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PHYSICAL, PETROGRAPHICAL AND GEOCHEMICAL PROPERTIES OF WEATHERED GRANITES

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風化花崗岩의 物理的, 岩石學的 및 地球化學的 特性*

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要 約

安養花崗岩體에서 肉眼等級法에 의해 風化花崗岩 試料를 6等級으로 分類 採取하여 몇가지 物性試驗(bulk density, effective porosity, quick absorption index, sonic velocity, Schmidt hammer value, point load strength)과 顯微鏡下에서의 岩石鑛物學的 特徵, 그리고 主成分 및 微量元素 分析에 의한 地球化學的 特性 및 走査電子顯微鏡下에서의 表面 組織 變化 等에 대한 研究가 遂行되었다.

各 物性試驗은 可能한한 ISRM (International Society for Rock Mechanics)에서 定한 標準試驗方法에 의거하여 實施하였으며 新鮮한 鑛物과 變質鑛物의 比로 表示되는 micropetrographic index와 10mm traverse上에 存在하는 microcrack의 數로 나타내는 microfracture index는 薄片의 顯微鏡 觀察을 通하여 구하였다. 化學分析은 岩石 粉末을 metal block에서 HF-$HClO_4$-HNO_3混合酸으로 分解하여 AAS 및 ICAP로 分析하였고 走査電子顯微鏡 觀察用 試料는 試料를 引張破壞시킨 후 그 破壞面을 金으로 coating하여 觀察하였다.

風化花崗岩은 風化等級(風化度)에 따라 顯著한 物性 變化를 보이며 各 物性 사이에 또한 物性과 micropetrographic index, microfracture index 사이에는 簡單한 函數로 表示할 수 있는 相關關係를 갖는다. 元素含量의 相對的인 變化는 風化度가 增加함에 따라 Al, Ni, Cr等은 一定한 含量을 維持하는 反面 K, Na, Ca等은 減少하는 傾向을, Mn, Fe, Rb, Zn, Pb等은 減小하다가 風化末期인 殘留土壤에서 顯著히 增加하는 양상을 보여준다. 走査電子顯微鏡을 利用한 表面組織 變化의 觀察 結果 風化가 進行됨에 따라 構成鑛物의 表面組織이 顯著하게 變化하는 것을 確認할 수 있었다.

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1. Introduction

Weathered granite has been encountered in numerous civil engineering schemes and consequently its engineering properties and behaviours are well

known.[1-3] Some of the physical and mineralogical changes involved in the weathering of granite are also well documented.[4-9] And the details of the relationship between weathering and resultant engineering properties are occasionally reported.[10-12]

In classification of weathered granites, a number of qualitative classification have been devised for engineering geological purpose.[1,13] Kinds of classification based on degree of staining of rock material, staining and opening of discontinuities, rock and soil ratios, and presence and absence of the fabric of the original rock are all qualitative systems. But quantitative classifcation of different stages of weathering of granites could be possible by using relatively cheap and simple field and laboratory tests. Selective quantitative indices, such as the bulk density, effective porosity, quick absorption index, point load strength index, Schmidt hammer value and sonic velocity index have been proposed to examine the grade of weathering by Dearman and Irfan[14], and Baynes and Dearman.[15]

Irfan and Dearman[16] have applied petrographic hniques such as micropetrographic index (Ip) and microfracture index (I_f) as alternative approach to determine quantitatively the degree of weathered granites.

Geochemical studies of weathered granite have been carried out laying stress on the variation of major and minor elements such as K, Na, Ca, Mg, Fe, Al, Si, P, Mn, Ti, Zr and F etc[6,17-23]. But the geochemical dispersion of trace elements such as Cu, Pb, Zn, Rb, Sr, Li, Ni and Cr are poorly understood.

This study is concerned with the weathering of Anyang granite stock intruded in the most southern part of Seoul city, for which an extensive rock index and micropetrographic index tests were performed and correlation between these test results was discussed. Chemical analysis was carried out by using Atomic Absorption Spectrophotometer (AA) and Inductively Coupled Argon Plasma (ICAP). SEM (Scanning Electron Microscope) was also used in order to examine the microfabric changes owing to weathering process.

2. General geology and petrography

Anyang granite stock cuts upper pre-Cambrian gneiss in which their contact is sharp and no metamorphic facies is observed (Fig. 1). According to K/Ar age dating[24], the stock intruded in early Jurassic age (171×10^6 yrs). Hong[25] proposed that the Anyang granites belong to S-type and the ilmenite series.

The stock is coarse-to medium-grained granite with potash-feldspar (about 30% in volume), plagioclase (about 35% in volume) and quartz (about 33% in volume) as major constituents. Garnet, pyrite and iron-oxide are present as accessory minerals and biotite is relatively scarce (<0.3% in volume). Under microscope, quartz grains show undulose extinction, and intergrown each other. Potash-feldspar (mostly microcline), occasionally porphyritic, is intergranular with sharp interlocking grain boundary.

Most of plagioclase is euhedral, and was identified as albite by Michel-Levy method, and shows albite twinning mostly. Muscovite occurs as a fine-grained replacement product of potash-feldspar and plagioclase. Biotite is a greenish brown variety and suffered from chloritization and segregation of iron-oxide along cleavage traces (Fig. 2).

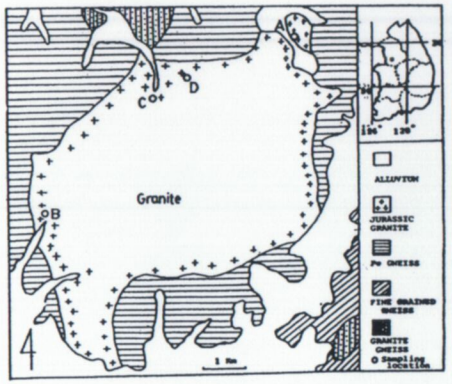


Fig. 1. Geologic map of Anyang granite and sampling sites.

3. Experimental

3-1. Field assessment of weathering grade

Visual assessment of the samples combined with a close examination of hand specimens using a hand-lens and a pen-knife to estimate the degree of change of feldspars to clay minerals shows that Anyang granite has been affected by weathering in the following sequence ;

1) Opening of discontinuities

2) Discoloration of discontinuity surface into yellowish-brown

3) Penetration of the yellowish-brown discoloration into the joint bounded blocks of the rock material, accompanied by decomposition of some minneral constituents to secondary mineral products

4) Increase in the volume of discolored part to more than 50 percent, with a somewhat paler grey colour than the fresh still present in the core of the block

5) Complete discoloration of the rock material accompanied by partial decomposition to clay minerals throughout the rock

6) Increase in the amount of decomposition of the mineral constituents to clay minerals, accompanied by a high degree of microfracturing and weakening of the rock

7) Complete decomposition of some of the original rockforming minerals.

3-2. Sample collection and preparation

Forty-one samples, representatives of six stages of weathered granite material (from the least affected rock to in-situ disturbed soil), were collected and its grading criteria are shown in Table 1. Each sample was collected with chisel and shovel after tested by in-situ Schmidt hammer. Irregular lumps were used for evaluating bulk density, effective porosity and quick absorption index, and specimens with parallel ground ends were for sonic velocity and point load strength test.

Fresh, slightly, and moderately weathered samples (representing grade I to III) were cut with diamond saw, and ground and polished using 400, 800 mesh carborundum (SiC) and alumina (Al_2O_3) to make their thin sections. Highly and completely weathered samples, and engineering soils (grade IV to VI) were impregnated with epoxy resin in va-

Table 1. Scale of weathering of rock mass.[26]

Term	Grade	Description
Fresh	I	No visible sign of rock material weathering ; perhaps slight discoloration on major discontinuity surfaces.
Slightly weathered	II	Discoloration indicates weathering of rock material and discontinuity surfaces. Some of the rock material may be discolored by weathering ; yet it is not noticeably weakened.
Moderately weathered	III	The rock material is discolored and some of the rock is appreciably weakened. Discolored but unweakened rock is present either as discontinuous framework or as core-stone.
Highly weathered	IV	Some of the rock material is decomposed and/or disintegrated to soil. Fresh or discolored or weakened rock is present either as a discontinuous framework or as core-stones within the soil.
Completely weathered	V	All rock material is decomposed and / or disintegrated to soil. The original mass structure and material fabric are still largely intact. (약간의 구조 가지고 있으나 긁어보면 토양이다
Residual Soil	VI	All rock material is converted to soil. The mass structure and material fabric are destroyed. There is a large change in volume, but the soil has not been significantly transported. Can be divided into a upper A horizon of eluviated soil and a lower B horizon of illuviated soil.

cuum drying oven for 30 minutes at −70torr, and then completely hardened specimen was treated as the same procedure for micropetrographical study.

For chemical analysis, samples were pulverized in mortar under 140 mesh after crushing by jaw crusher, and dissolved by strong acid attack using HNO_3-HClO_4-HF mixtures in metal block. Careful quality control was carried out by inserting some duplicates, blanks, and reference materials for each batch. Mean of precision is better than 10% on the 95% confidence level.

For scanning electron microscopic study, specimens were dried in the oven completely and tensile fractured surfaces were made by hammer, chisel and crowbars.[26] Gold was coated about 300Å thick as a conducting material by ion sputter. Then, prepared surface was observed with scanning electron microscope.

3 − 3. Quantitative micropetrographic properities

1) Micropetrographic indices

Modal petrographic analysis were carried out on the thin sections using a polarizing microscope with mechanical stage for piont counting. Adopted method was the standard point count technique.[27]

Taking into consideration of the grain size, magnification of x50 was used, and a horizontal spacing of point along the line of traverse was 0.5mm and so was vertical spacing. 150 to 250 points were counted on each slides.

The micropetrographic index is given as[28]

$$I_P = \frac{\%\ \text{sound constituents}}{\%\ \text{unsound constituents}}$$

Ip가 낮아질수록 weathered

In this study, sound constituents are primary minerals such as quartz, plagioclase, potash-feldspar, muscovite, biotite and other ferromagnesian minerals, and accessory minerals such as garnet, zircon and pyite. Unsound constituents are secondary minerals such as sericite, kaolinite, gibbsite (all three present in altered feldspars), chlorite, secondary muscovite, iron oxides plus microcracks and voids.

2) Microfracture indices

Microfracturing, including both microcracks and voids, may be quantified by counting the number of fractures in a traverse on the thin sections.[5]

In this study, three 10mm-long traverses were used. The microfracture index is the number of fractures per 10mm length, hence the mean of three was calculated for each sildes (I_r).

4. Results and discussion

4 − 1. Description of weathered samples

Selected samples from the weathering zone show distinctive change from fresh rock in terms of discoloration, chemical decomposition and disintegration, and are graded (classified) as follow (see Fig. 2).

1) Fresh granite (weathering grade Ⅰ) : The rock shows no changes attributable to weathering. Light bluish-grey in color and extremely strong (Schmidt hammer value, SHV>59) with highly interlocking texture.

2) Slightly weathered granite (grade Ⅱ) : The rock is stained brownish yellow in color on the joint surface. Discoloration is less than 50 per cent by volume, There is slight grittiness in the feldspars. Biotite begins to bleach (SHV : 51−59).

3) Moderately weathered granite (grade Ⅲ) : Discoloration is more than 50 per cent by volume but less than 100 per cent. Outer rim is yellowish brown and the inner core is pale yellowish grey in color. Some of feldspars are gritty in outer zone and biotitesare decomposed and leave brown iron stainings scattered. Fractures are somewhat loosened (SHV : 46−56).

4) Highly weathered granite (grade Ⅳ) : The rock is completely stained yellowish brown to yellowish orange. Feldspars are partially decomposed and fractures are open. There is a tendency for grain boundaries to be opened (SHV : 35−46).

5) Completely weathered granite (grade Ⅴ) : The rock is discolored and bleached. Feldspars are partially to completely decomposed. This is a transitional stage between the completely weathered rock and granitic soil. The rock is weakened due to opening up of grain boundaries and intense microfracturing (SHV <20).

6) Granitic soil (grade Ⅵ) : Completely discolored and gritty. But structure still remains in some

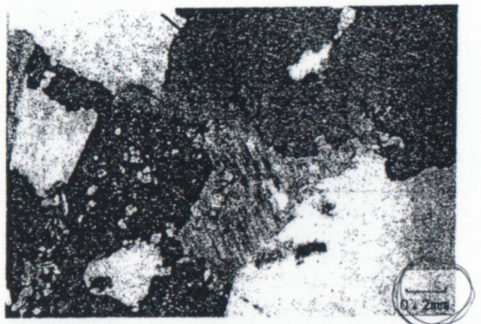


Fig. 2(a) Fresh quartz and muscovite. Weathering grade Ⅰ. (Crossed nicols) No. 1B3

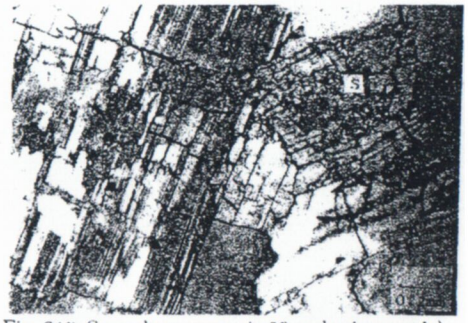


Fig. 2(d) Secondary muscovite(M) and microcrack developed perpendicular and parallel to twinning planes. Sericite(S) is the weathered product of plagioclase. (Crossed nicols) Weathering grade Ⅳ. No. : 4C3

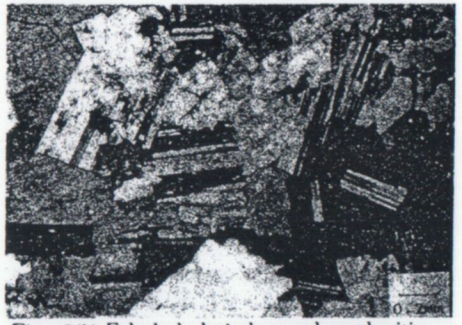


Fig. 2(b) Euhedral plagioclase and porphyritic texture. Weathering grade Ⅱ. (Crossed nicols) No. : 2D6

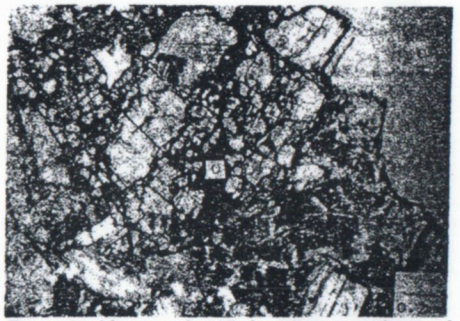


Fig. 2(e) Microcracks filled with iron-oxide(O) and bleached biotite(B) and clay minerals(C) in orthoclase. Weathering grade Ⅴ. (Crossed nicols) No. : 5A1

Fig. 2(c) Stained microcrack in plagioclase. Weathering grade Ⅲ. (Crossed nicols) No. : 3A1

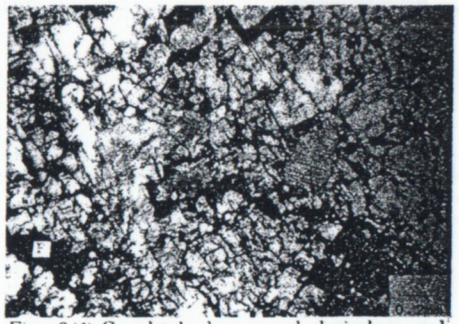


Fig. 2(f) Completely decomposed plagioclase and secondary muscovite and epoxy resin(E). Weathering grade Ⅵ. (crossde nicols) No. : 6D5

Table 2. Characterization of weathering grade of granites.

Mass weathering grade	Quick absorption QI%	Dry bulk density	Sonic velocity m/s	Schmidt hammer value	PLS*	Micro-petrographic index (Ip)	Micro-fracture index (Ir)%
Fresh (I)	<0.5	>2.60	>4400	>59	>110	>10	<1
Slightly weathered (II)	0.5~1.0	2.60~2.53	4400~3700	59~50	110~55	8~10	1~2
Moderately weathered (III)	1.0~1.4	2.53~2.49	3700~3000	56~46	100~48	5~8	2~4
Highly weathered (IV)	1.4~1.8	2.49~2.49	3000~2000	46~35	35~18	3~5	4~7
Completely weathered (V)	>1.8	<2.46	<2000	<20	<22	<3	>7

*PLS : Point Load Strengh

samples. Slakes readily in water (SHV : no instrutal response).

A typical ranges of physical and micropetrographical properties of granite in all stages of weathering are given in Table 2.

4-2. Correlation of the quantitative physical properties (Fig. 3)

*Dry bulk density and effective porosity : The simplest relationship by the least square curve fit analysis gives a linear regression of $D_d = 2.64201 - 0.03379 * P_{eff}$ with a correlation coefficient of −0.89.

*Effective porosity and sonic velocity : Sonic velocity is greatly influenced by effective porosity of rock material, which increases rapidly on weathering by removal of alteration products in solution and high intensity of microfracturing. The least square curve fit analysis gives a linear regression of $P_{eff} = 8.72351 - 0.00154 * V_s$ with a correlation coefficient of −0.91.

*Schmidt hammer value and sonic velocity : For saturated sonic velocity, least square curve fit analysis shows a linear regression with a high correlation coefficient of 0.95. $SHV = 3.5673 + 0.01214 * V_s$

*Schmidt hammer value and effective porosity : Least square curve fit analysis shows a linear relationship with a correlation coefficient of −0.90. $P_{eff} = 8.78138 - 0.11812 * SHV$

*Schmidt hammer value and point load strength : Least square curve fit analysis shows a good exponential relationship with a relatively high correlation coefficient of 0.93 $SHV = 12.899 + 0.15967 * V_d$

*Point load strength and quick absorption index : The relationship is exponential with a correlation coefficient of −0.86. $PLS = 168.50408 * \exp(-1.13165 * QI)$

*Point load strength and bulk density : Least square curve fit analysis shows a exponential relationship with a correlation coefficient of 0.93. $PLS = 1.24995 \times 10^{-7} * D_d^{2.47624}$

4-3. Interrelationship between quantitative micropetrographic properties and selected index properties (Fig. 4)

*Micropetrographic index and bulk density : The least square curve fit analysis shows that the equation is given as fractional form with a

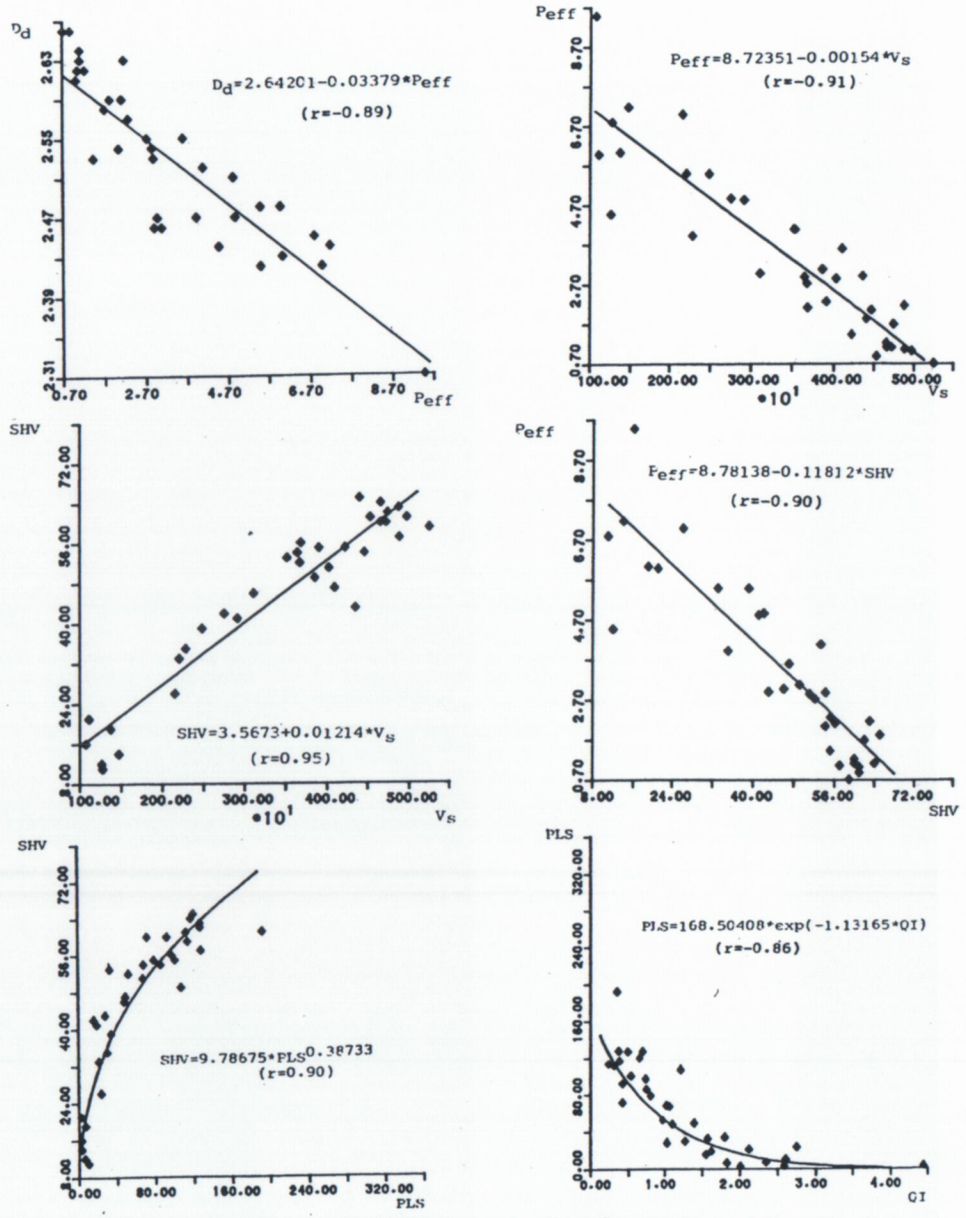


Fig. 3. Correlation diagram of the couple of quantitative physical properties.
D_d (dry bulk density), P_{eff} (effective porosity), V_s (sonic velocity), SHV (Schmidt hammer value), PLS (point load strength), QI (quick absorption index).

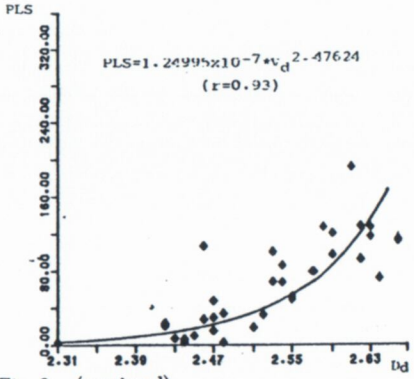


Fig. 3. (continued)

correlation coefficient of 0.80.

$I_p = 1 / (4.43033 - 1.6623 * D_d)$

* Micropetrographical index and effective porosity : Least square curve fit analysis shows a exponential relationship with a correlation coefficient of −0.88.

$I_p = 15.49504 * \exp(-0.29479 * P_{eff})$

'icropetrographic index and point load strength : .east square curve fit analysis shows a linear relationship with a correlation coefficient of 0.83.

$I_p = 1.87317 + 0.08248 * PLS$

* Microfracture index and effective porosity : The simplest relationship is linear with a correlation coefficient of 0.81.

$I_p = -0.26926 + 1.21696 * P_{eff}$

* Microfracture index and Schmidt hammer value : The relationship is linear with a correlation coefficient of −0.81.

$I_f = 12.20638 - 0.18334 * SHV$

4 - 4. Geochemical properties

1) Major element geochemistry

* Aluminium : Concentration of aluminium increases slightly with intensity of weathering. However, it should be emphasized that the apparent increase in aluminium is due to the loss of other constituents during weathering processes. By this reason, in this study, all contents of major and minor elements are normalized on the basis of mean content of aluminium of 4.53% in weathering grade I and II. Mean contents of aluminium in each weathering grades range from 4.5 to 5.0%.
* Potassium : Potassium is one of the most important elements which compose potassium feldspar (orthoclase). Potassium feldspar has relatively strong resistance against chemical weathering. In this study, potasium is stable in earlier stages of weathering, but in the latest stage (weathering grade VI), the content of potassium diminishes considerably owing to alteration of potassium feldspar.
* Sodium : The primary control on sodium mobilization during the weathering of granitic rook is the relative stability of plagioclase feldspar, the major carrier of sodium in most granite. In comparison with potassiumfeldspar, plagioclase is more acceptable to weathering and easily releases sodium ions. As shown in Fig. 5. normalized sodium content decrease gradually during the transformation of rock to soil.
* Magnesium : Ferromagnesian minerals, for example, biotite and and hornblende, are known as the most acceptable minerals in weathering procedure. As weathering proceeds, biotite is firstly decomposed and release magnesium ions, and organic rich materials appear to absorb the released magnesium ions. As shown in Fig. 5, in initial stages of weathering, normalized magnesium contents are almost constant but in later stages, slight increase is detected and enormous enrichment is recognized in the latest stage.
* Calcium : Anyang granite is generally classified as low calcium granite.[25] Calcium is one of the elements that compose plagioclase feldspar. Microscopic observation of plagioclase reveals that most of plagioclase is albite and oligoclase (Na-rich and Ca-poor feldspar). Consequently, calcium contents are extremely low, ranging from 43 to 190 ppm. As shown in Fig. 5, calcium contents increase in earlier stages of weathering while considerable depletion is detected in later stages.
* Iron : The tendency to a depletion of iron during the transformation of rock to soil is recognized. Ferromagnesian minerals and iron sulfides are very sensitive to weathering. As weathering proceeds, they are easily decomposed and release iron ions, and released iron ions are absorbed in

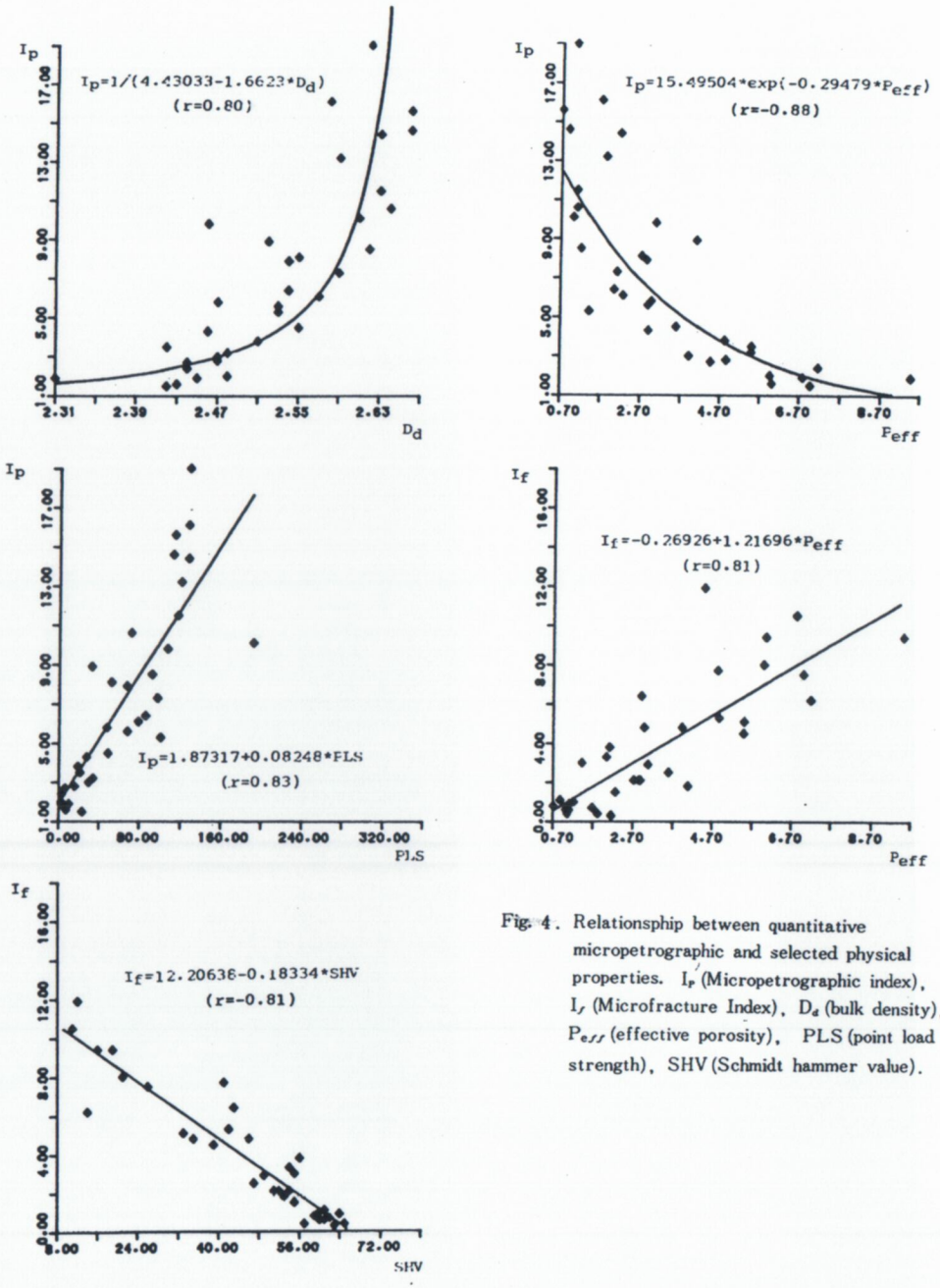
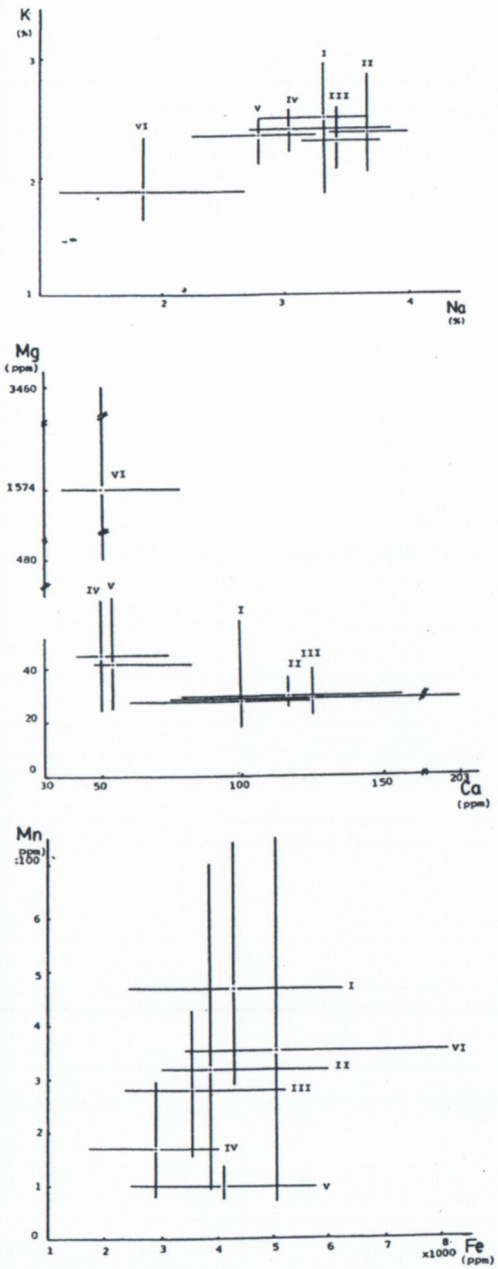


Fig. 4. Relationsphip between quantitative micropetrographic and selected physical properties. I_p (Micropetrographic index), I_f (Microfracture Index), D_d (bulk density), P_{eff} (effective porosity), PLS (point load strength), SHV (Schmidt hammer value).



organic rich materials in later stages of weathering.

* Manganese : Similar tendency to iron is detected from manganese. Manganese is depleted as weathering proceeds, but in the latest stage, considerably enriched to form manganese oxides and the hydroxides.

2) Trace element geochemistry

* Rubidium : Anyang granite is known as late differentiated granite so that rubidium content in whole rock should be high. The content of rubidium is almost 10 times as high as world average (150ppm). In this study, rubidium is depleted in earlier stages of weathering, and slightly enriched in intermediate and later stages of weathering.
* Strontium : Strontium is depleted about one twentith of world average (285ppm) owing to strong differentiation of granite. As shown in Fig. 6, strontium content is stable in earlier stages of weathering and depleted in later stages.
* Lithium : The lithium content shows a irregular variation even in the same weathering grade of granites probably owing to difference in mineralogy and degree of differentiation.
* Copper : The distribution of copper in each weathering grade is very irregular.
* Lead : The tendency to a gradual depletion of lead is noted, but in the latest stage of weathering lead is slightly enriched.
* Zinc : The redistribution pattern of zinc during weathering is similar to that of lead, i. e. depletion in earlier stage and enrichment in latest stage.
* Nickel : Regular variation of nickel in weatthering procedure is detected. There is tendency to a slight increase in the latest stages of weathering
* Chromium : The same tendency with nickel is detected. from chromium.

4 – 5 Scanning Electron Microscopic Study

Scanning electron microscope (SEM) has been used to observe the microfabric changes during the weathering of granite. The initial ingress of weathering agencies occurs along the primary cracks or pores and open cleavages, and results in decomposition and solution along the structurally controlled planes in feldspars, or decomposition and expansion of biotite lattice, and microfracturing of quartz.[30]

In terms of fundamental material nature of weathered granite, the initial stages of weathering are dominated by the opening of grain boundaries, microfracturing and the development of an intragranular porosity in feldspars. The later stages of

Fig. 5. Change of major element contents from weathering grade Ⅰ to Ⅵ.

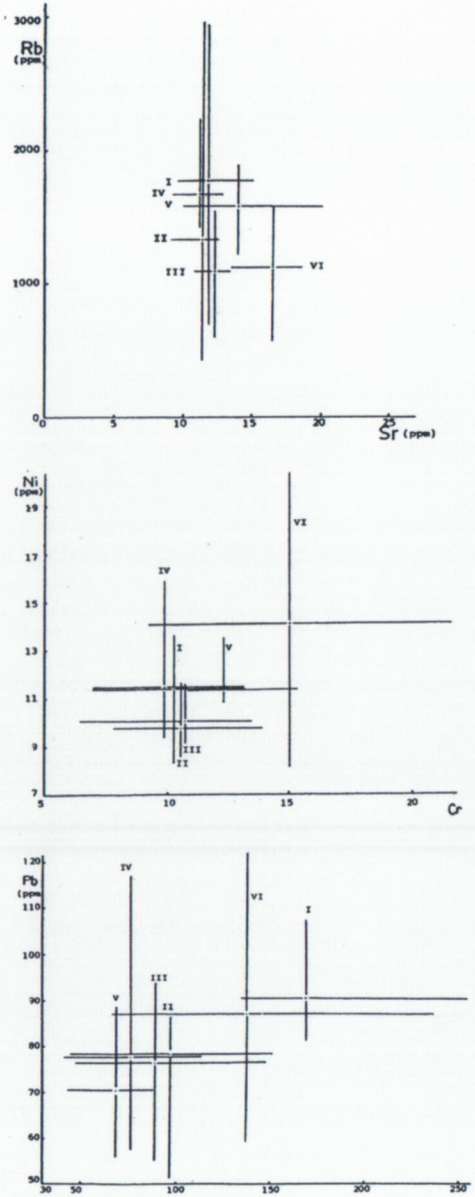


Fig. 6. Change of trace element contents from weathering grade Ⅰ to Ⅵ.

Fig. 7 (a) Tensile fracture surfaces of fresh granite. Fresh biotite and K-feldspar are shown. Scale bar is 10 microns. No. : 1B5

Fig. 7 (b) Tensile fracture surfaces of slightly weathered granite. Quartz and K-feldspar are still clean, but prismatic etch pits begin to appear in plagioclase. Scale bar is 100 microns. No. : 2A2

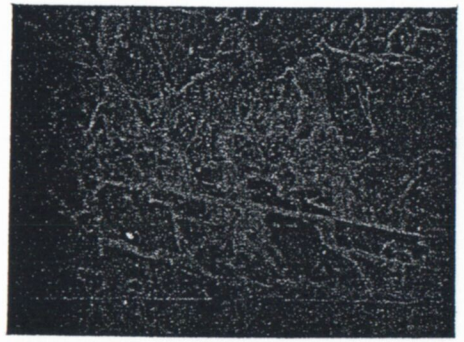


Fig. 7 (c) Tensile fracture surfaces of moderately weathered granite. Prismatic etch pits penetrate plagioclase and intragranular microfractures are shown. Scale bar is 100 microns. No. : 3A2

Fig. 7 (e) Tensile fracture surfaces of completely weathered granite. K-feldspar is still discernible with round edges, plagioclase is completely decomposed. Scale bar is 100 microns. No. 5D7

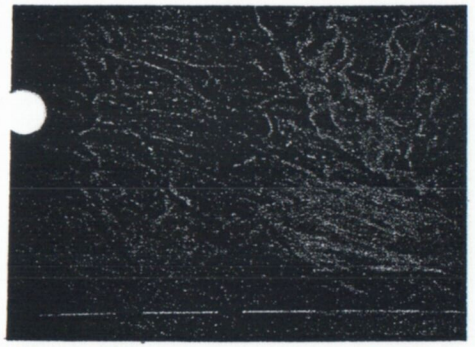


Fig. 7 (d) Tensile fracture surfaces of highly weathered granite. Irregular etch crevasses penetrate plagioclase. The edge of crevasses are rounded. Scale bar is 10 microns. No. : 4C3

Fig. 7 (f) Tensile fracture surfaces of residual soil. Card house structure of clay particles are shown below. Clay in accicular crystal form is shown above. Scale bar is 10 microns. No. : 6D5

weathering are dominated by the variable nature of weathering products.

The result of SEM study reveals some of the fundamental microfabric changes that occur during the weathering of granite.

5. Conclusion

The conclusion reached from this study on the physical, petrographical and geochemical properties of weathered granite are summarized as follow;

1) Visual assesment of weathering grade matches well with the result of selected index tests such as bulk density, effective porosity, sonic velocity, Schmidt hammar value, point load strength and quick absorption index.
2) Selected physical properties such as sonic velocity, point load strength, bulk density and Schmidt hammer value are correlated each other with relatively high correlation coefficients.
3) Detailed quantitative micropetrographic analysis provides an important insight into the change of mineralogy and microcrack regimes involved in progressive weathering.
4) As weathering proceeds, Mg tends to increase while K, Na and Ca tend to decrease. Al, Ni and Cr show regular variation and Mn, Fe, Rb, Pb and Zn tend to decrease in earlier stages of weathering and increase in latest stage.
5) Considerable changes of the surface texture of plagioclase are denoted as weathering proceeds.

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