Petrophysical and durability tests on sandstones for the evaluation of their quality as building stones using Analytical Hierarchy Process (AHP)

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Abstract
Due to their widespread availability, sandstones are commonly used as a natural stone for buildings, monuments and sculptures. In the current study, nine sandstone samples from the Upper Red Formation (specified by the letters A, B, C, CG, S, S1, Sh, Tr and Min) were studied from a petrophysical point of view and their durability was evaluated. Then, their suitability as building stones was assessed using an AHP model. Laboratory tests, including polarizing optical microscopy, hydric tests, ultrasound, uniaxial compressive strength, salt crystallization cycles, freeze–thaw cycles and slake durability index tests, were performed. Accelerated ageing tests caused some changes in the dry weight, P-wave velocity, slake durability index and uniaxial compressive strength, especially during salt crystallization cycles. The results from our laboratory investigations show that sandstones from the same stratigraphic layer can show major differences in their petrophysical and weathering properties. These differences result from their different diagenesis (causing varying pore space, water balance and strength properties) and also from the mineralogical composition. In the next stage of this study, an AHP model was developed to classify the qualities of sandstones according to their physical and mechanical properties, and also their resistance against weathering processes. Seven primary-level criteria, including uniaxial compressive strength, strength reduction factor (R), Initial porosity, weight loss (%) in salt crystallization test, Id_{15} under salt crystallization test, main grain contact type and main mineralogical composition, and 23 secondary level criteria were selected as input parameters. Results showed that the AHP model can considerably predict the suitability of building stones. Of the analysed sandstones, samples B and C are very suitable for construction purposes because of their good strength properties (high compressive and tensile strength, low softening degree) as well as their low porosity. Furthermore, samples Tr, S and S1 are very unsuitable sandstones for use in construction due to their high number of lithoclasts, high porosity and low compressive and tensile strength.

Keywords: *sandstone, Upper Red Formation, building stone, ageing test, AHP.*

Introduction

Sedimentary rocks such as sandstones have been part of many architectural heritages and their look and characteristics depend on their source material, transport processes and mineralogical composition, as well as the depositional environment and diagenesis to which the sediments were subjected (Cultrone *et al*., 2012). Therefore, it is necessary to acquire detailed information on sedimentological, petrographical and petrophysical parameters of sedimentary stones to predict their properties during construction (Morales Demarco *et al.,* 2007; Rudrich *et al*., 2010). Sandstones' weathering phenomena were extensively investigated by different researchers and their physical, mechanical and mineralogical properties were studied in detail. Based on these studies, it was found that the pore space, such as porosity, permeability and pore geometry, are very important for the weathering behaviour of porous sandstones (e.g., Putnis *et al*., 1995; Putnis & Mauthe, 2000; Rudrich *et al*., 2010). The response of natural building stones to environmental conditions is mainly controlled by their characteristics and also the weathering environment (Doehne, 2002). The deterioration phenomenon may be relatively rapid in cases in which stones contain one or more minerals with high susceptibility to weathering, or have high permeability or a large number of micro-fissures (Dragovich & Egan, 2011). The increasing emission of pollutants is one of the most important deterioration agents of building stones in industrial society (Siegesmund & Snethlage, 2011). In such conditions, the acid-forming sulphur compounds penetrate into the microstructure of the stones and then become precipitated as sulphate-rich salts (especially gypsum enrichment) and are responsible for the many observable damages. Also, it has been shown that pollution levels (especially sulphur dioxide) are different in urban and rural atmospheres and that these differences cause different weathering rates. The destructive effects of different salt solutions were investigated and compared with each other by different researchers

(Goudie & Viles, 1997; La Iglesia *et al*., 1997; Rothert *et al*., 2007; Ruiz-Agudo *et al*., 2007; Yu & Oguchi, 2010). These studies showed that sodium sulphate solutions have considerable influence on the porous materials compared with other salts. Another relevant process is freeze-thaw action, which can deteriorate building stones in cold regions. The mechanisms which lead to ice formation from solution are well known. This process consists of stages including nucleation and crystal growth (Chahall & Miller, 1965). When the stresses resulting ice crystallization within the rock fabric exceed tensile strength, different types of deterioration can be identified. Therefore, the exact weathering behaviour of a natural stone has to be defined in terms of structural and engineering qualifications before their selection as building material (Siegesmund & Snethlage, 2011). The main goal of this study was to study the petrophysical characteristics and durability of sandstones collected from the Upper Red Formation (Miocene in age) to evaluate their durability and to establish a ranking order on the basis of their quality. This study was performed in three stages, as follows:

1- In the first stage of the study, field observations have been made and representative fresh sandstone samples have been collected from quarries. Then thin sections were provided and mineralogical compositions and texture characteristics were determined.

2- In the second stage of the study, accelerated weathering tests such as Na_2SO_4 salt crystallization and freezing–thawing were carried out on the fresh sandstone. Changes occurred in physical and mechanical properties, including weight loss (%) and loss in P-wave velocity (%). Then, changes in point load strength and Brazilian tensile strength were measured in different cycles and macroscopic evidences such as deterioration forms were documented. Additionally, durability of the sandstones under study were assessed using the slake durability indices under wet, freeze-thaw and salt crystallization actions.

3- In the final stage of the study, the analytical hierarchy process (AHP) and weighted linear combination (WLC), as two techniques of multi-criteria evaluation, were used to construct a model for determining the usability of Upper Red Formation sandstones as building stones. For this purpose, seven primary-level criteria, including uniaxial compressive strength, strength reduction factor (R), initial porosity, weight loss (%) in salt crystallization test, Id_{15} under salt crystallization test, main grain contact type and main mineralogical composition, and 23 secondary-level criteria were selected as input parameters. The main goal of this model is to propose a simple and acceptable method to determine the sandstone's usability as building stone. This method is based on simple laboratory tests and can be used as an appropriate tool in practical projects.

Materials and methods

Representative sandstone blocks were collected from different parts of the Upper Red Formation (Fig. 1).

More than 300 test samples were prepared from the sandstone blocks in the laboratory to determine their material and durability properties. The laboratory tests on the physico-mechanical properties of the fresh sandstone samples included dry and water-saturated unit weight, effective porosity, water absorption by weight, dry and water-saturated sonic velocities, dry and water-saturated uniaxial compressive strength (UCS), point load strength index (Is_{50}), indirect (Brazilian) tensile strength and slake durability test. In order to characterize the petrographical properties, thin sections were prepared from fresh sandstones and their mineralogical and textural characteristics were determined under a microscope. Additionally, accelerated weathering tests such as Na_2SO_4 salt crystallization, freezing-thawing test and slake durability index test on samples subjected to salt crystallization and freeze- thaw were carried out. Changes that occurred in physico-mechanical properties and slake durability index were measured during and after each ageing test.

Mineralogical and petrographical characteristics of the sandstones under study

The assessment of the geological setting of sandstones is necessary during their selection process as construction materials. The petrophysical properties, mineralogical composition and weathering behaviour of natural building stones are influenced by geological conditions. In the current study, thin sections were used to determine the mineralogy and the petrological features influencing the weatherability of sandstones. Based on this study, it was found that calcite grains and

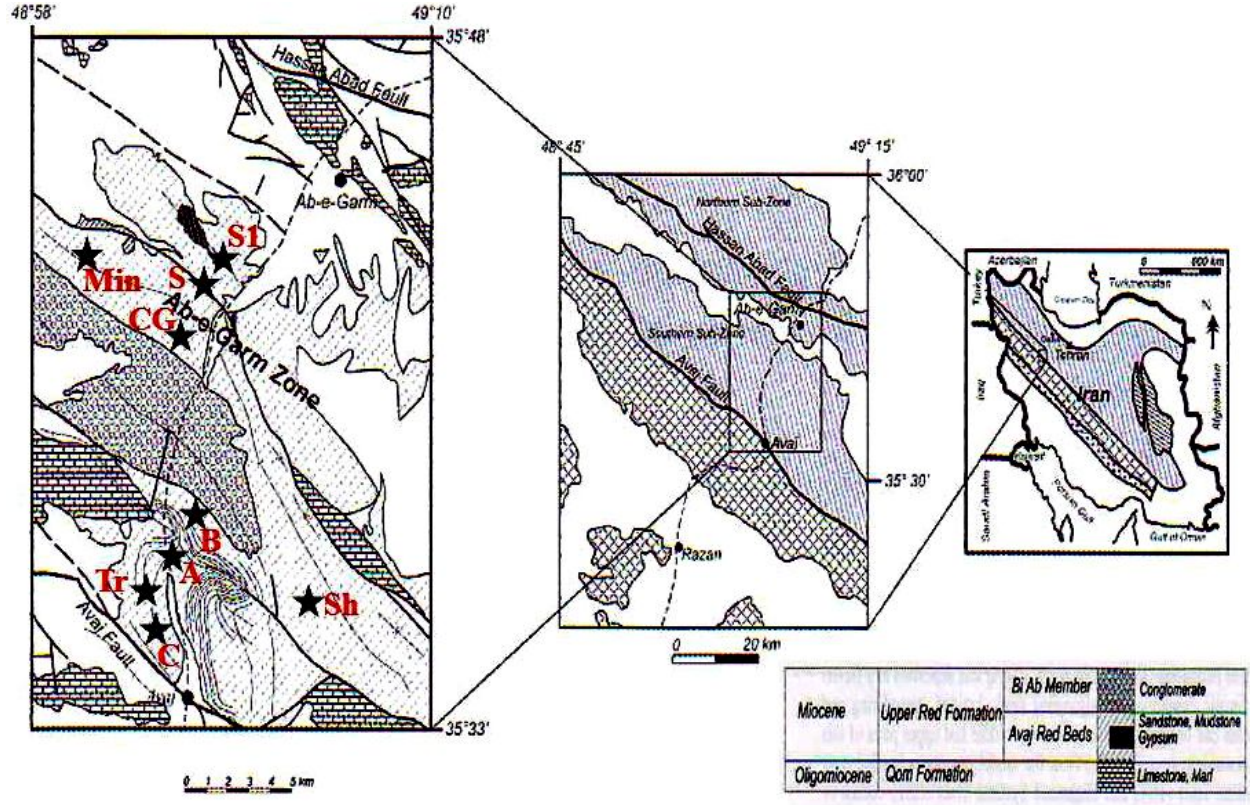

Figure 1: Simplified geological map of the studied area and the location of sampling points

Table 1: Results of petrographic analysis of sandstones under study

sandstone	Modal composition (%)										Sandstones class Folk (1986)
	Quartz	Feldspar	Lithic Fragments					Cement		Main grain contact type	
			Calcite grains	metamorphic	volcanic	plutonic	chert	carbonate	Iron oxide		
A	19.2	4.6	53.2	5.4	12.6	-	-	5	-	Lo	calclithite
B	13.8	4.2	45.1	6.4	27.5	-	-	1	2	Co-Co	calclithite
C	29	8.5	32	15.5	9.5	-	-	5.5	-	Co-Co	calclithite
CG	5	6	60	11	11	-	4	3	-	Lo	calclithite
S	15.5	5	10	53	8.5	7	-	1	-	Lo	pyhllarenite
S1	19.5	6	6	23.5	8.5	24	8	4.5	-	Lo	pyhllarenite
Sh	17.5	4	55.5	12	6.5	-	-	4.5	-	Co-Co	calclithite
Tr	22	6.5	44.5	19.5	6.5	-	-	1	-	Lo	calclithite
Min	14.5	3	61.5	13	3.5	-	-	4.5	-	Co-Co	calclithite

rock fragments are major constituents of sandstones (Table 1).

Mineralogical composition and textural properties of the sandstones under study are discussed in detail as follows:

Type A sandstone

The fine-grained, grey sandstones are characterized by some random lamination. This sandstone consists of minerals such as calcite, quartz, feldspars and lithoclasts (Table 1). Based on thin section analysis using a polarization microscope, it has been shown that there are different types of contact between grains, including long (Lo), concave–convex (Co-Co), sutured (Su) and tangential (Ta). However the elongated and concave- convex type of grain contact is more prevalent (Fig. 2). The main cementing material is calcite which is observed in some parts of the thin section under study.

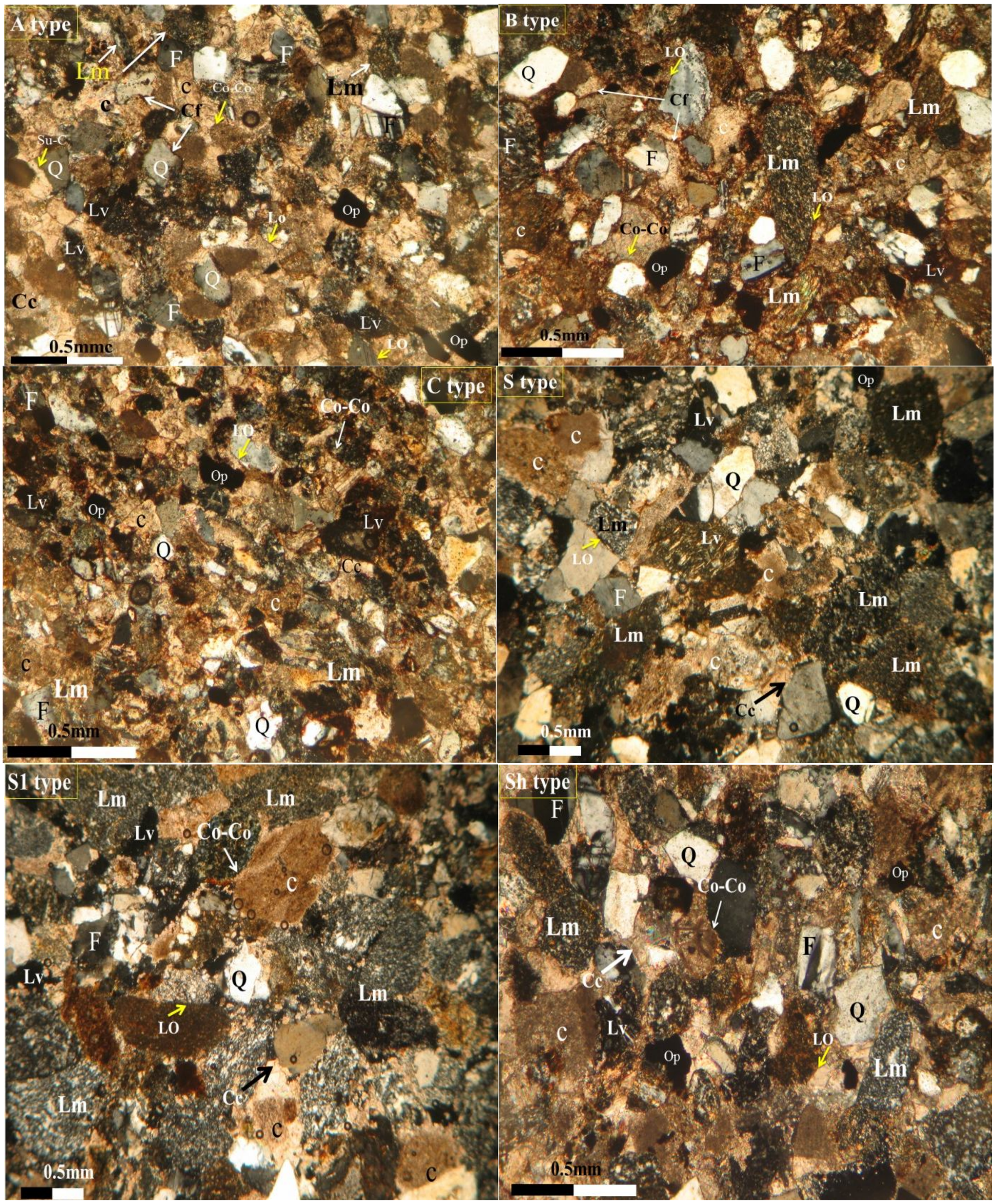

Figure 2: Photomicrographs of composition and texture of sandstones on thin-section (Q: quartz, F: feldspar, Lm: metamorphic lithic fragments, Lv: volcanic lithic fragments, Op: opaque mineral, C: calcite grain, Cf: Ferruginous cement, CC: calcitic cement, Su-c: sutured contact, Lo: long contact, C0-C0: concave-convex contact)

Type B sandstone
The fine-grained sandstones are characterized by a specific light brown colour. There is no lamination or other thin layers. The sandstone consists of about 45 % calcite grains and 30 % rock fragments (Table 1). The grain contact is concave-convex to long. Iron oxide cement was observed in some areas, which is the main cause of the brown colour at macroscopic scale.

Type C sandstone
The fine-grained, red coloured sandstone is macroscopically characterized by thin layers. This sandstone is composed of 32% calcite grains, 29% quartz grains, 25% lithoclasts, 8.5% feldspar and 5% calcitic cement. The prevalent grain contacts are the concave-convex followed by the long type.

Type CG
The grey coloured sandstone is characterized by thin layers of coarse-grained sandstone. The stone is composed of 60% calcite grains. The grains are somewhat rounded to sub-angular in shape. The grain contact is concave-convex.

Type S sandstone
A light yellow–grey, fine- to medium-grained sandstone, which can be easily broken by hand. The sandstone is mainly composed of rock fragments (more than 65%). The most common grain contact is the long type; however, concave-convex is observable in some parts of the thin sections.

Type S1 sandstone
A light yellow-grey, medium- to coarse-grained sandstone, which can be easily broken by hand. This sample is characterized by thin layers of fine-grained sandstone which is in contact with coarse-grained sandstone. Rock fragments are considered major constituents of sandstone. The long type of contact between grains is prevalent.

Type Sh sandstone
A medium-grained, grey sandstone with no macroscopically observable laminations; the stone is composed of 55.5% calcite grains, 17.5% quartz, 18.5% metamorphic and volcanic rock fragments and 4% feldspar. The most common grain contact is the concave-convex type. The main cementing material is calcite, which is observed in some parts of the thin section under study.

Type Min sandstone
These fine- to medium-grained, grey sandstones are characterized by weathering surfaces and cross-bedding. Calcite grains (more than 60%) are prevalent as the sandstone constituent. The most common grain contact is the concave-convex type. The main cementing material is calcite, which is observed in some parts of the thin section under study.

Type Tr sandstone
The medium-grained, grey sandstones are characterized by mass texture (without any observable lamination). Calcite grains (44.5%), metamorphic and volcanic rock fragments (26%), quartz (22%) and feldspar (6.5%) are the major constitutive elements of this sandstone. The most common grain contacts are the long and concave–convex types.

Physical and mechanical properties
In order to determine the physical properties of fresh sandstones, index tests were performed in the laboratory. Test results are given in Table 2. The porosity and density were determined according to the ISRM (1981). The porosities of the investigated sandstones vary between 1.06% and 11.56%. These sandstones also have densities between 20.2 and 25.4 KN/m^3. Among the most important parameters controlling the weathering behaviour of stones are strength properties, such as tensile strength and compressive strength. This is because the stresses induced by mechanical weathering processes have to exceed the strength of a material for failure to occur. Thus, these parameters can be considered a measure for the grain fabric cohesion (Graue *et al*., 2011). Indirect Brazilian tensile test were performed on disc-shaped specimens (with the diameter-to-height ratio of 0.5-0.75). The tensile strength varies between 1.21 and 18.25 MPa. The uniaxial compressive test was performed on cylindrical samples (height/diameter: 2.5-3) with coplanar end faces (with accuracy of 0.1%) in the dry and water-saturated state. During the test, the load was applied to the end faces of the specimen with a strain rate of 1,000 N/s until failure. The compressive strength varied between 11.82 and 170.16 MPa (Table 3).

Table 2: Physical properties of the fresh sandstones and standards used for testing

test	Standard	Sandstone samples								
		A	B	C	CG	S	S1	Sh	Min	Tr
Dry unit weight (KN/m^3)	ISRM (1981)	23.94	25.41	25.02	23.54	20.21	20.40	24.92	25.31	22.96
Water saturated unit weight (KN/m^3)	ISRM (1981)	24.62	25.51	25.31	24.33	21.39	21.48	25.11	25.60	23.74
Effective porosity (water) (%)	ISRM (1981)	6.65	1.06	2.54	7.23	11.56	11.13	2.89	3.04	8.28
Water absorption by weight-atmospheric pressure (%)	ISRM (1981)	2.73	0.41	1	3.01	5.62	5.35	1.14	1.18	3.54
Ultrasonic P wave velocity (dry) (m/s)	ISRM (1981)	3444.19	4621.59	3654.03	2926.05	1342.19	1726.49	3439.71	3504.64	2484.80
Ultrasonic P wave velocity (wet) (m/s)	ISRM (1981)	3490.45	4781.86	4080.01	3173.84	1088.66	1429.55	3901.80	3965.61	2724.86

Table 3: Mechanical properties of the fresh sandstones and standards used for testing

test	Standard	Sandstone samples								
		A	**B**	**C**	**CG**	**S**	**S1**	**Min**	**Tr**	**Sh**
Uniaxial compressive strength (dry) (MPa)	ISRM (1981)	98.8	169.4	135.8	109	33.75	11.82	170.16	57.66	123.68
Uniaxial compressive strength (sat) (MPa)	ISRM (1981)	45.6	146.2	103.5	60.53	13.7	3.6	85.06	24.6	74.45
Point load strength index. Is_{50} (dry) (MPa)	ISRM (1985)	4.15	9.34	7.9	6.2	1.23	0.9	8.72	3.88	7.7
Point load strength index. Is_{50} (sat) (MPa)	ISRM (1985)	2.8	7.96	6.16	3.17	0.7	0.48	5.89	1.21	4.25
Indirect tensile strength (Brazilian test) (dry) (MPa)	ISRM (1981)	6.44	18.25	13.33	7.98	1.89	1.21	16.02	6.3	13.54
Indirect tensile strength (Brazilian test) (sat) (MPa)	ISRM (1981)	4.06	13.8	10.62	3.1	0.91	0.63	9.32	1.89	7.33
Strength reduction factor; $R=UCS_{wet}/UCS_{dry}$	Jeng *et al.*, 2004	0.46	0.86	0.76	0.56	0.41	0.30	0.51	0.43	0.60

Laboratory weathering tests

There are different types of weathering mechanisms which control the actual state of the building stones. Generally, these mechanisms can be divided into chemical, physical and biological processes. However, these processes overlap each other and lead to deterioration in stone. In order to determine the resistance of sandstones to weathering agents, freezing-thawing and salt crystallization were simulated and accomplished in the laboratory.

These tests were performed on the NX-sized cylindrical core samples obtained from the fresh sandstone blocks. These tests are discussed in detail in the following.

Salt attack test

In order to determine the resistance of the investigated sandstone to the crystallization of salt within the pore space, salt attack tests were performed. For this purpose, sandstone samples were saturated with a solution of 14% Na_2SO_4. After 12 h of saturation the samples were placed into an oven (with temperature controlled at 103°C) for 12 h. Then, samples were taken out of the oven and changes in their dry mass were measured. Macroscopic damages were also photographically documented. This experiment was repeated for 20 cycles, and the physical and mechanical properties of the sandstones, including weight loss (%), loss in P-wave velocity, changes in point load strength and Brazilian tensile strength, were recorded in cycles of five, 10 and 20. It should be noted that most samples (except B and C) deteriorated until cycle 10. The changes in sandstone properties are shown in Fig. 3. Most samples showed a slight increase in their dry mass in the initial test cycles, which led to weight loss (%) of less than zero (Fig. 3a). This is because in this stage of the test, crystallization of salt within the pore spaces did not cause any damaging effects. On the other hand, weight loss resulting from deterioration cannot exceed weight increase because of salt precipitation. For the following cycles, a considerable loss in sample weights is observable. The salt crystallization test had a considerable effect on the stability of the sandstone samples and caused different types of deterioration and development of cracks.

Freeze-thaw test (F-T)

It is assumed that alternating freezing and thawing cycles are the major factors responsible for most deterioration damages in natural building stones during winter (Ruedrich *et al*., 2011). In order to check the frost resistance of building materials such as stone breaks, etc., freeze-thaw test can be used. In the current study, freezing-thawing tests were performed using domestic water to assess the durability of sandstones by determining their physical and mechanical properties during the test.

For this purpose, saturated sandstone specimens were placed into a freezer and were conditioned at a temperature of -20°C for 12 h. Then, they were taken out of the freezer and placed into a water bath at 20°C for 6 h to be thawed. Every cycle takes 18 h to become complete. Changes in physical and mechanical characteristics of samples (including weight loss (%), changes in wave velocity, Brazilian tensile strength and point load strength) were checked in cycles 15, 30 and 60 and the presence of any macroscopic changes was recorded. The changes in these parameters are shown in Figure 4.

Slake durability index test under accelerated conditions

The ability of rock to resist against weathering agents and to retain its original size, shape, strength and appearance over an extensive period of time is described by the slake durability index (Id), which is calculated through the slake durability test in two cycles (Bell, 1993). This test was performed by different researchers in acidic, basic and salt solutions (Ghobadi & Mousavi, 2012; Singh *et al*., 2005; Gupta & Ahmed, 2007; Ghobadi & Momeni, 2011). The results of such experiment, taken together, have indicated that not only mineral composition (texture, strength, etc.), but also the characteristics of solution (or environmental effects) can considerably influence the slake durability index of rocks. Dhakal *et al*. (2002) investigated the effect of aqueous solutions with dissolved electrolytes of NaCl and $CaCl_2$ on the slake durability of pyroclastic rocks, tuffaceous sandstone and mudstone, and concluded that the type of dissolved electrolyte and its concentration in the aqueous solution can considerably affect the measure of the slake durability index. In the current study, in order to investigate the effect of weathering processes on the slake durability index of sandstones, prepared samples were subjected to freeze-thaw and salt crystallization tests and changes in Id were recorded in 15 cycles.

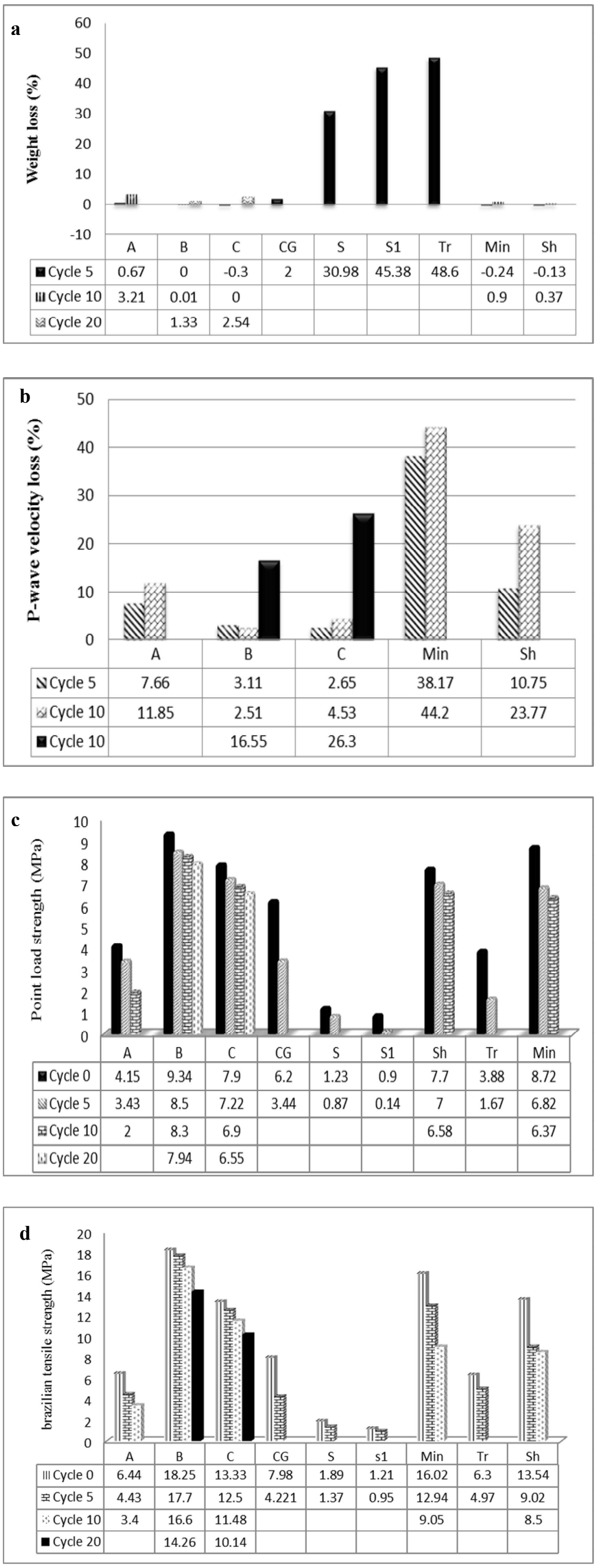

Figure 3. Changes in physical and mechanical properties of sandstones during salt crystallization phenomenon; a) weight loss (%), b) loss in P-wave velocity; c) changes in point load strength; d) changes in Brazilian tensile strength

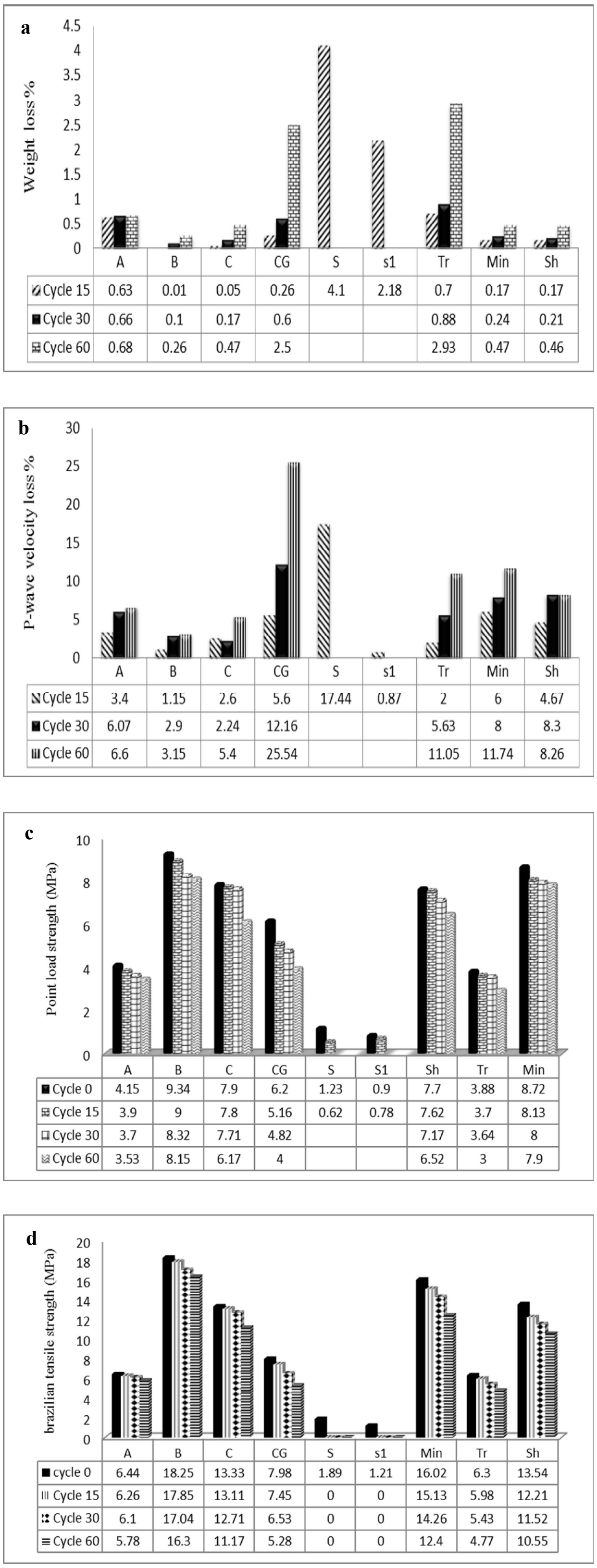

Figure 4: Changes in physical and mechanical properties of sandstones during freeze- thaw action; a) weight loss (%), b) loss in P-wave velocity; c) changes in point load strength; d) changes in Brazilian tensile strength

After completing every freezing-thawing process (cycle), the slake durability test was performed on the samples for 15 cycles and the Id was calculated. To simulate the effects of salt weathering on Id, Na_2SO_4 solutions were also used with concentration values of 14% by weight and the effects on Id were recorded for 15 cycles. The effects of freeze-thaw and salt crystallization on Id are shown in Figure 5.

Analytic Hierarchy Process (AHP)

In this study the analytic hierarchy process (AHP) proposed by Saaty (1980) was used to establish a judgement model, and the sandstones' qualities as building stones were also divided into different classes. The analytic hierarchy process (AHP) is a method which enables people to make the most appropriate choice among many criteria. Therefore, this analysis is used for diverse fields such as earth sciences, medical sciences, biology, social sciences and others (Luria & Aspinall, 2003; Javaheri *et al*., 2006; Kallas *et al*., 2007; Levy *et al*., 2007). This method can be used to analyse criteria which have multiple and even competing objectives (Guiqin *et al*., 2009; Cay & Uyan, 2013). A literature review shows that this method has been commonly used as a powerful tool along with GIS analysis for landfill site selections and landslide risk analysis (Ghobadi *et al*., 2013, Sener *et al*., 2010; Donevska *et al*., 2012, Korucu & Erdagi, 2012, Gorsevski *et al*., 2012, Eskandari *et al*., 2012).

Modelling theory

In order to perform a pairwise comparison process, a matrix is generated and criteria weights are reached as a result of these calculations. When comparing the importance of criterion with one another, judgements were expressed verbally by a degree of preference: equally preferred = 1, moderately preferred = 3, strongly preferred = 5, very strongly preferred = 7 and extremely preferred = 9. The numbers 2, 4, 6 and 8 are used to distinguish similar alternatives (Saaty, 1980) (Table 4). The AHP method is composed of the following processes to determine the relative weights of criteria (in this process, n is the number of criteria) (Chakraborty & Banik, 2006; Cayand Uyan, 2013; Uyan 2013).

a. At the first step, a pairwise comparison matrix ($A = n \times n$) must be defined for n objectives assumed for the problem (Eq. 1).

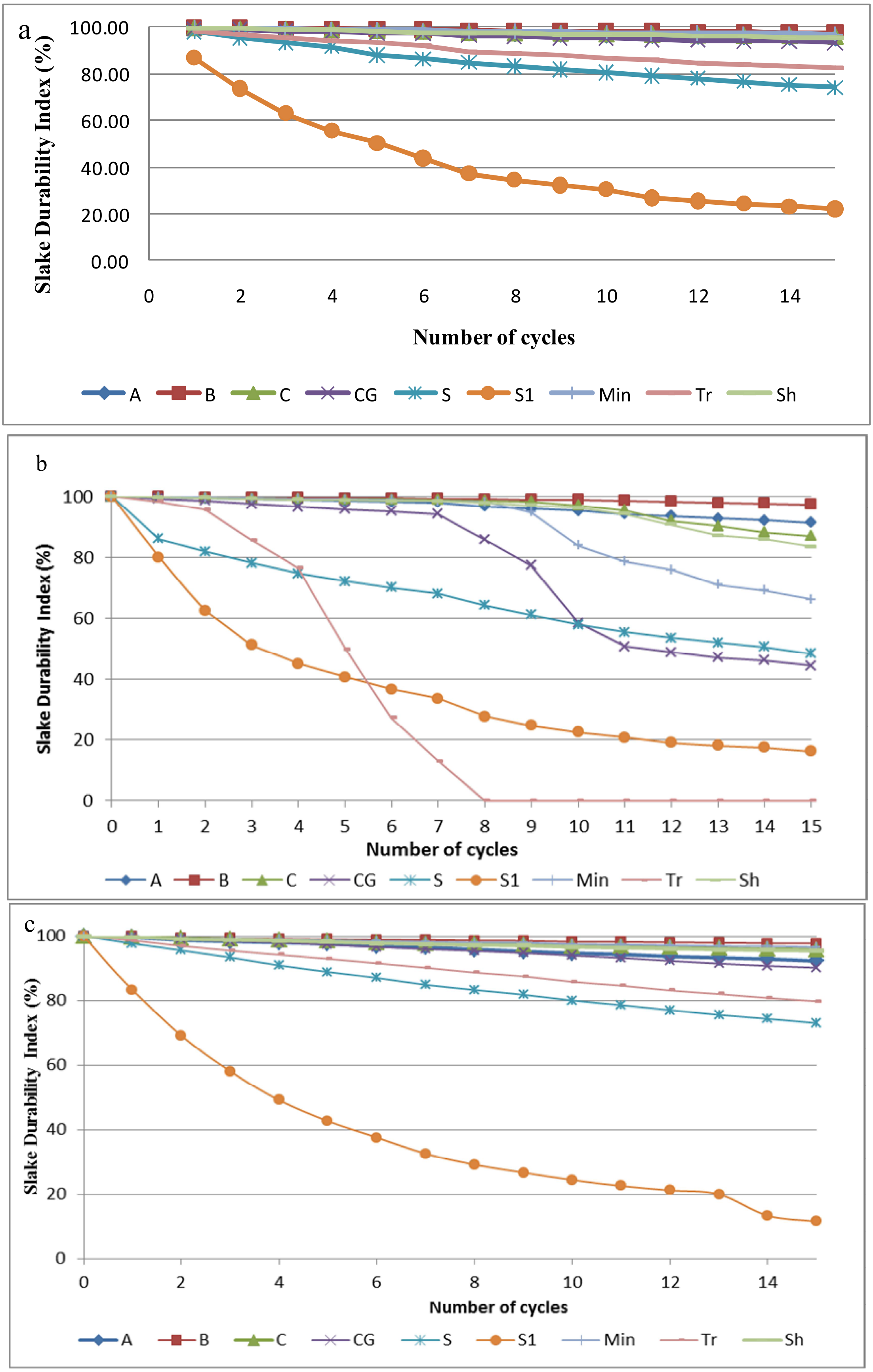

Figure 5: Slake durability index tests: a) standard state (wet state) test; b) salt crystallization test; c) freeze- thaw test

Table 4: The comparison scale in AHP (Saaty, 1980)

Intensity of importance	Definition	Remarks
1	Equal importance	Two activities contribute equally to the objective
3	Weak importance of one over another	Experience and judgment slightly favor one activity over another
5	Essential or strong importance	Experience and judgment strongly favor one activity over another
7	Demonstrated importance	An activity is strongly favored and its dominance is demonstrated in practice
9	Absolute importance	The evidence favoring one activity over another is of the highest possible order of affirmation
2, 4,6,8	Intermediate values between the two adjacent judgments	When compromise is needed
Reciprocals of above nonzero	If activity i has one of the above nonzero numbers assigned to it when compared with activity j, then j has the reciprocal value when compared with i	

$$A=\begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \cdot & & & \cdot \\ \cdot & & & \cdot \\ \cdot & & & \cdot \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix} \qquad (1)$$

During calculation processes, it should be noted that for all i and j, it is necessary that $a_{ii} = 1$ and $a_{ij} = 1/a_{ji}$. In the comparison process, there are nine possible conditions which are shown in Table 4.

b. After defining matrix A and comparing the objectives with each other, each value in column j must be divided by the total of the values in the same column. The total of the values in each column of the new A_w matrix must be 1. This matrix is called the normalized pairwise comparison matrix.

$$A_w=\begin{bmatrix} \frac{a_{11}}{\sum a_{i1}} & \frac{a_{12}}{\sum a_{i2}} & \cdots & \frac{a_{1n}}{\sum a_{in}} \\ \cdots & \cdots & \cdots & \cdots \\ \cdot & & & \cdot \\ \cdot & \cdots & \cdots & \cdot \\ \cdot & & & \cdot \\ \frac{a_{n1}}{\sum a_{i1}} & \frac{a_{n2}}{\sum a_{i2}} & \cdots & \frac{a_{nn}}{\sum a_{in}} \end{bmatrix} \qquad (2)$$

c. In the next step of the AHP process, the c_i is determined by finding the principal eigenvector of the matrix A. The ci can be calculated as the average of the values in row i of A_w and its values show the relative degree of importance (weight) of the ith objective.

$$C=\begin{bmatrix} C_1 \\ \cdot \\ \cdot \\ \\ \\ C_n \end{bmatrix} = \begin{bmatrix} \frac{\frac{a_{11}}{\sum a_{i1}}}{n} + \frac{\frac{a_{12}}{\sum a_{i2}}}{n} + \cdots + \frac{\frac{a_{1n}}{\sum a_{in}}}{n} \\ \cdots \quad \cdots \quad \cdots \quad \cdots \\ \cdot \qquad \qquad \cdot \\ \cdot \quad \cdots \quad \cdots \quad \cdot \\ \cdot \qquad \qquad \cdot \\ \frac{\frac{a_{n1}}{\sum a_{i1}}}{n} + \frac{\frac{a_{n2}}{\sum a_{i2}}}{n} + \cdots + \frac{\frac{a_{nn}}{\sum a_{in}}}{n} \end{bmatrix} \qquad (3)$$

d. At the end of AHP modelling, it is necessary to know whether the pairwise comparison has been consistent. This is to accept the results of the process. For this purpose, the parameter called the consistency ratio (CR) is used. This parameter is a measure of how much variation is allowed and must be less than 10 % (Lane & Verdini, 1989; Saaty, 1999). In order to determine the CR values, the consistency vector (the calculation of A×C matrix) must first be determined. Then, x_i, which is a second and a better approximation to the eigenvector, can be obtained.

$$A\times C=\begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \cdot & & & \cdot \\ \cdot & & & \cdot \\ \cdot & & & \cdot \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix} \times \begin{bmatrix} C_1 \\ C_2 \\ \\ \cdot \\ \cdot \\ C_n \end{bmatrix} = \begin{bmatrix} x_1 \\ x_2 \\ \\ \cdot \\ \cdot \\ x_n \end{bmatrix} \qquad (4)$$

Now it is possible to estimate the $\lambda_{\max}$ (eigenvalue of the pairwise comparison) using the following formula:

$$\lambda_{\max} = \frac{1}{n}\sum_{i=1}^{n}\frac{x_i}{c_i} \quad (5)$$

Then, an approximation of the consistency index (CI) is calculated as follows:

$$CI = \frac{\lambda_{\max} - n}{n-1} \quad (6)$$

Finally, to ensure the consistency of the pairwise comparison matrix, the consistency judgement must be checked for the appropriate value of n by CR (Zou & Li, 2008):

$$CR = \frac{CI}{RI} \quad (7)$$

In this equation, RI is the random consistency index and its values for different numbers of n are shown in Table 5. If CR ≤ 0.10, the degree of consistency is satisfactory. When CR>0.10, it shows that there are serious inconsistencies. In this case, the AHP may not yield meaningful results (Chakraborty & Banik, 2006).

Table 5: RI values recommended by Saaty (1980)

n	1	2	3	4	5	6	7	8	9	10
RI	0.00	0.00	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

Discussion

The experimental investigations indicate that there are strong differences between the various rock types in respect to their suitability for construction. This is because their respective depositional environment and geological history are different, which has led to variations in the fabric and their petrophysical properties. This study shows that the deterioration of the sandstones was mainly controlled by physical weathering processes such as salt crystallization and freezing-thawing.

Visual assessment of damages during accelerated tests

The arising decay phenomena observed during accelerated tests were classified into the categories of delamination, loss of particles and crustal formation:

a. Delamination: weathering agents acting along discontinuities such as micro-fractures, lamination, etc., can cause a type of deterioration called delamination.

b. Loss of particles: this type of deterioration affects the whole surface of stones. Here, the stone loss was represented by shapes generated from back weathering and relief. Relief is defined for all decay phenomena, which cause a heterogeneous loss of material parallel to the surface.

c. Crustal formation: this includes every change on a rock surface, characterized by the peeling of the rock and includes sanding, flaking and scaling. Sanding is defined as a process in which the displacement of millimetre-sized particles or smaller can be observed. Flaking also means the displacement of loose, small, centimetre-sized particles, which peel parallel to the surface. Sometimes the displacement occurs in a blister-like manner or as a bulging. Large-scale displacement parallel to the surface is defined as scaling (Stuck *et al*., 2011). Furthermore, crustal deformation includes all decay phenomena containing surface accretion of material (this means visually recognizable changes in the rock surface, including biological settling, crusting and efflorescence which can reach a thickness of up to 5 mm) (Fig. 6). Experimental studies show that deterioration patterns are different in shape and intensity, and are also specific for each rock and each weathering agent. For S, S_1 and Tr samples subjected to salt crystallization process, the common decay patterns are a loss of material, slaking and flaking (Fig. 6b). Furthermore, delamination or crack formation is detectable for the A, Min and CG samples (Fig. 6c-d). It should be noted that delamination has occurred in both freezing-thawing and salt crystallization phenomena. In contrast to freezing-thawing action, sandstone subjected to salt crystallization process shows a higher variation in the type of decay. The most common decay types occurring in sandstones under freeze-thaw action are delamination and flaking. Sandstones such as B and C did not show any observable decay during freeze-thaw action, while, after reaching the 15th cycle of the salt attack test, the samples exhibit slaking and flaking (Fig. 6a).

Figure 6: Selected decay phenomena occurred during salt crystallization phenomenon. a) Slaking and flaking (type C sandstone); b) loss of material, slaking and flaking (Tr type sandstone); c) and d) delamination (type A and CG sandstones)

Classification of sandstones' usability as building stones using an AHP model

In this section, an AHP model for the assessment of sandstone usability as building stones was created.

This involves building a hierarchy of criteria and then making comparisons between each possible pair in each cluster (Saaty, 1999). This gives a relative weight for each criterion within a level of the hierarchy. For this purpose, three levels of criteria are used here: the goal (determining the quality of sandstones) to be achieved, the primary criteria (main factors affecting the sandstones' applications), and the secondary criteria (or sub-criteria which describe the primary criteria).

As the criteria used in this process serve as the performance measures for the application of the AHP model, their selection is critical and important for a decision process (Kim *et al*., 2009). To determine the primary and secondary criteria, different factors related to sandstones' physical and mechanical properties including their durability and resistance against weathering agents were considered. Determination of the mechanical strength properties of natural building stones is one of the most important parameters when deciding their suitability for use under various loads (Eren & Bahali, 2005; Karaca & Onargan, 2008; Cardani & Meda, 1999; Benavente *et al*., 2006). Determination of uniaxial compressive strength (UCS) is particularly important for load-bearing masonry units and pavements. Meanwhile, tensile strength is an important property for applications such as flooring, cladding and roofing with slabs as it is a measure of the ability of a stone to withstand pressure (Dai *et al*., 2010; Vasconcelos *et al*., 2008). Considering these points, the first criterion B_1 of the primary level was determined as uniaxial compressive strength. Studies on sandstones have shown that some of the tertiary sandstones exhibit wetting softening behaviour. This causes sandstones to lose some degree of their initial UCS values in wet conditions. Since the uniaxial compressive strength of wet sandstone (UCS_{wet}) is often lower than that of dry sandstone (UCS_{dry}), a measure R (strength reduction ratio, indicating the reduction of strength due to wetting) is defined as (Jeng *et al*., 2004):

$$R = \frac{UCS_{wet}}{UCS_{dry}} \quad (8)$$

Therefore, the second criterion (B_2) of the primary level was selected as strength reduction ratio (R values). As porosity is one of the most important physical features controlling the deterioration of building stones, the sandstones were classified into two groups to observe the effect of porosity on their deterioration (Akin & Ozsan, 2011): sandstones with porosity values of less than 5% (group A or less porous samples) and sandstones with porosity values of more than 5% (group B or porous samples). Thus, porosity was determined as a third criterion B_3. Salt attack is more aggressive than most other physical weathering processes such as freeze-thaw, heating-cooling and wetting-drying. Thus, it can be used as a measure of durability of porous building materials (Luquer, 1985; Yu & Oguchi, 2010).

Therefore, in order to select appropriate stones for restoration works as well as for new constructions, various forms of salt weathering tests must be performed. Considering these points, weight loss (%) and Id under salt crystallization test were taken as the fourth (B_4) and fifth (B_5) criteria. Fabric parameters determined by thin section analysis include grain contacts as well as mineralogical composition. Laboratory investigations have shown that sandstones containing quartz as a binding material are the strongest, followed by calcite and ferrous minerals; rocks with rock fragments and clayey binding material are the weakest (Vutukuri *et al*., 1974). Also, it is expected that an increase in concave-convex and sutured type contacts result in the strength increase of sandstones (Ulusay *et al*., 1994). Finally, grain contact type and mineralogical composition were determined as the sixth (B_6) and seventh (B_7) criteria respectively. The hierarchical model of the influencing factors is shown in Figure 7.

The judgement matrix of primary- and secondary-level criteria, their relative weight and related CR values are shown in Tables 6 to 14.

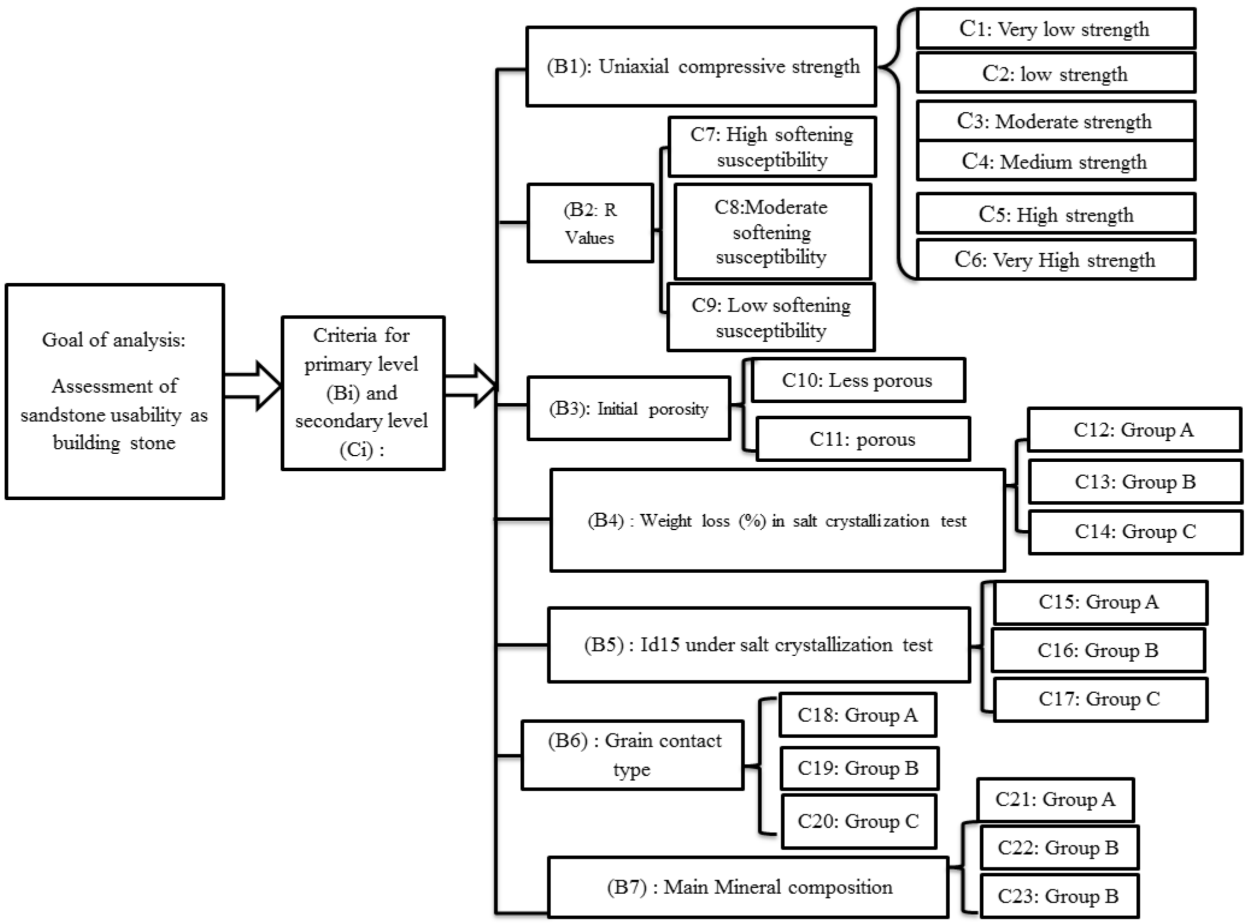

Figure 7: Hierarchical model of the influencing factors

Table 6: Judgement matrix of primary level criteria and their relative weight (CR=0.0076)

	B1	**B2**	**B3**	**B4**	**B5**	**B6**	**B7**	**weight**
B1	1	2	2	3	3	4	4	0.303
B2	0.5	1	1	2	2	3	3	0.184
B3	0.5	1	1	2	2	3	3	0.184
B4	0.33	0.5	0.5	1	1	2	2	0.104
B5	0.33	0.5	0.5	1	1	2	2	0.104
B6	0.25	0.33	0.33	0.5	0.5	1	1	0.060
B7	0.25	0.33	0.33	0.5	0.5	1	1	0.060

The letters at the decision criteria are) B_1: uniaxial compressive strength, B_2: Strength reduction factor (R), B_3: Initial porosity, B_4: Weight loss (%) in salt crystallization test, B_5: Id_{15} under salt crystallization test, B_6: Main grain contact type, B_7: Main Mineral composition

Table 7: The pairwise comparisons matrix and relative weight of the B_1 sub-criteria (CR=0.019)

B1	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**	**weight**
C1	1	0.5	0.33	0.25	0.2	0.17	0.044
C2	2	1	0.5	0.33	0.25	0.2	0.065
C3	3	2	1	0.5	0.33	0.25	0.102
C4	4	3	2	1	0.5	0.33	0.16
C5	5	4	3	2	1	0.5	0.249
C6	6	5	4	3	2	1	0.379

The letters at the decision criteria are) C_1: 1-5 MPa, C_2: 5-25, C_3: 25-50, C_4: 50-100, C_5: 100-250, C_6: >250 MPa

Table 8: The pairwise comparisons matrix and relative weight of the B_2 sub-criteria (CR=0.0034)

B2	**C7**	**C8**	**C9**	**weight**
C7	1	0.5	0.33	0.163
C8	2	1	0.5	0.297
C9	3	2	1	0.539

The letters at the decision criteria are) C_7: high softening susceptibility ($R<0.5$), C_8: Moderate softening susceptibility ($0.5<R<0.75$), C_9: Low softening susceptibility ($0.75<R<1$)

Table 9: The pairwise comparisons matrix and relative weight of theB$_3$ sub-criteria

B3	**C10**	**C11**	**weight**
C10	1	2	0.66
C11	0.5	1	0.33

The letters at the decision criteria are) C_{10}: less porous materials, C_{11}: porous materials

Table 10: The pairwise comparisons matrix and relative weight of the B_4 sub-criteria (CR=0.0034)

B4	**C12**	**C13**	**C14**	**weight**
C12	1	0.5	0.33	0.163
C13	2	1	0.5	0.297
C14	3	2	1	0.539

The letters at the decision criteria are) C_{12}: lose more than 15 % of their weight after the 5th cycle (Group A), C_{13}: lose less than 15 % of their weight until 10th cycle (Group B), C_{14}: Less than 5 % material loss until 20 cycles (Group C)

Table 11:The pairwise comparisons matrix and relative weight of the B_5 sub-criteria (CR=0.0034)

B5	**C15**	**C16**	**C17**	**weight**
C15	1	0.5	0.33	0.163
C16	2	1	0.5	0.297
C17	3	2	1	0.539

The letters at the decision criteria are) C_{15}: Id_{15} = 0-40 % (Group A), C_{16}: 40-80% (Group B), C_{17}: 80-100% (Group C)

Table 12: The pairwise comparisons matrix and relative weight of the B_6 sub-criteria (CR=0.0034)

B_6	C_{18}	C_{19}	C_{20}	weight
C_{18}	1	0.5	0.33	0.163
C_{19}	2	1	0.5	0.297
C_{20}	3	2	1	0.539

The letters at the decision criteria are) C_{18}: point type contact (Group A), C_{19}: long type contact (Group B), C_{20}: concavo–convex and sutured (Group C)

Table 13: The pairwise comparisons matrix and relative weight of the B_7 sub-criteria (CR=0.0034)

B_7	C_{21}	C_{22}	C_{23}	weight
C_{21}	1	0.5	0.33	0.163
C_{22}	2	1	0.5	0.297
C_{23}	3	2	1	0.539

The letters at the decision criteria are C_{21}: Rock fragment (Group A), C_{22}: calcite (Group B), C_{23}: Quartz (Group C)

Table 14: Total weights of the sub-criteria

Criteria	Criteria weight	Subcriteria (SC)	Subcriteria weight(SCwi)	Total weight (Twi)
B_1	0.303	C_1	0.044	0.013
		C_2	0.065	0.020
		C_3	0.102	0.031
		C_4	0.16	0.048
		C_5	0.249	0.075
		C_6	0.379	0.115
		total	1	0.303
B_2	0.184	C_7	0.163	0.030
		C_8	0.297	0.055
		C_9	0.539	0.099
		total	1	0.184
B_3	0.184	C_{10}	0.66	0.121
		C_{11}	0.33	0.061
		total	1	0.184
B_4	0.104	C_{12}	0.163	0.017
		C_{13}	0.297	0.031
		C_{14}	0.539	0.056
		total	1	0.104
B_5	0.104	C_{15}	0.163	0.017
		C_{16}	0.297	0.031
		C_{17}	0.539	0.056
		total	1	0.104
B_6	0.060	C_{18}	0.163	0.010
		C_{19}	0.297	0.018
		C_{20}	0.539	0.032
		total	1	0.060
B_7	0.060	C_{21}	0.163	0.010
		C_{22}	0.297	0.018
		C_{23}	0.539	0.032
		total	1	0.060
total	$\sum_1^7 Cwi = 1$			$\sum_1^7 (Cwi \times SCwi) = 1$

To evaluate the suitability of the sandstones under study, the suitability index (SI) should be calculated for each type. This suitability index provides a total evaluation score for the sandstones and it shows the relative suitability of sandstones for construction purposes. The WLC (weighted linear combination) allows for each criterion to display its potential because of the criteria weights. The advantage of this method is that all criteria contribute to the solution based on their importance (Eastman *et al.*, 1995). The weight (W) of each criterion was calculated as described in the section ‘‘Modelling theory’’ (Tables 6-14). The CR values of all comparisons were lower than 0.10, which shows that the weights were suitable. As a result, the overall score of alternatives and the suitability of the sandstones as building stones were determined by calculating the suitability index (SI):

$$SI = (B_1Cwi \times B_1SCwi) + (B_2Cwi \times B_2SCwi) + ... + (B_7Cwi \times B_7SCwi) \quad (9)$$

where Cwi and SCwi are the criteria weight index and the sub-criteria weight index, respectively.

Tables 15 and 16 show the suitability index (SI) ranges and its values obtained using Eq. 9 for each sandstone type, respectively. As illustrated in the following tables, the suitability of studied sandstones is divided into five groups, from very low to very high.

Table 15: Suitability index obtained using AHP model

Suitability index (sk)	Usability as building stone
0.16 -0.23	Very low
0.23 -0.30	Low
0.30 -0.37	Medium
0.37 -0.44	high
0.44 -0.51	Very high

Table 16: Classification of sandstones based on their usability as building stone

samples	B_1SC_{wi}	B_2 SC_{wi}	B_3SC_{wi}	B_4SC_{wi}	B_5 SC_{wi}	B_6 SC_{wi}	B_7 SC_{wi}	SK	Usability as building
A	0.16	0.163	0.33	0.297	0.539	0.297	0.297	0.26	Low
B	0.249	0.539	0.66	0.539	0.539	0.539	0.297	0.46	Very high
C	0.249	0.539	0.66	0.539	0.539	0.539	0.297	0.46	Very high
CG	0.249	0.297	0.33	0.297	0.297	0.297	0.297	0.29	Low
S	0.102	0.163	0.33	0.163	0.297	0.297	0.163	0.19	Very low
S1	0.065	0.163	0.33	0.163	0.163	0.297	0.163	0.17	Very low
Sh	0.249	0.297	0.66	0.297	0.539	0.539	0.297	0.39	High
Tr	0.16	0.163	0.33	0.163	0.163	0.297	0.297	0.21	Very low
Min	0.249	0.297	0.66	0.297	0.297	0.539	0.297	0.37	high

Conclusion

Laboratory test results carried out on fresh sandstone samples obtained from the Upper Red Formation (western Iran) have shown that these materials have large variations in porosity, strength and resistance to weathering agents. Thus, a detailed method must be provided before their selection as building material. For this purpose, a simple laboratory programme along with a mathematical model was proposed in the current study. Sandstones were subjected to weathering agents such as freezing-thawing and salt crystallization. Uniaxial compressive strength, point load strength, Brazilian indirect tensile, weight loss and P-wave velocity measured during these phenomena have shown that the salt crystallization test can considerably affect the physical and mechanical properties of sandstones compared to freezing-thawing. The strength of sandstones is important for resistance against weathering, because when the strength of a rock is exceeded the fabric begins to disintegrate. The measured tensile and compressive strength of the Upper Red Formation sandstones depend on some factors such as the porosity, the grain contact and the mineralogical composition. Sandstones such as B and C, with low porosity and concave-convex to sutured grain contacts, exhibit a high tensile and compressive strength, as well as high resistance to weathering processes. In contrast, sandstones such as the S and S1 samples are characterized by highly ductile lithoclasts that do not allow the formation of stable grains necessary for generating a strong granular structure. The findings reported in this paper can be summarized as follows:

1. The strength of the sandstones seems to influence their sensitivity to weathering agents. Sandstones showing low strength, such as the S, S1 and Tr samples, are less resistant than rocks with high strength, like B and C samples.
2. The crystallization of salt in the pore space of the sandstones can considerably weaken them in comparison to freezing-thawing.
3. The AHP may be used to study the main influencing factors affecting sandstone's usability as building material.
4. The main influencing factors may be sequenced from most important to least important as follows:

uniaxial compressive strength, strength reduction factor (R), initial porosity, weight loss (%) in salt crystallization test, Id_{15} under salt crystallization test, main grain contact type and main mineralogical composition.

5. Results obtained from the proposed AHP model showed that the studied sandstones have different suitability classes, from very low to very high. Samples like S, S1 and Tr were shown to be very unsuitable materials for construction, while B and C sandstones have very high suitability for use as building stones.

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