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Prediction of sulfate expansion of PC mortar using adaptive neuro-fuzzy methodology

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Abstract

The prediction of sulfate attack is essential for concrete structures since it causes drastic decrements in strength and in expansion attributes of cementitious systems. In this study, the nonlinear mapping among sulfate expansion of PC mortar and some selected parameters (C_3A content, C_3S/C_2S ratio, sulfate concentration and mineral admixture substitution level) was simulated using adaptive neuro-fuzzy system. Experimental data that had been previously collected for various levels of accounted parameters were treated in the analyses. In neuro-fuzzy inference system, Sugeno-type inference technique and linear output function were used to perform approximate reasoning of fuzzy input variables. In addition, hybrid learning algorithm, combining backpropagation learning and linear least-squares estimator, were preferred for the adaptation of free parameters. Consequently, neuro-fuzzy model was compared with results obtained using linear and nonlinear multiple regression methodologies to make comparison among different techniques. Outcomes indicated that neuro-fuzzy model exhibits superior performance.
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Keywords: Sulfate attack; Mortar; Fuzzy logic; Neural networks; Regression analysis

1. Introduction

Sulfate attack is a chemical reaction between sulfate ions and some constituents of the hydrated cement paste. Sulfate ions are generally found in marine environment, groundwater, agricultural and alkali soils, as calcium, potassium, sodium, and magnesium sulfate [1,2]. Virtually, the degradation of cementitious systems upon sulfate attack may occur in two different forms, expansion of concrete or progressive loss of strength and mass [1,3]. The efficiency of the deterioration processes is based on the type and concentration of the sulfate ions in the contact water as well as on the composition of cement paste in concrete [4]. In case of expansion existence, the permeability of concrete increases and penetration ability of the aggressive ions becomes higher [1,2].

Fuzzy logic is a powerful tool for the simulation of complex nonlinear mappings, dealing with the uncertain information with the consideration of every variable as a matter of degree [5]. Adaptive neuro-fuzzy inference system (ANFIS) is a methodology to simulate complex nonlinear mappings utilizing neural network learning and fuzzy inference methodologies [6–8]. In the literature, there are several studies in material science carried out using fuzzy logic and neuro-fuzzy methodologies. Ghaboussi et al. [9] presented an neural network (NN)-based model simulating stress-strain curves of concretes and composites. Hancheng et al. [10] applied neuro-fuzzy technique for the strength estimation of gray cast iron using its composition and microstructure. In another notable study, Akkurt et al. [11] developed a fuzzy logic model for the compressive strength prediction of cement mortar accounting variables such as alkali, SO_3, and C_3S content of cement and its fineness.

In this context, it is possible and plausible to simulate the complex mapping among sulfate expansion and related parameters, namely C_3A content, C_3S/C_2S ratio of the cement, admixture substitution level, and sulfate concentration. In order to realize this, several experiments were carried out for different extents of considered parameters

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and sulfate expansions were measured to obtain necessary numerical data. Later, ANFIS methodology was applied for the modeling of nonlinear mapping constituted by collected input-output data. Furthermore, for the evaluation of the performance of neuro-fuzzy model, it was compared with regression-based methodologies. Results indicated that ANFIS is superior to predict sulfate expansion level. Obviously, it is also plausible to establish a model using only NN method; nevertheless, large amount of training data is required for the precision of NN models. Therefore, with the consideration of existing data, this idea was neglected within the context of this study.

2. Experimental study and statistical analysis of test data

Three types of portland cements having different C_3A contents were utilized to make mortars with the fly ash and the natural pozzolan. Mineral admixtures were replaced with portland cements by 0, 10, 20, 30, and 40 wt%. Consequently, 27 different mortar mixes were prepared within the context of this study. The portland cements, natural pozzolan and fly ash were designated as PC1, PC2, PC3, T and FA, respectively. Sulfate expansion of mortar specimens was evaluated using ASTM C1012 testing procedure. $NaSO_4$ solutions of 3% and 5% concentrations were used in the experiments. Results of the experimental study can be found elsewhere [12].

The descriptive statistical parameters of resulting data are given in Table 1. For the observation of the performance of classical statistical methods, linear multiple regression was first employed to characterize mapping among control variables and sulfate expansion. The result of multiple regression analysis is given as

$$y = a_1x_1 + a_2x_2 + a_3x_3 + a_4x_4 + a_5, \quad (1)$$

where, y is 15-week expansion upon exposure to sulfate solution, x_1 is C_3A content of cementitious system, x_2 is C_3S/C_2S ratio of the cement, x_3 is mineral admixture substitution level, x_4 is concentration of sodium sulfate solution, and a denotes coefficient vector. The determination coefficient (R^2) and Fisher value (F) were calculated as 0.91 and 109, respectively. In Fig. 1(a), the scatter plot for calculated and measured expansion values is depicted.

Furthermore, the second attempt for the characterization of mapping among considered parameters was made by nonlinear multiple regression analysis. Within this context, 179 different regression equations were developed to establish the correlation between design variables by nonlinear multiple regression analyses. Due to outcomes of the analyses, four regression equations (Eqs. (2)–(5)) were

Table 1
Descriptive statistical parameters of experimental data

Statistical parameters	C_3A (%)	C_3S/C_2S	Admixture inclusion (%)	Sulfate concentration (%)	Expansion (%)
Mean	6.452	2.939	22.222	4.200	0.017
Standard deviation	2.390	1.126	13.295	0.991	0.005
Coefficient of skewness	0.504	−0.167	−0.125	−0.422	0.527
Kurtosis coefficient	−0.855	−1.699	−1.150	−1.908	−0.013
Maximum	11.391	4.378	40.000	5.000	0.029
Minimum	3.289	1.629	0.000	3.000	0.008
Variance	5.712	1.267	176.768	0.982	0.000
Coefficient of variation	0.370	0.383	0.598	0.236	0.282

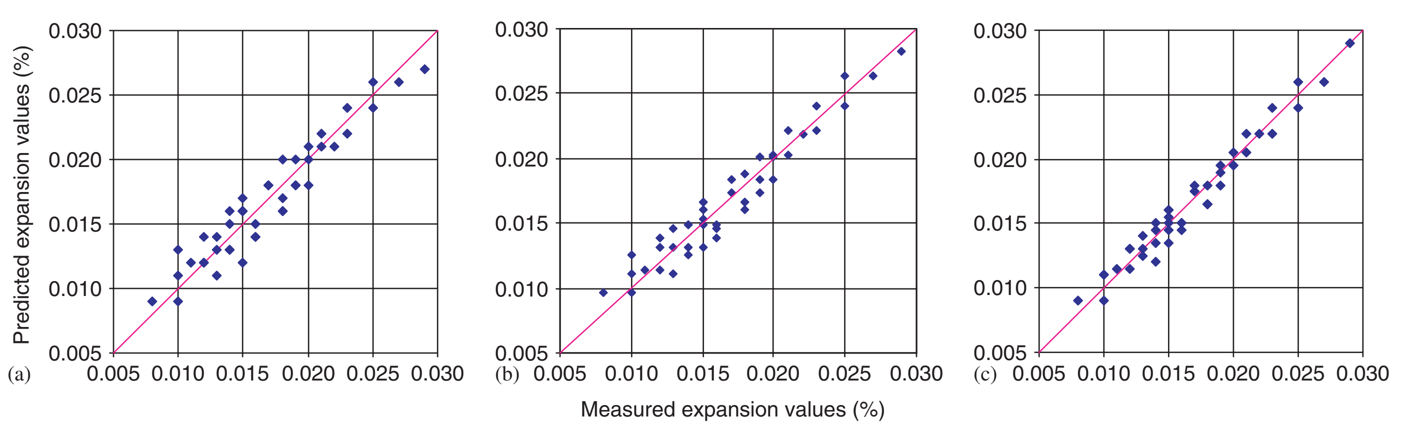

Fig. 1. Scatter plots (a) linear regression (b) nonlinear regression for Eq. (4) (c) ANFIS model.

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