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Alteration dependent physical-mechanical properties of quartz-diorite building stones

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ABSTRACT

The microscopic and geomechanical properties of igneous building stones include the extent of alteration, presence of micro cracks, peak strength, porosity, proportion of detrimental minerals, etc. Porosity has reportedly a devastating impact on the peak strength of igneous rocks. The quartz diorite rock samples in this study were selected from five quarries in Natanz of Iran and were subjected to microscopic and geomechanical investigations. The extent of alteration and the detrimental minerals affecting the strength of the samples were identified from examination of thin sections. Therefore, the geomechanical tests on density, porosity, durability index, the Brazilian, and triaxial tests were conducted following the ISRM standards. The findings from microscopic studies revealed that compared to porosity, alteration has a more intense impact on rock's peak strength. The results were compared to standard values and a qualitative correlation between strength and microscopic properties was detected revealing the importance of construction stones microscopic studies. The correlation thereupon may be adopted in the exploration, exploitation, and processing of construction stones to avoid heavy expenses and damages to the environment.

Keywords: *Microscopic properties; Geomechanical characteristics; Alteration; Building stone; Quartz-diorite*

1. Introduction

Due to their high strength and resistance to weathering, diorites (quartz-diorites) have a wide range of applications in facades, stairs, and tunnel floors. They appear in greenish gray, beige, and occasionally black colors. The stones selected for decorative purposes must meet specific minimum requirements: 1) durability against alteration, 2) absence of geological defects including cracks and fractures, 3) ease of pulverization, polish, and cutting, 4) Mohs hardness between 5 to 6, 5) color versatility, 6) porosity of 0.2% to 1.4% and the respective water absorption ranges of 0.3% to 0.8%, 7) minimum peak strength of 100MPa to 350MPa and adequate tensile strength of 10% to 40% of compressive strength, 8) sufficiently high resistance against fire, freezing temperatures, atmospheric agents, etc., and 9) blockability and the appropriate capacity of the quarry [1]. The requirements thereupon are often partially relied on these factors, the first and second ones being the most important requirements in determination of stone durability. The probability of alteration necessitates microscopic studies of thin sections. Microscopic alteration in igneous rocks is the dominant stimulus to strength reduction. Numerous researches have been conducted in order to identify a correlation between microscopic parameters and physical and mechanical characteristics of building stones. These reports include various categories with regards to the aforementioned correlation. The following investigations are to name a few efforts to relate the geomechanical characteristics of granitic stones with specific agents: grain size distribution [2- 7], weathering [8- 10], micro-cracks [11- 13], porosity [11], micro-structural characteristics [8, 13-17], mineral composition [18], grain boundaries [19], shape and spatial arrangement of minerals [2] and capillary absorption and p-wave velocity as crack network properties [20]. These studies suggest a meaningful correlation between grain size distribution and relative fragility, where coarser grains stimulate the propagation of cracks [21]. The ratio of quartz to feldspar has a considerable effect on mechanical strength of granite stones [11, 12]. Salt fog is a type of alteration in building stones where mineral degradation is the main modification on silicic rocks, with biotite representing a key mineral in the alteration process due to its cleavage and possibly composition [22]. Alteration of diabase negatively influences the mechanical properties of rock [23]. The investigation of grain size effect on fracture toughness was reported by [24]. These experimental results highlight the importance of petrographic studies amid experimental probes. Moreover, Norouzi et al. 2013 investigated this effect on micro/macro mechanical properties of intact marbles in a two dimensional numerical modeling [25]. Their findings emphasize the fact that grain size distribution affects the rock's strength. The objective of the present research is to use thin sections examination as an efficient, practical, and economical approach to determine the extent of alteration

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in quarries and to compare its outputs with those of strength and alteration tests. It is intended to identify a qualitative correlation between the aforementioned parameters which will reduce costs in the various stages of exploration, exploitation, and processing of construction stones, and contributes to the detection of potential zones for quarries. Initially, in this research, using field excursions and surveys, 5 coupes of stones at the dimensions of 0.5m × 0.5m × 0.75m were collected from five quarries in the west of Natanz, Iran. Iran has a very high potential for production and export of dimension stones [26]. Microscopic investigations were then conducted on thin sections, and the mechanical evaluations were performed with standard samples.

2. Experimental Setup

2.1. Field surveys

A sufficiently large number of rock samples for microscopic and mechanical investigations were collected from five active quarries in the west of Natanz, Iran. The products are sliced and polished at stonecutting centers in Mahmoudabad industrial town in Isfahan which is a center for constructional and decorative industries. The samples were respectively tagged as Gs$_1$, Gs$_2$, Sd$_1$, Sd$_2$ and Az to correspond to quarries 1 to 5 (Figure 1). Sampling was carried out in form of relatively large blocks so that all the required specimens were possible to be cut. Five samples from quarries 1 to 5 were prepared. The plutonic stones in this study belonged to a stock of black quartz-diorite intruded into the light granites. All igneous masses belong to the magmatism at the Urumieh-Dokhtar magmatic arc (zone).

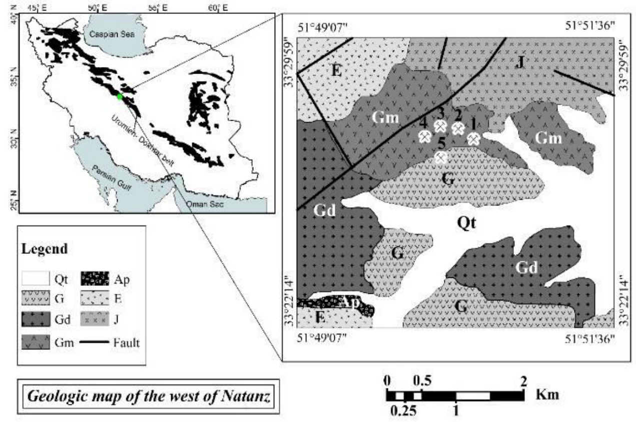

Figure 1. The geological map of the area of interest and the location of the samples (modified from the geological map of Natanz. Qt: Old terraces and elevated alluvial fans, G: Oligocene-Miocene granite, Gd: Granodiorite and tonalite (Oligocene-Miocene), Gm: Diorite-quartzdiorite-monzodiorite-gabbro (following Eocene-Oligocene), Ap: Aplite and granophyre, E: Basalt, trachyandesite, tuff, sandstone, shale and limestone at base, J: Alternation of sandstone and shale [27].

2.2. Petrographic Studies

The residues of the prepared cores were used to make 90 thin sections (6 sections from each of 15 core samples), some of which were built along the cores axes and some perpendicular to them. Studying the thin sections did not reveal any specific direction. The percentages of the mineral phases were determined with a polarizing microscope and using the point-counting method. Approximately, five hundred uniformly distributed points were counted in each section; then the average values were calculated. These mineral content values from microscopic studies are presented in Table 1. These samples were identified as quartz-diorite due to the abundance of feldspar minerals (plagioclase), amphiboles, and presence of more than 5% for the ratio of quartz to other light minerals. The stones show subhedral granular to intergranular textures.

The extent of alteration in the samples was also examined. The feldspars have been altered to sericite, chlorite, and clay and the amphiboles have been altered to chlorite. Chlorites resemble pseudomorphs of amphiboles and some of them are scattered between other minerals. Since chlorites are widespread in the samples, it shows that the rocks have been subjected to intense alteration. In intensively altered rocks, the feldspars have been more altered to sericite, chlorite, and clay.

Table 1. Minerals content (%) of samples by microscopic examination.

Mineral	Specimen				
	Gs$_1$	Gs$_2$	Sd$_1$	Sd$_2$	Az
Feldspar (Plagioclase)	51.2	55.2	63.8	37.2	57
Biotite (Bio)	2.9	2.8	3.5	11.4	5.5
Amphibolite (Amph)	26.7	26	9.2	36	20
Chlorite (Chl)	5.4	1.6	17.1	4.8	2
Quartz (Qz)	7.8	3	4.6	5.8	5.75
Opaque (Opac)	6	8.4	1.8	4	4.75
Apatite (Ap)	-	1	-	-	0.75
Clinopyroxene (Cpx)	-	2	-	0.8	4.25

Chloritization percentage (alteration) of the rocks have been determined by Eq. (1) and are shown in Table 2.

$$\text{Chloritization percentage (\%)}=\frac{\text{Chlorite(\%)}}{\text{Feldspar(\%)}+\text{Amphibole(\%)}+\text{Chlorite(\%)}}\times 100 \qquad (1)$$

Table 2. Chloritization percentage of the rocks.

Specimen	Gs$_1$	Gs$_2$	Sd$_1$	Sd$_2$	Az
Chloritization percentage (%)	6.48	1.93	18.98	6.15	2.53

Figures 2-3 show the alteration of amphiboles and feldspars to chlorite in two specimens. Table 3 provides the average size of minerals for the five categories. The estimated sizes alongside Figures 4-6 confirm the fine-gained structure of these stones. Figures 4-6 are respective illustrations of microscopic analyses regarding the Gs$_1$, Sd$_1$ and Az specimens. According to the microscopic studies and based on Figures 4-6, it may be concluded that the extent of alteration in Sd$_1$ samples is higher than that of other samples.

Table 3. Average sizes of the minerals of the five samples.

Mineral	Average sizes of the minerals (mm)				
	Gs$_1$	Gs$_2$	Sd$_1$	Sd$_2$	Az
Feldspar (Plagioclase)	1.02	1	1.52	1.4	0.92
Biotite	0.6	0.36	0.51	0.76	0.64
Amphibole	1.04	0.87	1.56	1.54	0.94
Chlorite	<0.01	0.26	0.68	0.33	0.38
Quartz	0.89	0.53	0.79	0.63	0.27
Opaque	0.41	0.48	0.45	0.34	0.31
Clinopyroxene (Cpx)	-	0.48	-	0.63	0.53
Apatite	-	0.5	-	-	0.32

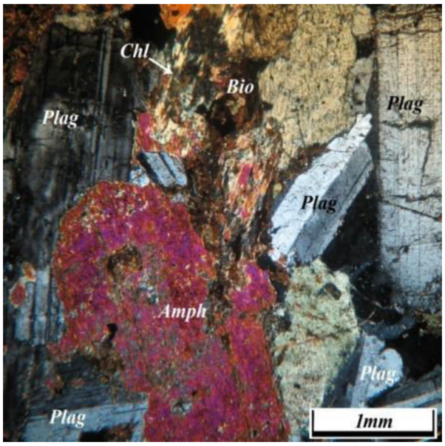

Figure 2. Photomicrograph showing alteration of amphibole minerals to chlorite at cross-polarized light.

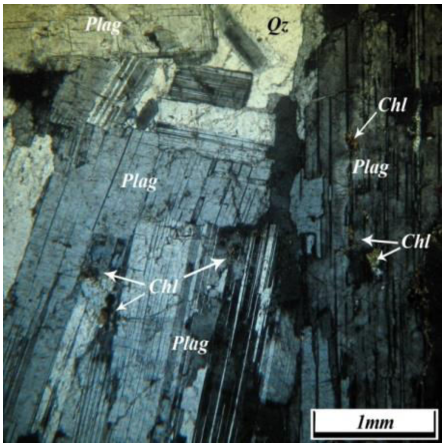

Figure 3. Photomicrograph showing alteration of feldspar minerals to chlorite at cross-polarized light.

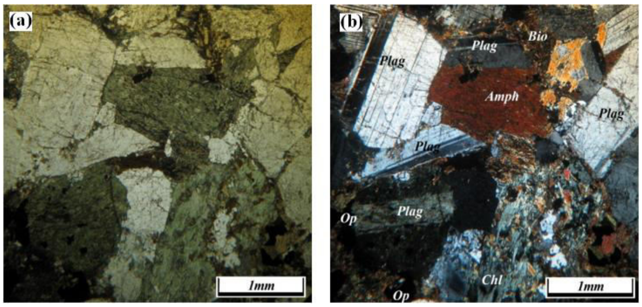

Figure 4. Photomicrograph of quart-diorite Gs_1 (a) at plane-polarized (b) at cross-polarized light. [Plagioclase (Plag), Opaque (Op), Chlorite (Chl), Biotite (Bio), Amphibole (Amph)].

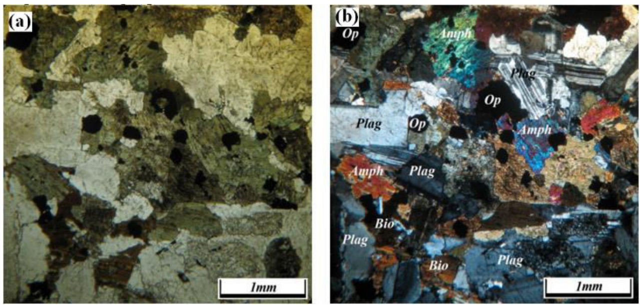

Figure 5. Photomicrograph of quartz-diorite Sd_1 (a) at plane-polarized (b) at cross-polarized light. [Plagioclase (Plag), Opaque (Op), Chlorite (Chl), Biotite (Bio), Amphibole (Amph)].

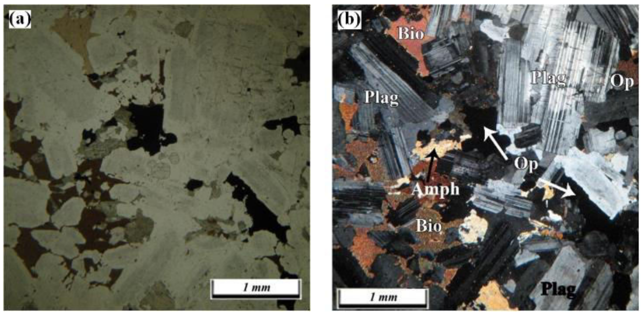

Figure 6. Photomicrograph of quart-diorite Az (a) at plane-polarized (b) at cross-polarized light. [Plagioclase (Plag), Opaque (Op), Biotite (Bio), Amphibole (Amph), Opaque (Op), Quartz (Qz)].

2.3. Measuring the physical properties of rocks

The dry density, porosity, water absorption coefficient, and durability index were measured using the International Society for Rock Mechanics (ISRM) instructions in [28]. The samples subject to these tests were obtained in form of lumps from the cores of Gs_1, Gs_2, Sd_1, Sd_2 and Az rocks. The averages of the values from three-time repetitions are tabulated in Table 4. The Gs_1 sample has more porosity than other rocks with relatively equal values of dry density and durability index.

Table 4. Average values of three replicates of the physical tests.

Sample	Density ρ_b (gr/cm3)	Porosity n (%)	Water content W (%)	Durability index Id (%)
Gs_1	2.94	2.091	0.0561	99.72
Gs_2	2.89	1.851	0.0572	99.7
Sd_1	2.82	1.526	0.058	99.67
Sd_2	2.8	1.061	0.0589	99.64
Az	2.82	0.71	0.072	99.6

Ultrasonic pulse was adopted to determine the quality index of rocks [28]. The samples subject to triaxial compressive test were used to measure sonic velocities. Each rock is assigned a unique sonic velocity. This reference value alongside the measured ones and the indices of durability using Eq. (2) are listed in Table 5.

$$IQ\% = {}^{v}\!/_{v^*} \times 100 \qquad (2)$$

Where,

v = measured velocity (m/s)

v^* = ideal velocity (m/s)

IQ = index of quality (%)

The classes corresponding to each rock based on index of quality are presented in Table 5, where Gs_1, Gs_2 and Sd_2 are moderately fissured but Sd_1 and Az are slightly fissured.

Table 5. Identified velocities and classifications.

Sample	V (m/s)	IQ (%)	Rock classification
Gs_1	5446	81.28	moderately fissured
Gs_2	5569.5	83.13	moderately fissured
Sd_1	6133	91.53	slightly fissured
Sd_2	6195	84.71	moderately fissured
Az	6133	91.53	slightly fissured

2.4. Measuring the mechanical properties of rocks

Different mechanical properties of rocks were measured in laboratory based on ISRM suggested methods. Generally, triaxial compressive test is conducted where axial stress along the symmetric confining ones is imposed on the rock core. The test configuration was comprised of an ELE triaxial testing device made in England Hoek's cell at the rock mechanics laboratory of Department of Mining Engineering, Isfahan University of Technology. The specimens were of a diameter of 54.4 mm (NX) with polished bases [28]. Triaxial tests were carried out on 16 cylinder cores separately produced for the Gs_1, Gs_2, Sd_1, Sd_2 and Az samples and the obtained values are reported in averages in Figure 7. The applied confining stresses differed in both tests. Table 6 presents the parameters determined through linear fitting according to the Mohr-Coulomb criterion.

Table 6. Parameters obtained through linear fitting using the Mohr-Coulomb criterion.

Parameter	Sample				
	Gs_1	Gs_2	Sd_1	Sd_2	Az
Internal friction angle φ	51.77	61.59	56.12	70.2	59.87
Cohesion C (MPa)	20.59	23.7	11.35	11.25	25.37
Uniaxial Compressive Strength σ_c (MPa)	118.8	158.95	74.52	128.93	188.47
Uniaxial tensile strength σ_t (MPa)	14.27	8.23	6.91	3.93	13.56

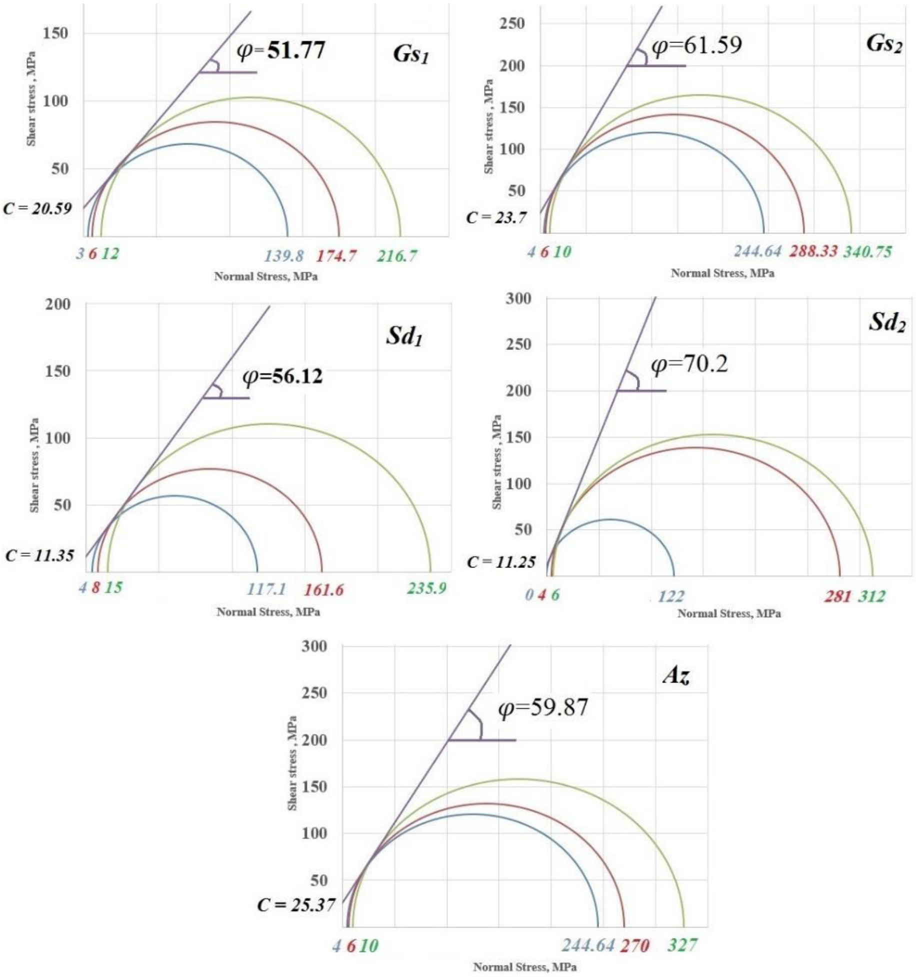

Figure 7. Mohr's circles of triaxial compressive tests on the samples.

Tensile strength was measured through an indirect measurement method – Brazilian test [28]. Table 7 lists the resulted values corresponding to 5 samples for Gs$_1$, Gs$_2$, Sd$_1$, Sd$_2$ and Az specimens with a thickness of 27 mm and a diameter of 54 mm calculated using Eq. (3). Compared to Table 6, the values of tensile stress are noticeably higher, and the Gs$_1$ samples exhibit higher tensile strength.

$$\sigma_t=\frac{2P}{\pi dt} \quad (3)$$

Where,

P = the load on the disc at failure (KN)

d = the disc diameter (m)

t = the disc thickness (m)

Table 7. Tensile strength values from Brazilian tests.

Sample	Gs$_1$	Gs$_2$	Sd$_1$	Sd$_2$	Az
Tensile strength σ_t (Brazilian) (MPa)	18.225	14.091	10.865	16.656	15.513

3. Discussion

Apparently, the five selected quartz-diorites bear no cracks and weathering defects, whereas the mineralogical characteristics underline alteration in the thin sections. The alteration comprises chlorite minerals where the chloritization ratio of each sample may be expressed in terms of chlorite proportion, being 1.93% in Gs$_2$ to 17.1% in Sd$_1$.

Comparison of the physical and mechanical tests and the reported results from our samples reveal that the density is within the domains mentioned by [1]; however, the porosity values from three specimens are above the actual ones, emphasizing the role of porosity in igneous rocks [11]. According to the measured sound velocity in Table 5, the IQ values are in a close agreement, and are classified between moderately fissured and fissured which indicates the absence of high fracture density in the samples. Table 6 lists the rocks strength from triaxial tests indicating that Sd$_1$ sample exceeds the reported range of 100 MPa-350 MPa [1]. The tensile strength values obtained from Brazilian tests (Table 6) and triaxial tests (Table 7) show reliable results being 10-40% of the rock peak strength. In order to investigate the effect of alteration on the peak strength of the rock, two different curves were fitted to the values of alteration and peak strength, one an exponential function (with a correlation coefficient of 0.92) and the other one a linear function (with a correlation coefficient of 0.82 (Figure 8). Equations (4) and (5) were found to be the best fitting functions for exponential and linear behaviour, respectively.

$$UCS=181.86e^{-0.049\times Alteration(\%)} \quad (4)$$

$$UCS=-5.6339\times Alteration(\%)+174.58 \quad (5)$$

Both equations show a significant effect of alteration extent on the rock peak strength, although the alteration may not be apparent. According to Equations (4) and (5), if a construction stone in one of these quarries reaches an alteration extent of 40%, the strength value will reduce around 25MPa which disqualifies the stone quality despite the invisibility of the phenomenon. The present research attempted to develop a new technique to evaluate the effect of alteration on the peak strength of diorites by means of microscopic studies. Our results are in accordance with the previous reported results in the literature [23]. If one uses the same algorithm to calculate the alteration percentage as provided in Eq. (1), scattering of data is more concentrated on special ranges of alteration intensities (Figure 9). In case a different formulation is facilitated for calculating rock alteration intensity, where percentage of altered minerals is divided on almost total minerals (soft and hard minerals) such as provided in [23], scattering of data becomes more homogeneous. Small number of tests can yield to a general trend, and further detailed results require additional experiments.

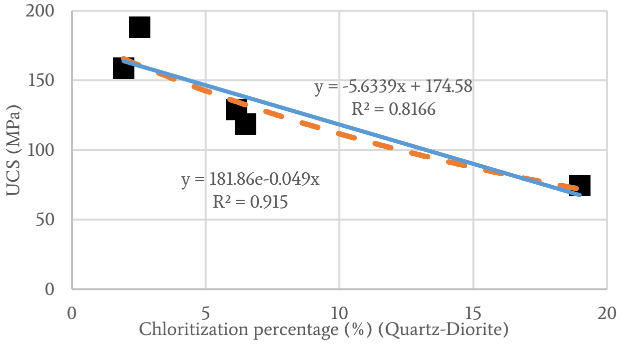

Figure 8. The relationship between uniaxial compressive strength (UCS) and effective alteration of Quartz-Diorite (%).

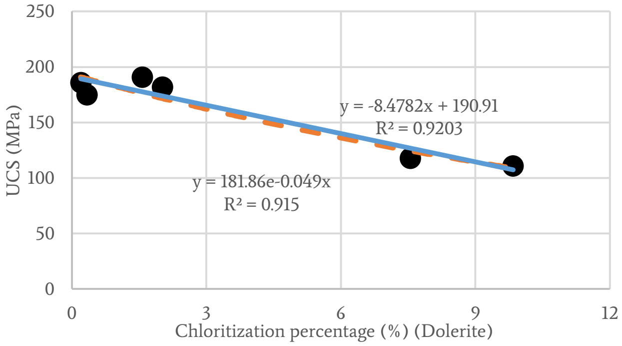

Figure 9. The relationship between uniaxial compressive strength (UCS) and effective alteration of Dolerite (%) [23].

4. Conclusions

The following remarks may be concluded from the microscopic and geomechanical studies regarding quartz-diorite samples taken from quarries in west of Natanz.

- The extent of alteration indicates the importance of microscopic studies of construction stones and the deficiency of classification solely based on macroscopic appearance.
- Geomechanical analyses confirm the importance of agreement of mechanical properties of rocks with microscopic studies of minerals and the extent of alteration. Although Sd$_1$, for instance, has an adequate appearance and approximately similar physical properties than other samples, it shows an intensive alteration and a less strength.
- Since microscopic studies are easier and more cost-effective than the geomechanical tests, it is emphasized that employing microscopic studies at primary stages of the exploration of quarries can avoid high exorbitant costs of geomechanical experiments and opening the fronts with inadequate qualities and can prevent environmental issues.

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