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ANN and GEP prediction for simultaneous effect of nano and micro silica on the compressive and flexural strength of cement mortar

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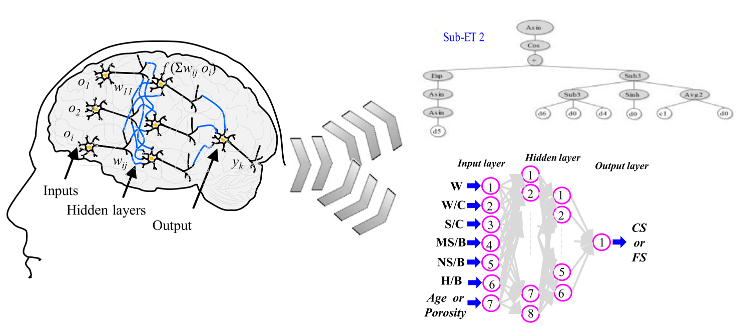
HIGHLIGHTS

- Effort to predict the mechanical properties of cement mortar containing nano silica and micro silica.
- 640 data collected from literature to evaluate the existing model in prediction.
- New ANN and GEP were conducted to predict the mechanical properties of cement mortar.
- Considering porosity as input and normalized input parameters led to more accurate prediction.

GRAPHICAL ABSTRACT



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ABSTRACT

Artificial neural networks (ANNs) and genetic expression programming (GEP) have recently been used to model the properties of cement mortar containing nano silica (NS) or micro silica (MS) to minimize the experimental work. Appropriate ANN and GEP models were proposed in this paper to predict the simultaneous effect of NS and MS on cement mortar properties because available models are not suitable to predict simultaneous effect of NS and MS. For this purpose, ANN and GEP models were trained on 640 different mixture proportions considered from literature and the prediction results were compared to available models. Moreover, in order to validate the proposed ANN and GEP models, a total of 480 compressive ($50 \times 50 \times 50$ mm) as well as 96 flexural ($40 \times 40 \times 160$ mm) specimens were constructed while considering cement strength class of 42.5 MPa and also, mechanical properties were tested.

The higher accuracy results observed when in proposed models for predicting of compressive strength of cement mortar used normalized input parameters. Moreover, flexural strength of cement mortar estimated by the new ANN and GEP models is validated by experimental effort and the results show high accuracy compared to previous models. Finally, a comparative evaluation was also performed on two conditions of with and without considering porosity as an input parameter in the new suggested ANN and GEP models.

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1. Introduction

Supplementary admixture in the form of natural pozzolan or industrial product not only modifies the microstructure of cement based materials (like concrete and mortar), but also improves mechanical properties [1–5]. The most effective admixtures to modify the microstructure are nano silica (NS) and micro silica (MS), which contribute to the improvement of cement mortar and concrete properties due to their pozzolanic reaction and smaller particle size than cement particles [6–11]. The NS [12–14] or MS [15–17] in combination with superplasticizer which is the

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usual way to obtain lower porosity that consequently improves the compressive strength (CS) and durability of mortar have been studied. For instance, Jalal et al. [18] used NS and MS in just three concrete mixture designs in both separate and simultaneous usages and demonstrated that the simultaneous consideration of NS and MS in a mixture leads to higher CS compared to the situation of separate usage. Also, Hendi et al. [5] investigated the simultaneous effects of MS and NS on self-consolidating concrete in sulfuric acid medium in which cement was partially replaced with NS at levels of 0, 1 and 3%, and MS at levels of 5, 7 and 9% by weight. Their results illustrated that the effect of MS on residual CS is more considerable than NS and the combination of MS and NS in sulfuric acid environment was more effective than when used separately. Generally, NS and MS improve the properties of cement mortar, therefore, prediction of these properties such as CS and flexural strength (FS) by means of artificial intelligence could help to save costs and time [19,20].

Artificial intelligence methods like artificial neural networks (ANNs) and genetic expression programming (GEP) have become popular and used by many researchers in a variety of engineering applications. ANN and GEP are forms of computing systems inspired by the biological neural networks and replication of the DNA molecule at the gene level, respectively [21–23].

In recent years, several researches were reported in which the ANN [24–26] and GEP [27,28] were used to estimate the mechanical properties of concrete containing NS or MS. Saridemir [26] predicted the CS of concrete containing MS by applying two different multilayer artificial neural network architectures (8-10-1 and 8-9-8-1) on 33 different mixtures with 195 specimens. As a result, CS values of concretes containing silica fume can be predicted in the multilayer feed forward artificial neural networks model. Besides, Tanyildizi et al. [28] indicated that GEP evaluates various combinations of parameters to be considered for formulation that best fits with experimental results based on high correlation coefficient. They used GEP for modeling mechanical performance of lightweight concrete containing incorporating 0, 10, 20 and 30% MS exposed to high temperature, for this purpose, two GEP models were proposed which included 30 chromosomes, 8 head size and 4 genes as well as linking functions of addition and multiplication. On the other hand, NS and MS have significant role on porosity value and since the strength of cement mortar is significantly influenced by porosity [13,29], it seems that the use of porosity as an independent input parameter could increase the precision of the prediction models.

Despite the fact that several research studies have predicted the properties of cement based materials containing NS or MS, there is no appropriate models on the prediction of simultaneous effects on cement mortar properties to minimize the experimental work as well as save cost and time. Therefore, proposed ANN and GEP models in this study trained on 640 mix designs were considered from literature to predict these effects, and also to validate the prediction models, a total of 32 mixture designs were prepared wherein the cement was partially replaced by NS (1.4, 2.8 and 4.2%) and MS (4, 9 and 13%) by weight. Normalized form of the input parameters was obtained [30] and applied in the mentioned models in order to increase the correlation between input parameters and target to predict more accurate the compressive and flexural strength of cement mortar. Furthermore, as mentioned above, the porosity was considered as an independent input parameter in these models. Finally, the prediction procedures were performed using the modified models and the results were compared with the existing models.

2. Application NS and MS in cement mortar

Supplementary cementitious materials (SCM) divided into natural SCM and artificial SCM. These admixtures have been used as cement replacement in cement materials production during the past decades [9]. Among these materials, NS and MS are particularly effective because of their particles size that are finer than cement as well as pozzolanic reactivity with calcium hydroxide $Ca(OH)_2$ which released in hydration of Portland cement lead to forming calcium-silicate-hydrate (C-S-H) [1,13]. Due to these attributes, NS and MS have an effective influence on improving the mechanical and microstructural characteristics and mechanical properties such as strength, porosity, water absorption and consequently durability [31,32]. Incorporating NS and MS in cement base materials lead to decrease in flowability, initial and final setting time of cement pastes. On the other hand, addition of NS and MS in cement mortar increase the strength while the porosity is decrease. Combined effect of NS and MS on mechanical properties is more than the case of separate using them, because of following possible causes: firstly, acceleration of cement hydration in consequence of pozzolanic effect. Incorporating NS and MS in cement hydration release $Ca(OH)_2$ to produce further C-S-H gel, which contributes to increase the strength and density of mortar. So that large surface area of NS and MS increases the intensity of reaction [33]. Secondly, As a result of the extremely small size of NS and MS particles they have the filling effect of filling into the voids between cement grains. Moreover, because MS is finer than cement and NS is finer than MS, the voids between cement and aggregate fill by MS and voids between MS and cement fill by NS. This amplify the filler effect of these SMCs and improving its microstructure and potentially increase the packing density when correctly dosed and dispersed [34].

3. Methodology

3.1. Artificial neural network

ANN is a nonlinear method to obtain existing complex relations between various parameters, which attempts the biological neural structure of human brain and consists of plenty interconnected neurons [35,36]. ANN includes five main parts: inputs, weights, sum function, activation function and outputs [37,38]. Inputs are information that are considered as decision variables enter from neurons or external world. Weights are values that express the effect of inputs or processes element on each other. Sum function is a function that calculates the effect of inputs and weights totally on this process element. The weighted sums of the input components $(\mathrm{net})_j$ are calculated by using the following equation:

$$(net)_j = \sum_{i=1}^{n} w_{ij} o_i + b \tag{1}$$

where (net)j is the weighted sum of the jth neuron for the input received from the preceding layer with n neurons, wij is the weight between the jth neuron in the preceding layer, and oi is the output of the jth neuron in the preceding layer [39,40]. The quantity b is called the bias and is used to model the threshold. Activation function is a function that processes the net input obtained from sum function and determines the cell output. On the contrary, sigmoid function is used as the activation function (f(net)) for multilayer receptive models. The output of the j neuron (out)j is calculated with a sigmoid function as follows [39,41,42]:

$$(out)_j = f(net)_j = \frac{1}{1 + e^{-\alpha (net)_j}} \tag{2}$$

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