UDC 691.32.001.4
DOI: 10.15587/2706-5448.2020.214771

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RESEARCH OF WATERPROOFING SCREENS OF INCREASED EFFICIENCY FOR PRESERVATION OF OBJECTS OF CULTURAL HERITAGE

The object of research is the technology of constructing waterproofing screens of buildings and structures from limestone-shell rock. The paper discusses the causes of the violation of the waterproofing of the underground parts of buildings which are made of limestone-shell rock. The problems of preservation of historical buildings and structures made of limestone-shell rock are revealed on the example of such buildings in Ukraine and Moldova:

- *Odessa Opera and Ballet Theatre;*
- *House of Stratz;*
- *Brodsk Synagogue;*
- *House of Marazli;*
- *Bilhorod-Dnistrovsk and Bendery Fortresses;*
- *Tower of Winds;*
- *Church of St. Cajetan;*
- *Powder Cellar of the Tiraspol Fortress;*
- *Water Mill;*
- *Church of the Archangel Michael in the village Stroenets and many others.*

Based on the methods of the mathematical theory of the experiment, a complex of experimental-statistical models has been constructed, the analysis of which allowed to estimate the intensity of capillary absorption of the «waterproofing screen – limestone-shell rock» system depending on the depth of injection, the diameter of the injector and the step of its location. An arrangement of injection holes was proposed and justified to ensure waterproofing of structures, which allows filling the capillary-porous masonry space for 6–12 % more than other schemes. The accepted physical model of the distribution of the injectable composition in the porous structure of limestone-shell rock allowed to analyze the depth, diameter, and injection step, which affect the distribution area of the solution in the structural array. The depth of injection is indeed one of the most important technological characteristics in the construction of an intra-structural waterproofing screen. From a technological point of view, the degree of influence of the injection step on the intensity of capillary moisture transfer is quite high, since it directly affects the amount of active waterproofing composition in the injected thickness, as well as labor costs when performing waterproofing works. The diameter of the borehole does not significantly affect the studied parameter within the selected experimental conditions.

Keywords: *limestone-shell rock, injection waterproofing, waterproofing screen, capillary absorption, mathematical modeling of injection.*

Received date: 07.05.2020
Accepted date: 11.06.2020
Published date: 31.10.2020

1. Introduction

At present, there is a tendency for the population to revive an active interest in the history of their region. Reconstruction of historical buildings has become socially significant. In this regard, there is an acute problem of preserving historical buildings and structures, the unsatisfactory condition of which requires measures to save them from damage, which is clearly evidenced by numerous cracks, collapsed structures, or even destruction of unique structures.

The sharpest decrease in the operational reliability of underground parts of facilities, that is, facilities with damaged or broken vertical and horizontal waterproofing located in the soil environment, as evidenced by the data of surveys of buildings and structures. Often, construction firms, without proper critical analysis, use materials and technologies that are not designed for certain hydrogeological conditions. As a result, after the performed waterproofing works, the condition of the building or structure does not improve.

When choosing the type of waterproofing, it is necessary to determine its compliance with the requirements, taking into account the specifics and condition of a particular object, hydrogeological conditions, the depth of underground structures, the impact of environmental changes. Only after these actions, the composition of the adopted waterproofing is determined (number of layers, thickness) [1].

Scientists have been studying the physical and mechanical properties of shell rock [1–3]. Many works are devoted to the protection of structures of the underground part of buildings and the device of waterproofing [4–6].

Waterproofing methods for old buildings must meet the requirements for both their structural integrity and the preservation of their external appearance [7, 8]. Therefore, studies devoted to the search for optimal technological solutions for the construction of waterproofing screens for buildings made of limestone-shell rock are relevant.

Many buildings and structures of cultural heritage are built from shell rock, which has been a local building material for many years. The problems of preservation of historical buildings and structures made of limestone-shell rock are revealed on the example of such buildings in Ukraine and Moldova (Fig. 1):

– Odessa Opera and Ballet Theatre;
– Stratz House;
– Brodsk Synagogue;
– House of Marazli;
– Bilhorod-Dnsstrovsk and Bendery Fortresses;
– Tower of Winds, Church of St. Cajetan;
– Powder Cellar of the Tiraspol Fortress;
– Water Mill;
– Church of the Archangel Michael in the village Stroenets and many others.


a *b* *c*

d

e

Fig. 1. The buildings and structures built of sawn limestone: *a* – Water Mill (Stroenets, Moldova); *b* – Church of St. Cajetan (Rashkov, Moldova); *c* – House of Marazli (4, Pushkynska str., Odesa, Ukraine); *d* – Bendery Fortress (Moldova); *e* – Akkerman Fortress (Bilhorod-Dnistrovsk, Ukraine)

The laying of underground parts of buildings made of shell limestone is exposed to destructive processes associated with groundwater filtration, leaching, which gradually leads to the loss of structural integrity and deterioration of the physical and mechanical properties of the structure. As a result, physical wear and tear of these structures occurs, which manifests itself in the formation of cracks, voids, failures, which often leads to the collapse of individual parts of the structure or the structure as a whole.

Also, the reason for the short service life of waterproofing can be: low quality of waterproofing materials, a large number of manual operations, imperfection and lack of mechanization means.

In recent years, research has been carried out at an ever increasing pace to improve the technology and mechanization of waterproofing works, develop new technological processes, create new materials, the use of which would make it possible to obtain high-quality waterproofing with high operational efficiency.

Thus, *the object of research* is the technology of constructing waterproofing screens of buildings and structures from limestone-shell rock. *The aim of research* is to conduct a study of the effectiveness of injection technology when installing waterproofing screens, depending on the following factors: injection depth (x_1); hole diameter (x_2); injection step (x_3).

2. Methods of research

The injection depth is 14, 16 and 18 cm. The diameters of the holes used are 8, 12 and 16 mm. The injection step is 10, 15 and 20 cm (Fig. 2).

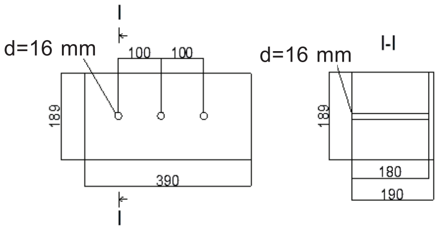

Fig. 2. The layout of the injector with a diameter of 16 mm with a step of 10 cm

The experiment was carried out using samples of shell limestone from the Grigoriopol quarry (Moldova), grade M35. The macrostructure of the sample is shown in Fig. 3. The change in the value of capillary moisture transfer for the samples subjected to injection with a waterproofing composition SiltekVP-35 was determined. Lift height of liquid with capillary suction: 5, 10 and 15 mm.

Fig. 3. The structure of the samples of the Grigoriopol quarry

Experiments to determine the quality criterion of the material (capillary suction) were carried out according to a three-level 15-point three-factor plan of type B3.

The calculation of coefficients and regression analysis of models of type (1) were carried out using the COMPEX system [9, 10]:

$$\hat{Y}=b_0+b_1x_1+b_{11}x_1{}^2+b_{12}x_1x_2+b_{13}x_1x_3+b_2x_2+$$
$$+b_{22}x_2{}^2+b_{23}x_2x_3+b_3x_3+b_{33}x_3{}^2. \qquad (1)$$

The transition from natural variables to coded ones was carried out according to the standard technique:

$$x_i=(X_i-X_{0i})/\Delta X_i, \qquad (2)$$

where $X_{0i}=0.5(X_{imax}+X_{imin})$; $\Delta X_i=0.5(X_{imax}-X_{imin})$.

3. Research results and discussion

Based on the calculation results in the COMPEX software package, the following experimental-statistical models (3)–(5) of capillary liquid transfer were obtained at a liquid rise height of 5, 10 and 15 mm:

$$\hat{Y}_1=99.24-10.80x_1-27.56x_1^2+17.44x_2^2-$$
$$-14.30x_3+7.94x_3^2; \qquad (3)$$

$$\hat{Y}_2=130.47-16.70x_1-28.83x_1^2+5.13x_1x_2+$$
$$+22.67x_2^2+3.88x_2x_3-20.40x_3+8.67x_3^2; \qquad (4)$$

$$\hat{Y}_3=151.82-9.00x_1-18.78x_1^2+6.50x_1x_2+$$
$$+3.60x_2+16.22x_2^2-21.80x_3+11.22x_3^2. \qquad (5)$$

Analysis of the ranking graphs in Fig. 4 showed that the degrees of influence of the variable factors on the indicator of the intensity of capillary moisture transfer (the height of the liquid rise is 5 mm) are the same in the zones of maximum and minimum with the same character of the ranking. The most significant factor is the depth of injection. The size of the injection step has a great influence. In this case, the size of the borehole diameter does not significantly affect the intensity of capillary moisture transfer.

When considering the ranking of the degree of influence of variable factors on the indicator of the intensity of capillary moisture transfer at a liquid rise height of 10 mm (time 5 min), it turns out that the degrees of influence of factors in the extreme zone are different, although the nature of their ranking is the same (Fig. 5).

In the maximum zone, two factors have the greatest influence on the intensity of capillary moisture transfer: the depth of injection (to a greater extent), and also the step of injection. The injection diameter does not significantly affect the change in the intensity indicator. In the minimum zone, the effect of injection depth is also most significant; the degree of influence of the injection step decreased slightly. The significance of the borehole diameter in this factor space has slightly increased.

As can be seen from Fig. 6, at a liquid rise height of 15 mm (time 5 min), the injection step has the greatest effect on the intensity of capillary moisture transfer in the maximum zone. At the same time, the degree of influence of the injection depth and borehole diameter are approximately at the same level (rather low). In the zone of the minimum, the influence of the injection step is also most significant. The influence of the injection depth and borehole diameter increased.

Thus, the analysis of the graphs in Fig. 4–6 showed that the depth and step of injection have the greatest influence on the intensity of capillary moisture transfer within the selected factor space. In this case, the significance of the injection step increases as the height of the liquid rise increases. The borehole diameter does not significantly affect the investigated indicator in the entire range of change in the height of the fluid rise.

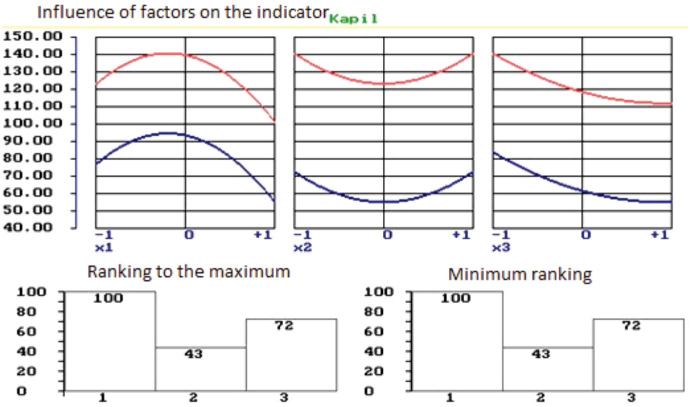

Fig. 4. Ranking of the influence of variable factors on the indicator of the intensity of capillary moisture transfer at a liquid rise height of 5 mm

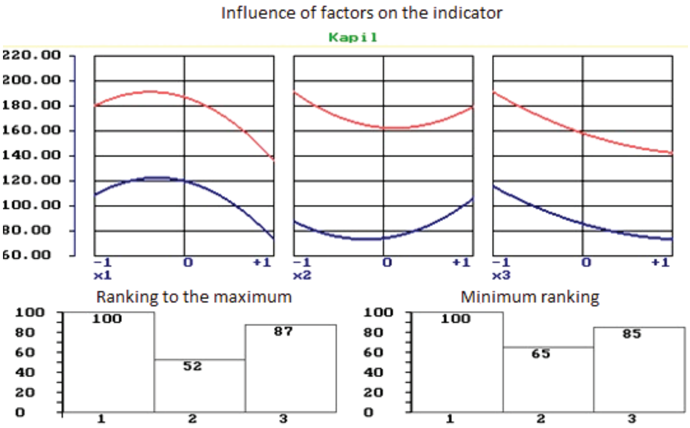

Fig. 5. Ranking of the influence of variable factors on the indicator of the intensity of capillary moisture transfer at a liquid rise height of 10 mm

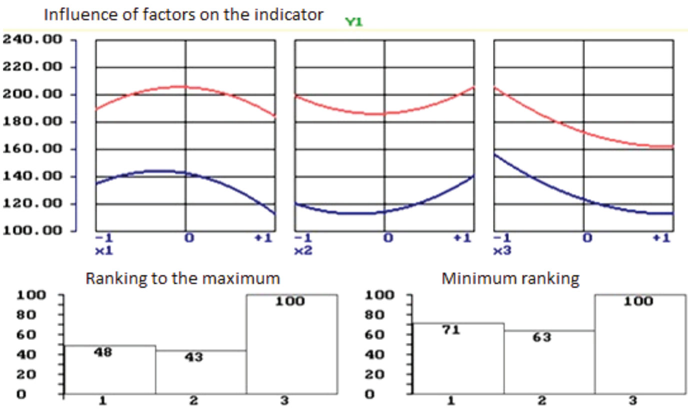

Fig. 6. Ranking of the influence of variable factors on the intensity indicator of capillary moisture transfer at a liquid rise height of 15 mm

As it is known, the influence of each of the factors on the calculated value of the system output $\hat{Y}$ is described by a parabola. However, in its influence on the quality indicator $\hat{Y}$, the factor x_i is not independent, but interacts with other factors x_j, which is quantified in the effects of a model like $b_{ij}x_ix_j$. Therefore, the analysis of the influence of factors should be carried out according to quasi-one-factor models of the form:

$$\hat{W}_i=\hat{Y}\{x_j\}-b_{0j}=(b_i+b_{ij}x_j)x_i+b_{ii}x_i^2, \tag{6}$$

where b_{0j} is a free term reflecting the influence on the output of all terms of the polynomial, except for those included in model (6). Thus, for a model of type (1), in the general case, three quasi-one-factor models of type (6) can be obtained.

It should be noted that in the model of the intensity of capillary transfer of liquid at a liquid rise height of 5 mm (3), there are no interaction effects.

For model (4), three quasi-one-factor models of the type (7)–(9) were obtained:

$$\hat{W}_{3/1}=(-16.70+5.13x_2)x_1-28.83x_1^2; \tag{7}$$

$$\hat{W}_{3/2}=(+5.13x_1+3.88x_3)x_2+22.67x_2^2; \tag{8}$$

$$\hat{W}_{3/3}=(-20.40+3.88x_2)x_3+8.67x_3^2. \tag{9}$$

Important results were obtained from the analysis of models (7)–(9). Interaction effects b_{ij} change the value of the linear effect b_i. Since each factor is investigated in the range from −1 to +1, their substitution in the model (7)–(9) leads from a single parabola to a family of parabolas:

$$\hat{W}_{3/1}=(-16.70\pm5.13)x_1-28.83x_1^2,$$

$$-21.83\leq b_{x1}\leq-11.57; \tag{10}$$

$$\hat{W}_{3/2}=(\pm9.01)x_2+22.67x_2^2,$$

$$-9.01\leq b_{x2}\leq+9.01; \tag{11}$$

$$\hat{W}_{3/3}=(-20.40\pm3.88)x_3+8.67x_3^2,$$

$$-24.28\leq b_{x3}\leq-16.52. \tag{12}$$

Such families of parabolas are shown in Fig. 7, on which the central and two boundary parabolas are plotted, and the zone of existence of the families is shaded. Interaction effects move the vertex of the unchanged parabola along the x_i axis.

Analysis of quasi-one-factor models in Fig. 7 made it possible to draw conclusions about the role of each factor, taking into account the effects of interaction.

The transition to a deeper hole depth first leads to an increase in Y, then this effect decreases. The position of the factor x_1 corresponding to the maximum value of the output is determined by the level of stabilization of other factors.

An increase in the borehole diameter to 12 mm causes a decrease in Y; further increase in diameter leads to an increase in Y.

An increase in the injection step leads to a decrease in the entire range of X_3 variation.

For model (5), three quasi-one-factor models are also obtained, shown in Fig. 8. It should be noted that the nature of the influence of factors on Y has not changed over time.

The analysis showed that the maximum value of Y in all three cases is provided by the same levels of factors: insignificant hole depth, maximum hole diameter, minimum injection step, which corresponds to an injection depth of 14 cm, a hole diameter of 8 mm, and an injection step of 15 cm.

The minimum value of Y throughout the experiment is ensured by the maximum depth of the borehole with a significant injection step, which corresponds to an injection depth of 18 cm, an injection step of 20 cm. The borehole diameter does not exceed 12 mm.

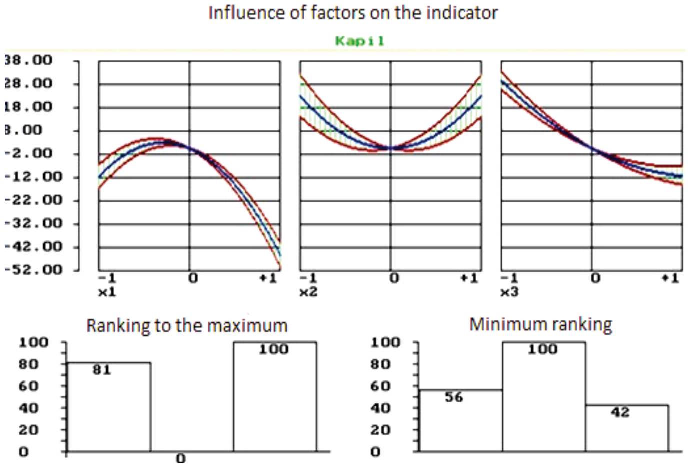

Fig. 7. Graph of the influence of factors on the intensity indicator of capillary moisture transfer at a liquid rise height of 10 mm

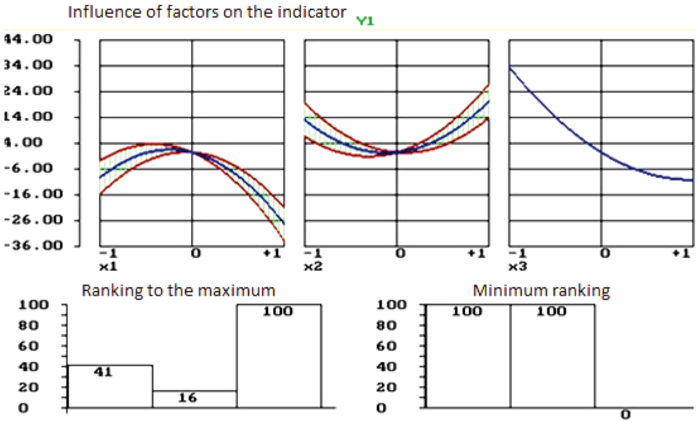

Fig. 8. Graph of the influence of factors on the intensity indicator of capillary moisture transfer at a liquid rise height of 15 mm

4. Conclusions

The layout of the injection holes is proposed and substantiated to ensure waterproofing of structures, which allows filling the capillary-porous space of the masonry by 6–12 % more in comparison with other schemes.

The accepted physical model of the distribution of the injectable composition in the porous structure of the shell limestone made it possible to analyze the depth, diameter, injection step, which affect the area of distribution of the solution in the structure mass. The depth of injection is indeed one of the most important technological characteristics when installing an in-structure waterproofing screen. From a technological point of view, the degree of influence of the injection step on the intensity of capillary moisture transfer is quite high, since it directly affects the amount of the active waterproofing composition in the injected layer, as well as labor costs when performing waterproofing work. The size of the borehole diameter does not have a significant effect on the studied indicator under the selected experimental conditions.

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