Prediction of physico-mechanical rock characteristics from electrical resistivity tests

by S. Kahraman[1] and E. Öğretici[2]

Affiliation:
[1]Mining Engineering Department, Hacettepe University, Ankara, Turkey
[2]Graduate School of Natural and Applied Sciences, Niğde Omer Halisdemir University, Niğde, Turkey

Correspondence to:
S. Kahraman

Email:
sairkahraman@yahoo.com

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ORCID:
S. Kahraman
http://orcid.org/0000-0001-7903-143X

Abstract

The indirect estimation of intact rock properties is particularly useful for preliminary investigations in engineering projects. In this paper we examine the usability of electrical resistivity, a nondestructive measurement, for the prediction of physical and mechanical rock characteristics. Physico-mechanical tests (uniaxial compression, Brazilian tensile, density, and porosity tests) and electrical resistivity measurements were performed on specimens of 36 rock types. Before the resistivity tests, the specimens were completely saturated with saline solution. Evaluation of the test results showed that there are medium or strong correlations between resistivity and rock properties. There are also strong or stronger correlations between the two parameters for the rock classes. The regression equations developed were statistically tested, and their validity was confirmed. The results were also compared with previous studies. The conclusion is that electrical resistivity measurement can be used for reliably estimating physical and mechanical rock characteristics.

Keywords

electrical resistivity, rock strength, density, porosity

Introduction

Among the characteristics of intact rocks, unconfined compressive strength (UCS), Brazilian tensile strength (BTS), density, and porosity are important parameters. These physico-mechanical rock characteristics are often used in various engineering projects for different purposes. Civil engineers use them, for instance, when designing engineering structures that are constructed on or in rock masses. On the other hand, mining engineers design rock excavation projects using the UCS and BTS. Density and porosity values are essential parameters for geoscientists or engineers working in the field of oil and gas exploration.

Well-prepared, smooth core specimens are essential for conducting standard tests to determine physico-mechanical rock characteristics. For very soft rock types, preparing the required samples is difficult and sometimes impossible. On the other hand, direct test methods are overpriced, tedious, and time-consuming for preliminary studies. Therefore, many researchers have recommended the use of indirect test methods to predict the physico-mechanical characteristics of rock formations, especially for preliminary studies (Broch and Franklin, 1972; Gunsallus and Kulhawy, 1984; Sachapazis, 1990; Kahraman, 2001; Ulusay, Gokceoglu, and Sulukcu, 2001; Yasar and Erdogan 2004; Fener et al., 2005; Kahraman, Fener, and Kozman. 2012; Kahraman et al., 2017; Kahraman and Ince, 2023). Schmidt hammer, point load, sonic velocity, and block punch index tests are the common indirect testing methods.

Although they are practical and inexpensive, indirect tests have some disadvantages. They cannot be applied any time and anywhere, and on any type of rock or specimen. Rock specimens are disturbed during point load and block punch index tests. The Schmidt hammer test cannot be conducted on soft or very weak rocks. It is also unreliable for very hard rocks. On the other hand, core specimens of hard rocks can be broken under the impacts of the Schmidt hammer. Although it can be applied to both smooth and unshaped specimens, the conversion factor between the point load index and the UCS varies in a wide range according to rock types or classes. Similarly, the correlations between sonic velocity and rock properties vary considerably according to the rock types or classes.

An electrical resistivity test, which is a nondestructive technique, may be a viable indirect testing technique to predict rock characteristics if good correlations are established for all rock classes. The method can be applied to any type of rock and is simple, inexpensive, and quick.

Electrical conductivity and resistivity have been widely used for the characterization of ground or exploration for subsurface features. Many scientists have used electrical measurements in the laboratory to characterize rock properties and derived correlations with porosity and some other rock properties (Archie, 1942; Brace, Orange, and Madden, 1965; Collett and Katsube, 1973; Shankland and Wa, 1997; Vinegar and Waxman, 1984; Schmeling, 1986; Jodicke, 1990; Chelidze, Gueguen, and Ruffet, 1999; Shogenova et al., 2001; Kaselow and Shapiro, 2004). However, few studies have been carried out to correlate electrical properties with other rock characteristics.

Kate and Sthapak (1995) correlated rock strength to indirect test results and derived a nonlinear correlation between electrical resistivity and UCS. They showed that electrical resistivity increased with increasing UCS. Bilim, Ozkan, and Gokay (2002) conducted electrical measurements and strength tests on synthetic specimens, and found an inverse relationship between voltage drop and rock strength and density. Kahraman and Alber (2006) correlated electrical resistivity to the physico-mechanical properties of core specimens prepared from a fault breccia. They found that the electrical resistivity was strongly correlated to UCS, elastic modulus, density, and porosity values. Vipulanandan and Garas (2008) investigated the correlations between electrical resistivity and the properties of carbon fibre-reinforced cement mortar. They derived reliable equations for the relationships between electrical resistivity and density, Young's modulus, and P-wave velocity. Kahraman and Fener (2008) examined the use of electrical resistivity tests to estimate the abrasion resistance of rock aggregates. They established good correlations between abrasion loss and resistivity. Kahraman and Yeken (2010) investigated the predictability of the UCS and the BTS of magmatic rock specimens using electrical resistivity, and derived reliable relationships between the resistivity and both UCS and BTS. They also derived multiple linear regression equations, which included density and porosity, stronger equations than simple regression equations. Kahraman and Alber (2014) developed reliable relationships between resistivity and the UCS of a fault breccia. Su and Momayez (2017) studied the relationship between electrical resistivity, physico-mechanical characteristics, and the Los Angeles abrasion loss of rocks. They derived reliable relationships between resistivity and physico-mechanical characteristics. However, they found that the electrical resistivity was poorly correlated to Los Angeles abrasion loss. Ince (2018) examined the relationships between pyroclastic rock characteristics and electrical resistivity. He found good correlations between rock characteristics and resistivity values. The correlations between UCS and electrical resistivity for granites were examined by Ranjbar and Nasab (2019), and a very good relationship between the two parameters was found.

In this research, electrical resistivity and physico-mechanical experiments were carried out on 13 metamorphic and 11 sedimentary rocks. The data, together with the results from Kahraman and Yeken (2010), was evaluated to develop predictive relationships between physico-mechanical properties and electrical resistivity.

Sampling

Thirteen metamorphic and eleven sedimentary rocks were tested. Large blocks of rocks were obtained from marble or stone factories and quarries in Turkey and transported to the laboratory for the experimental studies. The rock types and locations are listed in Table I.

Experimental

Strength, density, relative porosity, and electrical resistivity values were determined for the rock samples. Average results for each test are given in Table II. Brief explanations of the tests are given in the following paragraphs.

Unconfined compressive strength (UCS) test

Smooth-cut core specimens with a diameter of 47 mm and length of 95 mm were prepared for the UCS experiments. The stress rate used in the tests ranged between 0.5 and 1.0 MPa/s. Five or more specimens of each rock type were used in in the tests, and average result recorded.

Brazilian tensile strength (BTS) test

Smooth-cut disc samples 47 mm in diameter and 24 mm in thickness were used for the BTS experiments. To ensure that failure would be visible after 5 minutes of loading, the specimens were continuously subjected to a steady stress rate. Seven or more specimens were used in each test, and the average results recorded.

Density test

Well-prepared core specimens were employed to determine density values. Sample volumes were determined using caliper measurements. Sample masses were determined using a bascule with an accuracy of 0.01 g. Three specimens were tested for each rock type, and the averages recorded.

Porosity test

The porosities of the specimens were determined by saturation and caliper techniques. The volume of pores was determined from the dry and wet masses and the sample volume was calculated using caliper readings. Three specimens of each rock type were tested, and the average results recorded.

Electrical resistivity tests

The parameters influencing the electrical resistivity of rock materials are porosity, the salinity and resistivity of pore fluid, saturation degree, clay content, temperature, and pressure. The salinity of the pore fluid, saturation degree, temperature, and pressure were kept constant during the measurements.

Specimens 54.7 mm in diameter and 50 mm in length were used in the resistivity experiments. Both ends of the specimens were polished to obtain smooth surfaces. The specimens were fully saturated using a 2% (by weight) NaCl solution prepared from distilled water and high-purity salt. Brine resistivity was 0.58 m at room temperature.

The two-electrode technique was implemented for the experiments. Stainless steel discs were used as electrodes. Each specimen was fastened between two electrodes using a hydraulic ram before testing (Figure 1). A pad of filter paper saturated with the brine solution was inserted between the core and the electrodes to provide a good coupling. The electrical resistivity was measured using a resistivity meter.

The resistivity of each sample was measured at three distinct voltage levels. Voltage drops and currents were recorded during the tests. Using the measured parameters, the cross-sectional area, and the length of the sample, the resistivity values were computed from the following equations:

$$R = \frac{V}{I} \qquad [1]$$

Table I

The rock types and their locations used in the tests

Rock code	Rock type	Location	Rock class
1	Basalt	Altinhisar/Niğde	Igneous
2	Andesite	Yesilburç/Niğde	Igneous
3	Traki-andesite	Ulukışla/Niğde	Igneous
4	Volcanic bomb	Meke/Konya	Igneous
5	Granite	Uckapılı/Niğde	Igneous
6	Granite (Anadolu grey)	Ortaköy/Aksaray	Igneous
7	Granite (Kaman Rosa)	Kaman/Kırşehir	Igneous
8	Granite (Kırcicegi)	Kaman/Kırşehir	Igneous
9	Granite (King Rosa)	Unknown	Igneous
10	Granite (Rosa Porrino)	Porrino/Spain	Igneous
11	Granite (Pink Porrino)	Porrino/Spain	Igneous
12	Granite	Kozak/Balıkesir	Igneous
13	Limestone	Bursa	Sedimentary
14	Dolomitic limestone	Yahyalı/Kayseri	Sedimentary
15	Limestone	Bünyan/Kayseri	Sedimentary
16	Travertine	Yıldızeli/Sivas	Sedimentary
17	Travertine	Finike/Antalya	Sedimentary
18	Travertine	Bucak/Burdur	Sedimentary
19	Travertine	Demre/Antalya	Sedimentary
20	Travertine	Gödene/Konya	Sedimentary
21	Travertine	Mut/İçel	Sedimentary
22	Travertine	Karaman/Konya	Sedimentary
23	Anhydrite	Ulukışla/Niğde	Sedimentary
24	Amphiboleschist	Gümüşler/Niğde	Metamorphic
25	Quartzite	Gümüşler/Niğde	Metamorphic
26	Micaschist	Gümüşler/Niğde	Metamorphic
27	Serpentinite	Kılavuzköy/Niğde	Metamorphic
28	Gneiss	Gümüşler/Niğde	Metamorphic
29	Marble	Kütahya	Metamorphic
30	Marble	Muğla	Metamorphic
31	Marble (Afyon sugar)	İscehisar/Afyonkarahisar	Metamorphic
32	Marble	Gümüşler/Niğde	Metamorphic
33	Marble	Marmara Island/Balıkesir	Metamorphic
34	Marble (Kaplan postu)	İscehisar/Afyonkarahisar	Metamorphic
35	Marble	Milas/ Muğla	Metamorphic
36	Marble	Kemalpaşa/Bursa	Metamorphic

$$\rho = \frac{RA}{L} \qquad [2]$$

where *R* is the electrical resistance, *V* the voltage drop, *I* the current, ρ the electrical resistivity, *A* the cross-sectional area of the sample, and *L* is sample length.

Three samples were tested for each rock type. Additional specimens were tested when the standard deviation was high.

Evaluation of results

Regression analysis was performed to evaluate the test results. Regression equations were developed by correlating resistivity values to rock characteristics. As shown in Figure 2, UCS has a strong positive linear correlation with resistivity. The relationship is given by:

$$\sigma_c = 0.09\rho + 42.96 \quad r = 0.79 \qquad [3]$$

where σ_c is UCS (MPa) and ρ is electrical resistivity (Ω·m).

BTS is also strongly correlated to resistivity (Figure 3). The relationship is given by:

$$\sigma_t = 0.007\rho + 4.88 \quad r = 0.79 \qquad [4]$$

where σ_t is tensile strength (MPa) and ρ is electrical resistivity (Ω·m).

As illustrated in Figure 4, density is strongly correlated to resistivity. The relationship follows a power function. High-density rocks have higher resistivity values than those of low-density rocks. The equation for the curve is:

$$\gamma = 1.92\rho^{0.05} \quad r = 0.76 \qquad [5]$$

where γ is density (g/cm³) and ρ is electrical resistivity (Ω·m).

As indicated in Figure 5, resistivity values strongly correlate to porosity. The function of the relationship is logarithmic. Resistivity increases with decreasing porosity. The data for Altinhisar basalt is an outlier in this correlation. This is most likely caused by the high porosity and high UCS value. High-strength rocks usually have low porosity. The equation of the curve is:

Table II

Average results of the tests

Code	UCS (MPa)	BTS (MPa)	Density (g/cm³)	Porosity (%)	Resistivity (Ω-m)
1*	202.9	17.0	2.58	5.50	1558.7
2*	77.5	9.0	2.46	5.27	84.6
3*	78.2	8.5	2.29	10.74	50.8
4*	50.2	6.9	2.27	3.75	135.4
5*	133.2	11.4	2.63	1.15	848.4
6*	114.5	9.0	2.55	0.62	849.9
7*	84.9	8.0	2.61	0.63	386.9
8*	89.6	6.6	2.47	0.98	627.9
9*	120.3	14.8	2.62	0.36	976.9
10*	90.0	7.5	2.59	0.9	673.6
11*	120.0	12.6	2.53	2.81	469.5
12*	121.8	11.6	2.69	0.70	591.2
13	128.8	5.6	2.56	0.69	580.9
14	136.7	10.2	2.58	0.31	759.6
15	175.0	7.4	2.57	0.93	661.5
16	83.3	5.8	2.4	3.12	336.4
17	80.0	4.3	2.31	5.93	50.0
18	50.3	2.8	2.13	12.57	9.9
19	57.6	4.8	2.39	2.15	272.8
20	45.4	4.6	2.33	4.08	311.8
21	60.0	2.2	1.93	8.74	11.7
22	50.3	4.1	2.29	4.04	178.9
23	48.8	5.2	2.71	6.08	67.4
24	186.5	16.6	2.69	1.90	711.4
25	111.5	13.9	2.72	0.85	1193.6
26	70.9	9.4	2.75	1.95	588.0
27	210.6	18.1	2.75	0.91	2014.2
28	85.9	14.3	2.70	0.79	366.9
29	73.4	10.2	2.67	0.06	745.2
30	26.1	5.7	2.61	0.30	271.5
31	28.5	8.7	2.62	0.13	415.2
32	69.8	9.9	2.68	0.79	552.4
33	40.0	6.1	2.60	0.20	180.5
34	29.0	5.8	2.59	0.23	196.4
35	29.6	4.9	2.58	0.69	228.4
36	24.1	6.9	2.64	0.48	195.0

*Data from Kahraman and Yeken (2010

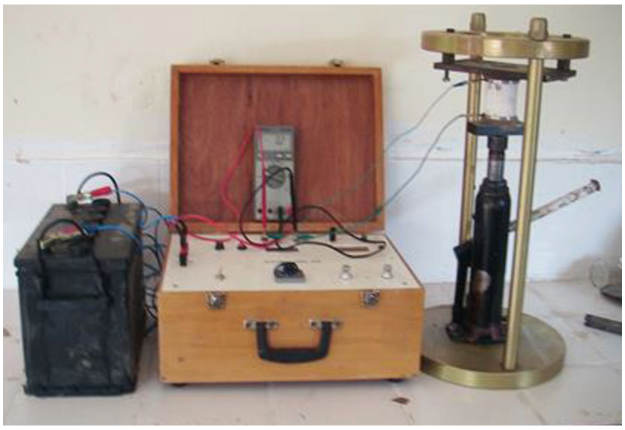

Figure 1—The experimental set-up used for measuring electrical resistivity

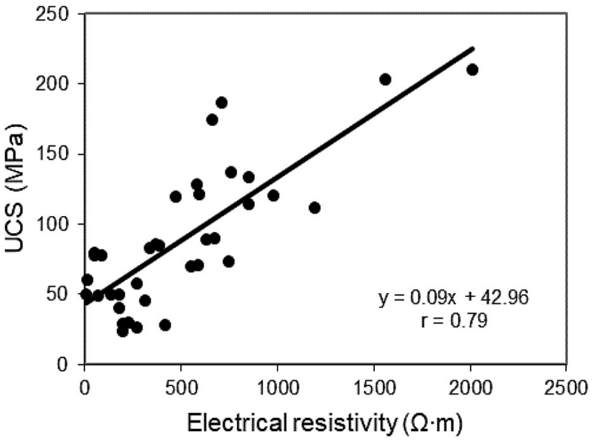

Figure 2—Electrical resistivity versus UCS

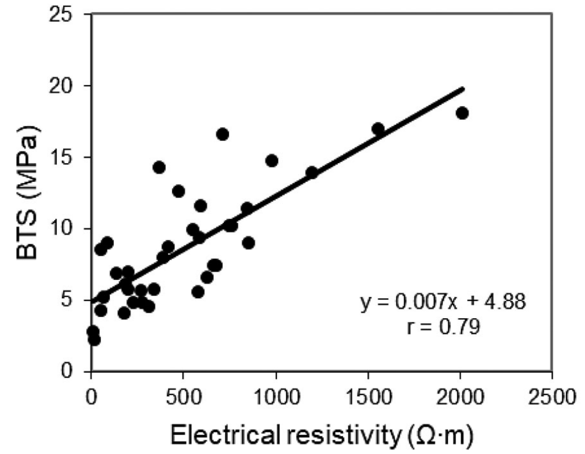

Figure 3—Electrical resistivity versus BTS

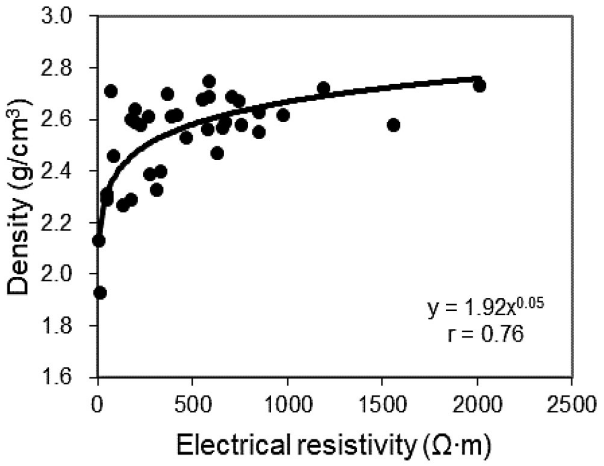

Figure 4—Electrical resistivity versus density

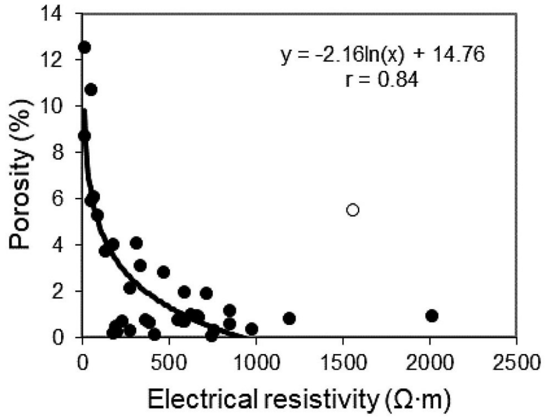

Figure 5—Electrical resistivity versus porosity

$$\gamma = 1.92\rho^{0.05} \quad r = 0.76 \qquad [6]$$

where n is relative porosity (%) and ρ is electrical resistivity (Ω·m).

To investigate the relationships between resistivity and rock characteristics for various rock classes, regression analysis was repeated for igneous, metamorphic, and sedimentary rocks. As depicted in Figures 6 to 9, the correlation coefficients of the derived equations for these rock classes are generally higher than those for all tested rocks. Owing to the narrow range of porosity values of the tested metamorphic rocks (less than 1.90%), no correlation between resistivity and porosity could be obtained; therefore, there is no regression curve for the metamorphic rocks shown in Figure 9. The derived regression equations and the correlation coefficients for the rock classes are as follows:

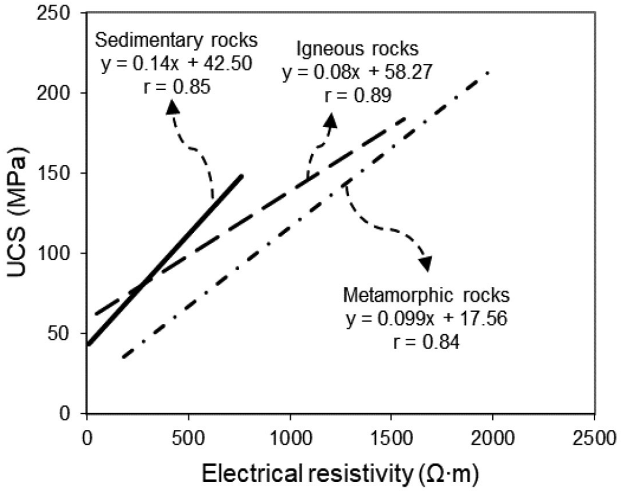

Figure 6—Electrical resistivity versus UCS for the various rock classes

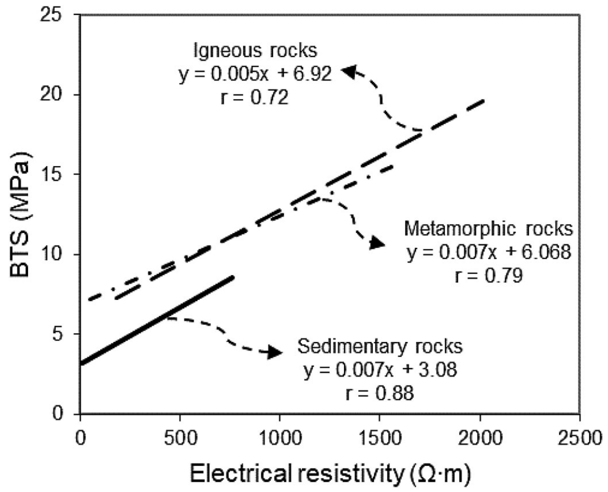

Figure 7—Electrical resistivity versus BTS for the various rock classes

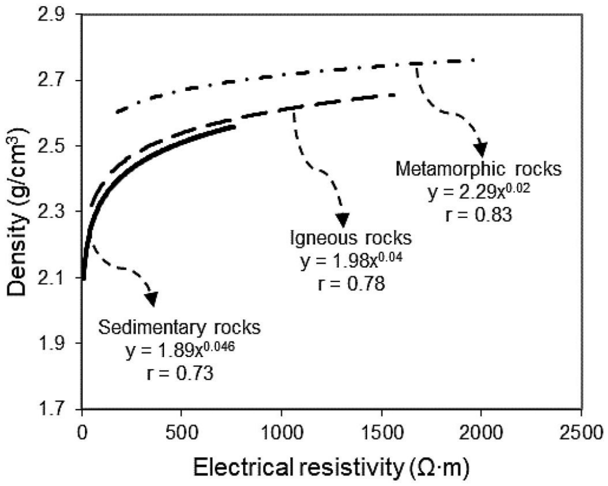

Figure 8—Electrical resistivity versus density for the varrious rock classes

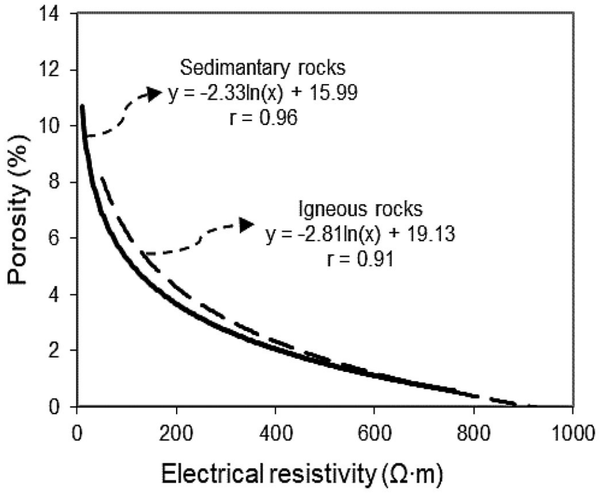

Figure 9—Electrical resistivity versus porosity for the various rock classes

$$\sigma_c = 0.08\rho + 58.27 \quad r = 0.89$$ [7]

$$\sigma_t = 0.005\rho + 6.92 \quad r = 0.72$$ [8]

$$\gamma = 1.98\rho^{0.04} \quad r = 0.78$$ [9]

$$n = -2.81 ln\rho + 19.13 \quad r = 0.91$$ [10]

For metamorphic rocks:

$$\sigma_c = 0.099\rho + 42.96 \quad r = 0.84$$ [11]

$$\sigma_t = 0.007\rho + 6.07 \quad r = 0.79$$ [12]

$$\gamma = 2.29\rho^{0.02} \quad r = 0.83$$ [13]

For sedimentary rocks:

$$\sigma_c = 0.14\rho + 42.50 \quad r = 0.85$$ [14]

$$\sigma_t = 0.007\rho + 3.08 \quad r = 0.88$$ [15]

$$\gamma = 1.89\rho^{0.05} \quad r = 0.73$$ [16]

$$n = -2.33 ln\rho + 15.99 \quad r = 0.96$$ [17]

Validation of the derived equations

Statistical tests should be used to verify the validity of the established equations, even if they have good or strong correlation coefficients. The t- and F-tests are commonly used to validate regression equations. For executing these tests, there should be a normal distribution of parameters. Figures 10 and 11, which are provided as examples, show that the histogram plots have a non-normal distribution. However, when the number of data points is greater than 30, it can be assumed that the data approaches a normal distribution, and the t- and F-tests can be used.

In the t-test, the computed t-value is compared to the tabulated t-value using the null hypothesis. If the computed t-value is greater than the tabulated t-value, the null hypothesis is rejected. This means that r is significant. The selected confidence level is 95% for this test. As indicated in Table III, the computed t-values are greater than the critical t-values for all derived equations. Therefore, it can be stated that the equations are valid according to the t-test.

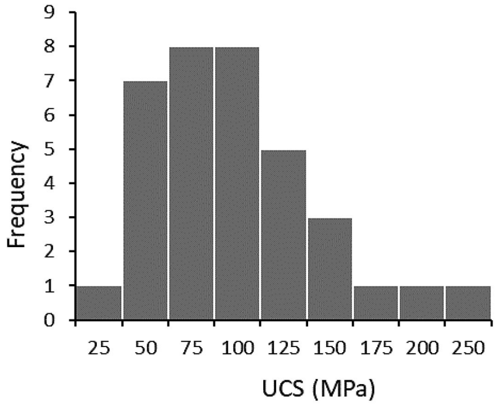

Figure 10—Histogram plot for UCS

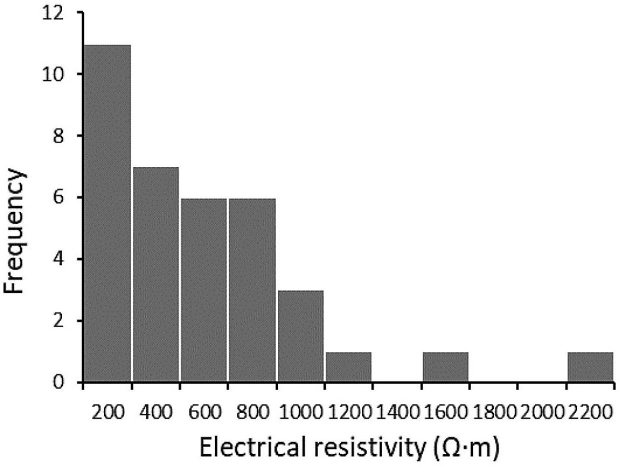

Figure 11—Histogram plot for electrical resistivity

To determine whether regressions were meaningful, analysis of variance was conducted. The chosen confidence level is 95% for this test. In the F–test, if the computed F-value is greater than the critical value found in the table, the null hypothesis is rejected, suggesting there is an actual correlation between two variables. As seen in Table III, the computed F-values are greater than the critical values of F for all equations. Hence it can be said that the derived equations are valid as regards the F-test.

Comparison of derived equations with previous equations

Making a detailed comparison between the results of the present research and prior investigations is difficult because the brine resistivity and the testing conditions are different in each study. Only a general comparison can be made. Figure 12 depicts the comparison between Equation [3] (UCS vs. resistivity) and the equations derived by other authors for resistivity values ranging from 50 to 500 Ω·m. The equation developed by Kahraman and Alber (2006) shows quite a different trend from the other equations, owing to the much lower brine resistivity used (0.0579 Ω·m). Although the equations derived by Kate and Sthapak (1995) and Ince (2018) are nonlinear, they indicate fairly similar trends to those of Equation [3]. The differences between the models are due to the different brine resistivities used in the studies.

Conclusions

Physico-mechanical and electrical resistivity experiments were conducted on 36 different rock types and the results assessed using regression analysis to develop prediction models for rock

Table III

F-test results

Eq. no.	t-table	t-test	F-table	F-test
[3]	±1.96	7.51	1.76	56.45
[4]	±1.96	7.52	1.76	56.67
[5]	±1.96	6.34	1.76	45.83
[6]	±1.96	-9.28	1.76	50.56
[7]	±2.20	6.34	2.80	39.71
[8]	±2.20	3.28	2.80	10.73
[9]	±2.20	2.49	2.80	15.94
[10]	±2.20	-3.71	2.80	42.71
[11]	±2.18	5.10	2.69	26.06
[12]	±2.18	4.31	2.69	18.64
[13]	±2.18	3.61	2.69	24.91
[14]	±2.22	4.75	2.98	22.53
[15]	±2.22	5.51	2.98	30.39
[16]	±2.22	2.30	2.98	10.30
[17]	±2.22	-4.78	2.98	112.10

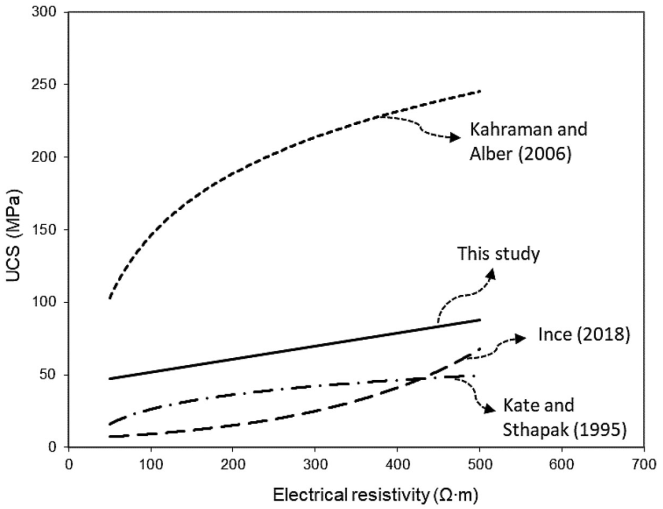

Figure 12—Comparison between this study and previous studies

characteristics. Good relationships were established between resistivity and UCS, BTS, density, and porosity. Estimation models were also derived for igneous, metamorphic, and sedimentary rock classes. The equations derived for rock classes have generally higher correlation coefficients than those of the equations developed for all tested rocks. It is concluded that electrical resistivity measurement is a reliable method for the estimation of physico-mechanical rock characteristics.

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