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Prediction of the Uniaxial Compressive Strength of a Greywacke by Fuzzy Inference System

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Abstract. Rock engineering projects require the uniaxial compressive strength of intact rock. High quality core samples are needed for the application of uniaxial compressive strength in laboratory. In this study, to establish some predictive models taking into consideration multiple regression techniques and fuzzy inference system is aimed. Ankara greywackes is selected as the material, because of its highly problematic nature as mentioned by many previous researchers. For this purpose, a series of rock mechanics tests were carried out, and uniaxial compressive strength, point load index, block punch index, unit weight, apparent porosity, water absorption by weight, P-wave velocity, Schmidt hardness and tensile strength of greywacke were obtained. Using the obtained results, two prediction models were constructed to predict the uniaxial compressive strength of selected greywacke. The values account for and root mean square error indices were calculated as 41.49% and 15.62 the multiple regression model; 81.24% and 13.06 for the fuzzy inference system. As a result, these indices revealed that the prediction performances of the fuzzy model are higher than that of multiple regression equations.

Keywords: empirical relationships, fuzzy inference system, multiple regression, prediction, uniaxial compressive strength

1 Introduction

Indirect estimation of the mechanical parameters of thinly bedded and highly fractured rocks is one of the major study areas of the engineering geologists and rock engineers. The highly fractured greywackes crop out Ankara, capital city of Turkey. A dense urbanisation occurs and population rapidly grows in Ankara. For this reason, many engineering projects are planned and constructed, and the geomechanical properties of the greywackes are increasingly needed. Due to its problematic nature, the core samples required for the uniaxial compressive strength can not extracted easily. The purpose of the present study is to establish regression and fuzzy models for predicting the uniaxial compressive strength of the Ankara greywackes, using some simple index tests such as point load, block punch index etc., because these tests require relatively small samples.

2 Sampling and Test Results

A reliable prediction model requires sufficient number and high quality data. In this study, an extensive field study was performed to select the blocks to be used in the standard core preparation workings in laboratory. Although approximately 200 blocks were collected from the field, only 82 sample sets for the rock mechanics tests were obtained in accordance with the procedures given by ISRM (1981), ISRM (1985) and Ulusay et al. (2001). Each data set includes uniaxial compressive strength, point load index, block punch index, unit weight, and apparent porosity, water absorption by weight, P-wave velocity, Schmidt hardness, and tensile strength.

3 Prediction Models

To predict the uniaxial compressive strength (UCS) of the Ankara greywacke, some prediction models were established based on multiple regressions and fuzzy inference system.

3.1 Regression Analyses

The simple regression analyses were performed to define type of the relation between dependent and independent parameters by considering linear, power, logarithmic, exponential functions. The relations were given in Table 2 with their

Table 1. The summary of the test results (number of data=82).

Statistical Parameter	Unit Weight	Water Absoption by Weight	Apparent Porosity	P-Wave Velocity	Schmidt Hardness	Block Punch Index	Point Load Index	Tensile Strength	Uniaxial Compressive Strength
Minimum	23.6 kN/m^3	0.2%	0.57%	2463.1m/s	29	4.0MPa	0.46 MPa	2.8 MPa	17.5 MPa
Maximum	27.6 kN/m^3	3.3%	7.96%	5800 m/s	53	32.7 MPa	6.34 MPa	13.7 MPa	156.0 MPa
Average	25.4 kN/m^3	1.03%	2.60%	4321.1 m/s	40	16.5 MPa	3.12 MPa	6.7 MPa	58.5 MPa
St.Deviation	0.92	0.67	1.61	1.61	6.63	6.93	1.46	1.46	26.5

Table 2. Correlation coefficients of the simple regressions between the uniaxial compressive strength and the other parameters.

Independent Variable	Uniaxial Compressive strength, UCS Number of data: 82 Type of function			
	Linear	Logarithmic	Power	Exponential
Unit Weight	0.26	0.26	0.27	0.27
Water Absorption by Weight	-0.42	-0.37	-0.44	-0.49
Apparent Porosity	-0.42	-0.37	-0.44	-0.49
P-Wave Velocity	0.52	0.52	0.56	0.56
Schmidt Hardness	0.50	0.51	0.52	0.51
Block Punch Index	0.71*	0.67*	0.71*	0.71*
Point Load Index	0.64*	0.57	0.58	0.63*
Tensile Strength	0.65*	0.62*	0.62*	0.62*

*Statistically significant at P=0.05 level

correlation of coefficients. The UCS values exhibit much more meaningful relations with block punch index (BPI), point load ($Is_{(50)}$) and tensile strength (σ_t) than the other parameters. In addition, the relationships between the uniaxial compressive strength and unit weight, P-wave velocity, Schmidt hardness are not meaningful, although many previous researchers (Sachpazis, 1990; Grasso et al., 1992; Gokceoglu, 1996) determined the relationships with high correlation coefficients. Rock type is an important consideration for the empirical relation between the Schmidt hammer rebound number and compressive strength values (Cargill and Shakoor, 1990). The P-wave velocity (Vp) was also used in the multiple regression analyses by considering slightly higher correlation coefficient among the other parameters. A multiple regression analysis was performed between dependent parameter (UCS) and independent parameters (Vp, BPI, $Is_{(50)}$ and σ_t). Consequently, the following relation was obtained:

$$UCS=0.0065\ Vp + 1.468\ BPI + 4.094\ Is_{(50)} + 2.418\ \sigma_t - 225 \quad (r=0.80) \qquad (3.1)$$

The crosscheck between the measured and the predicted values was illustrated in Figure 1. As can be seen in Figure 1, the multiple prediction model is more reliable than the simple regression equations. In addition, the determination of P-wave velocity, block punch index, tensile strength, and point load index requires relatively small samples when compared with the uniaxial compressive tests. For this reason, this predictive model based on multiple regression can be used in practical engineering purposes.

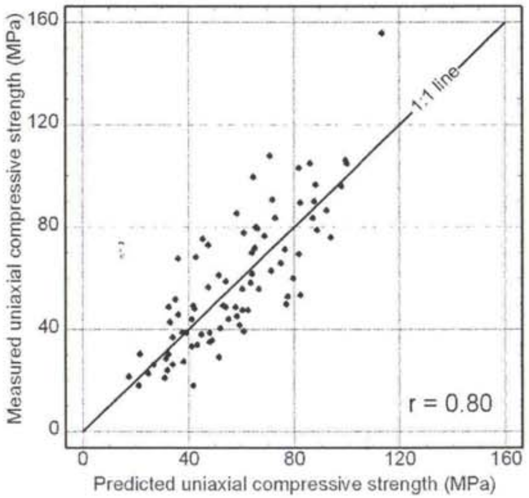

Fig. 1. The cross-check between the measured and the predicted uniaxial compressive strength values predicted from the multiple regression (Eq. 3.1).

4 Fuzzy Inference System

In the last years, the fuzzy inference systems began to be used in the areas of rock mechanics and engineering geology (e.g. Alvares Grima and Babuska, 1999; Finol et al., 2001; Gokceoglu, 2002; Sonmez et al., 2003 etc.). In this study, the Mamdani fuzzy inference system was employed to construct a prediction model for the uniaxial compressive strength of the Ankara greywackes. The model includes four inputs (P-wave velocity, block punch index, point load index, tensile strength) and one output (uniaxial compressive strength) (Figure 2). In this study, the fuzzy sets of the membership functions were obtained from the relationships between the inputs and the output. The graphical illustrations of the membership function are given in Figure 3 for the input parameters and Figure 4 for the output parameter. As shown in both Figure 3 and Figure 4, inputs and output parameters are normalized considering the highest values of them. Therefore, the range of both inputs and output vary between zero and one. The other component of a fuzzy inference system is the "if-then" rules. Total number of the linguistic rules of the fuzzy inference system constructed in this study is 53. Due to the calculation simplicity, the centroid method is considered for the defuzzification process. A typical example of the constructed fuzzy model with used if-then rules for given input values is illustrated in Figure 5. In other words, 5 of 53 if-then rules are used for the input values given in the example. The cross-corelations between predicted and measured data were applied (Figure 6) and the strong coefficient of correlation of 0.82 was obtained.

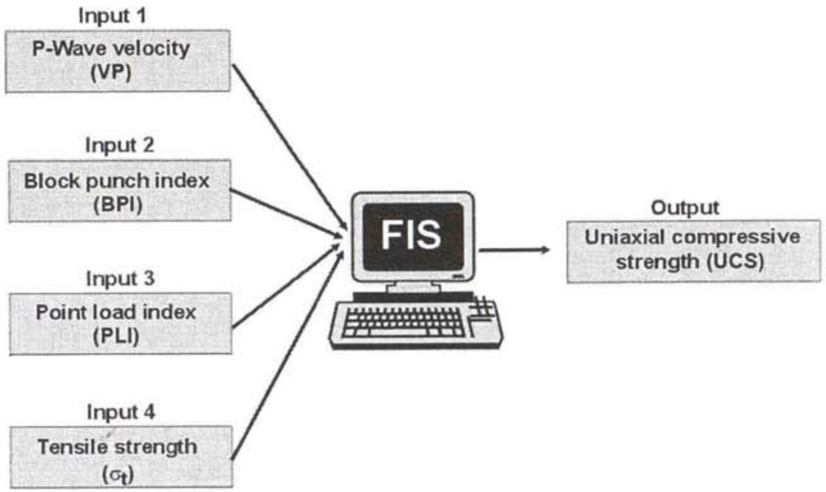

Fig. 2. The schematic illustration of the fuzzy inference model.

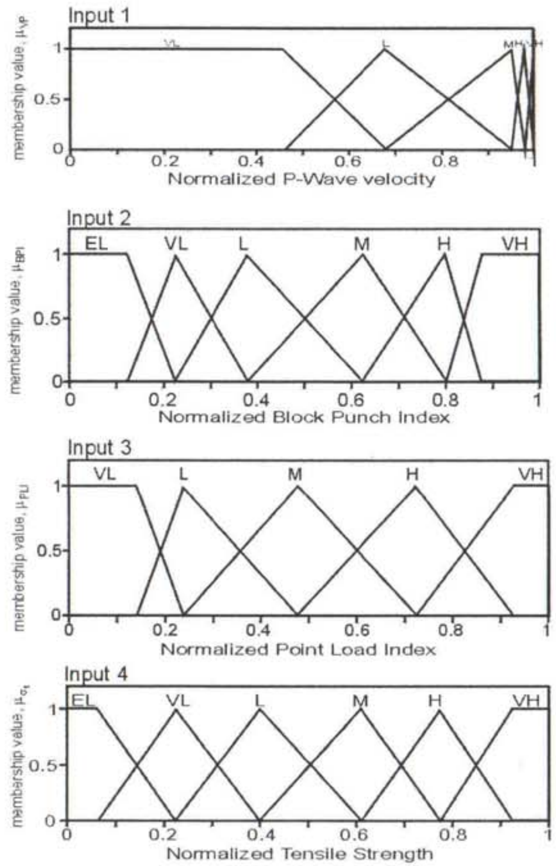

Fig. 3. The membership functions of the normalized input parameters.

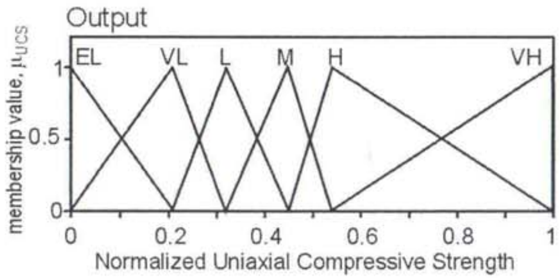

Fig. 4. The membership functions of the normalized output parameter.

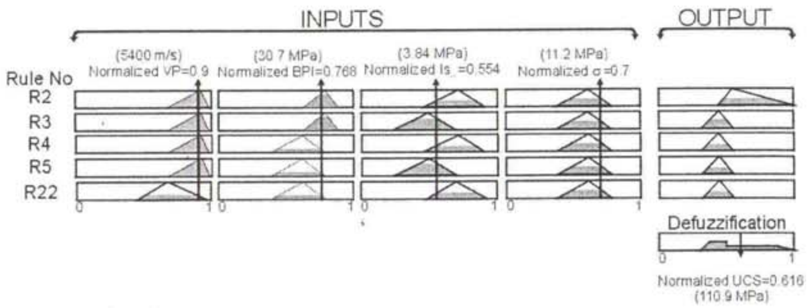

Fig. 5. An example calculation for the fuzzy inference model.

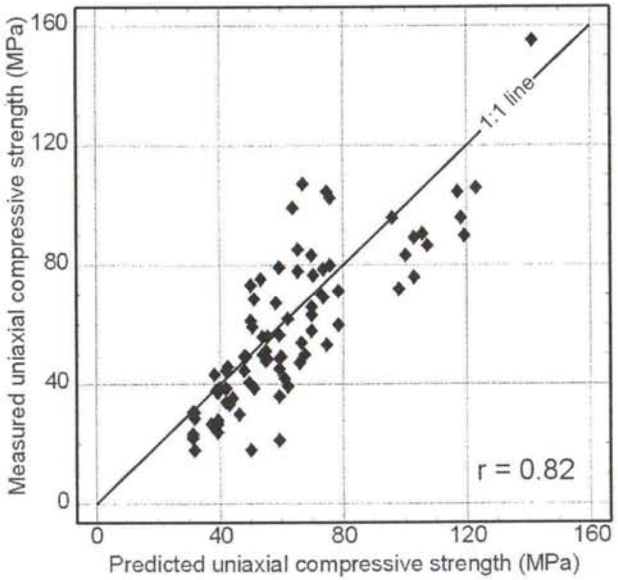

Fig. 6. The relation between the measured and the predicted uniaxial compressive strength values from the fuzzy inference system.

5 Assessment of the Prediction Performance

The variance account for (VAF) and the root mean square error (RMSE) indices were calculated to assess the prediction performance of the models developed in the study as employed by Alvarez Grima and Babuška (1999), Finol et al. (2001), Gokceoglu (2002) and Nefeslioglu et al. (2003). The calculated indices are given

in Table 3. If the VAF is 100 and RMSE is 0, the model will be excellent. When making a comparison between fuzzy model and multiple regression equation, the prediction performance of the fuzzy model is higher than that of the multiple regression model, taking into consideration the performance indices (see Table 3).

Table 3. The values account for (VAF) and the root mean square error (RMSE) indices of the prediction models.

Model	VAF (%)	RMSE
Multiple Regression	41.49	15.62
Fuzzy Inference System	81.24	13.06

6 Results and Conclusions

In this study, a multiple regression equation for the prediction of the uniaxial compressive strength were developed. In addition, a fuzzy inference system having four inputs, one output and 53 linguistic rules was developed for the same purpose. To assess the prediction capacities of the developed models, the values account for (VAF) and the root mean square error (RMSE) indices were obtained as 41.49% and 15.62 the multiple regression model; 81.24% and 13.06 for the fuzzy inference system. The fuzzy based model exhibited the most reliable predictions when compared with the simple and multiple regression models. The developed models have a sufficient capacity to use in practical purposes.

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Self-healing of Fractures around Radioactive Waste Disposal in Clay Formations

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Abstract. The feasibility of storing radioactive waste in low permeable clays is studied extensively nowadays. Fracturing and healing of fractures is of great importance as they determine to a large extent the buffering properties for the transport of radionuclides. The research presented studies micro-fracturing and healing by recording acoustic emission in triaxial loading laboratory tests. The results show that increasing time delays between two successive loading cycles has an increasing effect on the recorded acoustic pattern. Future simulations with a boundary element code might enable to link the results closer to the mechanisms of micro-fracturing and self-healing.

Keywords: Self-healing of fractures, clay, acoustic emission, Kaiser-effect.

1 Introduction

Clay is one of the possible host rock formations for the underground geological disposal of radioactive waste. At several research sites in Europe, the feasibility of clay as a natural barrier for this type of storage is investigated. Around an excavation at least locally, stresses are redistributed resulting in possible fracturing at different scales (Mertens et al. 2002). The deterioration in permeability and strength due to these induced fractures imply the overall performance to decrease. However, under a triaxial stress state, these fractures might close over time and possibly be healed again. It is important that these mechanisms linked to fracturing and healing are well understood in order to predict the transport of radionuclides accurately over long time periods. At the KULeuven, the occurrence and possible healing of micro-cracks is studied by means of acoustic emission (AE) during laboratory tests. This research is done within the framework of the EU-SELFRAC project and examines the former phenomena in particular in Boom Clay from the Mol research site (B) and Opalinus Clay from the Mont Terri research site (CH). Other research groups within this project examine the evolution of porosity and permeability. The tertiary Boom clay is primarily a mixture of illite, smectite and kaolinite with some pyrite inclusions (Wouters and Vandenberghe, 1994). The laboratory samples are excavated at a depth of around 200m during the recent construction of the extension of the underground laboratory. The