SPATIUM
No. 42, December 2019, pp. 8-15

UDC 679.85:7.025.4]:666.971.4
691.2:7.025.4]:666.971.4
Original scientific paper
DOI: https://doi.org/10.2298/SPAT1942008K

OPTIMIZATION OF REPAIR MORTAR USED IN MASONRY RESTORATION

Aleksey Kharitonov, Department of Technology of Building Materials and Metrology,
St. Petersburg State University of Architecture and Civil Engineering,
Saint-Petersburg, Russia
Olga Smirnova[1], Department of Constructing Mining Enterprises and Underground Structures,
Saint-Petersburg Mining University, Saint-Petersburg, Russia

Deterioration of ancient masonry is a contemporary problem. The initial properties of the masonry material that determine its durability, deterioration and degree of preservation have led to the appearance of different approaches towards choosing the technology for restoring masonry. The success of any restoration is largely determined by its compatibility with the original materials used, which requires, as a rule, a complex and long process of selecting their composition. One of the main technological approaches in the science of restoration materials is to search for the optimal composition of the material within a given time limit. This paper presents an approach which uses a large number of variables within strict boundary conditions. The solution to this problem can be found in the field of mathematical modelling using experiment planning methods. The paper presents a method developed for mortar optimization which makes it possible to obtain the desired result within a relatively short period of time.

***Key words*: stone restoration, composition optimization, multicomponent restoration mortar, vapour permeability, lime mortar.**

INTRODUCTION

Deterioration of masonry in architectural monuments is a common problem. Different types of masonry damage accumulate over the years: destruction of the surface layers and facing, the formation of cracks and voids, local deformations leading to solidity of the masonry and weakening of the cross section. All this results in the appearance of emergency conditions (Belentsov *et al.*, 2017; Kharitonov *et al.*, 2019; Formisano and Marzo, 2017; Giordano *et al.*, 2018), which can be corrected by replacing all the masonry elements, strengthening the masonry surface or restoring the stone (Forster *et al.*, 2011; Pauletta *et al.*, 2018; Ribilotta *et al.*, 2019). The initial properties of the masonry material and the degree of its deterioration mean that there are a lot of possible combinations with regard to the technological methods and materials required for its restoration (Heravi *et al.*, 2018; Myasnikova and Pervunina, 2019; Šoukal *et al.*, 2016; Kalina *et al.*, 2018; Kazanskaya *et al.*, 2019; Gailitis *et al.*, 2019). The type of intervention required for a monument therefore depends on its actual state, as well as on the exact type of material in question. Use of repair mortars is currently a readily available and common method for restoring various construction products and structures (Plugin *et al.*, 2017; Upadhyaya *et al.*, 2019; Torney *et al.*, 2014).

Restoration of masonry on the basis of brick or natural stone results in large volume of existing masonry being replaced. This is complicated and requires expensive technology (Kazanskaya and Belentsov, 2019; Ochkurov and Vilenskii, 2019); hence, the application of repair mortars has become very popular and widespread worldwide since the 1960s (Forster *et al.*, 2011; Ashurst *et al.*, 1988; Zarzuela *et al.*, 2018; Hosseini and Karapanagiotis, 2018; Sakiyama *et al.*, 2018).

Restoration issues concerning architectural heritage require individual methods for calculating the structure that take into account an extremely wide range of influencing factors (Micelli and Cascardi, 2019; Clementi et al., 2016; Lourenço and Roque, 2006; Lourenço *et al.*, 2012). The methods used to develop different restoration materials also require an individual approach. For example, the properties of the cement matrix and reinforcing material (e.g., mesh or fiber) should also be considered when selecting the mortar composition (Cascardi *et al.*, 2018; Castellano *et al.*, 2019; Tilocca *et al.*, 2019), which complicates the process of selecting the composition of the mortar.

---

[1] 21-st Line V.O., 2, 190031 Saint-Petersburg, Russia
smirnovaolgam@rambler.ru

Today, many factors are known to have a negative impact on the state of masonry, the majority of which result from the wrong choice of materials used in restoration. This can be seen in the lack of external similarity between the selected material and the masonry, as well as in the lack of the necessary physical and mechanical properties. The incorrect choice of material can lead to defects that disfigure the visual appearance of architectural monuments. For example, changes in the color of the restoration material in the cracks of natural stone masonry are shown in Figure 1. This is caused by aging of the polymer composition under the influence of ultraviolet light, temperature change and other atmospheric influences.

Figure 1. Color changes in the restoration material used in natural stone cracks on a facade (photo by Olga Smirnova in Malaga city center in 2019)

Masonry damage can be caused by the use of restoration materials with low vapour permeability, namely, mortar based on Portland cement. Low vapour permeability helps to retain moisture inside the stone (Vicente et al., 2018; Hendrickx and De Clercq, 2019). This leads to the accelerated deterioration of the masonry due to frost destruction and salt formation. High-strength lime mortars based on hydraulic lime also have low vapour permeability. Hence, it is necessary to ensure sufficient vapour permeability when designing new restoration materials.

The principles of "scientific restoration" were laid down in the Venetian Charter on the conservation and restoration of architectural monuments (1964) as well as in the Recommendations of Icomos/Iscarsah (2003). These principles must be used in restoration projects for architectural monuments of any status:

- The main objective of the restoration work is to strengthen the genuine parts of the monument;
- The minimum amount of invasive works on the monument should be done to achieve this objective;
- It is possible to use modern technology and physical methods in the restoration to strengthen the monument;
- It is possible to use different materials. Externally and physically they must correspond to the monument's original materials. However, faking the original materials is not allowed;
- Disassembling the original parts of the monument is not allowed. Modern restoration techniques should strengthen the damaged walls without violation; and
- It is necessary to conduct a thorough and comprehensive study of the monument before the restoration operations.

Negative consequences of applying cement-based mortars in combination with brittle porous materials, for example with ceramic bricks, can be seen when monitoring restored cultural heritage (Odgers and Henry, 2012; Gibbons, 2003; Williams, 2001; Smirnova, 2016). On the other hand, there are no signs of deterioration in dense stone materials when Portland cement compositions are used.

The requirement of compatibility between the artificial or natural stones and the restoration materials is paramount when choosing the restoration material (Schueremans *et al*., 2011; Sabri *et al*., 2018; Groot, 2016; Vavričuk *et al*., 2018; Kosenkova *et al*., 2019). The definition of compatibility is considered as "the use of materials that do not bear negative consequences for historical materials" by many scientists (Vavričuk *et al*., 2018; Righetti *et al*., 2016; Lindqvist and Johansson, 2019; Kayan *et al*., 2016; Apostolopoulou *et al*., 2018). Accordingly, the key parameters of compatibility that the restoration materials should have must be stated.

The aim of the paper is to present a method for finding the optimal composition of the restorative materials taking into account a large number of variables within strict boundary conditions within a short time period.

PROBLEM STATEMENT

Compliance with the principle of historicism involves using the results of historical research and archival materials, as well as the study of technologies and techniques in the restoration of monuments in accordance with the concept of scientific restoration, which originated in the middle of the 19th century. The knowledge of historical materials and technologies is a key factor in the development of a restoration project (Forster *et al*., 2011; Ashurst and Ashurst, 1988).

A schematic representation of approaches to the restoration technology used in stone and brick masonry is shown in Figure 2.

Work on creating materials for each item of cultural heritage begins with the study of historical samples using modern analytical methods. A decision on the composition of the restoration material used should be made only on the basis of the data obtained. X-ray analysis is the most reliable method for studying the composition of material samples taken from cultural heritage. The results are refined by other methods of analysis such as electron microscopy or petrography if necessary. The first stage in developing the compositions used in restoration is to study the composition of the historical material, based on the x-ray and other data. Development of a method for optimizing the quantity of the components which make up restoration materials is the main subject of this paper.

A better understanding of the negative consequences of using Portland cement-based mortars in combination with brittle porous materials comes from monitoring restored structures based on these porous materials (Odgers and Henry, 2012; Gibbons, 2003; Williams, 2001). The study of technological approaches to the restoration of porous and dense stone materials using different binder compositions is required since there are not enough published data on this problem.

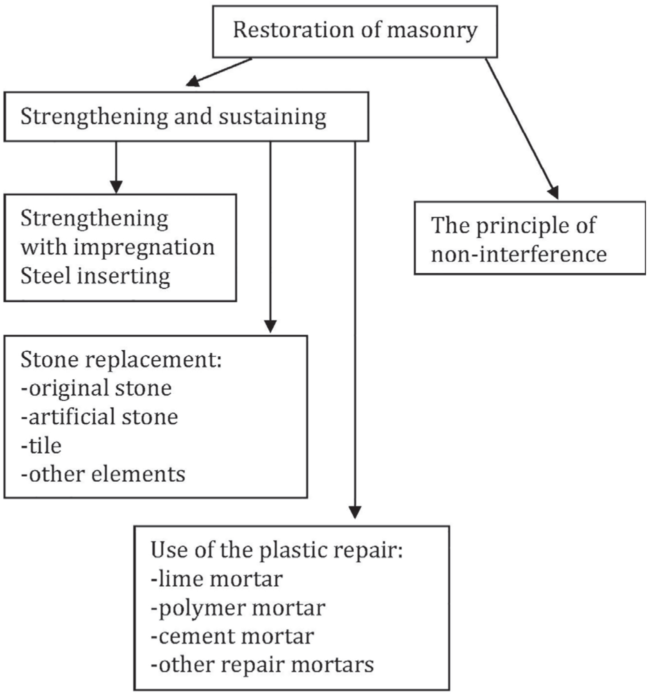

Figure 2. Schematic representation of approaches to restoration technology

In the past, mortar based on air lime was used in the construction of historic buildings for brick walls and for their decoration. Unfortunately, lime was gradually replaced by cement when the technology for binders was developed. The reasons for this are clear – cement mortars make it possible to work faster. The workability of cement mortar is a positive property, but the use of cement mortars has led to poor results. Brick walls that have been repaired with cement mortars have been irreversibly destroyed. This error was recognized by the restoration schools. The decision not to use Portland cement for the restoration of external plaster was made at the world congress for the preservation of monuments of architecture in Paris in 1957.

First of all, the mortar for masonry restoration should not change the mass transfer of moisture through the structure, i.e. it should not differ from the masonry vapour permeability. In addition, the composition of the material must correspond to the historical masonry mortar according to restoration principles. The use of cement and polymeric substances as a binder is unacceptable.

First of all we should consider the requirement of compatibility between the restoration materials and the stone base. It is necessary to set the key compatibility parameters that the restoration materials must have. The following parameters can be selected as the key parameters of compatibility: compressive strength, tensile strength, adhesive strength, density, vapor permeability, capillary water absorption, hygroscopicity, thermal capacity etc. This list is incomplete and can be supplemented or changed depending on the specific conditions and purposes of the masonry, as well as the architectural and construction activities for cultural heritage (Chmielewski and Muzolf, 2018; Fusade *et al*., 2019a; Bencardino *et al*., 2017; Carmona-Quiroga *et al*., 2018). It is also necessary to select the material in accordance with the colour and texture of the surface. All these conditions make the task of selecting the material used to restore masonry and choosing the technological works extremely complicated and expensive activities (Stefanidou *et al*., 2017; Govaerts *et al*., 2018; Fusade *et al*., 2019b). Another important condition is the time limit given for work on a site, which may not be long enough for selecting material with the required parameters. This often leads to disregard for the principles of scientific restoration.

RESEARCH METHOD

The main problem of choosing the restoration material can be formulated on the basis of the above-stated information. Namely, it is finding the optimal composition of the material with a large number of variables in the presence of strict boundary conditions within a given time limit.

Solution to this problem can be presented using mathematical modelling and experiment planning methods to find the optimal value of the response function. This makes it possible to obtain an approximating polynomial that describes the surface of the response function.

Mathematical optimization methods have long historical roots. Their foundations were laid in the 18th century. These methods include variational calculus, numerical methods, etc. A large number of methods aimed at solving optimization problems have been developed to date (Ashurst and Ashurst, 1988; Odgers *et al*., 2012; Gibbons, 2003).

Mathematical model for the process studied here or for an object can be used for optimization. In the latter case the optimization is done empirically. Experimental and statistical methods are used for objects of probabilistic nature that can include many construction and restoration materials. These methods make it possible to determine the values of factors (arguments) corresponding to the extreme values of the target function. Some of the most commonly used methods in experimental optimization are: the simplex method, coordinate optimization method, gradient methods and the deformable polyhedron method.

A review of the optimization methods related to various technologies and objects shows that a step-by-step process using a gradual approach to finding the optimum value is a characteristic of all methods (Blokhin and Gludkich, 1997; Adler *et al*., 1975). The use of these methods in order to find the optimal values of multi-component mixtures for the restoration of masonry is very difficult due to the long duration of the experimental studies. For example, it is necessary to wait 28 days for mortar to harden and reach the required strength. In this case, one month is required to determine the value of one parameter and in the case of an unsatisfactory value for this parameter, several months will be required to find the optimal value.

The main idea that underlies the proposed method is the use of an experimentally derived mathematical model to find the optimal values of the properties in the form of an objective function. This objective function describes the dependence of the parameters of the physical and mechanical properties of restoration materials (including other criteria in the optimization process) on the quantitative ratios among the mortar components. The authors have developed software that implements the mathematical model and makes it possible to carry out numerical experiments during the process of optimization.

Mathematical models that provide the interpolation function and describe the considered response surface within the factor space were obtained on the basis of processing the results of experimental work using regression analysis methods.

The proposed approach includes the following steps:

- It is necessary to select the optimality criterion and prepare the objective function that represents its dependence on the factors determining the objective function value. The parameters of the physical and mechanical properties of the materials as well as the economic, technological and other parameters can be selected as the criteria. Key requirements are: the criteria should be quantitative, measurable and easily computable;
- It is also necessary to: plan and carry out experiments in order to obtain regression equations approximating the surface of the required factor space; process experimental results with statistical methods; calculate and correct the coefficients of the regression equations; assess the adequacy of the equations, and; determine the statistical significance of the coefficients. The planning of experiments should be carried out using second-order polynomials in the case of available a priori information about the presence of nonlinear dependencies in the processes;
- After that, it is necessary to select the optimization method to find the extreme values of the objective function. Any numerical method can be used at this stage. The steep ascent method, as shown in Figure 3, is proposed in connection with applying the results of numerical experiments using a computer. Figure 3 shows the execution of the working motion along the vector gradient defined in the area of the starting point until the partial extremum of the response function in the direction of the gradient is reached, without its correction at each working step.

  The closed lines in Figure 3 are the isolines of a function where the values of this function are the same. The straight line is the gradient direction. The gradient is the shortest path to the top, i.e. to the optimum area. The optimum area is indicated as N.

  The points in Figure 3 indicate experiments with the coordinates of the factors lying on the gradient. M_0 is the initial arbitrary point for determining the first direction of the gradient. Points 1, 2, 3, 4, ..., 14 are the numbers of the experiments for determining the gradient. M_1 is the point for determining the new direction to the optimum area N.

  The optimum (maximum or minimum of the target function) can be found by performing experiments with the values of the factors lying on the gradient. The gradient is the line perpendicular to the isolines of the target function. At first, four experiments are performed in order to determine the gradient and then the values of the factors lying on the gradient are calculated. The experiments are carried out step by step until the position in which the subsequent value of the function begins to decrease. Next, four new experiments are performed to determine the new direction of the gradient. Finding the optimum continues until the maximum or minimum value of the function is found;
- The chosen optimization method should use the results of numerical experiments and the stated mathematical model. Then, the values of the factors (in our case the determination of mixture composition of restoration material) that correspond to the optimal values of the objective function are determined; and
- Experimental verification of the physical and mechanical properties of the given composition of the restoration material is performed by making laboratory samples. The duration of the experimental studies is reduced by using numerical modelling and obtaining the objective function during the optimization process. The great volume of experimental works and studies can relate to obtaining mathematical models for approaching polynomials (namely regression equations) and can be performed in quite a short period of time.

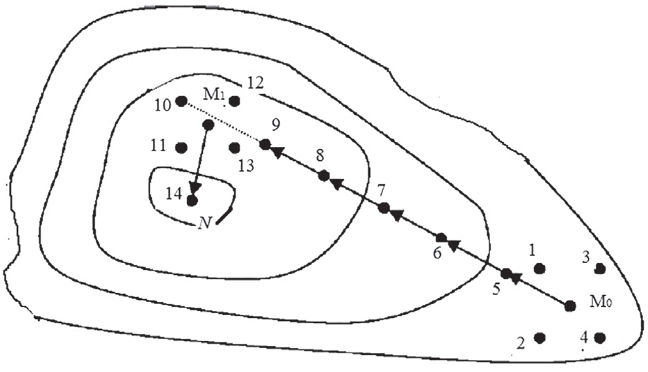

Figure 3. Optimization process with the steep ascent method

The software can be useful for carrying out the numerical experiments using mathematical models. The automation of the whole optimization procedure is complicated by the presence of informal actions related to decision making in the process of searching for an extremum. This methodology abandons the automation procedure in favour of freely choosing an optimization method. The program is flexible and enables different variations of mathematical models to be implemented in the form of polynomials.

RESULTS AND DISCUSSION

An evaluation of the effectiveness of the proposed methodology was carried out as follows.

Mathematical model was chosen in the form of a regression equation that can usually be obtained for studying the properties of building materials. An admixture was added into this equation as a random variable distributed according to the normal law, and simulating the various errors that occur in real experiments. This model was implemented on a computer using a specially developed program that makes it possible to perform numerical experiments using this model.

It was further accepted that the above-mentioned model was unknown. Hence, the task to determine the maximum value of a specific target function within the given limits of the factor space was set using a step-by-step optimization method, i.e. the steep ascent method. All this is necessary for determining the required number of experiments that could be sufficient for solving the problem.

Then, the type of objective function was also stated in order to determine the required number of experiments. The mathematical model obtained was used to determine the maximum of the objective function using the simplex method.

Ensuring the visibility of the results, both intermediate and final, is an important point when using the chosen method. A mathematical model of the process is presented here using the two-factor polynomial of the second degree. It has the following form:

$$y = 30 - 2.2 \cdot x_1 + 3 \cdot x_2 - 2 \cdot x_1^2 + 1.5 \cdot x_2^2 + \varepsilon \tag{1}$$

where

y - the response function (the objective function in the optimization),

x_1 and x_2 - the factors affecting it,

ε - the error distributed according to the normal law.

The y function is smooth and continuous. It is defined in the region of positive values. The last condition is fulfilled by the choice of constraints of the factors (factor space).

The study of function (1) shows that it has no extremum. This means that in this case the optimization problem should be reduced to determining the maximum values of this function within a given factor space. The highest value of the selected function has a minimum value of x_1=2.3 and a maximum value of x_2=3.84. All this should be confirmed by the study of this function using the method of planning experiments.

Finding the extremum of the function in question by means of the steep ascent method shows that the maximum values of the target function really correspond to the following values of the factors x_1=2.3 and x_2=3.84. The initial region used to determine the gradient is located in the middle of the factor space.

The dependence as noted earlier is unknown. This was taken into account when determining the type of target function (regression equation) by experiment planning methods. In view of this it was initially assumed that the mathematical model is a linear polynomial. Statistical analysis of this model shows that it is inadequate and therefore a second-order polynomial should be chosen.

The adequate regression equation obtained in coded values of factors with statistically significant coefficients has the following form:

$$Y = 30.78 - 10.81 \cdot X_1 + 11.57 \cdot X_2 - 1.08 \cdot X_1^2 + 1.28 \cdot X_2^2 \tag{2}$$

The equation is in the form of real variables:

$$Y = 31.44 - 2.7 \cdot x_1 + 2.49 \cdot x_2 - 1.92 \cdot x_1^2 + 1.58 \cdot x_2^2 \tag{3}$$

Comparison of the regression equation (3) with the original one (1) shows that the equations are very close and a small discrepancy can be explained by the imposition of “noise”.

Starting point from which the search for the maximum begins is in the middle of the factor space, as with the steep ascent method. This was assumed when finding the maximum of the target function in question using regression equation (2) and the simplex method. The implementation of the simplex method using the results of numerical modelling by equation (2) shows that the maximum values of the function Y correspond to the values of the factors x_1 = 2.3 and x_2 = 3.84.

The following results were obtained by finding the maximum of the two-factor response function by various methods. The desired maximum was found using the results of 22 experiments taking into account the verification of the presence of a maximum in the vicinity of the point of the expected maximum using the method of steep ascent. The desired maximum was found using the results of 13 experiments without taking into account verification of the presence of a maximum in the vicinity of the point of the expected maximum. The required maximum was found in 16 experiments using the simplex method. The number of real experiments for obtaining the regression equation in the form of the polynomial of the second degree was 7. Thus, the use of the proposed technique for a two-factor experiment makes it possible to halve the number of real experiments. It is obvious that this result will persist even with an increase in the number of factors.

The effect is even greater when considering the effectiveness of the proposed technique in terms of the duration of the tests. For example, if we assume that 28 days are required to estimate the strength of a cement composition, then 1 year is required to find the maximum of the response function for the strength of the samples using the gradient step-by-step method. This period can be reduced up to two or three months taking into account the experimental confirmation of the maximum, found using the proposed technique.

CONCLUSION

The masonry restoration of architectural monuments is a contemporary task. The initial properties of the masonry material that determine its durability, deterioration and degree of preservation have led to the appearance of different approaches towards choosing the technology used to restore masonry. One of the main technological approaches in the science of restoration materials is therefore the search for the optimal composition of the material with a large number of variables, in the presence of strict boundary conditions and within a given time limit. The proposed approach for the optimization of multicomponent restoration mortars makes it possible to develop a material with properties that meet the key parameters of compatibility between the mortars and natural or artificial stone within a limited period of time. The basic idea of the proposed approach is the use of an experimentally obtained mathematical model for optimization of the material composition in the form of the objective function. The objective function describes the dependence of the parameters of the physical and mechanical properties of the restorative materials or the other optimization criteria upon the quantity of the components. Special software has been designed that can carry out the mathematical model and hold numerical experiments in the optimization process. The solution to the problem can be found in the field of mathematical modelling using the experiment planning method. The desired results can be obtained within a relatively short period of time using the method for mortar optimization presented here.

REFERENCES

Adler, Yu. P., Markova, E. V., Granovsky, Yu. V. (1975) *The Design of Experiments to Find optimal conditions*. Moscow: Mir Publishers.

Apostolopoulou, M., Aggelakopoulou, E., Bakolas, A., Moropoulou, A. (2018) Compatible mortars for the sustainable conservation of stone in masonries, in Hosseini, M., Karapanagiotis, I. (eds.) *Advanced Materials for the Conservation of Stone*, Verlag: Springer International Publishing, pp. 97-123.

Ashurst, J., Ashurst N. (1988) *Practical building conservation: stone masonry: English heritage technical handbook, Volume 1*. Avon: Gower Technical Press.

Belentsov, Y., Shangina, N., Larisa, M., Kharitonov, A. (2017) Brickwork structure influence on reliability of structures being constructed. In *IOP Conference Series: Earth and Environmental Science*, IOP Publishing, Vol. 90, No. 1, pp. 1-5, https://iopscience.iop.org/article/10.1088/1755-1315/90/1/012086/pdf , accessed 1st Dec 2019.

Bencardino, F., Condello, A., Castiglione, F. (2017) An Innovative Solution for the Structural Consolidation of RC Modern Cultural Heritage. *International Journal of Architectural Heritage*, Vol. 11, Iss. 6, pp. 829-842.

Blokhin, V. G., Gludkich, P. O. (1997) *Modern experiment: preparation, implementation, analysis of results*. Moscow: Radio and communication.

Carmona-Quiroga, P. M., Martínez-Ramírez, S., Viles, H. A. (2018) Efficiency and durability of a self-cleaning coating on concrete and stones under both natural and artificial ageing trials. *Applied Surface Science*, Vol. 433, pp. 312-320.

Cascardi, A., Micelli, F., Aiello, M. A. (2018) FRCM-confined masonry columns: experimental investigation on the effect of the inorganic matrix properties. *Construction and Building Materials*, Vol. 186, pp. 811-825.

Castellano, A., Fraddosio, A., Scacco, J., Milani, G., Piccioni, M. D. (2019) Dynamic Response of FRCM Reinforced Masonry Arches, in Di Tommaso, A., Gentilini, C., Castellazzi, G. (eds.) Mechanics of Masonry Structures Strengthened with Composite Materials III, Key Engineering Materials, Vol. 817, pp. 285-292. Zurich: Trans Tech Publications Ltd.

Chmielewski, R., Muzolf, P. (2018) Selected problems of protection of historic buildings against the rainwater and the groundwater. In Beben, D., Rak, A., Perkowski, Z. (eds.) *Proceedings of the 3rd Scientific Conference Environmental Challenges in Civil Engineering (ECCE), MATEC Web Conferences*, Vol. 174, EDP Sciences, pp. 1-10, https://www.matec-conferences.org/articles/matecconf/pdf/2018/33/matecconf_ecce2018_03012.pdf, accessed 1st Dec 2019.

Clementi, F., Gazzani, V., Poiani, M., Lenci, S. (2016) Assessment of seismic behaviour of heritage masonry buildings using numerical modelling, *Journal of Building Engineering*, Vol. 8, pp. 29-47.

Formisano, A., Marzo, A. (2017) Simplified and refined methods for seismic vulnerability assessment and retrofitting of an Italian cultural heritage masonry building, *Computers & Structures*, Vol. 180, pp. 13-26.

Forster, A. M., Carter, K., Banfill, P. F., Kayan, B. (2011) Green maintenance for historic masonry buildings: an emerging concept, *Building Research & Information*, Vol. 39, Iss. 6, pp. 654-664.

Fusade, L., Orr, S. A., Wood, C., O'Dowd, M., Viles, H. (2019a) Drying response of lime-mortar joints in granite masonry after an intense rainfall and after repointing, *Heritage Science*, Vol. 7, p. 1-19.

Fusade, L., Viles, H., Wood, C., Burns, C. (2019b) The effect of wood ash on the properties and durability of lime mortar for repointing damp historic buildings, *Construction and Building Materials*, Vol. 212, pp. 500-513.

Gailitis, R., Sprince, A., Pakrastins, L., Shakhmenko, G., Kozlovskis, T. (2019) Comparison of the Long-Term Properties in Compression of Different Size Foamed Concrete, in *Proceedings of the 12th International Scientific and Practical Conference, Volume III*. Rezekne: Rezekne Academy of Technologies, pp. 41- 44.

Gibbons P. (2003) *Preparation and use of lime mortars. Historic Scotland*. Scottish Conservation Bureau. TCRE Group, Edinburgh, Scotland.

Giordano, A., Cascardi, A., Micelli, F., Aiello, M. A. (2018) Theoretical study for the strengthening of a series of vaults in a cultural heritage masonry building: A case study in Italy, in Milani, G., Taliercio, A., Garrity, S. (eds.) *Proceedings of the 10th International Masonry Conference (10IMC)*, Milan: The International Masonry Society, pp. 2510-2531.

Govaerts, Y., Hayen, R., de Bouw, M., Verdonck, A., Meulebroeck, W., Mertens, S., Grégoire, Y. (2018) Performance of a lime-based insulating render for heritage buildings, *Construction and Building Materials*, Vol. 159, pp. 376-389.

Groot, C. (2016) Repair mortars for historic masonry: Effects of the binder choice on durability, *Heron*, Vol. 61, No. 1, pp. 33-56.

Hendrickx, R., De Clercq, H. (2019) Heat and moisture simulations of repair mortars: benchmark experiments and practical cases in conservation, in Hughes J., Válek J., Groot C. (eds.) *Historic Mortars*. Cham: Springer, pp. 319-336.

Heravi, A. A., Smirnova, O., Mechtcherine, V. (2018) Effect of strain rate and fiber type on tensile behavior of high-strength strain-hardening cement-based composites (HS-SHCC), RILEM *Bookseries*, Vol. 15. pp. 266-274.

Hosseini, M., Karapanagiotis, I. (2018) *Advanced Materials for the Conservation of Stone*. Verlag: Springer International Publishing.

Kalina, L., Bílek, V., Bartoníčková, E., Krouská, J. (2018) Polypropylene Glycols as Effective Shrinkage-Reducing Admixtures in Alkali-Activated Materials, *ACI Materials Journal*, Vol. 115, Iss. 2, pp. 251-256.

Kayan, B. A., Forster, A. M., Banfill, P. F. (2016) Green Maintenance for historic masonry buildings: an option appraisal approach, *Smart and Sustainable Built Environment*, Vol. 5, No. 2, pp. 143-164.

Kazanskaya, L., Privalov, N., Privalova, S. (2019) Fine ground granulated blast furnace slag for saving quantity of binder, E3S Web of Conferences, Vol. 110, pp. 1-6.

Kazanskaya L. F., Belentsov Yu. A. (2019) Methods of Assessing the Strength of Masonry to Ensure the Reliability of Reconstructed Structures, *International Journal of Innovative Technology and Exploring Engineering*, Vol. 8, Iss. 10, pp. 3435-3439.

Kharitonov, A., Smirnova, O., Vilenskii, M. (2019) Principles of green architecture for the historical part of Saint-Petersburg, *Urbanism Architecture Constructions*, Vol. 10, No. 2, pp.103-112.

Kosenkova, N., Litvinov, D., Kosenkova, Y. (2019) Revisiting architectural landmarks, *E3S Web of Conferences*, Vol. 135, pp. 1-7.

Lindqvist, J. E., Johansson, S. (2019) The Development of Binders and Mortars in Sweden, in Hughes J., Válek J., Groot C. (eds.) *Historic Mortars*. Cham: Springer, pp. 257-263.

Lourenço, P. B., Roque, J. A. (2006) Simplified indexes for the seismic vulnerability of ancient masonry buildings, *Construction and Building Materials*, Vol. 20, Iss. 4, pp. 200-208.

Lourenço, P. B., Trujillo, A., Mendes, N., Ramos, L. F. (2012) Seismic performance of the St. George of the Latins church: Lessons learned from studying masonry ruins, *Engineering structures*, Vol. 40, pp. 501-518.

Micelli, F., Cascardi, A. (2019) Structural assessment and seismic analysis of a 14th century masonry tower, *Engineering Failure Analysis*, Vol. 107, pp. 1-28.

Myasnikova, O. V., Pervunina, A. V. (2019) Integrated use prospects for low-carbon shungite-bearing rocks in Karelia, *Gornyi Zhurnal*. No. 3, pp. 78-82.

Ochkurov, V. I., Vilenskii, M. Yu. (2019) Comparative evaluation of the saving of binder with fine ground slag, *IOP Conference Series: Materials Science and Engineering*, Vol. 666, No. 1, pp. 1-8.

Odgers, D., Henry, A. (2012) *English heritage practical building conservation stone.* Farnham: Ashgate Publishing Limited.

Odgers, D., Henry, A., Martin, B., Wood, C. (2012) *Practical Building Conservation: Stone by English Heritage*. Farnham: Ashgate Publishing Limited.

Pauletta, M., Di Luca, D., Russo, E., Fumo, C. (2018) Seismic rehabilitation of cultural heritage masonry buildings with unbonded fiber reinforced elastomeric isolators (U-FREIs) – A case of study, *Journal of Cultural Heritage*, Vol. 32, pp. 84-97.

Plugin, A., Dedeneva, E., Kostyuk, T., Bondarenko, D., Demina, O. (2017) Formation of structure of high-strength composites with account of interactions between liquid phase and disperse particles. In Vatulia, G., Plugin, A., Darenskyi, O. (eds.) *Proceedings of the 6th International Scientific Conference "Reliability and Durability of Railway Transport Engineering Structures and Buildings" (Transbud-2017), MATEC Web of Conferences*, Vol. 116, EDP Sciences, p. 1-8, https://www.matec-conferences.org/articles/matecconf/pdf/2017/30/matecconf_trs2017_01010.pdf, accessed 1st Dec 2019.

Ribilotta, E., Giordano, E., Ferrante, A., Clementi, F., Lenci, S. (2019) Tracking Modal Parameter Evolution of Different Cultural Heritage Structure Damaged by Central Italy Earthquake of 2016, in Di Tommaso, A., Gentilini, C., Castellazzi, G. (eds.) Mechanics of Masonry Structures Strengthened with Composite Materials III, Key Engineering Materials, Vol. 817, pp. 334-341. Zurich: Trans Tech Publications Ltd.

Righetti, L., Edmondson, V., Corradi, M., Borri, A. (2016) Fiberglass grids as sustainable reinforcement of historic masonry, *Materials*, Vol. 9, Iss. 7, 603, pp. 1-17.

Sabri, M. M., Shashkin, K. G., Zakharin, E. Ulybin, A. V. (2018) Soil stabilization and foundation restoration using an expandable polyurethane resin, *Magazine of Civil Engineering*, 82(6), pp. 68-80.

Sakiyama, N. R. M., Frick, J., Garrecht, H. (2018) Cultural heritage compatible insulation plaster: Analysis and assessment by hygrothermal simulations, in Broström, T., Nilsen, L. (eds.) *Proceedings of the 3rd International Conference on Energy Efficiency in Historic Buildings (EEHB2018)*, Visby: Uppsala University, pp. 23-29.

Schueremans, L., Cizer, Ö., Janssens E., Serre, G., Van Balen, K. (2011) Characterization of repair mortars for the assessment of their compatibility in restoration projects: research and practice, *Construction Building Materials*, Vol. 25, Iss. 12, pp. 4338-4350.

Smirnova, O. M. (2016) Compatibility of Portland cement and polycarboxylate-based superplasticizers in high-strength concrete for precast constructions, *Magazine of Civil Engineering*, No. 6, pp. 12-22.

Stefanidou, M., Kesikidou, F., Antoniadis, K. (2017) The Role of Application Techniques for High Performance Traditional Renders, *Procedia environmental sciences*, Vol. 38, pp. 242-247.

Šoukal, F., Koplík, J., Ptáček, P., Opravil, T., Havlica, J., Palou, M. T., Kalina, L. (2016) The influence of pH buffers on hydration of hydraulic phases in system CaO-Al2O3, *Journal of thermal analysis and calorimetry*, Vol. 124, pp. 629-638.

Tilocca, A. R., Incerti, A., Bellini, A., Savoia, M. (2019) Influence of Matrix Properties on FRCM-CRM Strengthening Systems, in Di Tommaso, A., Gentilini, C., Castellazzi, G. (eds.) Mechanics of Masonry Structures Strengthened with Composite Materials III, Key Engineering Materials, Vol. 817, pp. 478-485. Zurich: Trans Tech Publications Ltd.

Torney, C., Forster A. M., Szadurski E. M. (2014) Specialist 'restoration mortars' for stone elements: a comparison of the physical properties of two stone repair materials, *Heritage Science*, 2:1, pp. 1-12.

Upadhyaya, S., Nanda, B., Panigrahi, R. (2019) Experimental Analysis on Partial Replacement of Fine Aggregate by Granite Dust in Concrete, in Das B., Neithalath N. (eds.) *Sustainable Construction and Building Materials. Lecture Notes in Civil Engineering*, Vol. 25. Springer, Singapore, pp. 335-344.

Vavričuk, A., Bokan-Bosiljkov, V., Kramar, S. (2018) The influence of metakaolin on the properties of natural hydraulic lime-based grouts for historic masonry repair, *Construction and Building Materials*, Vol. 172, pp. 706-716.

Vicente, R., Lagomarsino, S., Ferreira, T. M., Cattari, S., Mendes da Silva, J. A. R. (2018) Cultural Heritage Monuments and Historical Buildings: Conservation Works and Structural

Retrofitting, in Costa, A., Arêde, A., Varum, H. (eds.) *Strengthening and Retrofitting of Existing Structures. Building Pathology and Rehabilitation*, Vol. 9, Singapore: Springer, pp. 25-57.

Williams, G. (2001) *Repointing stone and brick walling: technical pamphlet 5*. London: Society for the Protection of Ancient Buildings.

Zarzuela, R., Luna, M., Carrascosa, L. A., Mosquera, M. J. (2018) Preserving Cultural Heritage Stone: Innovative Consolidant, Superhydrophobic, Self-Cleaning, and Biocidal Products, in Hosseini, M., Karapanagiotis, I. (eds.) *Advanced Materials for the Conservation of Stone*, Verlag: Springer International Publishing, pp. 259-275.

Received August 2019; accepted in revised form December 2019.