dr inż. Piotr Konca [1)]
ORCID: 0000-0002-5415-5169
dr hab. inż. Jacek Szer, prof. uczelni [1)*]
ORCID: 0000-0002-7830-2952

Physical and mechanical tests of clay plasters

Badania fizykomechaniczne tynków glinianych

DOI: 10.15199/33.2024.06.04

Abstract. The main objective of this study was to test the water resistance of clay plaster and modified plaster, while ensuring performance properties such as adhesion and vapour permeability. Four types of specimens were prepared for testing: a control specimen of clay plaster, a plaster with an admixture of a hydrophobizing agent and water-glass. The last samples, where part of the clay plaster was replaced with hydrated lime. The best results were obtained for the admixture of the hydrophobizing agent.
Keywords: clay; physical properties; plaster.

Streszczenie. Głównym celem badań było określenie wodoodporności tynków glinianych i modyfikowanych, przy jednoczesnym zapewnieniu właściwości użytkowych, takich jak przyczepność i paroprzepuszczalność. Do badań przygotowano cztery rodzaje próbek: kontrolną z tynku glinianego, tynk z domieszką środka hydrofobizującego oraz tynk ze szkłem wodnym. W ostatnich próbkach część tynku glinianego zastąpiono wapnem hydratyzowanym. Najlepsze wyniki uzyskano przy domieszce środka hydrofobizującego.
Słowa kluczowe: glina, właściwości fizyczne, tynk.

Covering interior and exterior wall surfaces with clay plaster have been known since the beginning of civilization. Still popular at the beginning of the 20th century, this finishing method was superseded by the more durable lime plaster and later, by modern cement-lime plaster.

The resurgence of clay cladding was driven by the trend towards ecological construction. The main representative of this trend in construction is wood. It is not the only material used in ecological buildings. Increasingly, builders are choosing to use straw or clay to reduce their carbon footprint. Reducing greenhouse gases during the production and transport of materials is increasingly important.

The Primary Energy Intensity (PEI) per unit of mass or volume is used. It includes all transport and production processes needed to obtain the finished product. Natural materials have very low PEI values, while industrially obtained products have high values. Saving primary energy always means reducing CO_2 production. Examples of PEI ratings for selected building materials are shown in Figure 1 [1].

The problems that clay posses as a building material: poor water resistance, high shrinkage on drying and a rather high thermal conductivity coefficient, were well known in the past. Past methods of improving these characteristics of clay are below. **Increasing water resistance:**

- animal products: blood, urine, casein, bone glue;
- mineral-animal mixtures: lime with slurry and curd;

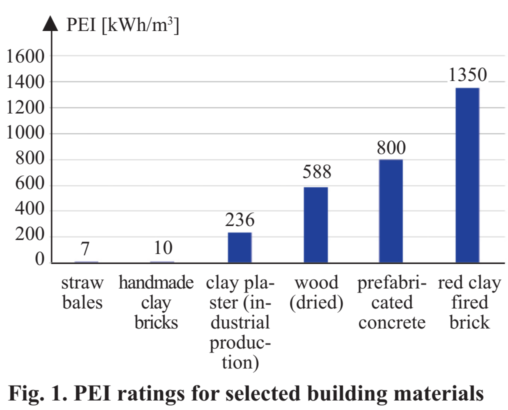


Fig. 1. PEI ratings for selected building materials
Rys. 1. Wskaźniki PEI różnych materiałów budowlanych

- plant products: sisal agave oil, bananas, wolfberries, starch, molasses;
- synthetic products: wax, latex, paraffin wax;
- bituminous emulsions.

Reduction of shrinkage:

- chemicals: water glass, baking soda, humic acid;
- fibres: animal hair, coconut fibre, straw, flax, hemp fibre, pine needles, hay.

Increasing thermal insulation:

- vegetable additives: straw, reeds, sea grass, cork;
- mineral additives: pumice, perlite.

Advantages and disadvantages of clay as a building material

Clay has a number of characteristics related to the material itself, its production or processing, which positively and negatively affect its usefulness as a building material. Compared to industrial materials, clay has the following disadvantages:

- clay is a mixture of several soil fractions, its properties can vary depending on the actual composition used for testing or on site. This fact is further complicated by a kind of 'specialisation' of this material. Clay plasters and other related products are often produced in small quantities or by small manufacturers. This makes it difficult to obtain accurate laboratory test results to determine the physical and mechanical properties of a particular batch of material;
- clay is not resistant to water. The material itself must be protected from moisture during extraction, storage and handling. Building components made of clay are vulnerable to damage from, for example, rain, capillary water or leaks from installations [2];

[1)] Politechnika Łódzka, Wydział Budownictwa, Architektury i Inżynierii Środowiska
[*)] Correspondence address: jacek.szer@p.lodz.pl

■ as the clay dries, its volume decreases; similarly, when the clay is worked on site, its volume increases due to the added water required to make the material workable. This characteristic adversely affects external as well as internal plasters. Studies have shown that desiccation cracking is a complex, coupled suction and shrinkage process sensitive to boundary conditions (relative humidity, ambient temperature, basal friction, clay layer thickness, etc.) and internal soil properties (clay content) [3];

■ clay is not a good insulator. A wall built of solid clay, in terms of insulating capacity, usually corresponds to a wall of the same thickness made of clay bricks;

■ the low mechanical resistance makes it difficult to use clay for cladding in rooms exposed to heavy human or vehicle traffic;

■ the material is rarely used, and it is therefore difficult to find skilled workers who have the necessary skills and knowledge to carry out the various elements of a building in a professional and appropriate manner.

The reasons for choosing this material for construction of modern buildings:

● clay render can easily absorb and release water vapour from the environment [4];

● the specific heat allows thermal energy to be stored. The heating process of the clay's heat release protects against excessive temperature fluctuations [5];

● the process of extracting and processing clay does not require much energy, compared to the production of cement or lime. In addition, clay is available in many places, often close to the construction site [6];

● the material is completely reusable. The clay left over after construction does not become waste. It can be re-mixed with water and used in another building;

● covering structural elements with clay further protects them from fire. This feature is particularly used for wooden structures [7];

● this material contains fewer admixtures than other machine-made plasters and is more environmentally friendly due to its lower content of artificial compounds;

● the clay preserves the wood by acting as a barrier to fungi and insects.

Clay plaster

The most common use of unprocessed clay in the building industry is in plastering, while clay is also the least frequently used material for this purpose. The clay used for plastering consists mainly of dust and sand; the clay must ensure the adhesion and cohesion of the mixture. The amount of clay in the plaster should oscillate around 5%. When the clay content increases to around 10% the plaster will show more shrinkage and this will cause cracks and fissures. It is quite difficult to determine the precise composition of the ideal wall covering mix. This is due to the aforementioned diversity of the clay material. This is influenced, among other things, by the size and composition of the sand grains, the type of clay, the way the mix is prepared, the amount of water or additives added to the mix.

The plasters do not chemically bond to the substrate but can be applied to all rough surfaces: brick masonry, clay blocks, cement blocks, natural stone, concrete walls, wooden elements or other plaster facings. If the roughness of the surface is not sufficient, it should be further scratched to increase the possibility of the plaster adhering to it. In the case of smooth materials, plastering on a mesh backing is possible.

The 'eco-friendliness' of the material is also an important factor: the absence of additional chemicals in the mix and the reduced need for long-distance transport. Often the properties that lead builders to choose clay are its effect on indoor humidity and its good vapour permeability.

Interior clay plasters are found quite often in sustainable construction, but it is also possible to use clay for the exterior finish. This carries additional requirements in terms of mix, workmanship and additional structural elements to protect the wall. The advantages of this material for finishing from the inside apply equally well on the other side of the walls. In this case, one has to deal with the susceptibility to weathering, which is a fundamental disadvantage of clay.

The most common way to protect clay-clad walls is to shape a sufficiently large roof over the partition so that rain cannot come into direct contact with the cladding. **It is important that clay render is not used where the wall is in contact with the ground.** It is recommended that the wall is plastered from a height of 30 – 50 cm above the ground. This effect can be achieved, for example, by appropriately raising the floor level of the building above the ground. Another method to enable the use of clay plasters on external walls is to add suitable additives to the mixture to improve its physical and mechanical properties.

Stabilized clay plasters are plasters that contain, in addition to clay, other mineral or organic binding agents, such as lime, cement, gypsum, modified starch, methyl cellulose, cow dung, oils, resins, bitumen emulsions or synthetic binding agents. These agents are not soluble in water once they have hardened.

Test materials

Plaster mix used for testing. Clay plaster mixes can be purchased on the market from many manufacturers. Unfortunately, these are mainly mixes made in a 'cottage industry' manner, so it is difficult to obtain accurate mix specifications. In this study, a factory mix from a well-known manufacturer that has been tested and approved for marketing and use was used. This mix can be used for exterior plaster, primer and levelling. The manufacturer has stated that the product does not contain any chemicals, but the exact composition is not known.

Variants of the plaster mixture. All variants used the same amount of liquid component, i.e. 17% by dry weight.

Clay plaster (control sample). Samples were made by combining the mixture with water, adding 17% water by weight. When the samples were made, significant shrinkage of the binding mix was noted.

Bulk hydrophobized plaster. In the first mix, an additive hydrophobic agent was used in the fresh mix. The mixture used here was a silicone emulsion for hydrophilization of cementitious products. The emulsion was added to the mix at a rate of 1% by weight, while replacing 1% by weight of water. According to the manufacturer's recommendations, the added agent provides a hydrophobic effect and reduces water absorption by up to 80%.

Plaster with sodium water-glass. Another more traditional method of water protection was the use of water-glass. This additive has been used in construction since the 19th century to improve fire and water resistance properties. The sodium water-glass was added to the mixture in an amount of 1% by weight, replacing 1% by weight of water.

Plaster with hydrated lime added. Another addition to the mix was hydrated lime. Slaked lime was often used in the past. The addition of lime was intended to provide increased water resistance and strength properties. The lime made up 10% of the dry mix by weight.

Test methods and results

Flexural and compressive strengths (Figure 2**).** The tests were executed according to standard [8]. The test was carried out on 40 x 40 x 160 mm beams, which were also used for density measurements.

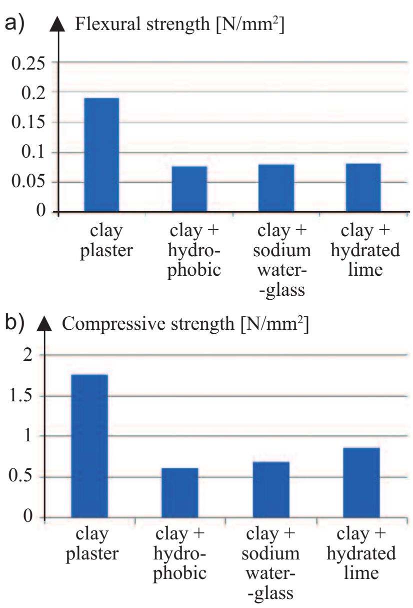


Fig. 2. Flexural (a) and compressive strength (b) results of plaster samples
Rys. 2. Wytrzymałość na zginanie (a) i ściskanie (b) próbek tynków

Water absorption (Figure 3). Capillary rise of water was determined by determining the value of the rate at which each type of specimen soaked [9]. The

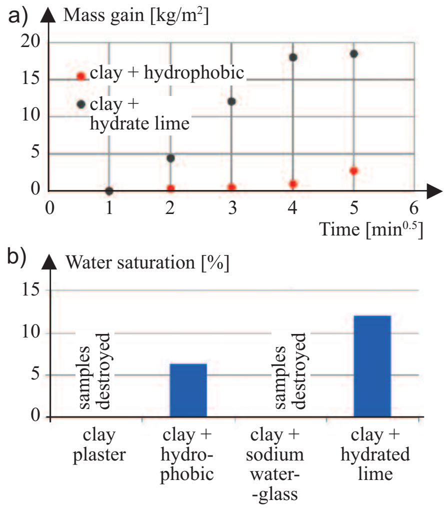


Fig. 3. Capillary rise of water (a) and water saturation (b) results of plaster samples
Rys. 3. Podciąganie kapilarne (a) oraz nasiąkliwość (b) próbek tynków

test was executed for each of the 4 types of specimens. The suction was expressed as a unit [kg/m^2/min$^{-0,5}$].

The pure clay and water-glass modified samples disintegrated and could not be tested. Water absorption by weight was determined according to the percentage change in weight of the dried sample and the sample saturated with water. As with the capillary rise of water tests, the clay plaster and water-glass modified samples disintegrated and could not be tested.

Hydrophobicity testing using the droplet method (Photo 1). Hydrophobicity was tested using the drop method. It consists of measuring the slope account of a water droplet placed on the surface of the material. Determining the value of this slope shows to what extent the material was wetted. The results are presented in degrees.

Adhesion to the substrate (Figure 4). The test was carried out on mortar discs with a diameter of 50 mm. Adhesion was determined as the ratio between the maximum pull out force and the surface area of the test specimen [10].

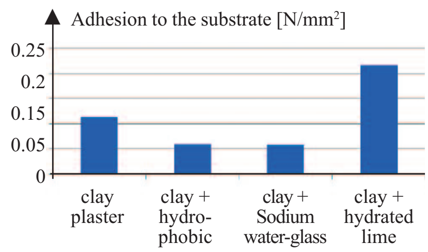
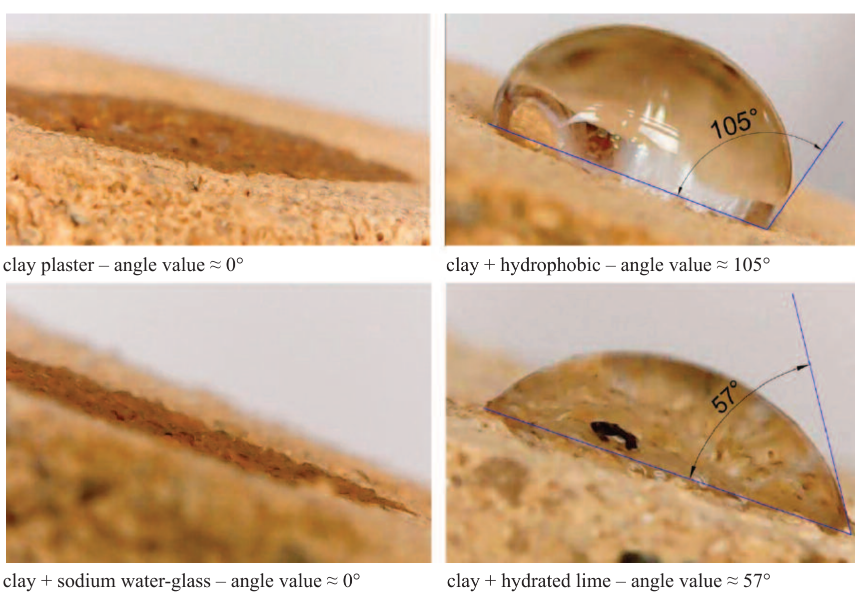


Fig. 4. Adhesion of plaster samples to the concrete substrate
Rys. 4. Przyczepność próbek tynków do podłoża betonowego

Vapour permeability test (Figure 5). The vapour permeability test [11] was carried out using special cups containing a supersaturated salt solution – potassium nitrate. A specially prepared layer of plaster was placed on the cups.

DVS sorption isotherm tests (Figure 6). Methods for determining sorption isotherms can be divided into static and dynamic. The traditional method for testing this characteristic is the gravimetric method. Two alternative methods can be



clay plaster – angle value ≈ 0°
clay + hydrophobic – angle value ≈ 105°
clay + sodium water-glass – angle value ≈ 0°
clay + hydrated lime – angle value ≈ 57°

Photo 1. Wetting angle for four types of plasters
Fot. 1. Kąt zwilżenia w przypadku czterech różnych typów tynków

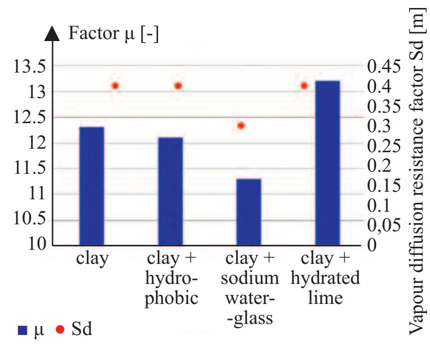


Fig. 5. Vapour conductivity coefficient µ and relative diffusion resistance of plaster samples
Rys. 5. Współczynnik przewodności pary wodnej µ i opór dyfuzyjny względny próbek tynków

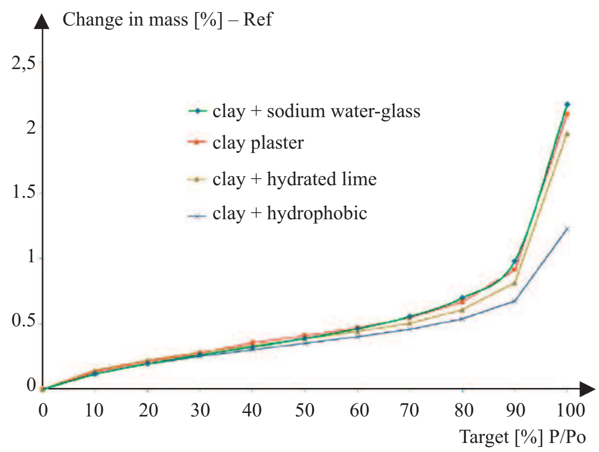


Fig. 6. Moisture sorption tests over the entire RH range
Rys. 6. Izotermy sorpcji w zależności od wilgotności względnej powietrza RH

Physical parameters of clay plasters
Parametry fizyczne tynków glinianych

Parameters	Clay plaster	Clay + hydrated lime	Clay + sodium water-glass	Clay + hydrophobic	
Total Intrusion Volume	0,16	0,20	0,15	0,17	cm^3/g
Total Pore Area	4,16	3,64	1,24	0,86	m^2/g
Median Pore Diameter (Volume)	165460	15033	161298	155428	nm
Median Pore Diameter (Area)	142	395	674	740	nm
Average Pore Diameter (4V/A)	1581	2167	4996	8121	nm
Bulk Density at 0.52 psi	1,89	1,78	1,87	1,80	g/mL
Apparent (skeletal) Density	2,74	2,74	2,64	2,63,	g/mL
Porosity	31,06	35,04	28,98	31,39	%

used to determine the sorption properties of porous building materials using desiccators or climate chambers. The DVS Intrinsic Plus gravimetric sorption analyzer was used in this study.

The sorption of the clay plaster after hydrophobisation is 50% lower, at RH around 100%, compared to the other solutions (a decrease from 2.5 to 1.2% by weight).

Mercury Intrusion Porosimetry (MIP)

MIP is a powerful technique utilized for the characterization of pore size distribution, pore volume and porosity of a variety of solid and powder materials (table). Samples analyzed by this technique are placed in a sample cell with liquid mercury surrounding the sample. Mercury, as a non-wetting liquid, intrudes into the pore space under an assumed pressure. As the mercury enters the pore space, the volume of mercury that has been injected into the sample for a given pressure is recorded in the form of a curve – this is known as the intrusion curve. When the maximum pressure is reached, the pressure drops and a drying curve, the so-called extrusion curve, is recorded. The shape of the curve plotted for decreasing pressures is the primary source of information on the magnitude of the deviation of the real pore space from the cylindrical model. The intrusion and extrusion curves usually have a different course, which is referred to as the hysteresis effect. From this effect, the ratio of pores to intrusions connecting the pores can be calculated. Mercury porosimetry allows the effective porosity to be calculated, but does not take into account the closed porosity, as this is not accessible to the injected mercury. Analysis of the test results obtained from the AutoPore IV 9500 mercury porosimeter involves calculating and interpreting a range of quantities calculated from the capillary pressure curves and analyzing the shape of the capillary pressure curves. For the purposes of this article, the porosimetry analysis was executed over a pressure range of 0.5-60,000 psi. A cumulative curve of the distribution of pore diameters and effective porosity values corresponding to the volume of mercury that migrated into the pore space was obtained (Figure 7). The dependence of the capillary pressure magnitude on the radius size, pore shape and the network of connections between pores of different radii was used.

Analysis of test results

The flexural as well as compressive strength results of the pure clay sample without additives and admixtures are higher than those of the modified samples. The admixtures and additives used in the tests reduced the strengths of the samples. In the case of plasters, flexural and compressive strength is not a factor, and their suitability is more influenced by adhesion and the absence of cracks.

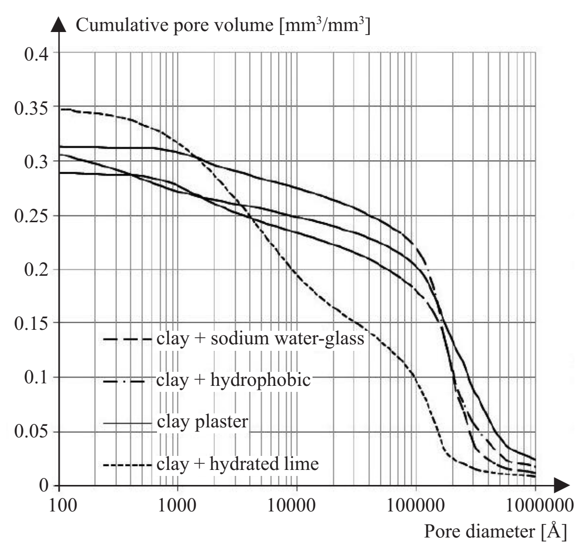


Fig. 7. Cumulative pore volume curves of plaster samples
Rys. 7. Skumulowane krzywe rozkładu wielkości porów próbek tynków

a)

b)

Photo 2. Clay plaster samples after the capillary rise of water (a) and with the water absorption (b) tests
Fot. 2. Próbki tynków glinianych po badaniach podciągania kapilarnego (a) i nasiąkliwości wodą (b)

clay plaster | clay + hydrophobic | clay + sodium water-glass | clay + hydrated lime

Photo 3. Clay plaster samples used in the drop method
Fot. 3. Próbki tynków glinianych użyte w metodzie kropli

The main objective of the research presented in this paper was to improve the characteristics related to the water resistance of plasters. The lack of water resistance is the most important disadvantage of clay and clay plasters. In order to determine the effectiveness of the admixtures added, three test methods were used: capillary absorption, saturation and the drop method to test surface water repellency.

Attempts to determine capillary rise of water and saturation for the unmodified plaster and the plaster with water-glass added were unsuccessful. The samples dissolved and results were only obtained for the samples modified with hydrophobic and hydrated lime. A curve can be plotted on the time dependence of the absorbed mass, which shows how the material's capillary rise of water capacity develops. Modifying the samples with a hydrophobising agent is the most effective method of improving this characteristic (Photo 2).

A test of the surface hydrophobicity of the material was also executed using the droplet method. The largest wetting angle was obtained for the hydrophobised sample. The clay and water-glass samples absorbed the drops immediately (Photo 3).

Admixtures added to the clay mixture can significantly increase its resistance to water. Improving this characteristic can result in a deterioration of other material properties. From the results, the increased adhesion of plasters with lime additives can be seen. The minimum adhesion of lime plaster to the substrate is 0.01 MPa and that of cement-clay plaster is 0.025 MPa [12], so it is possible to use hydrophobically modified plaster to cover the walls of buildings.

Vapour-permeability is a characteristic of clay that greatly influences the rational use of this material for wall covering. Thanks to the good diffusion of water vapour, such a plaster provides a suitable microclimate for the rooms. It was considered whether the improvement in water resistance would block the flow of vapour. In the test results, there was no decrease in vapour conductivity and the diffusion resistance remained at a similar level. MIP tests indicate that there was no significant change in porosity, with the pore size distribution differing only for the lime-modified samples. Moisture sorption up to RH 80% is at a similar level for all samples. It is only above this value that the hydrophobisation of the clay plaster is clearly in favour. The loss of the key positive properties of the render after modification with hydrophobizing agents is not to be feared.

Literature

[1] Waltjen T. Deatils for Passive Houses. A Catalogue of Ecologically Rated Constructions. Springer Verlag. 1999. Vienna, Austria, ISBN 978-3-211-29763-6

[2] Gernot M. Podręcznik budowania z gliny. Fundacja Cohabitat 2012.

[3] Darith-Anthony H, Julien Y, Guilleminotb J, Abdelali D, Anh-Minh T, Bornertc M. Desiccation cracking of heterogeneous clayey soil: Experiments, modeling and simulations. Engineering Fracture Mechanics. 2021; 258: 108065.

[4] Altmäe E, Ruus A, Raamets J, Tungel E. Determination of Clay-Sand Plaster Hygrothermal Performance: Influence of Different Types of Clays on Sorption and Water Vapour Permeability. Springer International Publishing. 2019; str. 945 – 955

[5] El Fgaier F, Lafhaj Z, Chapiseau C, Antczak E. Effect of sorption capacity on thermo-mechanical properties of unfired clay bricks. J. Build. Eng. 2016; 6: 86 – 92.

[6] Kamieniarz M. Building with clay in the aspect of energy efficiency and environmental protection. Materiały Budowlane. 2014; 11.

[7] Jiang Y, Phelipot-Mardele A. Tuleja zaciskowa. F, Lanos C, Lemke M, Ansell M, Lawrence, M. Moisture buffer, fire resistance and insulation potential of novel bio-clay plaster. Construction and Building Materials. 2020; 244, 118353.

[8] PN-EN 1015-11:2020-04; Methods of test for mortar for masonry – Part 11: Determination of flexural and compressive strength of hardened mortar.

[9] PN-EN 1015-18:2003; Methods of test for mortar for masonry – Part 18: Determination of water absorption coefficient due to capillary action of hardened mortar.

[10] PN-EN 1015-12:2016-08; Methods of test for mortar for masonry – Part 12: Determination of adhesive strength of hardened rendering and plastering mortars on substrates.

[11] PN-EN 1015-19:2000/A1:2005. Methods of test for mortar for masonry – Part 19: Determination of water vapour permeability of hardened rendering and plastering mortars.

[12] Żeńczykowski W. Budownictwo Ogólne, tom 3/2, Roboty wykończeniowe i instalacyjne. Arkady 1987.

Accepted for publication: 04.04.2024 r.