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New weathering indices for evaluating durability and weathering characterization of crystalline rock material: A case study from NE Turkey

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ABSTRACT

There are several methods to characterize petrochemical properties of crystalline rocks. One method is based on the ionic model. In the model, large oxygen atoms of the rock-forming minerals are close-packed framework structures. The distribution of cations, which is defined by the "Cation-Packing Index" or the *k*-value for each (stoichiometric) mineral phase, can be correlated with the petrophysical properties. These properties, representing the engineering behavior of the rock materials show a dependence on the physical and chemical changes due to weathering. The fundamental systems of the chemical weathering of rocks are the leaching of the alkaline and alkali-earth elements and the redistribution of the residual elements into secondary minerals. In this study, these conditions are considered as the basis for new petro-chemical weathering indices based on the cation-packing value for evaluating weathering characterization of crystalline rocks. These indices are the *k*-product index, the *k*-leaching index and the *k*-weathering index. The *k*-product index represents the quantity of the weathering product suggested in this study, whereas the *k*-leaching index represents the amount of chemical leaching during the weathering. The *k*-weathering index was defined as the sum of the *k*-leaching index and the *k*-product index. In addition to these new engineering indices, a *k*-durability index based on a slake durability index and the *k*-value of the rock materials was suggested in this study to estimate the durability and the mechanical properties of rock materials. These indices were applied to granitic rock samples weathered to various degrees, from the Kurtun Granodiorite in northeastern Turkey. The results of the regression analysis performed in this study show that the *k*-weathering index can be used as a weathering indicator and that the *k*-durability index can be used to evaluate the durability and the mechanical behaviors of the investigated samples. It would be useful to conduct further research to confirm the results of the present study.

1. Introduction

Decomposition of rocks is one of the fundamental processes that modify the earth's surface (Lee et al., 2008). During the chemical weathering process, some alkaline and alkali-earth elements are easily leached from rocks and the residue reconstituted with components from the atmosphere form new minerals that are in a stable or metastable equilibrium with the environment (Loughnan, 1969). For this, in can be said that "*Chemical weathering process* including leaching and forming weathering product *is one of the vital processes in the geochemical distribution of elements*" (Lee et al., 2008).

Decomposition due to weathering and hydrothermal alterations are calculated in different ways, including using the normalised values of elements (or oxides) by using their parent rock concentrations or the immobile element concentrations in the samples (Krauskopf, 1967), employing standard cell calculation (Colman, 1982), calculating the ratio of elements to immobile elements (Chesworth et al., 1981; Colman, 1982; Guan et al., 2001), the gamma-ray spectrometric study (Chen and Chan, 2002), determining cation exchange capacity (Arikan et al., 2007) and using an EC/pH meter (Shalkowski et al., 2009). Alternative methods of calculating the change in weight or volume of rock materials due to chemical weathering include using immobile elements (Huston, 1993), modelling compositional changes (Eynatten et al., 2003), using the *k*-value (Ceryan et al., 2008b; Ceryan, 2011) and applying chemical weathering indices (Price and Velbel, 2003; Ceryan, 2008; Gong et al., 2013).

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Chemical weathering indices are widely used for evaluating elemental mobility during weathering (Irfan, 1996; Guan et al., 2001; Bern and White, 2011), characterizing modern and ancient in situ weathering profiles and their interpretation (e.g., Fedo et al., 1995; Le Pera et al., 2001; Begonha and Sequeira Braga, 2002; Kirschbaum et al., 2005; Munroe et al., 2007), demonstrating the impact of climate on bedrock weathering (e.g., Neall, 1977; Liu et al., 2012), quantifying the engineering properties of regolith (Duzgoren Aydin et al., 2002), evaluating soil fertility and development (Delvaux et al., 1989; Heimsath and Burke, 2013) and categorising soil and evaluating soil weathering (Souuri et al., 2006; Figlia et al., 2007; Betard, 2012). Additionally, the chemical weathering indices were used for the assessment of chemical weathering of granite in an acidic rainfall environment (Lee et al., 2008), for the evaluation of chemical overprinting of magmatism by weathering (Kamei et al., 2012), within the mineralogical norm calculation (Voicu et al., 1997) and for assessing the deterioration mechanisms of monuments (Topal, 2002). Recently, weathering indices have been used as a palaeo-climatic indicators and for palaeo-environmental implications (e.g., Yang et al., 2004; Gallagher and Sheldon, 2013) and for characterizing alterations associated with neotectonic delineations and the subsequent implications for provenance studies (Young, 2002; Osae et al., 2006). In addition, chemical weathering indices provide input for prediction models to assess the engineering behaviors of rocks (e.g., Onodera et al., 1974; Irfan, 1996; Tugrul and Gurpinar, 1997; Ceryan, 2008; Khanlari et al., 2012) and predicting the durability and the weathering state of building stones (e.g., Esaki and Jiang, 1999; Korkmaz and Ceryan, 2011; Yavuz, 2012).

With the consideration of the chemical weathering processes, leaching and forming weathering products, and their effects on durability of crystalline rocks, it can be said that new petro-chemical indices are required to take into account petro-chemical characteristics including mineralogical composition, mineral chemistry and durability indicator such as the slake durability index. These petro-chemical indices allow for the assessment of the effects of chemical weathering on crystalline rocks and the assessment of the engineering behavior of the rock materials.

An ionic model is used in which the large oxygen atoms of rock-forming minerals are considered to be closely packed structures to characterize crystalline rocks with a single quantity (Rybach and Buntebarth, 1984). Thus, the distribution of cations defined by the "Cation-Packing Index" for each (stoichiometric) mineral phase will correlate with petro-physical properties such as the elastic wave velocity (Rybach and Buntebarth, 1984; Kern and Siegesmund, 1989; Ceryan et al., 2008a). These studies show that the petro-physical properties increase with increasing *k*-values (Rybach and Buntebarth, 1984; Kern and Siegesmund, 1989; Ceryan et al., 2008a,b). According to Ceryan et al. (2008a,b), the *k*-value for rock-forming mineral is greater than the value of weathering products of a given mineral; therefore, the *k*-value can be used to evaluate the rock weathering condition and durability. Although these useful results were determined, an index to evaluate weathered rocks based on *k*-values has not been developed. Considering the fundamental system of chemical weathering and the information gained from previous studies on the *k*-value, new petro-chemical indices based on the *k*-value were proposed for evaluating the effects of chemical weathering on crystalline rocks.

Other common properties used for estimating the behavior of weathered rocks are the intrinsic characteristics of rock materials and the slake durability. Moreover, there are many examples of the slake durability index used as an input parameter to correlate the durability of rocks with their petro-chemical characteristics, mechanical properties and weathering conditions (Koncagul and Santi, 1999; Dhakal et al., 2002; Fuenkajorn, 2011; Yagiz et al., 2012). Therefore, a different approach from those of previous studies is introduced in which a durability index for crystalline rocks considers both the *k*-value representing the petro-chemical characteristics of rock materials and the slake-durability index. The new *k*-durability index was developed in this study for the assessment of the mechanical properties and durability of crystalline rocks.

Furthermore, the *k*-weathering and *k*-durability indices developed in this study were applied to granitic rock samples, weathered to varying degrees, from the Kurtun Granodiorite, NE Turkey.

2. Material characteristics and testing procedure

2.1. Geological setting

The geological characteristics of this study area are given in detail in Ceryan (2008). The geology of the area consists mainly of thick volcanic, volcanoclastic and intrusive rocks (Fig. 1, Ceryan, 2008). The Kurtun Granodiorite is a Late Cretaceous (68.4 ± 3.4 Ma) batholith with intruding Late Cretaceous volcanoclastic rocks (Ceryan, 2008). The intrusion is represented by hornblende-biotite-granodiorite, which is frequently crosscut by dykes of quartz porphyry, dacite and dolerite (Ceryan, 2008). The granodiorite is holocrystalline with an equigranular texture and is coexistent with the plagioclase forms of porphyritic megacrystals (Ceryan, 2008).

2.2. Testing procedure

The samples investigated were collected from homogeneously weathered zones without residual soils. (Fig. 2). The techniques applied in this study are not applicable for the residual soil because of the residual soils does not have their original volume due to frame collapse. A total of 38 block samples, each sample having the approximate dimensions $35 \times 35 \times 30$ cm were collected in the field. The core samples were prepared from the rock blocks using the core-drilling machine of the Rock Mechanics Laboratory in the Engineering Faculty at the Karadeniz Technical University. They were 50 mm in diameter, and the edges of the specimens were cut parallel and smooth.

Mineralogical and chemical analyses, physico-mechanical tests, P-wave velocity measurements, the slake-durability test, the $MgSO_4$ soundness test and the modified aggregate impact value (MAIV) test were carried out on the granitic rock samples from the Kurtun Granodiorite that were weathered to various degrees to describe the decomposition effects on the petro-chemical properties and the engineering behavior of the samples. The weathering indices and the durability estimator used in this study (Table 1) were obtained using this analysis (Tables 2–6).

Thin-section analyses are performed to determine weathering product amount, the micro-fracture plus voids ratio and the mineralogical composition of the samples (Table 2). Transmitted light microscopy was used, and a minimum of three thin sections from each sample was investigated. The samples were classified according to weathering using the results of these analyses. The classification was based on the amount of weathering products and the micro-fracture plus voids ratio (Figs. 3 and 4). These parameters represent the mineralogical and physical changes due to weathering, respectively (Ceryan et al., 2008a). Whole rock samples were analyzed by X-ray fluorescence (XRF) at the Karadeniz Technical University, Turkey (Table 3). The values of the chemical indices for the samples at various weathering stages were obtained from the chemical analyses (Table 4).

Core samples were tested for uniaxial compressive strength and physical properties according to the standard test procedures suggested by the ISRM (2007) (Table 5). At least 15 specimens were