Modelling the Durability of Cementitious Composites Elements by Means of Soft Computing Techniques

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Abstract. Proper modeling of the durability of cementitious composite elements is necessary to schedule maintenance and servicing of civil engineering structures. Knowing when the elements need their repair is a high-demand necessity in order to avoid sometimes very serious damage. It has been very often done using non-destructive testing (NDT) or other methods suitable for evaluation of the technical state of the buildings. However, the fact that there is an increasing number of research topics considering prediction of durability of cementitious composites structures using soft computing techniques indicates that this approach might also be effective solution for this purpose.

In this research, the authors would like to present a review of the latest research on the modelling of the durability of the cementitious composites with different admixtures using different machine learning algorithms. In this review, the most commonly used soft computing techniques for this purpose will be described and compared. Also, the main potential threats to loss of the durability of these elements such as wear of the material due to temperature (e.g. frost), mechanical (e.g. abrasion) and chemical (e.g. chloride concentration) will be recognised. Thanks to this review, an alternative approach to the evaluation of the technical state of buildings and its durability will be emphasized.

Keywords: Soft computing techniques · Durability of structures · Neural networks · Machine learning

1 Introduction

Concrete structures operate under adverse environmental and exploiting influences that can cause a decrease in their durability. It is stated that there are three important aspects that affect the durability of the structures. There are: proper design of cementitious composite mixture, erecting of the structure should be done fulfilling all of the requirements and during lifecycle of the structure it should be used according to its destiny and maintenance as well as periodic repair should not be neglected [1].

Unfortunately, it is a more difficult task than it looks, due to many variable factors related to the cementitious composite mixture and the influences during the life cycle [2].

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In many cases, traditional techniques failed because they were costly, time-consuming, or sometimes impossible to use [3]. Thus, there is a necessity to propose other techniques which are competitive to e.g. laboratory or in-situ tests. With the acceleration of inventing novel machine learning algorithms, soft computing techniques have become a powerful device for solving many construction problems [4]. In this article the authors have focused on describing well-known usage of machine learning algorithms for prediction of the mechanical properties of cementitious composites and also for prediction of the potential threats connected with the environment in which the concrete structures might operate.

2 Soft Computing Techniques

For the purpose of modelling the durability of concrete structures, many different soft computing techniques are used. Analyzes using these techniques, for the purpose of finding a solution of the engineering problem, are performed during the training and testing processes. In this section, the short, schematic description of a few selected machine learning algorithms is presented.

2.1 Artificial Neural Networks

The most commonly used among others, the artificial neural networks imitating the biological neural connections in human brain, consist of fundamental units called neurons, which are grouped in layers. The first layer of the algorithm is an input layer composed of vectors that represent input parameters. The last layer called the output layer presents the solution of the scientific problem and consists of output vectors. The layers between these two are hidden layers consisting of hidden nodes. The layers between each other are connected and activated by activation functions. The training process is performed due to the learning algorithms and iterative adjustment of the weight between the nodes in neighboring layers. The most commonly used structure of the neural network is multi-layer perceptron which visual presentation is shown in Fig. 1.

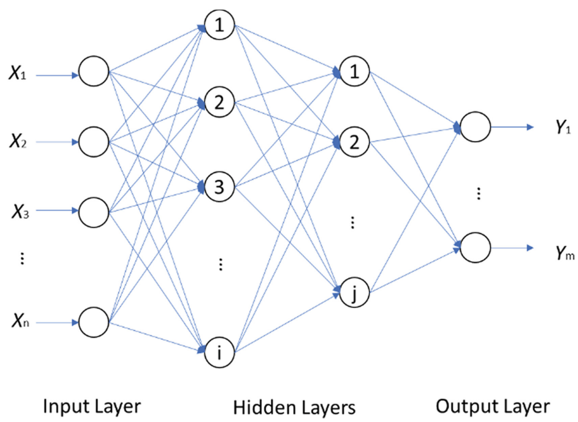

Fig. 1. The scheme of the multi-layer perceptron neural network.

2.2 Support Vector Machine

The Support Vector Machine is a soft computing technique used for analyzing classification and regression data, which is represented as a map of points in space and the solution is the hyperplane (lane in 2D, plane in 3D etc.) with the widest possible gap between the different classes. Each point in this space is described with a support vector (which is perpendicular to the hyperplane), as is shown in Fig. 2.

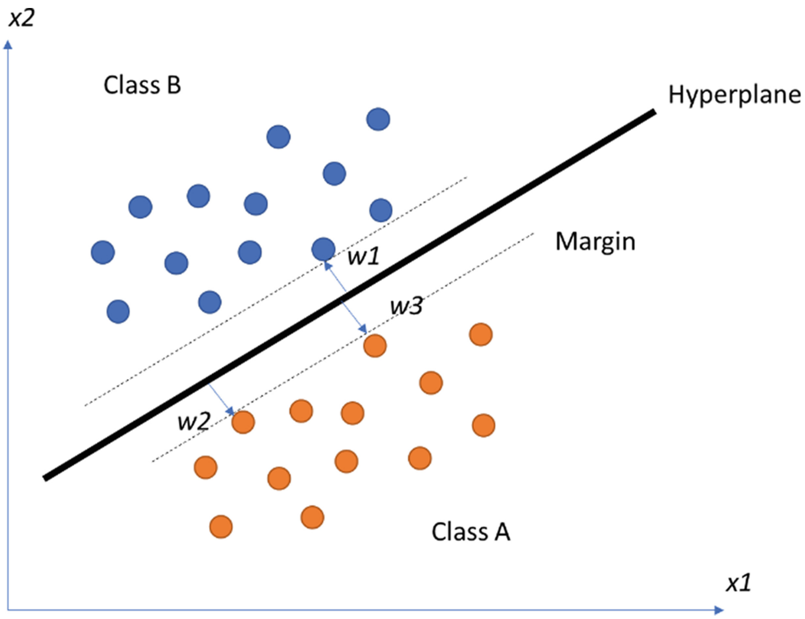

Fig. 2. The scheme of the support vector machine.

2.3 Ensemble Models

The ensemble models consist of decision trees which considered as supervised machine learning algorithm are able to solve both the regression and classification problems. The structure of such decision tree is consisting of nodes in which the binary decision is made, and this division is continued till the moment the algorithm will not be able to separate the data in the node. The most commonly used ensemble model algorithm is random forest, which consists of many decision trees and is schematically presented in Fig. 3.

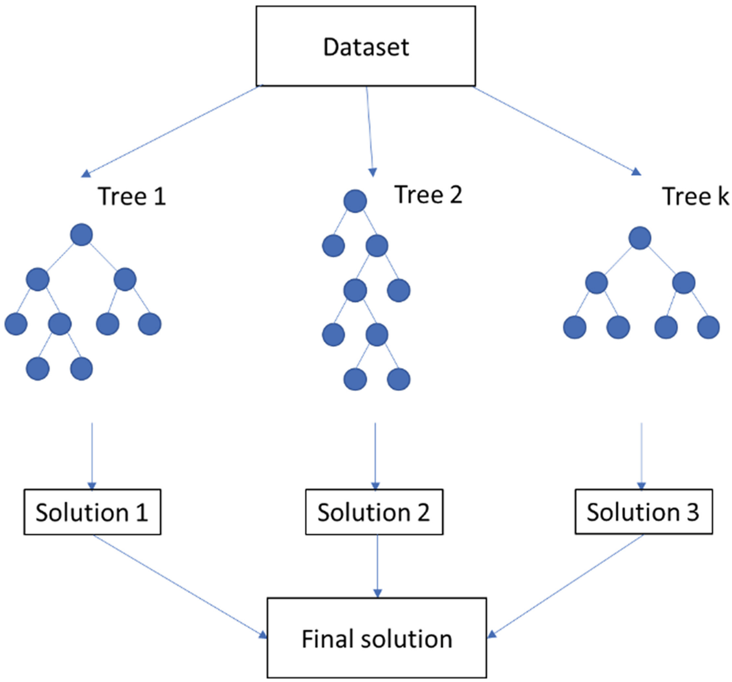

Fig. 3. The scheme of the random forest algorithm

3 Prediction of the Properties of Cementitious Composites

The aforementioned soft computing techniques are very often used to predict many important variables that are very connected or affect the durability of the entire structures. In this section, examples of such prediction of a few selected properties of elements made of cementitious composites are presented.

3.1 Compressive Strength

The most commonly predicted mechanical property of cementitious composites is compressive strength. This property is also considered to be the most important in the case of durability because the higher the compressive strength of the concrete, the better the durability. Therefore, lots of researches are performed in order to analyze this property by means of machine learning algorithms. They mostly investigate the compressive strength of concrete containing ordinary Portland cement using various algorithms such as neural networks [5], ensemble models [3], and support vector machine [7].

Recently, more often, self-compacting concretes have been subjected to studies [5]. In addition, the researchers tried to modify the mixture of concretes, these ordinary and self-compacting, by using eco-friendly admixtures. Such predictions were made successfully using neural networks for concretes containing ground granulated blast furnace slag [9], fly ash [10], silica fume [11], granulated rubber [12] and other materials that are wastes, but can be incorporated into cementitious composites as a admixture or substitute for cement, fine aggregate, or coarse aggregate.

Since the beginning of the XX century, the modeling of hardened concrete compressive strength plays a vital role in its technology development [13]. It is promising that after the laboratory inventions, the newest concrete mixtures, follow the numerical analyses, which accurately describes the properties of the designed mixtures. What is also important is the fact that in most of the aforementioned articles the parameters describing performance of these analyses confirm very high accuracy of these models.

3.2 Flexural Strength

Another commonly predicted property of cementitious composites is the flexural strength. It is mainly due to the fact that concrete is a brittle material and the potential threat of cracking could be dangerous to the safety of the structures [14]. Very often, the flexural strength is evaluated combined with the compressive strength due to the procedure of the strength tests. First, the beam samples are subjected to the 3-point bending test, and after the tests the remaining halves from the beams are subjected to the compression tests. It can be seen, as presented in [8] that using neural networks for the prediction of the flexural strength of self-compacting mortar can be as accurate as predicting the compressive strength. Recently, more research has been done to predict the flexural strength of reinforced concrete beams using the latest soft computing techniques such as gene expression programming [15]. However, even though the admixtures and reinforcements strongly affect the mechanical properties, the models presented in the literature are more often describing the prediction of the compressive strength instead of flexural strength as illustrated in Fig. 4.

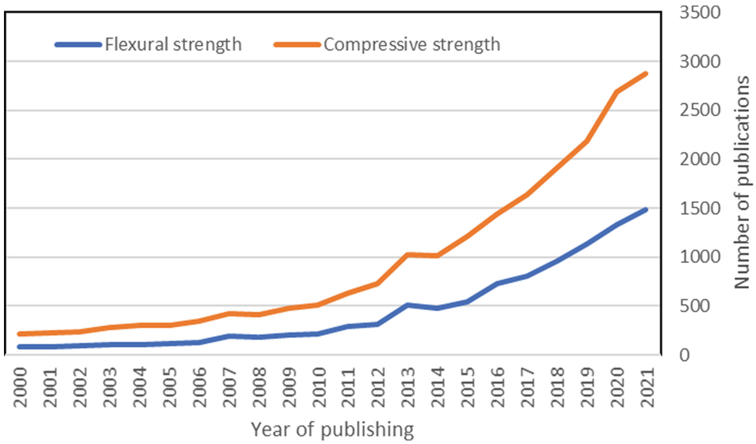

Fig. 4. The number of publications per year describing the prediction of the flexural strength of compressive strength in the Science Direct database.

According to Fig. 4 there are approximately twice more articles every year covering the topic of compressive strength prediction in comparison to the articles covering the topic of predicting flexural strength. It should be emphasised that when it comes to durability, fatigue loading during which tensile stresses occur is more dangerous due to potential threats of early corrosion [16].

3.3 Bonding Strength

The bonding strength of the cementitious composite was successfully predicted using a a neural network and information on the silica fume content in the mixture, compressive strength after 28 days and compressive strength after 90 days as input [17]. It has to be explained that bonding strength is not only the property of the material but also might be expressed as the adhesion between the two materials. Such prediction, of the two layers, cementitious composites have been made for newly constructed flooring elements where both layers were made of concrete [18] using neural networks. The interlayer bonding was also evaluated by means of neural networks for existing concrete elements with constant thickness of the layers[19], as well as for elements with variable thickness of the layers, the new one [20] and repaired [21].

In work [17], in which the most accurate model was obtained, the mechanical property evaluated was the bond strength of the subsurface layer, which is affected only by one material, not like in studies [18–21] where it is affected by the substrate and the overlay. It is a more difficult task to prepare such a model. It is also visible by the higher values of errors made by the machine learning algorithms, as shown in Fig. 5 for selected publish articles.

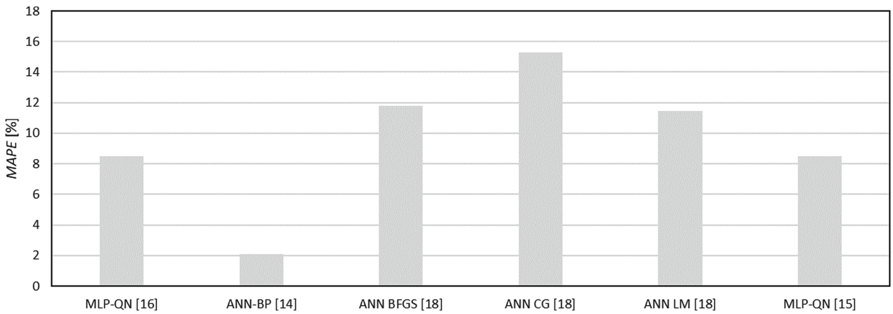

Fig. 5. Values of the mean percentage error to predict the bonding strength of cementitious composites elements.

The evaluation of the interlayer bonding is important from the durability point of view. The lower the adhesion, the lower the durability of the element. For this purpose there is a need to know the adhesion between the layers especially if the competitive method is destructive and cannot be performed in every place. What is also important is the fact that it is still possible to obtain more accurate results, compared to presented in Fig. 5, using other soft computing techniques.

3.4 Chemical Resistance

Cementitious composite elements are also exposed to different chemical influences, especially if they are located in coastal zones. These elements are highly affected by the penetration of chloride ions, and their failure in durability is mainly due to corrosion of steel reinforcements [22]. Thanks to the machine learning algorithms: neural networks and ensemble models there is a possibility to predict the chloride surface concentration [23] and based on experimental curves the depth of chloride ions penetration into the element can be estimated.

However, even for the most accurate model using gene expression programming [21], the values of the performance parameters, for example, the linear coefficient of correlation R^2 equal to 0.88, are not the highest among other properties investigated. Thus, there is still a need to improve the quality of the models presented in order to predict the chloride surface concentration. The performance of the selected models, in terms of linear coefficient of correlation, is presented in Fig. 6.

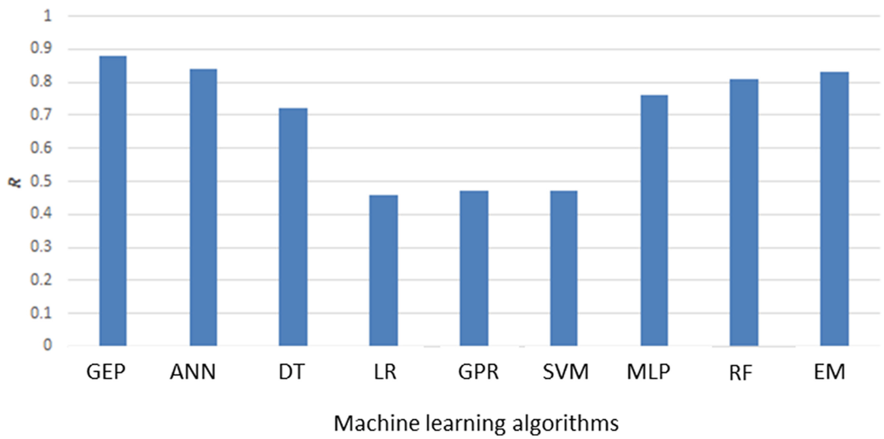

Fig. 6. The performance of selected models for predicting the chloride surface concentration.

The authors suppose that one of the main reasons why these models are not that efficient is the fact that chloride penetration into the concrete element is made by different mechanisms of transport of ions into the material in different zones.

3.5 Abrasion Resistance

In some cases the cementitious composites elements are exposed to various types of loading. One of these there is an abrasion which in some cases, e.g. concrete floors might be more important than compressive strength. This is due to the fact that the resistance to abrasion is primarily responsible for the durability of the concrete surface [25]. However, on the contrary, the compressive strength is strongly correlated with the resistance to abrasion and plays a vital role in the prediction of this property [26]. It is very promising that in [25] and [26] the values of the linear coefficient of correlation are very high, close to 1.0. It means that these models using neural networks accurately predict the abrasion resistance.

Although due to the fact that the abrasive wear of the surface of cementitious composites can be caused in many different ways, evaluating it only on the basis of the Boehme test and rotating cutter, could be slightly misleading, and it is the main limitation of these studies.

3.6 Hygrothermal Resistance

Due to different environmental influences in terms of temperature and humidity the concrete structures especially the concrete facades exposed outside are predestined to a physical and chemical damage. It is caused by the corrosion of reinforcing steel and freezing-thaw processes. In this case, it is important to evaluate, based on the data obtained from the hygrothermal monitoring system, the corrosion rate and other deterioration of the facade. This can be done by the recurrent neural network and the data collected consisting of hygrothermal values of temperature and relative humidity [27].

4 Conclusions

In this study, the review of the recent trends in the usage of soft computing techniques in order to predict the properties and influences affecting the durability of cementitious composite structures has been emphasized. In terms of the mechanical property, the most advanced models are presented for prediction of the compressive strength. This is mainly due to the fact that the quality of the concrete plays a vital role in durability and the higher the compressive strength, the higher the quality of the concrete. On the contrary, there are few very accurate models for such properties as bonding strength and chemical resistance of elements made of cementitious composites. The main reason for this is the fact that these cases are more difficult because more than one material is involved, and the phenomena, e.g. chloride ion transport, are difficult to describe. As the most common soft common technique used, the neural networks have been chosen. However, there are some other algorithms, e.g. gene expression programming, which in some cases perform better than neural networks.

Future research consisting of designing novel models in order to predict the durability of cementitious composites structures will be undertaken due to the constant necessity and their advantage in comparison with laboratory tests or in-situ tests.

Predicting many potential threats to these structures might be beneficial in avoiding unnecessary damage and costs related to their maintenance.

Thus soft computing techniques are competitive tools for evaluation of the durability of structures made of cementitious composites.

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References

1. Hooton, R.D.: Future directions for design, specification, testing, and construction of durable concrete structures. Cem. Concr. Res. **124**, 105827 (2019). https://doi.org/10.1016/j.cemconres.2019.105827
2. Qu, F., Li, W., Dong, W., Tam, V.W.Y, Yu, T.: Durability deterioration of concrete under marine environment from material to structure: a critical review. J. Build. Eng **35**, 102074 (2021). https://doi.org/10.1016/j.jobe.2020.102074
3. Farhat, H.: Chapter 7 - NDT processes: Applications and Limitations, Operation, Maintenance, and Repair of Land-Based Gas Turbines, Elsevier, Amsterdam pp. 159–174 (2021). https://doi.org/10.1016/B978-0-12-821834-1.00004-6.
4. Yu, Y., Nguyen, T.N., Li, J., Sanchez, L.F.M., Nguyen, A.: Predicting elastic modulus degradation of alkali silica reaction affected concrete using soft computing techniques: a comparative study. Constr. Build. Mater. **274**, 122024 (2021). https://doi.org/10.1016/j.conbuildmat.2020.122024
5. Nikoo, M., Moghadam, F.T., Sadowski, L.: Prediction of concrete compressive strength by evolutionary artificial neural networks. Adv. Mater. Sci. Eng., 849126 (2015). https://doi.org/10.1155/2015/849126
6. Asteris, P.G., Skentou, A.D., Bardhan, A., Samui, P., Pilakoutas, K.: Predicting concrete compressive strength using hybrid ensembling of surrogate machine learning models. Cem. Concr. Res. **145,** 106449 (2021). https://doi.org/10.1016/j.cemconres.2021.106449
7. Ling, H., Qian, C., Kang, W., Liang, C., Chen, H.: Combination of support vector machine and K-fold cross validation to predict compressive strength of concrete in marine environment. Constr. Build. Mater. **206**, 355–363 (2019). https://doi.org/10.1016/j.conbuildmat.2019.02.071
8. Nasr, D., Behforouz, B., Borujeni, P.R., Borujeni, S.A., Zehtab B.: Effect of nano-silica on mechanical properties and durability of self-compacting mortar containing natural zeolite: experimental investigations and artificial neural network modeling. Constr. Build. Mater. **229**, 116888 (2019). https://doi.org/10.1016/j.conbuildmat.2019.116888
9. Czarnecki, S., Shariq, M., Nikoo, M., Sadowski, L.: An intelligent model for the prediction of the compressive strength of cementitious composites with ground granulated blast furnace slag based on ultrasonic pulse velocity measurements. Measurement **172**, 108951 (2021). https://doi.org/10.1016/j.measurement.2020.108951
10. Song, H., Ahmad, A., Ostrowski, K.A., Dudek, M.: Analyzing the compressive strength of ceramic waste-based concrete using experiment and artificial neural network (ANN) approach. Materials **14**(16), 4518 (2021). https://doi.org/10.3390/ma14164518
11. Sun, L., Koopialipoor, M., Jahed Armaghani, D., Tarinejad, R., Tahir, M.M.: Applying a meta-heuristic algorithm to predict and optimize compressive strength of concrete samples. Eng. Comput. **37**(2), 1133–1145 (2019). https://doi.org/10.1007/s00366-019-00875-1
12. Hadzima-Nyarko, M., Nyarko, E.K., Ademovic, N., Milicevic, I., Sipos, T.K.: Modelling the influence of waste rubber on compressive strength of concrete by artificial neural networks. Materials **12**(4), 561 (2019). https://doi.org/10.3390/ma12040561
13. Karni J.: Prediction of compressive strength of concrete. Mat. Constr. **7**, 197–200 (1974). https://doi.org/10.1007/BF02473835
14. Sucharda O., Pajak M., Ponikiewski, T., Konecny P.: Identification of mechanical and fracture properties of self-compacting concrete beams with different types of steel fibres using inverse analysis. Construct. Build. Mater. **138**, 263–275 (2017). https://doi.org/10.1016/j.conbuildmat.2017.01.077
15. Murad, Y., et al.: Flexural strength prediction for concrete beams reinforced with FRP bars using gene expression programming. Structures **33**, 3163–3172 (2021). https://doi.org/10.1016/j.istruc.2021.06.045

16. Shen, J., et al.: Corrosion cracking process of reinforced concrete under the coupled effects of chloride and fatigue loading. KSCE J. Civ. Eng. **25**(9), 3376–3389 (2021). https://doi.org/10.1007/s12205-021-0768-4
17. Sancak, E.: Prediction of bond strength of lightweight concretes by using artificial neural networks. Scientific Research and Essay **4**(4), 256–266 (2009)
18. Sadowski, Ł, Hoła, J.: New nondestructive way of identifying the values of pull-off adhesion between concrete layers in floors. J. Civ. Eng. Manag. **20**(4), 561–569 (2014). https://doi.org/10.3846/13923730.2014.897642
19. Sadowski, Ł, Nikoo, M., Nikoo, M.: Hybrid metaheuristic-neural assessment of the adhesion in existing cement composites. Coatings **7**, 1–12 (2017). https://doi.org/10.3390/coatings7040049
20. Sadowski, Ł, Hoła, J., Czarnecki, S.: Wang, D: Pull-off adhesion prediction of variable thick overlay to the substrate. Autom. Constr. **85**, 10–23 (2018). https://doi.org/10.1016/j.autcon.2017.10.001
21. Czarnecki, S., Sadowski, Ł., Hoła, J.: Artificial neural networks for non-destructive identification of the interlayer bonding between repair overlay and concrete substrate. Adv. Eng. Softw. **141**, 102769 (2020). https://doi.org/10.1016/j.advengsoft.2020.102769
22. Ju, X., Wu, L., Lin, C., Yang, X., Yang, C.: Prediction of chloride concentration with elevation in concrete exposed to cyclic drying-wetting conditions in marine environments. Constr Build. Mater. **278**, 122370 (2021). https://doi.org/10.1016/j.conbuildmat.2021.122370
23. Cai, R., et al.: Prediction of surface chloride concentration of marine concrete using ensemble machine learning. Cem. Concr. Res. **136**, 106146 (2020). https://doi.org/10.1016/j.cemconres.2020.106164
24. Ahmad, A., Farooq, F., Ostrowski, K.A., Sliwa-Wieczorek, K., Czarnecki, S.: Application of novel machine learning techniques for predicting the surface chloride concentration in concrete containing waste material. Materials **14**(9), 2297 (2021). https://doi.org/10.3390/ma14092297
25. Malazdrewicz S., Sadowski L.: An intelligent model for the prediction of the depth of the wear of cementitious composite modified with high-calcium fly ash. Compos. Struct. **259**, 113234 (2021). https://doi.org/10.1016/j.compstruct.2020.113234
26. Gencel, O., Kocabas, F., Gok, M.S., Koksal, F.: Comparison of artificial neural networks and general linear model approaches for the analysis of abrasive wear of concrete. Constr. Build. Mater. **25**(8), 3486–3494 (2011). https://doi.org/10.1016/j.conbuildmat.2011.03.040
27. Taffese, W.Z., Sistonen, E.: Neural network based hygrothermal prediction for deterioration risk analysis of surface-protected concrete façade element. Constr. Build. Mater. **113**, 34–48 (2016). https://doi.org/10.1016/j.conbuildmat.2016.03.029