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Designing eco-friendly cement composites mixtures aided by artificial neural networks

S. Czarnecki and M. Moj

Department of Building Engineering, Wroclaw University of Science and Technology, Wroclaw, Poland

Abstract

The paper predicts the pull-off strength of the substrate layer of a cementitious composite containing granite powder and fly ash replacing up to 30% of the cement weight. For this purpose, intelligent artificial neural network (ANN) models were used and compared. A database was build based on and mix composition, curing time and curing method, and non-destructive Schmidt hammer compressive strength measurements. The model developed to predict the pull-off strength of the substrate layer of cementitious composites containing granite powder and fly ash was shown to be accurate. This method can be used especially for designing cement mortars with granite powder and fly ash additives replacing cement in the range of 0% to 30% of its weight. These mortars can be used for floor substrates.

Keywords: eco-friendly cement composites, artificial neural networks, granite powder, fly ash, modelling structures.

1 Introduction

The production of 1 ton of cement emits about 900 kg of carbon dioxide into the atmosphere [1]. Therefore, its reduction in materials produced with this binder is a popular procedure used today to reduce their carbon footprint. A wide range of additives and fillers in the form of quartz dust, fly ash, marble or granite powder are used to reduce the amount of cement in concrete mixes and mortars [2-5]. The granite fraction below 0.1 mm is formed during stone processing and currently has little use in the economy, while its amount in the environment is constantly increasing due to the development of the stone industry. The incompatible composition, fine fraction and low pH of this material make its spread in the environment destructive to it. The solution may be the use of granite powder as a filler in cement composites.

Making cement mortar floors is currently one of the most common applications of this type of composites. Using standards [6-8], it has been found that the basic parameters that should be met by the cementitious material used to make a pedestrian traffic floor are a minimum compressive strength of 20 MPa and a minimum pull-off strength of 1.0 MPa. Concrete substrates are recommended to be made of composites with a cement to aggregate ratio of 1:3 and a cement-water ratio within the range of 1.5-2.0. Due to the lack of unambiguous methods in the available literature [9-13] for designing cement composites taking into account the addition of granite powder above 15 wt.% of cement, the use of fly ash additive and the combination of both additives as a target assuming the pull-off strength condition of the floor substrate, it is necessary to use technologically advanced methods.

Predictive technologies currently used in solving design problems in the construction industry save time and often high costs of performed tests. One of the most established technologies is the use of artificial neural network (ANN) in the form of multilayer perceptron (MLP) [14-17]. To the best of our knowledge, there is not any developed method to predict the pull-off strength of cement mortar with the above mentioned additives using ANN. Therefore, the objective of this study is to use ANN to develop a method to design concrete floors substrates with increased pull-off strength, which is one of the main properties of floor layers.

2 Methods

This research were conducted in two stages. In the first, the experimental part, different cement mixes were prepared with different compositions in terms of the amount of granite powder and fly ash used. The first reference mix (REF) contained only Portland cement as binder. In the other mixes, Portland cement was partially replaced by granite powder and fly ash. The amount of water was taken as constant for all mixes and was determined for the reference composition for a water-cement ratio of 0.5. The amount of sand was also taken as constant for each mix. Slabs of 500 mm x 500 mm x 40 mm were made from the samples and cured for the required time (56 days or 90 days). The samples were cured in air (AIR) and in a wet environment (WET), created by applying moist sponges to the surface of the samples, at a temperature of 18±3°C. The environmental conditions in which the samples were cured were maintained for 28 days.

Pull-off tests for adhesion strength of the surface layer were performed on each disc for 8 discs (4 after each curing time). The tests were performed according to the standard [18].

A Schmidt hammer tests were also performed on the discs according to the method of [19]. At each location of the pull-off strength test, 3 impact tests were performed.

In the second stage, an attempts were taken to create an artificial neural network to predict the pul-off strength of the floor substrate layer. For this purpose, a database was created based on the information obtained from the experimental part. Then, statistical parameters were calculated. The database was divided into 3 sets for the process of training, testing and validation of ANNs. Artificial neural networks were made for selected machine learning algorithms. After modeling the artificial neural networks for all possible combinations of layer activation functions and number of hidden layer neurons, an important part of the class was to evaluate the effectiveness of the obtained values. The following indices were used to evaluate the effectiveness of the parameters: 1) coefficient of determination (R^2), 2) root mean square error (RMSE), 3) absolute error (MAE), 4) absolute percentage error (MAPE). Based on these indices, using the rank method, the best fitting network could be selected.

3 Results

In the experimental part, the most important property tested was the pull-off strength of the surface layer fh. The test was conducted on samples cured 56 and 90 days in air and in humid environment. It was observed that the change of the results was mostly influenced by the content of additives in the blend and the curing method.

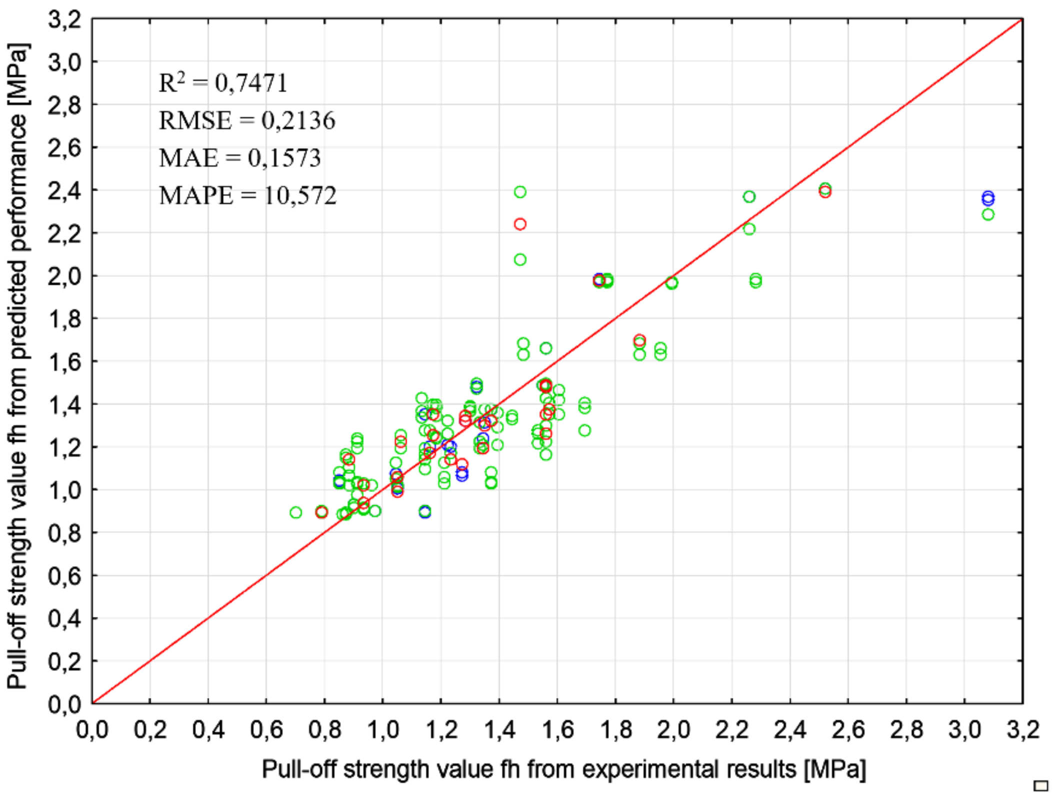

Figure 1: Graph of the relationship between predicted and experimental values of the pull-off strenght fh for ANN with the BFGS learning algorithm for mortar with granite powder additive.

The sclerometric test mainly shows a slight decrease in compressive strength as a function of the amount of fillers in the mix. The strength itself was taken as equal to the f_L value read for the obtained reflection number L from the base curve according to [20]. All specimens met the minimum compressive strength of the floor subfloor of 20MPa.

On the basis of statistical calculations and correlation of input and output parameters, it was decided to use data on mix composition, w/c ratio, curing method and time, compressive strength and pull-off strength of the substrate to create artificial neural networks. After selecting the best-fit networks, graphs were prepared showing the dependence of the predicted value on the experimentally obtained peel strength value. Figure 1 shows an example of such a graph for the BFGS learning algorithm. The green color indicates the results obtained in the training process, the blue color indicates the results obtained in the testing process, and the red color indicates the results obtained in the validation process.

The given example shown in Figure 1 obtained the values: $R^2 = 0.7471$; RMSE = 0.2136; MAE = 0.1573 and MAPE = 10.572. These are values described in the literature [21] as good or very good fits. For the BFGS algorithm, the best-fit ANN networks are those with the output layer hidden layer activation function as logistic, exponential or hyperbolic tangent and the number of hidden neurons in the range of 8-18. Then for the Conjugate Gradient and Gradient Descent algorithm, the best-fit network was obtained for the hidden and output layer activation functions as logistic, exponential or hyperbolic tangent and the number of hidden neurons in the range of 1-10.

4 Conclusions and Contributions

On the basis of numerical analyses, supplemented by experimental studies, a modern method of designing cement composites with the addition of waste granite powder and fly ash is proposed. The most suitable for this purpose is a multilayer artificial neural network with input parameters in the form of information about: mix composition, water-cement ratio, mortar curing method and time, and compressive strength fc estimated from Schmidt hammer tests. The effectiveness of the selected design method using ANN is evidenced by the satisfactory results of R^2, RMSE, MAE, MAPE indices. This method can be used especially for designing cement mortars with granite powder and fly ash additives replacing cement in the range of 0% to 30% of its weight. These mortars can be used for floor substrates.

Unfortunately, the presented method does not allow the determination of the pull-off strength in the early stages of sample curing (e.g. 7 days). The necessary information to determine pull-off strength is the composition of the mix, so this method is not suitable for composites of unknown formulation. The extent of cement substitution in the mixture is limited to 30% by weight. In addition, the method does not allow the use of additives other than those listed. Despite some elements indicating the shortcomings of the method, an attempt can be made based on it to evaluate the pull-off strength of the substrate for cementitious composites of similar material composition in order to verify the presented solution. The prepared database can be extended with further results for more universal application of ANN.

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