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Operational characteristics of limestone and methods to increase its strength

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Abstract. Since ancient times, limestone has been known as an inexpensive and reliable building material. The main problem of limestone materials in the construction of buildings is its reduced longevity due to various factors, such as wind and rain. These factors have a huge impact on the strength characteristics of the building material, so adherence to special recommendations is an important practical task. A review of literature on the problem of durability and the use of limestone is presented. With the help of experience, the strength of nummulite limestone is established. The analysis of the obtained data is made, as well as its comparison with the indices of other artificial and natural stones. The main methods of strengthening the structures made of limestone are considered at three different stages. Practical recommendations for minimizing the impact of negative factors on this material are given.

1 Introduction

Limestone is one of the cheapest and most popular building materials of natural origin. It is a widespread sedimentary rock that includes calcite (calcium carbonate).

Limestone has been used as a building material since ancient times. Its main advantages are that the stone is kind for dressing, durable, wear-resistant, prevents unwanted heating of the building, has high environmental and biological compatibility with humans, and has pronounced natural antiseptic and antiallergenic properties. The "museum" of ancient limestone buildings is the peninsula of Crimea, where large deposits of this rock are also located. On the peninsula, such varieties of limestone as the yellowish shell rock, the white Inkerman block, and also the most accessible limestone on the peninsula — rubble — are widely used. Shell rock is predominantly used in ancient Crimean buildings. In Sevastopol, there are the ruins of Tauric Chersonesos (Fig. 1) made of this type of limestone. However, today, there are preserved limestone constructions in cave cities between Sevastopol and Bakhchisarai. Large halls, passages, and galleries are carved from a solid limestone massif. Underground cities such as Bakla, Eski-Kerman, Inkerman were created in limestone cliffs.

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In the construction of embankments and quay walls in Sevastopol, recrystallized organogenic clastic limestone with the inclusion of quartz gravel was used (the local name is Krymbalskiy stone). Unlike other types of limestone, it nearly does not change its properties when it is wet, due to which it has become widely used in hydrotechnical construction.

But, like any rock, the mechanical properties of limestone weaken over time under the influence of natural and anthropogenic factors. Despite its internal strength, limestone belongs to soft rocks, and because of this, one of its main disadvantages is its susceptibility to weathering. On average, limestone products begin to break down after 75 years, and buildings and various constructions, as experience shows on the example of the Crimean structures, after 200-400 years. The cause of destruction are:

- high humidity;
- mechanical stress;
- physical weathering;
- chemical reactions of a stone with a gas-laden atmosphere and chemically active waters;
- active human actions.

As a result, chemical decomposition of minerals and acids dissolved in water occurs in the stone. It is leached, cracks and cavities begin to form, the strength and stability of the rock decreases.

Preserving the cultural heritage and preventing the negative impact of external factors in future limestone buildings is an important practical task. To protect the building, an individual approach to each object of construction is required. The building must be carefully examined; a physical and chemical analysis of the stone should be carried out. After that, the most effective ways to restore the structure and methods to protect it for a long term are selected. Due to the relevance of studying the mechanical characteristics of limestone, more and more papers related to the study of the strength properties of this stone are published. In their paper, Frolova Yu.V. and Arakcheeva Ya.A. consider the dependence of the strength of limestone samples from the Domodedovo open-pit mine under uniaxial compression on their absolute and relative size, shape, and friction at the contacts between their ends and the loading plates. In the scientific work of Borodin I.N. and Abramyan A.K., a number of three-dimensional effects arising from the numerical simulation of dynamic loading of limestone samples in the Hopkinson-Kolsky bars are demonstrated. Various modes of destruction of porous limestone samples and the corresponding deformation curves were studied [1-2].

In the works of Kondratiev S.A., Rostovtsev V.I., Kulagin O.R., and Sivolap B.B., studies of the mechanical properties of limestone during the handling of its core samples with accelerated electrons are described. The ultimate strength under uniaxial loading, static and dynamic elastic moduli, and Poisson’s ratios are determined depending on the dose absorbed by the samples [3].

Limestone is one of the main components in the design of cement and concrete. It has a great influence on the strength properties of the constructed structures. There are a number of works in which changes in the characteristics of concrete and cement are investigated depending on the content of limestone in them. Nastich O.B. and Khvorost V.V. conducted studies of the strength and durability of reinforced concrete structures with the addition of limestone under the influence of aggressive environment. In the work of S. Palma and K. Muller, the properties of mortars and concretes based on cements with high limestone content are determined. Usmanova L.Z. and Usmanova D.Z. investigated the feasibility of using limestone as the main component of cement produced in the Republic of Bashkortostan. Piyachev V.A. and Ishutin K.S. partially replaced the natural gypsum with limestone in the manufacture of Portland cement [4-7].

The authors of many Russian and foreign scientific papers are concerned about the durability of building materials. Such aspects as the safety of construction materials in time, the service life of the material after its handling with various compositions, as well as after a long or short impact of various external factors (radiation, heat, long-term static loading, etc.) on the material are considered [8-15].

The purpose of this study is to identify improved methods for strengthening buildings and structures made of Crimean limestone. To achieve this goal, the following tasks were set:

- Carry out the strength test of nummulite limestone according to GOST 30629-2011;
- Draw conclusions about the strength and durability of this rock, consider its features;
- Suggest methods to strengthen buildings and structures made of limestone.

2 Materials and methods

Nummulite limestone got its name due to the presence of nummulite shells in their composition. The deposits of this limestone are located in the Crimea and are mainly developed for wall materials; only a small amount is used for the production of tiles. Certain types of nummulite limestone are durable, as evidenced by the good preservation of some Egyptian pyramids made of this material.

The physical and mechanical properties of limestone are extremely heterogeneous. However, these properties are directly dependent on their structure and texture. Depending on the content of quartz, dolomite, and other minerals, the density of limestone ranges from 2700 kg/m3 to 2900 kg/m3.

For information on the strength of nummulite limestone in compression, a test was conducted according to GOST 30629-2011. Five samples-cubes with the size of edges 5 cm were made from the core. The edges of the samples of the cubes were handled on a cast-iron faceplate.

Table 1. Weights of samples (before drying).

Sample number	1	2	3	4	5
Weight, g	221,64	223,78	221,15	219,65	223,61

The test was conducted in a dry and water-saturated state. For the first test, the samples were dried to constant weight. For the second experiment, the samples were kept in water for 48 hours.

Table 2. Weights of samples (after drying).

Sample number	1	2	3	4	5
Weight, g	220,61	223,75	221,13	219,61	223,65

Table 3. Weights of samples (48 hours in water).

Sample number	1	2	3	4	5
Weight, g	243,22	248,27	245,14	244,38	249,22

After the samples are ready for testing, they were installed in the center of the lower support plate of the hydraulic press, aligning the axis of the sample with the center of the lower support plate, and pressing by the upper plate of the press, which should fit snugly along the entire face of the sample. During the experiment, the load evenly and continuously increased (from 0.3 to 0.5 MPa per second).

3 Results and their discussion

3.1 Results of the experiment

Thus, the following values of the maximum breaking load were obtained:

Table 4. Maximum breaking load in the dry state.

Sample number	1	2	3	4	5
Ultimate compressive strength, MPa	25,054	21,896	13,098	24,112	22,798

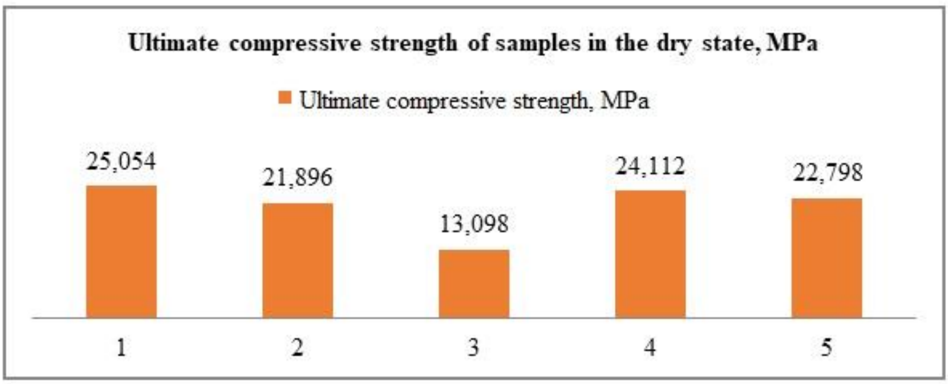

Fig. 1. Maximum breaking load in the dry state.

Table 5. Maximum breaking load in water-saturated state.

Sample number	1	2	3	4	5
Ultimate compressive strength, MPa	5,1	6,2	8,1	8,5	8,6

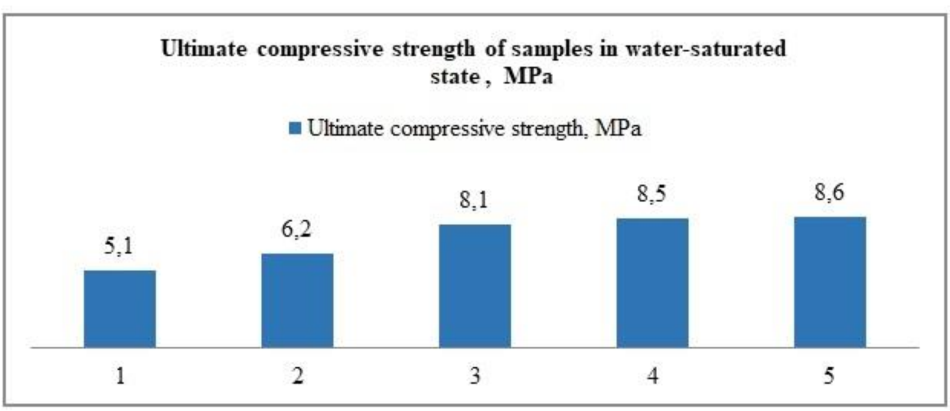

Fig. 2. Maximum breaking load in water-saturated state.

Thus, the ultimate compressive strength of limestone in the dry state:

$$R_{\text{com}} = \frac{R_1+R_2+R_3+R_4+R_5}{5} = \frac{25{,}054+21{,}896+12{,}110+24{,}112+22{,}798}{5} = 21{,}194 \text{ MPa} \quad (1)$$

The ultimate compressive strength of limestone in water-saturated state:

$$R^1_{\text{com}} = \frac{R_1+R_2+R_3+R_4+R_5}{5} = \frac{5{,}1+6{,}2+8{,}1+8{,}5+8{,}6}{5} = 7{,}3 \text{ MPa} \quad (2)$$

The ultimate compressive strength of limestone in the dry state ranges from 10 MPa (for porous) to 50 MPa (for marble limestone) according to GOST 9479-98 “Blocks of rocks for the production of facing, architectural, construction, memorial, and other products. Technical conditions”. Thus, the strength of the nummulite limestone is close to the shell rock and does not have the highest strength among the limestone rocks. However, due to the relatively low strength, stone handling (sawing and hewing) will have less energy and labor costs.

Below is a table of artificial and natural stones often used in the construction and their indicators of strength in the dry state according to: GOST 530-2012 “Ceramic brick and stone. General technical conditions”- for bricks; GOST 26633-91 “Heavy and fine-grained concretes. Technical conditions”- for concrete; GOST 14050-93 “Limestone (dolomitic) flour. Technical conditions”- for dolomite; GOST 9479-98 “Blocks of rocks for the production of facing, architectural, memorial, and other products. Technical conditions” - for marble and granite.

Table 6. Strength indicators of popular building materials

Material name	Brick	Concrete	Dolomite	Marble	Granite
Compressive strength, MPa	2,5-100	4,5-77,06	20-60	50-150	100-300

According to the data obtained, it can be said that the sample provides sufficient strength comparable to that of concrete and brick. It can also be noted that the strength of nummulite limestone is significantly less than that of granite and marble, but this cannot prevent the use of this stone for the manufacture of wall materials.

Comparing the obtained results of strength in dry and water-saturated states, it can be concluded that in the second state, the strength of limestone is much lower. The reduction in compressive strength of limestone in a water-saturated state ΔR, %, is calculated by the formula:

$$\Delta R = \frac{R_{\text{com}}-R^1_{\text{com}}}{R_{\text{com}}} \cdot 100\% = \frac{21{,}194-7{,}3}{21{,}194} \cdot 100\% = 65{,}56\% \quad (3)$$

The high porosity and hygroscopicity of this sample explains such a loss in strength after saturation with water.

3.2. Ways to strengthen limestone structures

Experience has shown that limestone as a building material has its disadvantages and needs to take special measures to strengthen it. With the help of various methods of fortification of limestone structures, it is possible to achieve an increase in strength characteristics and durability.

A sample that was subjected to strength testing refers to low-strength rocks (dynamic surface strength up to 40 MPa), and therefore its processing and use are associated with a large amount of waste, which requires the adoption of special measures to strengthen it. Strengthening of a natural stone can be made at three stages.

The first stage is the manufacture of a building material and its handling before exploitation. To prevent undue destruction and increase durability at the early stages of manufacturing products, solutions of acrylic and organosilicon polymers in toluene, xylene, and mixtures of these solvents with alcohols are used. But such additives cannot be used in all cases. To strengthen the concrete in hydraulic structures and for well casing, substances that do not contain soluble glass should be used. For such cases, bitumen emulsions are applicable with suitable coagulators introduced into them or the use of milk from the most finely ground Portland cement.

Limestone reinforcement also occurs when using a 20% barium hydroxide solution and a mixture with a 5% urea solution. From the barium hydroxide dissolved in hot water, a saturated solution is obtained, to which a calculated amount of urea is added. The sample with small size is placed for 24 hours in a solution heated to boiling temperature to completely saturate the partially destroyed stone. The larger samples are impregnated with a 25% glycerol solution, using a brush. The procedure is performed several times within 5-7 days; the stone is covered with a film between treatments. After this, the anti-rain impregnation of the material is carried out to complete the strengthening process.

The effect is achieved due to the formation of crystalline barium carbonate with the gradual decomposition of urea. When barium carbonate crystals combine, microcracks are strengthened, the sample structure itself is compacted, and porosity is reduced by 20-25% due to the colmatage of pores.

The second stage is the strengthening of the material during its direct construction and installation. Porous limestone is widely used for decoration of the building. It is recommended to install the plates in the warm and dry season in order to exclude the ingress of rain moisture between the finish and the base. If the walls do not require insulation, the limestone slabs are attached directly to the plane of the primed wall, using cement-sand mortar or special glue. The task is much more difficult if the insulation does exist, and it is necessary to lay the limestone cladding. In this case, in capital private construction, a reinforcing net is applied to the not completely congealed plaster in order to avoid a situation in which, after some time, the tile will begin to collapse along with the plaster.

As it was revealed earlier, when moisture gets into the pores of the limestone, the stone loses its strength and becomes brittle. The solution could be an arrangement of continuous hollow between the limestone cladding and the main wall. Stone slabs will be hung using special fasteners made of stainless steel. An air gap of 2–3 centimeters will facilitate the removal of the formed steam from moisture, provided that there are special holes and slots above and below, through which air will circulate. This measure will provide an effective service of natural stone for many years.

The third stage is the treatment of the material after its construction. To protect the facade from the effects of precipitation, it is treated with special compounds that are able to seal the surface and protect it from moisture penetration. Such chemical treatments as hydrophobization and fluidizing reduce the salt washing out of the stone and prevent fading on the wall surface. They can be done both from the outside and from the inside of the material to protect against moisture entering through the wall from the room. However, the space between the plate joints is recommended to be filled with "breathing" solutions in order to allow moisture to easily evaporate from the surface of the wall.

Hydrophobization is used to impart water repellency to the surface of limestone plates and prevent the formation of salt efflorescence (white salt haze on the surface of the material). To do this, it is necessary to use aqueous solutions that have good hydrophobicity. Such is alumomethylsilicate AMSR-3, which is applied manually or mechanically. A polyorganosilosan resin is also used in 2–3 layers, which is also capable of reinforcing the surface layer, and alkyl siliconates (their consumption is 200–300 g per 1 m). The strength after treatment with resin may increase to 20%. This result is achieved in cases where it is possible to introduce solutions to the entire depth of the stone.

Using fluidizing, the density and weather resistance of limestone are increased. Aqueous solutions of hydrofluosilicic acid salts are applied to the surface of the cladding, which leads to the formation of insoluble compounds that seal the outer surface of the stone. This operation allows increasing frost resistance and reducing water absorption without changing the appearance of the cladding.

Other organosilicon compounds are used for the restoration of architectural monuments made of limestone. They are used together with polyorganosiloxane, since the destruction of the organosilicon materials increases the water absorption of the whole structure, and the use of polyorganosiloxane reduces moisture absorption by up to 1%. At the same time, the steam will flow freely even with the introduction of a large amount of resin.

The question of the use of protective coatings and impregnations causes many disputes among various specialists in this field, since there are many negative events of this method of strengthening and increasing the service life. For example, hydrophobizated coatings lose their water-repellent properties after 3-4 years, and their repeated renewal badly affects the personal properties of the material. If you increase the water resistance of impregnations, the stone will not be able to pass air through itself, and moisture will accumulate on the inner surface of the material. The stone will gradually begin to break down and lose its strength properties due to changes in its structure.

An assessment of the durability of this material can be obtained only after checking the operation of limestone structures with different coatings and impregnations under conditions of long-term operation.

4 Conclusion

1. A characteristic problem of limestone as a building material is its hygroscopicity, loss of strength when saturated with water, slow dissolution in a large amount of water.
2. Reinforcing nets are able to protect limestone slabs from mechanical damage. They securely fasten the facing stone to the surface of the insulation, increase the service life of the facing, and do not allow it to crumble. The method of strengthening the structure with reinforcing net is suitable at the initial stage of construction. After the construction of buildings, as well as for the restoration of old buildings, this method of strengthening cannot be applied.
3. Reliable protection for limestone is impregnations (stone reinforcement compounds), which increase the durability, strength, and coherence of limestone building structures. It is worth remembering that the impregnation is able to protect and strengthen the personal properties of the stone. If limestone will have low compressive strength and high porosity, impregnation will not be able to fully protect the stone from external factors. Stone reinforcement composition is used both at the initial stage of construction to increase the durability of the stone and for the restoration and strengthening of buildings.

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