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Weathering Indices and its Relation to Uniaxial Compressive Strength of Hamedan Hololeucogranite Rocks in West of Iran

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Abstract: Weathering leads to a general weakening of a rock due to the alternation of minerals, the development of voids and disintegration. In this research, the weathering process of Alvand hololuecogranite rocks in Hamedan has been studied by chemical analysis, petrographical studies and geomechanical tests. The results indicated that, engineering properties of weathered hololeucogranite vary over the wide range depending on the degree of weathering. Applications of many existing weathering indices such as WPI, CIA, LOI, β, CIW, Ip, Xd and QAI on the Hamedan hololeucogranite samples are good quantitative indicators for describing the degree of weathering. Using of these indices in the assessment of uniaxial compressive strength of the hololeucogranite rocks, yields suitable and meaningful results.

Key words: Weathering indices · Geomechanical tests · Granite · Petrographical studies

INTRODUCTION

Weathering is generally defined as the process of alteration and breakdown of rocks at and near the earth's surface by physical and chemical effects [1], and leads to a number of changes in the rocks. Chemical change during weathering and hydrothermal alteration are quantified in several ways including the ratio of elements to immobile elements [2], measurement and calculation of loss or gain of weight based on immobile element [3] and chemical weathering indices [4, 5]. Weathering indices have been devised to quantify the changes in the index properties of rock materials, some of which are relevant to the engineering properties.

Some of these weathering indices have been specifically developed for granitic rocks. In this paper the weathering grade of Alvand hololeucogranite rocks are described in-situ and samples for mechanical test, petrographical studies and chemical analysis are collected and examines some weathering indices suggested for petrographical, engineering and chemical considerations and discusses their usefulness for granitic rocks. Furthermore, statistical correlations between weathering and chemical, engineering and petrographic indices and their significance have indicated some important points that will be usefulness for assessment of weathering in granites. It must be mentioned that the Alvand plutonic batholith is located in the West part of Iran (Fig. 1a). It is one of the largest plutonic bodies in the Sanandaj-Sirjan Metamorphic Belt (SSMB) (Fig. 1b).

MATERIALS AND METHODS

Material Identification: The qualitative methods of weathering are based on observational descriptions and index properties of rocks. These are color changes [6] and observational description of physical weathering grade [7]. The quantitative method for weathering classification is based on weathering classification schemes. When applying quantitative classification schemes, petrographical, index properties and chemical properties are considered [8-10]. In this study, both qualitative and quantitative methods are employed in order to determine the weathering degree of the Alvand hololuecogranites. The Alvand hololeucogranite rocks exhibits a range of weathering profiles, from fresh to completely weathered rocks. In this study, the weathering classification proposed by the ISRM [7] was used. This includes six degrees of weathering: W_1 (fresh rock with no signs of weathering), W_2 (slightly weathered rock with discoloration in discontinuity surfaces), W_3 (moderately weathered rock with less than half of

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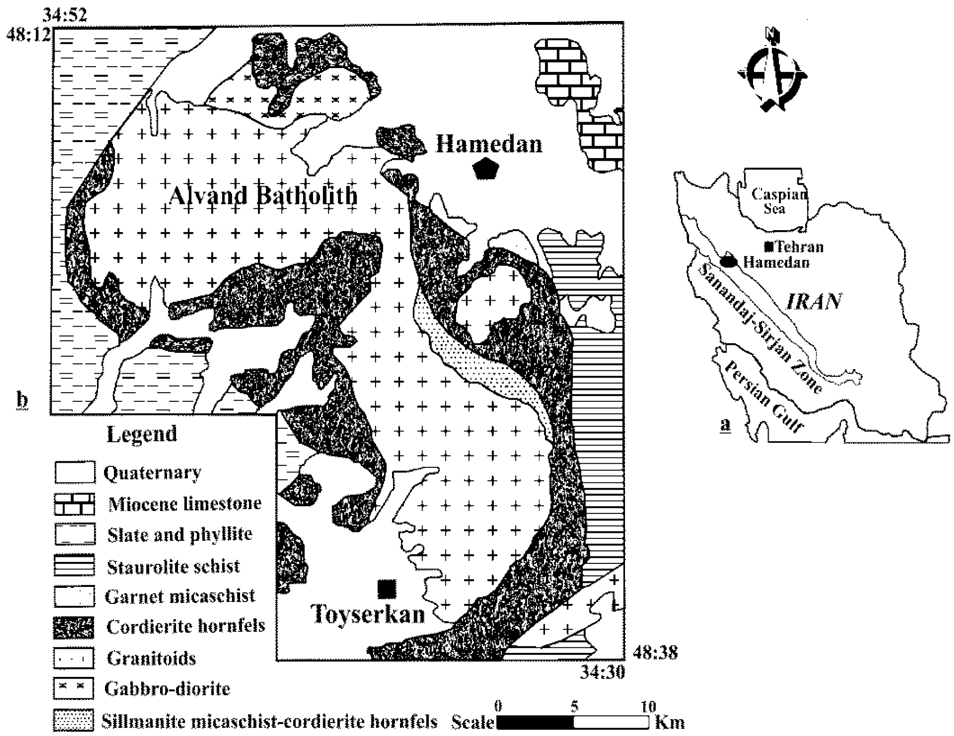

Fig. 1: (a) The Sanandaj-Sirjan zone in Iran with location of study area, (b) Location map of the granitic rocks tested

the rock decomposed), W_4 (highly weathered rock with more than half of the material transformed to a soil), W_5 (completely weathered rock with all the material transformed to a soil but the original mass structure still largely intact) and W_6 (residual soil). To describe the qualitative weathering classifications of the hololeucogranite rocks, color changes, staining, textural changes, disintegration, altered/unaltered minerals were determined.

Sampling and Laboratory Studies: The samples representing different weathering degrees were collected from homogenously weathered zones. Weathered samples that were highly prone to collapse by disturbance, were immediately covered with plaster and safely transported to the laboratory. Test samples were prepared in the laboratory. No sample was collected from residual soil (the grade W_6) in the weathering profile and tests were not performed on it.

The physical index properties such as specific gravity, dry and saturated densities, effective porosity and water absorption were determined for each rock following the standard test procedures suggested by the ISRM [11]. The slake durability index (Id) was found to be an extremely useful method for defining the difference between a soil and a rock sample and was subsequently standardized by the ISRM [11].

Mechanical properties determined on the core samples included the uniaxial compressive strength (UCS) and the tensile strength (σ_t). The uniaxial compressive strength tests for fresh rocks were carried out on cylindrical specimens (L/D=2.5) under dry and saturated conditions following the recommendations of the ISRM [11]. For moderately, highly and completely weathered hololeucogranite, cubic specimens were prepared and tested. The results were converted into cylindrical strength by a multiplying factor obtained after testing both cubic and cylindrical specimens for samples.

In order to record mineralogical abundance and textural features in each sample, thin sections were studied using petrological microscope. Modal analysis of hololeucogranite has been performed using an automatic point counter mounted on Leitz Orthoplan Microscope. The contents of quartz, plagioclase, K-feldspars, biotite and other minerals were distinguished for each thin section. XRF analysis of major oxides was performed using X-ray fluorescence spectrometry on powder pellets.

A Review of the Weathering Indices: There are several weathering indices proposed by various investigators for characterizing weathering degree of granitic rocks.

The most commonly used indices have been derived from chemical and mineralogical analysis and can be broadly categorized as petrographical, engineering and chemical indices.

Petrographical Indices: A number of petrographical methods have been suggested to quantify the mineralogical properties of the weathered rocks. Lumb [12] defined a quantitative index (Xd), related to the weight ratio of quartz and feldspar in the decomposed granite of Hong Kong as equation (1):

$$Xd = \left(\frac{Nq - Nq_0}{1 - Nq_0}\right) \quad (1)$$

Where N_q and N_{q0} are the weight ratio of quartz and feldspar in weathered and fresh rock samples, respectively. In this research work, Xd was determined for the hololeucogranite rock samples.

Based on comprehensive studies on the weathered granites in UK, Irfan and Dearman [10] suggested the micropetrographic index (Ip) to characterize the degree of weathering of rocks. The Ip can be expressed by the equation (2):

$$I_P = \frac{SC\%}{UC\%} \quad (2)$$

Where SC is sound constituents such as quartz, feldspars and biotites. UC are unsound constituents such as sericite, chlorite and iron-oxide.

Engineering Indices: From engineering geology standpoint, indices based on mechanical properties have more applicability than those based on chemistry and petrology.

A rapid test to obtain a quick absorption index (QAI) has been proposed by Hamrol [13] for the assessment of weathering of granite and schist. The coefficient of weathering (K) was developed by Iliev [14] based on the velocity of compressional waves of monzonitic rock materials (equation 3):

$$K = \frac{(V_0 - V_W)}{V_0} \quad (3)$$

Where K is coefficient of weathering, V_0 is velocity of ultrasonic waves in fresh rock and V_w is velocity of ultrasonic waves in weathered rock.

Chemical Indices: Most chemical weathering indices which guess the mechanical properties of weathered rocks regard only chemical leaching such as Parker index [15], lixiviation index [16], mobiles index [10], mobility index [2], but only a few consider the amount of the weathering products such as product index [17]. Chemical weathering indices are calculated using the molecular proportions of major element oxides. The molecular proportion of each oxide is calculated from the percent of the oxides based on their weight. Various researchers [9, 10, 17] have proposed chemical indices for characterizing the weathering degree of rocks. The chemical weathering indices evaluated in this study are listed in Table 1. These indices have been used to determine the weathering state of hololeucogranite samples.

Table1: Summary of chemical weathering indices evaluated in this study

Index	Formula	Trend of index by weathering grade
PI	$PI = \left[\left(\frac{Na}{0.35} + \frac{Mg}{0.9} + \frac{K}{0.25} + \frac{Ca}{0.7}\right) \times 100\right]$	Negative
CIA	$CIA = \frac{100 \times Al_2O_3}{Al_2O_3 + CaO + Na_2O + K_2O}$	Positive
CIW	$CIW = ACN = 100\left[\frac{Al_2O_3}{(Al_2O_3 + Na_2O + CaO)}\right]$	Positive
SA	$SA = \frac{Sio_2}{Al_2o_3}.$	Negative
WPI	$WPI = \frac{(K_2O + Na_2O + CaO - H_2O^+) \times 100}{(SiO_2 + Al_2O_3 + Fe_2O_3 + TiO_2 + CaO + MgO + Na_2O + K_2O)}$	Positive
β	$\beta = \frac{A_{weathered}}{\left(Afresh + \frac{CaO}{MgO}\right)} \rightarrow A = \frac{K_2O + Na_2O}{Al_2O_3}$	Negative
LOI	Loss On Ignition	Positive

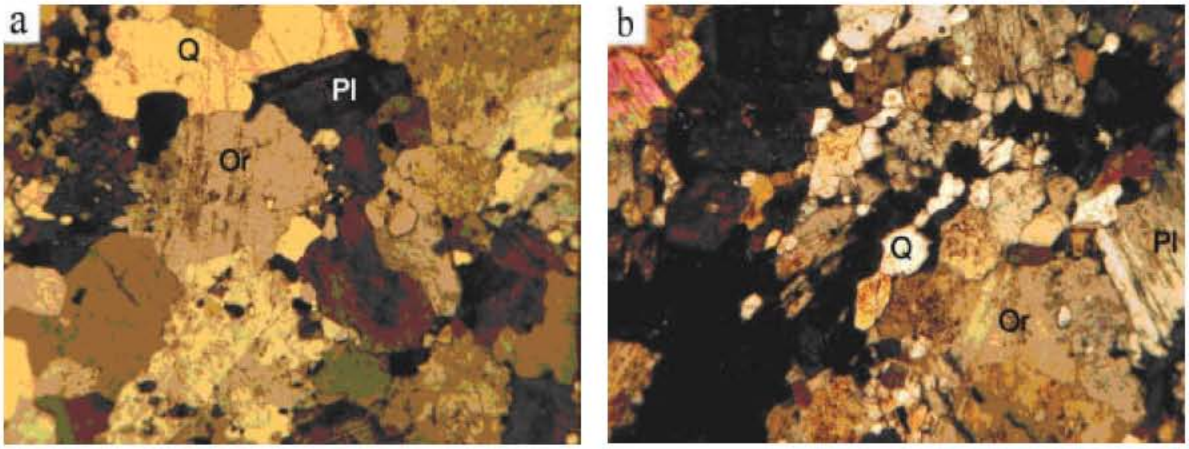

Fig. 2: Photomicrograph of (a). Fresh hololeucogranite with pseudo porphyritic granular, Composed of quartz, K-feldspar and plagioclase. (b) Moderately weathered hololeucogranite. Composed mainly of microfissured quartz, K-feldspar, sericitized plagioclase and Plagioclase (enlargement 10×).

RESULTS AND DISCUSSION

Mineralogical Characteristics: All samples were subjected to mineralogical analysis in order to characterize their composition. The thin sections were examined under a petrographic microscope for mean grain size and modal composition. Photomicrographs of fresh and moderately weathered samples are presented in Fig. 2.

Petrographical studies of hololeucogranite show fine grains pseudo porphyritic quartz, Subhedral plagioclase and orthoclase. These samples have a fine-grained matrix that is composed mainly of feldspar and quartz with curved grain boundaries and 1–2 mm long ragged aggregates of ortoclase phenocrysts. The modal compositions of the Alvand hololeucogranite rocks at various weathering grades are given in Table 2. Quartz, plagioclase and K-feldspar are the main minerals in all samples.

Weathering in Alvand hololeucogranite rocks are identified trough the development of clay minerals and sericitization of plagioclase. According to the results of the analysis, feldspar is altered in to sericite at the beginning stages of the weathering process. At the intermediate stage, clay minerals are formed. Biotite is converted into clay minerals deteriorating their chemical structures. In the latest stages of the weathering, the soil formation takes place and the hololeucogranite material is converted into residual soil. For the whole rock analysis, the X-ray fluorescence (XRF) was performed to obtain the oxides contents of samples having different weathering degree (Table 3).

Table 2: The modal compositions of the hololeucogranite rocks at various weathering states from the Alvand granitic rocks

Weathering grade	Qtz	Or	Pl	Mus	Bt	Ky	Oth
W_1	43	19	26	4	3	4	1
W_2	43	17	23	4	4	5	4
W_3	42	17	16	6	4	5	10
W_4	40	13	11	4	3	7	22
W_5	40	9	7	4	3	7	30

Qtz: quartz, Or: orthoclase, Pl: plagioclase, Mus: muscovite, Bt: biotite, Ky: kiyanite, Oth: other minerals (that mainly included termolite, garnet, sericite and clay minerals), w_1: fresh; W_2: slightly weathered; W_3: moderately weathered; W_4: highly weathered; W_5: completely weathered

As shown in the Table 3 the weathered samples investigated show decreases slightly in SiO_2 concentrations, with increasing degree of weathering and the amount of CaO, K_2O and Na_2O decrease during the early stages of weathering. It can be seen that the amount of Na_2O and CaO decreases from grade W_1 to grade W_5. Indeed CaO and Na_2O decrease quickly during the early stages of weathering.

The decomposition of feldspar would result in a direct loss of Na_2O, CaO and SiO_2. During the weathering process, FeO is oxidised and changed into Fe_2O_3, then the amount of Fe_2O_3 increases with the increasing degree of weathering (Table 3).

This result, indicate that the oxidation is an important weathering process for iron-bearing minerals such as biotite commonly found in Hamedan hololeucogranite rocks.

Table 3: Elemental composition obtained by XRF of the samples at various weathering states from the Alvand granitic rocks

Sample	SiO_2	Al_2O_3	Na_2O	MgO	K_2O	TiO_2	MnO	CaO	Fe_2O_3	P_2O_5	LOI
H_1	62.14	19.99	7.19	0.42	0.44	0.64	0.01	8.56	0.63	0.23	0.34
H_2	62.12	20.14	7.13	0.38	0.34	0.69	0.01	7.74	0.68	0.32	0.42
H_3	62.11	20.23	7.06	0.33	0.31	0.70	0.03	7.54	0.87	0.26	0.52
H_4	61.46	21.01	6.94	0.25	0.28	0.72	0.01	7.52	0.96	0.03	0.67
H_5	61.36	21.11	6.37	0.23	0.27	0.74	0.01	7.44	1.14	0.03	1.21

Table 4: Physical properties of Alvand granitic rocks at various degree of weathering

Weathering grade	γ_d (gr/cm^3)			γ_{sat} (gr/cm^3)			QAI(%)			n (%)			Vp (m/s)
	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Mean
W_1	2.59	2.66	2.63	2.60	2.66	2.67	0.20	0.26	0.24	0.74	1.50	0.96	4424.58
W_2	2.42	2.64	2.62	2.58	2.65	2.64	0.24	0.47	0.35	0.94	1.71	1.20	2480.46
W_3	2.59	2.61	2.61	2.67	2.63	2.63	0.51	0.81	0.71	1.89	2.35	2.18	3305.25
W_4	2.50	2.57	2.53	2.54	2.60	2.57	1.14	1.55	1.31	3.15	4.56	3.84	2798.32
W_5	2.37	2.49	2.48	2.43	2.54	2.51	1.77	2.54	2.02	4.11	6.52	5.48	1026.12

Table 5: Mechanical properties of Alvand hololeucogranite rocks at various degree of weathering

Weathering grade	Durability index	Uniaxial Compressive Strength (MPa)			Tensile Strength (MPa)		
		Min	Max	Mean	Min	Max	Mean
W_1	99.79	270.89	315.65	288.25	12.22	18.27	15.62
W_2	99.82	133.43	159.33	145.92	10.92	17.59	14.67
W_3	99.76	63.79	199.68	105.66	6.45	12.37	9.49
W_4	98.76	69.77	72.514	71.718	2.12	4.63	3.29
W_5	97.34	25.38	32.88	28.71	2.02	4.86	2.73

The amount of TiO_2 and Loss on Ignition (LOI) increases. LOI appears to be a good indicator of chemical weathering as it reflects the content of altered minerals.

Physical and Mechanical Properties: The results of the physical tests undertaken on the hololeucogranite, presented in Table 4. According to the test results, for all samples, with the increasing grade of the weathering, effective porosity increases and the amount of microcracks and voids increases. Similar trends have also been observed for the quick water absorption index. The comparison between the values of the ultrasonic wave velocity measured in fresh and weathered granitic rocks are shown in Table 4. From the results, it can be concluded that the higher values of the Vp is belong to less weathered rock samples.

Slake durability index (Id) is generally accepted as a good indicator for weatherability of rocks, in a laboratory-simulated weathering environments. For different samples, the results of the slake durability test after the second cycle (Id_2) are shown in Table 5. In each case, the reduction in Id_2 is minimal at the initial stages of weathering, but is very high towards to the end of the weathering sequence. This indicates that weatherability, in terms of disintegration, increases with increasing weathering grade. Based on the tests results, the slake durability index is very high for hololeucogranite. It should be noted that in the hololeucogranite samples, the quartz remained relatively unaltered throughout the slake durability test.

As a result, the UCS of the all samples decreases while the weathering grade increases (Table 5). The fine grained hololeucogranite is very strong in the fresh state with a UCS value of 288 MPa. Breaking of intergranular bonds while the weathering grade increases and occurence of microfractures, reduces the tensile strength significantly (Table 5). This means that, analysis of the brazilian tensile strength tests indicates obvious trend.

Table 6: Alvand hololeucogranitic petrographical and engineering indices values

Weathering grade	Xd	Ip	K	QAI
W_1	0.00	99.00	0.00	0.24
W_2	1.84	24.00	0.44	0.35
W_3	4.06	6.00	0.25	0.71
W_4	8.50	3.54	0.36	1.31
W_5	17.87	2.33	0.77	2.02

Table 7: The average of chemical indices values for Alvand hololeucogranite

Weathering grade	WPI	PI	LOI	SA	β	CIW	CIA
W_1	16.19	74.50	0.34	3.11	1.00	55.93	55.75
W_2	15.32	74.30	0.42	3.08	0.97	57.57	56.98
W_3	15.03	74.00	0.52	3.07	0.95	58.08	57.58
W_4	14.86	73.00	0.67	2.93	0.90	59.74	58.78
W_5	14.27	72.70	1.21	2.91	0.82	60.45	59.99

Weathering Indices: For Alvand hololeucogranite rocks, petrographic and engineering weathering indices were evaluated. The results are presented in Table 6. It can be seen, the Xd index increase with increasing weathering degree. From the results, it can be concluded that decreasing of Ip leads to increasing the weathering degrees. It is well known that quartz is very hard to be weathered, whereas feldspar (including plagioclase and K-feldspar) and biotite are more vulnerable to weathering. As the percentages of transformation of sound feldspar and biotite are closely relative to degree of weathering, it is reasonable to include feldspar and biotite rather than quartz in the index. Ip values are >6 in the fresh rocks, 6–2.8 in slightly weathered materials, 2.8–1.4 in moderately weathered materials, 1.4–0.7 in highly weathered materials and 0.7–0.4 in completely weathered rocks.

The coefficient of weathering index (K) value is varied from zero to one for fresh and completely weathered rocks, respectively. The quick absorption index (QAI) for the different weathering classes, which shows a successive increase with increasing weathering grade for each sample.

The chemical weathering indices for various weathering grade samples have been calculated using the molecular proportions of major element oxides. The chemical weathering indices for the samples are presented in Table 7. It can be seen that the weathering potential index (WPI) values decreasing with increasing weathering degree. The WPI values change from 16.19 for fresh samples to 14.27 values for completely weathered samples. This index provided a good indication of weathering state for the hololeucogranite. This may be due to this fact that the WPI index includes alkaline earth metals as mobile elements and these are dominate in the feldspars of hololeucogranite. As this index includes many chemical components, it may be more reliable than in a simple index, which only relies on one or two components. The parker index (PI) indicates the extent of weathering in terms of alkali metals remaining after weathering. The PI index value decrease with increasing weathering hololeucogranite samples.

According to the test results, the LOI index increase with increasing weathering degree. This can be explained by the fact that LOI is related to secondary mineral formation such as clays, iron oxides and chlorites.

The silica-Alumina ratio (SA) to be affected by the Sio_2 and Al_2o_3 content in the parent rock and hence is suitable for determining the weathering degrees of granitic rocks. The silica-Alumina ratio (SA) values decreasing with increasing weathering degree. The lixiviation index (β) was also determined and the result is summarized in Table 7. This index shows a relatively consistent variation for weathering of hololeucogranite samples. As a result of tests, in the Chemical Index of Weathering (CIW) and Chemical Index of Alteration (CIA), there were consistent increases from fresh hololeucogranite samples to completely weathered samples.

Correlation Between UCS and Weathering Indices: Statistical analysis was applied to explore the possible relationship between the proposed weathering indices and the uniaxial compressive strength of the weathered rock materials from selected weathering profiles. Coefficients of determination (R^2) and best-fit curves were calculated by the 'least squares curves fit' method.

Based on the results, a good relationship with best-fit lines (R^2=0.97) between Ip and UCS is shown for hololeucogranite sample (Fig. 3a).

As it is clear from Fig. 3b, the relationship between UCS and Xd index for hololeucogranite samples reveals that there is a good linear correlation (R^2=0.93).

Based on the results, K index is relatively good correlated with UCS (R^2=0.82) (Fig. 3c) but quick absorption index (QAI) showed good nonlinear correlation (R^2=0.93) with UCS (Fig. 3d).

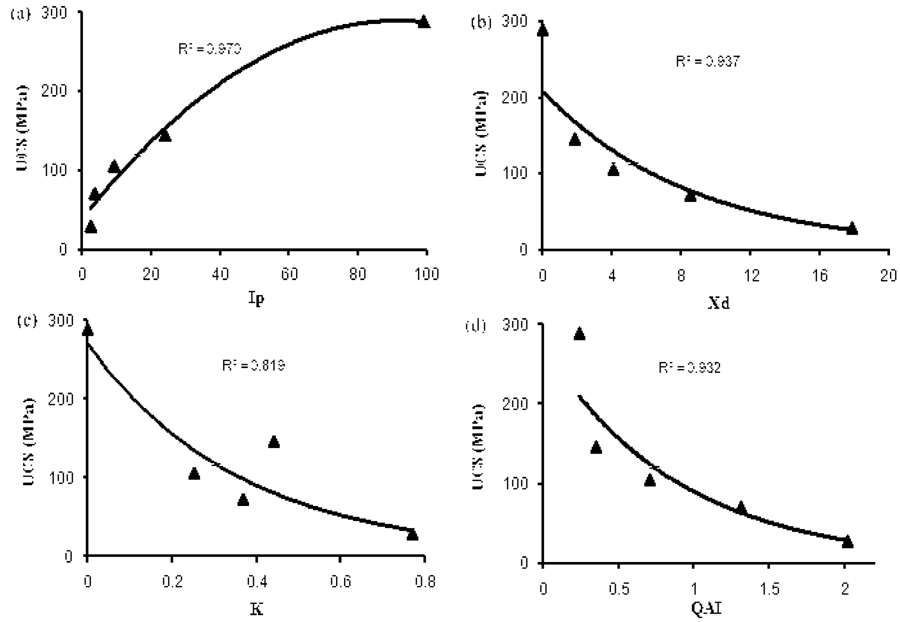

Fig. 3: Relationship between UCS and (a) Ip, (b) Xd, (c) K, (d) QAI.

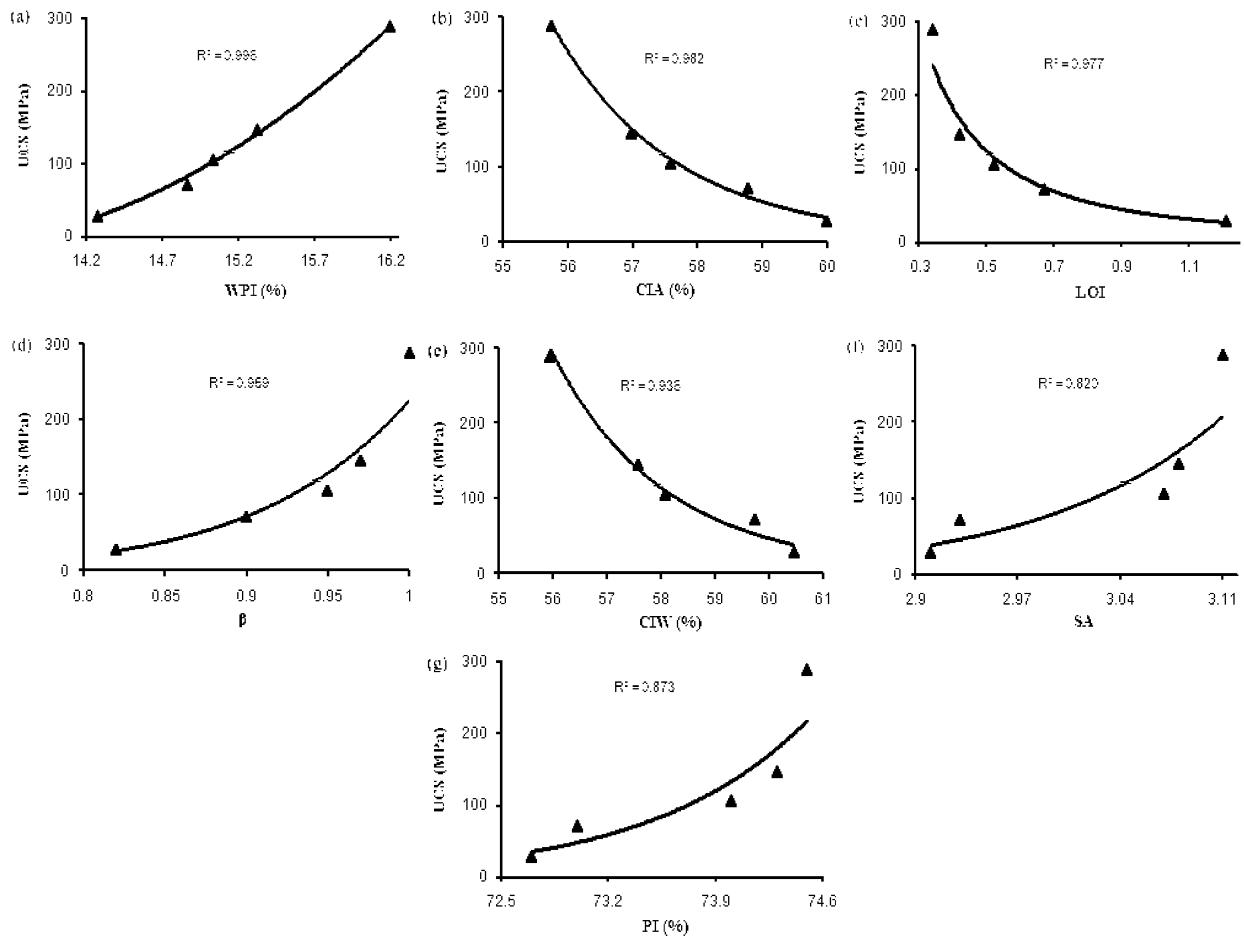

Fig. 4: Relationship between UCS and (a) WPI, (b) CIA, (c) LOI, (d) β, (e) CIW, (f) SA, (g) PI.

The best linear correlation coefficient (R^2=0.99) was found between UCS and WPI index (Fig. 4a). The Correlations between CIA (R^2=0.98), LOI (R^2=0.97), β (R^2=0.95), CIW (R^2=0.93) indices showed strong clear correlations with uniaxial compressive strength value (Fig. 4b, c, d, e). As can be seen from the coefficient of determination, there are statistically significant correlations between these chemical indices and UCS of the weathered hololeucogranitic rock materials studied. Whereas, the SA index (R^2=0.82) and PI index (R^2=0.85) showed relatively good correlation with uniaxial compressive strength (Fig. 4f, g).

CONCLUSION

An attempt was made to investigate the weathering mechanisms and to describe quantitatively the degree of weathering for Alvand hololeucogranite rocks in Iran. The conclusions obtained from this study can be brief as follows:

- As the weathering increase, the percentage of Fe_2o_3, LOI, TiO_2 increases, but the percentage of SiO_2, Na_2O, K_2O and CaO decreases.
- Based on the results from the application of many existing quantitative chemical indices on the hololeucogranite rocks in Hamedan, it can be concluded that the chemical indices such as WPI, CIA, LOI, β and CIW are good quantitative indicators for describing the degree of weathering. Application of these indices in the assessment of uniaxial compressive strength of the hololeucogranite rocks yields suitable and meaningful results.
- The study has shown that, Ip values as a petrographic index exhibits good correlations with UCS and can also be good indicators of granite rock weathering. This index is simple to determine, as for practical purposes the only mineralogical diagnosis that has to be made under microscope is between fresh, sound constituents and unsound constituents.
- Various weathering indices can be used to classify the weathering state, but the degree of decomposition index (Xd) as a petrographic index, was proved to be unsuitable for hololeucogranite in the Hamedan area.
- The relationships between the chemical weathering indices and UCS are better than the petrographical and engineering weathering indices with UCS.
- Engineering properties of weathered hololeucogranite vary over the wide range depending on the degree of weathering. As a result, the effective porosity and quick water absorption of the all samples increase while the weathering grade increases, whereas wave velocity, dry and saturated density, UCS, tensile strength and slake durability of samples decreases.

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