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Prediction of specific cutting energy in natural stone cutting processes using the neuro-fuzzy methodology

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ABSTRACT

Specific cutting energy (SE_{cut}) values are used for the determination of energy requirements of the stone cutting process and are thus useful in predicting the cost and production schedule. In this study, adaptive hybrid intelligence (AHI) techniques were employed to develop SE_{cut} prediction models based on 40 different natural building stones in nineteen different stone processing plants. The feed rate, depth of cut, which are cutting process working parameters, and uniaxial compressive strength, bending strength and point load strength of the rock to be cut which constitute rock physico-mechanical properties were used as the input parameters in the development of SE_{cut} prediction models. The AHI techniques included Adaptive Neuro-Fuzzy Inference System (ANFIS), Dynamic Evolving Neuro-Fuzzy Inference System (DENFIS), and Evolving Fuzzy Neural Networks (EFuNN). Among the AHI techniques, ANFIS gave the best SE_{cut} prediction accuracy. The results also showed that it is possible to predict specific cutting energy of natural stone cutting operations with higher accuracy ($R^2=0.95$) with the developed ANFIS prediction models using depth of cut, feed rate and uniaxial compressive strength values of natural building stones.

1. Introduction

Developments in artificial intelligence and computer sciences make it possible to model the problems in earth science research with increasing reliability and accuracy. Evaluation of the behaviors observed in nature together with the modeling results has strengthened the empirical approaches. This explains why the applications of artificial intelligence (expert systems, artificial neural networks, etc.) are preferred today [1]. Artificial intelligence (AI) based models are a form of systematic human thought adapted to the machines. One of the most important features of AI based models is that the model has the ability to make inference for different situations with the experience gained through analyzing the information introduced to them. Thus, artificial intelligence based models can be adapted to different situations easily and quickly. Because of these capabilities, along with rapid developments in computer technology, the AI based models are widely used in stone cutting processes and other areas related to rock engineering [2–12].

There are several studies reported in the literature on the investigation of the natural stone cutting process. In most of these studies, the modeling of the actual cutting process is directed by the laboratory-scale studies. The natural stone sawing process is a complex system influenced by a variety of factors [13]. Sawing mechanism and structural properties of diamond impregnated circular saws were investigated by Büttner [14] and Konstanty [15] in their earlier studies. They evaluated the factors that affect the cutting process and explained the mechanism involved. Saw blade performance was studied by Jennigs and Wright [16] determined the optimum choice of diamond sawblades with respect to various factors that affect the saw blade performance. In summary, the mode of cutting, peripheral speed, machine conditions, properties of the rock being cut, and operator skills are among the most important factors that affect the performance and therefore the service life of the sawblade.

Ersoy and Atici [17] in their laboratory-scale study examined the effects of operating and the rock parameters on the performance of the diamond saws. They described the relationships among the cutting variables. Their results indicated that the diamond circular saw performances were significantly affected by the cutting variables. They emphasized that the specific cutting energy was a very significant measure of cutting performance because it indicated the amount of energy required to cut the rock. Regression models for the prediction of slab production of carbonate rocks were studied by Kahraman et al. [18], and they

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investigated, in particular, the models developed for large diameter circular saws. Models that take into account the Schmidt Hammer value, point load strength, impact strength, and *P*-wave velocity were favored according to their study with respect to rapid estimation of the sawability of carbonate rocks. In another study by Ersoy and Atici [19], a theoretical model for the explanation of the relationship between the SE_{cut} of the sawblade operating parameters and rock properties was proposed. It was supported by the laboratory tests that were conducted on three groups of rocks with the help of three types of diamond disk saws with various feed rates and cutting depths at constant peripheral speed. They used bending strength, Schmidt rebound hardness, and wear factor as their model parameters.

The SE_{cut} is an important factor for specifying the mechanical performance of a machine and its basic indicator of the cutting efficiency and performance. It indicates the amount of energy required to cut the unit volume of rock. Cutting energy is often used as a parameter for monitoring the stone cutting process [20–22].

Thus, in almost all the studies reported in the literature focusing on natural stone cutting processes, the data were obtained from laboratory tests. However, in this study the data is obtained from in-situ cutting conditions. Also, there is no study using adaptive hybrid intelligence (AHI) techniques such as DENFIS, EFuNN concerning the natural stone cutting process in the current literature. In this study AHI based models were used for estimating the values of SE_{cut} based on optimal set of inputs.

2. Specific cutting energy in natural stone sawing process: theory

Specific cutting energy is defined as the energy required to remove a specific volume of workpiece material [23]. Generally, mechanical efficiency is at a maximum when specific energy is at a minimum [24]. Specific cutting energy values are affected by several parameters. Generally, specific cutting energy is a function of the machine working parameters, the properties of the blade used, and the mineralogical–petrographical and physico-mechanical properties of the rock being cut. The specific cutting energy can be calculated using

$$SE_{cut} = E_t / Q \quad (1)$$

where SE_{cut} is the specific cutting energy (J/mm^3), E_t is the total energy consumed during cutting (Ws), and Q is the volume of the channel cut in the stone by the saw during cutting (mm^3).

The SE_{cut} value for each cut can be calculated as the amount of the energy found divided by the volume of the channel cut by the sawblade on the stone:

$$SE_{cut} = Pt / V_f t\, dw \quad (2)$$

where P is the average power consumption during cutting (W), t is the cutting time (s), V_f is the feed rate (m/min), d is depth of cut (mm), and w is the average width of cutting zone (mm).

3. Machine studies

Block cutters are widely used in natural stone processing plants because of low initial investment costs and the opportunity to cut relatively small size and irregular-shaped blocks of natural stones. Knowing the sawability properties of natural stones (cut by block-cutters) is very important in terms of planning the production and estimating the cost of the natural stone cutting process.

This study was carried out on 40 different natural stones in nineteen different stone processing plants and was focused on the sawability of carbonate rocks (cut with the use of large-diameter circular diamond saws in the block cutter) marketed in Turkey and around the world.

The data collection phase of the study in the stone processing plants included two parts: the electrical data obtained from the electrical panel of the block cutter and the time measurement and the data obtained from the block during and at the end of sawing.

To determine the amount of energy consumed during the cutting, electrical data from the cutting process is needed. To do this a digital power meter is located on the power line that transfers electricity to the block cutter vertical sawing disc in the block cutter electrical panel. During the time that the block cutter cut along the block, the data was obtained through clamp sensors and voltage test leads. The cuts were repeated four times. The electrical parameters in the cutting process, such as the active power, apparent power, reactive energy, power factor, current and voltage that passed through each cut were recorded for analysis by the computer with the digital mobile power meter.

The cutting depth, cutting length, the cutting channel width cut on the block by the sawblade (a total of 40 measurements at the beginning, in the middle and at the end of the cutting), and the time spent on each cutting were measured and recorded. Based on the collected data, basic descriptive statistics of the SE_{cut} values calculated via the cutting depths and the feed rates measured are provided in Table 1.

4. Laboratory studies

In order to keep the range wide in choosing natural building stone to be analyzed in terms of sawability, it was important to choose rocks with different mineralogical, petrographical, and physico-mechanical properties. The mineralogical, petrographical, and physico-mechanical properties of the stone samples chosen for this purpose were determined through laboratory investigation and were intended to be associated with the sawability properties.

The mineralogical and petrographical definitions of the stones among thin section samples prepared for each stone sample were provided based on the known trade names in this study. Folk's [25] classification was taken as the reference in classifying the stones during the application of the modal analysis method.

4.1. Uniaxial compressive strength tests

Uniaxial compression tests were performed on cubic samples, which had a dimension of 70 mm at a 0.6 MPa/s constant loading rate. Tests were carried out according to Turkish standard TS EN 1936 [26].

Table 1
Basic descriptive statistics of the all data.

	UCS (MPa)	*BS (MPa)*	*PLI (MPa)*	*SH (MPa)*	*BTS (MPa)*	N_R	*P-Wave (m/s)*	Water Ab. (%)	Density (g/cm^3)	Porosity (%)	SE_{cut} (J/mm^3)
Min	24.50	9.12	3.79	28.15	2.55	54.20	3235.98	0.01	2.35	0.03	0.56
Max	192.98	22.71	11.45	65.80	8.06	71.00	6224.58	3.35	2.73	7.88	3.32
Mean	89.44	15.47	6.81	48.20	4.50	64.75	5293.11	0.71	2.62	1.77	1.43
St. deviation	38.33	3.74	1.68	10.60	1.12	4.35	604.66	0.81	0.12	1.94	0.58