Journal of Sciences, Islamic Republic of Iran 28(3): 231 - 241 (2017) http://jsciences.ut.ac.ir
University of Tehran, ISSN 1016-1104

Estimating the Mechanical Properties of Travertine Building Stones Due to Salt Crystallization Using Multivariate Regression Analysis

A. Jamshidi*[1], M.R. Nikudel[2], M. Khamehchiyan[2], A. Zalooli[2] and H. Yeganehfar[3]

[1]Department of Geology, Faculty of Basic Sciences, Lorestan University, Khorramabad, Islamic Republic of Iran
[2]Department of Geology, Faculty of Basic Sciences, Tarbiat Modares University, Tehran, Islamic Republic of Iran
[3]Department of Geology, Faculty of Basic Sciences, Payame Noor University, Tehran, Islamic Republic of Iran

Received: 22 October 2015 / Revised: 3 September 2016 / Accepted: 13 January 2017

Abstract

Salt crystallization is one of the most powerful weathering agents that may cause a rapid change in the mechanical properties of stones, and thus limit their durability. Consequently, determining the mechanical properties of stones due to salt crystallization is important for natural building stones used in marine environmental and mild climatic conditions, which expose excessive salt crystallization cycles. In this study, multivariate regression analysis was performed for estimating the mechanical properties of travertine building stones after salt crystallization test. For this purpose, 12 travertine samples were selected and their physical and mechanical properties (density, porosity, uniaxial compressive strength, Brazilian tensile strength, and P-wave velocity) were determined. Then salt crystallization test was carried out at sodium sulfate solution (Na2SO4) up to 50 cycles and, after every 5 cycles, the uniaxial compressive strength, Brazilian tensile strength and P-wave velocity of the samples were measured. Using data analysis, regression equations were developed for estimating the mechanical properties of deteriorated samples at any cycle of the salt crystallization test. In these equations, the mechanical properties of the samples after salt crystallization were considered to be the dependent variable, which is dependent on the independent variables of the number of salt crystallization cycles, initial mechanical properties of the stones and their porosities. The validity of the equations was verified with the mechanical properties data of a researcher for salt crystallization test. The results showed that regression equations are in good accuracy for estimating the mechanical properties of stones, and thus making a rapid durability assessment.

Keywords: Salt crystallization; Uniaxial compressive strength; Brazilian tensile strength; P-wave velocity; Regression equations.

Introduction

Travertine is a chemical sedimentary rock formed mostly in tectonic areas and has been successfully used in many buildings and other construction projects for thousands of years. Nowadays, travertines with different color, texture and pattern are widely used as building materials for construction and decoration purposes, especially for outdoor applications such as flooring, paving and wall cladding.

The physical, mechanical, chemical and petrographical properties of stones are very important to

---

* Corresponding author: Tel: +986633350564; Fax: +986633350564; Email: jamshidi.geo85@yahoo.com

select the materials for outdoor applications [1]. Uniaxial compressive strength, Brazilian tensile strength and P-wave velocity are among most important mechanical properties to assess stones' durability against weathering agents [2, 3]. However, change in the mechanical properties of stones due to weathering agents can affect their durability in the course of time [4].

Salt crystallization is the most powerful weathering agents, particularly in marine environmental and mild climatic conditions, and specially when combined with frost action [5]. Crystallization pressure is the most important decay mechanism that occurs during the salt crystallization, which depends mainly on the pore size and the degree of supersaturation [6]. When the crystallization pressure reaches the tensile strength of the stone, new microfractures are developed and the present ones are deepened and widened [4]. These can in turn affect the mechanical properties and durability of stones. Thus it is necessary to understand the change of mechanical properties of stones when salt crystallization is considered as one of the weathering agents.

Different aspects of the effects of weathering agents on the rocks have so far been studied [7-15]. Yavuz and Topal [16] studied the thermal and salt crystallization effects on 6 marble samples from Western Anatolia, Turkey. Angeli et al. [17] investigated the influence of temperature and salt concentration on the salt weathering of a sedimentary stone with sodium sulfate. Yu and Oguchi [7] studied the role of pore size distribution in salt uptake, damage, and predicting salt susceptibility of eight types of Japanese building stones Akin and Ozsan [18] evaluated the long-term durability of yellow travertine using a decay function model, proposed by Mutluturk et al. [19]. Cultrone et al. [10] investigated the petrophysical and durability tests on sedimentary stones to evaluate their quality as building materials. Vazquez et al. [20] studied the weight changes of sedimentary building stones due to salt crystallization. Ghobadi et al. [2] investigated the petrophysical and durability tests on sandstones for the evaluation of their quality as building stones using Analytical Hierarchy Process (AHP).

Although in most of previous studies, different aspects of the effects of salt crystallization on the rocks have been investigated for several decades, but numerical methods are insufficient for estimating the mechanical properties and durability of rocks against salt crystallization action [2, 6, 18].

The aim of this study is to develop multivariate regression equations for estimating the mechanical properties (uniaxial compressive strength, Brazilian tensile strength and P-wave velocity) of 12 travertine building stones at any cycle of the salt crystallization test. In these equations, the mechanical properties of stones after salt crystallization was considered to be the dependent variable, which is dependent on the independent variables of the number of salt crystallization cycles, initial mechanical properties of the stones and their porosities.

Materials and Methods

To carry out the research, a number of travertine samples were subjected to salt crystallization test in a sodium sulfate solution under the same conditions. The test up to 50 cycles was carried out and, after every 5 cycles, the mechanical properties (uniaxial compressive strength, Brazilian tensile strength and P-wave velocity) of the samples were measured. Using data analysis, multivariate regression equations were developed for estimating the mechanical properties of samples at any cycle of the salt crystallization test. These equations were developed by incorporating a multivariate regression equation (that only can estimate the mechanical properties for 50 cycles of salt crystallization test) into a simple exponential or linear regression equation.

1.1. Rock sampling

To fulfill the aim of the research, 12 travertine building stones were selected from various quarries in Iran (Fig. 1). These travertines are generally used as facing dimension stone, ornamental material, building stone, or lime and cement production material in the industrial sector. For each travertine, some blocks that varied from 0.2×0.35×0.35 to 0.30×0.40×0.40m in size were collected. During the sampling, the travertine types having no bedding planes were selected to eliminate any anisotropy effects on the measurement.

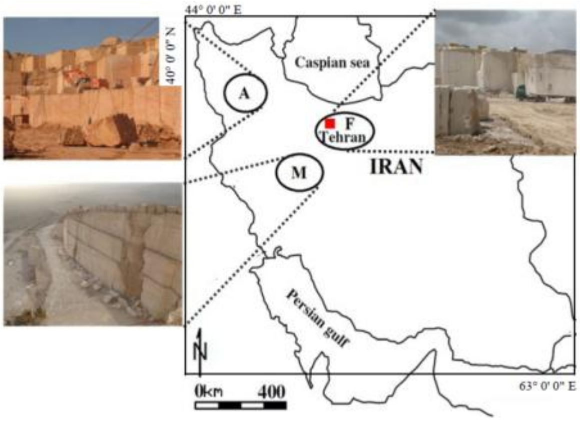

Figure 1. The location of sampling and some of the quarries

The name, type and location of the collected travertines are given in Table 1.

1.2. Physical properties

Some physical properties of the samples including dry density and effective porosity were determined using saturation method, which use Archimeds' principle and give accurate results. This method is suitable for the samples tested in this study because they have no friable and swelling potentials.

Five specimens from each stone type were used for determination of dry density and effective porosity in accordance with ISRM [21]. The results of these tests are given in Table 2.

1.3. Salt crystallization test

Salt crystallization test has been used since 1828 to evaluate the durability of construction materials. In this study, salt crystallization test was carried out by total immersion according to EN 12370 [22]. A sodium sulfate solution was selected because its occurrence in nature is quite common, it has worldwide distribution, and it is frequently used in salt crystallization laboratory tests.

For salt crystallization test, firstly, clean and dry samples were introduced into a container and completely covered with a 14% w/w sodium sulfate solution at 20±3°C for a period of 4 h (immersion stage). Secondly, the samples were removed from the solution, and settled into the drying oven at 105±5°C for a period of 16 h (drying stage). Finally, the samples were subjected to room conditions (20±3°C) for a period 4 h (cooling stage). Each cycle of the salt crystallization test was completed for 24h and for each stone type, the test procedure was repeated for 50 cycles.

Two series of samples were prepared for each stone type to identify their uniaxial compressive strength, Brazilian tensile strength and P-wave velocity before and after the treatment. The first series were utilized for determination of fresh stone properties (initial properties), and the second series were subjected to salt crystallization cycles. After every 5 cycles of salt crystallization, the measurements were made on five specimens under saturated conditions. The experimental procedure was performed according to the methods suggested by the ISRM [21]. The results of salt crystallization test on the samples are given in Table 3

Table 1. Name, type, class and location of the samples under study

Commercial name	Rock type	Rock class	Location	
Azarshahr silver	Travertine	Sedimentary	Azarshahr	05 75 086-41 72 118
Dastjerd red	Onyx travertine	Sedimentary	Azarshahr	05 79 419-41 77 952
Dastjerd green	Onyx travertine	Sedimentary	Azarshahr	05 79 714-41 78 401
Dastjerd white	Onyx travertine	Sedimentary	Azarshahr	05 78 893-41 75 830
Atashkooh white	Travertine	Sedimentary	Mahallat	05 38 037-39 50 348
Abasabad light cream	Travertine	Sedimentary	Mahallat	04 57 520-37 45 511
Abasabad white	Travertine	Sedimentary	Mahallat	04 57 518-37 45 512
Abyar white	Travertine	Sedimentary	Mahallat	04 58 520-37 45 541
Dareh bokhari cream	Travertine	Sedimentary	Mahallat	05 39 037-39 50 842
Atashkooh cream	Travertine	Sedimentary	Mahallat	04 63 828-37 48 441
Firuzkuh chocolate	Travertine	Sedimentary	Firuzkuh	06 36 414-39 49 491
Firuzkuh cream	Travertine	Sedimentary	Firuzkuh	06 34 361-39 49 023

Table 2. The statistical distribution of dry density and effective porosity of the samples under study

Commercial name	Dry density (g/cm^3)				Effective porosity (%)			
	Min.	Max.	Ave.	⋆SD	Min.	Max.	Ave.	SD
Azarshahr silver	2.40	2.49	2.46	0.037	3.03	3.27	3.17	0.103
Dastjerd red	2.57	2.71	2.66	0.054	1.58	1.99	1.77	0.151
Dastjerd green	2.65	2.72	2.69	0.032	0.47	0.61	0.54	0.055
Dastjerd white	2.70	2.75	2.72	0.019	1.02	1.81	1.39	0.286
Atashkooh white	2.44	2.59	2.47	0.065	4.06	4.47	4.20	0.165
Abasabad light cream	2.40	2.48	2.43	0.032	4.66	5.07	4.86	0.161
Abasabad white	2.40	2.43	2.42	0.011	4.03	4.75	4.53	0.289
Abyar white	2.33	2.47	2.41	0.057	3.30	3.88	3.58	0.214
Dareh bokhari cream	2.31	2.43	2.38	0.048	6.16	6.65	6.40	0.190
Atashkooh cream	2.39	2.50	2.46	0.044	3.47	4.63	4.20	0.478
Firuzkuh chocolate	2.32	2.46	2.38	0.051	2.65	3.37	3.00	0.264
Firuzkuh cream	2.31	2.38	2.34	0.029	4.00	4.45	4.10	0.194

⋆Standard deviation

Table 3. The mechanical properties of fresh samples and deteriorated samples after 50 cycles of salt crystallization test

Commercial name	**Uniaxial compressive strength (MPa)**			**Brazilian tensile strength (MPa)**			**P-Wave velocity (m/s)**		
	*Initial value	**Deteriorated value	% loss of initial value	Initial value	Deteriorated value	% loss of initial value	Initial value	Deteriorated value	% loss of initial value
Azarshahr silver	55.5	42.1	24.1	5.71	4.20	26.4	4930	3736	24.2
Dastjerd red	65.7	56.0	14.8	6.17	5.17	16.2	5260	4366	17.0
Dastjerd green	64.5	55.3	14.3	5.95	5.15	13.4	5310	4566	14.0
Dastjerd white	62.4	53.9	13.6	6.42	5.37	16.4	5450	4766	12.6
Atashkooh white	49.3	36.8	25.4	4.88	3.53	27.7	4600	2875	37.5
Abasabad light cream	41.3	26.4	36.1	4.32	3.09	28.5	4150	2649	36.2
Abasabad white	43.7	34.7	20.6	4.39	3.14	28.5	4410	2644	40.0
Abyar white	51.4	42.7	16.9	5.33	4.20	21.2	4690	3390	27.7
Dareh bokhari cream	37.4	25.6	31.6	3.71	2.55	31.3	4135	2600	37.1
Atashkooh cream	45.7	37.5	17.9	4.69	3.80	19.0	4510	3240	28.2
Firuzkuh chocolate	59.9	43.6	27.2	5.90	4.57	22.5	5010	3664	26.9
Firuzkuh cream	50.7	40.4	20.3	5.21	4.00	23.2	4470	3189	28.7

*Fresh condition

**After 50 cycles of salt crystallization test

and graphically illustrated in Figs. 2–4.

Figs. 2–4 show the variations in the uniaxial compressive strength, Brazilian tensile strength and P-wave velocity of the samples during the salt crystallization test. A declining pattern was determined for these properties during the salt crystallization test. The reduction in the uniaxial compressive strength and Brazilian tensile strength of the samples after 50 salt crystallization cycles was found to be between 14.3% to 36.1% and 13.4% to 31.3% of the initial values, respectively. These results show that deterioration of samples due to salt crystallization was significant. The reductions in uniaxial compressive strength and Brazilian tensile strength in this study are in good agreement with the findings of Akin and Ozsan [18].

As shown in Fig. 4, in spite of a rapid increase in the

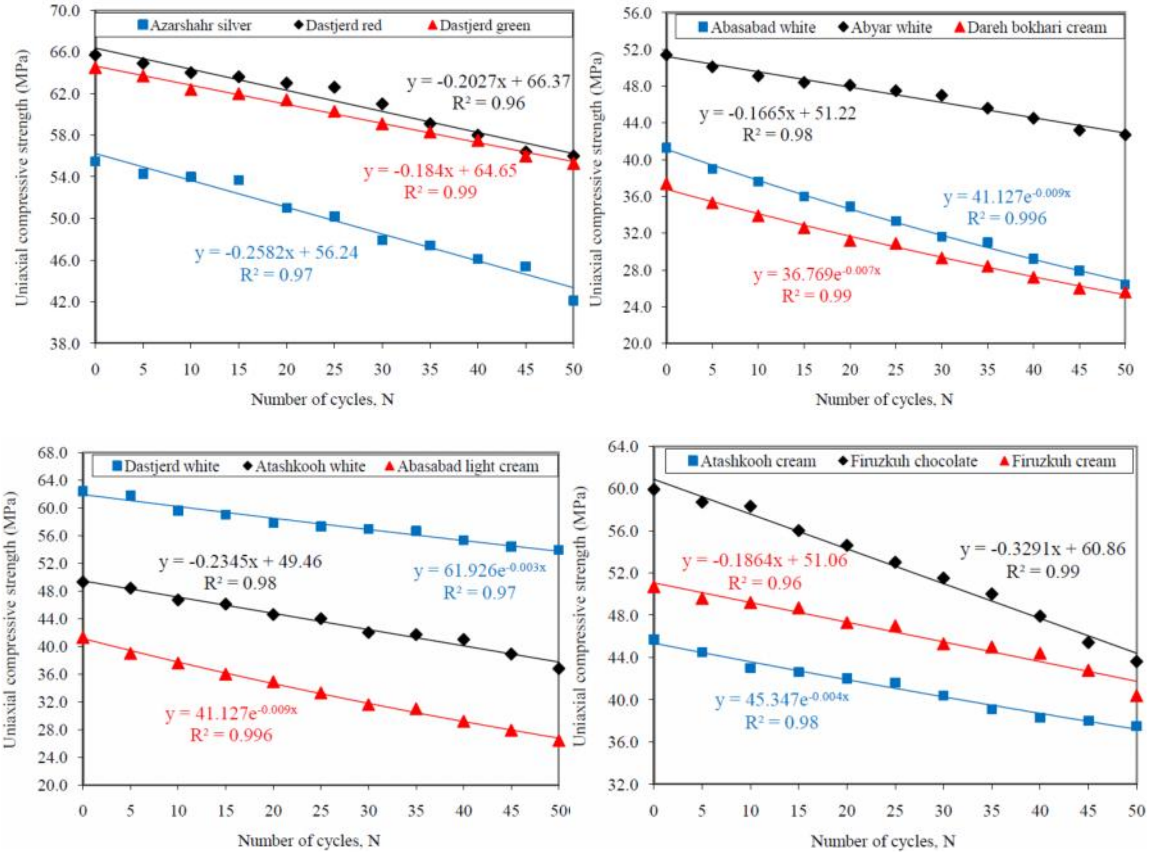

Figure 2. Uniaxial compressive strength measured during the salt crystallization cycles

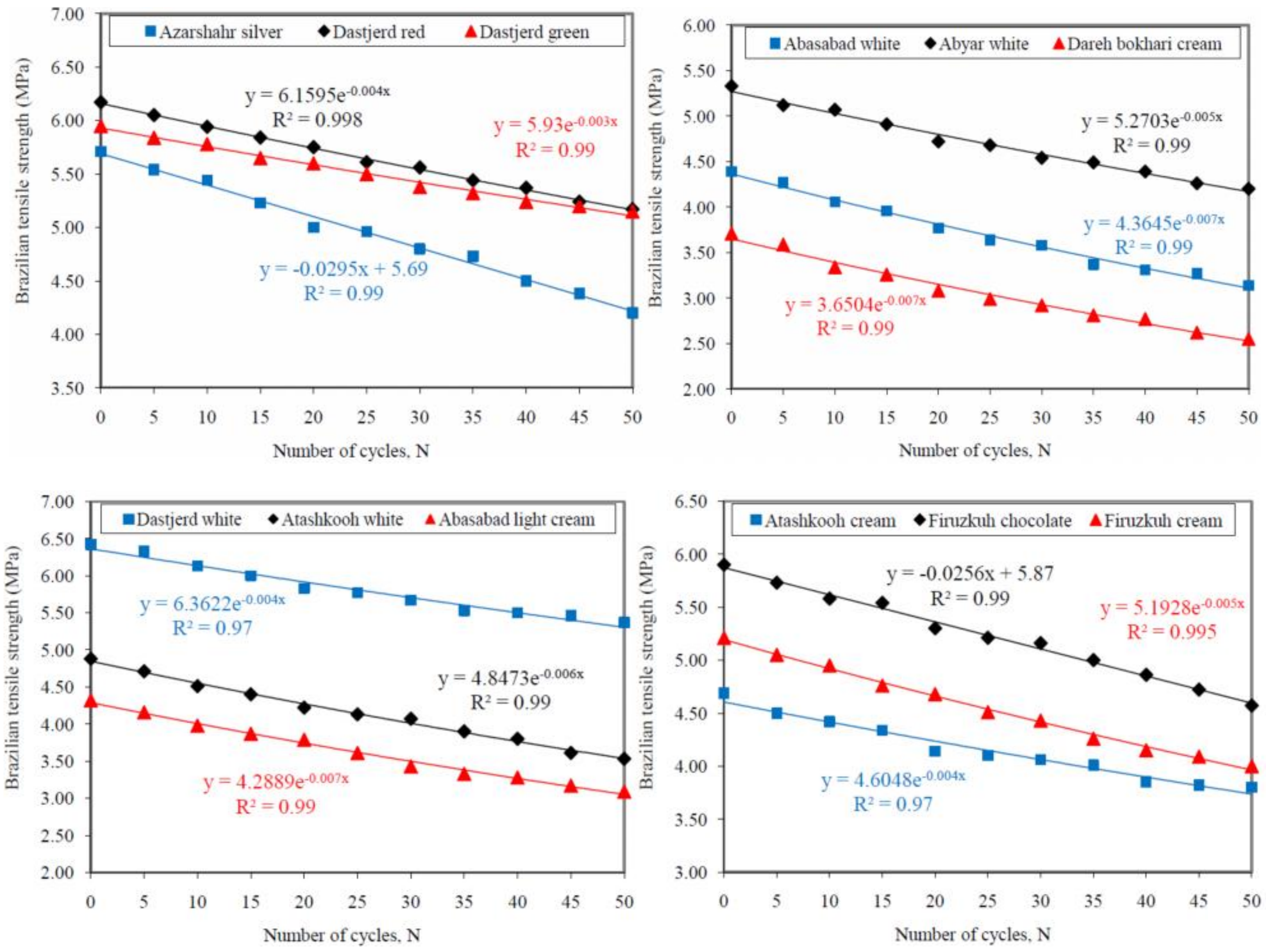

Figure 3. Brazilian tensile strength measured during the salt crystallization cycles

P-wave velocity of samples at the initial cycles of salt crystallization, in the following, a gradual decrease is detected with additional cycles due to the creation of new microcracks or enlargement of the existing ones. The main reason for the increase of P-wave velocity at the initial cycles of salt crystallization is the accumulation of salt crystals in the pores. In general, the initial P-wave velocity of samples is significantly changed due to salt crystallization. A reduction of 12.6% – 40.0% in the P-wave velocity of samples was observed after 50 salt crystallization cycles. The study of Akin and Ozsan [18] on the yellow travertine showed a constant reduction in P-wave velocity during the salt crystallization test. However, they did not observe any increase in the P-wave velocity of samples at beginning of the salt crystallization test.

The authors of this work attempted to develop the best correlation between the mechanical properties values during the salt crystallization test and the test cycles to attain the most reliable empirical model. The equations of the best fit line, the 95% confidence limits, and the determination coefficients (R^2) were determined for each regression.

As shown in Figs. 2–4, in all cases, an exponential or linear regression equation was found to fit well with the data obtained. The general form of exponential and linear equations is defined as Eqs. (1) and (2), respectively:

$$M_N = M_0 e^{-\lambda N} \quad (1)$$

$$M_N = -\lambda N + M_0 \quad (2)$$

where M_N is the uniaxial compressive strength, Brazilian tensile strength or P-wave velocity of the samples after N cycles of salt crystallization, and λ is a decay constant indicating the average integrity loss by the action of any single cycle.

As can be seen from Figs. 2–4, the decay constant is inversely related to the integrity pattern. A sudden decrease in the integrity of uniaxial compressive strength, Brazilian tensile strength and P-wave velocity indicates high decay constant values and a rapid

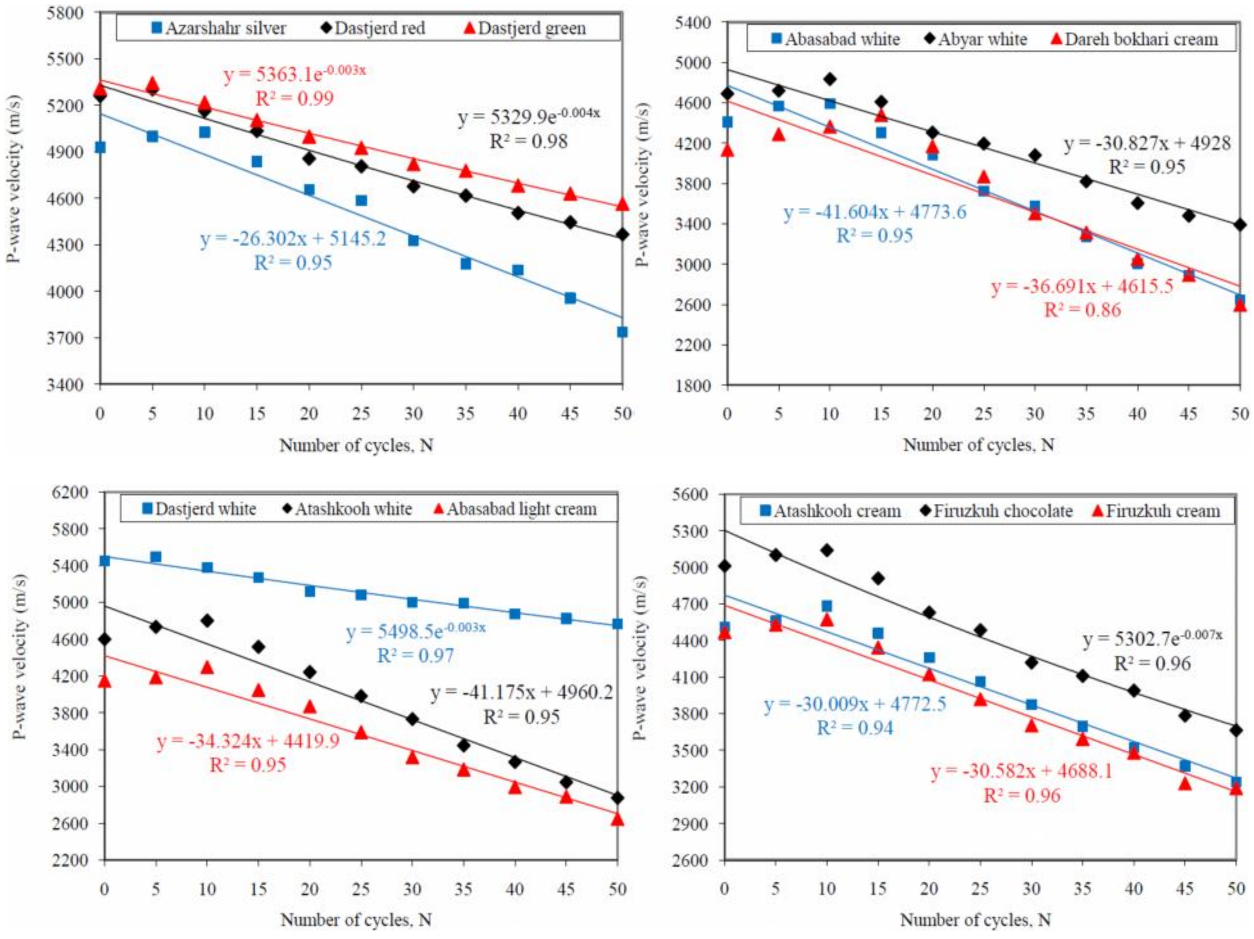

Figure 4. P-wave velocity measured during the salt crystallization cycles

disintegration rate due to salt crystallization. For example, Firuzkuh chocolate looses only 0.3291 MPa of its uniaxial compressive strength value, on average, after a single salt crystallization cycle; whereas this value for Firuzkuh cream is 0.1864 MPa (Fig. 2). Therefore, the integrity loss rate of Firuzkuh chocolate is about 1.77 times more than that of Firuzkuh cream.

Results and Discussion

1.1. Estimating the mechanical properties after 50 cycles of salt crystallization test

Multivariate regression is one of the most common accepted methods of data analysis that may be appropriate whenever a quantitative variable (dependent variable) is to be examined in relationship to any other parameters (independent variables). In this study, the multivariate regression equations were used for estimating the mechanical properties of the deteriorated samples. In these equations, the mechanical properties of the samples after 50 cycles of salt crystallization test were considered to be the dependent variable, which is dependent on the independent variables of the initial mechanical properties of the samples and their porosities. Multivariate regression equations were undertaken with 95% confidence level and the best-fit curves were obtained using the least squares method. Coefficient of multiple determination (R^2) and standard error of estimate (SEE) were used as the numerical measures of the goodness of fit for the regression equations.

The general equation for estimating the mechanical properties of the samples after salt crystallization test is expressed as below:

$$M_{50} = \alpha_0 + \alpha_1 M_0 + \alpha_2 n \qquad (3)$$

where M_{50} is the estimated value of the mechanical properties (uniaxial compressive strength, Brazilian tensile strength or P-wave velocity) for the samples for 50 cycles of salt crystallization test, M_0 is the fresh mechanical properties or, in other words, the initial mechanical properties (initial uniaxial compressive strength, Brazilian tensile strength or P-wave velocity),

Table 4. Regression equations coefficients for estimating the mechanical properties of the samples after 50 cycles of salt crystallization test from Eq. (3) and the results of statistical tests

Equation code no.	Estimates mechanical property	Estimator	Coefficient	Coefficient of multiple determination (R^2)	Standard error of estimate (SEE)	F-ratio	Tabulated F-ratio
E1	UCS (MPa)	Constant	18.84	0.947	2.58	80.02	4.26
		UCS_0 (MPa)	0.604				
		n (%)	–2.63				
E2	BTS (MPa)	Constant	1.45	0.975	0.16	176.35	4.26
		BTS_0 (MPa)	0.648				
		n (%)	–0.22				
E3	V_P (m/s)	Constant	–1797.08	0.943	200.57	75.02	4.26
		V_{P0} (m/s)	1.206				
		n (%)	–129.51				

UCS: uniaxial compressive strength; BTS: Brazilian tensile strength; V_P: P-wave velocity

n is the porosity of the fresh sample, α_0 is a constant, and α_1 and α_2 are the regression coefficients of M_0 and *n*, respectively.

The data given in Tables 2 and 3 were analyzed using the SPSS® v.16 code statistical software. The results of these analyses are given in Table 4.

The degree of fit to a curve can be measured by the value of the coefficient of multiple determination (R^2), which measures the proportion of variation in the dependent variable and the standard error of estimate (SEE), which is an important measure for indicating how close the measured data points fall to the estimated values on the regression curve, are given in Table 4 for each mechanical property determination of sample due to salt crystallization.

The R^2 of equations E1, E2 and E3 given in Table 4 is higher than 0.943 that is at acceptable level. The SEE value for equations E1, E2 and E3 is 2.58, 0.16 and 200.57, respectively. These measures show that the above mentioned equations can be accepted as a highly reliable estimate for the mechanical properties after 50 cycles of salt crystallization test with the coefficients given in Table 4.

To test the global usefulness and the significance of equations, analysis of variance for the regressions was also performed. F statistics test is widely used in regression and analysis of variance. The null hypothesis for this test is H_0: $\alpha_1 = \alpha_2 = 0$ against the alternative hypothesis H_1: at least one of α_1 or α_2 is not equal to zero. The results of analysis of variance for the regressions are given Table 4. For a significance level of 5%, the tabulated F-ratio with the degree of freedom $\upsilon_1=2$ and $\upsilon_2=9$ is 4.26. Since all of the F-ratios computed for the equations are quite larger than the tabulated F-ratios, the null hypothesis is rejected. So, it can be concluded that the equations given in Table 4 are appropriate for estimating the mechanical properties of the samples after 50 cycles of salt crystallization test.

The relationship between the measured mechanical properties and the estimated values from the equations given in Table 4 using 1:1 slope line is shown in Fig. 5. A point lying on the line indicates an exact estimation. The figure indicates that the data points fall close to the 1:1 slope line and are scattered uniformly around it, suggesting that the equations E1, E2 and E3 with the suggested coefficients are appropriate for estimating the mechanical properties of the samples after 50 cycles of salt crystallization test.

1.2. Estimating the mechanical properties at any cycle of salt crystallization test

Eq. (3) can estimate the mechanical properties for 50 cycles of salt crystallization test, and can be extended for estimating the mechanical properties at any other cycles. In Eqs. (1) and (2), we attained simple exponential and linear equations for estimating the mechanical properties of a sample at any cycle (*N*) of salt crystallization test. The unknown in using these equations is decay constant (λ), which is needed to be determined with salt crystallization test for each sample to describe the complete behaviour depending on the test cycles.

M_N in Eqs. (1) and (2) is equal to M_{50} in Eq. (3) for 50 cycles (N=50). By incorporating Eq. (3) with Eq. (1) and Eq. (2), λ can then be found as the following equations, respectively:

$$\lambda = -0.02 \ln\left(\frac{\alpha_0 + \alpha_1 M_0 + \alpha_2 n}{M_0}\right) \quad (4)$$

$$\lambda = \frac{-(\alpha_0 + \alpha_1 M_0 + \alpha_2 n) + M_0}{50} \quad (5)$$

So, incorporating the right-hand side of expression in Eq. (4) instead of λ in Eq. (1), and that of Eq. (5) instead of λ in Eq. (2) results in the following equations, respectively:

$$M_N = M_0\left(\frac{(\alpha_0 + \alpha_1 M_0 + \alpha_2 n)}{M_0}\right)^{0.02N} \quad (6)$$

$$M_N = \left(\frac{(\alpha_0+\alpha_1 M_0+\alpha_2 n\text{-}M_0)}{50}\right)N + M_0 \qquad (7)$$

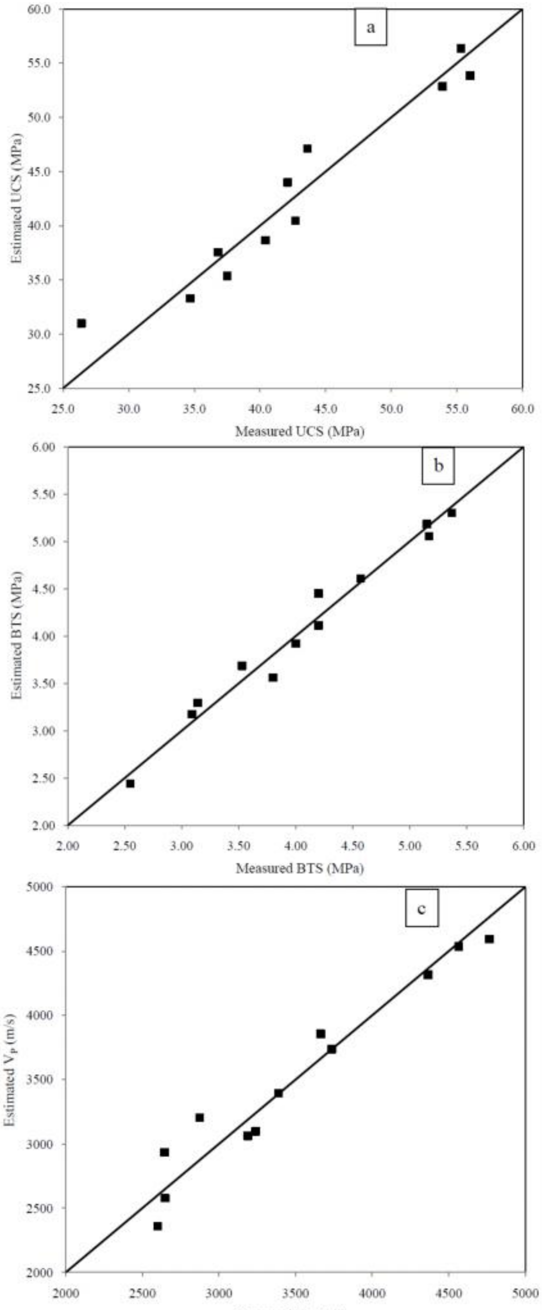

Figure 5. The measured mechanical properties versus the estimated mechanical properties of the samples after 50 cycles of salt crystallization test: (a) the measured uniaxial compressive strength versus the estimated uniaxial compressive strength from Eq. (E1) given in Table 4, (b) the measured Brazilian tensile strength versus the estimated Brazilian tensile strength from Eq. (E2) given in Table 4, and (c) the measured P-wave velocity versus the estimated P-wave velocity from Eq. (E3) given in Table 4.

Eqs. (6) and (7) can estimate the mechanical properties of a travertine at any cycle of salt crystallization test from the known mechanical properties and effective porosity of fresh sample with the coefficients given in Table 4.

The validity of Eqs. (6) and (7) has been established by using the data some marble samples from the western Anatolia, Turkey. Yavuz and Topal [16] subjected 6 different marbles up to 40 cycles of salt crystallization test in a 14% Na_2SO_4 solution and measured their uniaxial compressive strength, Brazilian tensile strength and P-wave velocity. The actual values of these properties in Yavuz and Topal's [16] research and those that we estimated from Eqs. (6) and (7) are given in Table 5 and graphically illustrated in Figs. 6-8.

It can be seen from Figs. 6-8, that the estimated mechanical properties from Eqs. (6) and (7) are in fair agreement with the actual values of mechanical

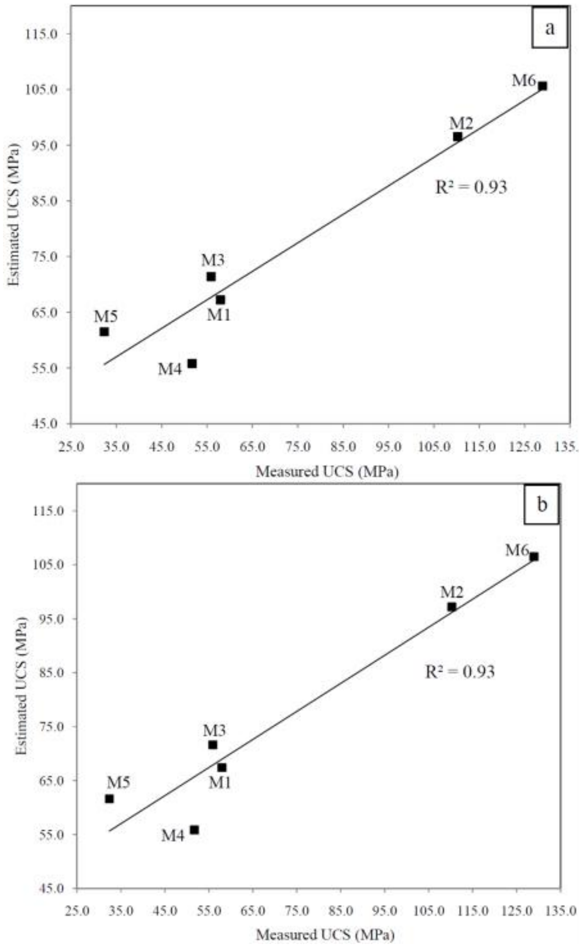

Figure 6. The measured uniaxial compressive strength by Yavuz and Topal [16] versus the estimated uniaxial compressive strength: (a) from Eq. (6) and (b) from Eq. (7).

Table 5. The actual values of mechanical properties from Yavuz and Topal's [16] research and also their estimated values from Eqs. (6) and (7) developed given in this study

Sample no.	Commercial name	Uniaxial compressive strength (MPa)			Brazilian tensile strength (MPa)			P-Wave velocity (m/s)		
		⋆Actual value	Estimated value from Eq. 6	Estimated value from Eq. 7	Actual value	Estimated value from Eq. 6	Estimated value from Eq. 7	Actual value	Estimated value from Eq. 6	Estimated value from Eq. 7
M1	Afyon white	58.0	67.3	67.4	4.50	4.77	4.77	2905	3354	3375
M2	Belevi black	110.3	96.5	97.2	6.86	7.67	7.70	4995	4988	4995
M3	Kemalpasa white	55.9	71.4	71.6	4.67	4.58	4.58	2822	3214	3236
M4	Manyas white	51.7	55.8	55.8	4.59	4.85	4.86	3330	3999	4012
M5	Mugla white	32.3	61.5	61.6	2.95	3.96	3.96	1596	3051	3075
M6	Sedef (Milas)	129.0	105.6	106.5	8.50	6.50	6.51	4693	4819	4827

⋆For 40 cycles of salt crystallization test (Data from Yavuz and Topal[16])

properties found by Yavuz and Topal [16] with an R^2 value of more than 0.81. This result shows that the developed regression equations can be reliably used for estimating the mechanical properties after any cycle of salt crystallization test.

The difference in the actual values of mechanical properties of the marble in Yavuz and Topal's [16] research and those estimated from Eqs. (6) and (7) is probably due to difference in the stone type, physical and mechanical properties of the samples used, the samples' conditions for testing (the dry or saturated state of sample), and the method of testing salt crystallization such as the duration of each salt crystallization cycle.

Moreover, the significant difference in the actual values of mechanical properties of Mugla white (Sample code; M5) and those estimated from Eqs. (6) and (7) is due to the significant reduction in its

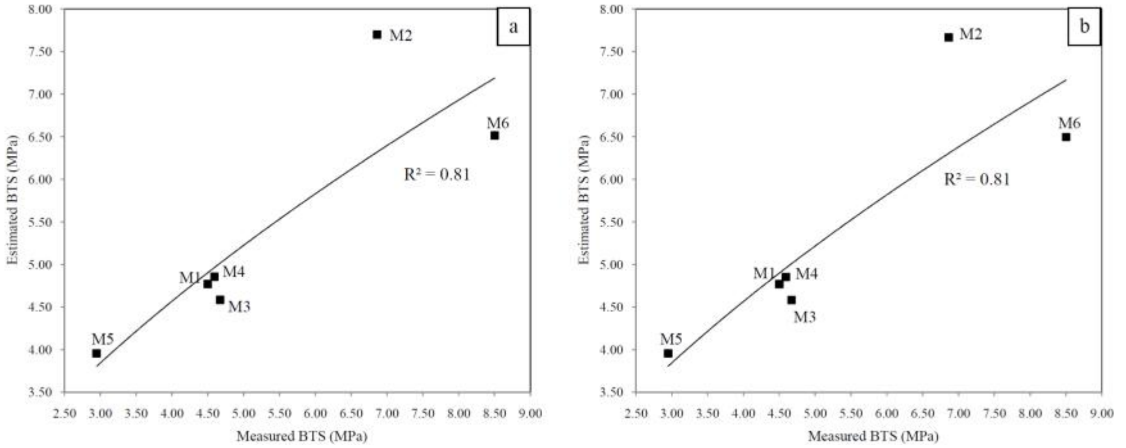

Figure 7. The measured Brazilian tensile strength by Yavuz and Topal [16] versus the estimated Brazilian tensile strength: (a) from Eq. (6) and (b) from Eq. (7)

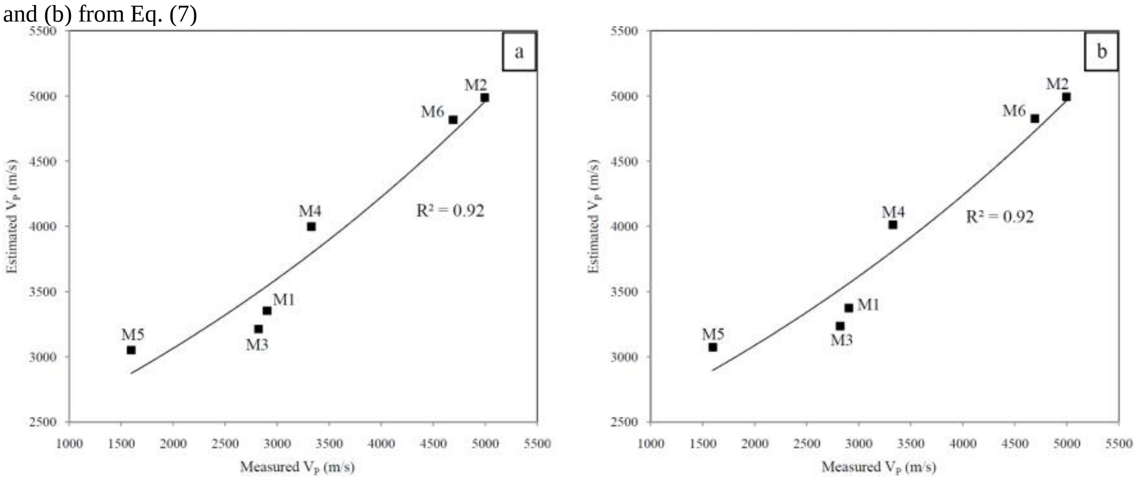

Figure 8. The measured P-wave velocity by Yavuz and Topal [16] versus the estimated P-wave velocity: (a) from Eq. (6) and (b) from Eq. (7)

mechanical properties after salt crystallization test (Table 5).

Conclusion

Salt crystallization test is a well-known test for the mechanical properties and durability assessment of building stones and construction materials. However, performing the salt crystallization test is a very laborious and time-consuming, and there are no regression equations for estimating the mechanical properties at any cycle of this test. In this paper, multivariate regression equations were developed for estimating the uniaxial compressive strength, Brazilian tensile strength, and P-wave velocity of 12 travertine samples at any cycle of salt crystallization test. These equations were extended by incorporating a multivariate regression equation (that only can estimate the mechanical properties for 50 cycles of salt crystallization test) into a simple exponential or linear regression equation. The validity of equations has been established by using the data of a researcher for salt crystallization test.

The results showed that the developed regression equations are in good accuracy for estimating the uniaxial compressive strength, Brazilian tensile strength and P-wave velocity of samples, and thus making a rapid durability assessment. As a result, these equations avoid performing salt crystallization test, which is laborious and time-consuming.

Acknowledgement

The present study was funded by Tarbiat Modares University, Tehran, Iran.

References

1. Bayram F. Predicting mechanical strength loss of natural stones after freeze–thaw in cold regions. *Cold Reg. Sci. Technol.* **83–84:**98–102 (2012).
2. Ghobadi M.H., Babazadeh R., and Khodabakhsh S. Petrophysical and durability tests on sandstones for the evaluation of their quality as building stones using Analytical Hierarchy Process (AHP). *J. Geope*. **4 (1):**25–43 (2014).
3. Jamshidi A., Nikudel M.R., and Khamehchiyan M. Evaluation of the durability of Gerdoee travertine after freeze-thaw cycles in fresh water and sodium sulfate solution. *Eng. Geol*. **202:** 36–43 (2016).
4. Jamshidi A., Nikudel M.R., and Khamehchiyan M. Predicting the long-term durability of building stones against freeze-thaw using a decay function model. *Cold Reg. Sci. Technol*. **92:**29–36 (2013).
5. Jefferson D.P. Building stone: the geological dimension. *Q. J. Eng. Geo.* **26:**305–319 (1993).
6. Benavente D., Garcia del Cura M.A., Fort R., and Ordonez S. Thermodynamic modeling of changes induced by salt pressure crystallization in porous media of stone. *J. Cryst. Growth* **204:**168–178 (1999).
7. Yu S., and Oguchi C.T. Role of pore size distribution in salt uptake, damage, and predicting salt susceptibility of eight types of Japanese building stones. *Eng. Geol.* **115:**226–236 (2010).
8. Buj O., and Gisbert J. Influence of pore morphology on the durability of sedimentary building stones from Aragon (Spain) subjected to standard salt decay tests. Environ. *Earth Sci.* **61:**1327–1336 (2010).
9. Dragovich D., and Egan M. Salt weathering and experimental desalination treatment of building sandstone, Sydney (Australia). *Environ. Earth Sci.* **62:**277–288 (2011).
10. Cultrone G., Luque A., and Sebastián E. Petrophysical and durability tests on sedimentary stones to evaluate their quality as building materials. *Q. J. Eng. Geol. Hydro*. **45:**415-422 (2012).
11. Ghobadi M.H., and Momeni, A.A. 2011. Assessment of granitic rocks degradability susceptive to acid solutions in urban area. *Environ. Earth Sci*. **65:**753–760 (2011).
12. Martínez–Martínez J., Benavente D., Gomez–Heras M., Marco–Castaño L.,and García–del–Cura M.A. Non-linear decay of building stones during freeze–thaw weathering processes. *Constr. Build. Mater.* **38:**443–454 (2013).
13. Ghobad M.H., and Babazadeh, R. Experimental Studies on the Effects of Cyclic Freezing–Thawing, Salt Crystallization, and Thermal Shock on the Physical and Mechanical Characteristics of Selected Sandstones. *Rock Mech. Rock Eng*. **48:**1001–1016 (2015a).
14. Ghobadi,M.H., and Babazadeh R. An investigation on the effect of accelerated weathering on strength and durability of Tertiary sandstones (Qazvin province, Iran). *Environ. Earth Sci.* **73:** 4237–4250 (2015b).
15. Momeni A., Khanlari G.R., Heidari, M., Bagheri, R., and Bazvand E. Assessment of physical weathering effects on granitic ancient monuments, Hamedan, Iran. *Environ. Earth Sci*. **74:** 5181–5190 (2015).
16. Yavuz A.B., and Topal T. Thermal and salt crystallization effects on marble deterioration: Examples from Western Anatolia, Turkey. *Eng. Geol*. **90:**30–40 (2007).
17. Angeli M., Heber R., Menendez B., David C., and Bigas J.P. Influence of temperature and salt concentration on the salt weathering of a sedimentary stone with sodium sulphate. *Eng. Geol.* **115:**193–199 (2010).
18. Akin A., and Ozsan A. Evaluation of the long-term durability of yellow travertine using accelerated weathering tests. *Bull. Eng. Geol. Environ*. **70:**101–114 (2011).
19. Mutluturk M., Altindag R., and Turk G. A decay function model for the integrity loss of rock when subjected to recurrent cycles of freezing–thawing and heating–cooling. *Int. J. Rock Mech. Min. Sci.* **41:**237–244 (2004).
20. Vazquez P., Alonso F.J., Carrizo L., Molina E., Cultrone G., Blanco M., and Zamora I. Evaluation of the petrophysical properties of sedimentary building stones in order to establish quality criteria. *Constr. Build. Mater.* **41:**868–878 (2013).
21. ISRM. Rock characterization testing and monitoring.

ISRM suggested methods. In: Brown ET (ed), Pergamon Press, Oxford, pp 211 (1981).

22. EN 12370. Natural stone test methods - Determination of resistance to salt crystallization. *European Committee for Standardization* (1999).