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Prediction of UCS and CBR of microsilica-lime stabilized sulfate silty sand using ANN and EPR models; application to the deep soil mixing

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Abstract

Desert sands in Iran, which usually contain small amounts of silt and sulfate, do not have significant strength, and thus, are not suitable for foundations or road construction. This paper applies the results of 90 Unconfined Compressive Strength (*UCS*) and California Bearing Ratio (*CBR*) tests on sulfate silty sand stabilized with different lime and microsilica percentages as the two main stabilizers. Based on the obtained databank from the tests, Back Propagation Artificial Neural Network (BP-ANN) and Evolutionary Polynomial Regression (EPR) models are developed to predict the *UCS* and *CBR* values. Assessing the different architectures (one- and two-hidden layer neural networks) and functions (polynomial, exponential and hyperbolic tangent functions for the EPR models), a BP-ANN model with 5-5-8-1 layers and an EPR model with a hyperbolic tangent function showing high accuracy are introduced as the best models for predicting the *UCS*. Through a sensitivity analysis, the most and the least influential parameters on the *UCS* are presented and the results are further discussed using scanning electron microscopy (SEM). The presented EPR models can be useful for practitioners when selecting the optimized percentage of stabilizers or for controlling purposes in the QC/QA phases of deep soil mixing projects. In this regard, the application of the proposed models to the design of deep soil mixing is presented and elaborated using an example. In this example, the optimum and the best practical amounts of stabilizers are obtained through the graphical optimization of the models. In addition, by applying the developed relationships to a new case, the comprehensiveness of the developed relationships is further declared and it is shown that the proposed relationships are practical and can be efficiently used in the preliminary design stage.

Keywords: Sulfate silty sand; Microsilica-lime stabilization; Unconfined compressive strength; California bearing ratio; Neural networks; Evolutionary polynomial regression; Sensitivity analysis; Deep soil mixing

1. Introduction

The base material and subgrade soil of most road projects on desert sands usually contain a small amount of silt, which means the sands do not have significant strength and are not suitable for highway or construction operations. They may experience swelling and the loss of strength under soaked conditions. This is the main problem of road construction projects on desert sands in Iran, where there are more than 30 million acres of desert and prairie dandruff. In such cases, soil stabilization can be addressed as an efficient way to decrease the soil swelling potential and to increase its strength (Basha et al., 2005; Celik and Nalbantoglu, 2013; McCarthy et al., 2014; Bahmani et al., 2014; Zhang et al., 2015; Makki-Szymkiewicza et al., 2015; Jha and Sivapullaiah, 2015). Microsilica and lime are two useful additives, which are broadly used to

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Notation

ANN	artificial neural network
BP-ANN	back propagation artificial neural network
CBR_{10}	California bearing ratio of samples compacted with 10 blow counts
CBR_{30}	California bearing ratio of samples compacted with 30 blow counts
CBR_{65}	California bearing ratio of samples compacted with 65 blow counts
CC	curing condition
CD	curing days
EPR	evolutionary polynomial regression
L	lime percentage
M	microsilica percentage
m	length of vector x_i
n	number of data sets
O_i	predicted values of *CBR*s and *UCS*
QA	quality assurance
QC	quality control
R^2	coefficient of determination
RMSE	root mean squared error
r_{ij}	strength of relationship between x_i and x_j
T_i	measured values of *CBR*s and *UCS*
UCS	unconfined compressive strength
X	data array of X in X-space
x_i	a vector with the length of *m* showing each element of array X
x_{ik}	each element of vector x_i

solve the material's swelling and strength problems (Ghorbani et al., 2015). Microsilica is a very fine dust of silica from a blast furnace generated during silicon metal production, which was previously discharged into the atmosphere before the mid-1970s (Kalkan, 2009). Moreover, microsilica is a carcinogenic material that is very dangerous to human health and the environment. Hence, instead of discharging the microsilica into the environment, it is advised that it be used in different projects. In the early seventies, factories had to collect and discard this dangerous material in landfills (Abd El-Aziz et al., 2004). Nowadays, this material, which is widely used in industry, is not a threat to the environment and is commonly used as a soil stabilizer (Ghorbani et al., 2015). However, the existence of an activator, such as lime, is essential for the participation of microsilica in pozzolanic reactions. Results of research have shown the positive effects of microsilica on the stabilization of problematic silty sands (Ghorbani et al., 2015). By mixing microsilica and lime in the presence of water, the pH of the environment increases and the active silica reacts with calcium hydroxide and forms calcium silicate hydrated gels (Demir and Baspinar, 2008; Lin et al., 2003; Tastan et al., 2011). Eqs. (1)–(3) show these reactions (Tastan et al., 2011).

$$\mathrm{CaO} + \mathrm{H_2O} = \mathrm{Ca(OH)_2} \tag{1}$$

$$\mathrm{Ca(OH)_2} = \mathrm{Ca^{2+}} + 2\mathrm{(OH)^-} \tag{2}$$

$$\mathrm{Ca^{2+}} + 2\mathrm{(OH)^-} + \mathrm{SiO_2} = \mathrm{CaO \cdot SiO_2} + \mathrm{H_2O} \tag{3}$$

In some cases, when a road is constructed over poor subgrade or problematic soil, ground improvement by means of mechanical or chemical stabilization is introduced to improve both the mechanical and the hydrological properties of the existing natural subgrade, to increase the load support capacity and subgrade stability and to limit volumetric changes due to the environment, and hence, to provide better short-term and long-term performances. In order to achieve these objectives, the required mix proportions and mixture properties must be quantified throughout a series of laboratory experiments. The ultimate goal of the mix design process is to assure that the mixture meets the optimum requirements with respect to engineering and economic viewpoints. In addition, other important parameters for any soil stabilization method (i.e., type and amount of stabilizing agents, moisture-density state of the mixture, mixing and compaction procedures, allowable delay time, required stiffness/strength at a given curing time and so on) must be specified prior to the construction.

Unconfined Compressive Strength (*UCS*) and California Bearing Ratio (*CBR*) tests are two measures for the strength of soil samples. Nevertheless, since the failure mechanism imposed by these two tests is different, they cannot be replaced by each other. In this regard, *CBR* tests can only be used as a hint for engineers to decide about the quality of stabilized sub-grades and to classify the subgrade conditions for road projects, while *UCS* tests can be used as an index for the strength of stabilized soil and can be applied to the design and construction QA/QC practice of engineering projects. In addition, it is noteworthy that since the index and the physical properties of samples (e.g., the states of density and moisture, the amounts of coarse and fine contents, the Atterberg's limits, etc.) can affect the *CBR*, it can be used as an effective parameter in the determination process of *UCS*. Indeed, *CBR* (as a parameter, which stands for the engineering and physical properties of samples, and controls the hydration process and chemical reactions) can be assumed as an input for the prediction of *UCS*.

It is also noteworthy that with exceptions and cautions, a more direct strength assessment, the Unconfined Compression Strength (*UCS*) test, a conventional compressive