

Multicriteria decision-making analysis based methodology for predicting carbonate rocks' uniaxial compressive strength

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ABSTRACT

Uniaxial compressive strength (UCS) deals with materials' ability to withstand axially-directed pushing forces and especially considered to be rock materials' most important mechanical properties. However, the UCS test is an expensive, very time-consuming test to perform in the laboratory and requires high-quality core samples having regular geometry. Empirical equations were thus proposed for predicting UCS as a function of rocks' index properties. Analytical hierarchy process and multiple regression analysis based methodology were used (as opposed to traditional linear regression methods) on data-sets obtained from carbonate rocks in NE Turkey. Limestone samples ranging from Devonian to late Cretaceous ages were chosen; travertine-onyx samples were selected from morphological environments considering their surface environmental conditions. Test results from experiments carried out on about 250 carbonate rock samples were used in deriving the model. While the hierarchy model focused on determining the most important index properties affecting on UCS, regression analysis established meaningful relationships between UCS and index properties; 0.85 and 0.83 positive coefficient correlations between the variables were determined by regression analysis. The methodology provided an appropriate alternative to quantitative estimation of UCS and avoided the need for tedious and time consuming laboratory testing.

Keywords: Compressive strength, empirical equations, carbonate rock, analytical hierarchy.

RESUMEN

La resistencia a la compresión uniaxial (RCU) trata con la capacidad de los materiales para soportar fuerzas empujantes dirigidas axialmente y, especialmente, es considerada ser uno de las más importantes propiedades mecánicas de los materiales rocosos. Sin embargo, una prueba de RCU es costosa, lleva mucho tiempo para hacerlo en el laboratorio y requiere muestras de núcleos de alta calidad que tienen una geometría regular.

Por lo tanto, ecuaciones empíricas fueron propuestas para la predicción de RCU como una función de las propiedades índice de las rocas. Las metodologías de proceso analítico jerárquico (PAJ) y análisis de regresión múltiple fueron utilizados (en vez de los métodos tradicionales de regresión lineal) en conjuntos de datos obtenidos de las rocas carbonatadas en el noreste de Turquía. Muestras de rocas calizas que van desde el Devónico hasta finales del Cretácico fueron escogidas; muestras de travertino y ónix fueron seleccionadas de ambientes morfológicos teniendo en cuenta sus condiciones ambientales de superficie.

Los resultados de los experimentos llevados a cabo en alrededor de 250 muestras de rocas carbonatadas fueron utilizados para derivar un modelo. Mientras que el modelo de jerarquía se centró en determinar las propiedades índice más importantes afectados por la RCU, el análisis de regresión establece relaciones significativas entre la RCU y las propiedades del índice; coeficientes de correlación positivas de 0,85 y 0,83 fueron determinadas por análisis de regresión entre las variables. La metodología proporciona una alternativa adecuada para la estimación cuantitativa de la RCU y evita la necesidad de realizar pruebas del laboratorio las cuales son tediosas y dispendiosas.

Palabras claves: Resistencia a la compresión, ecuaciones empíricas, rocas carbonatadas, jerarquía analítica.

Record

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Introduction

Intact rocks' uniaxial compressive strength (UCS) is the main parameter used for almost all rock mechanical studies in most civil, geological and mining projects (Bieniawski 1974; Cargill and Shakoor 1990); however, regular geometry, high-quality core samples are necessary for determining UCS. Standard cores cannot always be extracted from weak, highly-fractured, thinly-bedded, foliated rocks. This test is thus expensive, time-consuming and requires well-prepared rock samples. Recent trends in estimating UCS from simple laboratory index tests has been improved to overcome such difficulties, and simple prediction models have become attractive for engineering geologists using non-destructive and easily-applied techniques such as rocks' ultrasonic wave velocity (UWV) and index properties. Many

attempts have been made to predict intact rocks' UCS (Kahraman 2001; Katz *et al.*, 2000; Koncagul and Santi 1999; Chau and Wong 1996). Some researchers have found that sound velocity is closely related to rock properties (Gaviglio 1989; Chang *et al.*, 2006; Yalçınalp *et al.*, 2008; Babacan *et al.*, 2009; Moradian and Behnia, 2009) whilst other have correlated UCS with index properties such as porosity, density and UWV (Ramana and Venkatarayana 1973; Yasar and Erdogan 2004; Kanik 2010).

Simple statistical methods-based multiple regression techniques have been used to establish predictive models; new techniques such as artificial neural networks and fuzzy inference systems have been used for developing predictive models for estimating the required parameters during recent years (Grima and Babuska 1999; Kayabasi *et al.*, 2002, Gokceoglu and Zorlu 2004; Sonmez *et al.*, 2003; Karakus and Tutmez 2006; Deh-

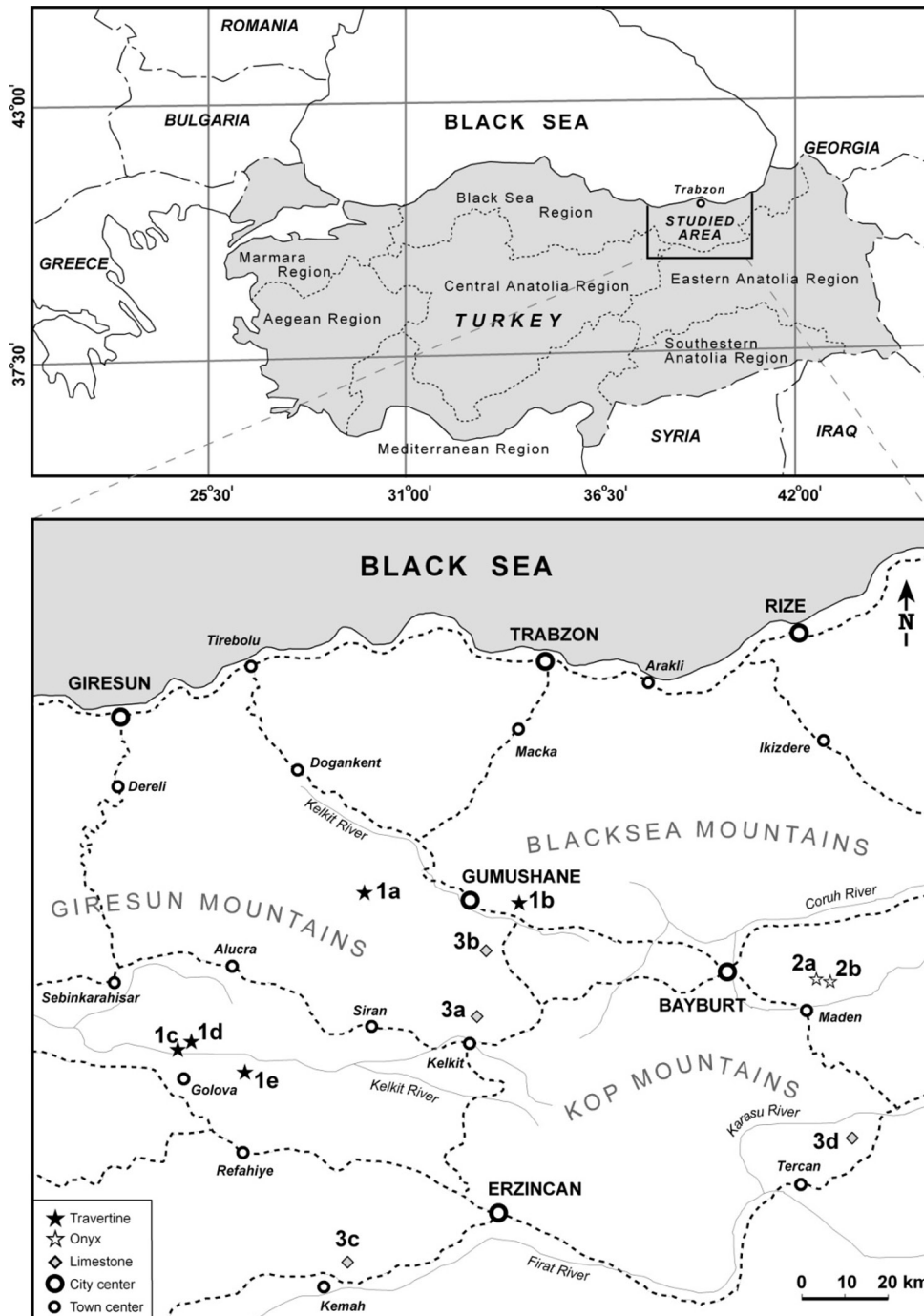


Figure 1. Map showing the location of the area being studied.

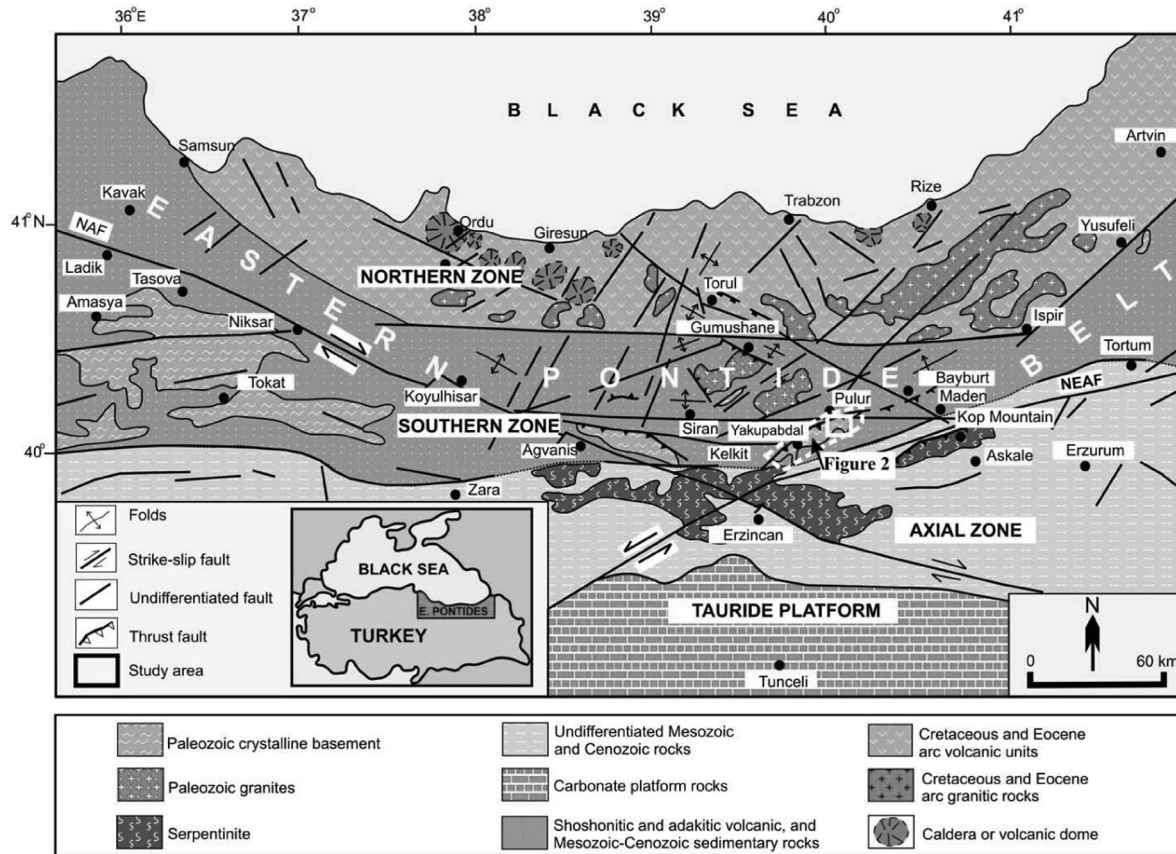


Figure 2. Main tectonic units and zones in the Eastern Pontides. NAF: North Anatolian Fault; NEAF: Northeast Anatolian Fault (Eyüboğlu 2006).

ghan *et al.*, 2010, Yagiz *et al.*, 2011). Different evaluation methods have been developed to establish predictive models; such methods include linear vector approach, matrix method, fuzzy set theory, checklist methods, parametric ranking methods and multi criteria decision analysis based methodologies. Analytic hierarchy process (AHP), was developed as a type of multi-criteria analysis, to standardise multi-criteria decision-making (Saaty 1980). However, AHP uses a quantitative comparison method based on pair-wise comparisons of decision-making criteria, rather than utility and weighting functions. Many engineering geological projects have adopted such as approach (Cook *et al.*, 1984; Siddiqui *et al.*, 1996; Ersoy and Bulut 2009).

The paper presents multi-criteria decision-making and multiple regression analysis-based methodology for predicting UCS regarding carbonate rocks' index properties. The model is based on non-destructive and relatively easy to apply laboratory tests.

Research methodology

Sampling location and geology

The morphology of mountainous region being studied in north-eastern Turkey (Figure 1) consist of rough, irregular land having steep slopes and peaks reflecting the eastern Black Sea region's geology and tectonic features. The main morphological units (mainly faults and folds) have been shaped by structural elements in the region trending NE-SW. The region is drained by the Harşit and Çoruh rivers, forming the most significant fluvial system. Deep incision forms like v-shaped valleys are characterised by deep gorges and steep slopes in these drainage systems.

Turkey is located in the Alpine-Himalayan orogenic belt having the world's richest natural stone formations; it is the country having 5 billion tons of reserves and almost 35% of the world's natural stone reserves.

The eastern Black Sea region has rich potential in terms of the variety of carbonate-bearing rocks. The region has around 450 million tons natural stone reserves almost 70% of production today consists of travertine and limestone, the remaining 30% being volcanic rocks. The rock samples for this study were collected from 5000 km² in the southern zone of the eastern Pontides (NE Turkey). The Eastern Pontide Belt is a major metallogenetic province in the eastern Black Sea coastal region and forms a 500 km long and 100 km wide mountain chain along the Black Sea coast. The Eastern Pontides may be subdivided into northern and eastern zones on structural and lithological differences (Özsayar *et al.*, 1981; Okay and Sahintürk 1997). The northern zone is dominated by Late Cretaceous and Middle Eocene volcanic and volcanoclastic rocks, whereas pre-Late Cretaceous sedimentary rocks are widely exposed in the Southern Zone (Arslan *et al.*, 1997; Eyuboglu 2006; Sen 2007) (Figure 2).

The limestone samples were selected from pre-Late Cretaceous platform carbonates which are widely exposed in the area and Liassic-aged formations; travertine and onyx samples were selected from the Gümüşhane, Bayburt and Giresun area. Three rock types from ten rock formations were sampled and tested for this study. Table 1 gives the rock type, age, location and description of the samples.

Sample preparation and laboratory tests

Several carbonate rock samples were collected in this study to determine physical and strength properties. Seven oriented block samples for each group of carbonates were collected from the field for laboratory testing; each block was represented by at least ten core specimens. 225 NX-size core specimens having a 2.5:1 length to diameter ratio were prepared from the block samples. Rock samples were carefully inspected before testing, to obtain the most representative stone samples for performing laboratory tests.

UWV, unit weight, water absorption and content are the rock materials' most important index properties and they are often related to porosity. Porosity is the ratio of the non-solid volume to the total volume of material and it also describes how densely the material is packed. In the study, firstly unit weight, water content, apparent porosity and water absorption by weight were determined with respect to the description criteria of ISRM (1981). A Pundit Plus ultra-sonic pulse (USP) instrument giving more precise rock sample measurements and two 54 KHz transducers having piezoelectric properties were used in this study to calculate ultrasonic longitudinal wave velocity. The transducers were located parallel to the surface of the sample, transit time was measured and ultrasonic wave velocities were calculated from transit time.

UCS was determined for the study according to ISRM (1981) description criteria. Core surface flatness was supplied for the UCS test to obtain an even load distribution; specimens were loaded axially up to failure.

Establishing decision-making methods

Regression analysis includes any techniques for modelling and analysing several variables when the focus is on the relationship between a dependent variable and one or more independent variables (Freedman 2005). Multiple regression is aimed at learning more about the relationship between several independent or predictable variables and a dependent or criterion (Davis 1986). Regression analysis was used in this with analytic hierarchy process (AHP), a widely accepted decision making method. Constraints are compared to each other in AHP, to designate each variable's relative importance in accomplishing an overall goal. Numerical values were assigned to each pair of constraints using established guidelines and

a constrained matrix is built. The sum of each column within the matrix was then normalised and weighting was calculated. Mathematic formulation (simple additive weighting) was defined following an equation for calculating final grading values in multiple criteria problems (Saaty 1980);

$$v(y) = \sum_{j=1}^q w_j y_{ij} \quad (1)$$

where, $v(y)$ was area's suitability index, w was a criterion's weighting or importance factor of a, y was a criterion's degree or compliance level, i was the criterion number and q was the number of criteria.

Pairwise comparisons were used to determine each criterion's relative importance; AHP is based on such approach. Decision makers can quantify their opinions about the criteria magnitude by using a verbal scale when comparing pairs of criteria. The pairwise comparison matrix (PCM) constructed by decision-makers in the previous had to have the following attributes;

$$w_{ij} = w_{ji}^{-1} \quad (2)$$

The next step was to calculate the criteria's relative importance weighting implied by previous comparisons. Saaty (1980) proposed estimating PCM's right principal eigenvector which can be approximated using the geometric mean for each row of the PCM (by multiplying the elements in each row and then taking the n^{th} root, where n is the number of criteria). This mode is known as multiplicative AHP (Saaty and Millet 2000) and was used in the present work. The calculated geometric means were then normalised and relative importance weighting extracted.

Table 1. Location and general properties of the carbonate rocks.

Rock type	Rock description	Age	Location
1a. Travertine (28 samples)	Porous and soft White-pale cream in colour	Quaternary	Bahçecik (Gümüşhane)
1b. Travertine (25 samples)	Porous and soft Pale cream in colour	Quaternary	Kalecik (Gümüşhane)
1c. Travertine (25 samples)	Porous and soft White-pale cream in colour	Quaternary	Çamoluk (Giresun)
1d. Travertine (10 samples)	Compact and soft White-pale cream in colour	Quaternary	Çamoluk (Giresun)
1e. Travertine (13 samples)	Compact and soft White-pale cream in colour	Quaternary	Gölova (Giresun)
2a. Onyx (23 samples)	Compact and soft White-pale grey and cream in colour Contained cream colored band	Quaternary	Yaylapınar (Bayburt)
2b. Onyx (15 samples)	Compact and soft Light green, pale cream in colour Contained green colored band	Quaternary	Yaylapınar (Bayburt)
3a. Limestone (20 samples)	Hard and compact Light grey in colour Contained some micro fossils	L. Cretaceous Dogger-Malm	Kelkit (Gümüşhane)
3b. Limestone (24 samples)	Fractured and slightly metamorphosed Reddish in colour Contained a number of fossils	Liassic	Esenyurt (Gümüşhane)
3c. Limestone (20 samples)	Hard and compact Light grey and white in colour	Cretaceous Jurassic	Kemah (Erzincan)
3d. Limestone (20 samples)	Hard and slightly metamorphosed light Purple and white in colour Contained light brown colored band	Cretaceous Devonian	Tercan (Erzincan)

Table 2. Water absorption, water content and apparent porosity values of the rock groups studied.

Sample location and type	Water content (%)				Water absorption by weight (%)				Apparent porosity (%)			
	Max	Min	SD	Mean	Max	Min	SD	Mean	Max	Min	SD	Mean
Kalecik travertine (1a: 30 samples)	0.20	0.08	0.04	0.13	3.33	0.88	0.73	1.39	7.37	2.16	1.36	3.29
Bahçecik travertine (1b: 15 samples)	0.77	0.12	0.15	0.34	1.20	0.48	0.24	0.77	2.88	1.18	0.57	1.90
Çamoluk travertine (1c: 25 samples)	2.48	0.49	0.43	1.40	2.90	0.98	0.48	1.88	6.65	2.37	1.01	4.28
Çamoluk (2) (1d: 10 samples)	0.62	0.45	0.06	0.59	1.30	0.91	0.12	1.07	3.03	2.44	0.28	2.61
Gölova travertine (1e: 13 samples)	0.31	0.18	0.04	0.23	0.62	0.37	0.063	0.47	1.55	0.94	0.15	1.19
Bayburt onyx (2a and b: 21)	0.79	0.01	0.18	0.07	0.72	0.02	0.02	0.10	1.95	0.06	0.32	0.26
Kelkit limestone (3a: 12 samples)	0.06	0.03	0.01	0.05	0.18	0.13	0.01	0.15	0.48	0.34	0.04	0.40
Esenyurt limestone (3b: 15 samples)	0.46	0.04	0.09	0.14	0.31	0.06	0.07	0.19	0.08	0.16	0.19	0.51
Kemah limestone (3c: 21 samples)	0.14	0.01	0.03	0.03	0.07	0.02	0.01	0.04	0.18	0.05	0.03	0.11
Tercan limestone (3d: 25 samples)	0.09	0.01	0.01	0.06	0.12	0.04	0.02	0.09	0.31	0.12	0.05	0.24

Table 3. Unit weight, P wave velocity and UCS values for the rock groups being studied.

Sample location and type	Unit weight (kN/m ³) velocity (m/s)				P wave				UCS (MPa)			
	Max	Min	SD	Mean	Max	Min	SD	Mean	Max	Min	SD	Mean
Kalecik travertine (1a: 30 samples)	24.7	22.2	0.8	24.0	4541	3813	220	4050	65	34	8	53
Bahçecik travertine (1b: 15 samples)	25.1	24.1	0.3	24.6	5072	4091	297	4598	44	25	5	37
Çamoluk travertine (1c: 25 samples)	24.6	24.1	0.2	24.4	3693	3506	61	3590	44	30	5	38
Çamoluk (2) travertine (1d: 10 samples)	25.4	24.9	0.2	25.2	4727	3913	268	4323	43	39	1.2	41
Gölova travertine (1e: 13 samples)	29.2	22.2	0.9	25.0	5072	3813	374	4430	66	20	10	40
Bayburt onyx (2a and b: 21 samples)	27.4	26.5	0.3	27.1	6800	4121	805	5240	70	20	13	45
Kelkit limestone (3a: 12 samples)	27.1	26.8	0.1	27.0	6321	5988	98	6200	154	30	38	80
Esenyurt limestone (3b: 15 samples)	27.4	26.6	0.2	27.0	6103	5562	169	5760	117	40	24	70
Kemah limestone (3c: 21 samples)	27.1	26.8	0.1	27.0	6353	6127	59	6250	162	25	39	90
Tercan limestone (3d: 25 samples)	27.3	25.3	0.6	26.8	6057	4327	371	5414	101	79	9	85

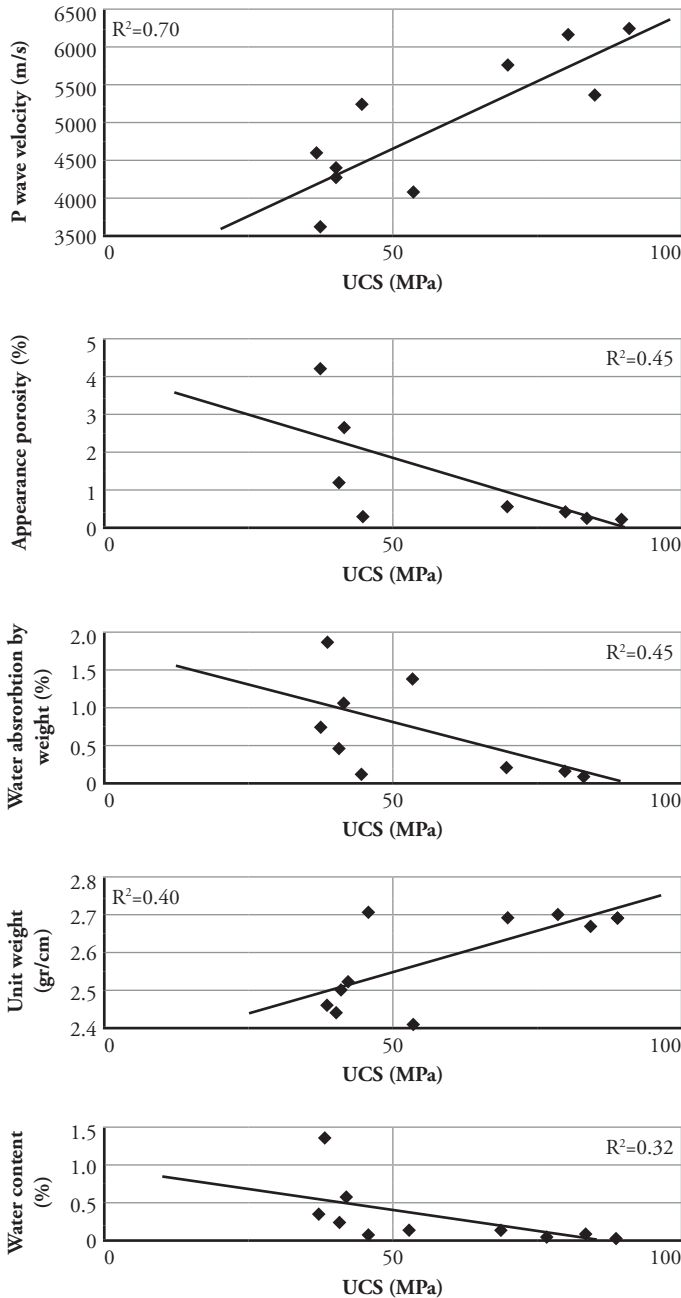


Figure 3. The empirical relationship between UCS and index parameters for different carbonate rock groups.

Integrating site selection criteria was based on multi-criteria assessment methods (Eastmen, 1995):

$$S_k = (\sum_i f_i * w_i \prod_j r_j)_k \tag{3}$$

$$S = \sum (S_k * w_k) \tag{4}$$

where, S_k was the land's suitability for landfill for objective k (priority groups), $(f_i)_k$ was factor i (discriminating features) for objective k , $(w_i)_k$ was the weighting for factor i (score given experimental studies) for objective k , $(r_j)_k$ was constraint j for objective k (value 0 or 1), S was multi-objective suitability and w_k was the weighting for objective k .

Results

The rocks' index and strength properties

UCS is an expensive and very time-consuming test. The core surfaces have to be ground down to make them parallel at a specified tolerance and a high load capacity loading frame is usually required. Thus, in the study, ten groups of carbonate rock samples were collected in the Southern Zone of the eastern Pontides (NE Turkey) to establish some relationships between UCS and index properties.

In the study the index and strength properties of the rocks were determined in accordance with ISRM (1981). The results of the laboratory studies are given Table 2 and Table 3. When taking into consideration the mean values of the water content, water absorption by weight, apparent porosity, P wave velocity and UCS value data, the highest values were observed for Erzincan limestone and the lowest values were observed for Gümüşhane travertines. However, the values of the UCS were obtained between 20 and 66 MPa for travertines, 20 and 70 MPa for onyx and 25 and 162 for different limestones. Depending on the mineral shapes, weathering features and occurrence of the microcracks, the UCS values varied in a wide range as found in the study.

Empirical relationship between index and strength properties

Rock materials' uniaxial compressive strength greatly depends on their index properties such as porosity, water content, water absorption and mineral composition. P wave velocity and porosity are the most preferred properties for predicting UCS amongst such properties (Sachpazis 1990; Tugrul and Zarif 1999; Palchik 1999).

Regression analysis is usually preferred for establishing statistical relationships between different variables. Relationship intensity of between variables is defined by regression values and correlation coefficients; explanatory variables must thus be weighted regarding dependent variables before mul-

Table 4. Pairwise comparison matrix and relative importance weighting for index properties.

	A	B	C	D	E	Eigenvector	Weighting
A	1	2	3	3	4	3.23	0.45
B	1/2	1	2	3	3	2.34	0.33
C	1/3	1/2	1	2	3	0.73	0.10
D	1/3	1/3	1/2	1	2	0.60	0.08
E	1/4	1/3	1/3	1/2	1	0.30	0.04

A: ultrasonic wave velocity, B: apparent porosity, C: water absorption by weight, D: water content, E: unit weight

1: equal importance, 2: weak or slight

(two parameters contributed equally to the objective)

3: moderate importance, 4: moderate plus

Experience and/or analysis slightly favoured one parameter over another

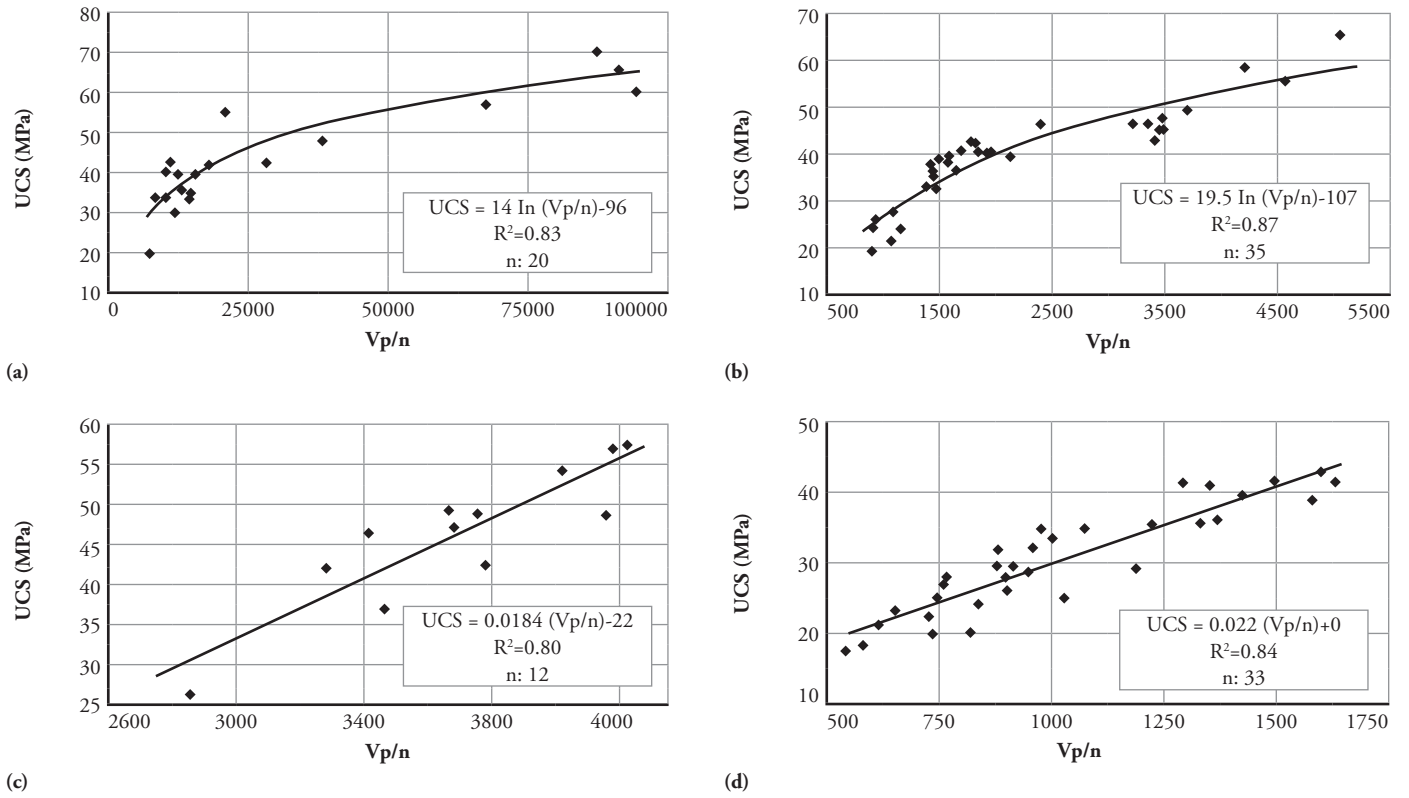


Figure 4. The empirical relationship between UCS and Vp/n for different travertines and onyx (a: Bayburt onyx, b: Bahçecik and Kalecik, c: Çamoluk and d: Gölova travertines).

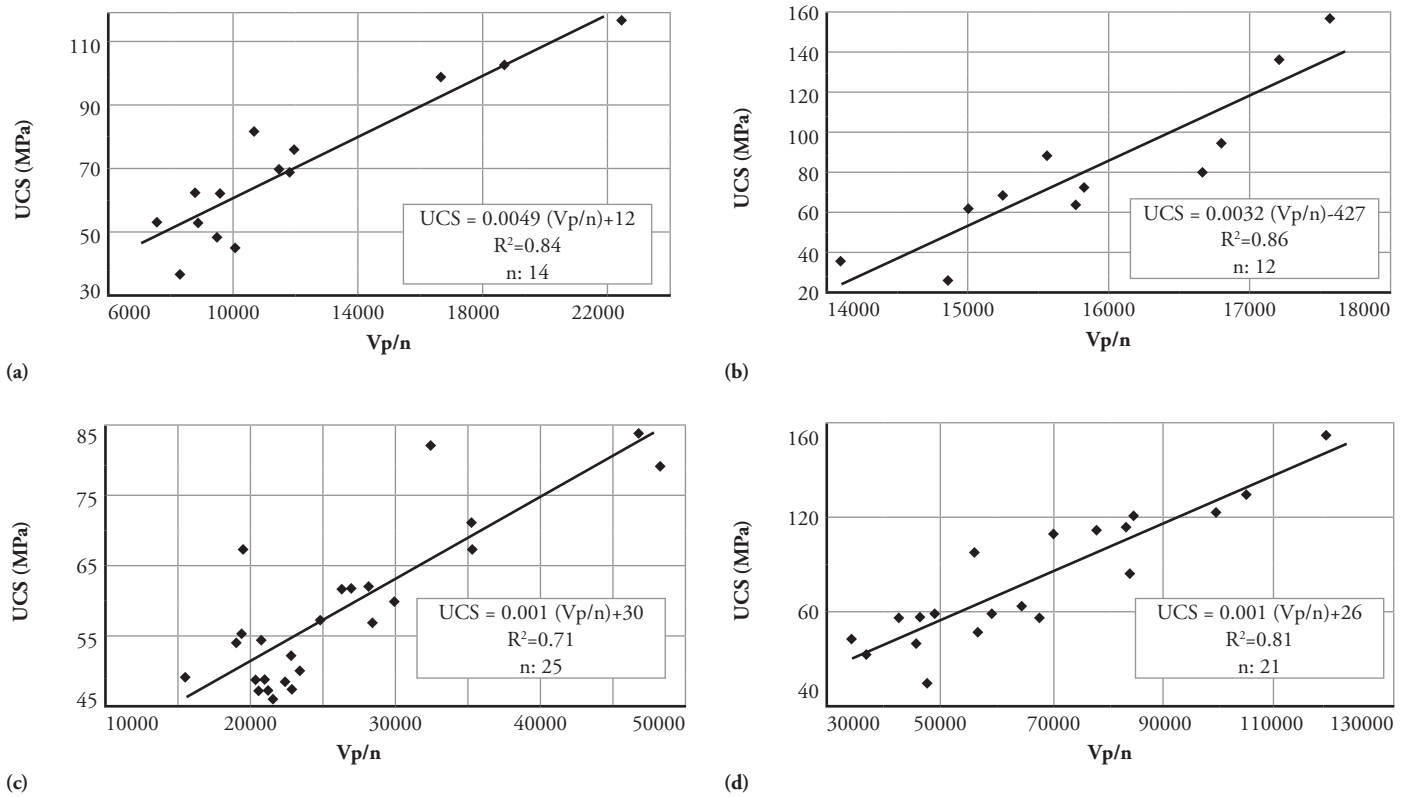


Figure 5. The empirical relationship between UCS and Vp/n for the different limestones (a: Esenyurt, b: Kelkit, c: Tercan and d: Kemah).

Table 5. The formulas used for estimating UCS in this study .

Rock description	Formulas	R ²
Onyx (21 samples)	UCS= 14 ln (Vp/n) - 96	83
Travertine (76 samples)	UCS= 15 ln (Vp/n) - 73	86
Limestone (60 samples)	UCS= 0.0009 (Vp/n) + 38	83

multiple regression analysis to establish an empirical model. AHP used the data obtained from linear regression analysis results concerning ten rock groups (Table 1 and Figure 3) to decide which material properties should be selected as explanatory variables from rock materials' index properties.

This represents a tool which reduces time and the cost involved in many engineering models. Table 4 lists the priority vectors for all criteria; relative importance weightings are included in the final column of this table. AHP parameters are also shown in the table, indicating that the judgments (and therefore final relative importance weightings) seemed to be reasonable. The method needed a scale of numbers indicating how many times more important or dominant one element was over another

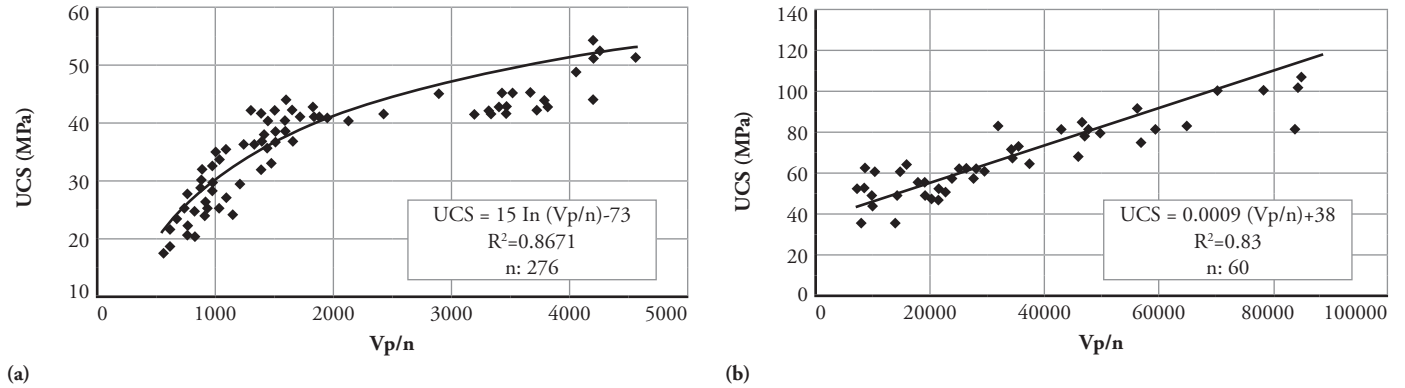


Figure 6. The empirical relationship between UCS and Vp/n for all travertine (a) and limestone (b) samples.

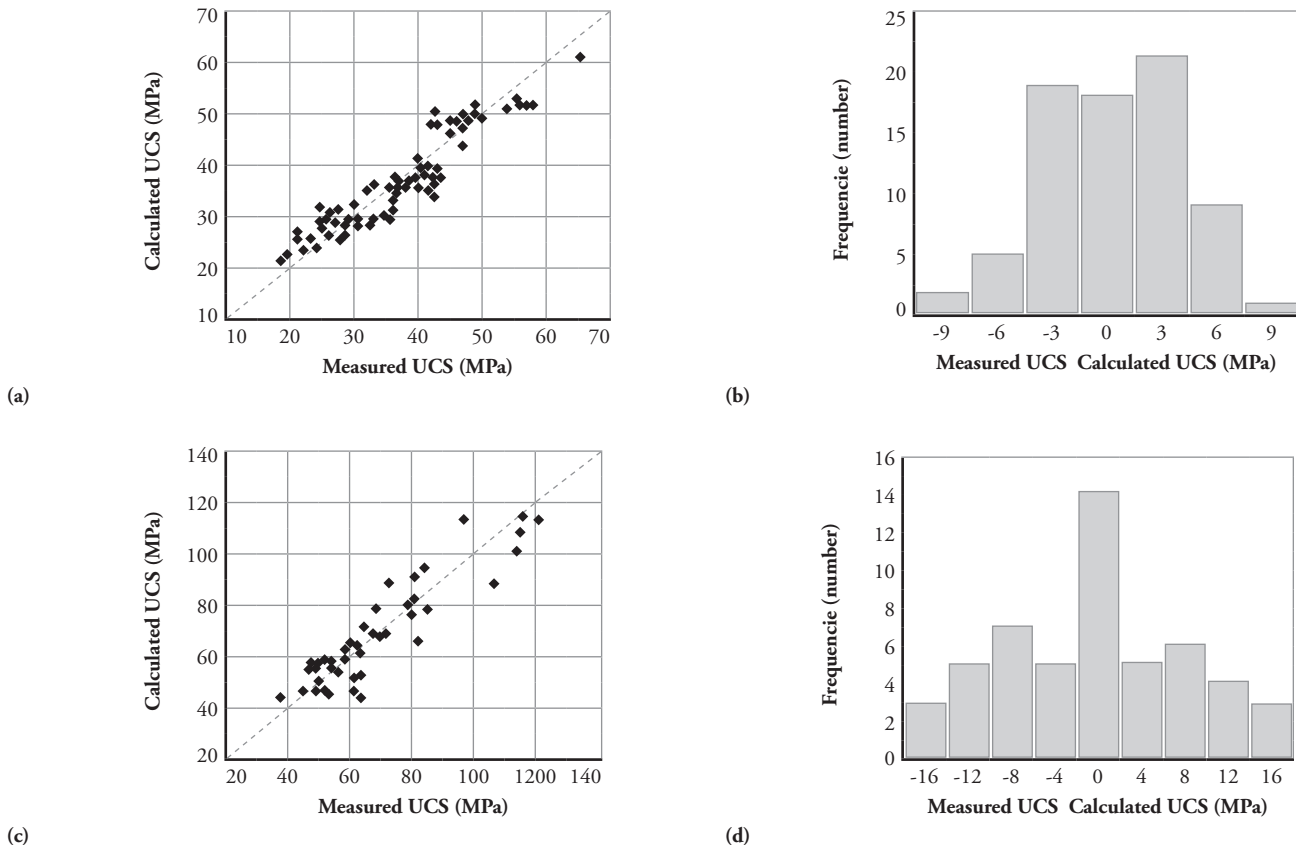


Figure 7. Line-scatter plot diagrams for measured compared to calculated UCS values and histograms showing frequency versus difference in measured and calculated UCS (a and b: travertines, c and d: limestones)

element regarding the criterion or property to which they were being compared. The AHP analysis showed that the most important criteria affecting on UCS for the carbonate rocks being studied were UWV (45% weighting) and apparent porosity (33 % weighting). The other index properties' weighting did not surpass %10.

As regression analysis provides a means of summarising the relationship between variables, multiple regression analysis-based methodology was used to establish some numerical relationships between rock materials' ultrasonic wave velocity, apparent porosity and UCS. Furthermore it is known that V_p decreases with increased porosity. V_p and n^{-1} were thus used in the equations for predicting UCS in this study. Index properties were considered to be explanatory variables, and the UCS a depending variable. Figure 4 and 5 show multiple regression analysis results, involving some positive correlations between UWV rate regarding apparent porosity and UCS: such relationships were characterised by 0.71 and 0.87 regression coefficients. However, Figure 6 indicates meaningful empirical relationships for all travertines and limestones and the relationships are represented by the formulas given in Table 5.

A goodness of fit test establishes whether an observed frequency distribution differs from a theoretical distribution; however, a model's suitability is tested using the difference between observed and expected values. Normal distribution is a continuous probability distribution which is often used as a first approach for describing real-valued random variables tending to cluster around a single mean value. A normal distribution would thus be expected in the histograms showing difference between observed and expected values. Line-scatter plot diagrams of observed-expected values (Figure 7a and c) and histograms of difference between observed and expected values (Figure 7b and d) were prepared and normal distributions were observed. Histograms having a normal distribution showed that these equations did fairly well in estimating UCS using V_p/n . The results showed that the model being tested was suitable for the study.

Conclusions

This study involved three types of carbonate rocks being collected from ten rock formations in the north-eastern Turkey. Laboratory studies were conducted in line with ISRM (1980) to establish some relationships between P wave velocity, apparent porosity and UCS and AHP-based multiple regression analyses methodology was used for statistically analyzing the suggested methods and results. AHP analysis indicated that UWV (45% weighting) and apparent porosity (33% weighting) were the most important index properties affecting on UCS regarding the carbonate-bearing rocks being studied. Multiple regression analysis correlations indicated by the 0.81-0.87 regression coefficient were determined for UWV rate regarding apparent porosity and UCS. The equations obtained by such analysis results were practical, simple and accurate enough to apply and may be recommended for use in practice.

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