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Experimental approach to evaluate weathering condition of granite using electrical resistivity

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Abstract. Weathering is the breaking/cutting down process of rocks due to physical and chemical processes in natural as well as artificial environment including CO_2 injection for storage in the sediment, or natural resource recovery process. This study suggests an alternative method to estimate the degree of weathering for granites. A series of laboratory and field experiments are performed to measure electrical resistivities on various rock samples experienced different degrees of weathering and their residual soils under different saturation conditions. It is found that the normalized electrical resistivity increases with a decrease in water absorption and the saturation. Simple boundaries are suggested to identify the weathering degree of granites, based on limited data. Field test results for three sites confirm that the suggested method could be estimated well the degree of weathering of granites compared with the other methods suggested previously. Although further research is required, this study suggests that an electrical resistivity could be an effective approach to estimate the degree of weathering of granites compared with the other methods suggested previously.

Keywords: degree of weathering; electrical resistivity; Korean granite; weathering classification

1. Introduction

In Weathering is a destructive process where rocks react with the surrounding environment (Selby 1993). There are two principle weathering processes: physical and chemical weathering; occasionally a biological weathering is involved. Physical weathering is the breaking rock and soil particles into smaller sizes through the application of a series of stresses without chemical changes

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in the nature of the minerals, whereas chemical weathering is the changes in the nature of the constituent minerals to stable or meta-stable secondary mineral products through various chemical reactions (Reiche 1950). Weathering processes can lead to significant changes in rock properties, including significant reductions in the compressive and tensile strengths of rocks due to disruptions in the grain bonding and the development of microfractures (Dearman and Irfan 1978, Pasamehmetoglu *et al*. 1981, Beavis 1985, Turk *et al*. 1994), increases in the deformability (Ebuk *et al*. 1993, Ifran and Powell 1985, Viles 2013), changes in the stress state (Castellanza and Nova 2004), and alterations in the failure mode (Raisbeck 1973).

The mineral composition of weathered rock is different from that of its parent rock due to the chemical weathering, and this causes variations in the engineering characteristics (Ifran 1996, Olsson-Francis *et al*. 2012). Thus, it may become more difficult to estimate suitable design parameters, to adopt appropriate analytical approaches, and to select appropriate construction methods for civil engineering projects involving weathered rocks (Chen *et al*. 2011). Currently, there are two groups of rock weathering classification systems: a qualitative system based on the visual identification of geological characteristics; and a quantitative system based on the mechanical characteristics and chemical decomposition (Akin 2010). Although the degree of weathering classification systems could be beneficial in resolving problems, the current systems encounter many difficulties in practical use and provide somewhat inconsistent results for the same weathered rock (Lee and de Freitas 1988, Kim and Park 2003).

This paper proposes a new method for estimating the degree of weathering for several granite specimens using electrical resistivity. Experimental studies were conducted with various rock samples experienced different degrees of weathering and their residual soils. Chemical indices of samples were analyzed and the electrical resistivity was measured with different degrees of saturation.

2. Laboratory experimental study

2.1 Materials tested

Granite rocks with various degrees of weathering and residual soils were sampled from construction sites in South Korea. Cylindrical cores of the weathered rocks were obtained by drilling and their dimension was 34.4 mm in diameter and 70.0 mm in length. Samples of weathered granitic soil were collected from a near-surface horizon (< 0.5 m depth). The natural density and dry unit weight of the residual soils were measured using a sand-cone density apparatus in the field (ASTM D1556 2007). Tables 1 and 2 summarize the index properties of the residual soils (RS) and weathered rocks (WR), respectively.

2.2 Electrical resistance measurement system

Two disc type electrodes (34.4 mm in diameter, stainless steel) were used to measure the electrical resistance of the rock cores. For the residual soils, a plastic cubic cell (70.0 mm in length and 6 mm in thickness) was constructed with a pair of spherical electrodes (10.0 mm in diameter, stainless steel) installed in its lateral wall to measure the electrical resistance. Electrical resistance measurements were performed at the temperature of 22 ± 1°C. An electrical resistivity prospecting system (EPS) was used to measure the electrical resistances. The EPS consists of a control program,

Table 1 Index properties of residual soils (RS)

Index properties	RS1	RS2	Method
Specific gravity (-)	2.63	2.65	Pycnometer (ASTM D854)
Natural density (g/cm^3)	1.50	1.61	Sand-cone (ASTM D1556)
D_{50} (mm)	1.15	1.12	Sieve (ASTM D421)
Coefficient of uniformity, C_u (-)	7.08	6.91	
Coefficient of curvature, C_c (-)	0.81	0.83	
Void ratio (-)	1.10	0.80	Oven dry
Water content (%)	19.17	9.32	
Degree of saturation (%)	46.17	30.82	

Table 2 Index properties of weathered granites (WR)

Index properties	Weathered granite samples					Method
	WR1	WR2	WR3	WR4	WR5	
Apparent specific gravity (-)	2.66	2.64	2.53	2.56	2.48	ASTM D6473
Apparent density (kg/cm^3)	2674.0	2665.9	2656.5	2637.2	2664.0	

a data acquisition system (NI PXI-1042), a digital multimeter, a power supply, a switch controller (NI PXI-4021), and electrodes (details can be found in Ryu *et al*. 2008).

2.3 Experimental procedures

The chemical contents of the residual soils and rock cores were evaluated by using X-ray diffraction, XRD (XPERT MPD, Philips, maximum radiation: 3 kW). The angles scanned were from 5 to 80° (2θ) at a rate of 0.04°/sec (2θ/sec).

The water absorption of the rock cores was measured following a procedure presented in ASTM D6473 (2010). The cores were completely dried in ambient air and submerged in distilled water for 24 hours. The buoyant mass of the cores was measured in the water and the mass of the saturated surface-dry cores was also measured. The cores were dried for 24 hours in an oven (110 ± 5°C), and then the oven-dried mass of cores was measured after cooling.

The cores were immersed in distilled water for 5 days to ensure full saturation, and then dried in ambient air. During the drying process, the weight of the rock cores was measured continuously with the electrical resistance measurement.

The residual soils were reconstituted to have the same density as the natural unit weight condition and a predetermined amount of water was added to the soils. The wet soil was homogenized in a container for 15 minutes and carefully scooped into the cell to obtain the desired density. The degree of saturation of the soil specimens changed according to the predetermined amount of water added until the soil reached full saturation. The electrical resistance of the soils was measured at different degrees of saturation. The electrical resistance was measured at least three times at each step for the residual soils and rock cores.

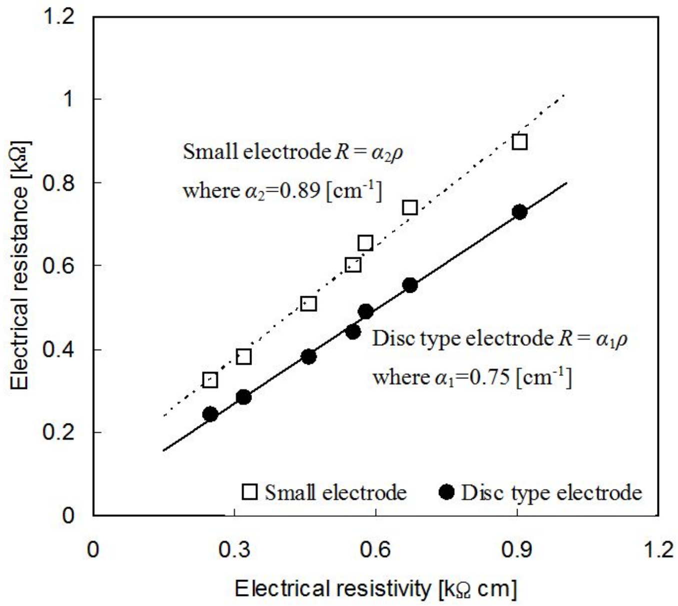

Fig. 1 Calibration test for shape factors

2.4 Data reduction: Calibration

The electrical resistivity (ρ) is related to the electrical resistance (R) with geometrical considerations (i.e., shape factor) as follows

$$R = \rho \cdot \frac{L}{A} = \rho \cdot \alpha \tag{1}$$

where L is the length of the core, A is the area of the core, and α is the shape factor that can be determined by a calibration test (Lee and Santamarina 2010, Kim *et al*. 2011). The calibration test was performed by measuring the electrical resistances at known different electrical resistivities, and the results are shown in Fig. 1. The shape factor (α) obtained was 0.75 cm^{-1} for the disc type electrodes and 0.89 cm^{-1} for the small electrode in the cell.

3. Experimental analyses

3.1 Chemical properties and quantitative analyses according to current weathering classification systems

The mineral contents of the tested specimens are summarized in Table 3. The main mineral contents are biotite, albite, microcline, quartz, muscovite, chlorite, and magnetite for the rock cores, while kaolinite is added in the residual soils. The XRD results of the tested specimens imply that the weathering process induces this variation in the mineralogy because it generates different weathering products at different weathering stages. The newly formed mineral is more stable than

Table 3 Mineral contents of tested specimens (as percent of total)

Mineral	Weathered granite samples					Residual soil samples	
	WR1	WR2	WR3	WR4	WR5	RS1	RS2
Biotite	4.4	6.6	3.9	2.0	1.8	1.9	2.4
Albite	46.4	38.2	35.8	52.1	30.5	32.5	22.9
Microcline	19.1	21.3	27.3	17.1	13.4	20.7	19.2
Quartz	24.3	29.1	28.4	21.3	40.4	25.3	32.8
Muscovite	-	-	-	-	11.9	10.8	12.4
Chlorite	3.9	3.4	3.2	5.2	1.6	5.6	5.2
Magnetic	1.9	1.3	1.5	2.2	0.4	-	-
Kaolinite	-	-	-	-	-	3.3	5.1

Table 4 Classification of weathering degree by existing methods for weathered granites

Samples	Water absorption Index[1]		Ruxton Ratio[1]		Chemical index of weathering[2]	
	Value	Description	Value	Description	Value	Description
WR1	0.3	Slightly	4.685	Fresh	73.269	Highly
WR2	0.48	Slightly	5.151	Fresh	75.523	Highly
WR3	1.24	Moderately	4.363	Fresh	72.123	Highly
WR4	1.9	Moderately	5.147	Fresh	76.830	Highly
WR5	2.86	Highly	5.393	Fresh	79.556	Highly
RS1	-	Soil	3.807	Completely	82.536	Soil
RS2	-	Soil	4.118	Moderately	86.389	Soil

[1] Gupta and Rao (2000)
[2] Hamois (1988)

the original. Biotite and albite are representative minerals at early weathering stages and are observed in all tested specimens, while kaolinite, only observed in the residual soils, is the representative mineral in the advanced weathering stages. The appearance of muscovite and clay minerals such as kaolinite reveals that the specimens have experienced more advanced weathering processes (Gupta and Rao 2000, Mitchell and Soga 2005).

Table 4 presents the classification of weathering degree using selected existing methods for granites. Although the selected quantitative systems suggest numerical guidelines for the classification of weathering degree, the defined degree of weathering is inconsistent for each criterion in the same specimen. Because the water absorption index is well matched with the optical observation, it is used to define the degree of weathering in this study.

3.2 Correlation of normalized electrical resistivity

As the weathering process proceeds, microcracks or microfractures are propagated in the rock. Subsequently, the water absorption increases with the weathering sequence under fully saturated

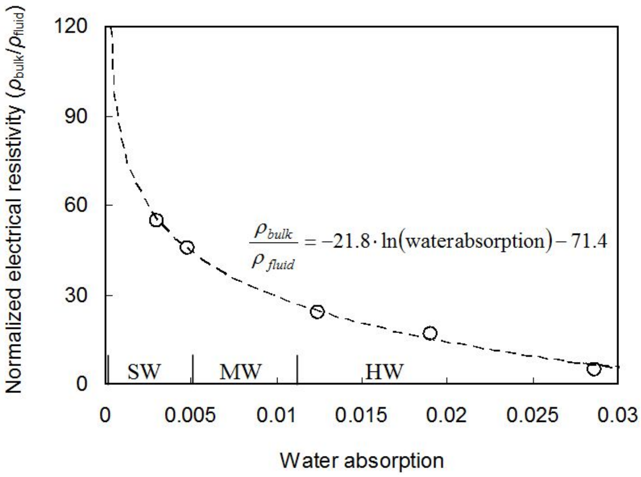

Fig. 2 Normalized resistivity of weathered rock specimens with water absorption at S = 100%. SW, MW, and HW are categorized by Gupta and Rao (2000) in the figure and denote the slightly weathered, moderately weathered, and highly weathered, respectively

conditions (Gupta and Rao 2000). The electrical resistivity of a weathered rock is controlled by the volume fraction of pore fluid resistivity filling the microcracks or microfractures. The normalized resistivity (by the resistivity of pore fluid) for fully saturated rock specimens is plotted with the water absorption, as shown in Fig. 2. Measured values of the water absorption range 0.30% to 2.86%. The normalized resistivity is a function of the physical properties of the rock including the intricate pore geometry, tortuosity, and decree of cementation when the electrical resistivity of the pore fluid is a constant. The normalized resistivity increases with a decrease in water absorption as follows

$$\frac{\rho_{bulk}}{\rho_{fluid}} = -21.8 \cdot \ln(\text{water absorption}) - 71.4 \tag{2}$$

Therefore, normalized resistivity can be used as an indicator to surmise the degree of weathering in a rock.

When the particle conduction is zero, the electrical conductivity of a rock is governed by its porosity and pore fluid saturation (Archie 1942). Fig. 3 shows the normalized resistivity as a function of the degree of saturation. The normalized resistivity increases with a decrease in the pore fluid saturation for both weathered rocks and residual soils because the connectivity of the pore fluid controls the bulk electrical resistivity. The residual soils and weathered rocks are separated by the normalized resistivity values. The normalized resistivity of the residual soils is much lower than that of weathered rocks due to the relatively high porosity of the soils. The normalized resistivity (ρ_{bulk}/ρ_{fluid}) can be modeled simply with the porosity (n) and the degree of saturation (S) as follows

$$\frac{\rho_{bulk}}{\rho_{fluid}} = \beta \cdot n^{-m} \cdot S^{-c} = F \cdot S^{-c} \tag{3}$$

where β, m, and c are the fitting constants, and F is the formation factor (Archies 1942, Winsauer *et al*. 1952). In this study, the values of F and c were experimentally identified for Korean granites in order to classify the degree of weathering based on the measured electrical resistivity data (F = 40 and c = 3 are the lower bounds of slightly weathered granite; F = 10 and c = 2 are the lower bounds of moderately weathered granite).

The electrical resistivity of a rock is varied by specific characteristics including the porosity, pore fluid, saturation, and mineralogy, and by external factors such as fault zones, fissures, and cracks (Chinh *et al*. 2000, Glover *et al*. 2000, Oh *et al*. 2014). The relationship between the normalized resistivity and saturation changes according to the rock types because the bulk electrical resistivity differs significantly with different types of rock (Carmichael 1986, Telford 1990). The F value is the normalized electrical resistivity when the saturation is zero and the exponent c is the saturation sensitivity of the electrical resistivity. The F value in Eq. (3) varies with the type and crystal structure of rock. In particular, for dried fresh rocks, the F value is higher when the strength is higher. Although the F value might never reach 1.0 in practice, in theory F = 1.0 indicates 100% electrical efficiency at the highest electrical-path (Archie 1942, Winsauer *et al*. 1952).

The phase connectivity plays an important role for the exponent c in rock-water mixtures when the F value is fixed. The normalized resistivity increases below a specific degree of saturation as shown in Fig. 3 when a high electrical path is formed in the rock. As also shown in Fig. 3, the absolute c value decreases as the weathering process advances because the relative differences between the electrical resistivity of the rock mass and the electrical resistivity of materials in the void decrease with the degree of saturation (Reitz *et al*. 1979). Furthermore, the variation of the electrical resistivity becomes smaller with the degree of saturation because the number of ionic materials in the rock mass increases due to the oxidation and reduction as the weathering progress advances (Lumb 1983).

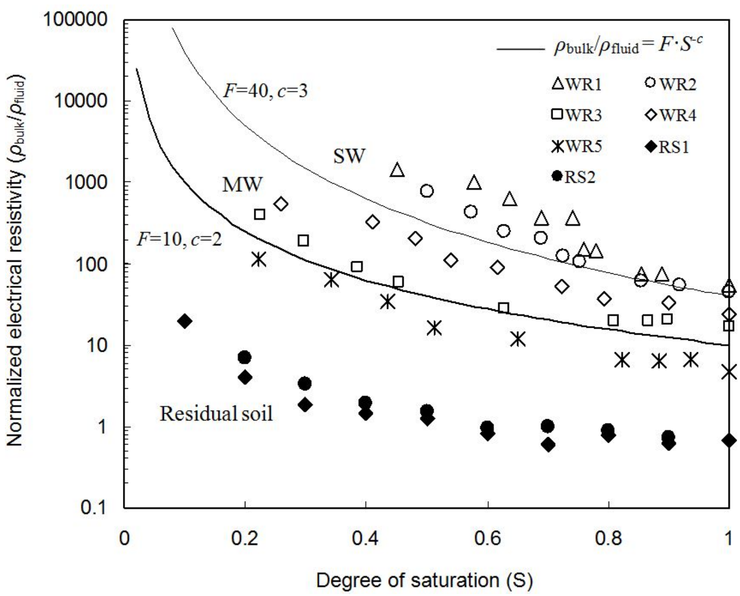

Fig. 3 Normalized resistivity as a function of saturation. Data are modeled using a simple relation: $\rho_{bulk}/\rho_{fluid} = F \cdot S^{-c}$ (solid line). SW and MW denote the slightly weathered and moderately weathered rock, respectively

4. Field application - verification

A series of field tests were conducted at three sites in South Korea using the EPS (i.e., Incheon, Siheung, and Hwasung site). A weathered zone was formed from the surface and passed through a tunnel at the Incheon site. It was expected that slightly weathered zones exist in the test sections at Siheung and Hwasung sites.

The electrical resistivity of the rock mass is calculated from the electrical resistance (R_{ir}) measured between two electrodes (ρ_{ir}) of the EPS and the electrode radius (a) based on the electric field analysis at an ideal semi-infinite surface (Reitz *et al*. 1979, Ryu *et al*. 2008)

$$\rho_{ir} = R_{ir} \cdot \pi \cdot \alpha \tag{4}$$

Fig. 4 shows the averaged normalized electrical resistivity values for the three field tests superimposed on the trends obtained from the laboratory test results (i.e., Fig. 3). Because it was difficult to precisely estimate the degree of saturation of the rock in the field, the degree of saturation of the rock was estimated using the groundwater conditions of mapping data around the measured areas: completely dry (S = 0~20%); damp (S = 21~40%); wet (S = 41~60%); dripping (S = 61~80%); flowing (S = 81~100%). The presumed degrees of saturation are between 21% and ~40% for the Incheon site, 0% and ~20% for the Siheung site, and 41% and ~60% for the Hwasung site. Thus, the degree of weathering is estimated using the degree of saturation for each site: the Incheon site is in a highly to moderately weathered state; the Siheung site is mostly in a slightly weathered state; and the Hwasung is in a moderately to slightly weathered state. Table 5 shows the comparison of the degree of weathering for granite samples estimated using measured

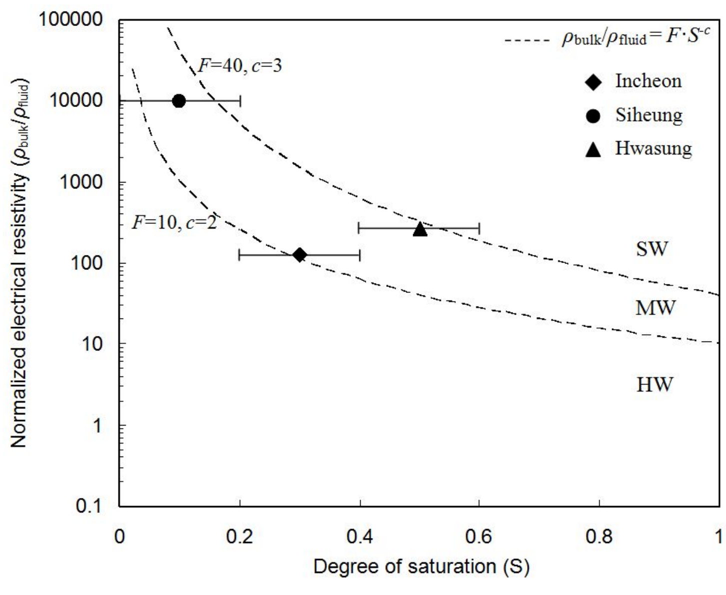

Fig. 4 Average of the normalized electrical resistivity for three field tests. The dotted lines from Fig. 3 are superimposed for comparison. Ranges of degree of saturation for each site in figure are presumed based on the mapping data. SW, MW, and HW denote the slightly weathered, moderately weathered rock, and highly weathered, respectively

Table 5 Comparison of the weathering degree by UCS and electrical resistivity

Sites	Measured UCS (MPa)	Weathering degree [1)]	Predicted weathering degree using electrical resistivity
Incheon	25~50	Highly weathered	Highly weathered ~ Moderately weathered
Siheung	130~150	Slightly weathered	Moderately weathered
Hwasung	50~100	Moderately weathered	Moderately weathered ~ Slightly weathered

[1)] Based on previous study (Lee and de Freitas 1989)
UCS is the uniaxial compression strength

uniaxial compressive strength (Lee and de Freitas 1989) and the electrical resistivity method proposed in this study. Although there was a slight difference due to the saturation conditions, the degrees of weathering predicted using the two methods are consistent.

5. Conclusions

The degree of weathering for granite was estimated using electrical resistivity. An experimental study was conducted with various rock samples that had experienced different degrees of weathering and their residual soils. The chemical indices were analyzed in order to define the main mineralogy and the electrical resistivity was measured with different degrees of saturation. The degree of weathering could be inferred from the mineralogy. However, the defined degree of weathering was inconsistent with each criterion for a same specimen.

The normalized electrical resistivity increases with a decrease in water absorption and the saturation. Thus, the normalized electrical resistivity is modeled using a simple relation of water saturation and is used for identifying the weathering degree of granites. Field test results for three sites confirm that the suggested method is effective and estimates well the degree of weathering of Korean granites compared with the other methods suggested previously. The presence or advance of fractures and voids could change the F value and the exponent c; therefore, the F and exponent c values could infer the degree of weathering of rock.

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