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Electrical resistivity measurement to predict uniaxial compressive and tensile strength of igneous rocks

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Abstract. **Electrical resistivity values of 12 different igneous rocks were measured on core samples using a resistivity meter in the laboratory. The resistivity tests were conducted on the samples fully saturated with brine (NaCl solution) and the uniaxial compressive strength (UCS), Brazilian tensile strength, density and porosity values of the samples were determined in the laboratory. The test results were evaluated using simple and multiple regression analysis. It was seen that the UCS and tensile strength values were linearly correlated with the electrical resistivity. The correlation coefficients are generally higher for the multiple regression models than that of the simple regression models. It was concluded that the UCS and tensile strength of igneous rocks can be estimated from electrical resistivity. However, the derived relations are purely empirical and they should be checked for other igneous rocks. The effect of rock types such as sedimentary and metamorphic rocks on the derived equations also needs to be investigated.**

Keywords. **Electrical resistivity; uniaxial compressive strength; Brazilian tensile strength.**

1. Introduction

The electrical measurement method is one of the non-destructive geophysical methods which can be applied both in the laboratory and in the field. Investigators and engineers working in various fields such as mining, geotechnical, and civil, underground engineering have commonly used the electrical measurement technique. Many researchers (Archie 1942; Brace *et al* 1965; Collett and Katsube 1973; Vinegar and Waxman 1984; Schmeling 1986; Jodicke 1990; Shankland and Waff 1997; Chelidze *et al* 1999; Shogenova *et al* 2001; Ara *et al* 2004; Kaselov and Shapiro 2004) working especially in geophysics area have investigated the electrical conductivity or resistivity of rocks in the laboratory for many years. However, there is very limited study on the relation between electrical resistivity and rock properties except porosity. Kate and Sthapak (1995) studied engineering behaviour of certain Himalayan rocks and developed some empirical relations between rock strength and index test values. They found a logarithmic relation between resistivity and uniaxial compressive rock strength. The compressive strength increases with increasing resistivity. Bilim *et al* (2002) carried out electrical measurements on artificial rocks and found that compressive strength, tensile strength, point load strength and density strongly correlated with voltage drop. Voltage drop decreases with increasing rock strength and density. Kahraman and Alber (2006) correlated the electrical resistivity values obtained from electrical impedance spectroscopy measurements with the corresponding physico-mechanical rock properties for the eight different samples cored from a fault breccia. They found significant correlations between resistivity and physico-mechanical rock properties. Recently, Vipulanandan and Garas (2008) investigated the electrical resistivity and mechanical properties of carbon fibre-reinforced cement mortar (CFRCM). They developed some empirical relations to relate the specific electrical resistivity to unit weight, Young's modulus and pulse velocity.

Measurements of mechanical rock properties generally require well-prepared rock samples and testing are time consuming and expensive. For this reason, some researchers have suggested indirect test methods to estimate the mechanical rock properties. If strong correlations can be established between electrical resistivity and mechanical rock properties, electrical resistivity measurement may be an indirect measure of rock strength. The preliminary results of this study showed that compressive and tensile strength of igneous rocks linearly correlated with electrical resistivity for eight igneous rocks (Kahraman *et al* 2006). In this study, additional test results of the four granite samples were combined with the previous data and evaluated using simple regression analysis. In addition, multiple regression analysis was performed using resistivity, porosity and density values.

2. Sampling

Twelve different igneous rocks were tested in this study. Rock blocks were collected from the stone processing

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plants, quarries and natural outcrops in Nigde and Konya area of Turkey. Each block sample was inspected for macroscopic defects so that it would provide test specimens free from fractures, partings or alteration zones. The name and locations of the rocks are given in table 1.

3. Laboratory studies

3.1 *Uniaxial compressive strength (UCS) test*

Uniaxial compression tests were performed on trimmed core samples, which had a diameter of 38 mm and a length-to-diameter ratio of 2. The stress rate was applied within the limits of 0·5–1·0 MPa/s.

3.2 *Brazilian tensile strength test*

Brazilian tensile strength tests were conducted on core samples having a diameter of 38 mm and a height to diameter ratio of 1. The tensile load on the specimen was applied continuously at a constant stress rate such that failure will occur within 5 min of loading.

3.3 *Density test*

Trimmed core samples were used in the determination of dry density. The specimen volume was calculated from an average of several calliper readings. The dry weight of the specimen was determined by a balance, capable of weighing to an accuracy of 0·01 of the sample weight. The density values were obtained from the ratio of the specimen weight to the specimen volume.

3.4 *Porosity test*

Porosity values were determined using saturation and calliper techniques. Pore volumes were calculated from dry and saturated weights and sample volumes were obtained from calliper readings. The porosity values were obtained from the ratio of the pore volumes to the specimen volume.

3.5 *Electrical resistivity measurements*

For most rocks where current is carried by ions in the pore fluid the resistivity depends on porosity, pore fluid resistivity (salinity), pore fluid saturation, clay content, temperature and pressure. In all tests conducted in this study, pore fluid salinity, pore fluid saturation, temperature and pressure were kept the same.

Resistivity measurements were performed on cylindrical samples of 54·4 mm diameter and of ~50 mm length. Axial end surfaces of the samples were ground flat and parallel. The samples were fully saturated with brine (NaCl solution) consisting of distilled water and a 2% by weight high-purity salt. Saturation was controlled by measurement of weight increase. The samples were assumed fully saturated when no additional increase in weight was observed. The brine resistivity was 0·58 Ω·m at room temperature.

A resistivity meter was used for the resistivity measurements. The samples were fixed between electrodes using a hydraulic ram (figure 1). Circular stainless steel electrodes were used in the tests in which two-electrode technique was employed. To ensure a good contact between the electrodes and samples, a pad of filter paper soaked with brine solution was placed between the core and the steel electrodes.

At least three samples were tested for each rock types and three different voltage levels were applied for each sample. Using the readings of current and voltage drop and the geometry of the samples, resistivity values were calculated from the following equation:

$$\rho = \frac{RA}{L}, \tag{1}$$

where ρ is the electrical resistivity, R the resistance, A the cross sectional area of specimen, and L the length of specimen.

Table 1. Location and name of rocks sampled.

Rock code	Location	Rock type
1.	Altinhisar/Nigde	Basalt
2.	Yesilburc/Nigde	Andesite
3.	Ulukisla/Nigde	Traki-andesite
4.	Meke/Konya	Volcanic bomb
5.	Uckapili/Nigde	Granite
6.	Ortakoy/Aksaray	Granite (Anadolu grey)
7.	Kaman/Kirsehir	Granite(Kaman Rosa)
8.	Kaman/Kirsehir	Granite(Kırcicegi)
9.	Unknown	Granite(King rosa)
10.	Porrino/Spain	Granite(Rosa Porrino)
11.	Porrino/Spain	Granite(Pink Porrino)
12.	Kozak/Balikesir	Granite

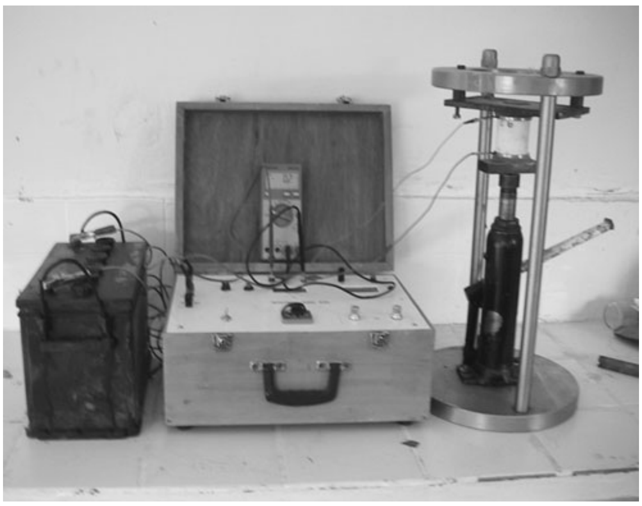

Figure 1. Resistivity measurement system.

Table 2. Physico-mechanical and resistivity test results.

Rock code	Compressive strength[5a] (MPa)	Tensile strength[5] (MPa)	Porosity[3] (%)	Density[3](g/cm^3)	Resistivity[3] (Ω·m)
1.	202·9±10·2[b]	17·0±3·8	5·50±0·10	2·58±0·07	1558·7±35·4
2.	77·5±6·7	9·0±0·4	5·27±0·02	2·46±0·04	84·6±2·5
3.	78·2±9·3	8·5±0·5	10·74±0·30	2·29±0·02	50·8±4·1
4.	50·2±5·4	6·9±1·4	3·75±0·15	2·27±0·09	135·4±11·4
5.	133·2±5·2	11·4±2·1	1·15±0·03	2·63±0·05	848·4±41·0
6.	114·5±4·3	9·0±0·7	0·62±0·02	2·55±0·07	849·9±106·8
7.	84·9±9·5	8·0±1·3	0·63±0·01	2·61±0·06	386·9±32·5
8.	89·6±11·6	6·6±0·6	0·98±0·01	2·47±0·05	627·9±93·5
9.	120·3±6·3	14·8±1·1	0·36±0·02	2·62±0·03	976·9±66·3
10.	90·0±7·2	7·5±1·0	0·90±0·13	2·59±0·05	673·5±36·4
11.	120·0±7·7	12·6±1·3	2·81±0·02	2·53±0·06	469·5±29·9
12.	121·8±3·9	11·6±0·8	0·70±0·15	2·69±0·04	591·2±18·3

[a] Minimum number of tested samples; [b] standard deviation values

Average resistivity values for each rock type are shown in table 2.

4. Statistical evaluation

4.1 *Simple regression analysis*

Uniaxial compressive strength (UCS), tensile strength, resistivity, density and porosity values are given in table 2. The UCS of granite normally varies between 100 and 250 MPa. The UCS values of some granites tested lower than 100 MPa. These granites have coarse grains. The cause of the low strength may be because of the coarse grained texture.

The data in table 2 were analysed using the method of least squares regression. Resistivity values were correlated with the corresponding compressive and tensile strength values. Linear, logarithmic, exponential and power curve fitting approximations were tried and the best approximation equation with highest correlation coefficient was determined for each regression.

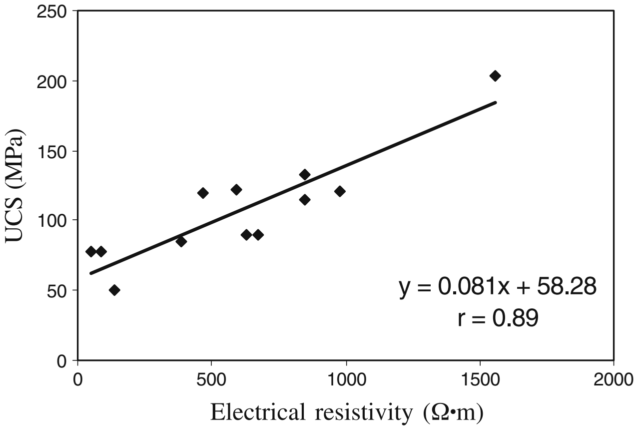

Figure 2. Relation between UCS and electrical resistivity.

A strong linear relation between UCS and resistivity values was found (figure 2). UCS values increase with increasing resistivity values. The equation of the line is:

$$\sigma_c = 0{\cdot}081\rho + 58{\cdot}28, \quad r = 0{\cdot}89, \tag{2}$$

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

A linear relation between tensile strength and resistivity values was found (figure 3). The equation of the line is:

$$\sigma_t = 0{\cdot}0055\rho + 6{\cdot}92, \quad r = 0{\cdot}72, \tag{3}$$

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

Figures 2 and 3 were compared with the results obtained by Kate and Sthapak (1995) as shown in figures 4 and 5. The Kate and Sthapak's data indicate a linear trend for the rocks having UCS values of 50 MPa and tensile strength value of 5 MPa. Therefore, there is a similar trend between

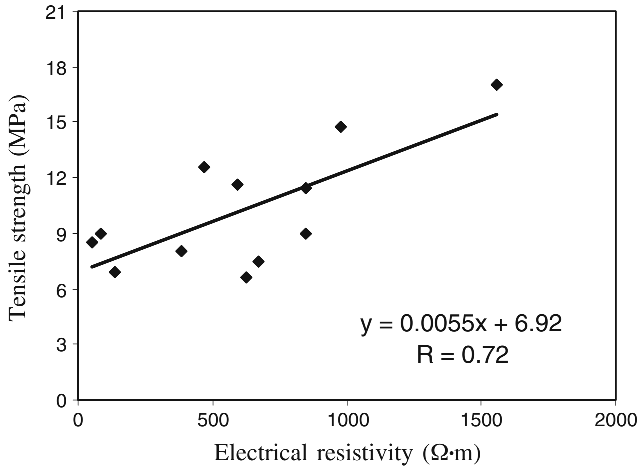

Figure 3. Relation between tensile strength and electrical resistivity.

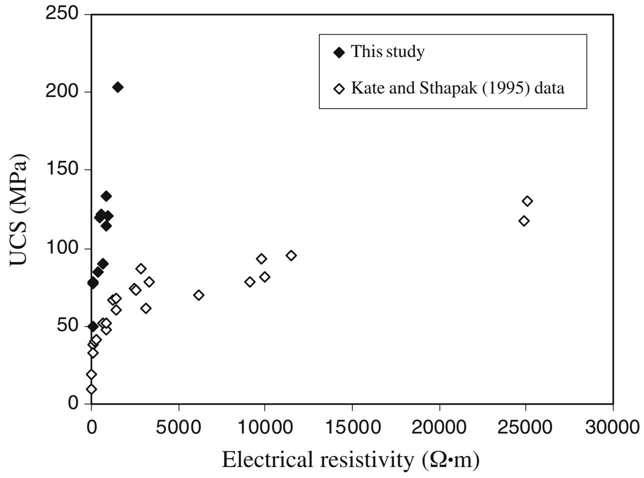

Figure 4. Comparison between figure 2 and Kate and Sthapak (1995) data.

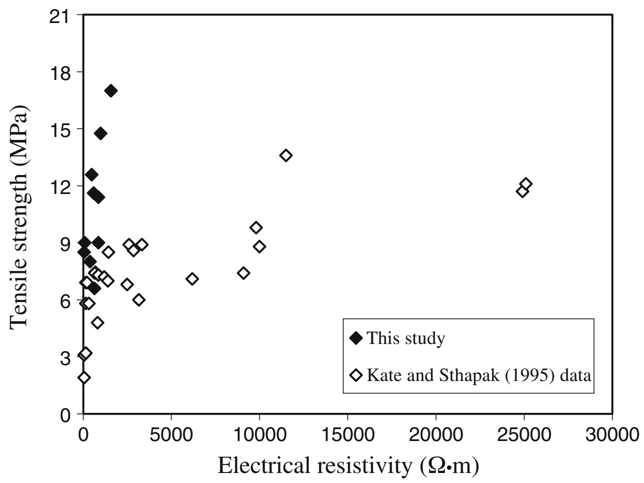

Figure 5. Comparison between figure 3 and Kate and Sthapak (1995) data.

figures 2 and 3 and the Kate and Sthapak's data. The slope difference between the two data is due to the resistivity value of the saturation fluid; the resistivity of the saturation fluid used in this study is 0·58 Ω·m and the resistivity of the saturation fluid used by Kate and Sthapak is 9·13 Ω·m.

Another result that can be drawn from figures 4 and 5 is that the effect of conductivity of the pore water fluid on the conductivity of rock for low strength rocks is less than that of the high strength rocks.

In addition, the resistivity values were correlated with the density and porosity values. As shown in figure 6, there is a good correlation between resistivity and density. Increasing density increases the resistivity. Altinhisar Basalt data shows anomalous value in the plot of resistivity versus porosity (figure 7). That is probably because Altinhisar Basalt has a high porosity but has a very high strength. After omitting this value from the correlation, a strong logarithmic relation between resistivity and porosity was found.

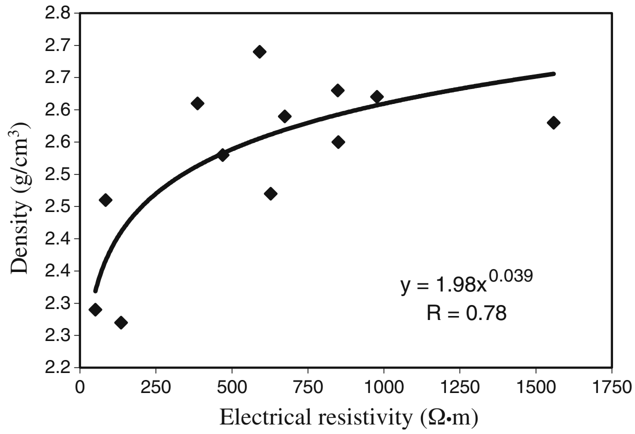

Figure 6. Relation between density and electrical resistivity.

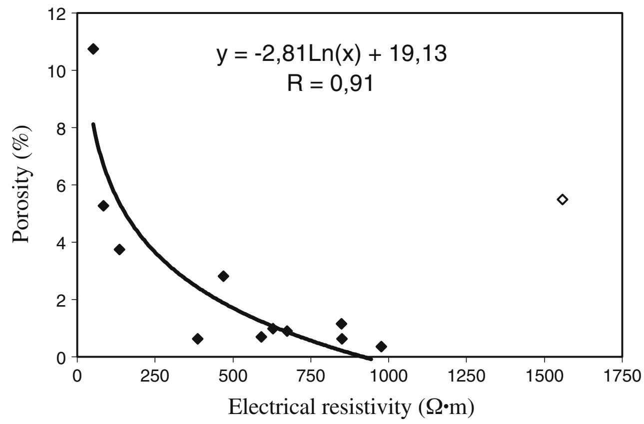

Figure 7. Relation between porosity and electrical resistivity.

4.2 *Multiple regression analysis*

Multiple linear regression analysis was performed in the expectation of obtaining more significant relations than that of the simple regression. Density and porosity together with resistivity were included in the models. The derived models for the estimation of UCS and tensile strength are the following:

$$\sigma_c = 14{\cdot}32 + 0{\cdot}077\rho + 18{\cdot}24\gamma \quad r = 0{\cdot}90, \tag{4}$$

$$\sigma_c = 44{\cdot}59 + 0{\cdot}088\rho + 3{\cdot}19n \quad r = 0{\cdot}93, \tag{5}$$

$$\sigma_c = -296{\cdot}16 + 0{\cdot}071\rho + 6{\cdot}33n + 135{\cdot}8\gamma \quad r = 0{\cdot}97, \tag{6}$$

$$\sigma_t = 2{\cdot}99 + 0{\cdot}0052\rho + 1{\cdot}63\gamma \quad r = 0{\cdot}72, \tag{7}$$

$$\sigma_t = 5{\cdot}57 + 0{\cdot}0063\rho + 0{\cdot}315n \quad r = 0{\cdot}77, \tag{8}$$

$$\sigma_t = -27{\cdot}32 + 0{\cdot}0045\rho + 0{\cdot}618n + 13{\cdot}11\gamma \quad r = 0{\cdot}83, \tag{9}$$

where σ_c is the UCS (MPa), σ_t the tensile strength (MPa), ρ the electrical resistivity ($\Omega \cdot$m), γ the density (g/cm^3) and n the porosity (%).

The correlation coefficients of multiple regression models are generally higher than that of the simple regression models. The highest correlation coefficients were obtained when resistivity, density, and porosity values were included in the models.

5. Conclusions

The UCS, tensile strength, electrical resistivity, density, and porosity measurements performed on 12 igneous rocks were evaluated using simple and multiple regression analysis. It was seen that the UCS and tensile strength values were linearly correlated with electrical resistivity. Compared to the simple regression, multiple regression analysis generally produced regression models having high correlation coefficients. In conclusion, the UCS and tensile strength of igneous rocks can be estimated from electrical resistivity. However, the derived relations are purely empirical and they should be checked for other igneous rocks. Further research is also necessary to check the validity of the derived equations for the other rock types such as sedimentary and metamorphic rocks.

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