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A Probability-Based Evaluation on Andesites for Their Use as Cladding Stone

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Abstract

Andesites with a satisfactory quality have been mainly considered as dimension stones worldwide. However, practical approaches are required to evaluate the dimension stone quality due to the increasing demand for natural resources. This study presents detailed laboratory investigations on andesitic rocks in NE Uşak, Turkey. For laboratory studies, representative rock blocks are obtained from unweathered (W0) to highly weathered (W3) rock masses. Laboratory test results demonstrate that progressive rock weathering has remarkable influences on the dry density (ρd), effective porosity (ne), pulse wave velocity (Vp), uniaxial compressive strength (UCS), flexural strength (FS), and Böhme abrasion value (AWR) of the andesitic rocks. Of the above parameters, ne seems to be the most affected rock property due to progressive rock weathering. Furthermore, based on the three-parameter Weibull distribution, andesitic rocks are evaluated for their use as cladding stones. A quantitative approach called the suitability index (SI) is proposed to quantify the quality of cladding stones for andesitic rocks, considering six different evaluation criteria (C1–C6). Two examples of SI calculations reveal the implementation of the proposed approach. The suitability of the proposed approach is also checked by Monte Carlo analysis, showing that the use of SI is suitable to quantify the cladding stone quality for the investigated andesitic rocks. However, the proposed approach should be improved by incorporating the mineralogical and textural characteristics into the SI calculations. Moreover, it should also be attempted to different andesitic rocks in order to observe the similarities or difficulties of quantifying the quality of cladding stones.

1. Introduction

Natural stones have been used as construction and building materials since the dawn of civilization. They have also been used to repair historical structures such as monasteries and monuments [1]. For instance, the cladding systems on pavements, walls, and other building surfaces are constructive elements, mainly composed of natural stones that protect the building heritage and increase its value [2]. In the light of the above explanations, it is clear that the supply and demand for natural resources have increased considerably in recent years. For example, the global natural stone market was valued at $35,120.1 million in 2018 and is projected to reach $48,068.4 million by 2026 [3].

Based on modern engineering geological approaches, the use of natural building stones can be encouraged by simplifying testing methods and developing new approaches to understand the behavior of rocks under different mechanical and environmental conditions [4]. For this purpose, several testing methods have been adopted to evaluate the quality of natural resources. More profoundly, the most widely used and preferred rock property is the uniaxial compressive strength (UCS) that reflects the mechanical quality of

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building stones. In addition, rocks with higher tensile strength properties are required in the facing and cladding systems [5].

Particular rock types such as granites and basalts are mainly preferred in cladding systems, as they have a higher resistance to mechanical and environmental conditions [6, 7]. On the other hand, other rock types such as limestone, marble, andesite, gabbro, and sandstone that meet technical specifications can also be used as cladding stones.

In most quarries, rock blocks as a building material are not of uniform quality; in some cases, the difference between high- and low-quality rocks is well observed, but low-quality rocks appear to be indistinguishable to the untrained eye [8]. In such circumstances, the selection of high-quality rocks depends on the experience of the stone manufacturers. However, laboratory investigations are required to finalize engineering judgments on the quality of building stones.

Several national and international standards [9–15] have widely documented several testing methodologies and technical supervision for cladding and dimension stones. In Turkey, for example, the technical specifications for andesites used as cladding and facing stones are listed in Table 1.

Table 1. Technical specifications of andesites for use as cladding and dimension stone (modified after [10]).

Parameter	Unit	Abbreviation	Maximum value	Testing method
Dry unit weight	g/cm^3	ρ_d	≥ 2.55	
Effective porosity	%	n_e	≤ 1.00	[16]
Water absorption by weight	%	w_a	≤ 0.70	
Freezing loss by weight	%	W_l	≤ 1	[17]
Uniaxial compressive strength	MPa	UCS	≥ 100 MPa	[18]
Flexural strength	MPa	FS	≥ 8 MPa	[19]
Böhme abrasion value	$cm^3/50cm^2$	AWR	≤ 17	[20]

However, the quality of the cladding or dimension stones can be highly affected by progressive rock weathering, which has not been considered in practical evaluations. Although rock weathering has been well noted to decrease the physical and mechanical rock properties [21–26], practical knowledge about progressive rock weathering is limited to evaluating the quality of building stones. Therefore, rock quarries must be investigated from the point of view of this critical phenomenon.

Keep in mind that since rock weathering is a prolonged and ongoing process, building stones should not bear weathering signs or weathered particles. Under the dominance of progressive rock weathering, the physical and mechanical rock properties would be widely distributed, allowing one to use probabilistic approaches to evaluate the quality of natural stones. In this regard, several researchers have presented some probabilistic approaches for various weathered rocks [27–29].

In this manner, the present study introduces a simple probabilistic approach to evaluate the quality of andesitic rocks for their use as cladding stones. For this purpose, a rock quarry located in NE Uşak, Turkey was considered. Detailed field observations were performed, and representative rock samples were obtained from the andesitic rock masses with different weathering grades (W_0–W_3). Physical and mechanical properties were determined for each rock type using the samples obtained.

The adverse effects of progressive rock weathering on the considered rock properties (i.e., dry density (ρ_d), effective porosity (n_e), uniaxial compressive strength (UCS), pulse wave velocity (V_p), flexural strength (FS), and Böhme abrasion value (AWR)) were revealed. The distribution of the considered rock properties due to progressive rock weathering was also established based on the three-parameter Weibull distribution. Based on these distributions in the rock properties, the quality of the andesitic rocks was explored for their use as cladding stones according to six different evaluation criteria (C1–C6).

2. Materials and methods

2.1. Studied area

The studied area is located in the NE part of Uşak, Turkey (Figure 1). The host rocks in the studied area are composed of Paleozoic-aged metamorphic units. The upper strata of the metamorphic units are defined as the Neogene-aged sedimentary and intrusive units. One of the most notable intrusive units in the studied area can be declared as andesitic rocks with a wide range of exposures [30]. In some cases, most andesitic rock exposures have weathering signs such as sericitization, chloritization, and argillization. Andesitic rock masses have a complex structure in terms of different weathering zones.

In most cases, andesites with different weathering zones coexist. On the other hand, they can also be differentiated with respect to cute structural zones (Figure 2). Herein, it should be mentioned that the investigated andesitic rocks have been used as cladding stones with an average quality in Uşak province [31].

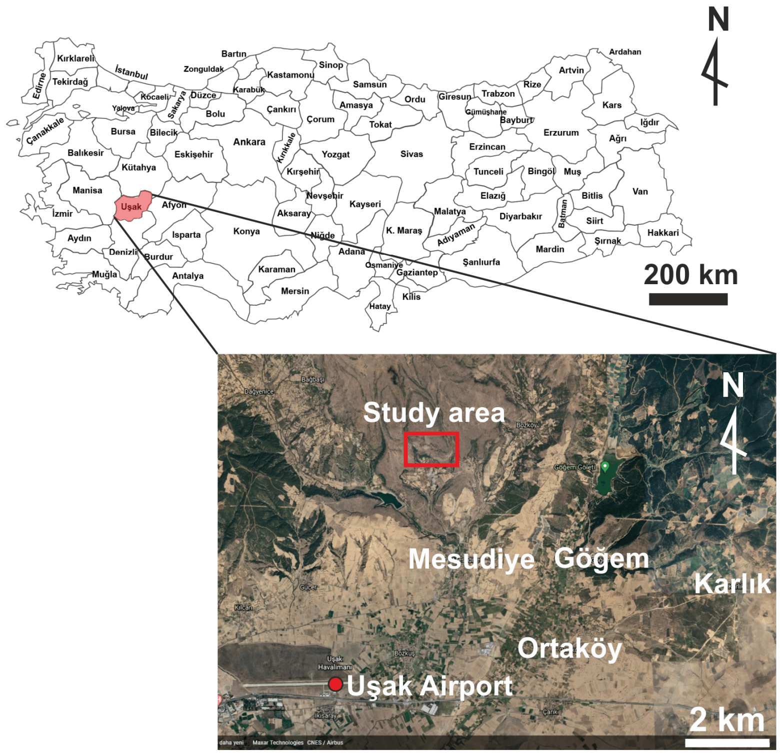

Figure 1. Location map of the studied area

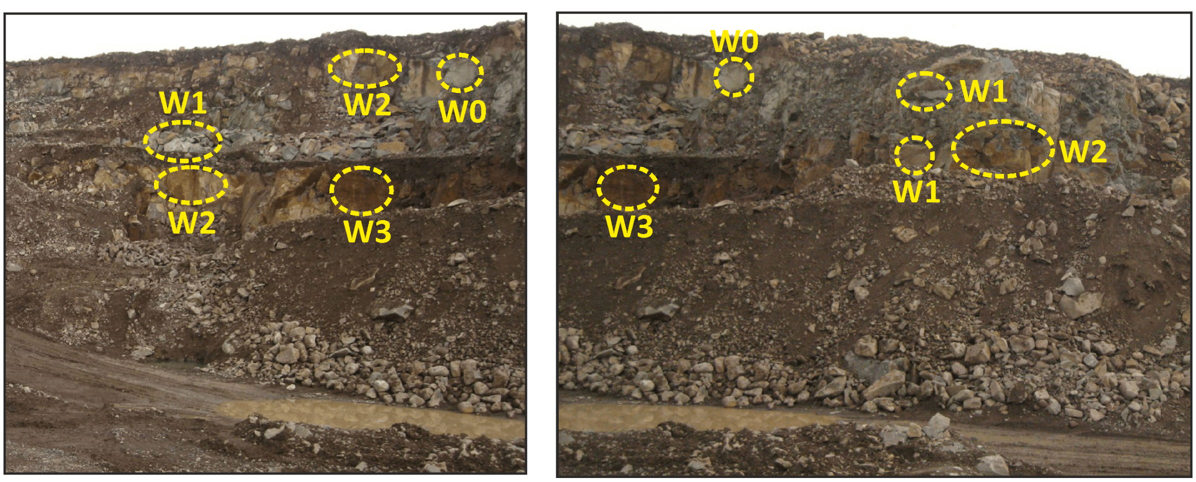

Figure 2. Typical andesitic rock masses with different weathering grades in the studied area (W_0: Unweathered, W_1: Slightly weathered, W_2: Moderately weathered W_3: Highly weathered).

2.2 Methods

Representative rock blocks were obtained from several andesitic rock masses with different weathering grades (i.e., unweathered (W_0), slightly weathered (W_1), moderately weathered (W_2), and highly weathered (W_3)). Typical andesitic rock masses with different weathering grades are illustrated in Figure 2. During the field observations, the qualitative approach suggested by the International Society of Rock Mechanics

[32] was selected in order to determine the different weathering grades of the rocks (Table 1).

Based on different weathering grades, representative sampling was performed for laboratory studies, where cubical and prismatic rock samples were prepared in this context. The correlations between the considered rock properties were revealed based on the laboratory test results. In addition, the suitability of the investigated andesites for use as cladding stones was also explored using a simple probabilistic approach.

Table 1. Qualitative criteria for rock weathering of rock materials [32]

Term	Description	Mentioned code in this study
Fresh	There is no visible sign of rock material weathering: perhaps slight discoloration on major discontinuity surfaces.	W_0
Slightly weathered	Discoloration indicates weathering of rock material and discontinuity surfaces. All rock material may be discolored by weathering and maybe somewhat weaker externally than in its fresh condition.	W_1
Moderately weathered	Less than half of the rock material is decomposed and/or disintegrated into the soil. Fresh or discolored rock is present either as a continuous framework or as corestones.	W_2
Highly weathered	More than half of the rock material is decomposed and/or disintegrated into the soil. Fresh or discolored rock is present either as a continuous framework or as corestones.	W_3
Completely weathered	All rock materials are decomposed and/or disintegrated into the soil. The original mass structure is still largely intact.	–
Residual soil	All rock materials are converted into soil. The mass structure and material fabric are destroyed. There is a significant volume change, but the soil has not been significantly transported.	–

3. Laboratory studies

In the laboratory studies, the cubical and prismatic rock samples (e.g., 50x50x50 mm, 70x70x70 mm, and 150x50x25 mm in dimensions) were prepared for each rock type with different weathering grades. Physical and mechanical properties considered in this study are dry density (ρ_d), effective porosity (n_e), pulse wave velocity (V_p), uniaxial compressive strength (UCS), flexural strength (FS), and Böhme abrasion value (AWR). The ρ_d and n_e values of the rocks were determined according to TS EN 1936 [16]. The V_p, UCS, FS, and AWR values were also determined according to TS 699 [17], TS EN 1926 [18], TS EN 13161 [19], and TS EN 14157 [20], respectively. Physical properties were determined using a desiccator filled with distilled water at 20±1 °C. To determine the UCS values, a stiff loading machine (2000 kN) was used. The V_p values were also measured using a Pundit-Plus testing apparatus. Each test was carried out at least three times under oven-dried conditions for the individual rock blocks. Twenty-four rock blocks were used in the laboratory studies, and the average values obtained from the laboratory test results were presented in this study. Some of the laboratory studies are illustrated in Figure 3. The laboratory test results are given in Table 2. Consequently, it can be claimed that the investigated rock properties are highly affected by progressive rock weathering. For instance, the average V_p and UCS values from the W_0 to W_3 types of weathering were found to be between 4.26 and 3.17 km/s and 98.33 and 36.91 MPa.

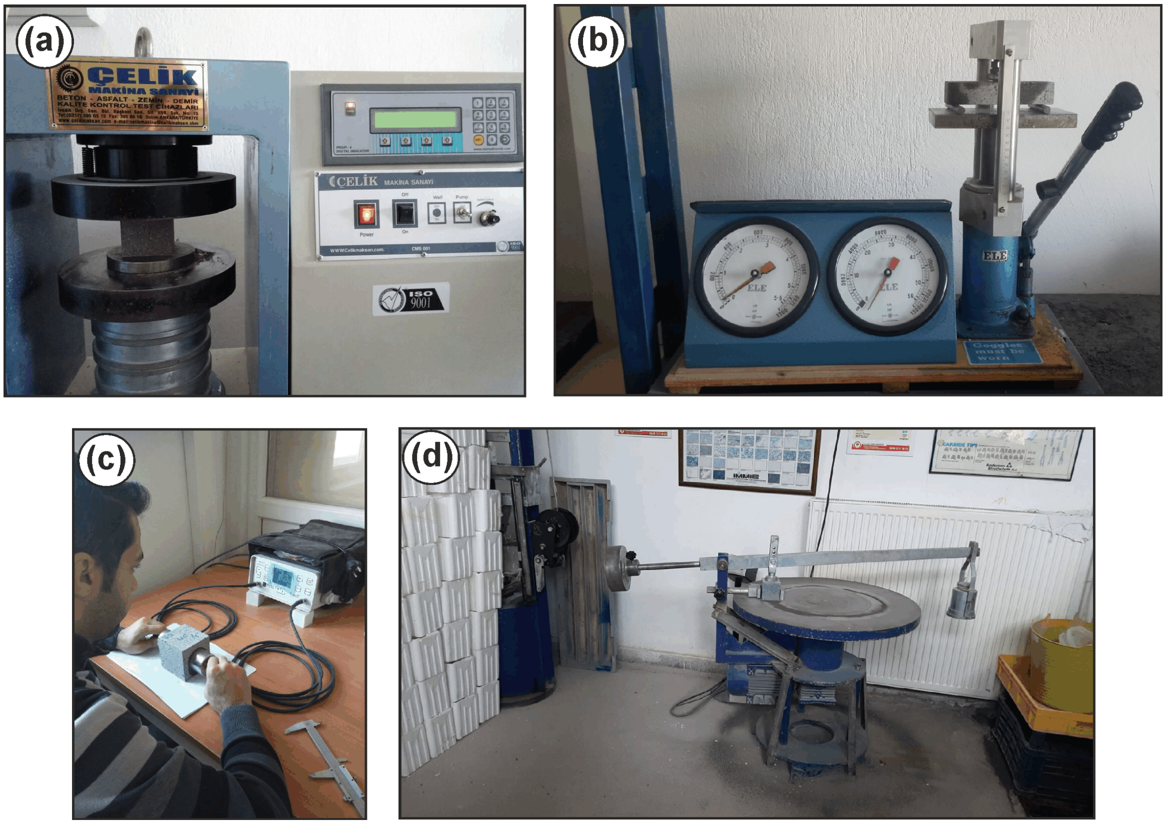

Figure 3. Laboratory studies a) UCS test b) FS test c) pulse wave (V_p) test d) AWR test.

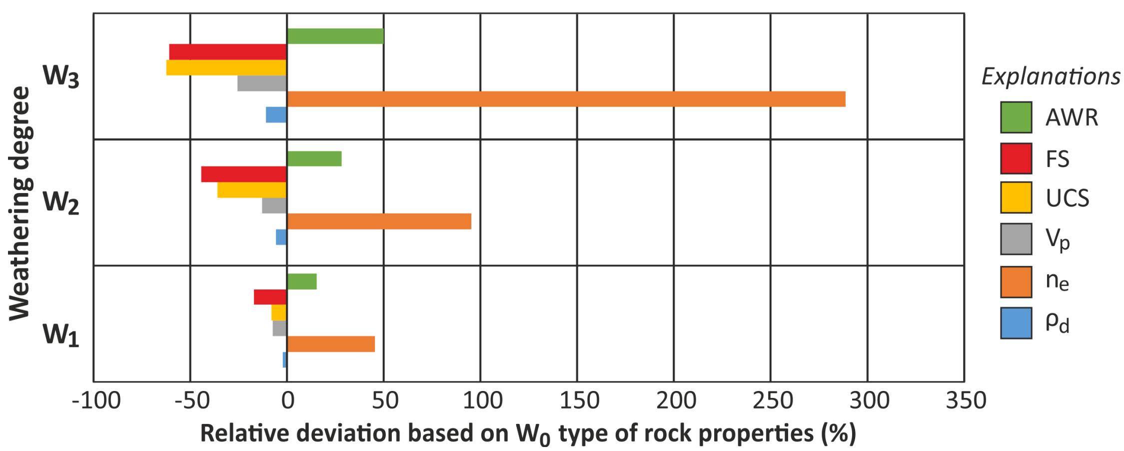

Figure 4. Variations in considered rock properties due to progressive rock weathering.

The decrease ratios for these properties were 25.58% and 62.46%, respectively. On the other hand, for the same comparison, the n_e and AWR values increased by 287% and 49.93%, respectively (Fig 4).

Of the investigated rock properties, n_e seems to be the most affected parameter by progressive rock weathering. Several researchers also reported similar findings [33–38]. In addition, the correlations between the considered rock properties were revealed by Pearson's correlation and regression analyses. The Pearson's correlation coefficient (r) values are listed in Table 3.

Accordingly, the considered rock properties are highly correlated under the dominance of progressive rock weathering. Significant relationships between the investigated rock properties were also obtained, which are given in Figures 5–7.

Table 2. Laboratory test results.

Dry density, ρ_d (g/cm^3)	Effective porosity, n_e (%)	Pulse wave velocity, V_p (km/s)	Uniaxial compressive strength, UCS (MPa)	Flexural strength, FS (MPa)	Böhme abrasion value, AWR (cm^3/50cm^2)	Weathering degree [29]
2.56	0.76	4.16	100.62	12.57	14.27	
2.54	0.80	4.23	90.07	12.15	12.46	
2.54	0.86	4.26	98.94	11.98	15.29	W_0
2.58	0.82	4.48	123.50	12.60	14.06	
2.53	1.06	4.16	78.52	9.25	15.71	
2.54	0.82	4.01	98.07	11.88	13.75	
2.46	1.84	3.61	74.29	8.64	17.32	
2.48	0.94	4.17	94.90	9.32	19.54	W_1
2.50	0.89	4.01	84.39	10.56	18.02	
2.48	1.75	3.92	100.22	8.17	14.18	
2.45	0.98	3.92	72.98	7.50	19.64	
2.45	1.51	4.02	76.80	7.39	16.25	
2.33	1.84	3.56	49.40	6.51	22.48	
2.44	1.85	3.75	51.76	5.72	17.39	
2.44	1.15	3.89	66.17	6.87	17.49	W_2
2.41	1.75	3.80	56.63	5.71	19.07	
2.40	1.43	3.75	76.78	7.93	13.59	
2.33	1.99	3.65	56.46	5.63	20.19	
2.43	1.60	3.47	64.18	6.05	17.26	
2.37	2.65	3.26	57.68	5.75	20.66	
2.35	2.46	3.33	35.65	4.99	19.20	
2.26	3.58	3.15	39.58	4.74	24.62	W_3
2.23	3.22	3.02	32.31	4.58	20.17	
2.23	4.08	3.17	40.09	3.99	22.14	

W_0: Unweathered, W_1: Slightly weathered, W_2: Moderately weathered W_3: Highly weathered.

Table 3. Pearson's correlation matrix of variables considered in this study.

Parameter	ρ_d	n_e	V_p	UCS	FS	AWR
ρ_d	1					
n_e	–0.911	1				
V_p	0.921	–0.904	1			
UCS	0.899	–0.804	0.893	1		
FS	0.897	–0.813	0.861	0.913	1	
AWR	–0.811	0.723	–0.727	–0.768	–0.756	1

Explanations: ρ_d: Dry density, n_e: Effective porosity, V_p: Pulse wave velocity, UCS: Uniaxial compressive strength, FS: Flexural strength, AWR: Böhme abrasion value.

Consequently, UCS, FS, and AWR are associated with ρ_d, n_e, and V_p of the investigated rocks. Nevertheless, one of the lowest correlations of determination (R^2) values, which ranged from 0.52 to 0.64, was obtained to estimate the AWR of the andesitic rocks.

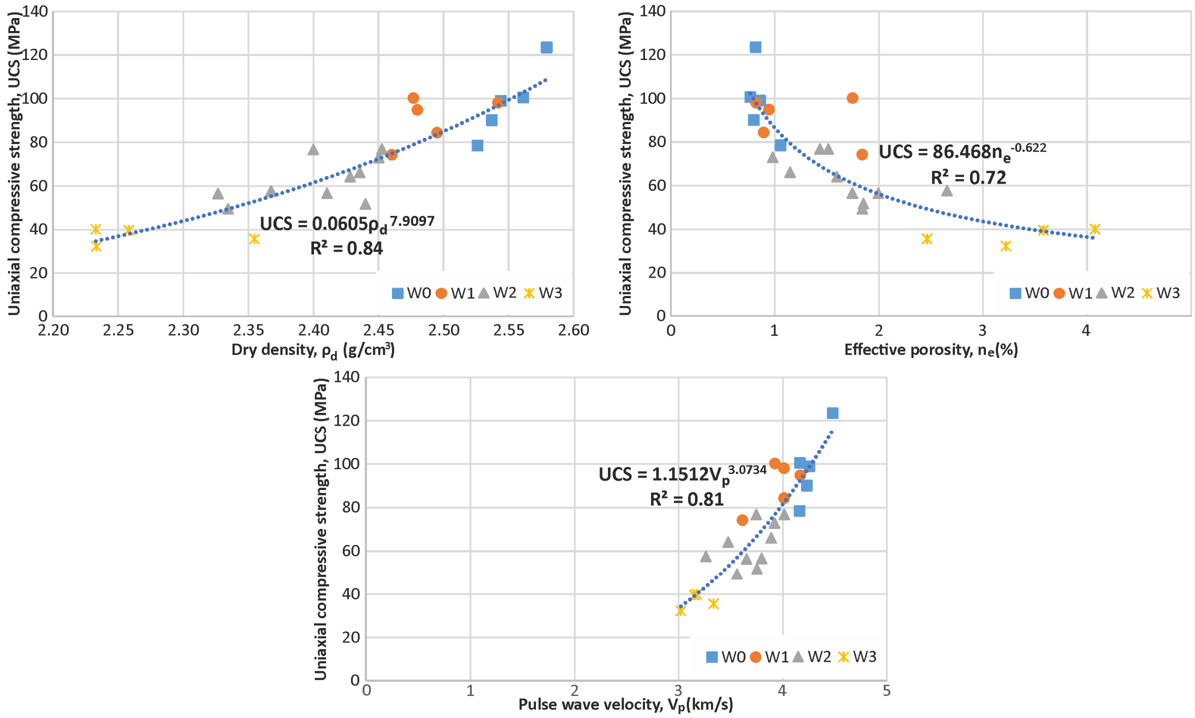

Figure 5. Relationships between UCS and some rock properties with respect to progressive rock weathering.

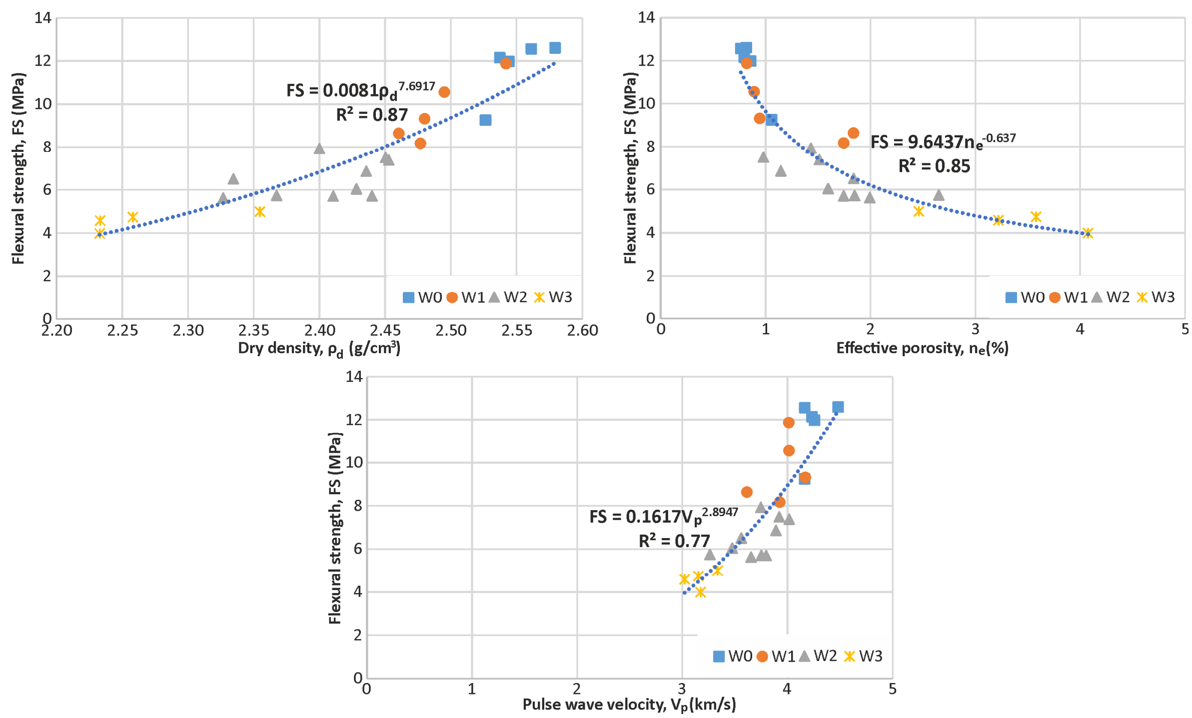

Figure 6. Relationships between FS and some rock properties with respect to progressive rock weathering.

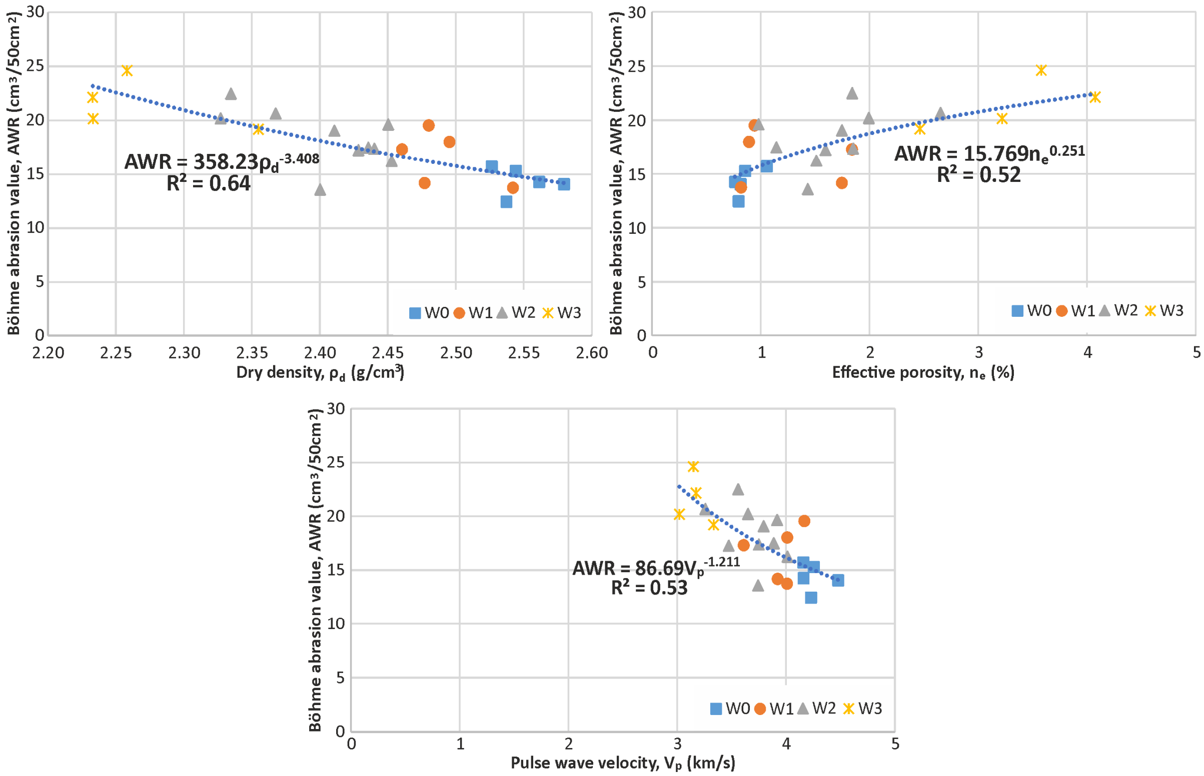

Figure 7. Relationships between AWR and some rock properties with respect to progressive rock weathering.

Therefore, the number of samples should be increased in order to obtain more comprehensive relationships in further studies. Anyhow, the relationships established in this study designate some correlative parameters in order to evaluate the durability of andesitic rocks from the point of progressive rock weathering.

More profoundly, variations in ρ_d, n_e, and Vp can designate the quality of natural stones, as they are sensitive parameters to progressive rock weathering. These rock properties are based on nondestructive testing methods; therefore, they could practically be used to evaluate the quality of natural stones. Consequently, rock weathering should be considered in relation to natural stone quality by focusing on variations in the physicomechanical properties of the rock. The importance of rock weathering to evaluate natural stone quality has previously been emphasized by Siegesmund *et al*. [39]. In addition to the adverse effects of progressive rock weathering on the rock strength properties, progressive rock weathering also influences the rock block geometry [40, 41], another critical parameter in the natural stone production processes. Although the rock block geometry was not focused on in this paper, it should be handled concerning rock weathering evaluations in future studies.

4. Evaluation of investigated andesitic rocks for use as cladding stone

This section introduces a probability-based evaluation of the suitability of the investigated andesitic rocks as cladding stones. For this purpose, the technical specifications listed in Table 1 were adopted. The distribution of the rock properties was revealed by the three-parameter Weibull distribution (Eq. 1); consequently, the shape (β), scale (η), and location (γ) parameters obtained from the database (Table 2) are listed in Table 4.

$$f(x)=\frac{\beta}{\eta}\left(\frac{x-\gamma}{\eta}\right)^{\beta-1} e^{-\left(\frac{x-\gamma}{\eta}\right)^{\beta}} \quad (1)$$

where β, η and γ are the shape, scale, and location parameters, respectively.

Table 4. Three-parameter Weibull distribution parameters.

Variable	Unit	Shape parameter, β	Scale parameter, η	Location parameter, γ	Number of observations
ρ_d	g/cm^3	222.7	18.03	–15.55	24
n_e	%	0.994	0.966	0.724	24
V_p	km/s	5.772	2.029	1.907	24
UCS	MPa	2.153	54.343	23.45	24
FS	MPa	1.485	4.550	3.810	24
AWR	cm^3/50cm^2	2.024	6.807	11.66	24

Based on the probability density functions (PDFs) of the variables (Figure 8), the suitability of andesites for their use as cladding stones was investigated using a straightforward approach. Consequently, six different evaluation criteria (C1–C6) were established. Furthermore, the limit values showing the suitability of andesitic rocks as a cladding stone in Turkey are also plotted in Figure 8.

Based on PDFs, the investigated andesites seemed suitable at an average rate of 9%, focusing on the variations in ρ_d, which was identified in the context of the first evaluation criterion (C-1). For the second criterion (C-2), very low-porosity rocks (n_e < 1%) can be available for use as a cladding stone in Turkey, according to Anon [42]. In this direction, the investigated rocks seemed suitable in proportion to 24.93%. However, andesites can also be rarely appropriate (12–13%), considering the evaluation criteria C-3 and C-4 mainly associated with rock strength properties.

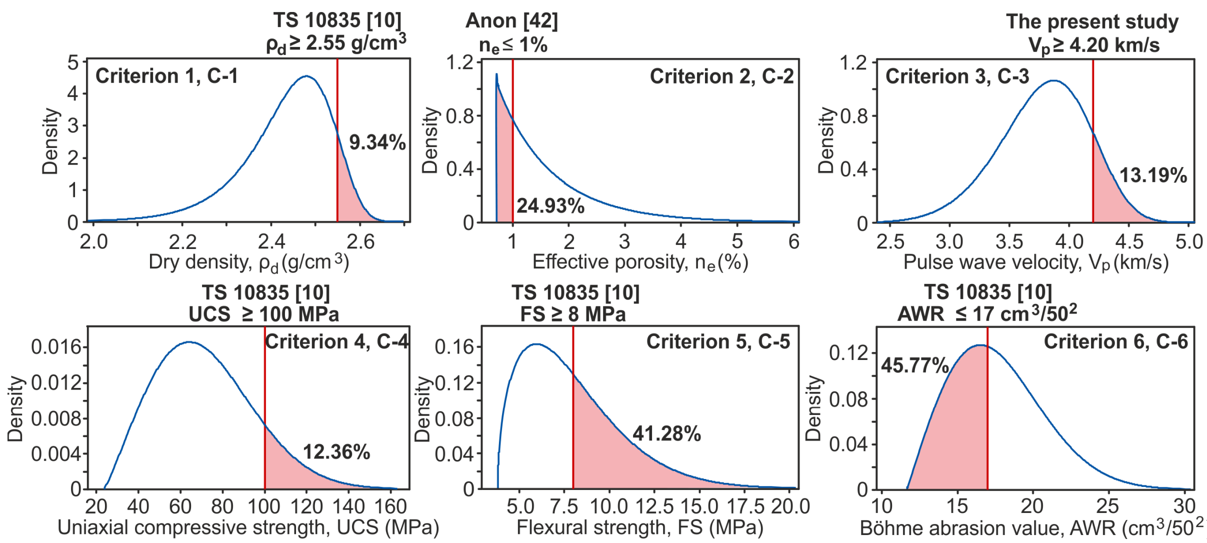

Figure 8. PDFs of variables considered in this study.

Related to the last two evaluation criteria (C-5, C-6), andesites appeared eligible at maximum suitability rates ranging from 41% to 46%. However, in this study, a simple calculation methodology based on PDFs was postulated in connection with technical limit values. As a result, the suitability index (SI) for the cladding stones can be calculated by Eq. 2.

$$SI = \frac{x_1 \times t_1 + x_2 \times t_2 + \frac{(x_3 + x_4)}{2} t_3 + x_5 \times t_4 + x_6 \times t_5}{\sum_{i=1}^{5} t_i} \quad (2)$$

where x is the suitability ratio (e.g., 9.34 for C-1, 24.93 for C-2, and 13.19 for C-3), t is the weighted participation index (e.g., if all the evaluation criteria are performed equally, t is then 20).

The implementation of SI for the investigated andesitic rocks can be given as two different examples. When considering the t indices acting equally (t=20), SI for the andesitic rocks can be calculated as follows:

$$SI=\frac{\left(\overset{C-1}{9.34}+\overset{C-2}{24.93}+\overset{C-5}{41.28}+\overset{C-6}{45.77}\right)\times 20+\left(\frac{\overset{C-3}{13.19}+\overset{C-4}{12.36}}{2}\right)\times 20}{100}=26.819$$

If the t values can be changeable based on the different rock engineering judgments, another SI can also be calculated as follows:

$$SI=\frac{9.34\times 15+24.93\times 25+\left(\frac{13.19+12.36}{2}\right)\times 20+41.28\times 30+45.77\times 10}{100}=27.149$$

It can be understood from the above examples that the SI values depend on the suitability ratio (x) extracted from the PDFs and the weighted participation index (t). On the basis of the above explanations, higher values of SI indicate the rocks with higher quality for their use as cladding stones.

The suitability of the proposed approach was also investigated through several Monte Carlo analyses in order to observe the similarities and difficulties in calculating such SI values. The analyses were performed in the Microsoft Excel environment. Accordingly, 1000 trials were attempted based on such SI calculations. The Monte Carlo analysis results are given in Figure 9.

Consequently, for the investigated andesitic rocks, the SI values were found to be between 21.95 and 36.73, within the 95% confidence interval. The average SI value for these rocks was 29.34. Since the investigated andesitic rocks were used as cladding stones with an average quality in the Uşak province in Turkey [31], its SI values could be defined between 22 and 37 (Figure 9). Furthermore, according to the results of the Monte Carlo analysis, these andesites can also be classified according to their quality for use as cladding stones (Table 5). However, in this evaluation, the mineralogical and textural effects were not integrated into the SI calculations due to the lack of information. Therefore, it is highly recommended to incorporate these effects as several coefficients into the SI calculations in future studies.

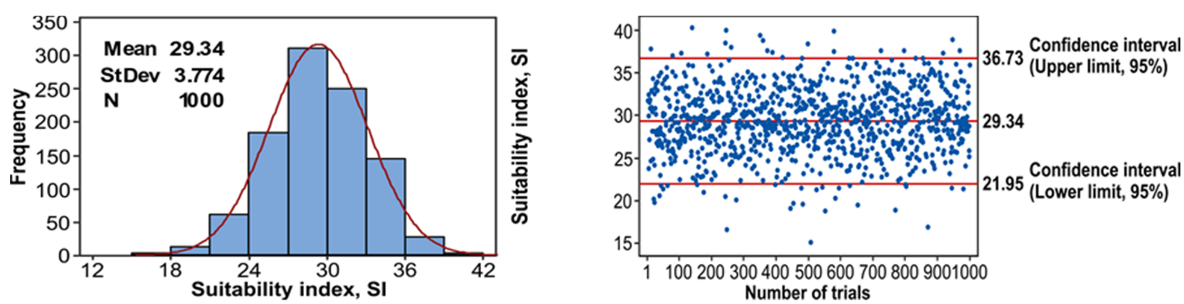

Figure 9. Monte Carlo analysis results.

Table 5. Proposed classification system for cladding stone quality.

SI	Description
< 12	Very low quality
12–22	Low quality
22–37	Moderate quality
37–60	High quality
> 60	Very high quality

The present study, in this context, could be declared a case study on how to quantify cladding stone quality for the andesitic rocks. In addition, this quantitative approach could also be used to classify the cladding stones according to performance indices such as service life and maintenance interval. However, many andesitic rocks from different locations should be investigated to improve the proposed classification system described in Table 5.

5. Conclusions

This study presented detailed laboratory investigations on the andesitic rocks with different weathering grades in NE Uşak, Turkey. It was determined that the investigated rock properties were highly affected by progressive rock weathering (Table 2). The regression analyses established the correlative parameters (i.e., ρ_d, n_e, and V_p) to evaluate UCS, FS, and AWR of the rocks (Figures 5 and 7). However, the number of samples should be increased for more precise estimations of the above parameters.

The investigated andesites were then evaluated for their use as cladding stones according to six different evaluation criteria (C1–C6). A probability-based approach was introduced by adopting the three-parameter Weibull distribution (Figure 8). Based on the Monte Carlo analysis results, the SI of the andesitic rocks was found to be between 22 and 37, which can reflect an average quality of cladding stones. For the investigated andesites, the cladding stone quality could also be classified according to the classification described in Table 5. However, many sites and laboratory investigations on different andesitic rocks are required to enhance the proposed approach. In addition, the mineralogical and textural characteristics are also supposed to be integrated into the calculation of SI.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this document.

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یک ارزیابی مبتنی بر احتمال بر روی آندزیت‌ها برای استفاده از آنها به عنوان سنگ روکش

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چکیده:

آندزیت‌ها به دلیل کیفیت رضایت بخش خود بصورت گسترده‌ای در سراسر دنیا به عنوان سنگ ساختمانی مورد استفاده قرار می‌گیرند. با این حال، به دلیل افزایش تقاضا برای منابع طبیعی، رویکردهای عملی برای ارزیابی کیفیت سنگ مورد نیاز است. این مطالعه بررسی‌های آزمایشگاهی دقیقی را بر روی سنگ‌های آندزیتی در شمال شرقی اوشاک، ترکیه ارائه می‌کند. برای مطالعات آزمایشگاهی، بلوک‌های سنگی از توده‌های سنگی تقریباً سالم و هوازده نشده (W0) تا بسیار هوازده (W3) مورد بررسی قرار گرفت. نتایج آزمایش آزمایشگاهی نشان می‌دهد که هوازدگی پیشرونده سنگ تأثیرات قابل‌توجهی بر چگالی خشک (ρd)، تخلخل مؤثر (ne)، سرعت موج پالس (Vp)، مقاومت فشاری تک محوری (UCS)، مقاومت خمشی (FS) و ارزش سایشی بوهمه AWR)) سنگ های آندزیتی دارد. در میان پارامترهای بررسی شده (ne) بیشترین تأثیر پذیری را از هوازدگی پیش‌رونده سنگ دارد. علاوه بر این، بر اساس توزیع سه پارامتری وایبول، سنگ‌های آندزیتی برای استفاده به عنوان سنگ‌های پوششی ارزیابی می‌شوند. یک رویکرد کمی به نام شاخص تناسب (SI) برای کمی کردن کیفیت سنگ‌های روکشی برای سنگ‌های آندزیتی، با در نظر گرفتن شش معیار ارزیابی مختلف (C1-C6) پیشنهاد شده است. دو نمونه از محاسبات SI عملکرد رویکرد پیشنهادی را نشان می دهد. مناسب بودن روش پیشنهادی نیز با تجزیه و تحلیل مونت کارلو بررسی شد و نشان داد که استفاده از SI برای کمی کردن و بررسی کیفیت سنگ روکش، برای سنگ‌های آندزیتی مناسب است. با این حال، رویکرد پیشنهادی باید با ترکیب ویژگی‌های کانی‌شناسی و بافتی در محاسبات SI بهبود یابد. علاوه بر این، برای مشاهده شباهت ها یا مشکلات کمی سازی کیفیت سنگ های روکش، باید سعی شود سنگ های آندزیتی مختلف نیز مورد بررسی قرار گیرد.

کلمات کلیدی: آندزیت، سنگ روکش، هوازدگی سنگ، توزیع ویبول.