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Weathering Indices for Assessment of Weathering Effect and Classification of Weathered Rocks: A Case Study from NE Turkey

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1. Introduction

Weathering state and weatherability of rocks are highly important for engineering geology projects and the use of rocks as building. The state of weathering resulting physical and chemical processes may be reflected by changes in index properties such as dry density, void ratio, clay content and seismic velocity. Thus, it is important for geotechnical engineers to estimate weatherability of rocks, quantitatively the changes during weathering and classification of the weathered rocks. In this study, first these topics which are the classification of weathered rocks and the indices for definition of the effects of the weathering is discussed and then a case study from NE Turkey is given. The research reported here was carried out in a 40 km^2 area of Upper Cretaceous Eocene granitic rocks along the River Harsit around Dogankent (Giresun) in the North eastern part of Turkey (approximately 41^0 N, 39 ^{0}E). In the case study, the definition of mineralogical and chemical changes created by the weathering of the Harsit granitic rocks and the classification of weathered rock materials and masses from the granitic rocks were investigated

2. Weathering indices

Several weathering indices have been devised for quantifying the changes in the intrinsic properties of rocks from different points of view, some of which can be related to the engineering properties of weathered rocks (Tecer 1999, Gupta and Rao 2001, Tecer and Cerit 2002, Ceryan et al. 2005). The most commonly used methods can be broadly categorized as chemical, mineralogical-petrographical and engineering indices (Gupta and Rao 2001). Several mineralogical and micropetrographical parameters have been proposed as the basis for weathering indices in view of their variation with weathering (e.g. Lumb 1962, Weinert 1964, Mendes et al. 1966, Dixon 1969, Onodera et al. 1974, Irfan and Dearman 1978a, 1978b, Cole and Sandy 1980, Howarth and Rowlands 1987, Tugrul and Gurpinat 1997, Rigopoulos et al 2010).
Chemical change during weathering and hydrothermal alteration are quantified in several ways including the normalized value of element (or oxide) using their parent rock concentrations or immobile element concentrations in the samples (Krauskopf 1967, Minarik

et al. 1983), standard cell calculation (Colman 1982), ratio of elements to immobile elements (Chesworth et al. 1981, Colman 1982, Guan et al. 2001), measurement and calculation of loss or gain of weight (or volume) based on immobile element (Gresens 1967, Grant 1986, MacLean 1990, Huston 1993), using cation packing index (Ceryan et al 2008c, Ceryan 2011), cation exchange capacity (Arikan et al. 2007), modeling of compositional change due to chemical weathering (Eynatten et al. 2003), using an EC/pH meter (Shalkowski et al. 2009) and chemical weathering indices (Vogel 1973, Jayawardena and Izawa, 1994a,1994b, Düzgören-Aydın et al. 2002, Düzgören-Aydın and Aydin 2003, Price and Vebel 2003, Bozkurtoglu et al 2006, Ohta and Arai 2007, Ceryan et al. 2008a,Yildiz et al 2010, Ceryan 2011). Chemical weathering indices have also been proposed by numerous authors. These indices were summerized in Duzgoren-Aydın et al. (2002).

According to Ceryan (2008), no single weathering index given in the literature meets the modeling of the process involved in chemical weathering outlined above, and no weathering index would give unequivocal results when applied to the prediction models to assess the mechanical behavior of rocks materials. Thus, a theoretical model was developed by Ceryan (2008). The said model depends on isovolumetric approach and take into consideration of the definition of Loughnan (1969). In order to explain the change of the volumetric concentration of major oxides across a weathering profile, the following steps were applied (Ceryan 2008).

- Modal analysis and whole rock analyses of the sample taken across a weathering profile are performed.
- The weight percentage of the major oxide under interest from whole rock analyses of fresh samples are multiplied by dry density of the respective sample. Then Amob value in Figure 1a is obtained. By means of this Amos value, a parallel line (OA) was drawn.
- For each sample weathered to various degrees, the weight percentage of the major oxide is multiplied by dry density. By this way, upon plotting of the dry density as a function of the volumetric concentration of the major oxide, the OB line in Figure 1a is obtained.
- By microprobe analysis of the fresh minerals, the major oxide composition of the minerals in the sample is determined.
- To calculate total amount of the major oxide in unaltered portion, the following equation (Banfield 1985) is applied.

$$Wmo = \left[\sum_{i=1}^{n} Mv(i) \times Ow(i) \right] \tag{1}$$

  where Wmo is the weight percentage of the major oxide in weathered sample, i values represent minerals such as plagioclase (i= 1), orthoclase (i= 2), hornblende (i=3), biotite (i=3), pyroxene (i= 4), quartz (i= 5), opaque minerals (i= 6), Mv is the volume percentage of minerals found by the modal analysis, Ow is the concentration (in weight percentage) of the major oxide in minerals from the microprobe analysis.
- The total amount of any major oxide from the equation 1 is multiplied by its dry density and then the volumetric concentration of the major oxide in the unaltered portion of the sample is found
- The volumetric concentration of the major oxide in the unaltered parts of the samples versus the dry density of the samples weathered to various degrees are drawn and then the OC line in Figure 1a is obtained.

Ca, Na, Mg, and K are geochemically mobile elements. Chemical leaching results in a significant decrease of the oxides of these elements. The ratio of the volumetric concentration of ($CaO+MgO+Na_2O+K_2O$) in a weathered sample to those in the fresh sample taken from the same weathering profile gives the amount of leaching for the weathered sample. Therefore, this ratio given at the Equation 2 is defined as the *Chemical Leaching Index* (CLI) (Ceryan 2008). Al, Fe, and Ti are less affected by chemical leaching than alkali and alkali-earth elements, but tend to concentrate in weathering products (Loughnan 1969). If the drainage is well-developed, Si moves away, if not, it also tends to concentrate in the weathering products. The ratio of the total amount of these oxides in weathering product to those in the respective sample yields the amount of weathering products. Therefore, the *chemical weathering product index* (CWPI) is defined through the Equation 3 (Ceryan 2008).

$$CLI = \frac{100(A_{mob} - B_{mob})}{A_{mob}} \tag{2}$$

$$CWPI = \frac{100(B_{immob} - C_{immob})}{B_{immob}} \tag{3}$$

where A_{mob} and B_{mob} are the total volumetric concentration of mobile oxides in fresh sample and weathered sample, respectively. B_{immob} and C_{immob} are the total volumetric concentration of immobile oxides in the whole sample and unaltered portion of the sample, respectively. If y axis in the Figure 1a represents the volumetric concentration of the mobile elements, likewise CLI can be found for the weathered sample.If y axis in the Figure 1b represents the volumetric concentration of immobile elements, CWPI can be found for the weathered sample as defined above.Considering the definition of Loughman (1969), *Total Chemical Weathering Index* can be defined as the sum of CWPI and CLI. Since the rock material can be weathered 100% at most, TCWI value should be also at most 100. Therefore, (CWPI+CLI) value has been divided by 2 in order to get TCWI given by the following equation (Ceryan 2008).

$$TCWI = \frac{(CWPI + CLI)}{2} \tag{4}$$

According to Olier (1984), the weatherability of a rock depends on the number of cation replaceable with hydrogen in a mineral. When considering this definition of the k-value, it is possible to say that the k-value can be used for characterizing the weathering state and weatherability of a rock (Ceryan et al 2008b, 2008c). In addition;

a. By using the k-value, the amount of the removed minerals by chemical leaching can be estimated,
b. The amount of weathering products can be found by the k-value,
c. The petro-physical properties of a rock can be expressed depending on weathering degree by k-value,
d. Although the chemical weathering indices are calculated by results of the chemical analyses, the k-value is obtained from modal analyses (Ceryan et al 2008c)

The cation distribution is defined by the "Cation Packing Index", k-value, for each (stochiometric) mineral phase. k-value (mole/cm^3) is described as follows:

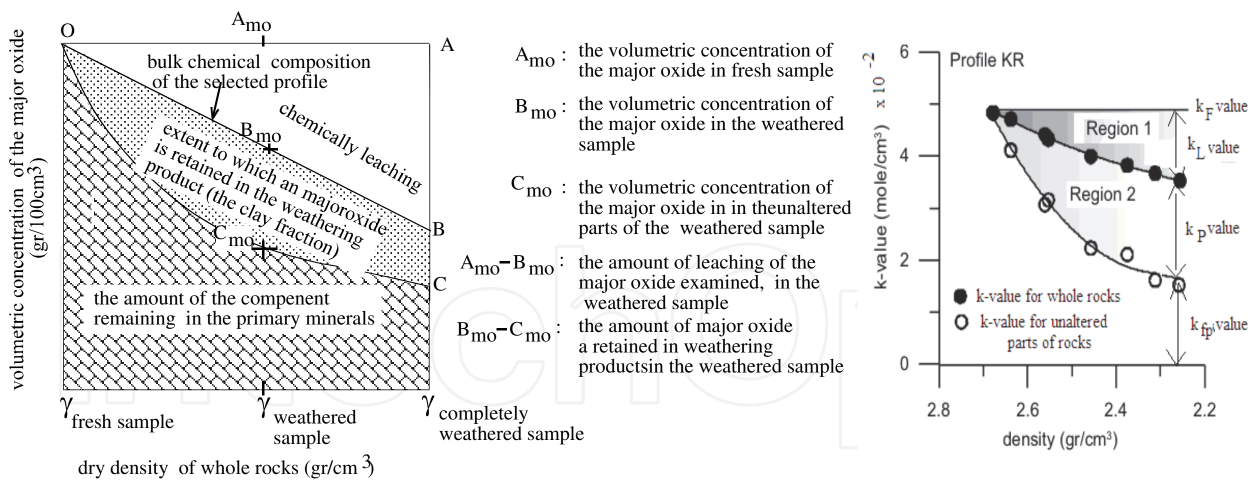


Fig. 1. A hypothetical model illustrating the behavior of major oxides during chemical weathering (modified Banfield 1985) (a), the graphs showing the relationhips between the density and the cation packing index, (k-value (Ceryan 2011) (b).

$$k = \frac{C}{N_L V_M} \tag{5}$$

where C is number of cations per mole, N_L is Avogadro's number and V_M is molar volume. For a certain rock, k-value can be calculated by using the following expression:

$$k = \sum x_i k_i \tag{6}$$

where k_i is the k value of the i mineral phase, x_i is is mod of the mineral in the rock determined by modal analysis of thin sections

Ceryan (2011) said that as decomposition of a mineral result in the formation of new minerals with lower k-value, the k-value of whole rocks is generally regarded as a measure of the degree of weathering (Table 1), therefore, it is possible to say that the k-value can be used for characterizing the weathering state and weatherability of a rock.

The region 1 on Figure 1b represents the chemical leaching ratio while the region 2 on Figure 1b gives the weathering product ratio. In the Figure 1b, k_F is cation packing index (k-value) of fresh sample, k_L is the amount of chemical leaching, k_P is k-value of weathered parts of samples (weathering products) and k_{pf} is k-value of unaltered parts of the samples (Ceryan 2011). The difference between the k-value of fresh sample (k_F) and the k-value (k_W) of weathered sample gives the amount of chemical leaching (k_L, Figure 1b). The ratio of the difference to k-value of the fresh sample taken from the same weathering profile is defined as k- leaching index (k^*_L). On the other hand The difference between the k-value of the whole sample and the k-value of the unaltered parts of the same samples (k_{fp}) gives the amount of weathering product. Therefore the ratio of the difference to k-value of the same sample is defined as k-product index (k^*_P) (Ceryan 2011);

$$k^*_L = \frac{k_L}{k_F} \tag{7}$$

$$k^*_P = \frac{k_P}{k_{fp}} \tag{8}$$

Minerals		PrI	Wm	Ks	k-value (10^{-2} mole/cm^3)	V_p (m//n)
Olivine	*Fayalite*	0.057	138.36	3.385	6.85	8400
	Forsterite	0.709	46.132	1.813	6.80	
Pyroxene	*Diopside*	0.362	24.434	1.829	6.05	7330-7200
	Enstatite	0.515	22.646	1.6431	6.37	
Amphibole	*Tremolite*	0.425	4.2954	1.004	5.54	6800
	Hornblende	0.849	2.8744	0.5296	5.309	
	Labradorite	0.389	0.542	0.144		
Plagioclase	*Andesine*	0.479	0.5875	0.088	4.99-4.97	7250-6250
	Oligooclase	0.529	0.5916	0.048		
Alkali-Feldspar	*Orthoclase*	0.719	0.7178	-0.0007	4.577	5800
Quartz		-	-		4.41	6050
Mica	*Moscovite*	-	-	-	4.98	5880
	Biotite	1.1613 *	4.3741*	0.5791	4,656	5360
Vermiculite		0.4439*	1.8176*	1.8176	3.95*	-
Chlorite (coronsite)		0.4996*	1.6406*	1.6406	4.10	5000
	Sericite	0.5547	0.2133	-0.4151	4.52	
Clay	*İllite*	0.1725	0.1907	0.0435	4.099	2400-1800
	Smectite	0.1044	0.1226	0.0697	3.997	
	Kaolinite	0.0462	0.0429	-0.0325	4.058	

Table 1. The chemical weathering indices values, k-value and P-wave velocity of selected rock-forming minerals and their weathering products (from Ceryan et al 2008b, 2008c)

From a geotechnical standpoint, indices based on key engineering properties generally have more applicability than those based on chemistry and mineralogy and are also usually more simple and less time consuming (Gupta and Rao 2001). Martin (1986) pointed out that in principle a simple quantitative degree of weathering scale can be established based on a reliable index of any rock property which changes unidi rectionally throughout the weathering process and whose value can be readily determined at any weathering stage. A simple and rapid test to obtain a quick absorption index (QAI) or void index has been proposed by Hamrol (1961) for the assessment of weathering of granite and schist. Water absorption by weight were used to determine weathering degree of marble by for marble Gulec (1973) and create weathering classification of rock materials by Kılıc (1995). Lee (1987) and Ceryan (1999) used it for predicting of mechanical properties of weathered granitic rocks. A different type of measure, the abrasion resistance hardness index (Ha), was devised by Conca and Cubba (1986) to study the abrasion hardness and extent of weathering in different rocks - sandstone, gabbro, tonalite and crystalline limestone (from Gupta and Rao 2001).

The slake durability index (Sd) was devised by Franklin and Chandra (1972) to assess the durability or weatherability of clastic sedimentary rocks such as mudstone, claystone and shale, particularly useful for rocks with significant clay content (Moon and Beattie 1995, Gokceoglu 1997, Koncagul and Santi 1999, Gokceoglu et al. 2000, Sadisun et al. 2005), but there are some limitations and weaknesses associated with this method (Erguler and Ulusay 2009). The other weathering indices are dry density (e.g.Banfield 1985, Turk and Dearman 1985, Eggleton et al. 1987, Irfan 1996, Ceryan 2008, Ceryan 2011), Schmidt hammer rebound value (e.g.Irfan and Dearman 1978a, Martin and Hencher 1982, İrfan and Powell 1985, Lee 1987, Guolin and Yushan 1990, Zhao et al. 1993, GCO 1994, Gokceoglu 1997, Ceryan et al 2008a, Basu et al 2009), the elastic wave velocity (e.g. Illev 1967, Kılıc 1995, 1999, Dearman and Irfan 1978, Krank and Watters 1983, Turk and Dearman 1985, Lee 1987, Dearman et al. 1987, Dobereiner et al. 1993, Weiss et al. 2002, Ceryan and Sen 2003, Kocbay 2003, Gurocak and Kilic 2005, Arikan et al. 2007,Ceryan et al. 2008a, 2008b, Basu et al. 2009, Korkmaz and Ceryan 2011), porosity, effective porosity and void ratio (e.g. Ondera et al. 1974, İrfan and Dearman 1978b, Türk ve Dearman 1985, Paşamehmetoğlu et al.1981, Lumb 1983, Lee, 1987, Esaki and Jiang 1999, Gupta and Rao 2001, Ceryan et al. 2008a, Gokceoglu et al. 2009, Rigopoulos et al. 2010, Marques et al. 2010). Ceryan et al (2008a) suggested new index base on porosity (n) and effective porosity (n_e).

$$Iefp = \frac{n_e - n}{n} x100 \tag{9}$$

Ceryan et al (2008b) suggested two new indices representing mineralogical and physical changes due to weathering. These indices, Mineralogical Change Parameter (Imp) and Physical Change Parameter (Ifp) were given following equations:

$$\mathrm{Im}\,p = \frac{100(V^*_{pf} - V^*_{pw})}{V^*_{pf}} \tag{10}$$

$$Ifp = \frac{100(V^*_p - V_p)}{V^*_p} \tag{11}$$

where Ifp is the Physical Change Parameter, V_p is P-wave velocity of the investigated dry sample and V_p^* is P wave velocity of the same samples which would have lacked pores and fissures (Foumaintraux 1976), w refers to weathered rocks, while f refers to fresh rocks. If the mineral composition of the samples is known, V_p^* can be calculated by employing the Equation 37 (Foumaintraux 1976).

$$\frac{1}{V^*_p} = \sum_{i=1}^{n} \frac{xi}{V_{pi}} \tag{12}$$

Where x_i is mod of the mineral in the rock and V_{pi} is P-wave velocity in the mineral constituent (i).

Aydın and Basu (2006) said that microstructural weakening accompanying this process is expected to be dramatic, especially in terms of tensile strength during the early stages of weathering and the behavior of rocks in tension may therefore be an effective indicator of their microstructure, and hence state of weathering. Considering the diffuculty the applicability of the index properties indicates obtained from their study, Gupta and Rao

(2001) sugested a new engineering index, strength ratio (Rs), based on unconfined compressive strength. This is expressed as

$$Rs=\sigma_{CA} / \sigma_{CFF} x100 \quad (13)$$

where; Rs is the strength ratio (%), σ_{CA} is the uniaxial compressive strength of altered rock,(MPa) and σ_{CFF} is the uniaxial compressive strength of fresh rock (MPa).

3. Classification of weathered rocks for engineering purpose

Although descriptions and classifications are related, their purpose is fundamentally different, the description of a rock being a record of what is present and the classification; of the rock being an assessment of its character in a form which permits a comparison to be made with other rocks of similar character. A classification is derived from descriptions whereas descriptions cannot be derived from a classifications (Lee 1987, Anon 1995, Ceryan 1999). Description and classification of weathered rocks are necessary to obtain the changes of its engineering properties. The first step in classification is to determine the parameters of rocks related to classification purpose and to define the rock according to these parameters and properties (Lee 1987, Anon 1995, Ceryan 1999). Defining the weathered rocks for the purpose of engineering goals is make sense to determine the degree of weathering effect, extend and characteristics in detail at that momen (Lee 1987, Anon 1995, Ceryan 1999). There are the disadvantages in using the classifications proposed for weathered rock (Table 2). Nevertheless, there are several good reasons for employing such classifications for certain rock types, particularly at higher degrees of weathering (Anon, 1995);

Disadvantages	Advantages
a. The possibility of finding rock mass properties not included in standard weathering scales in the field limits the use of these classifications.	a. Without an appreciation of the degree of weathering as a process a far poorer understanding of the engineering performance would result.
b. It is known that the classifications widely used are not handled identically and they are differently applied to all people in varying forms, and this shows that the said circumstance is treated bound to the thickness of weathering profile in that area and the knowledge and experience of the applicants.	b. Grades will often provide a framework within which test results can be interpreted and linked to engineering performance.
c. Classification includes interpretation and simplification, hence this constitutes missings in original data and descriptions.	c. Because extremely weathered rocks are often sensitive to disturbance during sampling and testing, good quality geotechnical test data can be difficult to obtain. The framework of understanding provided by a workable classification based on index properties can ensure the optimum use of the available information.

Table 2. Disadvantages and advantages in using the classifications of weathered rocks (Anon 1995)

In the literature, there are different classifications systems for weathered rocks.These systems, qualitative classification of weathered rocks, are mainly based on the visual definition of the geological properties, the index properties and the basic mechanical test that can be applied also in the field. The common properties used for classification of weathered rock materials are presence of original texture, degree of discolouration of rock, degree of chemical decomposıtion of biotite and feldspar, degree of physical disintegration, disintegration of material in water, relative rock material strength, breakability of NX core in the hand, friability, relative hardness by hammer blow, Schmidt hammer value, method of hand excavation, degree of plucking of individual grains, degree of penetration of geological pick or knife, hand penetrometer, tests (Dearman 1976, BSI 1981,Martin and Hencer 1986, Lee 1987, GCO 1994, Anon, 1995, Ceryan 1999, Ceryan et al 2008b). The common rock mass properties used in the weathered rocks classification system are rock mass: degree of discolorations along joint plane, presence of original structure, rock to soil ratio, degree of weathering along joint plane, angularity of corestone, opening of joint, NX core recovery, relative rock mass permeability, RQD (BSI 1981;Martin and Hencer 1986, Lee 1987, GCO 1994, Anon 1995, Ceryan 1999, Ceryan et al 2008b). In the present, the the most widely used weathering classification system among quantitative classification system in the literature were suggested by Anon (1995). Price (1993) suggested a ratings (quantitative) system for the description of rock mass weathering. Ratings for rock materials and ratings for discontinuity are mainly parameter used in the said system (Table 3). The system is based on visual impression. However, an approach which seems to be successful for many engineering applications is the use of a rating system to place a rock mass within a classification. In Figure 2, the rating system in graphical form and comparison of the rating system with the qualitative system suggested by Anon (19995). Akgun and Ceryan (2010) obtained that meaningful relationship between the rock mass strength properties and the weathering rating (Rw). (Eqs 13-16) And they said that Geological Strength Index (GSI) value and shear strenth of rock mass decrease with the weathering rating (Figure 3)

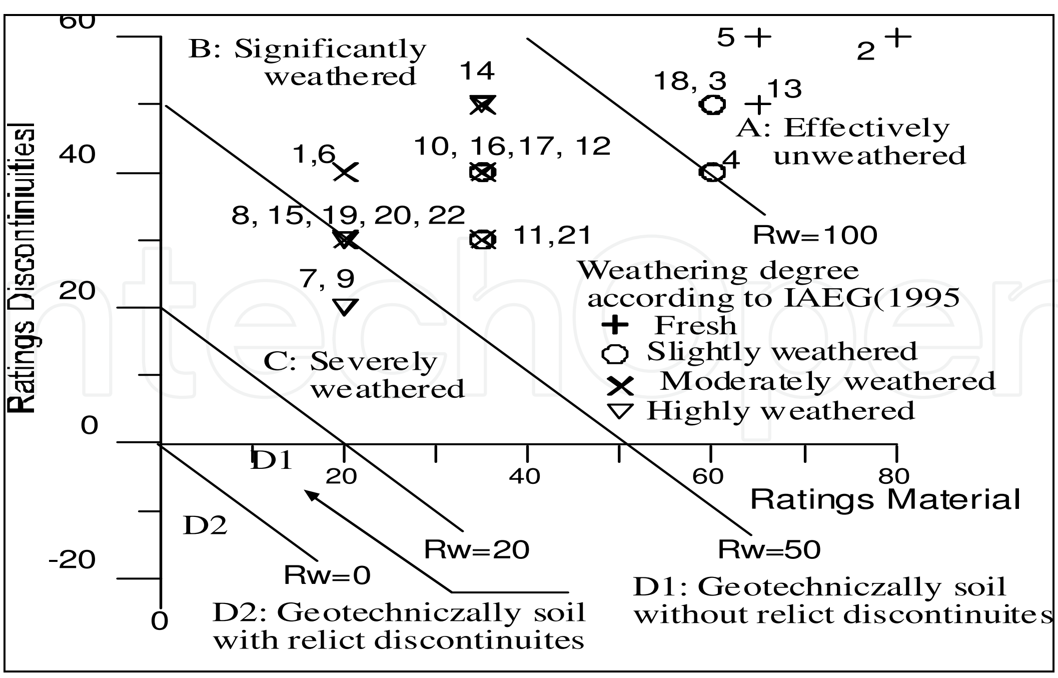


Fig. 2. The rating system in graphical form and showing the weathering degree of the geotechnical units selected from volcanic rocks from Giresun-Gumushane road, NE Turkey Number is representing geotecnical unit name (Akgun and Ceryan 2010).

Prp	Fresh	Discolored (some loss of strength)	Friable (and discolored) (considerable loss of strength, geotechnicaly an engineering soil, σ_{ci}<1.25 Mpa)
4/4	40	0	0
3 / 4	30	5	5
2 / 4	20	10	10
1 / 4	10	15	15
0	0	20	20

	Ignous rocks-joint only			All discontiniuties in all type of rocks
Prp	Unweathered	Surface stained	Rock material weathered to depth> joint wavines	Proportion of discoti-nuities present as relict in geotechnical soil
4 / 4	20	0	0	-20
3 / 4	15	5	5	-15
2 / 4	10	10	10	-10
1 / 4	5	15	15	-5
0	0	20	20	0

Sedimentary and metamorphic rocks (including limestone)- Ratings for joint and bedding or foliation planes

Prp	Unweathered	Surface staining or modified by solution	Rock material weathered to depth> joint waviness or open by solution
4 / 4	20	0	0
3 / 4	15	5	5
2 / 4	10	10	10
1 / 4	5	15	15
0	0	20	20

Table 3. Rating for all rocks materials and joint and relict discontinuities in all rocks (Price, 1993; Prp: Proportion)

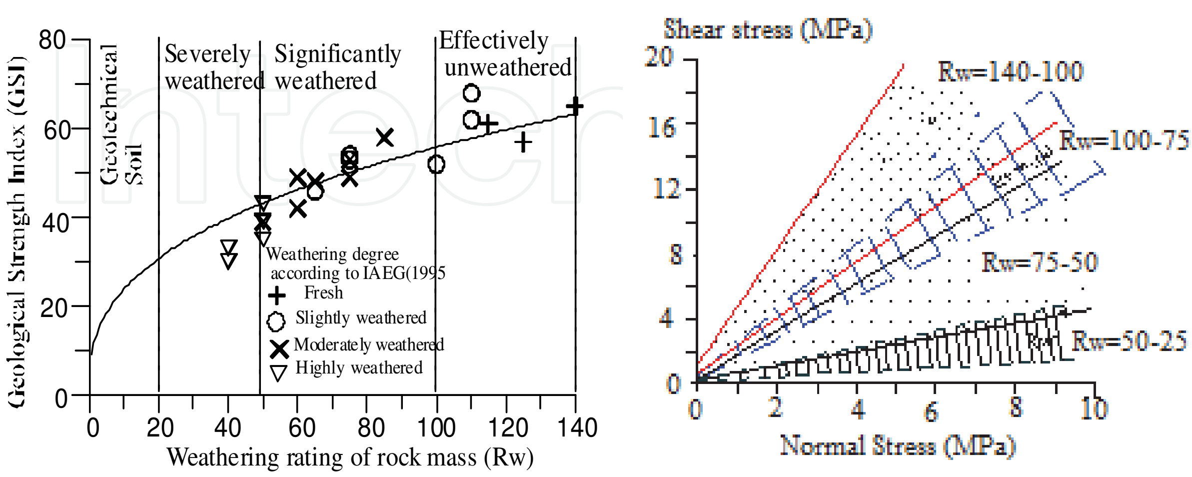


Fig. 3. Changing of the GSI and shear strength of the geotechnical units by weathering condition for volcanic rocks exposed Giresun-Gumushanr roads, NE Turkey (Akgun and Ceryan 2010).

$$GSI = 4.32Rw^{0.564} \text{ (r=0.930)} \tag{14}$$

$$\sigma_{cm} = 5.76Rw^{2.975} \text{ (r=0.945) and } \sigma_{tm} = -7.35Rw^{3.11} \text{ (r=0.923)} \tag{15}$$

$$E_m = 5.09Rw^{1.60} \text{ (r=0.938)} \tag{16}$$

$$c'_m = 6.54Rw^{1.982}10^{-5} \text{ (r=0.943) and } \phi'_m = 6.54Rw^{1.982} \text{ (r=0.928)} \tag{17}$$

Where σ_{cm} is uniaxial compressive strength of rock mass (MPa), σ_{tm} is tensile strength of rock mass (MPa), E_m is the deformation modulus of rock mass (MPa), c/ and ø/ are cohesion (MPa) and frictional angle (degree) rock mass,

The quantitative weathering systems are the second one in creating the classification systems of the weathered rock materials. The approaches used for the creation of the quantitative weathering classifications are handled within 4 groups (Ceryan et al 2008b). First approach is that the weathering grades are defined numerically according to the only one index property (Hamrol 1961, Onodera et al. 1974, Zhao and Broms 1993, Gokceoglu and Aksoy 2000). However, weathering may not be expressed by the change in one index property used in the classification. For example, measured crack density and dry density from different locations in a granitic batholith may vary depending on its heterogeneity. Moreover, crack density varies depending on the tectonic activity on the location of the sample and the technique used when preparing a thin-section. Furthermore, using only one index property does not give enough information about all the weathering processes. In the second approach, the change amount of an index property measured on weathered sample to the value measured in the fresh sample is taken essentially. In this approach, the qualitative definition of the weathering grade has been shown in the following equation.

$$WD = \frac{100(Z_{fresh} - Z_{weathered})}{Z_{fresh}} \tag{18}$$

where, WD is weathered degree of the sample, Z_{fresh} is the measured value of the fresh rock property basically used. $Z_{weathered}$ is the value of the measured weathered rock property

Weathering classifications using elastic wave velocity (Illiev 1967), water absorption (Gulec 1973) and unconfined compressive strength (Gupta and Rao 2001) are some examples for this approach. The third approach is the use of empirical formulae which are commonly used in obtaining the quantitative weathering scales. In these formulae, two or more properties are used. The approaches proposed by Guolin and Yushan (1990), Kılıç (1995, 1999), Kocbay (2003) and Lan and et al. (2003) can be given as examples.The last one proposing quantitative weathering scale uses the statistical analyses such as hieracical cluster analysis (Wei and Lui 1990) and multiple regression and factor analysis (e.g. Arikan et al. 2007).

The changes caused by weathering processes in rock material may be mainly considered under the two topics; first is the mineralogical change (and directly chemical change) and second is the physical change. Each of these changes can be defined separately and measured (Ceryan et al 2008b). The width of micro-cracks (Onodera et al. 1974), crack density (Dixon 1969, Davis 1984), micro-fracture index (Irfan and Dearman 1978a, Al-Qudami et al. 1997) and linear crack density (Sousa et al. 2006) were used order to measure the physical change occurred by the weathering in rock material (from Ceryan et al 2008b). To define the mineralogical and chemical changes numerically due to weathering, it is possible to find various methods in the literature including chemical weathering indices and petrographical indices given above (from Ceryan et al 2008b). If we are able to measure the mineralogical and physical changes separately in the weathered rock material, we can show each of these changes in the distant axis in the Cartesian coordinate system (in the continual axis set that the other one admitted) (from Ceryan et al 2008b). Fig 4a, the definition of weathering degree based on mineralogical change and the physical change shown in thin section image. In Fig. 4b from Al-Qudami et al. 1997, the mineralogical change was defined by the secondary mineral content and the physical change was described by micro fissuring index. As a consequence of the demonstration of the physical and mineralogical changes in this way (on the different axes in the Cartesian coordinate system), the weathering state can be defined as the distance from the origin (from Ceryan et al 2008b).

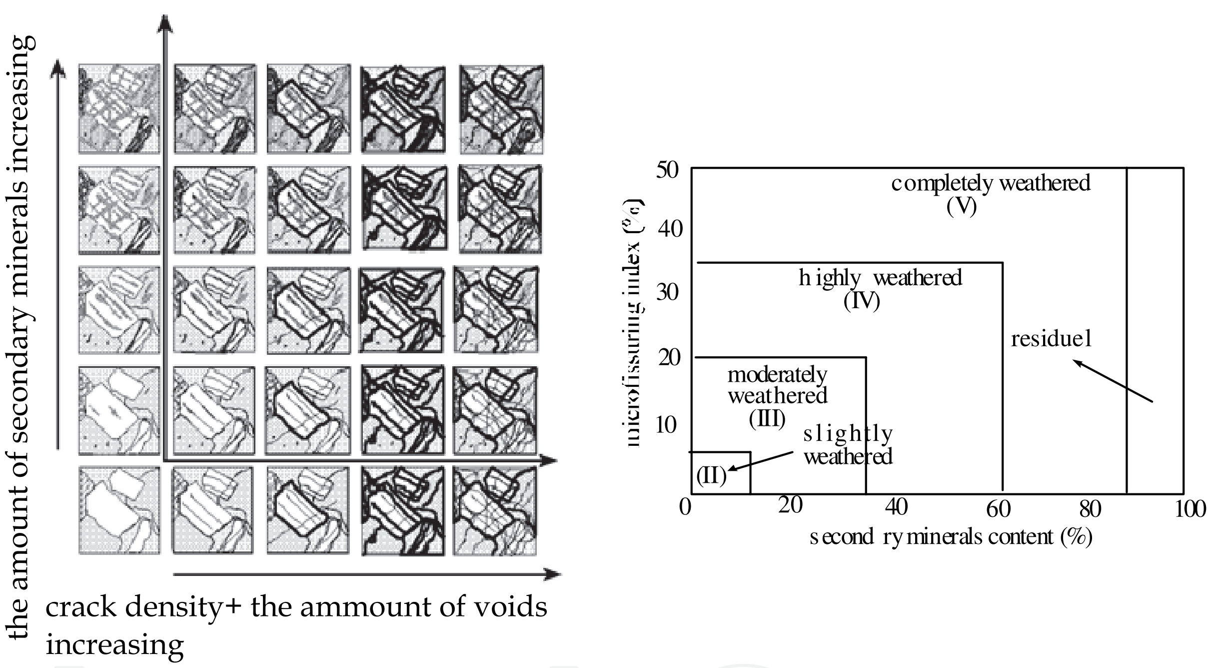


Fig. 4. The definition of weathering degree based on mineralogical change and the physical change caused by weathering processes(a) and the secondary mineral content and micro-fissuring index

Ceryan et al. (2008b) said that If Imp and Ifp are shown on the distance axis in the cartesian coordinate system, the distance from the origin will show the weathering condition of the sample. Therefore, “Weathering State Parameter ”, Iad, showing the weathering condition has been defined by the following equation (Ceryan et al 2008b).

$$Iad = \sqrt{\frac{Ifp^2 + \mathrm{Im}\,p^2}{2}} \tag{19}$$

Iad together with slake-durability index value (Id), an indicator of the rock to soil ratio in the weathered rock material (Lee and Freitas 1988), should be considered in order to be able to define the weathering grades completely and significantly. As a result of this approach, "Quantitative Weathering Index (Ia)" can be formulated following formula (Ceryan et al 2008b),

$$Ia = 100 - ((100 - Iad) * Id * 0.01) \tag{20}$$

Advantageous of the numerical weathering index proposed by Ceryan et al (2008b) were given as follows;

- During the P-wave velocity tests, the samples are not disturbed and hence, the test can produce many results using one sample.
- Descriptions of mineralogical and physical changes seperately allow to make a comparison between two. By using this comparison, it is possible to assess the weathering process.
- It is possible to construct some correlations between the numerical weathering index and the engineering properties of rocks. By using these correlations, the engineering properties of the weathered rock material can be predicted easily and reliably.
- It is possible to classify the weathering degrees of igneous rocks by using the numerical weathering index and the weathering classes provide important informations about engineering behaviour of igneous rocks.
- When determining the weathering degress of pyroclastic rocks such as tuff by using the numerical weathering index, the homogeneity of the rock to be employed should be checked, because the P-wave velocity shows a high variety depending on heterogeneity.
- It is evident that if the pre-existing voids and/or the voids created by weathering are oriented, V_p and mechanical properties also change depending on measurement orientation. To cope with this difficulty, the minimum V_p value can be used as stated by Weiss et al. (2002).
- The numerical weathering index should not be applied on the rocks showing the soluble type weathering.

4. A case study: Weathering and weatherability of Harsit granitic rock

4.1 Weathering of Harsit granitic rock

In the study area, the basement rocks are basalts, andesites and pyroclastic units (Figure 5). The Harsit granitoid was intruded in the Upper Cretaceous/Eocene period Towards the periphery of the pluton, it consists of lucocratic quartz diorite, quartz monzonite and quartz monzodiorite while towards the centre the rocks are granodiorite. Towards the NW and SE the granites are terminated by NE-SW faults (Ceryan 2008a). During these processes some elements are released and combine with other minerals to form new minerals, e.g., the development of smectite from plagioclase is a consequence of the addition of Ca, Na and Fe while the subsequent removal of these changes the clay mineral to kaolinite (Figure 6). Orthoclase minerals are more resistance to weathering than plagioclase and holes on their surfaces indicated acid attack at an early stage of the weathering (Figure 6).

Hydrothermal weathering products are sericite and allunite. The weathering of the minerals in the Harsit granitic rocks. The weathering and hydrothermal alteration of the minerals in the Harsit granitic rocks and the type of change which occurs are indicated in Figure 7. Chemical weathering causes variation in the composition of the rocks by leaching and the introduction/ development of new components. SiO_2 concentrations show a continuous decrease with increasing weathering. Some of the free silicon ions released during weathering are transported in solution but some combine to form new clay minerals. Al_2O_3, because of its low solubility, tends to be concentrated in residual weathering products. CaO and Na_2O, being soluble, either quickly move out of the system or combine with epidote and hornblende ± plagioclase. MgO is rapidly leached and removed in the early stage of chemical weathering, although a certain proportion is retained in the mineral structures of clays and chlorite. FeO remains relatively constant, although it may change from ferric to ferrous.

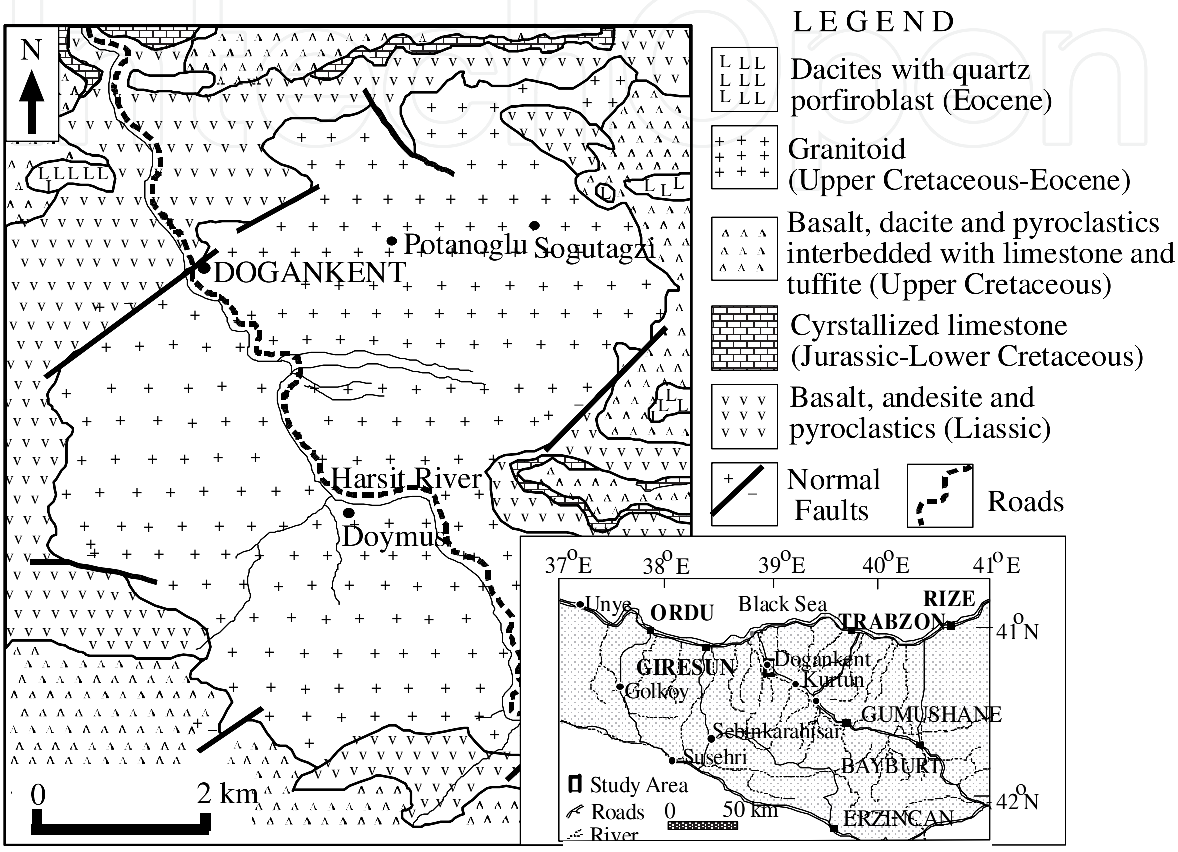


Fig. 5. Geological map of the study area

4.2 Weatheability of Harsit granitic rocks

Durability, i.e., the rock's ability to resist degradation during its working life, is depended on a number of important parameters; weatherability of rock material, degree of imposed during winning, production, placing and service, the climatic, topographic and hydrological environments in service (Fookes et al 1988). In the studies, which give assessment of durability of Harsit granitic rocks, performed Ceryan and Ceryan (2005) and Ceryan et al (2008), rock durability indicators, Static Rock Durability Indicator and Dynamic Durability Indicator purposed by Fookes et. al (1988) were used. Index properties, petrographic and chemical weathering indices and rock durability indices of rock materials from Harsit granitic rocks used these study were given in Table 4.

During chemical weathering; both chemical leaching of mobile elements (oxides) and forming weathering product occur on the rock materials. Thus, for the prediction of the engineering performance of the stone in service, Chemical Weathering Index and Chemical Leaching Index were used together in the study performed Ceryan and Ceryan. (2005). Simple and multiple regression analyses using chemical indexes, setting in this study, of the sample from the weathering profiles samples of the Harşit granitic rocks show that the rock durability indexes purposed by Fookse et al. (1988) can be obtained easily and cheaply. In the study performed by Ceryan et al (2008), an application of fuzzy modeling to the prediction of potential rock durability indexes from rock sample taken from Harşit Granitoid was given. Depending on cation packing index and micro-cracks plus voids ratio, important changes in Static Rock Durability Indicator (RDIs) were determined. However, weatherability of the building stone depends on both mineralogical properties and fabric. Therefore, cation packing index representing mineralogical and micro-cracks plus voids ratio representing fabric properties are considered together in the fuzzy model to estimate the durability of the sample from Harsit granitic rocks. In the fuzzy model described input-output relationships by fuzzy if-then rules, Cation Packing Index and micro-cracks plus voids ratio used such as input data. The fuzzy model constructed in this study exhibited higher performance and showed good generalization ability (Ceryan et al 2008)

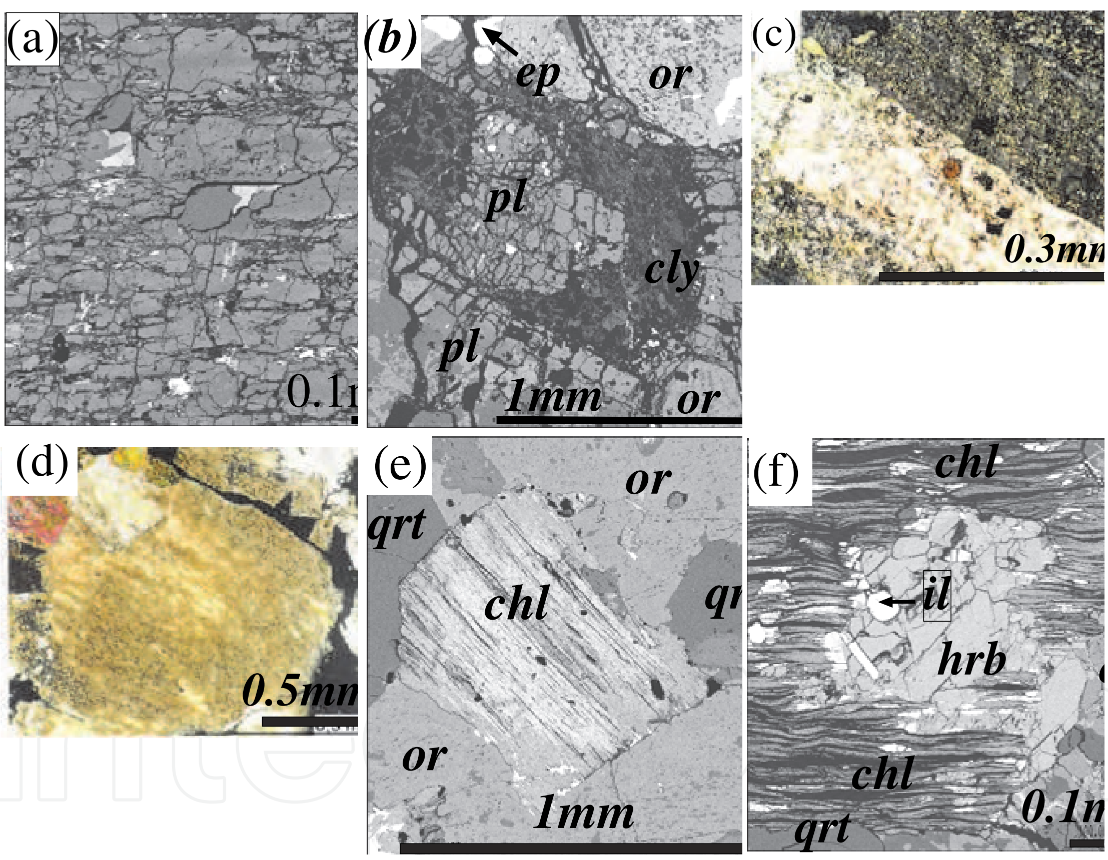


Fig. 6. Weathering products of plagioclase (a,b,c); clay minerals (dark phases)(a, b), epidote (bright phases)(a,b,c), the etching caused by the acid effect in orthoclase (b) the clays occured by the weathering of orthoclase (d), chlorite occurrence due to the hydrothermal alteration of the biotite(e), weathering products of hornblende, chlorite (fibrous phase) and titanite (bright phases)(f). (a,b,e and f are scaninig electron microskope images, c and d are optical microscope image; qrt: quartz; pl: plagioclase; or: orthoclase; ep: epidote; chl: chlorite; cly: clay ; bi: biotite, il:ilmenite; hrn: hornblende)

Sample	WG	Ip	SGssd	WA	Is(50)	SST	RDIs	CD (%)	k-value	CLI	CWPI
C-1A	F	8,158	2,706	0,4	6,65	0,3	2,37	0,25	4,621	0	0
C-23A	SW	2,882	2,698	0,5	3,59	8,7	0,92	1,84	4,449	21	23,92
C-3B	MD	1,521	2,63	1,2	0,785	34,6	-1,25	7,25	4,177	31,6	33,31
D-1A	F	28,387	2,68	0,4	6,865	0,3	2,48	0,16	4,682	0	0
D-1B	SW	3,129	2,674	0,5	3,915	5,8	1,15	0,18	4,61	-	-
D-2AB	SW	1,864	2,648	0,9	3,275	9,2	0,72	3,15	4,395	18,3	23,58
D-56	MW	1,159	2,615	1,4	0,725	42,6	-1,62	4,26	4,308	37,4	44,42
P-1A	F	7,149	2,719	0,6	7,845	0,2	2,77			0	
P-2A	F	5,502	2,705	0,5	5,935	0,3	2,09	1,17	4,654	0,69	9,397
P-2BC	MW	1,751	2,652	1,4	1,32	14,6	-0,32	3,85	4,417	-	-
P-3A	HW	1,18	2,629	1,5	0,305	43,1	-1,81	9,21	4,051	29	47,62
P-3B	HW	0,852	2,575	1,6		38,6				43,8	65,91
P-4	HW	1,089	2,605	1,3	0,28	45,6	-1,89	5,65	4,006	33	52,12
S-1A	F	14,198	2,693	0,5	6,58	0,5	2,33	0,61	4,728	3,79	0
S-3B	F	6,376	2,666	0,8	6,51	0,4	2,28	0,68	4,648	0	11,18
S-4A	SW	3,514	2,667	0,8	4,07	12,6	0,9	1,25	4,579	15,4	20,03
S-2A	MW	1,494	2,632	1,3	1,265	34,6	-1,08	3,42	4,427	26,2	34,74
S-3C	MW	1,697	2,628	1,4	2,68	24,7	-0,19	6,65	4,392	26,4	35,68
S-3A	MW	1,002	2,559	2	2,16	40,1	-1,11	2,48	4,407	27,6	41,48
S-5B	HW	0,84	2,611	1,5	0,905	58,6	-2,18	5,88	4,2619	45,4	51,74

(WG:weathering grade; SGssd=specific gravity (saturated and surface dry) $I_{s(50}$:point load index (I0,5 $I_{s(50)dry}$+0, 5 $I_{s(50)sat}$) (Mpa), WA: percentage water absorption (%) Ip:mikropetrographic index SST:MgSO4 soundness value (%); RDIs:static rock stability indicator, CD: micro-cracks plus voids ratio (%); k-value : cation packing index (10^{-2} mol/cm^3), *CLI:Chemical leaching Index; CWPI=Chemical Product Index)*

Table 4. Index properties, and rock durability indices of rock materials from Harsit granitic rocks (Ceryan and Ceryan 2005, Ceryan et al 2008)

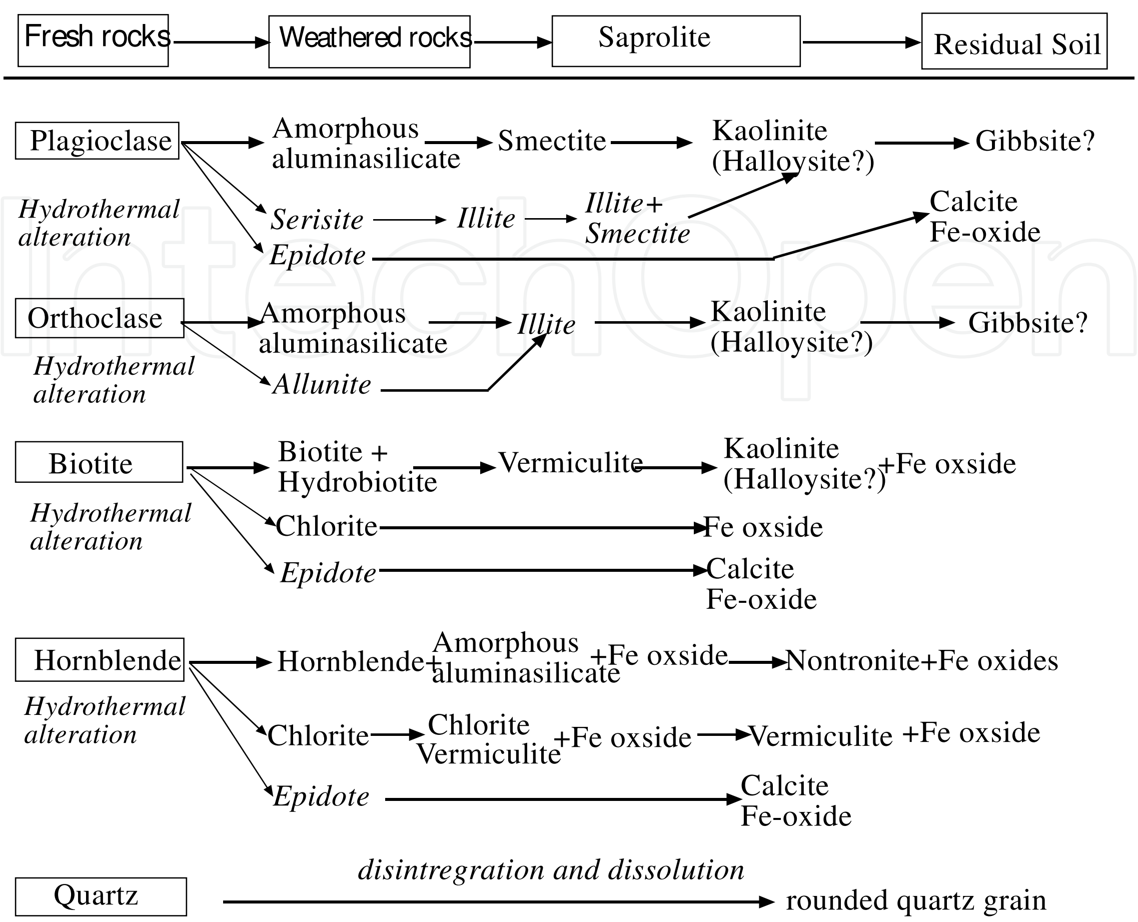


Fig. 7. Schematic representation of probable paths of rock-forming minerals transformation in the Harsit Granitoid

4.3 Classification of of Harsit Granitic Rocks for engineering purpose

Using petrographic techniques, the percentage of secondary minerals was established and relating this to the percentage microcracks and voids, a weathering classification from fresh to residual soils was established (Figure 8). While the engineering behaviors of the weathered rocks are assessed, the physical and mineralogical (directly chemical) changes caused by the weathering to be considered together will be significant (Table 5) The physical change is mainly in the direction of the ratio of effective porosity/total porosity increase and the ratio of micro-fracture + voids. Thus, this condition must be taken into consideration while the statistical relations between the weathering indices and the strength and deformation properties for weathered rocks. On the other hand, from the point of view of the geotechnical standpoint, indices based on the measurement of P-wave velocity generally have more applicability than those based on chemical, mineralogical and engineering properties (Ceryan et. al. 2008a). The classification of rock mass in the Harşit Granitoid is performed in accordance with the procedure suggested by Anon (1995) (Table 6). Transitions in the weathering zones of the Harsit Granitoid have graded. Because of changes even at the small scale, the same micro-region of the area in which exposed Harsit granitic rock masses in different weathering degrees (Figure 9).

Weathering Degree	Fresh	Slightly weathered	Moderately Weathered	Highly weathered	Completely weathered
			Weathering Indices		
γ (g/cm³)	2,664 (±0,042) (176)	2,634(±0,038) (99)	2,576(±0,053) (134)	2,553(±0,051) (87)	2,257 (±0,092) (127)
n (%)	1,92(±0,54) (176)	2,32(±0,59)(99)	4,43(±1,3)(134)	4,83(±1,6)(87)	15,32(±/3,7)(127)
ne (%)	1,50(±0,45(176)	1,92(±0,55)(99)	3,74(±1,2)(134)	4,11(±1,4)(87)	14,08(±3,6)(127)
Sa (%)	0,57(±0,18)(176)	0,73(±0,21)(99)	(1,46)(±0,5)(134)	1,55(±0,64)(87)	6,31((±1,9)(127)
FMC (%)	89,6(±4,1)(24)	73,2(±4,9)(18)	58,4(±5,5)(21)	47,5(±5,7)(15)	38,6(±4,1)(33)
SMC(%)	10,1(±4,7)(24)	25,2(±4,73)(18)	36,9(±6,3)(21)	42,3(±4,3)(15)	47,43(±4,9)(33)
CD (%)	0,66(±0,4)(24)	1,61(±1,3)(18)	4,65 (±1,9)(21)	7,79(±2,43)(15)	14,9(±3,7)(33)
Irms(%)	11,54(±5,9)(24)	34,9(±9,6)(18)	64,43(±17,7)(21)	88,9(±15)(15)	128,1(±29,4)(33)
WPI	12,8(±0,48)(12)	7,2(±1,7)(9)	3,7(±1,6)(13)	-0,1(±2,4)(11)	-5,61(±4,1)(11)
P	74,9(±6,4)(12)	64,1(±3,3)(9)	59,4(±2,4)(13)	60,2(±6,4)(11)	46,8(±8,0)(11)
PI	84,5(±0,8)(12)	83,4(±0,8)(9)	82,2(±1,5)(13)	82,1(±0,9)(11)	81,7(±1,29)(11)
Imob	0,0 (12)	0,137(±0,01)(9)	0,126(±0,01)(13)	0,118(±0,02)(11)	0,096(±0,02)(11)
CWPI(%)	4,1(±0,5)(12)	22,5(±1,8)(9)	37,9(±4,8)(13)	54,1(±6,9)(11)	60,2(±7,3)(11)
I_{QAB} (%)	0,21(±0,07) (8)	0,41(±0,21)(7)	1,20(±0,23)(7)	1,80(±0,68)(6)	7,36(±1,63)(11)
Id (%)	99,3(±0,40)(8)	98,4(±1,03)(7)	88,8(±10)(7)	56,8(±13)(6)	7,62(±(5,7)(11)
Iefp (%)	23,5 (±11)(176)	19,6(±6,9)(99)	16,7(±5,2)(88)	13,6(±6,1)(25)	13,2(±3,2)(66)
Vp (m/sn)	4111(±198)(176)	3553(±396)(99)	2769(±553)(134)	2158(±486)(87)	753(±184)(127)
Vpm (m/sn)	5732(±127)(176)	5109(±342)(99)	4507(±555)(134)	4079(±280)(87)	3617(±231)(127)
IQ(%)	75,6(±7,4)(176)	69,8(±7,2)(99)	59,7(±6,8)(134)	42,2(±14)(87)	20,0(±8,9)(127)
Ivp(%)	96,8(±1,8)(176)	83,0(±11,7)(134)	74,8(±6,8)(134)	65,6(±4,5)(87)	60,1(±0,06)(127)
PWD	0,5(±0,4)(12)	2,80(±1,9)(9)	10,4(±3,3)(13)	17,5(±13,7)(11)	17,5(±13,7)(11)
CWD	0,3 (±0,1)(1760)	10,2(±3,9)(99)	18,2(±5,9)(134)	27,3(±6,7)(87)	27,3(±6,7)(87)
			Mechanical Properties		
$I_{s(50)}$, MPa	7,3 (±1,8) (96)	5,0(±1,6)(68)	1,9(±0,9)(88)	1,0(±0,7)(61)	-
σ_c (MPa)	160,3(±34)(40)	128,9(±42)(37)	66,8(±33)(39)	39,3(±30)(27)	2,2(±1)(61)
σ_t (MPa	13,2(±1,4)(25)	8,4(±2,2)(20)	3,0(±1,8)(30)	1,8(±1,4)(14	-
Ed x10⁴ (MPa)	4,575(±0,5)(176)	3,407(±0,7)(134)	2,089(±0,8)(134)	1,269(±0,5)(87)	0,14(±0,06)(127)
Et x10⁴ (MPa)	5,483(±0,5)(8)	2,085(±0,4)(9)	0,869(±0,3)(15)	0,491(±0,17)(5)	-
Es x10⁴ (MPa	1,967(±0,48)(8)	1,499(±0,47)(9)	0,607(±0,26)(15)	0,355(±0,16)(5)	-

(γ (g/cm³): Dry density; n (%);Total prosity, ne (%)Effective porosity;, Sa (%) Water absorbtion, (atmospheric pressure); Vp: P-wave veloccity in dry samples; Vpm: : P-wave veloccity in solid part of the sample, I_{QAB} (%) Quick absorbsiyon, Id(%)Slake durability (second cycle), SHV: Schmidt rebound hardness ; $I_{s(50)}$ (MPa) Point load strength index , σ_c (MPa Unconfined compressive strength , σ_t (MPa) Indirect (Brazilian) tensile strength; Ed (MPa): Dynamic Elastisite modulu; Et (MPa) Tanjant Elastisite modulu, Es (MPa):Deformasyon Modulu, (N-type Schmid hammer is used),FMC: fresh mineral)

Table 5. Average (± standard deviation) and (number of data) weathering indices and mechanical properties of each weathering grade defined for granitic materials from Harsit Granotoid (Ceryan et. al. 2008a)

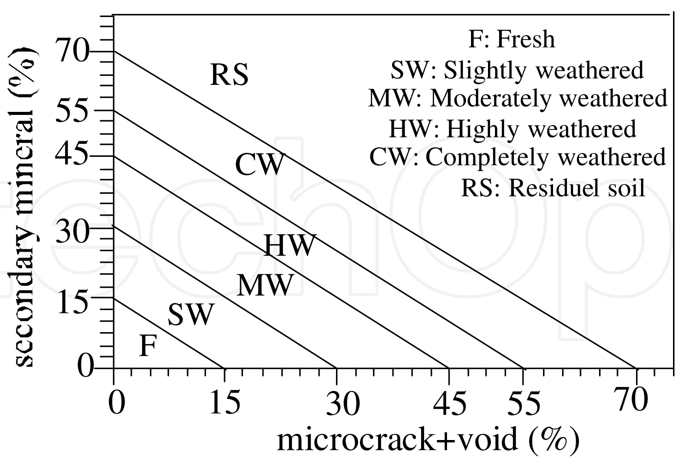
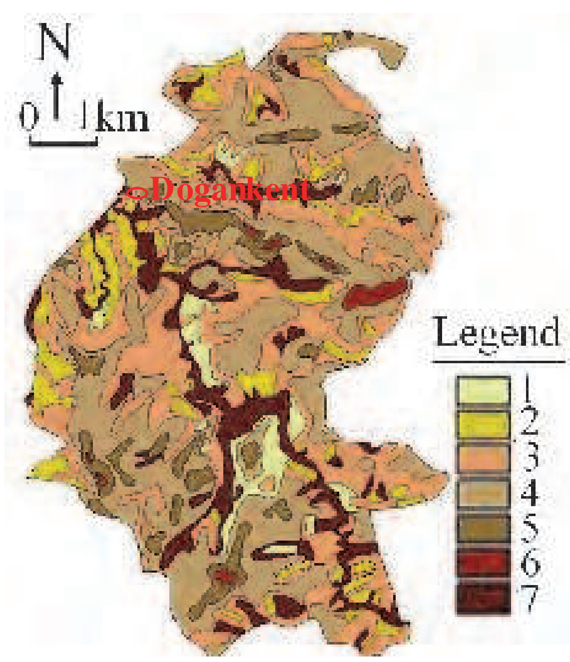


Fig. 8. The definition of the rock material weathering grade for Harsit Granitic Rocks



<u>*Micro-region adjusted to weathering*</u>

1. Un weathered rock masses % 80-100, Slightly weathering rock masses %0-20
2. Unweathered and Slightly weathering rock masses % 70-90, Moderately weathering rock masses %10-30,
3. Unweathered and Slightly weathering rock masses % 0-30, Moderately weathering rock masses %60-100, Saprolite % 0-40,
4. Moderately weathering rock masses %0-20, Saprolite % 0-80,
5. Saprolite % 10 0-90, Residual soils % 0-10,
6. Saprolite % 0-20, Residual soils % 100-80 and
7. Colluvium)

Fig. 9. Micro-region adjusted to weathering in urban area of Dogankent (NE Turkey (Ceryan and Ceryan (2008)

Zon	Weathering Profile	Description and typical characteristics
6		*Material:* % 100 RS-CW It is separated material including more sand, clay and silt.c=0.1-0.2 MPa, ϕ=36-40^o.,*Mass structure* : Mass structure isn't preserved. The thickness varies between 0.5 and 5m.
5		*Materia*l: >%30 F-MW, >%70 HW-RS. The dispersion of the material is generally in order and the zone is homogeneousϕ=38-42^o,c=0.2-0.3 MPa. *Discontinuities*: Systematic discontinuities and the fractures formed with weathering are preserved. Filling of the discontinuities usually consists of clay and iron oxide. ϕ_b=22-16^o, JRC=2-6, Discontinuity frequency (Df) = 142.4(±1.5(discontiunity length/m^2). *Rock mass structure:* May behave as soil although relict fabric may be significant. Weak grade will control behavior of soil mass. For rock mass with relict structure ϕ_m =18-20, c_m =0.06-0.04 MPa The thickness varies between 2.5 and 11 meter.
4		*Materia*l: % 30-50 F-MW, % 50-70 HW-CW. *Discontinuities:* The thickness of the filling become lager amount. The filling generally consists of silt and sand. Rock bridge is completely removed. There are plenty of fractures formed by weathering in the corestones. ϕb =26-18^o, JRC=2-4(±2), JCS=23(±12) MPa, Discontinuity frequency (Df)=11.6(±2.1) *Rock mass structure:* Corestones are beginning breaking and may be significant for investigation and construction Rock framework still locked and controls strength and stiffness, matrix control permeability. ϕm =21-24, cm=1.3-1.8 MPa The thickness varies 2.5 and 11 meter.
3		*Materia*l: % 50-90 G: I-lll % 10-50 G: IV- VI. *Discontinuities*: Weathering deepness is usually bigger than the roughness. The fractures formed by weathering are seen in the blocs. The number of rock bridges gets less. Spacing of the discontinuities is more less than first zone. ϕb =32-25^o, JRC=4-8(±2), JCS=53(±14) MPa, Df=2.4(±1.3)*Rock mass structure:* The edge of the corestones becomes circular. Mass structure is preserved. But the blocks tend to divide each other. Rock framework still locked and controls strength and stiffness, matrix control permeability. ϕm =22-25, cm=1.8-2.4 MPa The thickness varies 1.5 and 6 m.

2		*Material*: >%9U F-MW, <%10 HW-CW..*Discontinuities*: Weak materials along discontinuities. Shear strength stiffness and permeability affected. ϕb =28-26^o, JRC=6-10(±4), JCS=112(±21) MPa, Df=2.4(±1.3). *Rock mass structure* : The blocks are cornered and interconnect each other.For closely jointed rock masses ϕm =26-28^o, cm=2.3-4.4 MPa. The thickness varies 3 and 40 meter.
1		*Materia*l: %100 F-MW. *Discontinuities:* Discolour on discontinuities surface. ϕb =21-18^o, JRC=8-12(±2),JCS=160(±34) MPa Df=1.6(±0.3). *Rock mass structure* : The blocs are interconnect firmly each other Properties of deformation and strength depend on direction and properties of the discontinuities. Behaves as rock apply rock mechanics principles to mass assessment and design

Table 6. The weathering classification of rock mass of Harsit granitic rocks (Ceryan and Ceryan 2008)

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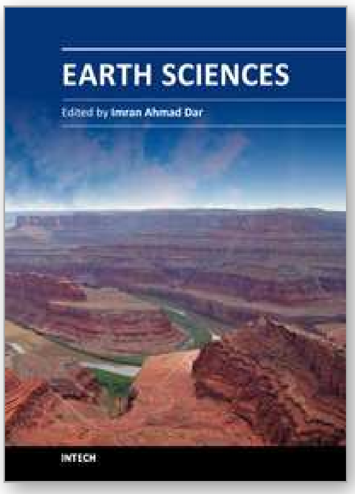

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The studies of Earth's history and of the physical and chemical properties of the substances that make up our planet, are of great significance to our understanding both of its past and its future. The geological and other environmental processes on Earth and the composition of the planet are of vital importance in locating and harnessing its resources. This book is primarily written for research scholars, geologists, civil engineers, mining engineers, and environmentalists. Hopefully the text will be used by students, and it will continue to be of value to them throughout their subsequent professional and research careers. This does not mean to infer that the book was written solely or mainly with the student in mind. Indeed from the point of view of the researcher in Earth and Environmental Science it could be argued that this text contains more detail than he will require in his initial studies or research.

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