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The effect of cyclic salt weathering test on deterioration potential of granitoid rocks

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Abstract

In this study, the salt weathering effects on engineering properties and weight loss potential of three types of granitoid rocks were investigated. Sodium and magnesium sulfates tests were performed on core and aggregate samples. The cyclic salt weathering tests on core samples were done up to 90 cycles, while these tests on aggregate samples were done up to 40 cycles. The results showed that deterioration effect of magnesium sulfate on weight loss was more remarkable than sodium sulfate. However, deterioration effect of sodium sulfate on weakening of physico-mechanical properties was more considerable than magnesium sulfate. Porphyroid monzogranite was far more affected by the salts in comparison with other rock types which were tested in the current study. The results showed that ultrasonic wave velocity parameter was more appropriate than other engineering parameters to demonstrate the damage processes. Finally, a crack development weathering pattern and a corrosive damage pattern were observed for sodium sulfate and magnesium sulfates, respectively.

Keywords*: Salt Weathering, Aggregate, Engineering Properties, Weathering Pattern*

Introduction

Granitoid rocks are the most common intrusive igneous rocks. Due to their high strength these rocks are widely used in construction industry including ancient buildings, ornamental elements and movable stone heritage artifacts (e.g., statues, stone pavements, altar pieces, benches, etc.), track ballast, concrete aggregate, and in monumental architectures. One of the most important earth surface processes which will damage these rocks, is salt weathering. It is generally accepted that the salt weathering damage will be generated by repeated cycles of crystallization or dissolution of soluble salts within rocks (Coussy, 2006). In fact, the repeated cycles cause fatigue phenomenon and reduce rock strength. Thus, it is obvious that the salt weathering is a natural hazard with significant cultural and economic consequences. In order to investigate the weathering process of salt crystallization, laboratory experiments are needed to test the damaging dynamics. Previous studies mainly were focused on salt weathering of limestone and sandstone rocks (Dragovich & Egan, 2011; Espinosa-Marzal & Schere, 2008; Ghobadi & Babazade, 2015; Alves *et al*., 2017). Deterioration behavior of granitic rocks exposed to salt weathering was mainly studied in qualitative basis in building stone and cultural heritage (Sousa *et al.,* 2017; Momeni *et al.,* 2015; López-Arce *et al.,* 2010). Consequently, a quantitative study on salt weathering effects on long-term physico-mechanical properties of granitic rocks was not reported comprehensively. Thus, the main purpose of the current study was to compare the durability behavior of three types of granitoid rocks exposed to sodium and magnesium salts tests. Also, the long-term decay in physico-mechanical properties of the rocks against cyclic salt tests was considered.

Geological setting

The Alvand plutonic batholith is located in the west part of Iran. It is one of the largest plutonic bodies in the Sanandaj–Sirjan metamorphic belt (Fig. 1a). This zone is characterized by the predominance of metamorphic rocks that are accompanied by sedimentary and magmatic rocks (Sepahi, 1999). The Alvand batholith consists of gabbro, diorite, tonalite, granodiorite, porphyroid granites and hololeucocratic granitoids. Among the mentioned rocks three types were selected to investigate in this study (see Fig 1b). Previous studies have shown that S-type granite-granodiorites are mostly per-aluminous and calc-alkaline; the gabbrodiorite-tonalite suite is mostly metaluminous and tholeiitic to calc-alkaline (Sepahi, 2008).

Materials and methods

The salt weathering effects were evaluated on three types of Alvand granitoid rocks by using both core and aggregate samples. Several large size blocks were considered to provide a sufficient number of core samples (200 core samples) to carry out the experimental testing program. The core samples were prepared with an aspect ratio of 2.5 with an average diameter of 54 mm. Also, 30 aggregate samples were prepared from the same blocks which were used for core samples. Initially, in order to record mineralogical abundance and textural features of Alvand granitoid rocks, thin sections were prepared and studied using petrological microscope. Based on ISRM (1981) suggested standard methods, physical properties (dry density (γ_d), the water absorption (by weight) (QAI), effective porosity (n), and ultrasonic wave velocity (Vp)) and mechanical properties (uniaxial compressive strength (UCS) and tensile strength (σ_t)) of all the samples were determined before performing the cyclic salt weathering tests. More than 180 core samples and Brazilian test samples (at least 5 samples for each test in different cycles) were subjected to the cyclic salt crystallization tests using sodium and magnesium sulfates. Each cycle included 18 h submerging in saline solution and after that, the samples were dried at 105C for 6 h. These tests were conducted up to 90 cycles and then, after 15 cycle intervals, physico-mechanical parameters of the rocks were measured. Soundness tests on aggregate samples using sodium and magnesium sulfate were carried out on aggregates according to ASTM C88 – 05 standard methods (ASTM, 1997). In this research, the first 7 sieves, proposed by ASTM standard for coarse grained aggregates were used and the top 3 large sieves were ignored. 40 cycles were considered for this test and the sample weight loss was measured after 4 cycle's interval. It should be mentioned that each cycle of aggregate soundness tests included 18 h submerging in saline solution and then 6 h drying in oven. The main criteria of salt weathering resistance in the tests were the visible changes of the sample surfaces, weight loss after each test cycle, and the alteration of engineering properties, especially in ultrasonic velocities.

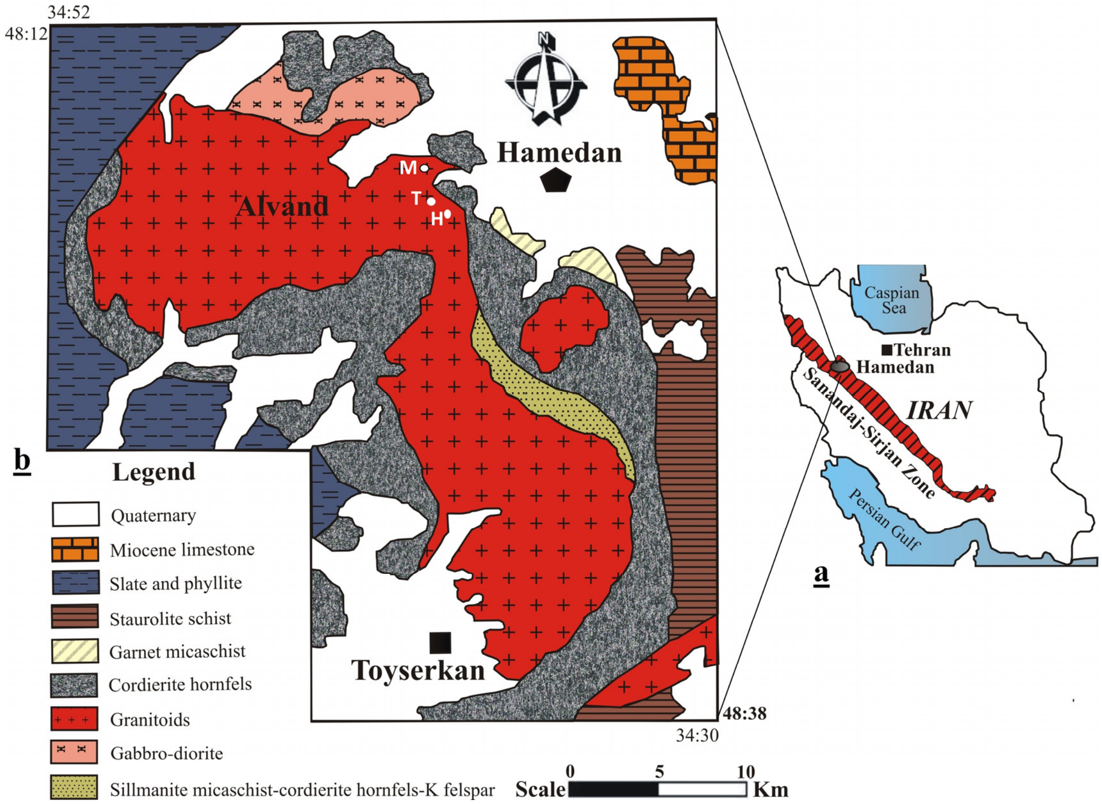

Figure 1. a: Sanandaj–Sirjan zone in Iran and the investigated location. b: Geological map and sampling location of the granitic rocks tested

The soundness index used in this paper was calculated by the following equation suggested by ASTM (1997);

$$S = (1 - weight\ loss) \times 100 \rightarrow S = \left[\left(\frac{M_b - M_a}{M_b}\right) - 1\right] \times 100 \quad (1)$$

where M_b and M_a are the sample mass before and after the test respectively.

Results and discussion

Petrographical studies

Mineralogical studies indicated that the studied rocks were monzogranite, hololeuco-granodiorite and tonalite. The used monzogranite for both salts solutions were collected from the same block. This rock is normally coarse grained (>5 mm) with a subhedral granular texture and porphyritic fabric. The mineral assemblages included quartz (25 %), orthoclase (25 %), plagioclase (25 %), biotite (20 %), and minor minerals (5 %) (Fig. 2a). All the prepared samples for hololeuco-granodiorite were collected from a large block. Petrographic analysis of this rock showed that it contains: fine grains pseudo porphyritic quartz (25 %), subhedral plagioclase (55 %), orthoclase (15 %), and other minerals (5 %). The samples comprised a fine-grained matrix that was mainly composed of quartz and feldspars. The feldspars often appeared as phenocryst (Fig. 2b). Compared to other types, in this type of rock, mafic minerals were absent which turned its color to white. The absence of flexible biotite caused a brittle behavior in this type of rock. The used tonalite core samples for sodium and magnesium sulfate solutions were drilled from different blocks which had a little different mineralogical composition. Mineral assemblages of tonalite for sodium sulfate samples include: quartz (17 %), orthoclase (2 %), plagioclase (35 %), biotite (23 %), amphibole (24 %) and other minerals (1 %).

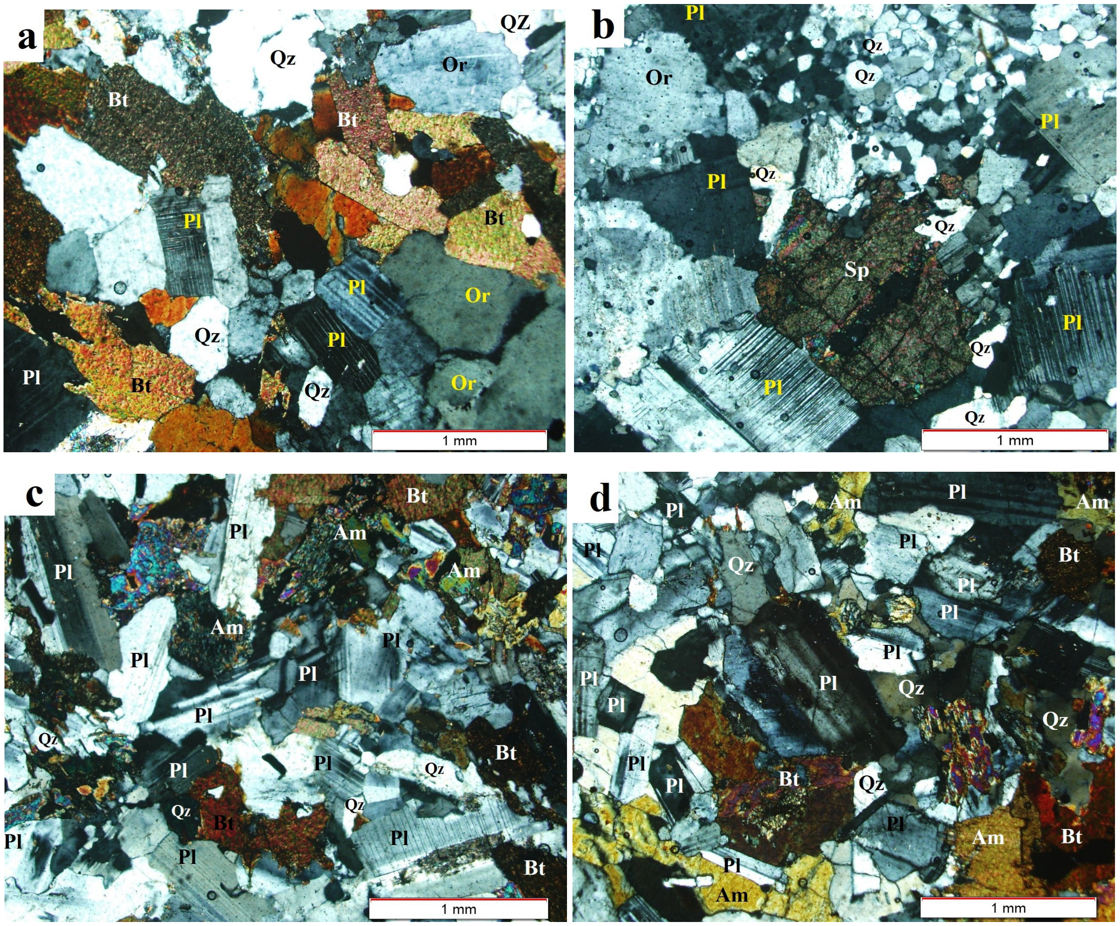

Figure 2. Mineralogical features of Alvand granitoid rocks: Pl: plagioclase, Qz: quartz, Bt: biotite, Or: orthoclase. Am: amphibole

The petrographic studies indicated that this rock has medium-grained (2–5mm) intergranular texture with interlocking subhedral to euhedral rectangular plagioclase, anhedral to subhedral orthoclase and biotite, anhedral quartz and subhedral amphibole (Fig. 2c). The mineralogical composition of tonalite core samples which were used for magnesium sulfate test included: quartz (15 %), orthoclase (2 %), plagioclase (43 %), biotite (20 %), amphibole (15 %), spinel (2 %), silimanite (2 %) and other minerals (1 %). Medium to fine grained subhedral granular texture was distinguished for this type of rock (Fig.1d).

Salt weathering effects on physico-mechanical properties

Before conducting cyclic salts tests, the physico-mechanical properties of the rocks were evaluated (Tables 1-4). The results indicated that tonalite and h-granodriorite showed highest and lowest dry density with 2.89 and 2.63 gr/cm^3, respectively. That is because of the presence and absence of dark minerals in the studied rocks. While the monzogranite showed highest effective porosity (1.04%) and quick water absorption index (0.32%), tonalite samples showed lowest values. Highest density and lowest porosity of tonalite samples led to registering maximum ultrasonic wave velocity (5297 m/s). However, monzogranite with highest porosity showed lowest ultrasonic wave velocity (3103 m/s). H-granodiorite samples demonstrated higher strength and highest UCS (184.6 MP) and BTS (16.3 MPa) magnitudes were recorded for this rock type. Whereas, monzogranite samples showed lowest UCS (85.1 MP) and BTS (10.9 MPa) values.

The results of cyclic magnesium and sodium sulfates tests on physico-mechanical properties of Alvand granitoid rocks are summarized in Tables 1-4.

Table 1. Dry density and porosity of Alvand granitoid rocks at various cycles of salt weathering test.

Test Type	C.N M,T-H		γ_d (gr/cm^3)						n (%)					
			M		T		H		M		T		H	
			Ave	SD	Ave	SD	Ave	SD	Ave	SD	Ave	SD	Ave	SD
Na_2SO_4	**0-0**		2.695	0.000	2.890	0.004	2.639	0.001	1.04	0.02	0.47	0.07	0.83	0.02
	15-15		2.692	0.000	2.888	0.004	2.640	0.001	1.12	0.08	0.38	0.02	0.42	0.04
	25-30		2.699	0.001	2.889	0.004	2.640	0.002	1.32	0.03	0.33	0.03	0.37	0.01
	30-45		2.689	0.005	2.887	0.003	2.637	0.001	2.35	0.24	0.51	0.04	0.60	0.02
	35-60		2.630	0.022	2.887	0.004	2.637	0.002	7.03	0.86	0.51	0.04	0.46	0.03
	--90		-	-	2.883	0.004	2.634	0.002	-	-	0.48	0.07	0.59	0.11
$MgSO_4$	**0-0**		2.685	0.000	2.839	0.046	2.634	0.005	1.37	0.01	1.03	0.07	0.96	0.11
	15-15		2.683	0.000	2.839	0.048	2.637	0.004	0.73	0.00	0.44	0.03	0.44	0.01
	25-30		2.686	0.000	2.837	0.045	2.635	0.004	0.52	0.02	0.67	0.19	0.57	0.06
	30-45		2.682	0.001	2.831	0.046	2.634	0.004	1.19	0.02	1.00	0.11	0.56	0.05
	35-60		2.679	0.000	2.831	0.043	2.633	0.005	1.23	0.04	0.80	0.21	0.63	0.10
	40-90		2.675	0.000	2.791	0.016	2.631	0.005	1.58	0.00	1.29	0.49	0.74	0.09

C.N: cycle number, M: monzogranite, T: tonalite and H: hololeuco-granodiorite

Table 2. Ultrasonic wave velocity and water absorption index of Alvand granitoid rocks at various cycles of salt weathering test.

Test Type	C.N M,T-H	Vp_{dry} (m/s)						QAI (%)					
		M		T		H		M		T		H	
		Ave	SD	Ave	SD	Ave	SD	Ave	SD	Ave	SD	Ave	SD
Na_2SO_4	0-0	3103	74	5297	122	5098	72	0.322	0.007	0.070	0.012	0.147	0.007
	15-15	3339	37	5415	168	5372	114	0.391	0.017	0.061	0.004	0.116	0.008
	25-30	3085	21	5397	287	5542	51	0.417	0.079	0.065	0.013	0.069	0.001
	30-45	2847	105	5267	212	5302	66	0.743	0.056	0.086	0.022	0.115	0.007
	35-60	868	240	5138	256	5301	97	1.999	0.112	0.096	0.022	0.098	0.008
	--90	-	-	4932	244	5213	52	-	-	0.137	0.028	0.096	0.022
$MgSO_4$	0-0	3272	33	4394	252	4887	69	0.376	0.007	0.224	0.088	0.174	0.016
	15-15	4055	21	5351	94	5561	49	0.241	0.001	0.162	0.072	0.134	0.009
	25-30	4017	68	5185	83	5389	30	0.142	0.003	0.096	0.031	0.091	0.012
	30-45	3937	15	5123	156	5356	24	0.264	0.012	0.181	0.076	0.084	0.009
	35-60	3882	72	5034	183	5300	72	0.386	0.033	0.149	0.021	0.109	0.012
	40-90	3801	46	4831	187	5187	15	0.456	0.021	0.197	0.070	0.112	0.021

C.N: cycle number, M: monzogranite, T: tonalite and H: hololeuco-granodiorite

Table 3. Uniaxial compressive strength of Alvand granitoid rocks at various cycles of salt weathering test.

Test Type	**C.N M,T-H**	**UCS (MPa)**					
		M		**T**		**H**	
		mean	**SD**	**mean**	**SD**	**mean**	**SD**
Na_2SO_4	0-0	107.2	10.0	168.5	8.1	184.6	12.2
	15-15	46.4	5.6	139.9	10.6	127.4	28.8
	25-30	28.1	4.5	120.2	5.6	143.9	30.1
	30-45	14.7	4.3	120.3	19.3	126.9	17.7
	35-60	9.8	1.2	147.7	7.9	165.1	4.8
	--90	-	-	133.5	11.9	146.2	34.3
$MgSO_4$	0-0	85.1	7.9	151.0	10.5	184.6	12.2
	15-15	87.6	8.0	136.5	9.3	173.9	24.8
	25-30	75.6	5.2	120.2	5.6	138.3	22.2
	30-45	72.5	10.1	149.6	14.2	153.1	20.6
	35-60	72.8	7.8	127.8	22.2	148.5	33.2
	40-90	62.6	6.2	116.3	24.9	136.1	19.5
	50--	31.5	7.5	-	-	-	-

C.N: cycle number, M: monzogranite, T: tonalite and H: hololeuco-granodiorite

Table 4. Brazilian tensile strength of Alvand granitoid rocks at various cycles of salt weathering test.

Test Type	**C.N M-T-H**	**σ_t (MPa)**					
		M		**T**		**H**	
		mean	SD	mean	SD	mean	SD
Na_2SO_4	0-0-0	10.94	0.6	15.24	1.8	15.14	1.6
	15-15-15	10.63	0.8	13.72	1.7	14.34	1.2
	26-30-30	7.36	0.5	11.10	2.8	14.29	0.4
	30-45- 45	5.44	1.5	10.46	1.4	14.16	1.3
	32-60-60	3.19	0.3	11.67	2.9	11.4	0.9
	34-90-90	1.80	0.6	9.86	3.2	12.12	1.0
$MgSO_4$	0-0-0	11.85	1.6	14.33	1.8	16.3	1.1
	15-15-15	10.65	0.2	14.26	1.7	15.6	0.8
	26-30-30	10.06	0.6	15.33	1.6	16.4	1.3
	30-37- 45	8.01	0.3	12.79	0.9	14.7	1.2
	32-45-60	7.83	0.4	12.18	2.2	15.5	1.1
	34-60-90	5.74	1.5	13.56	1.5	14.5	1.5

C.N: cycle number, M: monzogranite, T: tonalite and H: hololeuco-granodiorite

As can be seen from Table 1, and Figures 2a and 2b, dry density changes of monzogranite indicates that during sodium salt weathering, this parameter wasn't considerably affected up to cycle 30 and then it showed sensible decrease.

However, dry density gradually decreased during magnesium sulfate test. The test results on h-granodiorite showed that, dry density was kept more or less unchanged after 90 cycles of both two salt weathering tests due to its low porosity and high strength. In comparison with the other types, tonalite showed medium loss of dry density. The fresh and hard tonalite used for sodium sulfate test showed poorly linear reduction of dry density. Also, the tonalite used in magnesium sulfate test showed a sudden decrease of dry density after cycle 60. Monitoring of monzogranite porosity variation during sodium sulfate test (Fig. 3c) indicated that the trend line of this parameter exponentially increased. This parameter slightly increased up to the 25th cycle and after that it elevated dramatically. In contrast, porosity measurement during magnesium sulfate tests showed a porosity reduction (up to cycle 25) in the initial stage followed by an increasing trend in the subsequent cycles. In fact, filling of pore spaces by salt resulted in the porosity reduction and the fabric deterioration caused by salt attack may lead to an increase in this parameter. Likewise, in tonalite and h-granodiorite porosity reduced in the initial stage and then it was increased accordingly. Magnitude of porosity variations for these types of rocks was very low and sometimes irregular. Comparing with monzogranite, it can be concluded that porosity was not affected by salt attack for these rocks. Monitoring of QAI changes for monzogranite (Figs. 3a and 3b) showed similar behavior compared with the porosity for both the sodium and magnesium sulfate weathering tests. This parameter was more affected by Na-sulfate than magnesium sulfate test. Tonalite samples affected by sodium sulfate solution showed a slight decrease of QAI up to cycle 15which was then followed by an increase in trend in the subsequent cycles. However, magnesium sulfate solution samples showed relatively irregular variation behavior for QAI during the test. The H-granodiorite samples during sodium sulfate and s magnesium sulfate tests showed a decreasing trend up to cycle 45 and 60, respectively which was followed by a trend increment. Compared with monzogranite, the obtained QAI for these rocks were not affected during salt weathering.

Because of high sensitivity of Vp to fabric damage, analysis of this parameter is a helpful approach to characterize rock material deterioration. Results of sodium sulfate test on monzogranite (Table 2 and Fig 3c) indicated that Vp increased slightly up to the 15th cycle and after that it somewhat decreased up to cycle 30. Furthermore, in the subsequent cycles (30-35 cycles), the ultrasonic wave velocities decreased dramatically. This strong decrease of the Vp is an evidence for a structural damage of the material along the generated cracks. As can be observed in Fig. 4c, during magnesium sulfate test monzogranite revealed a pronounced increase of Vp up to the first 15 cycle. In the subsequent cycles, the ultrasonic wave velocities decreased slightly. To describe the reason of this trend for Vp variation, it can be suggested that a salt enrichment occurred in the initial stage, which did not lead to measurable deterioration and resulted in the elevation of Vp due to difference between density of air and solid salt. At the second state, repeated cycles of salt loading affected the rocks and the decay influenced Vp more than the enrichment of salt within the pore space of the granite. As mentioned earlier, it is clear that the sensitivity of Vp was sufficient to detect the beginning of fabric deterioration prior to observation of a macroscopic decay. Consequently, for monzogranite, 15 cycles of salt tests can be considered as the onset of deterioration induced by salt loading. Monitoring of Vp values during sodium sulfate test indicated that filling of pore space in tonalite and h-granodiorite led to an increase in ultrasonic velocities up to cycles 15and 30, respectively. In contrast, a fabric deterioration caused by salt attack is shown in the subsequent cycles which led to Vp reduction.

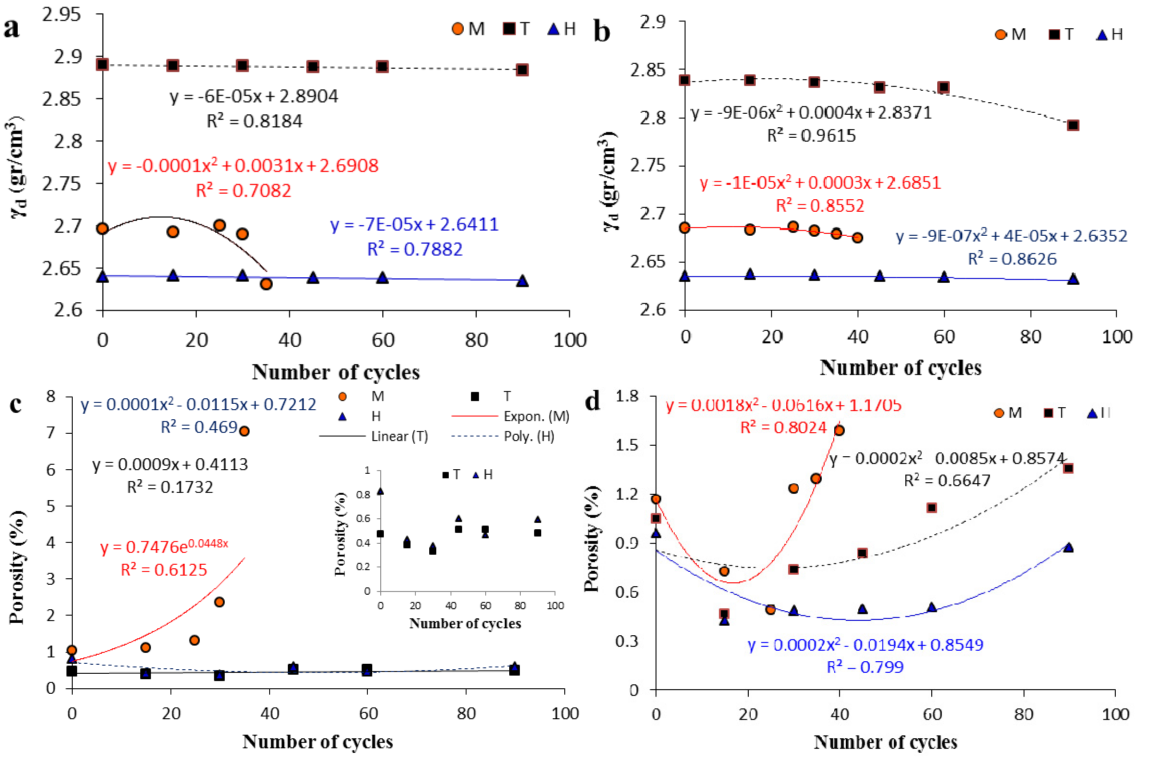

Figure 3. The effects of sodium sulfate (a and c) and magnesium sulfate (b and d) on dry density and porosity of the studied rocks

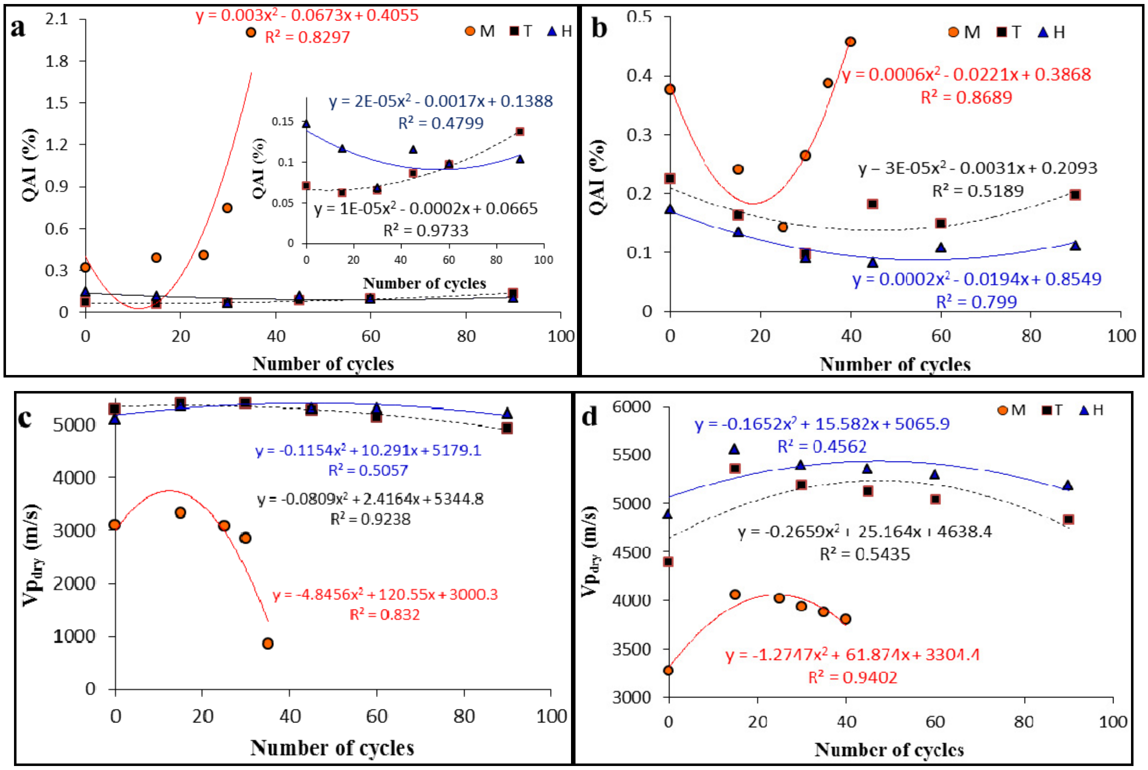

Figure 4. The effects of sodium sulfate (a and c) and magnesium sulfate (b and d) on water absorption and ultrasonic wave velocity of the studied rocks

The initial increasing state of Vp for these two types was derived subsequent to the initial 15 cycles in magnesium sulfate test.

A close inspection of the physical properties changes indicated that Na-sulfate affected the sample rock more than magnesium sulfate in the weathering test. This fact can be supported by changes in the Vp of monzogranite around 72% and 16% for sodium and magnesium sulfate tests, respectively. On the other hand, among the studied rocks, physical properties of monzogranite were obviously more affected than the other types. Higher porosity and lower strength of this type of rock in comparison to the other types can be suggested as reason of this behavior.

The results of mechanical properties changes versus sodium sulfate and magnesium sulfate cycles are summarized in Tables 3-4 and Fig. 5. As shown in these Tables 3 and 4 and figure 4, monzogranite strength properties were clearly influenced by the number of salt weathering cycles. During the sodium sulfate weathering test, the initial uniaxial compressive strength of monzogranite was 107.2 MPa and it was reduced to 9.8 MPa after performing 35 cycles and thus the UCS values decreased around 90%. The relationship between UCS and the number of sodium sulfate weathering cycles for this rock can be expressed by an exponential function which fits the test results (See Fig. 5a) (R^2=0.97).

The results of the magnesium sulfate weathering test indicated that the UCS values decreased from 85.1 to 31.5 MPa (i.e. 63% strength loss). For this type of test, polynomial function was fitted as the best relevant curve with determination coefficient of around 0.88. Assessment of UCS values for the tonalite and h-granodiorite rocks affected by the both salt tests indicated that this parameter generally showed a decreasing trend but the test data was highly scattered around regression lines. Therefore, these correlations demonstrated a low predictive value. Also, the UCS values of these rocks were not affected by salt weathering in comparison with the monzogranite.

The tensile strength of monzogranite slightly decreased up to 15 cycles and then it started to reduce dramatically in sodium sulfate test. The variation of this parameter ranged from 10.95 to 1.80 MPa with totally 83% tensile strength loss. Polynomial function was fitted to the results with determination coefficient around 0.99. Results of magnesium sulfate test for monzogranite showed that only after 26 cycles, there was a clear tendency of damage development in samples. In this test, variation of tensile strength was from 11.85 to 5.74 MPa with 51% loss totally. Beside sodium sulfate test, polynomial function was identified as the best fitted curve with determination coefficient of around 0.88 for magnesium sulfate test. Evaluation of tensile strength values for tonalite and h-granodiorite indicated that this parameter was more susceptible than UCS which resulted in obtaining higher coefficients of determination. Tonalite samples showed 35 % and 5 % of tensile strength reduction under 90 cycles in sodium sulfate and magnesium sulfate tests, respectively. In contrast, tensile strength loss of h-granodiorite was measured around 20% and 11% sodium sulfate and magnesium sulfate tests, respectively. Clearly, tonalite was susceptible than h-granodiorite rocks.

Comparing the results of sodium and magnesium sulfate test implies that the deterioration effect of sodium sulfate on the mechanical properties was more considerable than magnesium sulfate. As shown in Fig. 6, the observed damage phenomena are different in shape and intensity for each salt. A crack formation is detectable for sodium sulfate induced damage. Assessment of the sodium sulfate induced cracks on a thin section indicated that beside macro-cracks in the core sample, several intergranular and intragrnular crack were developed (Fig. 7). Furthermore, the magnesium sulfate induced visible damage phenomena is sanding at the edges of core samples (Fig. 6), which proposed a corrosion mechanism in the magnesium sulfate test.

Fatigue phenomenon occurs as a consequence of the cyclic salt weathering test. According to the damage mechanism of salt weathering, the generated stress in monzogranite would be responsible for all the fatigue phases including crack initiation phase, stable crack propagation phase and unstable crack propagation phase. The stable crack propagation phase can be obviously considered as a macroscopic crack as shown in the Fig. 6. In the case of tonalite and h-granodiorite, because of their high strength and low porosity, the salts induced pressures was not high enough to disintegrate the materials and it only induced a little crack nucleation.

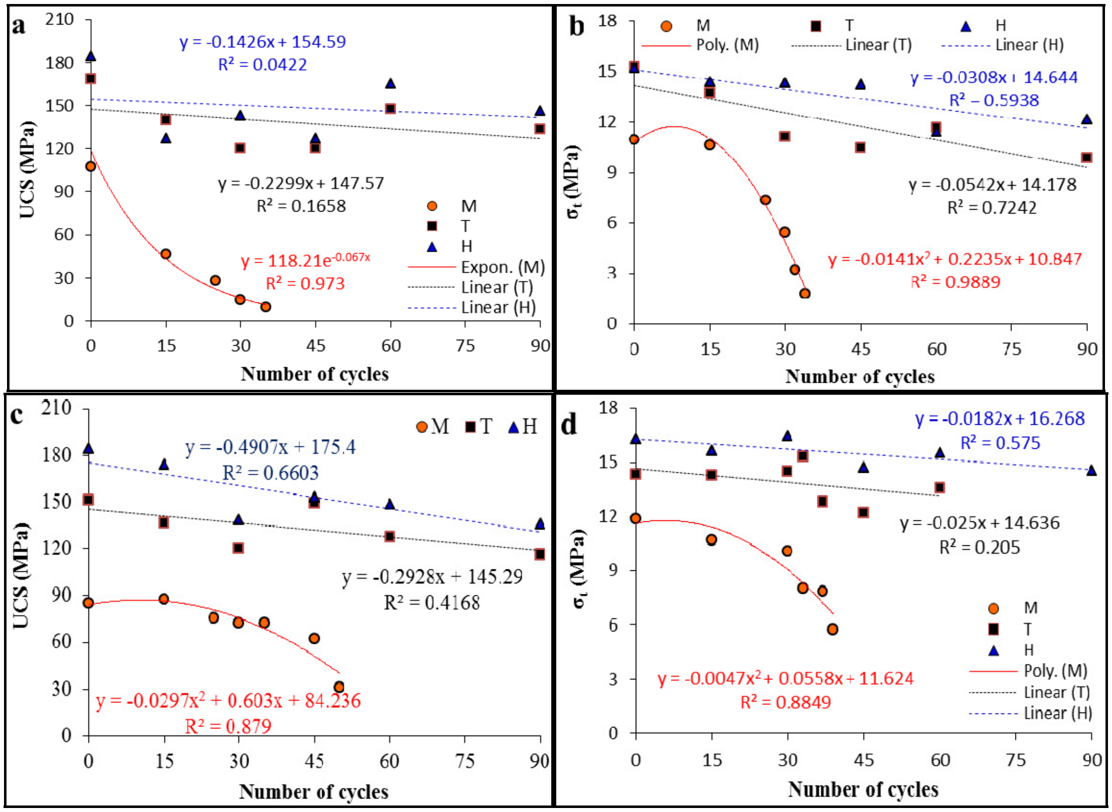

Figure 5. Uniaxial compressive strength and tensile strength variation during (a), (b): sodium sulfate salt test and (c), (d): magnesium sulfate salt test

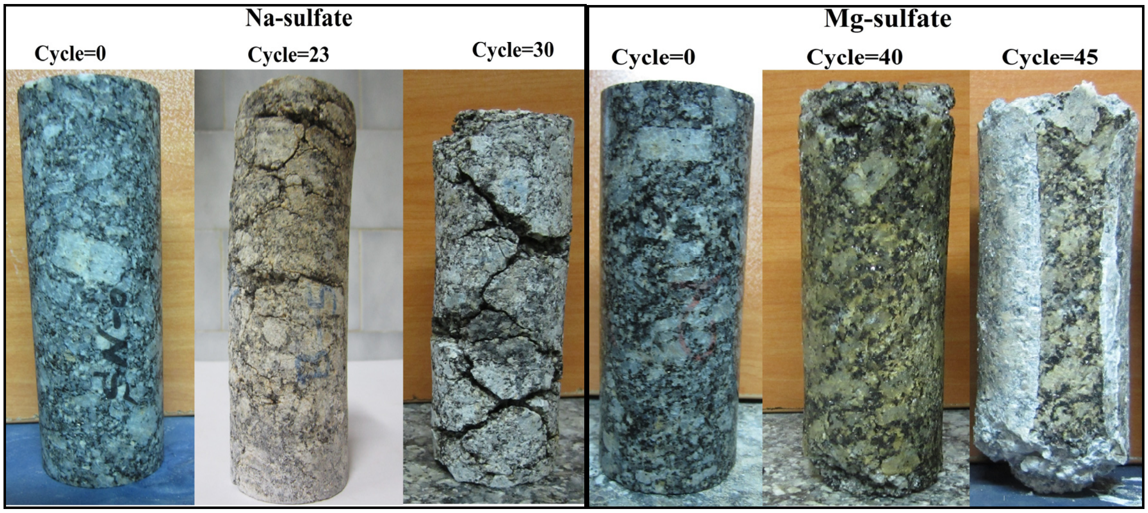

Figure 6. Comparison of salt damage mechanisms associated with (a) sodium sulfate and (b) magnesium sulfate crystallization.

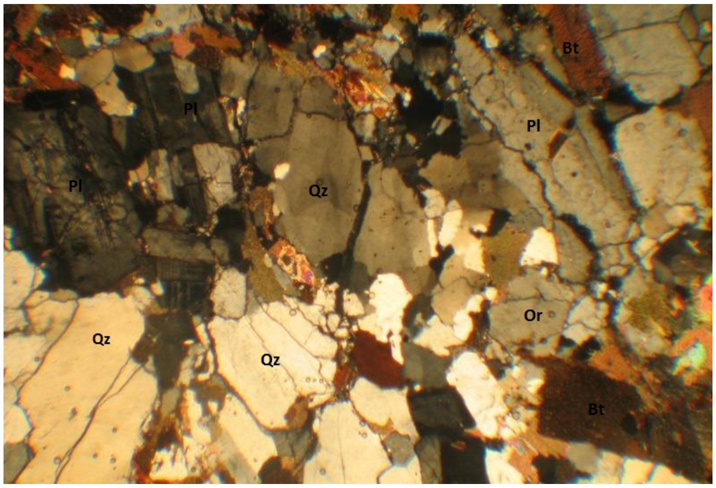

Figure 7. Development of microcracks in different minerals due to generated pressure by Na-sulfate

Thus, only Vp and mechanical properties were slightly affected and other physical properties were not influenced remarkably. In fact, the separate crack nucleuses reduced Vp and caused stress concentration zones during mechanical test.

To compare the influence of sodium and magnesium sulfate effects on physico mechanical properties of the studied rocks, analysis of variance (ANOVA) with repeated measure test was used. In this method significant of variation trend was evaluated by F and Sig. parameters. The significance level was set at $p<0.05$ for all analyses. Statistical analysis was performed using SPSS16. Also, effect size values for physico-mechanical properties which are affected by salt weathering were determined by $\eta 2$. The results of ANOVA test on the mentioned parameters during sodium sulfate test are summarized in Table 5. As can be seen from this table, variation of porosity and quick water absorption show significant changes for all the studied rocks and considerable portion of these variations were occurred due to degradation effects of sodium sulfate. Furthermore, assessing changes in these parameters show that the variations ($\eta 2>0.97$) in monzogranite samples were affected by sodium sulfate more than the other types of rock. Dry density variation trend in all types show significant changes and sodium sulfate weathering effects on dry density changes in h-granodiorite samples was considered more than the others ($\eta 2=0.95$). ANOVA test on saturation density data indicated that the variation of this parameter for monzogranite samples doesn't show significant changes whereas in other types show significant changes. Also, same as dry density results, effect of sodium sulfate on saturation density changes in h-granodiorite was considered more than the others (η2=0.99). Variation of P-wave velocity in both dry and saturation conditions for all the studied rocks show significant changes and monzogranite data variations were affected by sodium sulfate more than the other types. The results of ANOVA with repeated measures test on mechanical properties indicated that variation of tensile and compressive strength during sodium sulfate test for all types show significant changes and monzogranite samples with more than 98% affectability, were affected by sodium sulfate more than the others.

The results of statistical analyse of magnesium sulfate effects on physico-mechanical properties of Alvand granitoid rocks are shown in Table 6.

As is clear in this table, variations of porosity and quick water absorption in monzogranite and h-granodiorite show significant changes. Furthermore, changes in these parameters in monzogranite samples have influenced by magnesium sulfate more than h-granodiorite. Variation of dry density during cyclic magnesium sulfate test for all types of rocks show significant changes and monzogranite with 98% affectability of this parameter by magnesium salt weathering was affected more than the others. The results of ANOVA test parameters for saturation density indicated that variation of this parameter doesn't show significant changes. Instead, monzogranite samples show the highest changes with 95% affectability by magnesium sulfate weathering. Statistical analyses of P-wave velocity changes during cyclic magnesium sulfate test indicated that same as sodium sulfate test this property show significant changes. The results of ANOVA with repeated measures test on mechanical properties indicated that variation of compressive strength during magnesium sulfate test for all types of the rocks and variation of tensile strength for monzogranite and tonalite show significant changes. Among the studied rocks monzogranite samples with more than 98% affectability for compressive strength and 88% for tensile strength, were affected by magnesium sulfate more than the other types of rocks.

Aggregate soundness test

The effects of magnesium sulfate and sodium sulfate solutions on aggregate samples of the studied rocks were measured and shown in Fig. 8. Weight loss trend of monzogranite aggregate samples which were subjected to sodium sulfate solution indicated that weight loss was increased by decreasing the aggregate sieve size.

Table 5. Results of ANOVA with repeated measure test on variation of physico-mechanical properties of Alvand granitoid rock during cyclic sodium sulfate test.

Rock type	**Monzogranite**			**Tonalite**			**H-granodiorite**		
statistic	F	Sig	2η	F	Sig	2η	F	Sig	2η
n	75.8	0.000	0.97	6.1	0.003	0.67	26.7	0.000	0.90
Iv	176	0.000	0.99	17.2	0.000	0.85	5.5	0.004	0.67
γ_{dry}	12.7	0.002	0.86	32.4	0.000	0.91	58.0	0.000	0.95
γ_{sat}	0.27	0.890	0.11	32.3	0.000	0.91	681	0.000	0.99
Vp_{dry}	104	0.000	0.98	9.3	0.000	0.75	12.9	0.000	0.81
Vp_{sat}	95.9	0.000	0.98	24.8	0.000	0.89	274	0.000	0.98
${}_{c}\sigma$	125	0.000	0.98	10.7	0.001	0.84	7.4	0.004	0.78
${}_{t}\sigma$	99.6	0.000	0.98	7.9	0.003	0.80	14.4	0.000	0.88

Table 6. Results of ANOVA with repeated measure test on variation of physico-mechanical properties of Alvand granitoid rock during cyclic magnesium sulfate test.

Rock type	**Monzogranite**			**Tonalite**			**H-granodiorite**		
statistic	F	Sig	2η	F	Sig	2η	F	Sig	2η
n	327	0.000	0.99	3.2	0.055	0.61	21.3	0.000	0.91
Iv	95.4	0.000	0.98	0.92	0.503	0.31	10.9	0.001	0.84
γ_{dry}	110	0.000	0.98	3.8	0.032	0.66	34.6	0.000	0.20
γ_{sat}	37.8	0.000	0.95	3.9	0.032	0.66	0.49	0.774	0.19
Vp_{dry}	192	0.000	0.99	12.4	0.001	0.86	35.7	0.000	0.94
Vp_{sat}	12.9	0.000	0.86	3.8	0.033	0.65	8.8	0.002	0.81
${}_{c}\sigma$	91.8	0.000	0.98	7.9	0.003	0.80	21.3	0.000	0.91
${}_{t}\sigma$	14.6	0.000	0.88	6.9	0.002	0.77	1.0	0.442	0.34

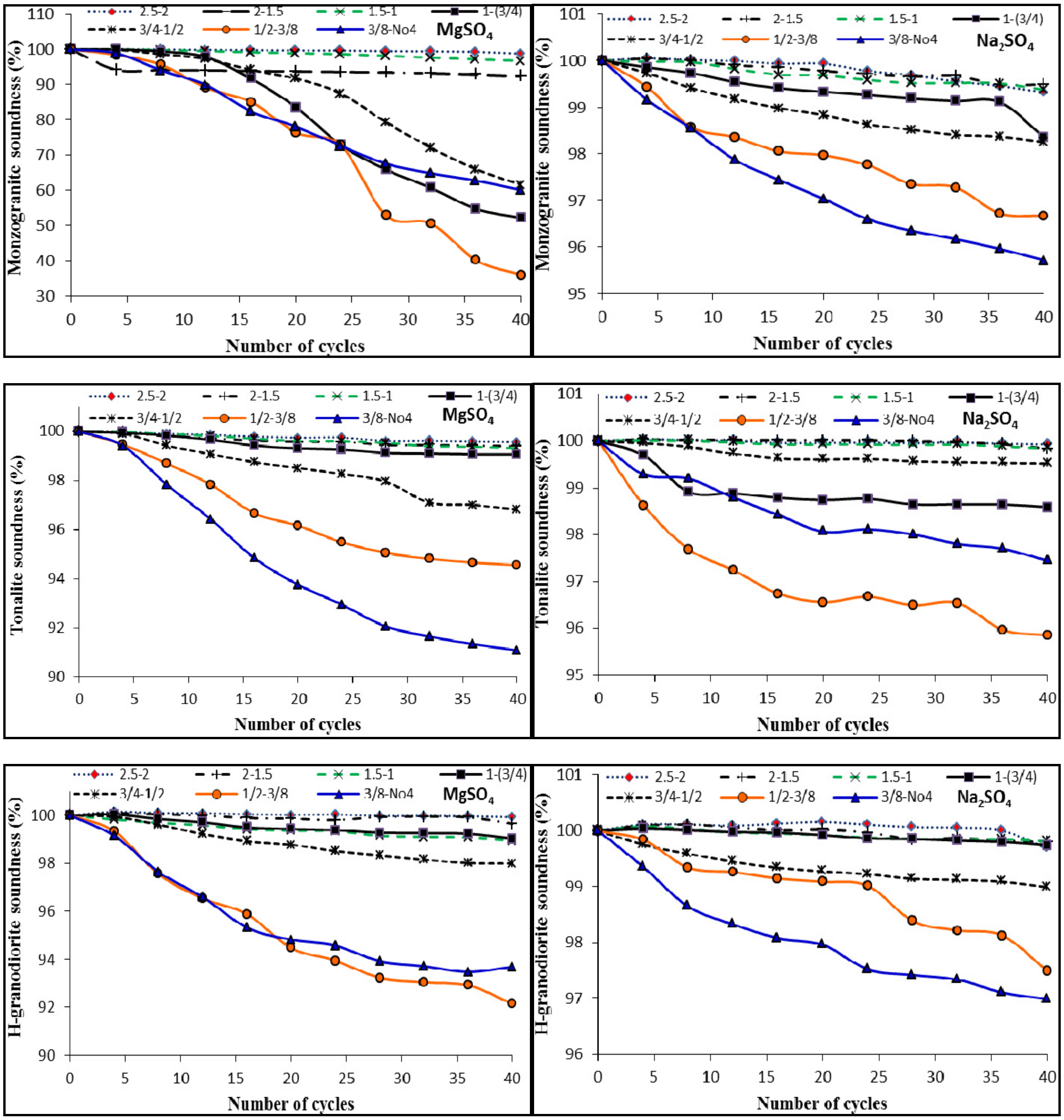

Figure 8. Aggregate soundness of the studied rocks for different sieves during both Na-sulfate and Mg-sulfate tests

Measuring weight changes of the two large sieves (2.5-2 in. and 2-1.5 in.) showed a slight weight growth up to first 8 cycles. This is because of salt crystallization phenomenon within the pore spaces of the rocks without any damaging effect. In the subsequent cycles slight weight reduction was observed. According to Fig. 8, it should be mentioned that these two sieves samples were unaffected by sodium sulfate solution. Trend of aggregate weight changes for the three medium sieves (1.5-1 in., 1-3/4 in. and 3/4-1/2 in.) suggested that by decreasing the sieves sizes, the slope of weight loss trend increased. At the end of 40 cycles, the soundness percentages of these sieves were about 99.3%, 98.3%, and 98.2 % of the initial state, respectively. The variation of weight changes of the two fine sieves (1/2-3/8 in. and 3/8in.-No4 (4.75mm)) showed a higher weight loss in comparison with the other sieves. After 40 cycles, soundness percentage of these sieves was measured about 96.7 % and 95.7 %, respectively. As is clear monzogranite had a good resistance against sodium sulfate attack. Magnesium sulfate soundness test results on monzogranite aggregate indicated that by decreasing of sieve sizes the weight loss percentage increased as well. Measuring weight changes of sieves 2.5-2 in. (up to cycle 8), 1.5-1 in. and 1-3/4 in. (up to cycle 4) showed an initial stage of mass elevation due to salt enrichment which was followed by a weight reduction stage. In the case of other sieves, weight changes showed decreasing trend from the beginning of the test. In fact, corrosive mechanism and induced damage of magnesium sulfate dominated and affected the rocks more than salt enrichment. At the end of this test, the maximum weight loss was observed in sieve 1/2-3/8 in. with soundness percentage of 35.9%. Thus, it had lost about 64.1% of its initial dry weight. Comparing the sodium sulfate, magnesium sulfate showed higher values of mass loss and difference between them is obvious.

Tonalite aggregate behavior against sodium sulfate solution indicated that for the first set of coarse sieves (i.e. 2.5-2, 2-1.5 and 1-5-1 in.), initial weight growth stage was observed up to 12, 24, and 8 cycles, respectively. This stage was followed by a slight weight reduction stage caused by the salt weathering and damage initiation. Evaluation of other sieves showed decreasing of weight in all cycles. Sieve 1/2-3/8 in. had maximum weight loss with soundness percentage around 95.85 % at the end of 40 cycles.

Comparing sodium sulfate test results, tonalite aggregate which was affected by magnesium sulfate solution indicated that weight loss increased in a better pattern while sieve sizes decreased. Because of more drastic effect of magnesium sulfate on the weight loss, soundness of all sieves aggregate showed decreasing trend during all cycles. The maximum damage was measured for the sieve 3/8in.-No 4 with soundness magnitude of 91.1 % at the end of the 40th cycle. Compared with monzogranite, tonalite showed lower values of mass loss which may be due to its low porosity and high strength.

H-granodiorite aggregate response was similar to the other types compared to sodium sulfate and generally with decreasing the sieves sizes, weight loss was increased. For the 4 coarse sieves (2.5-2, 2-1.5, 1-5-1, and 1-3/4 in.) initial weight growth stage was observed up to 36, 20, 8 and 8 cycles, respectively. With an increase in sieves sizes salt enrichment was dominant and damage took place with delay. This stage was followed by a weight decreasing stage due to occurrence of damage which was highlighted for fine sieves. Soundness of this type of rock against sodium sulfate solution was good and maximum damage was measured for aggregate of sieve 3/8 in.-No 4 with soundness percentage of 97% at the end of 40 cycles. H-granodiorite aggregate weight changes against magnesium sulfate solution had a relatively similar trend with sodium sulfate with a higher weight loss percentage. In the case of 3 sieves (2.5-2, 2-1.5, and 1-3/4 in.) initial weight increase stage was observed up to 24, 8 and 4 cycles, respectively. As is clear from Fig. 8, in magnesium sulfate test, damage took place faster and higher than sodium sulfate test. Among aggregates retained on different sieves, weight loss of two fine sieves aggregate (1/2-3/8 in. and 3/8 in.-No 4) was remarkable and higher than the other one. Maximum weight loss was measured for the aggregate size of 1/2-3/8 in. with maximum soundness of 92.1 % at the end of 40 cycles.

Monitoring weight loss of the studied rocks indicated that with decreasing sieve sizes soundness percentage was decreased. For description of this trend below reasons are suggested:

A: specific area increases with decreasing of aggregate size. Consequently, more sulfate solution will attack the rocks.

B: during preparation of samples, finer aggregates were subjected to more stresses and more preparation impact than others. Therefore, their induced micro-fractures must be higher than coarse aggregates.

C: by decreasing of sieve sizes, difference between sieves was decreased. Thus, when some parts of an aggregate were damaged and separated, not only the detached part was passed from standard sieve, but also the remained part had potential to pass the standard sieve. For example, in the case of fine aggregates (e.g. 8 mm) when the 4 mm specimen was separated from original aggregates, the remaining part passed the standard sieve; whereas, in the case of coarse aggregates (eg. 60 mm) the remaining part did not pass through the standard sieve.

After 40 cycles of soundness test disintegration rate of the studied rocks was evaluated using a decay function model. There is a disintegration rate for each rock type during cyclic soundness test which is depended to decay constant and can be mathematically expressed as follows:

$$-\left(\frac{dD}{dN}\right) \rightarrow \lambda D \qquad (2)$$

where $\left(\frac{dD}{dN}\right)$ is the disintegration rate which is a function of λ. Minus sign of disintegration rate indicates that the property is decreasing. Also, λ is the decay constant indicating the average integrity loss of rock soundness by the action of any single cycle of weathering tests, D is initial soundness, and N is the number of cycles. Furthermore, for measurement of long term disintegration, half-life of durability can be employed. The half-life (N 0.5), can be defined as the number of cycles necessary to reduce the rocks soundness to half its value. Based on the obtained regression equations, decay constant and half-life have been measured by equation 2 which are summarized in Tables 7and 8.

$$Exponential\ equation \rightarrow "D = D_0 e^{-\lambda N} + " \Rightarrow 50\% = D_0 e^{-\lambda N_{0.5}} \Rightarrow N_{0.5} = ln \frac{D_0}{50\lambda} \quad (3)$$

the term $e^{-\lambda N}$ is the decay factor, which indicates the proportion of the remaining integrity after N cycle of soundness test. Also, the decay constant (λ) indicates the mean relative integrity loss by the increase of any single cycle. The results of soundness decay model of the studied rocks during sodium sulfate test illustrate that monzogranite with averagely 0.04 % and h-granodiorite with 0.025 % show highest and lowest decay constant, respectively. Similar results were obtained for magnesium sulfate decay model and decay constants of monzogranite and h-granodiorite were 1.07 % and 0.073 %, respectively.

Also, the obtained decay constant for all types in sodium and magnesium sulfate tests is decreased by increasing aggregate size. Comparing the obtained decay constant of sodium and magnesium sulfate soundness test indicates that decay constants of magnesium sulfate test are 22.8, 4.9, and 2.5 times more than that of obtained in sodium sulfate test for monzogranite, tonalite and h-granodiorite, respectively.

The half-life is more significant for prediction of long-term disintegration of building stone against salt weathering test. This index provides an easy way to predict how many cycles are necessary to reduce a durability property to its half value. As seen from Tables 7 and 8, the half-life is inversely related to the decay constant in all rock types and aggregate size.

Table 7: The determination coefficient (R^2), decay constant (λ) and half-life ($N_{0.5}$) of studied rocks degradation process during cyclic Na-sulfate soundness test.

Rock type	**Monzogranite**			**Tonalite**			**H-granodiorite**		
sieve number	**R^2**	λ	$N_{0.5}$	**R^2**	λ	$N_{0.5}$	**R^2**	λ	$N_{0.5}$
4-3/8	0.95	-0.001	686	0.93	-0.0006	1148	0.92	-0.0007	982
3/8-1/2	0.94	-0.0008	860	0.80	-0.0008	851	0.94	-0.0006	1155
1/2-3/4	0.95	-0.0004	1252	0.87	-0.0001	6925	0.91	-0.0002	3456
3/4-1	0.87	-0.0003	2309	0.66	-0.0003	2294	0.94	-0.00007	9909
1-1.5	0.95	-0.0002	2499	0.88	-0.00004	17333	0.90	-0.00006	11560
1.5-2	0.96	-0.0001	6938	0.53	-0.00003	23121	0.78	-0.00007	9917
2-2.5	0.88	-0.0002	3473	0.74	-0.00002	34667	0.27	-0.00005	13892

Table 8: The determination coefficient (R2), decay constant (λ) and half-life (N0.5) of studied rocks degradation process during cyclic Na-sulfate soundness test.

Rock type	**Monzogranite**			**Tonalite**			**H-granodiorite**		
sieve number	**R^2**	λ	$N_{0.5}$	**R^2**	λ	$N_{0.5}$	**R^2**	λ	$N_{0.5}$
4-3/8	0.99	-0.014	51	0.95	-0.003	229	0.89	-0.002	341
3/8-1/2	0.92	-0.027	30	0.94	-0.002	344	0.95	-0.002	343
1/2-3/4	0.89	-0.013	60	0.98	-0.0009	771	0.97	-0.0006	1154
3/4-1	0.94	-0.019	42	0.93	-0.0003	2309	0.95	-0.0002	3466
1-1.5	0.96	-0.0009	1744	0.98	-0.0002	3466	0.97	-0.0002	3461
1.5-2	0.51	-0.001	654	0.94	-0.0002	3464	0.52	-0.00007	9910
2-2.5	0.86	-0.0003	2317	0.97	-0.0001	6931	0.59	-0.00004	17356

Monzogranite with highest decay constant show lowest half-life while tonalite with lowest decay constant show highest life-time. Coarse grain aggregates with lowest decay constant show highest half-life, while by decreasing aggregate size, generally half-life is decreased. Comparing the obtained half-life of sodium and magnesium sulfate soundness test indicates that half-life of sodium sulfate test are 18.8, 4.9, and 2.5 times more than that of obtained in magnesium sulfate test for monzogranite, tonalite and h-granodiorite, respectively.

Conclusions

The degradation potential of Alvand granitoid rocks against sodium sulfate and magnesium sulfate solutions as a function of weathering cycles was investigated by measuring physico-mechanical properties and weight loss. From the experimental results outlined earlier, the following conclusions can be drawn:

Sodium sulfate had more effects than magnesium sulfate on engineering properties. Meanwhile, magnesium sulfate effect on weight loss was considerably more effective considerable than sodium sulfate. Consequently, a damage mechanism based on crack propagation for sodium sulfate and corrosion mechanism for magnesium sulfate was distinguished.

Monzogranite underwent more damage than other types of rocks. The higher porosity of monzogranite in comparison to other types can be considered as a major critical damage parameter. The higher porosity resulted in a lower strength and higher salt loading.

Vp was found as a sensitive parameter and sufficient to detect the onset of structural damage before an observable macroscopic decay.

The repeated cycles caused fatigue phenomenon which reduced the strength of studied rocks. Monzogranite showed all fatigue phases while tonalite and h-granodiorite showed only the crack nucleation phase due to their high strength and low porosity.

The aggregate soundness test indicated that by decreasing aggregate sizes, soundness percentage reduced.

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