

Development of artificial hydraulic lime

Valentina I. Loganina^{1*} , Irina A. Garkina¹ , Evgenia V. Tkach² , Irina V. Stepina² 

¹ Penza State University of Architecture and Construction, 440028, Penza, ul. Titov, 28, Russian Federation

² National Research Moscow State University of Civil Engineering, 129337, Moscow, Yaroslavskoye shosse, 26, Russian Federation

* Corresponding author: e-mail: loganin@mail.ru

ABSTRACT

Introduction. Lime mortars used for the restoration of historical buildings are characterized by low resistance during operation. The durability of lime solutions can be increased by using hydraulic lime as a binder. However, the share of hydraulic lime in the lime binder production structure is only 19.8%. Given the low volume of production of natural hydraulic lime, it is promising to develop a formulation of artificial hydraulic lime. **Materials and methods.** To develop the formulation of artificial hydraulic lime, grade 2 slaked lime (pushonka) with an activity of 64% was used, as well as grade 2 air lime with an activity of 84% (GOST 9179-18). The technology for producing artificial hydraulic lime consisted of mixing slaked lime with pozzolan additives, as well as mixing air lime with pozzolan additives during the quenching process. When developing the formulation of the plaster mortar, quartz sand from various deposits was used as a fine filler. The optimal type of sand was selected based on the strength criterion of calcareous composites and sand activity, characterized by the value of free surface energy. **Results.** It has been established that the most effective is the addition of metakaolin. The compressive strength of the solution at the age of 28 days of hardening is 2.1 MPa when using second-grade quicklime. Increasing the dosage of metakaolin to 40% by weight of lime increases the compressive strength to 2.7–3.1 MPa. Pozzolan additives silica, dehydrated clay, diatomite at a dosage of 10% by weight of lime do not provide the required compressive strength of at least 2.0 MPa. The introduction of Portland cement in the formulation in an amount of 25% by weight of lime contributes to a significant increase in compressive strength, amounting to 2.9–4.0 MPa, depending on the type of additive and type of lime, as well as the technology of binder preparation. The porosity of calcareous stone based on artificial hydraulic lime was determined, amounting to 48–51%, while a decrease in the volume of closed pores was observed. Solutions based on artificial hydraulic lime provide sufficient adhesion strength to the brick substrate, amounting to 0.4–0.55 MPa/kg. It has been established that the use of methakaolin in the amount of 40–50% of the mass of air lime makes it possible to obtain artificial hydraulic lime. The developed compositions of artificial hydraulic lime are proposed to be used for the restoration of buildings of historical buildings, as well as finishing newly erected facilities. **Conclusion.** It has been established that the use of aerial quicklime in the preparation of artificial hydraulic lime promotes a more durable lime composite structure. The porosity of limestone based on artificial hydraulic lime is lower than that of limestone based on aerial lime, and for limestone based on cement-based compositions, it is lower than that of limestone based on hydraulic lime. HL artificial hydraulic lime and plaster mortar formulations based on it have been developed for the restoration of cultural heritage sites and the finishing of new buildings.

KEYWORDS: lime, pozzolan additives, strength, porosity, free energy of the surface

ACKNOWLEDGEMENTS: The work was carried out within the framework of a grant from the Industry Consortium “Construction and Architecture” for fundamental and applied scientific research).

FOR CITATION:

Loganina V.I., Garkina I.A. Tkach E.V., Stepina I.V. Development of artificial hydraulic lime. *Nanotechnologies in Construction*. 2026;18(2):159–166. <https://doi.org/10.15828/2075-8545-2026-18-2-159-166>. – EDN: WZDOJN.

Разработка искусственной гидравлической извести

Валентина Ивановна Логанина^{1*} , Ирина Александровна Гарькина¹ , Евгения Владимировна Ткач² ,
Ирина Васильевна Степина² 

¹ Пензенский государственный архитектурно-строительный университет, 440028, Пенза, ул. Г. Титова, 28, Российская Федерация

² Национальный исследовательский Московский государственный строительный университет, Москва, 129337, Москва, Ярославское шоссе, 26, Российская Федерация

* Автор, ответственный за переписку: e-mail: loganin@mail.ru

АННОТАЦИЯ

Введение. Известковые растворы, применяемые для реставрации зданий исторической застройки, характеризуются низкой стойкостью в процессе эксплуатации. Стойкость известковых растворов может быть повышена применением в качестве вяжущего гидравлической извести. Однако в структуре выпуска известкового вяжущего доля гидравлической извести составляет всего лишь 19,8%. Учитывая низкий объем производства натуральной гидравлической извести, перспективной является разработка рецептуры искусственной гидравлической извести. **Материалы и методы.** Для разработки рецептуры искусственной гидравлической извести применяли гашеную известь (пушонка) 2 сорта с активностью 64%, а также воздушную известь 2 сорта с активностью 84% (ГОСТ 9179-18). Технология получения искусственной гидравлической извести заключалась в смешивании гашеной извести с пуццолановыми добавками, а также в смешивании воздушной извести с пуццолановыми добавками в процессе гашения. При разработке рецептуры штукатурного раствора в качестве мелкого заполнителя применяли кварцевый песок различных месторождений. Выбор оптимального вида песка проводился из критерия прочности известковых композитов и активности песка, характеризующей значением свободной поверхностной энергии. **Результаты.** Установлено, что наиболее эффективной является добавка метакаолина. Прочность при сжатии раствора в возрасте 28 суток твердения составляет 2,1 МПа при применении негашеной извести второго сорта. Увеличение дозировки метакаолина до 40% от массы извести повышает прочность при сжатии до 2,7–3,1 МПа. Пуццолановые добавки (микрокремнезем, дегидратированная глина, диатомит) при дозировке 10% от массы извести не обеспечивают требуемой прочности при сжатии, равной не менее 2,0 МПа. Введение в рецептуру портландцемента в количестве 25% от массы извести способствует значительному повышению прочности при сжатии, составляющему 2,9–4,0 МПа в зависимости от вида добавки и вида извести, а также технологии приготовления вяжущего. Определена пористость известкового камня на основе искусственной гидравлической извести, составляющая 48–51%, при этом наблюдается уменьшение объема закрытых пор. Растворы на основе искусственной гидравлической извести обеспечивают достаточную прочность сцепления с кирпичной подложкой, составляющую 0,4–0,55 МПа. **Заключение.** Установлено, что применение воздушной негашеной извести при приготовлении искусственной гидравлической извести способствует более прочному формированию структуры известкового композита. Выявлено, что пористость известкового камня на основе искусственной гидравлической извести меньше по сравнению с камнем на основе воздушной извести, а для известкового камня на основе составов с применением цемента – меньше, чем на основе гидравлической извести. Разработаны составы искусственной гидравлической извести НЛ и штукатурного раствора на ее основе, предназначенные для реставрации объектов культурного наследия и отделки вновь возводимых объектов.

КЛЮЧЕВЫЕ СЛОВА: известь, пуццолановые добавки, прочность, пористость, свободная энергия поверхности

БЛАГОДАРНОСТИ: Работа выполнялась в рамках выполнения гранта Отраслевого консорциума «Строительство и архитектура» на проведение фундаментальных и прикладных научных исследований.

ДЛЯ ЦИТИРОВАНИЯ:

Логанина В.И., Гарькина И.А., Ткач Е.В., Степина И.В. Разработка искусственной гидравлической извести. *Нанотехнологии в строительстве*. 2026;18(2):159–166. <https://doi.org/10.15828/2075-8545-2026-18-2-159-166>. – EDN: WZDOJN.

INTRODUCTION

One of the challenges facing modern society is the global increase in CO₂ emissions and the associated rise in temperature. The construction industry is one of the largest sources of CO₂ emissions, accounting for over 15% of all greenhouse gas emissions. The cement industry alone accounts for 5–7% of global CO₂ pollution. One solution

to this problem is the wider use of lime mortars. However, lime mortars are characterized by low durability during operation. To increase strength and durability during operation, various modifying additives are added to lime mortar formulations [1–3].

The durability of lime mortars can be increased by using hydraulic lime as a binder. Demand for hydraulic lime has increased in recent years, particularly in connec-

tion with the preservation of historic buildings. Natural hydraulic lime is characterized by compatibility with old masonry, low shrinkage, resistance to salt and frost, and higher deformability and vapor permeability [4–6].

However, hydraulic lime accounts for only 19.8% of total lime binder production. Demand for this type of binder remains limited. The lime market's prospects in the near future will largely be determined by the dynamics of key consumption segments. Considering the low production volume of natural hydraulic lime, the development of a formula for artificial hydraulic lime is promising.

Artificial hydraulic lime can be produced by mixing air-blown lime with pozzolanic additives. Commonly used additives for lime include metakaolin, fly ash, microsilica, ground brick, dehydrated clay, etc. [7–11]. In addition to binary combinations (lime → pozzolan), ternary systems (lime:pozzolan:cement) have proven effective.

The properties of artificial hydraulic lime are influenced by early hardening conditions, including the presence of water, which facilitates the pozzolanic reaction and the transport of CO₂ for subsequent carbonation. The synergistic and competitive effect of these two reactions ensures the level of early strength in pozzolanic systems [12, 13].

The properties of artificial hydraulic lime are significantly influenced by the reactivity of lime and pozzolanic additive, as well as their ratio in the formulation [14]. Too much additive can lead to increased drying shrinkage [15]. Furthermore, the application technology of the mortar plays a fundamental role in the optimal curing of the fresh mortar [16, 17].

An analysis of scientific and technical literature shows that, despite the existing research results, many issues require more detailed consideration when developing a formula for artificial hydraulic lime. The aim of the work is to develop a composition of artificial hydraulic lime and plaster mortar based on it for the restoration of historical buildings.

METHODOLOGY

To develop the recipe for artificial hydraulic lime, slaked lime (fluff) of the 2nd grade with an activity of 64%, as well as air lime of the 2nd grade with an activity of 84% (GOST 9179-18) were used. The technology for obtaining artificial hydraulic lime consisted in mixing slaked lime with pozzolanic additives, as well as in mixing air lime with pozzolanic additives during the slaking process. In the work, diatomite of the Inzenskoye deposit, condensed uncompact microsilica MK-85 ($S_{sp} = 24\,000\text{ m}^2/\text{kg}$) with the content (in % by mass %) were used as a pozzolanic additive: SiO₂ – 92; Al₂O₃ – 0.9; C – 1.6; CaO – 0.85; MgO – 0.4; (YDD Corporation LLP, Kazakhstan), highly active metakaolin VMK-45 ($S_{sp} = 1700\text{ m}^2/\text{kg}$) with the following content (in % by weight): SiO₂ – 53;

Al₂O₃ – 42 and pozzolanic activity of 1210 mg/g (Sinergo LLC, Russian Federation), as well as clay from the Penza region (Belinskoye deposit) heat-treated at 600 °C. The composition of diatomite is represented by the following oxides, %: SiO₂ – 84–87, Al₂O₃ – 5.5–6, Fe₂O₃ 2.5–3, CaO – 0.61. The chemical composition of clays is presented in Table 1.

Table 1. Chemical composition of clay

Name of oxides	Content,%
SiO ₂	59.56
Al ₂ O ₃	11.85
Fe ₂ O ₃	4.54
Other	24.05

White cement PCB 1-500 D0 (GOST 965-89) was also used to develop the composition of artificial hydraulic lime. For comparison, natural hydraulic lime “Tamasli” NHL was used in the study. The hydraulic modulus of this lime is $M = 2.69$.

After molding, the samples were covered with polyethylene film, cured for 7 days, then removed from the mold and conditioned in water for 21 days. The compressive strength of the samples was determined after 28 days of curing in accordance with GOST 9179-2018 “Construction Lime Technical Specifications.”

When developing the plaster mortar formula, quartz sand from various deposits was used as fine aggregate. The optimal sand type was selected based on the strength of limestone composites and the sand's activity, characterized by its free surface energy [18].

The surface free energy (SFE) was determined using the OVRK method. Glycerin and water, each with known surface tension values and their dispersion and polar components, were used as working fluids. The contact angle was measured on tablet samples prepared by pressing sand into a 20 mm diameter metal mold. By extrapolating the dependence $\cos\Theta = f(\sigma_*)$ to $\cos\Theta = 1$, the critical surface tension of a solid surface was obtained. The polar and dispersion components were calculated using linear regression

$$\frac{\sigma_L(1+\cos\theta)}{2\sqrt{\sigma_L^d}} = \sqrt{\sigma_S^p} \cdot \sqrt{\frac{\sigma_L^p}{\sigma_L^d}} + \sqrt{\sigma_S^d}, \quad (1)$$

where σ_L is the surface tension of the working fluids;
 σ_S^d is the dispersion component of the surface tension of the working fluids;

σ_L^p is the polar component of the surface tension of the working fluids;

σ_S^d is the dispersion component of the surface tension of the material being studied;

σ_s^p is the polar component of the surface tension of the material being studied;

θ is the contact angle of the material being studied.

The dispersion component of the surface tension of the studied material (sand) σ_s^d was determined as the tangent of the angle of inclination of the line to the abscissa axis, and the segment intercepted by the line on the ordinate axis is equal to the value of the polar component of the surface tension of sand σ_s^p . At least five measurements were carried out for each sample.

The value of surface energy E was determined by the total surface area of the dispersed sample and was calculated using the following expression

$$E = \sigma S_{sp}, \quad (2)$$

where σ is the surface tension of the quartz filler;
 S_{sp} is the specific surface area of the quartz sand.

RESULTS AND DISCUSSION

Table 2 shows the results of the evaluation of the compressive strength of lime mortars.

Table 2. Compressive strength of lime mortar

No.	Type of binder	Compressive strength, MPa
1	Air lime	
2	NHL Hydraulic Lime	2.05
3	Air lime + Portland cement 25%	2.9/3.2
4	Air lime + 10% metakaolin	1.4/2.1
5	Air lime + 40% metakaolin	2.7/3.1
6	Air lime + 10% microsilica	1.2/1.6
7	Air lime + 10% microsilica + Portland cement 25%	3.4/3.7
8	Air lime + diatomite 10%	1.1/1.4
9	Air lime + dehydrated clay 10%	1.3/1.5
10	Air lime + diatomite 10% + Portland cement 25%	3.1/3.5
11	Air lime + 25% cement + 10% metakaolin	3.7/4.0

Note. * Above the line are the values of the compressive strength when using slaked lime, below the line – when using non-slaked lime.

Table 3. Porosity of limestone

No.	Type of binder	Porosity, %	Open pore volume, %	Closed pore volume, %	Water absorption, % by weight
1	Control	60	50	10	44
2	NHL Hydraulic Lime	52	38	14	36
3	Air lime + 10% metakaolin	57	46	11	34.8
4	Air lime + 40% metakaolin	54	41	13	32.7
5	Air lime + 10% microsilica + 25% Portland cement	51	41	10	36
6	Air lime + diatomite 10% + Portland cement 25%	53	43	10	33
7	Air lime + 25% cement + 10% metakaolin	48	39	9	31

For example, the porosity of limestone based on natural hydraulic lime is 52%, while that of mortars with pozzolanic additives and cement is 48–51%, with a decrease in closed pore volume observed.

The kinetics of lime binding with CaO during the hardening process was studied (Fig. 1).

An analysis of the experimental data indicates that the amount of free lime decreases over time. Thus, at 7 days, the amount of free CaO in the control sample was 85%, and at 28 days, 79% (Fig. 1, curve 1). In samples with the addition of metakaolin, the free lime content decreased to 64% by the 28th day of curing (Fig. 1, curve 2), and with the addition of metakaolin and cement, it decreased to 60% (curve 4).

The presence of free lime in hydraulic lime mortar ensures the self-healing of small cracks. This occurs as the lime in the mortar dissolves in water and, through evaporation, moves to the surface. The reaction between calcium hydroxide and atmospheric carbon dioxide gas forms calcite, which fills and seals the cracks.

When developing a plaster mortar formulation, the effect of quartz sand type on mortar strength was as-

essed. A thermodynamic method was used. To evaluate the optimal sand type, artificial hydraulic lime containing air-dried slaked lime and 40% metakaolin was used as a binder. The samples were cured in air-dry conditions. The results are presented in Table 4.

Analysis of the data presented in Table 4 indicates that with increasing surface free energy (SFE) values of quartz sand, an increase in the compressive strength of the limestone composite is observed. Thus, the compressive strength of the limestone composite based on Sura sand, characterized by a higher surface free energy (SFE) value of 70.285 mN/m, is 2.4 MPa, while that based on sand from the Chaadaevskoye deposit, whose surface free energy (SFE) is 62.8 mN/m, is 1.92 MPa

To summarize the above, it should be noted that the optimal sand from the energy point of view is the Sura deposit, which provides higher strength of the limestone composite.

Mortars based on artificial hydraulic lime provide sufficient bond strength to the brick substrate, amounting to 0.4–0.55 MPa (Fig. 2). The bond strength of

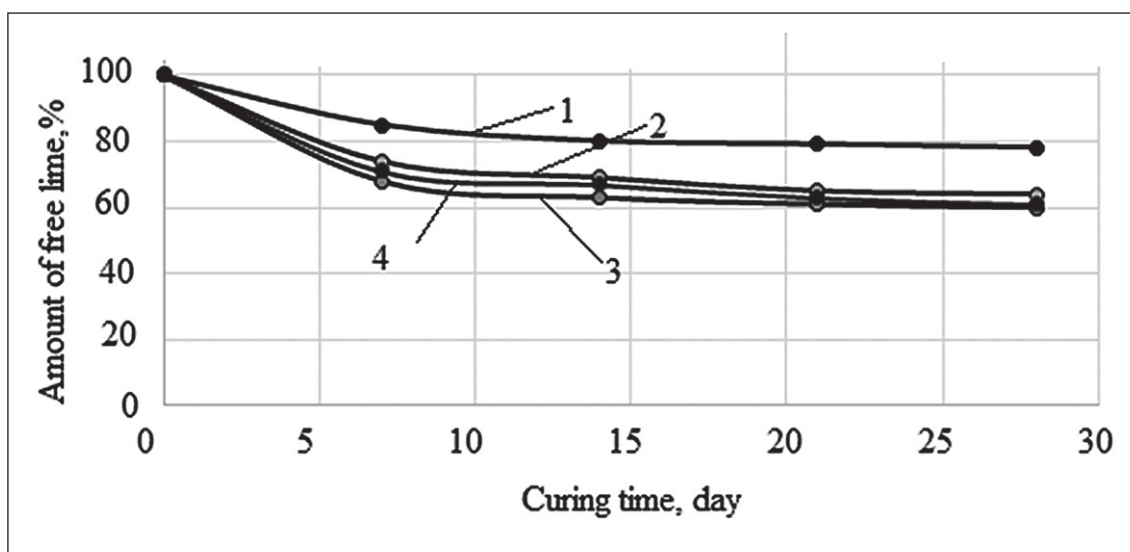


Fig. 1. Kinetics of changes in free CaO concentration in lime compositions: 1 – control lime composition without additives; 2 – artificial hydraulic lime (40% metakaolin additive); 3 – artificial hydraulic lime (10% metakaolin additive + 25% cement); 4 – artificial hydraulic lime (10% microsilica additive + 25% cement)

Table 4. Surface free energy (SFE) values of quartz sands

Name of sand	Polar component of the SEP, s	Dispersion component of the SEP, s	SEP, мДж/м ²	Surface energy, J/kg	Compressive strength, MPa
Rtishchevsky	50.48	18.49	68.97	593.142	2.1
Ramensky	53.08	16	69	614.1	2.3
Nikolsky	50.335	18.49	68.82	557.442	2.0
Sursky	51.79	18.49	70.285	687.106	2.4
Chaadaevsky	48.36	14.44	62.8	436.46	1.92

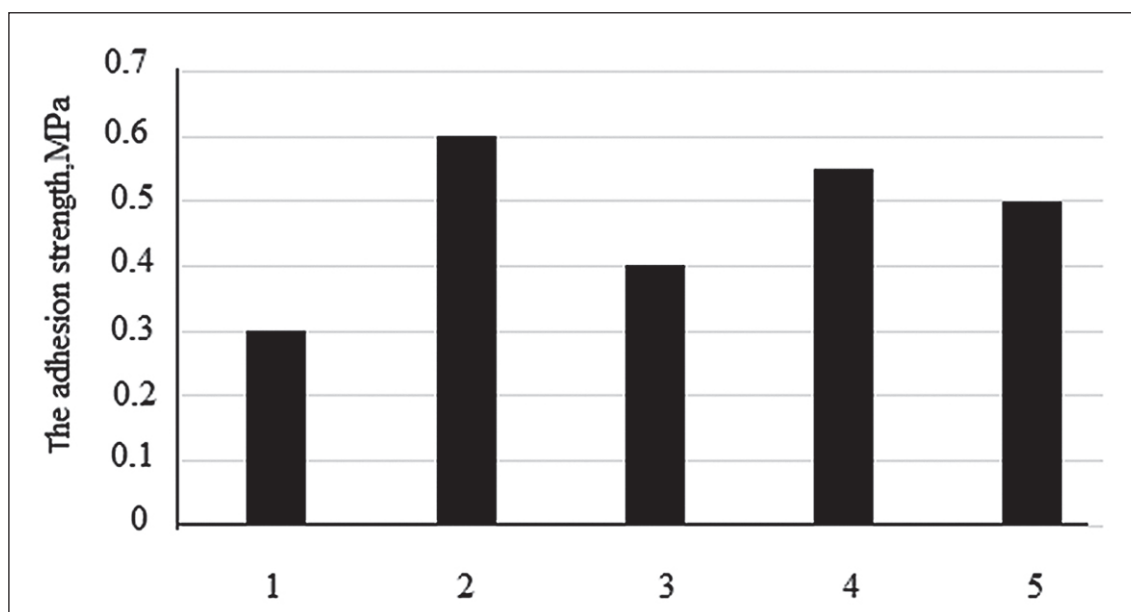


Fig. 2. The adhesion strength of mortar to a brick substrate: 1 – mortar based on air-dried lime; 2 – mortar based on hydraulic lime; 3 – mortar based on air-dried lime + 25% Portland cement; 4 – mortar based on slaked lime + 40% metakaolin; 5 – mortar based on quicklime + 10% metakaolin

mortar based on hydraulic lime is $R_{ad} = 0.6$ MPa. The increase in adhesion strength is explained by the pozzolanic reaction of metakaolin, which enhances the formation of calcium silicate hydrous gel (C–S–H), improving the microstructure and adhesive properties of the solution.

A comparison of the properties of a mortar based on artificial hydraulic lime HL with the properties of a mortar based on natural hydraulic lime NHL shows that the proposed formulation of artificial hydraulic lime meets the requirements of national and international regulatory documents (DIN 18550) in terms of achieving a minimum compressive strength of 2.0 MPa.

CONCLUSION

It has been established that the use of air quicklime in the preparation of artificial hydraulic lime contributes to a more durable formation of the structure of the lime composite. It has been revealed that the porosity of calcareous stone based on artificial hydraulic lime is lower than that of air lime-based stone, and for calcareous stone based on cement compositions – less than that based on hydraulic lime. Compositions of artificial hydraulic lime HL and plaster mortar based on it have been developed, intended for the restoration of cultural heritage sites and the finishing of newly constructed facilities.

REFERENCES

1. Loganina V.I., Makarova L.V., Tarasov R.V., Davydova O.A. Optimization of the composition of composites for general construction purposes modified with nanoscale additives. *Regional architecture and construction*. 2010;2:53-57.
2. Loganina V.I., Davydova O.A., Simonov E.E. Studies of the patterns of the effect of silicic acid sol on the structure and properties of diatomite. *Building materials*. 2011;12:62-65.
3. Pukharenko, Yu.V. Restoration of historical sites using modern dry building mixes / Yu.V. Pukharenko, A.M. Kharitonov, N.N. Shangina, T.Yu. Safonova. *Bulletin of Civil Engineers*. 2011;1:98-103.
4. Maravelaki-Kalaitzaki P., Bakolas A., Karatasios I., Kilikoglou V. Hydraulic lime mortars for the restoration of historic masonry in Crete. *Cem. Concr. Res*. 2005;35:1577-1586. <https://doi.org/10.1016/j.cemconres.2004.09.001>
5. Kang S.-H., Lee S.-O., Hong S.-G., Kwon Y.-H. Historical and Scientific Investigations into the Use of Hydraulic Lime in Korea and Preventive Conservation of Historic Masonry Structures. *Sustainability*. 2019;11:5169.

6. Shelikhov N.S. Hydraulic lime and roman cement from the mineral raw materials of Tatarstan / N.S. Shelikhov, R.Z. Rakhimov. *Construction Bulletin of Tatarstan*. 2002;2:48–53.
7. Arizzi A., Cultrone G. Aerial lime-based mortars blended with a pozzolanic additive and different admixtures: a mineralogical, textural and physical-mechanical study. *Constr. Build. Mater.* 2012;31:135–143. <https://doi.org/10.1016/j.conbuildmat.2011.12.069>
8. Aggelakopoulou E., Bakolas, A., Moropoulou A. Properties of lime–metakolin mortars for the restoration of historic masonries. *Appl. Clay Sci.* 2011;53:15–19. <https://doi.org/10.1016/j.clay.2011.04.005>
9. Stefanidou M., Tsardaka E.C., Pavlidou E. Influence of nano-silica and nano-alumina in lime-pozzolan and lime-metakaolin binders. *Mater Today Proc.* 2017;4:6908–6922. <https://doi.org/10.1016/j.matpr.2017.07.020>
10. Duran A., Navarro-Blasco I., Fernandez J.M. et al. Long-term mechanical resistance and durability of air lime mortars with large additions of nanosilica. *Constr Build Mater.* 2014; 58:147–158. <https://doi.org/10.1016/j.conbuildmat.2014.02.030>
11. Nunes C., Shizkova Z. Freezing and thawing resistance of aerial lime mortar with metakaolin and a traditional water-repellent admixture. *Constr Build Mater.* 2016;114:896–905. <https://doi.org/10.1016/j.conbuildmat.2016.04.029>
12. Ramenzanianpour A.A., Kazemian N., Sedighi S. et al. Study of durability of mortars with natural pozzolans under carbonation. *J. New Approach Civil Eng.* 2019; 3(3):63–75.
13. Ergenc D., Fort R. Accelerating carbonation in lime-based mortar in high CO₂ environments. *Constr Build Mater.* 2018; 188:314–325. <https://doi.org/10.1016/j.conbuildmat.2018.08.125>
14. Navratilova E., Rovnanikova P. Pozzolanic properties of brick powders and their effect on the properties of modified lime mortars. *Constr Build Mater.* 2016;120:530–539. <https://doi.org/10.1016/j.conbuildmat.2016.05.062>
15. Shangina N.N., Kharitonov A.M. Features of production and application of dry building mixes for restoration of architectural monuments. *Dry building mixes*. 2011;4:16–19.
16. Lukutsova N.P., Karpikov E.G., Pykin A.A., Panov D.M. Study of pozzolanic activity of highly dispersed wollastonite additive by the Frattini method. *Bulletin of the Belgorod State Technological University named after V.G. Shukhov*. 2024;9(12):8–17.
17. Tang V.L., Nguyen Z.T.L. Pozzolanic activity of finely dispersed mineral components of various origins in Vietnam. *Silicate Engineering and Technology*. 2021;28(1):7–18.
18. Abramovskaya I.R., Aizenshtadt A.M., Frolova M.A., Veshnyakova L.A., Tutygin A.S. Energy of highly dispersed composites of rocks. *Nanotechnology in construction: scientific online journal*. 2013;3:56–65.

ADDITIONAL INFORMATION

The authors declare that generative artificial intelligence technologies and technologies based on artificial intelligence were not used in the preparation of the article.

INFORMATION ABOUT THE AUTHORS

Valentina I. Loganina – Dr. Sci. (Eng.), Head of the Quality Management Department, Penza State University of Architecture and Construction, 440028, Penza, ul. Titov, 28, Russian Federation, loganin@mail.ru, <https://orcid.org/0000-0001-7532-0074>

Irina A. Garkina – Dr. Sci. (Eng.), Professor, Head of the Department of Mathematics and Mathematical Modeling, Penza State University of Architecture and Construction, 440028, Penza, ul. Titov, 28, Russian Federation, i.a.naum@mail.ru, <https://orcid.org/0000-0003-3371-3579>

Evgeniya V. Tkach – Dr. Sci. (Eng.), Professor of the Department of Urban Planning, National Research Moscow State University of Civil Engineering, 129337, Moscow, Yaroslavskoe shosse, 26, Russian Federation, tkachev@mgsu.ru, <https://orcid.org/0000-0003-2132-4971>

Irina V. Stepina – Cand. Sci. (Eng.), Associate Professor of the Department of Building Materials Science, National Research Moscow State University of Civil Engineering, 129337, Moscow, Yaroslavskoe shosse, 26, Russian Federation, kafSM@mgsu.ru, <https://orcid.org/0000-0002-5358-2935>

CONTRIBUTION OF THE AUTHORS

Valentina I. Loganina – scientific guidance, sample preparation, determination of specific surface area, collection, analysis and processing of results, writing an article.

Irina A. Garkina – sample production,

Evgeniya V. Tkach – project administration, verification of research results and conclusions.

Irina V. Stepina – literature review.

The authors declare no conflicts of interest.

The article was submitted 04.03.2026; approved after reviewing 05.04.2026; accepted for publication 10.04.2026.