1,580 ± 59	0.6 ± 0.036	32 ± 1.6
2	NHL Hydraulic Lime	1,700 ± 60	1.4 ± 0.056	30 ± 1.5
3	Air lime + Portland cement 30%	1,690 ± 56	1.2 ± 0.051	31 ± 1.5
4	Air lime + 10% microsilica	1,610 ± 44	0.75 ± 0.04	31 ± 1.5
5	Air lime + 20% microsilica	1,630 ± 36	0.83 ± 0.044	30.5 ± 1.6
6	Hydraulic lime NHL 3.5 + 25% air lime	1,680 ± 27	1.1 ± 0.06	30 ± 1.5
7	Hydraulic lime NHL 3.5 + 10% diatomite	1,730 ± 54	1.53 ± 0.07	29 ± 1.4
8	Air lime + 20% metakaolin	1,640 ± 37	0.79 ± 0.054	29 ± 1.4
9	Air lime + 50% metakaolin	1,650 ± 43	1.12 ± 0.048	29 ± 1.3
10	40% air lime + 25% cement + 10% metakaolin + 25% microcalcite	1,654 ± 29	1.28 ± 0.051	28 ± 1.3
11	Cement	1,900 ± 32	5.3 ± 0.212	28 ± 1.3

Note: *The values of the properties in the table are given taking into account the measurement error (confidence intervals).

As shown in **Figure 3**, the use of metakaolin as an additive to lime mortar provides increased adhesion to the substrate. Compositions 1, 8, and 9 showed an increase in adhesive strength from 0.3 to 0.57 MPa relative to the control sample. This effect is due to the occurrence of the pozzolanic reaction of metakaolin, which promotes the intensive synthesis of calcium hydrosilicates (C–S–H), which leads to a compaction of the microstructure and increased adhesion of the mortar to the substrate.

The introduction of pozzolanic additives into the formulation of mortars based on hydraulic lime helps to increase the compressive strength from 1.4 MPa to 1.53 MPa and increase the adhesion strength from 0.6 MPa to 0.65 MPa (compositions 2, 6, and 7). An analysis of the characteristics of solutions based on artificial hydraulic lime HL (compositions 3, 9, and 10) in comparison with analogues based on natural lime NHL (composition 2) confirms that the proposed formulation meets the requirements of current national and international standards, including DIN 18550. In particular, the minimum compressive strength of the material is 1.0 MPa.

Cement mortars have a more uniform pore size distribution and lower open porosity, amounting to 28% (composition 11). Compressive strength is 5.3 MPa, and bond strength is 0.9 MPa. Pure cement mortars exhibit better mechanical properties than lime mortars; however, it should be noted that cement mortars have lower vapor permeability. Therefore, the feasibility of using cement plaster mortars should be assessed based on compatibility with existing walls, taking into account the vapor permeability of the applied plaster layer and the potential for moisture accumulation at the interface with the wall of the building being restored. Therefore, from this perspective, achieving high strength values is not necessary.

When studying the structure formation (**Figure 4**), it was established that the morphology of the hydration products of stone based on hydraulic lime and air lime with pozzolanic additives demonstrates differences in microstructure. The difference in morphological characteristics is due to the process of hydration curing and the degree of reactions in the three types of lime solutions. Compared to materials containing airborne or artificial hydraulic lime, structures based on hydraulic lime are denser.

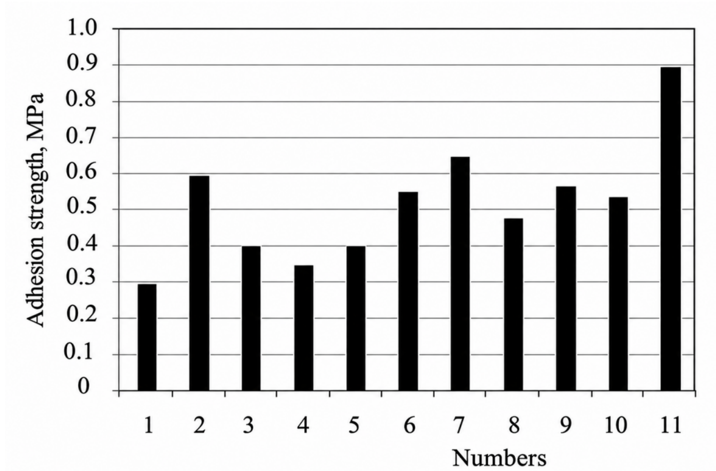


Figure 3. Adhesion strength of plaster mortar to the substrate.

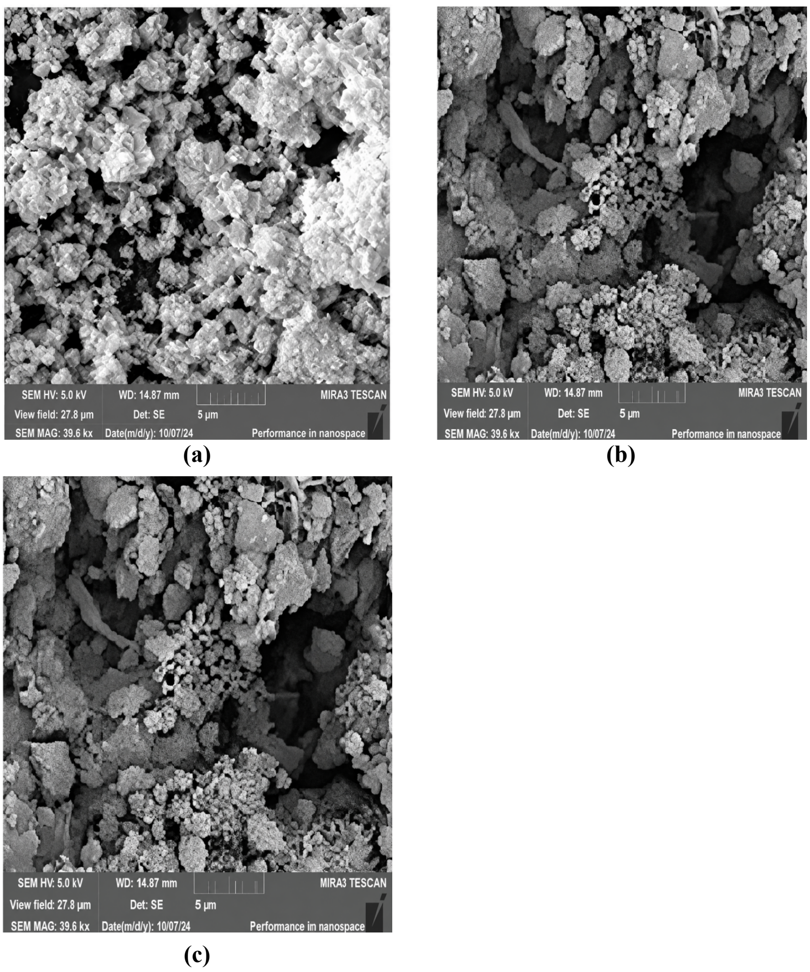


Figure 4. Structure of samples based on lime: (**a**) Natural lime NHL3.5; (**b**) Air lime with the addition of metakaolin; (**c**) Air lime.

The structure of NHL3.5 includes a fibrous calcium silicate hydrate (C–S–H) that wraps around the surface of calcium hydroxide, $Ca(OH)_2$. The presence of cubic $CaCO_3$ is observed, which is explained by the carbonation reaction of $Ca(OH)_2$. The structure of limestone-based on artificial hydraulic lime is dominated by small-sized clinker phase hydration products, with a small amount of carbonated products ($CaCO_3$) and $Ca(OH)_2$. $CaCO_3$, which is formed as a result of the carbonation reaction, is clearly visible, and the hydrated paste products are interconnected with each other. The pozzolan reaction between the binder and the active additive leads to a compaction of the material structure by reducing the overall porosity, which naturally increases the durability of lime-pozzolan mortars. Contrasting regions of nanometer-sized calcite and $Ca(OH)_2$ crystals were found in the structure of the lime composite based on air lime. $CaCO_3$ particles are layered on top of each other, forming a single whole, which is explained by the further intensification of the carbonization reaction.

Carbonation is one of the processes responsible for the hardening of lime mortars. The research results show that the depth of carbonization of calcareous compositions is determined by the density of the samples. The denser structure of the samples based on hydraulic lime slows down the process of carbon dioxide diffusion and reduces the thickness of the carbonized layer. The carbonation reaction of lime mortars based on NHL natural hydraulic lime is faster in the early stages of hardening, but slows later (**Figure 5**). The carbonation rate of lime mortars based on HL is somewhat slower. This is apparently due to the pozzolanic reaction, which consumes some of the $Ca(OH)_2$, suppressing the early carbonation reaction. Higher carbonation rates are characteristic of lime mortar. A greater amount of hydrated phases, $Ca(OH)_2$, in samples based on air lime promotes deeper carbonation due to the penetration of carbon dioxide through surface pores into the body of the lime composite and its interaction with portlandite. Data analysis shows that the rate of carbonation decreases over time, which fully corresponds to Fick's second law. A smaller angle of inclination of straight lines to the abscissa axis over time, starting from 60 days, indicates a decrease in the rate of $Ca(OH)_2$ interaction with CO_2; however, samples based on hydraulic lime are characterized by a lower angle of inclination both at the initial and subsequent stages of curing. The study of the obtained experimental results demonstrates that the intensity of carbonation processes varies at different stages of material use. This pattern is mainly due to the transformation of the internal structure of the samples. It has been established that during a certain time interval, the duration of which depends on the porosity of the composition, a change in the rate of decrease in the rate of carbonation reactions is recorded. Then, there are significant changes in the structure and properties of the coatings.

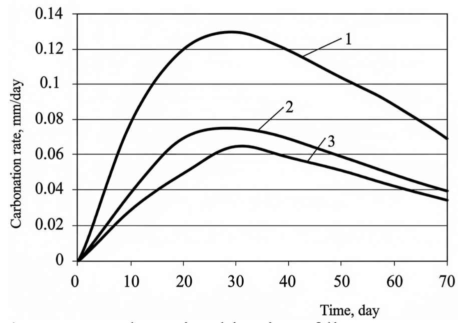
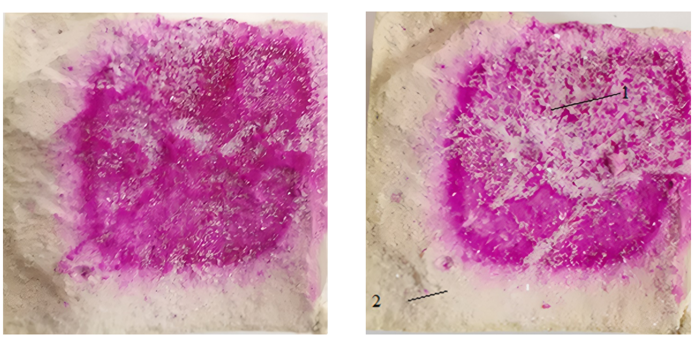


Figure 5. Carbonation kinetics of lime mortars.

Note: 1: air lime; 2: natural hydraulic lime (NHL); 3: air lime with cement and metakaolin (artificial hydraulic lime HL).

Carbonation of the material is initiated in the near-surface layers, as evidenced by the absence of staining in these areas, and as the reaction proceeds, the process front shifts deeper into the sample [22,23]. It has been found that the increased porosity of calcareous compounds facilitates the diffusion of carbon dioxide into the structure of the material, thereby providing a higher degree of carbonation (**Figure 6**).



(a) **(b)**

Figure 6. Dynamics of the depth of carbonization of samples after a two-month exposure period: (**a**) A sample based on hydraulic lime; (**b**) A sample based on air lime and metakaolin with cement.

Note: 1: non–carbonized layer; 2: carbonized layer.

As a model of the carbonization process, it is proposed to use a function that is the solution of a third-order differential equation:

$$Y(t) = C_1 e^{\alpha_1 t} + C_2 e^{\alpha_2 t} + C_3 e^{\alpha_3 t} \quad (10)$$

where t is the carbonation time;

$Y(t)$ is the carbonation rate;

C_1, C_2, C_3 are the constants of integration of the differential equation.

The coefficients $\alpha_1, \alpha_2, \alpha_3$ characterize the change in the controlled parameter at different stages of carbonation.

We have proposed a model of the carbonation rate of a lime composite based on hydraulic lime:

$$y_1(t) = -0.003e^{0.044t} - 1.114e^{-0.025t} + 1.117e^{-0.02t} \quad (11)$$

The model of the carbonation rate of a composite based on air lime and metakaolin with cement has the form:

$$y_2(t) = -0.009e^{0.043t} - 1.255e^{-0.036t} + 1.258e^{-0.027t} \quad (12)$$

The results of the calculation of the carbonation rate, calculated in accordance with Equations (11) and (12), indicate the convergence of experimental and calculated data.

Hygroscopic properties of mortars are of great importance because they significantly affect their effectiveness against water, frost, salt, and chemical weathering, which determine durability. To evaluate the behavior of the mortar in contact with liquid water, the samples were subjected to a capillary water absorption test after 28 days of air-dry curing at a temperature of 18–20 °C and a relative humidity of 60–70%. It was found that the softening coefficient of mortars based on NHL natural hydraulic lime was 0.8, while that of mortars based on air lime with metakaolin and cement was 0.81–0.84, which is likely due to the mortar's microporous structure. The porosity of the mortar based on natural hydraulic lime NHL is 30%, water absorption by capillary suction is 0.376 kg/($m^2 \cdot h^{0.5}$), the vapor permeability coefficient of the mortar is 0.096 mg/(m·h·Pa), and based on air lime with metakaolin and cement, respectively, are 29%, 0.476 kg/($m^2 \cdot h^{0.5}$), 0.103 mg/(m·h·Pa) (**Figure 7**). The vapor permeability coefficient of the mortar based on air lime is 0.12 mg/(m·h·Pa) with a porosity of 32%. The results obtained indicate a different nature of the pores in the structure of the solutions and, accordingly, a different rate of moisture migration in the liquid and vapor states in a plaster solution based on hydraulic and air lime.

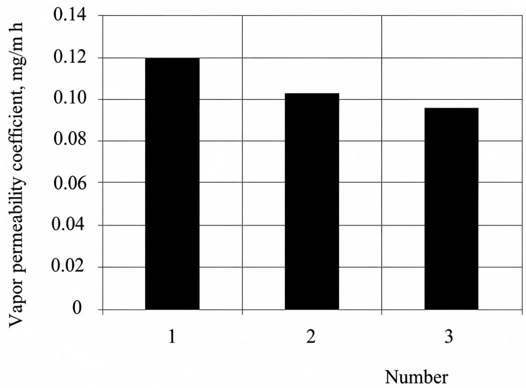


Figure 7. Vapor permeability coefficient of lime mortars.

Note: 1: air lime; 2: air lime with metakaolin and cement; 3: natural hydraulic lime NHL.

According to the authors, taking into account the characteristics of building mixes containing natural, artificial hydraulic and air lime (in particular, their ability to absorb water and vapor permeability), the process of applying plaster during the restoration of historical buildings should include the use of plaster mortar based on natural hydraulic lime NHL when applying the spray, a mortar based on artificial hydraulic lime NH when applying the base primer, and a mortar based on air lime when applying the top layer [24–26]. These mortars ensure vapor permeability of the finishing layer, structural compatibility with the restored structure, and sufficient mechanical properties.

4. Conclusions and Recommendations

The results obtained during the assessment of the properties of lime mortars are presented in order to recommend the technology of restoration plastering. It has been established that for the restoration of historic buildings, plaster mortars based on air lime with pozzolanic additives, as well as those based on artificial and natural hydraulic lime, should be used. The final selection of lime plaster mortar formulations should be based on an assessment of the potential of lime mortars depending on the expected service conditions. The porosity of the mortar based on natural hydraulic lime NHL is 30%, water absorption by capillary suction is 0.376 kg/($m^2 \cdot h^{0.5}$), the vapor permeability coefficient of the mortar is 0.096 mg/(m·h·Pa), and based on air lime with metakaolin and cement, respectively, are 29%, 0.476 kg/($m^2 \cdot h^{0.5}$), 0.103 mg/(m·h·Pa). The vapor permeability coefficient of the mortar based on air lime is 0.12 mg/(m·h·Pa) with a porosity of 32%. It is proposed that when restoring historic buildings, a plaster mortar based on NHL natural hydraulic lime should be used for spray coating, a mortar based on HL artificial hydraulic lime should be used for the base coat, and a plaster mortar based on air lime should be used for the top coat. However, the choice of a plaster mortar system should be determined by specific conditions.

Author Contributions

Conceptualization, V.I.L.; methodology, V.T.E.; validation, M.V.Z.; data curation, M.V.Z.; writing—original draft preparation, V.I.L.; writing—review and editing, I.V.S.; project administration, I.V.S. All authors have read and agreed to the published version of the manuscript.

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The results were obtained experimentally by the authors themselves. Data supporting the reported results are available from the Russian Science Citation Index.

Conflicts of Interest

The authors declare no conflict of interest.

AI Use Statement

The authors declare that no artificial intelligence (AI) tools were used in the preparation of this manuscript.

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