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ORIGINAL ARTICLE

Assessment of weathering processes effect on engineering properties of Alvand granitic rocks (west of Iran), based on weathering indices

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Abstract The Alvand batholith is one of the largest plutonic bodies in the west of Iran. In this research, several physico-mechanical tests have been performed on granodiorite and porphiroid monzogranite consisting of five degrees of weathering in Hamedan area, west of Iran. Furthermore, weathering process of Alvand granitoid is studied by chemical analysis and petrographical studies. The results indicated that engineering properties of weathered granodiorite and monzogranite vary over the wide range depending on the degree of weathering. On the other hand, this research is focused on the assessment of relationship between weathering indices and uniaxial compressive strength. For this reason, some of the most important weathering indices are reviewed. It should be noted that, application of these chemical, engineering and petrographical indices are good quantitative indicators for describing the degree of weathering. Using these indices for the assessment of uniaxial compressive strength of granodiorite and monzogranite rocks, yields suitable and meaningful results.

Keywords Weathering indices · Granodiorite · Monzogranite · Alvand granitoid

Introduction

Alavand granitoid is one of the largest plutonic bodies located in the southwest of Hamedan, western part of Iran. These granitic rocks are the widely used stones in construction of ancient buildings, ornamental elements and movable stone heritage artifacts (e.g., statues, stone pavements, altar pieces, benches, etc.) in the west of Iran, either in monumental or vernacular architecture (Fig. 1a, b).

Weathering is generally defined as the process of alteration and breakdown of rocks at near the earth surface by physical and chemical effects and leads to a number of changes on the rocks (Selby 1993). Weathering processes alter mineralogical, physical and geomechanical characteristics of rocks. The effects of weathering on the engineering properties of rocks have been studied by numerous investigators and in this regard various weathering classifications have been proposed. Anonymous (1995) and ISRM (1981b) suggested some classifications mainly based on the field observations and determined six classes with respect to the degree of weathering.

Chemical changes during weathering are quantified in several ways including the normalized values of element (or oxide) using their parent rock concentrations or immobile element concentrations in the samples (Krauskopf 1967), ratio of elements to immobile elements (Guan et al. 2001), measurement and calculation of loss or gain of weight based on immobile element (Huston 1993; MacLean 1990) and chemical weathering indices (Duzgoren and Aydin 2003; Price and Velbel 2003; Tugrul 1995). 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 granodiorite and monzogranite rocks is described by both using laboratory and in situ tests. Furthermore, some weathering indices are suggested for petrographic, engineering and chemical considerations of granitic rocks. Statistical correlations between uniaxial compressive

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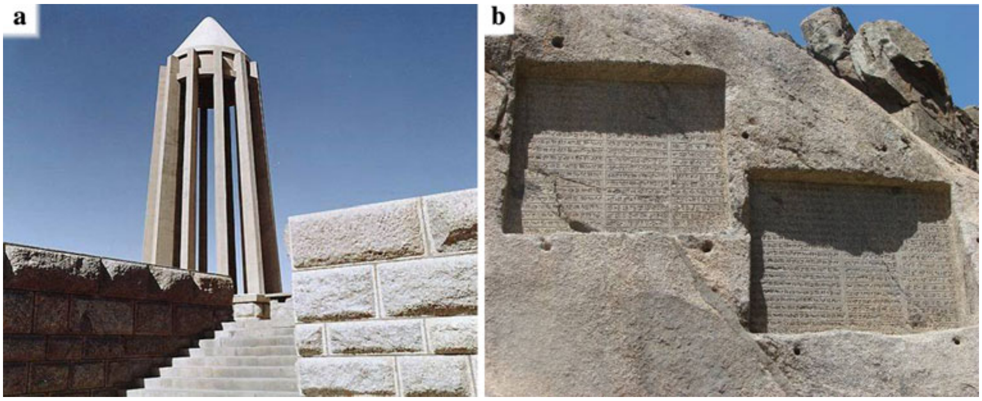

Fig. 1 **a** Bu-Ali Sina Tomb, Hamedan, Iran. **b** A very famous inscriptions of Darius in Ganjnameh, Hamedan, Iran (2,550 years ago)

strength and chemical, engineering, petrographic indices in the various degree of weathering have indicated some important points.

Geological setting

The Alvand plutonic batholith is located in the west part of Iran (Fig. 2a). It is one of the largest plutonic bodies in the Sanandaj–Sirjan metamorphic belt (SSMB) (Fig. 2b). This zone is characterised by the predominance of metamorphic rocks, accompanied by the sedimentary and magmatic rocks (Berberian and Alavitehrani 1977; Sepahi 1999). Alvand batholith consists of gabbro, diorite, tonalite, granodiorite, porphyroids granites and hololeucocratic granitoids. Previous studies have shown that S-type granite-granodiorites are mostly per-aluminous and calc-alkaline, the gabbro-diorite-tonalite suite is mostly metaluminous and tholeiitic to calc-alkaline (Sepahi 2008).

The tectonic evolution of the Sanandaj–Sirjan belt involved continental arc magmatism followed by collision. According to Valizadeh and Cantagrel (1975) mafic to intermediate plutonic bodies (olivine gabbro, gabbro, gabbro-norite, diorite, quartz diorite and tonalite) are older than crustally derived granitic plutons in the region (Alvand plutonic complex), but all intrusions formed during Cretaceous-tertiary subduction and collision (Baharifar et al. 2004). The plutons, including the granites, are commonly associated with contact aureoles defined by hornfelsic textures and mineral assemblages that overprint earlier minerals and fabrics.

Some of the most important primary (magmatic) and secondary (tectonic) structures of granitic rocks in this plutonic complex are as follows: the primary structures, including orientation of feldspar phenocrysts (Fig. 3a), mica, enclaves and primary fractures or joints. These structures confirm an internal magmatic flow and syn-emplacement fractures inside the intrusive body. Figure 3b shows two major joint systems in Alvand granitic rocks. The secondary structures include tectonic fractures and structural changes in rock bodies in the solid state after solidification of the plutonic body (Sadr et al. 2004).

For the present study, two types of Alvand plutonic that consist of granodiorite and monzogranite have been investigated. These types are located in the southern part and south and central part of the study area, respectively.

A review of the weathering indices

There are several weathering indices proposed by various investigators for characterizing weathering degree of granitic rocks (Aires-Barros 1978; Irfan and Dearman 1978b; Parker 1970; Hodder 1984). 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 (1962) defined a quantitative index (X_d), related to the weight ratio of quartz and feldspar in the decomposed granite of Hong Kong as Eq (1):

$$X_d = \left(\frac{N_q - N_{q_0}}{1 - N_{q_0}}\right) \tag{1}$$

where N_q and N_{q0} are the weight ratio of quartz and feldspar in weathered and fresh rock samples, respectively. Furthermore, it should be noted that ratio of quartz to feldspar (*Q/F*) can be considered as weathering index.

Based on comprehensive studies on the weathered granites in UK, Irfan and Dearman (1978b) suggested the

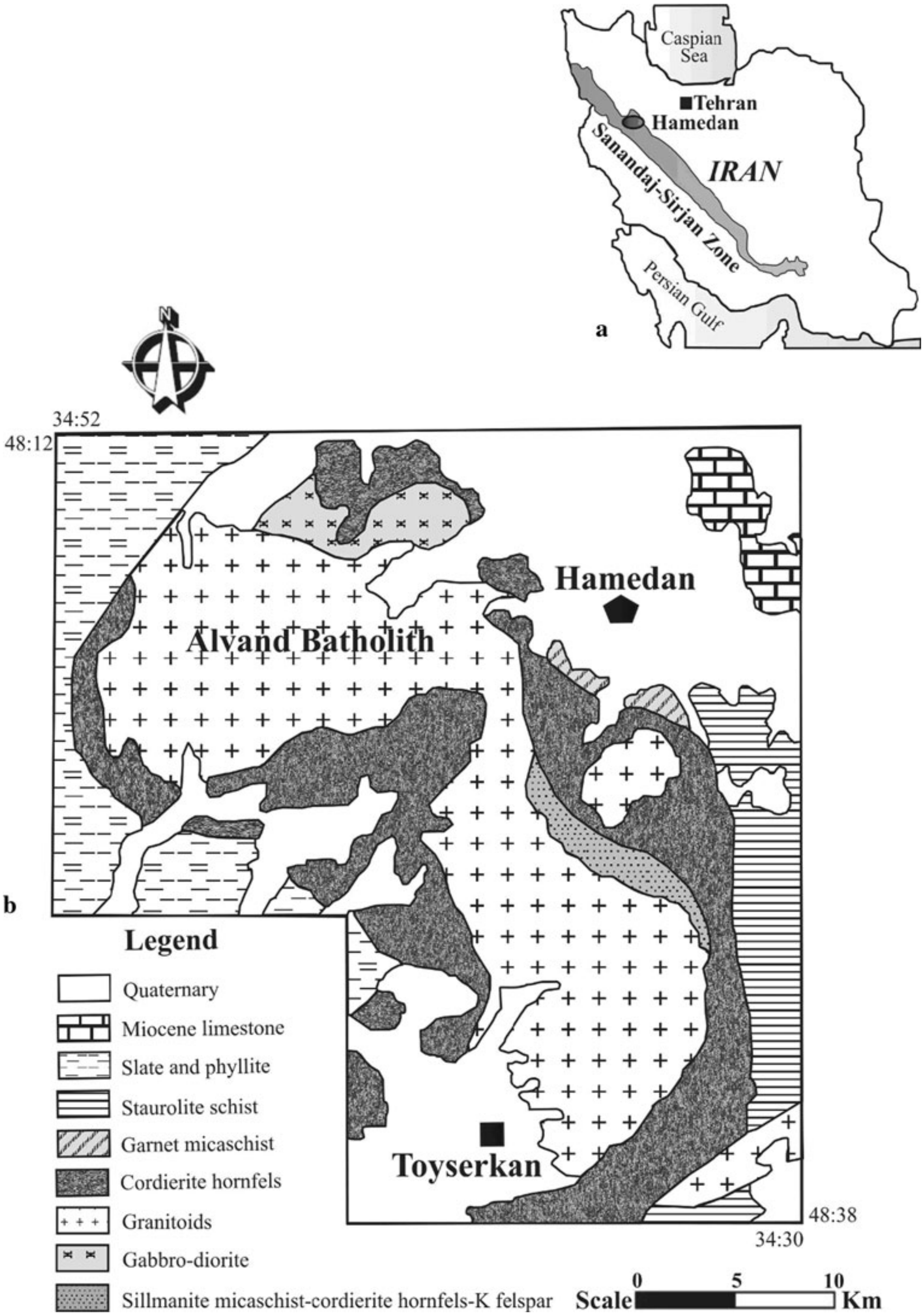

Fig. 2 **a** The Sanandaj–Sirjan zone in Iran with location of study area. **b** Location map of the granitic rocks tested (after Sepahi 1999 with modification)

micropetrographic index (I_p) to characterize the degree of weathering of rocks. The I_p can be expressed by the Eq. 2:

$$I_p = \frac{SC\%}{UC\%} \tag{2}$$

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

Engineering indices

From an engineering geology point of view, 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 (1961) for the assessment of weathering of granite and schist.

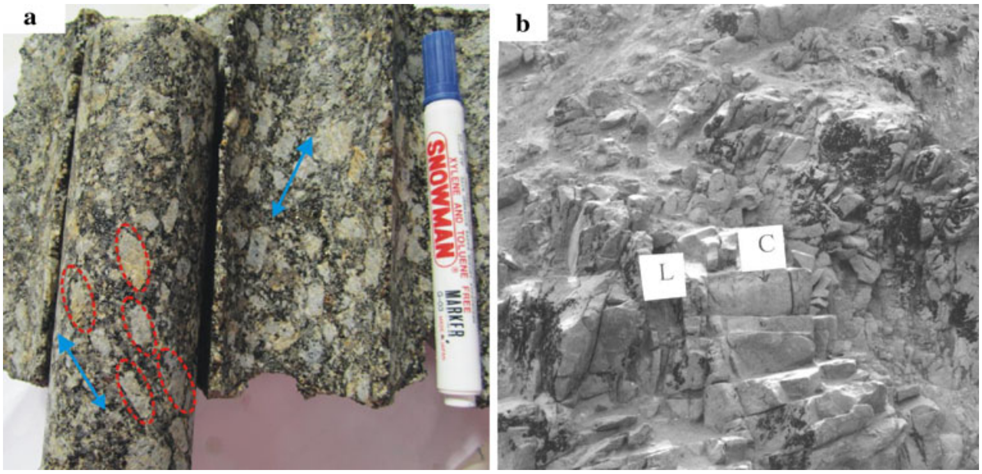

Fig. 3 **a** Illustration of porphyry granite with oriented feldspars. **b** Illustration of two orthogonal joints system in Alvand granitic rocks. The *C* joints are *horizontal* and formed later than the *L* joints which are *vertical*

The coefficient of weathering (K) was developed by Illev (1967) based on the velocity of compressional waves of monzonitic rock materials (Eq. 3):

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

where K is the 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 (Parker 1970), lixiviation index, mobiles index (Irfan and Dearman 1978a), mobility index (Guan et al. 2001), but only a few consider the amount of the weathering products such as product index (Reiche 1943). Additionally, the chemical weatherability index (Hodder 1984) is used to characterize the weathering state.

Chemical weathering indices are calculated using the molecular proportions of major element oxides. The molecular proportion of each oxide is calculated from the percentage of the oxides based on their weight. Molecular proportions may also be used to calculate weathering indices for rocks, which have been affected by mechanical processes. The chemical weathering indices calculated from molecular proportions are based on the assumption that major oxides, including Al_2O_3, Fe_2O_3 and TiO_2, considered to be "immobile", remained constant but some oxides including SiO_2, Na_2O, K_2O, CaO and MgO, considered to be "mobile", decreased and loss on ignition (LOI) content increased in the weathering processes.

Chemical change during weathering and hydrothermal alteration are quantified in several ways including the normalized value of oxide using their parent rock concentrations or immobile element concentrations in the samples (Krauskopf 1967), measurement and calculation of loss of weight based on immobile element (Huston 1993; MacLean 1990), ratio of elements to immobile elements (Guan et al. 2001). Various researchers (Gupta and Rao 2001; Irfan and Dearman 1978a; Nesbitt and Young 1982; Reiche 1943; Ruxton 1968) have proposed chemical indices for characterizing the weathering degree of rocks. Summary of chemical weathering indices evaluated in this study have been shown in Table 1.

Materials and methods

Material identification

In order to evaluate the weathering process, two main qualitative and quantitative methods can be used. The qualitative methods of weathering are based on observational descriptions and index properties of rocks. These are color changes (Lee 1987) and observational description of physical weathering grade (Irfan and Dearman 1978a; ISRM 1981a). Another method for weathering classification is the quantitative which is based on weathering classification schemes. For applying quantitative classification schemes, some researchers such as Arikan et al. (2007), Gupta and Rao (2001) and Irfan and Dearman (1978b) have considered the petrographical, chemical and index properties.

In this study, in order to determine the weathering degree of these two types of the granites, the weathering classification proposed by the ISRM (1981a) has been

Table 1 Summary of chemical weathering indices evaluated in this study

Index	Formula	Trend of index by weathering grade	Reference
PI	$\mathrm{PI} = \left[\left(\frac{\mathrm{Na}}{0.35} + \frac{\mathrm{Mg}}{0.9} + \frac{\mathrm{K}}{0.25} + \frac{\mathrm{Ca}}{0.7}\right) \times 100\right]$	Negative	Parker (1970)
CIA	$\mathrm{CIA} = \frac{100 \times \mathrm{Al_2O_3}}{\mathrm{Al_2O_3 + CaO + Na_2O + K_2O}}$	Positive	Nesbitt and Young (1982)
CIW	$\mathrm{CIW} = \mathrm{ACN} = 100 \times \left[\frac{\mathrm{Al_2O_3}}{(\mathrm{Al_2O_3 + Na_2O + CaO})}\right]$	Positive	Harnoiss (1988)
SA	$\mathrm{SA} = \frac{\mathrm{SiO_2}}{\mathrm{Al_2O_3}}$	Negative	Ruxton (1968)
WPI	$\mathrm{WPI} = \frac{\mathrm{K_2O + Na_2O + CaO - H_2O^+ \times 100}}{(\mathrm{SiO_2 + Al_2O_3 + Fe_2O_3 + TiO_2 + CaO + MgO + Na_2O + K_2O})}$	Positive	Reiche (1943)
β	$\beta = \frac{A_{\mathrm{weathered}}}{\left(A_{\mathrm{fresh}} + \frac{\mathrm{CaO}}{\mathrm{MgO}}\right)} \rightarrow A = \frac{\mathrm{K_2O + Na_2O}}{\mathrm{Al_2O_3}}$	Negative	Rocha-Filho et al. (1985)
LOI	Loss on ignition	Positive	Sueoka et al. (1985)

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 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 granitoid rocks, color changes, staining, textural changes, disintegration, altered/unaltered minerals were considered.

Sampling and laboratory studies

The samples representing different weathering degrees were collected from homogenously weathered zones. Large size blocks were preferred which were capable of providing a sufficient number of core samples. Weathered samples that were highly prone to collapse by disturbance, were immediately covered with plaster and safely transported to the laboratory. Suitable samples were prepared in the laboratory. As coring was sometimes difficult, cubical specimens were prepared for highly weathered rocks. No sample was collected from residual soil (the grade W_6) in the weathering profile and tests were not performed on it.

In order to record mineralogical abundance and textural features in each sample and their weathering, thin sections were studied using petrological microscope. From each degree of weathering three thin sections were prepared in order to study and analyze the petrographical properties of different weathering grades. The point-count method, as described by Hutchinson (1974), was used to determine modal composition. The contents of quartz, plagioclase, K-feldspars, biotite and other minerals were distinguished for each thin section. The mineral composition of each rock type also was investigated by XRD analysis. As shown in Fig. 3, the results of XRD analysis confirmed the mineral composition of the thin sections of the study XRF analysis of major oxides was performed using X-ray fluorescence spectrometry (Philips PW 1404/10) on powder pellets.

The physical index properties such as specific gravity, dry and saturated densities, effective porosity, ultrasonic velocity and water absorption were determined on samples which were prepared for uniaxial compressive strength test(UCS) for each rock following the standard test procedures suggested by the ISRM (1981b).

The slake durability index (I_{d}) was devised by Franklin and Chandra (1972) to assess the durability or weatherability of clastic sedimentary rocks such as shale, particularly useful for rocks with significant clay content. Lee and Freitas (1988) observed that the I_{d} is quite useful in the quantification of higher degrees of weathering in Korean granites.

The uniaxial compressive strength is the most common performance measure used by engineers for the quality assessment of rocks. For certain applications of natural dimension stones minimal values for the compressive strength are requested (Siegesmund and Snethlage 2011). Mechanical properties achieved from core samples included the uniaxial compressive strength (UCS) and the tensile strength (σ_{t}). The uniaxial compressive strength test for fresh and slightly weathered rocks has been carried out on 20 cylindrical specimens ($L/D = 2.5$) under dry and saturated conditions, following the recommendations of the ISRM (1981b). For moderately, highly and completely weathered granititoid, 30 cubic specimens with the size of ($H/D < 1$) were prepared and tested according to ASTM, (C170). The results were converted into cylindrical samples strength by a multiplying factor after testing of the cubic specimens.

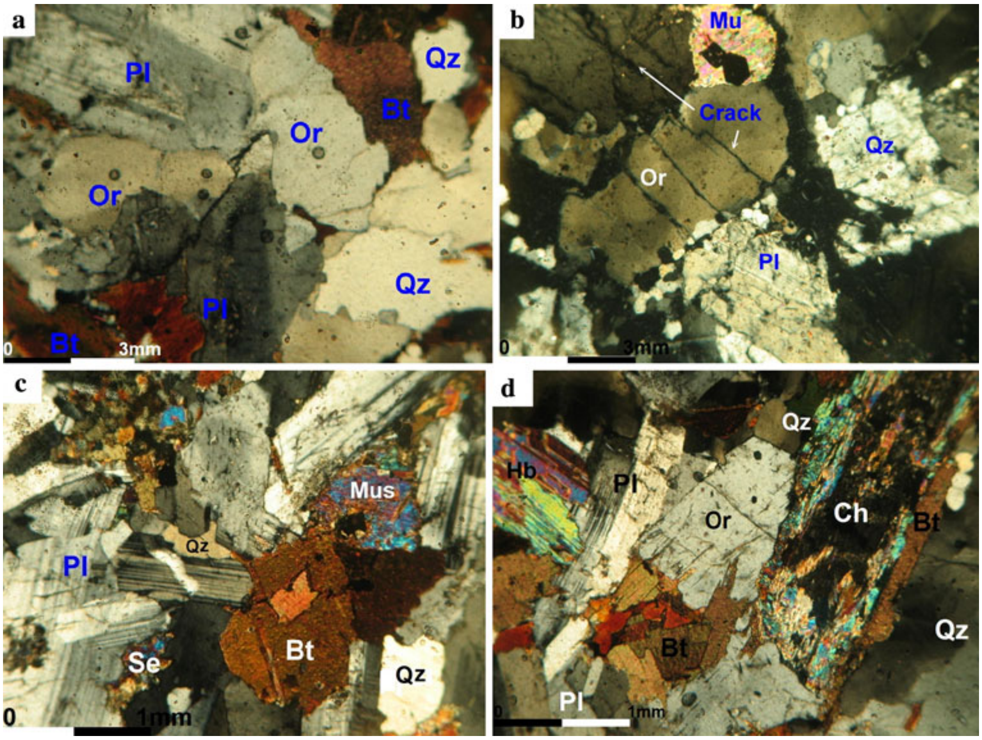

Fig. 4 Photomicrograph of **a** slightly weathered monzogranite **b** highly weathered monzogranite **c** slightly weathered granodiorite **d** highly weathered. *Qz* quartz, *Or* orthoclase, *Pl* plagioclase, *Mus* muscovite, *Bt* biotite, *Ch* cholorite, *Hb* hornblend

Results and discussion

Mineralogical characteristics

The results of site investigations show that for the granodiorite and monzogranite in the earlier stage of weathering, the color of feldspar and biotite changes from the olive black in fresh rock to the yellowish brown in the saprolite and soils. 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 slightly and moderately weathered samples are presented in Fig. 4.

Petrographical studies of monzogranite show anhedral granular texture to anhedral rectangular plagioclase, K-feldspar, coarse grain, anhedral quartz, biotite and microcline. It should be noted that the slightly weathered samples contain various amounts of medium to coarse-grained feldspar crystals but, in completely weathered monzogranites, sericitization of feldspars is developed.

The petrographical description of slightly weathered granodiorite shows a small part of sericitized subhedral, large tabular feldspar, biotite, medium grained and anhedral quartz. K-feldspar is slightly altered to clay minerals. Muscovites and biotites are chloritized and dark minerals are partly altered. Granodiorite generally have medium grain size distributions and the grain boundaries are straight. In highly weathered granodiorite, the degree of sericitisation of feldspars is high, and it filled the micro-cracks within the feldspar crystals. Finally, results from thin section studies and mineralogical features of all rocks collected from Alvand granitoid are summarized in Table 2.

Chemical analysis

The results of XRD analysis are shown in Fig. 5. These results confirmed the mineral composition of the granitic rocks which obtained by thin section studies. 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). Elemental composition was obtained by XRF of the samples at various weathering states from the Alvand granitic rocks. As shown in the Table 3, the weathered samples show decreases slightly in SiO_2 concentrations, with increasing degree of weathering. The amounts of CaO, K_2O and Na_2O decrease during the early stages of weathering for two types of rocks. Ceryan et al. (2008) show that the *k*-value of granitic rocks decrease with increasing weathering and the *k*-value has the potential for being applied in investigating the engineering lifetime of building stones. It can be seen that the amount of Na_2O and CaO decreases from grade W_1 to W_5

Table 2 The modal compositions of the Alvand granodiorite and monzogranite rocks

Qtz quartz, *Or* orthoclase, *Pl* plagioclase, *Mus* muscovite, *Bt* biotite, *Oth* other minerals [that mainly included hornblende (in granodiorit samples), garnet, seresite and clay minerals], W_1 fresh, W_2 slightly weathered, W_3 moderately weathered, W_4 highly weathered, W_5 completely weathered

Rock type	Weathering grade	Qtz	Or	Pl	Mus	Bt	Oth
Granodiorite	W_1	26	10	37	3	8	17
	W_2	24	7	33	3	6	27
	W_3	24	4	27	2	6	37
	W_4	24	2	22	1	4	47
	W_5	22	2	17	0	2	57
Monzogranite	W_1	30	25	27	1	14	3
	W_2	30	22	21	2	14	11
	W_3	29	20	17	3	12	19
	W_4	29	17	14	4	13	23
	W_5	28	14	10	2	11	35

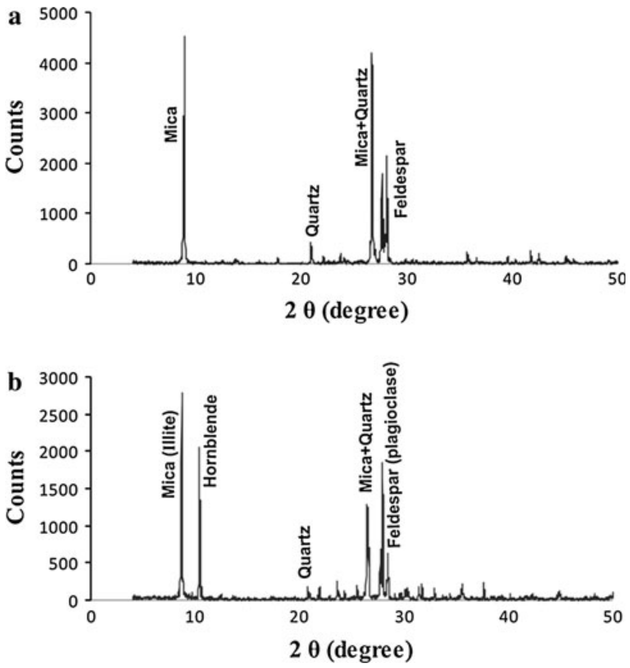

Fig. 5 Typical results of XRD analyses for the Alvand granitic rocks samples. **a** Monzogranite. **b** Granodiorite

(except for amount of CaO from W_1 to W_2 in the granodiorite samples). 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 increase of weathering degree. This result indicates that the oxidation is an important weathering process for iron-bearing minerals such as biotite commonly found in Alvand granitic rocks.

The amount of TiO_2 and loss on ignition (LOI) increases from grade W_1 to W_5 because of increase of clay minerals. LOI appears to be a good indicator of chemical weathering as it reflects the content of altered minerals. Tugrul and Gurpinar (1997) reported that LOI increases with the degree of weathering in the natural environment. According to the above results, it can be concluded that these changes are predominated for granodiorite samples.

Physical and mechanical properties

The results of the physical tests performed on the monzogranite and granodiorite samples, are presented in Table 4. As can be seen in Table 4, for all samples, with the increasing grade of the weathering, effective porosity increases because the amount of micro cracks and voids increases. These observations correspond to those records earlier by Irfan and Dearman (1978b). The porosity has a direct and indirect effect on most of the physical properties of rocks and is therefore considered the most important rock parameter Ruedrich et al. (2010). Between two granitic rocks types, granodiorite shows the highest increase in porosity with 1.08% in fresh rock to 12.75% for completely weathered rocks. 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 V_p belong to the low weathered rock samples. Among the all samples, the higher decreasing values of the V_p in granodiorite samples are 3039.40 and 960.80 m/s for fresh and completely weathered, respectively. Slake durability index (I_d) is generally accepted as a good indicator for weatherability of rocks. For different samples, the results of the slake durability test after the second cycle (I_{d2}) are shown in Table 5. In each case, the reduction in I_{d2} is minimal at the initial stages of weathering, but is very high towards the end of the weathering sequence.

Based on Gamble (1971) and Franklin and Chandra (1972) classifications, the slake durability index is medium for completely weathered monzogranite and low for the completely weathered granodiorite, respectively. These results can be depended on amounts of quartz in samples because the quartz remained relatively unaltered throughout

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

Rock type	Weathering grade	SiO_2	Al_2O_3	Na_2O	MgO	K_2O	TiO_2	MnO	CaO	Fe_2O_3	P_2O_5
Granodiorite	W_1	68.07	13.21	2.04	1.55	6.00	0.69	0.08	0.88	5.78	0.13
	W_2	68.01	13.27	1.98	1.50	5.60	0.71	0.10	1.83	6.23	0.17
	W_3	68.01	13.52	1.94	1.46	5.20	0.94	0.12	1.55	6.55	0.11
	W_4	66.57	13.72	1.87	1.36	5.05	1.00	0.09	1.55	6.65	0.09
	W_5	66.49	13.98	1.80	1.35	2.78	1.22	0.18	0.56	7.00	0.11
Monzogranite	W_1	63.67	14.63	2.62	2.29	5.42	0.70	0.11	2.26	7.32	0.15
	W_2	63.42	14.82	2.45	2.08	5.20	1.05	0.12	2.17	7.48	0.12
	W_3	63.15	15.23	2.42	1.70	4.88	1.13	0.09	2.15	7.50	0.16
	W_4	63.13	16.65	2.34	1.63	4.81	1.25	0.11	2.13	7.51	0.15
	W_5	63.02	16.70	2.12	1.52	4.40	1.26	0.16	1.98	7.53	0.11

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

Rock type	Weathering grade	γ_d (g/cm^3)			γ_{sat} (g/cm^3)			QAI			n (%)			V_p (m/s)		
		Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean
Monzogranite	W_1	2.65	2.74	2.71	2.67	2.76	2.72	0.40	0.50	0.46	0.96	1.61	1.36	2,820	3,670	3,039
	W_2	2.65	2.73	2.68	2.67	2.74	2.71	0.37	0.99	0.51	1.25	1.57	1.45	2,346	3,079	2,757
	W_3	2.62	2.65	2.63	2.63	2.66	2.65	0.45	0.66	0.53	1.34	1.64	1.53	2,415	2,730	2,584
	W_4	2.58	2.62	2.62	2.61	2.69	2.66	0.86	1.69	1.11	2.32	3.10	2.80	1,760	2,354	2,154
	W_5	2.12	2.17	2.15	2.24	2.26	2.25	2.74	4.62	3.71	8.78	11.44	10.11	640	1,094	960
Granodiorite	W_1	2.59	2.63	2.61	2.60	2.64	2.62	0.32	0.36	0.33	0.58	1.28	1.08	2,721	3,257	2,903
	W_2	2.57	2.60	2.58	2.60	2.63	2.61	0.82	2.08	1.24	2.23	3.36	2.66	2,483	3,079	2,782
	W_3	2.49	2.55	2.53	2.55	2.60	2.58	1.56	2.25	1.81	4.50	5.79	5.03	1,641	2,352	1,841
	W_4	2.39	2.48	2.44	2.44	2.53	2.49	1.94	2.35	2.09	4.47	6.97	5.13	1,084	1,321	1,254
	W_5	2.17	2.22	2.21	2.30	2.35	2.33	3.76	7.62	5.59	12.69	13.09	12.75	7,864	1,106	967

M monzogranite, *G* granodiorite, γ_d dry density, γ_{sat} saturated density, *QAI* quick absorption index, *n* porosity, V_p ultrasonic velocity

Table 5 Mechanical properties of Alvand granodiorite (T) and monzogranite (M) rocks at various degree of weathering

Rock type	Weathering grade	Durability index	Uniaxial compressive strength (MPa)			Tensile strength (MPa)		
			Min.	Max.	Mean	Min.	Max.	Mean
Monzogranite	W_1	99.55	104.45	158.19	125.64	8.02	13.21	9.49
	W_2	99.71	52.90	87.55	74.45	8.49	12.82	10.04
	W_3	99.42	51.98	146.86	69.59	4.18	9.76	6.77
	W_4	98.74	45.58	67.94	52.06	2.98	8.14	5.48
	W_5	73.97	9.10	25.78	14.81	1.13	3.08	2.08
Granodiorite	W_1	99.73	83.51	135.68	117.25	10.56	12.95	11.43
	W_2	98.81	54.28	70.26	63.36	7.13	11.19	8.63
	W_3	97.93	44.73	56.60	50.66	3.30	6.94	5.37
	W_4	93.58	24.14	34.23	30.79	1.26	2.42	1.91
	W_5	38.77	7.675	12.37	9.25	0.35	0.65	0.46

the slake durability test. In addition the effect of environmental factor such as pH has been studied by Ghobadi and Momeni (2011) on Alvand granitic rocks and their results show that these types of granitic rocks are resident to the this environmental disturbing factor.

As a result, the UCS of all samples decreases while the weathering grade increases (Table 5). Decreasing values of UCS is in the range of 108–110.83 MPa for granodiorite and monzogranite in sequence of weathering, respectively.

Table 6 Alvand granodiorite and monzogranite rocks chemical and engineering indices values

Rock type	Weathering grade	*Q/F*	X_d	I_p	QAI	*K*
Monzogranite	W_1	0.57	0.00	54.00	0.46	0.00
	W_2	0.69	0.28	8.10	0.51	0.09
	W_3	0.78	0.49	4.26	0.53	0.15
	W_4	0.93	0.84	3.37	1.11	0.29
	W_5	1.16	1.39	1.85	3.71	0.68
Granodiorite	W_1	0.55	0.00	49.00	0.33	0.00
	W_2	0.57	0.05	5.66	1.24	0.04
	W_3	0.77	0.49	3.76	1.81	0.36
	W_4	1.00	1.00	2.12	2.09	0.56
	W_5	1.15	1.35	1.56	5.59	0.66

Table 7 The average of chemical indices values for Alvand granitic rocks

Rock type	Weathering grade	WPI	PI	LOI	SA	β	CIW	CIA
Granodiorite	W_1	10.00	77.60	0.53	5.15	1.00	77.10	57.10
	W_2	9.50	77.10	0.63	5.12	0.94	77.67	58.49
	W_3	8.84	76.10	1.61	4.96	0.90	79.48	60.88
	W_4	8.65	75.70	2.05	4.85	0.87	80.05	61.85
	W_5	6.38	75.00	3.35	4.75	0.58	80.62	69.50
Monzogranite	W_1	10.41	73.80	0.84	4.35	1.00	74.99	58.69
	W_2	9.96	73.10	1.18	4.28	0.95	76.20	60.13
	W_3	9.92	72.60	1.39	4.15	0.91	76.90	61.71
	W_4	9.33	71.30	1.62	3.79	0.89	78.82	64.20
	W_5	8.62	71.20	1.68	3.77	0.81	80.30	66.29

Breaking of intergranular bonds while the weathering grade increases and occurrence of microfractures, reduce the tensile strength significantly (Table 5). This means that analysis of the brazillian tensile strength tests indicates obvious trend.

Weathering indices

For Alvand granodiorite and monzogranite rocks, petrographic and engineering weathering indices were evaluated. The results are presented in Table 6. It can be seen that the X_d and *Q/F* indices increase with the increase of weathering degree. From the results, it can be concluded that decreasing I_p leads to increasing of the weathering degrees. It is well known that quartz is very resistance to chemical weathering, whereas feldspar (including plagioclase and K-feldspar) and biotite are more vulnerable to weathering. As the percentages of transformation of sound feldspars and biotites are closely relative to degree of weathering, it is reasonable to include feldspar and biotite rather than quartz in the index.

The coefficient of weathering index (*K*) and quick absorption index (QAI) values show a successive increase with the increasing of 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 decrease with the increasing of weathering degree. This index provided a good indication of weathering state for the Alvand granitic rocks. This may be due to the fact that the WPI index includes alkaline earth metals as mobile elements and these are dominant in the feldspars of granodiorite and monzogranite rocks. As this index includes many chemical components, it may be more reliable than 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 the increasing of weathering in the rocks samples.

According to the test results, the LOI index increase with the increasing of 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) is 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.

Table 8 The best correlations between weathering indices and uniaxial compressive strength

Monzogranite rocks			Granodiorite rocks		
Variables	Formula	R^2	Variables	Formula	R^2
X_d vs. UCS	UCS = $97.46e^{-1.52(Xd)}$	89	X_d vs. UCS	UCS = $130.87e^{-1.44(Xd)}$	94
IP vs. UCS	UCS = 29.776 Ln(IP) + 11.57	92	IP vs. UCS	UCS = 29.538 Ln(IP) + 6.14	97
Q/F vs. UCS	UCS = −144.64 Ln(Q/F) + 36.46	94	Q/F vs. UCS	UCS = $641.07e^{-3.405(Q/F)}$	89
K vs. UCS	UCS = $112.84e^{-2.972(K)}$	98	K vs. UCS	UCS = $102.67e^{-2.8812(K)}$	81
QAI vs. UCS	UCS = $48.874\ (\mathrm{QAI})^{-0.878}$	93	QAI vs. UCS	UCS = −39.221 Ln(QAI) + 71.19	97
PI vs. UCS	UCS = $9.712\ (\mathrm{PI})^2 - 1{,}374\ (\mathrm{PI}) + 48{,}619$	87	PI vs. UCS	UCS = $7.3148\ (\mathrm{PI})^2 - 1{,}080\ (\mathrm{PI}) + 39{,}864$	92
CIW vs. UCS	UCS = −18.095 (CIW) + 1,468.6	91	CIW vs. UCS	UCS = −24.753 (CIW) + 2,009.4	86
WPI vs. UCS	UCS = $0.001e^{1.1279\ (\mathrm{WPI})}$	95	WPI vs. UCS	UCS = $0.1167e^{0.674\ (\mathrm{WPI})}$	96
β vs. UCS	UCS = 552.31 (β) − 436.39	95	β vs. UCS	UCS = $0.3044e^{5.696\ (\beta)}$	94
CIA vs. UCS	UCS = $0.6451\ (\mathrm{CIA})^2 - 93.061\ (\mathrm{CIA}) + 3{,}355.1$	90	CIA vs. UCS	UCS = $5e + 23\ (\mathrm{CIA})^{-12.367}$	97
SA vs. UCS	UCS = $294.33\ (\mathrm{SA})^2 - 2{,}251\ (\mathrm{SA}) + 4{,}338$	80	SA vs. UCS	UCS = $4e - 14\ (\mathrm{SA})^{25.916}$	88
LOI vs. UCS	UCS = −110.81 (LOI) + 216.02	90	LOI vs. UCS	UCS = $143.23e^{-0.7583(\mathrm{LOI})}$	94

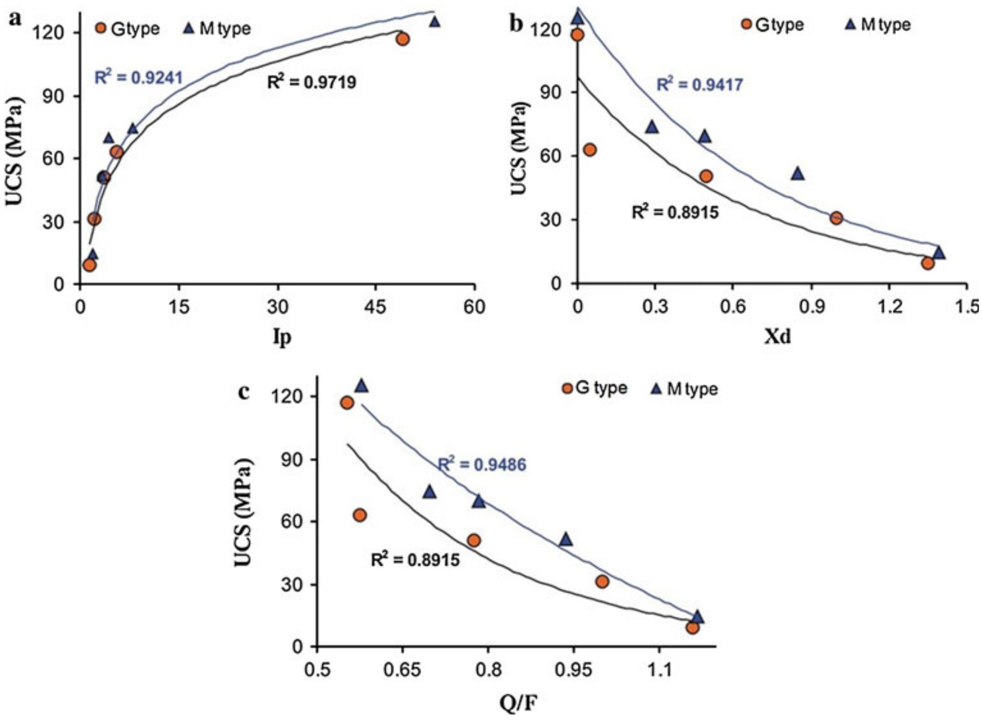

Fig. 6 Relationship between UCS and petrographical indices **a** I_p, **b** X_d, **c** Q/F

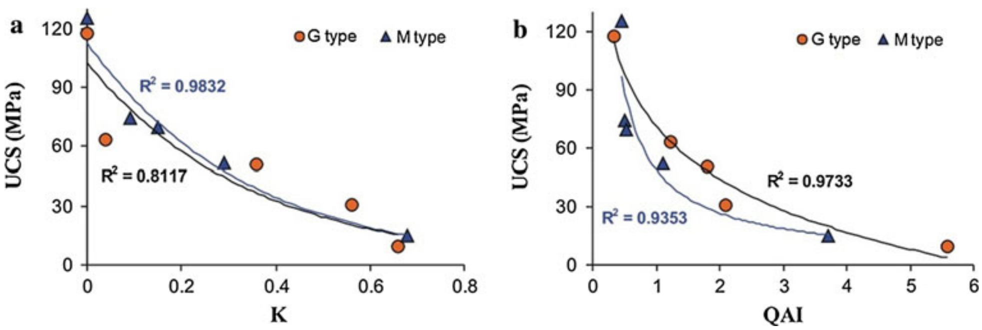

Fig. 7 Relationship between UCS and engineering indices **a** K, **b** QAI

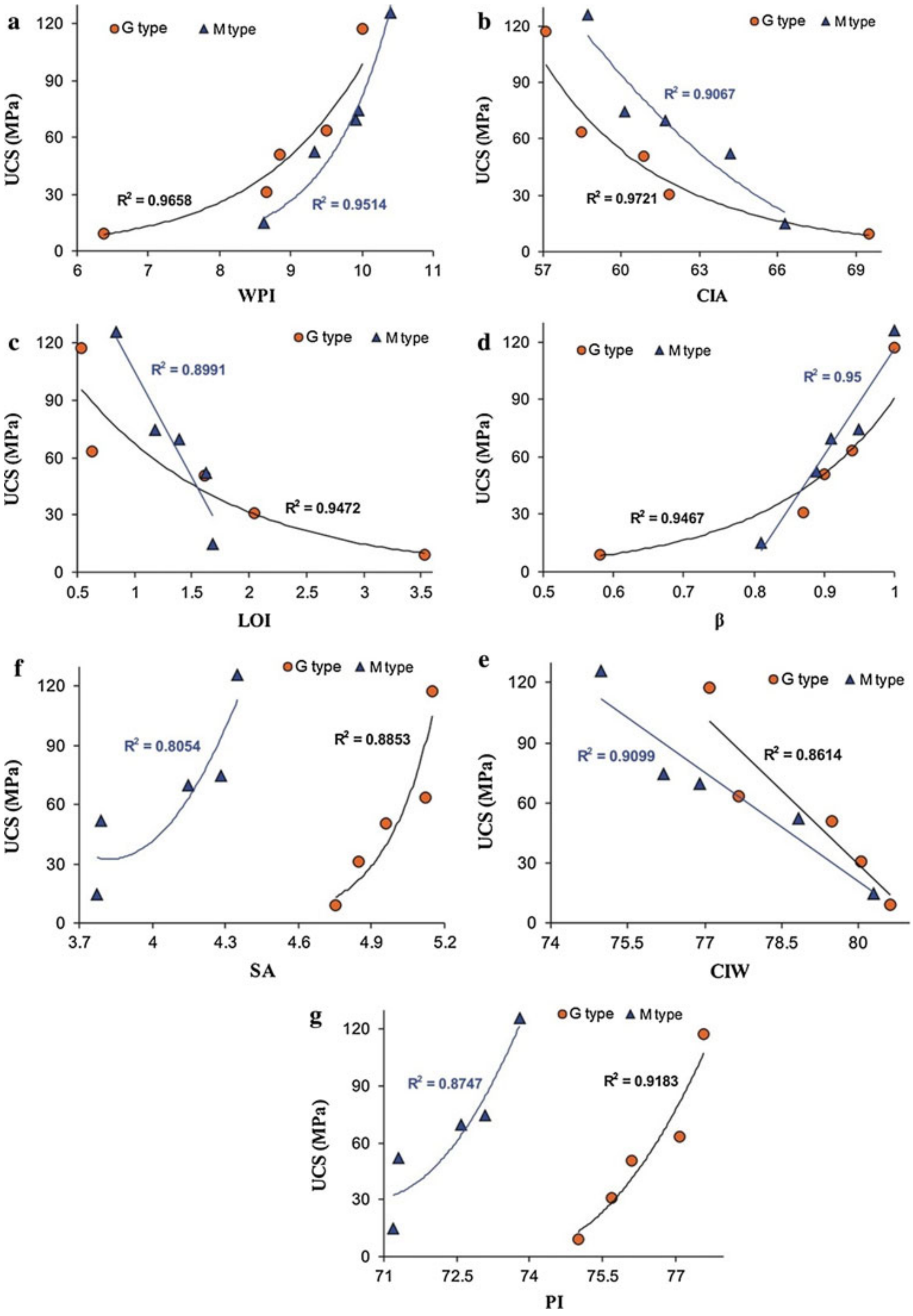

Fig. 8 Relationship between UCS and chemical indices **a** WPI, **b** CIA, **c** LOI, **d** β, **e** CIW, **f** SA, **g** PI

The silica–alumina ratio (SA) values decrease with the increasing of weathering degree. This trend was also observed by Tugrul and Gurpinar (1997). The lixiviation index (β) was also determined and the results are summarized in Table 7. This index shows a relatively consistent variation for weathering of granodiorite and monzogranite samples. Chemical index of weathering (CIW) and chemical index of alteration (CIA) increase from fresh 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. The results of these correlations are presented in Table 8 and Figs. 6, 7, and 8. Coefficients of determination (R^2) and best-fit curves were obtained by the 'least squares curves fit' method.

It should be noted that the results shown on the Figs. 6, 7, and 8, are derived as the average of at least ten tests on each sample.

According to these results, all of petrographical, engineering and chemical weathering indices show a valuable relationship with uniaxial compressive strength. As can be seen in Fig. 6a, a good relationship with best-fit lines between I_p and UCS for two types of rocks has been obtained. Correlation between the I_p index and mechanical properties of rocks has been recorded in the literature (Arel and Tugrul 2001). As it is clear from Fig. 6b and c, the relationship between UCS with *Q/F* and X_d index for granodiorite and monzogranite samples reveals that there are good and relatively good nonlinear correlations, respectively.

Based on the results, *K* index as an engineering index is strongly correlated with UCS for monzogranite and relatively good correlated for granodiorite (Fig. 7a). But quick absorption index (QAI) shows a good nonlinear correlation with UCS for two rock types (Fig. 7d).

As can be seen from the coefficient of determination, there are statistically significant correlations between these chemical indices and UCS of the weathered rock materials studied. For granodiorite samples, the correlations between CIA, LOI, β, WPI, CIW and PI indices show strong clear correlations with uniaxial compressive strength value (Fig. 8a–e) whereas the SA and CIW indices show relatively good correlation with uniaxial compressive strength (Fig. 8f, g). Furthermore, for monzogranite samples the correlations between CIA, LOI, β, WPI and CIW indices show valuable correlations with uniaxial compressive strength value while the SA, PI and LOI indices shows relatively good correlation with uniaxial compressive strength.

Conclusions

An attempt was made to investigate the weathering mechanisms and to describe quantitatively the degree of weathering for Alvand granodiorite and monzogranite rocks in the west part of Iran. The weathering characteristics of the Alvand granitic rocks are described by various methods such as field observations, petrographic analysis, physical, chemical and mechanical tests. The conclusions obtained from this study can be summarized as follows:

1. Weathering has important effect on geotechnical properties of these granitic rocks. In this research, acceptable relationships were found between the weathering degree of the granitic rocks and their physical and mechanical properties.
2. 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 decrease.
3. As the weathering increases, the percentage of Fe_2O_3, LOI, TiO_2 increases, but the percentage of SiO_2, Na_2O, K_2O and CaO decrease.
4. Based on the results from the application of many existing quantitative weathearing indices on granodiorite and monzogranite rocks in Hamedan, it can be concluded that all indices are good quantitative indicators for describing the degree of weathering. Application of these indices in the assessment of uniaxial compressive strength of the granitic rocks yields to suitable and meaningful results.
5. The study has shown that I_p as a petrographic index, QAI as an engineering index and CIA as a chemical index exhibit the best correlations with UCS for granodiorite samples and can also be good indicators of this granite rock weathering.
6. For monzogranite rock samples, *Q/F* as a petrographic index, *K* as an engineering index and WPI as a chemical index, exhibit the best correlations with UCS.

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Refrences

Aires-Barros L (1978) Comparative study between rates of experimental laboratory weathering of rocks and their natural environmental weathering decay. Bull Int Assoc Eng Geol 18:169–174

Anonymous (1995) The description and classification of weathered for engineering purposes. Geological Society Engineering Group Working, Party report. Q J Eng Geol 28:207–242

Arel E, Tugrul A (2001) Weathering and its relation to geomechanical properties of Cavusbasi granitic rocks in northwestern Turkey. Bull Eng Geol Environ 60:123–133

Arikan F, Ulusay R, Aydin N (2007) Characterization of weathered acidic volcanic rocks and a weathering classification based on a rating system. Bull Eng Geol Environ 66:415–430

Baharifar A, Moinevaziri H, Bellon H, Pique A (2004) The crystalline complexes of Hamadan (Sanandaj–Sirjan zone, western Iran): metasedimentary mesozoic sequences affected by late Cretaceous tectono-metamorphic and plutonic events, II. 40K–40Ar dating. Comptes Rendus Geosci 336(16):1443–1452

Berberian M, Alavitehrani N (1977) Structural analyses of Hamadan metamorphic tectonics, a paleotectonic discussion. In: Berberian M (ed) Contribution to the seismotectonics of Iran. Geol Surv Iran, pp 263–278

Ceryan S, Tudes S, Ceryan N (2008) Influence of weathering on the engineering properties of Harsit granitic rocks (NE Turkey). Bull Eng Geo Environ 67:97–104

Duzgoren N, Aydin A (2003) Chemical heterogeneities of weathered igneous profiles: implications for chemical indices. Environ Eng Geosci 9(4):363–376

Franklin JA, Chandra R (1972) The slake durability test. Int J Rock Mech Mine Sci 9:325–341

Gamble JC (1971) Durability-plasticity classification for shales and other argillaceous rocks. Ph.D. Thesis, University of Illinois

Ghobadi MH, Momeni AA (2011) Assessment of granitic rocks degradability susceptive to acid solutions in urban area. Environ Earth Sci 64(3):753–760

Guan P, Ng CWW, Sun M, Tang W (2001) Weathering indices for rhyolitic tuff and granite in Hong Kong. Eng Geol 59:147–159

Gupta AS, Rao KS (2001) Weathering indices and their applicability for crystalline rocks. Bull Eng Geol Environ 60:201–221

Hamrol AA (1961) Quantitative classification of the weathering and weatherability of rocks. In: Proceedings of the 5th international conference on soil mechanics and foundation engineering, Paris 2, pp 771–774

Harnois L, Moor JM (1988) Geochemistry and origin of the ore chemistry formation, a transported paleoregolith in the Greenville Province of Southeastern Ontario, Canada. Chem Geol 69:267–289

Hodder APW (1984) Thermodynamic interpretation of weathering indices and its application to engineering properties of rocks. Eng Geol 20:241–251

Huston DL (1993) The effect alteration and metamorphism on wall rocks to the Balcooma and dry river south volcanic-hosted massive sulfide deposits, Queensland, Australia. J Geochem Explor 48:277–307

Hutchinson CS (1974) Laboratory handbook of petrographic techniques. Wiley, New York

Illev IG (1967) An attempt to estimate the degree of weathering of intrusive rocks from their physico-mechanical properties. In: Proceedings of 1st congress of the international society for rock mechanics, Lisbon, pp 109–114

International Society for Rock Mechanics (1981a) Basic geotechnical description of rock masses. Int J Rock Mech Min Sci Geomech Abstr 18:85–110

International Society for Rock Mechanics (1981b) Rock characterization testing and monitoring. In: Brown ET (ed) ISRM suggested methods. Pergamon press, Oxford

Irfan TY, Dearman WR (1978a) Engineering classification and index properties of a weathered granite. Bull Int Assoc Eng Geol 32:67–80

Irfan TY, Dearman WR (1978b) The engineering petrography of a weathered granite in Cornwall. Engl Q J Eng Geol 11:233–244

Krauskopf KB (1967) Introduction to geochemistry, vol l76. McGraw-Hill Book Company, New York, pp 518–527

Lee SG (1987) Weathering and geotechnical characterization of Korean granites. Ph.D. Thesis, Imperial College, University of London

Lee SG, Freitas MH (1988) Quantitative definition of highly weathered granite using the slake durability test. Geotecnique 38(4):635–640

Lumb P (1962) The properties decomposed granite. Geotecnique 12:226–243

MacLean WH (1990) Mass change calculations in altered rock series. Miner Depos 25:44–49

Nesbitt HW, Young GM (1982) Early Proterozoic climates and plate motions inferred from major element chemistry of lutites. Nature 299:715–717

Parker A (1970) An index of weathering for silicate rocks. Geol Mag 107:501–504

Price JR, Velbel MA (2003) Chemical weathering indices applied to weathering profiles developed on heterogeneous felsic metamorphic parent rocks. Chem Geol 202:397–416

Reiche P (1943) Graphic representation of chemical weathering. J Sediment Petrol 13:58–68

Rocha-Filho P, Antuenes FS, Falcao MFG (1985) Quantitative influence of the weathering upon the mechanical properties of a young gneiss residual soil. In: Proceedings of first international conference on geomechanics in tropical lateritic and saprolitic soils, vol 1. Brasilia, pp 281–294

Ruedrich J, Kirchner D, Siegesmund S (2011) Physical weathering of building stones induced by freeze thaw action: a laboratory long term study. Environ Earth Sci 63:1573–1586

Ruxton BP (1968) Measures of the degree of chemical weathering of rocks. J Geol 76:518–527

Sadr AH, Sepahi AA, Khanlari GR (2004) The Study of the structures of Alvad granite. Iran Sci Q J Geosci 11(49):90–103

Selby MJ (1993) Hillslope materials and processes, 2nd edn. Oxford University Press, Oxford

Sepahi AA (1999) Petrology of the Alvand plutonic complex with special reference on granitoids. Ph.D. Thesis, Tarbiat-Moallem University of Tehran, Iran (in Persian)

Sepahi AA (2008) Typology and petrogenesis of granitic rocks in the Sannandaj–Sirjan metamorphic belt, Iran: with emphasis on the Alvand plutonic complex. N Jb Geol Palaont Abh 247(3):295–312

Siegesmund S, Snethlage R (2011) Stone in architecture, 4th edn. Springer, Berlin

Sueoka T, Lee IK, Muramatsu M, Imamura S (1985) Geomechanical properties and engineering classification for decomposed granite soils in Kaduna district, Nigeria. In: Proceedings of first international conference on geomechanics in tropical lateritic and saprolitic soils, vol 1. Brasilia, pp 175–186

Tugrul A (1995) Weathering effects of engineering properties of Basalt's in Niksar Area. Ph.D. Thesis, Istanbul University, Turkey (in Turkish)

Tugrul A, Gurpinar O (1997) A proposed weathering classification for basalts and their engineering properties. Bull Int Assoc Eng Geol 55:139–149

Valizadeh MV, Cantagrel JM (1975) Premieres donnees radiometriques (K-Ar et Rb-Sr) surles micas du complexe magmatique du mont Alvand pres Hamadan (Iran occidental), comptes rendus hebdomadaires des seances de l'academie des sciences. Serie D: Sci Nat 281:1083–1086