An Investigation of the Effect of Freezing on Strength and Durability of Dimension Stones Using Fuzzy Clustering Technique and Statistical Analysis

R. Mikaeil[1]*, A. Dormishi[2], G. Sadegheslam[1], S. Shaffiee Haghshenas[3]
1- Dept. of Mining and Metallurgy, Urmia University of Technology, Iran
2- Nour Branch, Islamic Azad University, Iran
3- Young Researchers and Elite Club, Rasht Branch, Islamic Azad University, Iran

* Corresponding Author: *reza.mikaeil@gmail.com*
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Abstract

Western and North-Western regions of Iran feature very cold winters, a lot of snow, and freezing temperatures during most nights in December, January, February, and March. This directly influences the selection and applications of dimension stones in these areas. Freezing influences both mechanical and physical properties of rocks. Therefore, measuring the changes in values of these parameters before and after freezing can be used to study the effects of freezing on rocks. The main objective of this study is to investigate the effect of freezing on the strength and durability of dimension stones. In this research, fourteen types of frequently utilized stones in North-Western parts of Iran were studied. Five freezing and thawing cycles were done on prepared cores. The results of statistical analysis showed that the uniaxial compressive strength and durability of stones respectively reduced by 7.99% and 1.07% after freezing. The uniaxial compressive strength reduced by 3.03% and durability by 0.6% in the case of the best stone. Using the fuzzy clustering technique, all rocks were classified in two separate clusters according to their properties and the reduction rate of uniaxial compressive strength and durability before and after freezing.

1. INTRODUCTION

Dimension stones are widely used in buildings and urban spaces. Outdoor usage is among their important and sensitive utilizations. The processed or raw stones are used in façade of buildings, long and high stony walls, yard floor, path ways and parks. In all of these cases, stones are environmentally exposed, hence influenced by the climate conditions. Investigations of these impacts are critical in stone engineering. Many studies have been conducted on various fields related to the properties and applications of dimension stones including their production rate prediction, wear rate assessment, and energy consumption modeling. These studies are summarized in Table 1.

Western and North-Western regions in Iran feature very cold winters, a lot of snow, and freezing temperatures during most nights in December, January, February, and March. This directly influences the selection and applications of dimension stones in these areas. Freezing influences both mechanical and physical properties of rocks. Therefore, measuring the changes in values of these parameters before and after freezing can be used to study the effects of freezing on rocks. As Table 1 also conveys, uniaxial compressive strength is one of the most important engineering properties of rocks.

Table 1. Literature review of sawability studies.

Researchers	UCS	BTS	YM	IS	SS	BS	H	A	D	Gs	Qc
Burgess (1978) [1]										●	●
Wright and Cassapi (1985) [2]	●	●					●	●			●
Birle and Ratterman (1986) [3]							●				
Jenning and Wright (1989) [4]	●	●					●				●
Clausen et al. (1996) [5]										●	●
Wei et al. (2003) [6]	●						●	●			●
Eyuboglu et al. (2003) [7]	●	●	●				●				
Ersoy and Atici (2004) [8]	●	●	●	●	●	●	●	●	●	●	●
Kahraman et al. (2004) [9]	●	●		●			●	●			
Gunaydin et al. (2004) [10]	●	●		●							
Ozcelik et al. (2004) [11]	●	●	●				●		●		●
Buyuksagis and Goktan (2005) [12]	●	●					●	●			●
Ersoy et al. (2005) [13]	●	●	●	●	●	●		●	●		●
Delgado et al. (2005) [14]							●				●
Kahraman et al. (2005) [15]					●						●
Fener et al. (2007) [16]	●	●		●			●	●			
Kahraman et al. (2007) [17]	●	●							●		●
Ozcelik (2007) [18]	●	●					●				●
Tutmez et al. (2007) [19]	●	●		●			●	●			
Buyuksagis (2007) [20]	●	●				●	●	●	●		●
Mikaeil et al. (2008) [21]	●										●
Mikaeil et al. (2011) [22]	●	●	●				●	●		●	●
Mikaeil et al. (2011) [23]	●	●					●	●			
Ataei et al.(2011) [24]	●	●					●	●			
Mikaeil et al. (2011) [25]	●	●									
Mikaeil et al. (2011) [26]	●	●	●				●	●		●	●
Mikaeil et al. (2011) [27]	●	●	●				●	●		●	●
Mikaeil et al. (2011) [28]	●	●									
Ataei et al.(2012) [29]	●	●					●	●		●	●
Ghaysari et al.(2012) [30]										●	
Mikaeil et al. (2013) [31]	●	●	●				●	●		●	●
Sadegheslam (2013) [32]	●		●					●			●
Mikaeil et al. (2014) [33]	●	●									
Mikaeil et al. (2015) [34]	●	●	●				●	●		●	●

UCS: Uniaxial compressive strength; YM: Young's modulus; BTS: Indirect Brazilian tensile strength; IS: Impact strength; SS: Shear strength; BS: Bending strength; H: Hardness; A: Abrasivity; D: Density; Gs: Grain size; Qc: Quartz content.

It is determined by many characteristics of rocks such as constitutive minerals and their spatial positions, weathering or alteration rate, micro-cracks and internal fractures, density and porosity [35]. The uniaxial compressive strength test is an acceptable and available test that can be used for studying the qualitative parameters such as matrix type and rock cementation [36]. Durability index is a very good method for evaluating rock strength against wetting and drying cycles [37]. According to the nature of these two tests, they can be considered as two quantitative parameters which can be used as suitable indices for studying rock freezing. In this paper, freezing has been considered as the most important reason behind the destruction of dimension stones and its effects on strength and durability of frequently employed stones in the North-Western regions of Iran have been studied.

2. STUDIED MINES

More than 55 types of stones from all over the country are commonly used in construction works in the North-Western regions of Iran but fourteen types are used more frequently. Nice color, good quality, and low cost are the most important reasons for the popularity of these types. Eight of these stones are produced in mines located in the North-Western regions of Iran and the others come from central Iran. Table 2 and Fig. 1 show the name and location of the mines that were studied. The samples of stones were collected from these mines and transferred to laboratory.

3. LABORATORY STUDIES

Regarding the laboratorial studies, firstly, eight standard NX core samples with a length to diameter ratio of 2.5:1 were prepared from each of the main samples of stones. Five cores have been selected for freezing tests and three for testing the natural strength of stones. Then two sets of standard samples were prepared for the durability test of each stone. One set was used for the natural durability test and the second one was preserved for after freezing. After sample preparation, standard tests were completed to measure the strength and durability of stones in natural conditions following the suggested methods by the ISRM [38, 39]. Table 3 shows the uniaxial compressive strength and durability indices of stones in natural conditions.

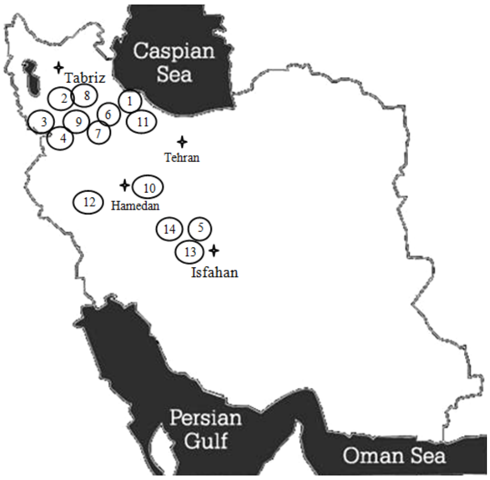

Figure 1. Location map of studied mines.

Table 2. Name and rock types of mines

No.	Name of mine/stone	Rock type
1	Khalkhal	Creamy travertine
2	Walnut	Brown travertine
3	Piranshahr	Olive granite
4	Mahabad	Grey granite
5	Naien	Red granite
6	Bahare	White and pink granite
7	Tekab	White travertine
8	Lemon	Lemon travertine
9	Sardarabad	Red travertine
10	Hamedan	Black granite
11	Khoramdareh	Chocolate granite
12	Harsin	Cream marble
13	Anarak- Chopanan	Cream-Pink travertine
14	Anarak- Haftoman	Cream-Pink marble

Table 3. Uniaxial compressive strength and durability of studied stones in natural conditions.

No.	Name of stones	Uniaxial compressive strength (MPa)	Durability (after 2 cycles) %
1	Khalkhal	50.5	97.69
2	Walnut	48.5	98.87
3	Piranshahr	105.5	99.38
4	Mahabad	189	99.57
5	Naien	177.5	99.72
6	Bahare	121	99.43
7	Tekab	89	98.73
8	Lemon	33	98.43
9	Sardarabad	52.5	99.12
10	Hamedan	173	99.56
11	Khoramdareh	133	99.31
12	Harsin	71.5	98.79
13	Anarak-Chopanan	73	99.14
14	Anarak-Haftoman	74.5	99.42

The second stage of laboratorial studies was the freezing test. All procedures of this test were carried out based on the national Iranian standards [40]. In this method, saturated rock samples were frozen at -15°C for six hours. Afterwards, they were dipped in water at 20°C for six hours. This cycle is repeated for five times. In order to realistically simulate the climate of North Western regions of Iran in laboratory, stones were frozen at -20°C, because according to personal experiences, in about 20 nights during the winter, the temperature of weather is -20°C. Table 4 shows the results of laboratory tests undertaken after freezing tests.

Table 4. The results of laboratory tests undertaken after freezing tests.

No.	Name of stones	Uniaxial compressive strength (MPa)	Durability (after 2 cycles) %
1	Khalkhal	43.5	96.12
2	Walnut	41	97.67
3	Piranshahr	98.5	98.68
4	Mahabad	182.5	98.07
5	Naien	169	98.86
6	Bahare	111.5	98.49
7	Tekab	82.5	97.64
8	Lemon	32	97.29
9	Sardarabad	48	98.18
10	Hamedan	166.5	98.88
11	Khoramdareh	126.3	98.1
12	Harsin	62	97.94
13	Anarak-Chopanan	65.5	98.23
14	Anarak-Haftoman	68	97.93

As shown in Table 4, Mahabad granite has the highest uniaxial compressive strength and Naien and Bahare are the second and third in degrees. Furthermore, Naien, Mahabad and Piranshahr granites have the top three durability indices. Also Lemon travertine has the lowest uniaxial compressive strength and Khalkhal has the lowest durability. In order to evaluate the effects of freezing on uniaxial compressive strengths of rocks, the data illustrated in Tables 3 and 4 were compared in pairs. The comparison between uniaxial compressive strengths of stones before and after freezing is shown in Table 5 and Fig. 2.

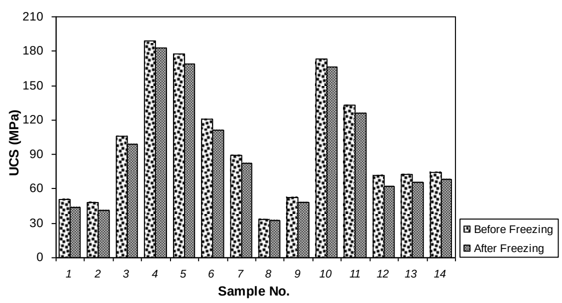

Figure 2. Comparison between uniaxial compressive strength of stones before and after freezing.

Table 5. Comparison between uniaxial compressive strength of stones before and after freezing.

No.	Name	Reduction of Uniaxial compressive strength (MPa)	Reduction Percentage (%)
1	Khalkhal	7	13.86
2	Walnut	7.5	15.46
3	Piranshahr	7	6.63
4	Mahabad	6.5	3.43
5	Naien	8.5	4.78
6	Bahare	9.5	7.85
7	Tekab	6.5	7.3
8	Lemon	1	3.03
9	Sardarabad	4.5	8.57
10	Hamedan	4.5	3.75
11	Khoramdareh	6.67	5.03
12	Harsin	9.5	13.28
13	Anarak- Chopanan	7.5	10.27
14	Anarak- Haftoman	6.5	8.72
		Mean:	7.99

Fig. 3 shows the reduction percentage of uniaxial compressive strengths of stones after freezing in a graphical form. As it is shown in Table 5 and Fig. 3, the reduction of uniaxial compressive strength of stones after freezing changes between 3.03% to 15.46% (mean=7.99%). Walnut travertine experiences maximal and lemon travertine minimal reductions.

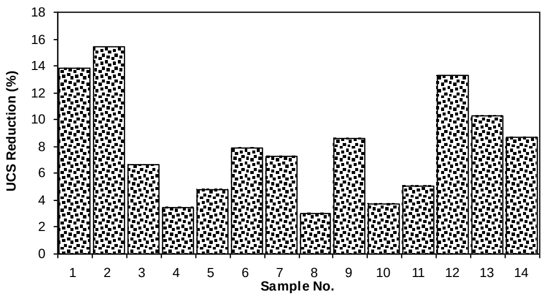

Figure 3. Reduction percentages of the uniaxial compressive strengths of stones after freezing.

According to Tables 3 and 4, the comparison between the durability of stones before and after freezing is shown in Table 6 and Fig. 4.

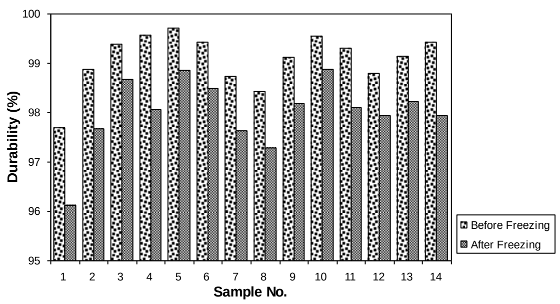

Figure 4. A comparison between durability of stones before and after freezing.

Table 6. A comparison between durability of stones before and after freezing.

No.	Name	Reduction of durability (%)	Reduction Percentage (%)
1	Khalkhal	1.57	1.607
2	Walnut	1.2	1.214
3	Piranshahr	0.7	0.704
4	Mahabad	1.5	1.506
5	Naien	0.86	0.862
6	Bahare	0.94	0.945
7	Tekab	1.09	1.104
8	Lemon	1.14	1.158
9	Sardarabad	0.94	0.948
10	Hamedan	0.68	0.6
11	Khoramdareh	1.21	1.22
12	Harsin	0.85	0.86
13	Anarak- Chopanan	0.91	0.91
14	Anarak- Haftoman	1.49	1.49
		Mean:	1.07

Fig. 5 shows the percentage of reduction in the durability of stones after freezing in a graphical form. As it is shown in Table 5 and Fig. Fig. 5, the minimal reduction witnessed in the durability of stones is 0.6% and the maximal is 1.607%. Also, the average reduction value in durability of stones is 1.07%.

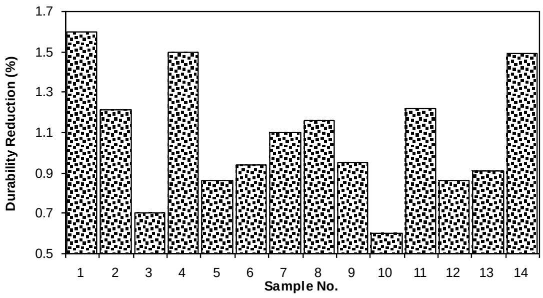

Figure 5. Reduction percentage of the durability of stones after freezing.

4. STATISTICAL ANALYSIS

In order to predict the behavior of stones after freezing cycles, simple regression analysis was administered. For this purpose, the effects of the uniaxial compressive strength and durability on present of the uniaxial compressive strength and durability reduction have been analyzed. Linear, exponential, logarithmic, and power curve fitting approximations were tried and the best approximation equation with the highest correlation coefficient was selected. Fig. Fig. 6 shows the relationship between the uniaxial compressive strength and the reduction of uniaxial compressive strength and durability. A strong relationship was found between uniaxial compressive strength and reduction of uniaxial compressive strength after freezing. As shown in this Fig. Fig. , as uniaxial compressive strength increases, the percentage of reduction decreases exponentially. Also, it shows that the downward slope of the curve in the case of carbonate rocks (including travertine and marble) is more than granite rocks. This means that the impact of freezing in the rocks with high uniaxial compressive strength (more than 90MPa) is comparably less. The equation of the curve is:

$$R_{UCS} = 0.1922e^{-0.009UCS} \quad (1)$$

where R_{UCS} is reduction of uniaxial compressive strength after freezing, in %.

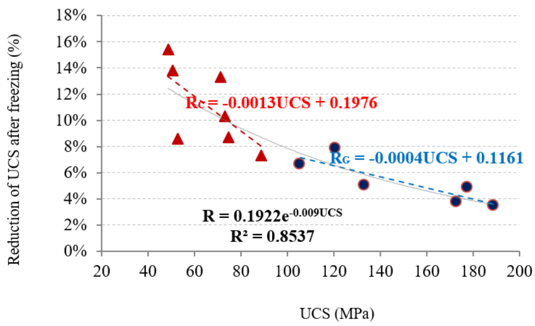

Figure 6. The effects of uniaxial compressive strength on reduction percentage of uniaxial compressive strengths of stones after freezing.

Reduction of durability weakly correlated with uniaxial compressive strength (Fig. 7).

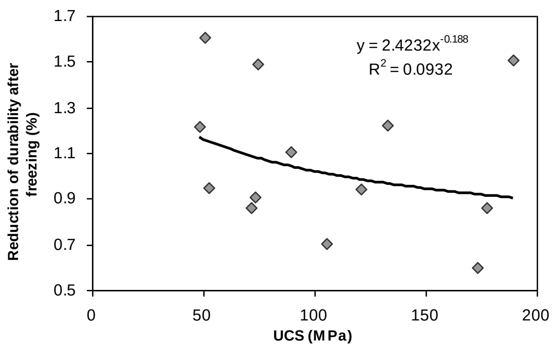

Figure 7. Effects of uniaxial compressive strength on the reduction of durability after freezing.

The relationship follows a power function. It seems that as uniaxial compressive strength increases, the reduction percentage of durability decreases but not with a good R^2 value. The decreasing trend of this relationship is related to the nature of the uniaxial compressive strengths of rocks. The high value of uniaxial compressive strength of stones represents the high quality of rock material and low porosity, high density, and low micro-structural discontinuities. Therefore, the effects of the freezing decrease as uniaxial compressive strength increases. The equation of the curve is:

$$R_d = 2.4232\ UCS^{-0.188} \quad (2)$$

A very weak correlation was found between durability and reduction of durability after freezing (Fig. 8). This relationship follows a power equation. The equation of the curve is:

$$R_d = 7E{+}44UCS^{-22.454} \quad (3)$$

It shows that as durability of the stones increases, the reduction percentage of durability after the freezing process decreases. However, the R^2 of this relationship in very low, but the general trend is clearly decreasing. The main reason behind the weakness of correlation is probably that the durability values of rocks are very similar. Most durability values fall within the range of 97–100%. If a wider range of durability values is included in the study, the correlation may be improved.

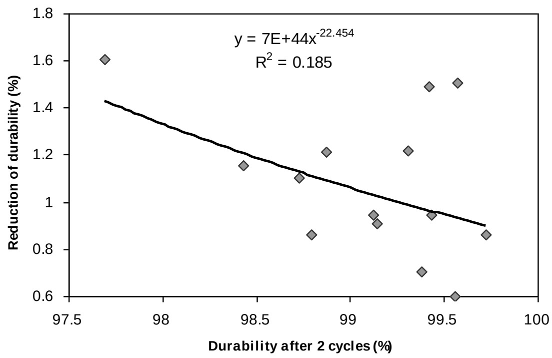

Figure 8. The relationship between the durability and the reduction percentage of durability of stones after freezing.

Finally, in order to find out if there is a significant relationship between the reduction of uniaxial compressive strength and durability of stones after the freezing process, another regression analysis was conducted on the collected data. The result of this analysis is illustrated in Fig. Fig. 9. As can be seen in this Fig. Fig. , there is no strong relationship between these two parameters. However, the total trend of points shows that as uniaxial compressive strength reduction increases, the reduction of durability increases, but this relation can never be used quantitatively. Therefore, in order to predict the reduction values of the parameters, other rock parameters such as physical parameters, especially density and water absorption, may also be useful and should be taken into consideration in future studies in this field.

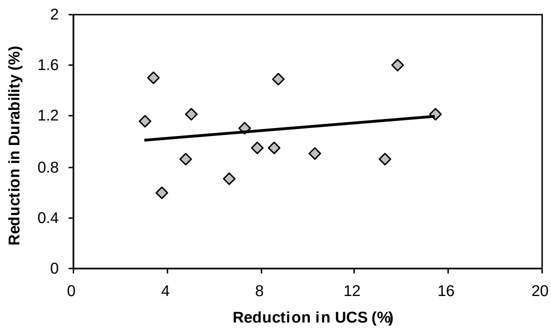

Figure 9. Regression analysis between the reduction of uniaxial compressive strength and reduction of durability after freezing.

5. A FUZZY CLASSIFICATION OF THE DIMENSION STONES BEFORE AND AFTER FREEZING

The fuzzy sets theory was first proposed by Lotfi Askarzadeh in 1965 [41]. It can be said that the most important feature of fuzzy logic compared to classical logic is that it facilitates the expression of humans' knowledge and experience in terms of mathematical relations. One of the most important practical aspects of fuzzy logic for modeling in civil engineering includes fuzzy rule-based systems, fuzzy clustering, fuzzy regression, fuzzy linear programming and fuzzy multi-criteria decision making models [42, 43, 44,45] The fuzzy clustering is one of the most useful tools used in modeling in engineering sciences. In fact, fuzzy c-means clustering is a developmental model of hard c-means clustering [46,47]. Fuzzy c-Means clustering or FCM clustering method is widely used in automatic programming, machine learning, civil engineering, operations research, geotechnical and mining engineering [48, 49,50].

In order to utilize the results of laboratory tests and relate it to the reduction of uniaxial compressive strength and of durability, the data sets were classified in 2 clusters by FCM method for the results of laboratory tests before freezing, after freezing, and the reduction of properties rate, respectively. In this paper, the limits in the clustering including: the weighting parameter of $m'=2$, maximum iteration of 100, minimum acceptance precision of $\varepsilon L=0.00001$ and the number of clusters $c=2$ are considered. Table 7 shows the results of data clustering based on the predetermined measures before and after freezing tests and reduction of properties rate.

Table 7. Optimization result of classification for all samples for three conditions.

No.	Name of mine/stone	Rock type	Class		
			Before freezing	After freezing	Based on reduction of properties rate
1	Khalkhal	Creamy travertine	1	1	1
2	Walnut	Brown travertine	1	1	1
3	Piranshahr	Olive granite	2	2	1
4	Mahabad	Grey granite	2	2	1
5	Naien	Red granite	2	2	1
6	Bahare	White and pink granite	2	2	1
7	Tekab	White travertine	1	1	1
8	Lemon	Lemon travertine	1	1	2
9	Sardarabad	Red travertine	1	1	2
10	Hamedan	Black granite	2	2	2
11	Khoramdareh	Chocolate granite	2	2	1
12	Harsin	Cream marble	1	1	1
13	Anarak- Chopanan	Cream-Pink travertine	1	1	1
14	Anarak- Haftoman	Cream-Pink marble	1	1	1

According to the classification of rock samples and rock types in Table 6, the results of categorization are appropriate. Moreover, classification based on the reduction of properties rate shows that three types of rocks have better qualities according to the reduction of uniaxial compressive strength and durability rate.

6. CONCLUSIONS

Climate may decrease certain qualities of dimension stones. Climatic effects might result from the existence of acids in air and rainwater (they cause the incipient decay of the mineral composition of some stones), salt in humid coastal air (it may have similar effects), and repetitive freezing and thawing. Freezing and thawing can eventually cause stripping, exfoliation, and cracking of dimension stones, particularly where water retention occurs, on horizontal surfaces, or in naturally porous stones. Therefore, it is very important to consider the influence of these factors on the quality of dimension stones.

In this research, freezing and thawing were investigated as the most important factors in damaging dimension stones. The main research question was which types of rocks are damaged worst by freezing and thawing. In this study, two types of dimension stones including granite and carbonate (such as, travertine and marble) were studied and the effects of freezing on some important stone parameters such as uniaxial compressive strength and durability have been investigated. Fourteen frequently employed dimension stones in the North Western regions of Iran have been selected for laboratory studies. The uniaxial compressive strength and durability of selected stones have been tested before and after freezing. The results conveyed that in all types of stones, uniaxial compressive strength and durability decrease as the result of freezing. The result of regression analysis between reduction of uniaxial compressive strength and durability of stones after freezing process showed that there is no powerful relationship between these parameters.

There was an average 9.777% reduction in uniaxial compressive strength in carbonate (travertine and marble) stones, an average 5.623% reduction and in granite. Durability decreased by 1.176% in carbonate stones and 0.953% in granite. In total, the results show that the uniaxial compressive strength and durability of stones decreased by an average of 7.99% and 1.07% after freezing. The results further conveyed that Khalkhal and walnut travertine without resin covers cannot be recommended for outdoor applications because of their uniaxial compressive strength and durability dramatically reduces after freezing.

In the latter part of this paper, fuzzy clustering was administered to classify the stones. The results showed that fuzzy clustering can be employed as a useful tool for classify dimension stones into two distinct categories based on their uniaxial compressive strength and durability after and before freezing and thawing.

7. ACKNOWLEDGEMENTS

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