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ORIGINAL PAPER

ASSESSMENT OF THE QUALITY OF TUFFS IN CENTRAL ANATOLIA, TURKEY: A QUANTITATIVE CLASSIFICATION APPROACH

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ABSTRACT

The growing global demand for dimension stones necessitates efficient and accurate evaluation methods to ensure their optimal use in various industries. To assess their suitability for various dimension stone applications, this study investigates tuffs from Central Anatolia, Turkey. For this purpose, the fundamental physical and mechanical properties of the tuffs were determined in laboratory studies, and a detailed durability assessment was conducted for each rock type. The analysis results indicate that most of the examined rocks are of low quality and more suitable for non-load-bearing applications. Based on the collected data, fuzzy clustering techniques were applied to develop a new classification system, categorising the tuffs into four classes (Class A–D) according to their potential applications. Additionally, a user-friendly MATLAB-based software tool was also developed to facilitate the implementation of the proposed classification system.

1. INTRODUCTION

The dimension stone industry is essential to construction, architecture, and infrastructure sectors. Therefore, choosing appropriate rock types for dimension stone production is vital to ensure the durability, aesthetic appeal, and structural integrity of rock-based engineering structures (Macedo et al., 2018; Sharma et al., 2024). Despite technological advancements in extraction and processing, the dimension stone industry still faces challenges related to material selection (Bustillo-Revuelta, 2021; Thyagaraj et al., 2025). One of the most important challenges is the use of unsuitable geomaterials in natural stone applications. Selecting natural stones with inappropriate physical, mechanical, or durability properties often leads to a greater rock susceptibility to damage and poor performance under harsh environmental and operational conditions (Prikryl et al., 2017). This results in rapid deterioration, safety risks, and economic losses.

Numerous studies emphasise the significance of material characterisation and understanding of rock behaviour. In this context, inadequate material characterisation, including mineralogical, structural, physical, and thermomechanical analyses, leads to a poor understanding of long-term performance and thereby contributes to the improper use of geomaterials in construction and architectural projects (Yang et al., 2012; Pereira et al., 2013; Murru et al., 2018; Alves et al., 2021; Ullah et al., 2025). Additionally, improper material selection and limited durability testing can lead to other problems within dimension stone applications. These problems, including weathering-induced discolouration (Ozdemir et al., 2022), rapid loss of mass and strength (Martínez-Martínez et al., 2018; Ma et al. ,2018; Guler et al., 2021; Vercher et al., 2024), microcracking (Luque et al., 2011; Freire-Lista et al., 2016; Amirkiyaei et al., 2021), and consequently high-water absorption (Karaca, 2010; Ozcelik and Ozguven, 2014; Fener and Ince, 2015; Scrivano et al., 2018) have been extensively documented within the natural stone community. Therefore, establishing reliable classification frameworks, conducting comprehensive material testing, and improving industry-wide standards are essential to minimize the risk of selecting unsuitable geomaterials and to ensure long-term performance in natural stone applications (Prikryl and Smith, 2021).

Parallel to technological developments, global industrial growth still requires rapid, accurate evaluation techniques to ensure efficient material utilisation, optimise resource management, minimise waste, and enhance overall productivity in the evaluation and manufacturing of dimension stones (Siegesmund and Snethlage, 2011; de Sousa Camposinhos, 2014; Sena da Fonseca et al., 2015; Jalalian et al., 2021). Accurate assessment methods

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Table 1 Durability classification system for tuffs (Ertaş-Deniz, 2016).

Input	Durability		
	Low durability (LD)	Moderate durability (MD)	High durability (HD)
γ_d (g/cm^3)	< 13.70	13.70 – 16.49	> 16.49
n_e (%)	> 33.89	24.30 – 33.89	< 24.30
V_p (km/s)	< 2.10	2.10 – 2.57	> 2.57
UCS (MPa)	< 14.60	14.60 – 33.19	> 33.19
S_{W-L} (%)	< 9.90	9.91 13.69	>13.69

Explanations: γ_d: Dry unit weight, n_e: effective porosity, V_p: pulse wave velocity, UCS: Uniaxial compressive strength, S_{W-} : salt crystallisation weight loss

can significantly enhance the quality of natural stone and mitigate the issues arising from misleading engineering interpretations. In addition, the maintenance interval and longevity of natural stones depend heavily on innovative classification systems and quantitative methods, which also play a significant role in assessing their relative quality.

Last but not least, advancements in rapid evaluation methods are crucial for maintaining effectiveness and meeting increasing quality standards and simultaneously addressing environmental concerns associated with dimension stone extraction and processing (Ashmole and Motloung, 2008; Cardecu et al., 2019; Şirin et al., 2021). The existing methods to evaluate the durability of dimension stones are based on their physical and mechanical properties. In this regard, several researchers have attempted to evaluate the durability and quality of dimension stones from different perspectives. More profoundly, Maurício et al. (2010) employed a pore structure model to assess the durability of dimension stones from Portugal. Based on their laboratory analysis, they recommend microtomographic imaging techniques to assess the durability of dimension stones. Přikryl (2013) reviewed several quantitative methods for evaluating the durability of dimension stones. In particular, he emphasised that effective porosity (n_e) is critical in assessing the durability and overall quality of dimension stones. Sousa (2014) declared that rock weathering directly deteriorates the physical and mechanical properties of granitic dimension stones in Portugal. Mustafa et al. (2015) evaluated various rock types from Pakistan for their potential use as dimension stones. They concluded that uniaxial compressive strength (UCS) is a vital factor when using dimension stone as load-bearing masonry units. Çobanoğlu (2015) adopted water absorption (w_a) as a critical indicator for identifying the relative quality of travertine dimension stones from Turkey. Based on principal component analysis (FPCA), Vazquez et al. (2018) proposed a novel statistical method to establish relationships between rock petrography and strength properties. Ahmed et al. (2021) reported a considerable correlation between quartz content and UCS in granitic rocks from northern Pakistan. Salvini et al. (2023) also highlighted the importance of petrographic properties that influence the durability of carbonate rocks in Italy.

Some critical mechanical and abrasion properties of dimension stones have also been modelled using non-destructive testing methods. For example, Farhadian et al. (2022) used pulse wave velocity (V_p) and Schmidt hammer value (SHV) to estimate the rock abrasivity index (RAI) and UCS of dimension stones from Iran. Based on a comprehensive database, Bayram (2020), Bozdağ (2020), and Strzalkowski and Köken (2022) estimated the Böhme abrasion value (BAV) using critical rock properties of dry density (ρ_d), w_a, Shore hardness (SH), V_p, and UCS. Recently, novel approaches have been proposed to investigate the relative quality of dimension stones in greater detail. For example, Köken and Başpınar-Tuncay (2022) introduced a probability-based evaluation method that considers critical physical, mechanical, and abrasion properties of rocks. Another remarkable contribution to the dimension stone industry is the quantitative classification systems proposed by Strzałkowski et al. (2023). With the help of artificial intelligence, Köken and Strzałkowski (2024) also proposed another evaluation methodology to quantify the relative quality of dimension stones. Dimension stones have also been classified based on their flexural strength (FS) (Çelik et al., 2025). The durability assessment of tuffs exposed in Kayseri and Aksaray, Turkey, was conducted by Ertaş-Deniz (2016).

The study evaluated 15 different tuff samples and categorised them into three distinct durability classes based on their physical and mechanical properties (Table 1). The physical and mechanical rock properties considered in that study were dry unit weight (γ_d), n_e, V_p, UCS, and salt crystallisation weight loss (S_{W-L}). Such classifications offer valuable insights into the long-term stability and weathering resistance of tuffs under various environmental conditions, making them useful for diverse engineering applications.

The above-mentioned studies indicate that dimension stones can be evaluated based on their inherent mineralogical, physical and mechanical properties. However, there is a noticeable gap in the literature regarding the correlation between quantified dimension stone properties and their specific applications. Understanding these relationships is essential for optimising material selection, enhancing durability, and ensuring the most effective use of natural stones in various construction and architectural

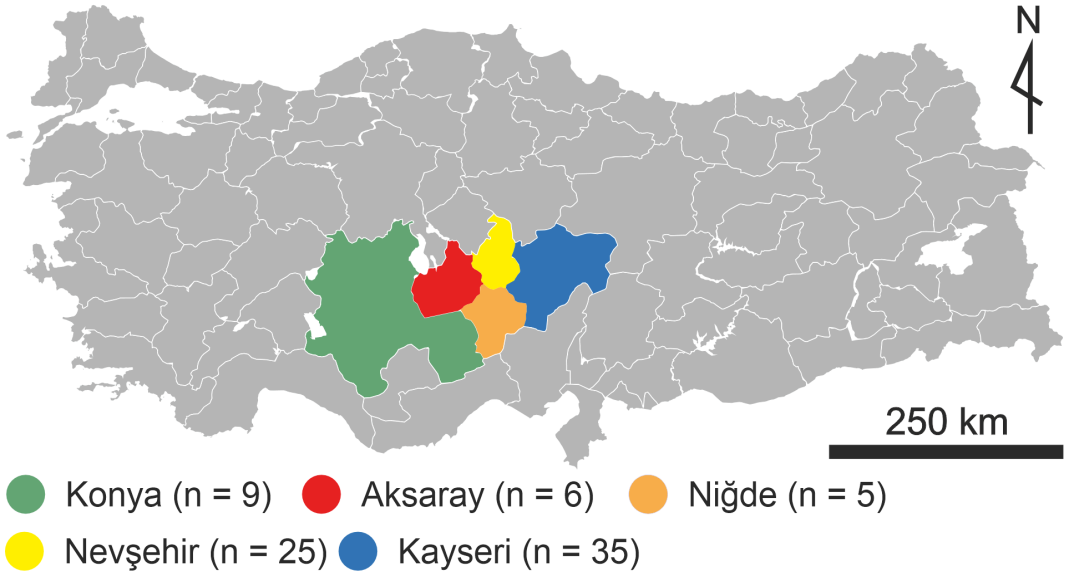

Fig. 1 Sampling location map (n: number of samples).

projects. From this perspective, tuffs from central Anatolia, Turkey, are analysed to assess their potential use in the dimension stone industry. For this purpose, representative rock blocks were collected from various exposures in and around central Anatolia, Turkey. Based on fundamental physical and mechanical properties, a systematic framework is proposed to determine the most suitable applications of the investigated tuffs in the dimension stone industry. This framework utilises a fuzzy clustering approach to classify dimension stones according to their physical and mechanical properties.

2. MATERIALS AND METHODS

For the experimental studies, representative rock blocks were collected from various locations in central Anatolia, Turkey (Fig. 1). A total of 80 rock blocks were obtained during field sampling. To prepare cubic samples, the rock blocks were reduced in size using an industrial rock saw, and 70×70×70 mm cubes were cut from each block. The physical and mechanical properties of the rocks were then determined using these prepared cubical samples. All laboratory tests were conducted under oven-dried conditions, ensuring each rock sample was fully dry before laboratory testing.

The investigated rock types are primarily volcanic, specifically tuff and ignimbrite. These rocks are an important resource for dimension stones in and around their regions. Due to their aesthetic appeal, ease of carving, and durability, they are extensively used in architectural and decorative applications. More specifically, tuff and ignimbrite have been widely employed in facades, wall cladding, flooring, countertops, signposts, and fountains, particularly in central Anatolia, Turkey (Fig. 2). Their historical and contemporary significance in construction and design further highlights their value as versatile building materials.

3. LABORATORY STUDIES

Physical properties, including γ_d and n_e, were determined using the standard procedures outlined in TS EN 1936 (2007). Each test was repeated at least 5 times to ensure consistent results. The V_p and UCS of rocks were also determined, considering the suggestions of the International Society of Rock Mechanics (ISRM 2007). A standard Pundit Plus ultrasonic testing apparatus (measuring resolution: 0.1 μs, nominal transducer frequency: 150 kHz) was used to measure the V_p of the rock samples. For each rock sample, a total of 20 V_p measurements were recorded, and the average V_p values were considered in the analyses. UCS values were also determined using a stiff loading machine with an ultimate capacity of 2000 kN. Some of the laboratory studies are illustrated in Figure 3. The laboratory test results were presented by sampling locations, as shown in Table 2. Table 2 provides descriptive statistics, including means, standard deviations, minimum and maximum values, and sample size. The laboratory test results for the investigated tuffs establish a comprehensive database available for analysing the relationship between rock properties and their practical applications. For the samples obtained from the Kayseri region, the average values of γ_d, n_e, V_p, and UCS were found to be 14.95 kN/m3, 26.54 %, 2.45 km/s, and 22.45 MPa, respectively.

The database described in Table 2 is used to classify the investigated rock types by their quality. The investigated tuffs were mostly classified as having low to moderate strength, according to the ISRM (2007).

4. FUZZY CLUSTERING ALGORITHM

Clustering is a fundamental data analysis technique that groups similar data points, enabling the identification of patterns across domains such as machine learning, image processing, and

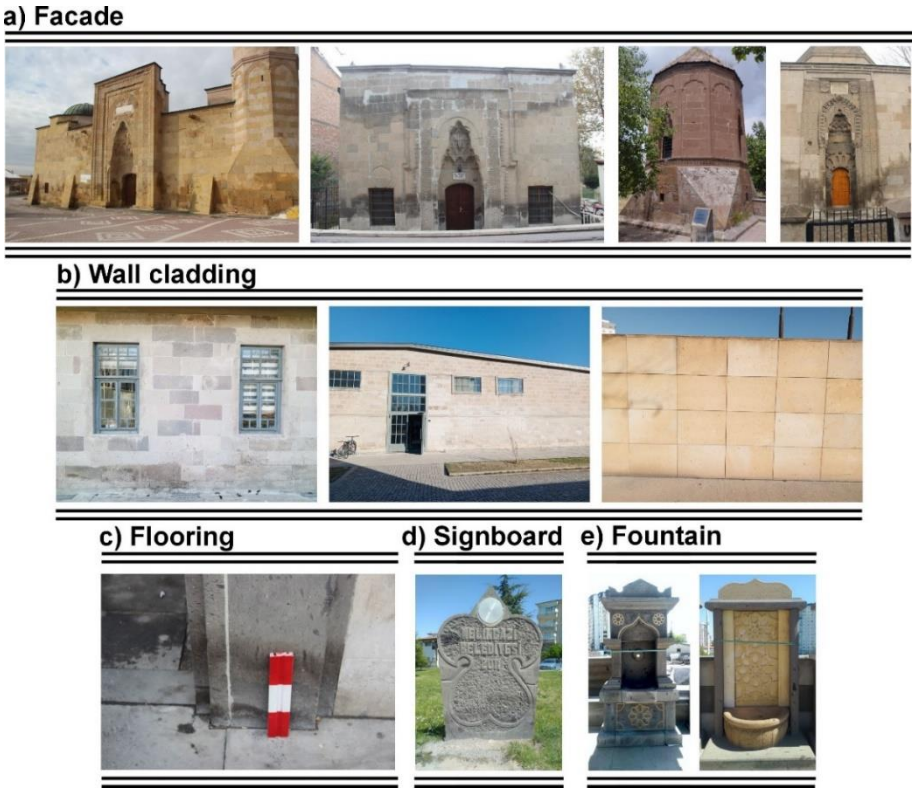

Fig. 2 Various dimension stone applications of the investigated rock types in central Anatolia a) Facade b) Wall cladding c) Flooring d) Signboard e) Fountain.

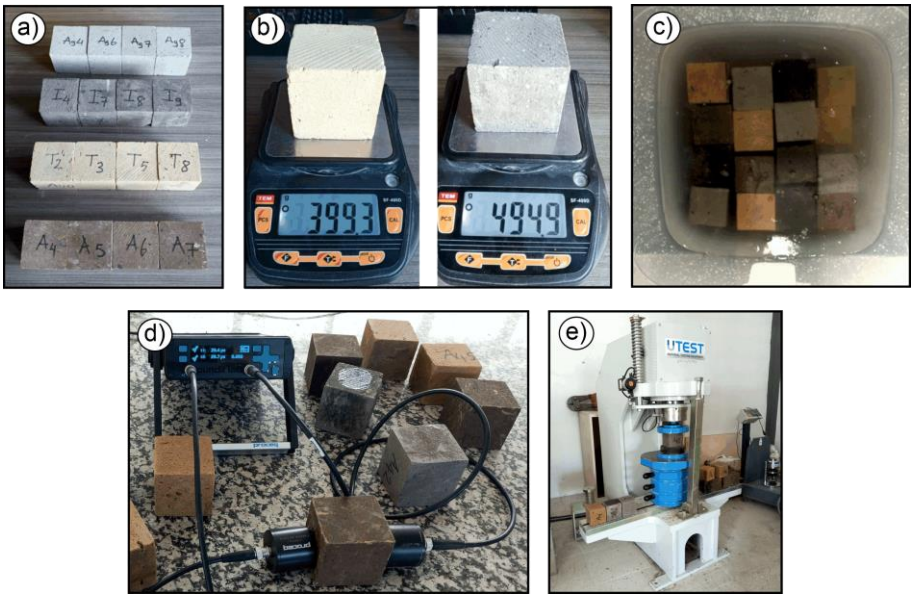

Fig. 3 Laboratory studies: a) Some of the cubical rock samples b) Weighing the oven-dried rock samples c) Saturation of rock samples for determining n_e d) V_p measurement e) UCS test.

bioinformatics. Unlike traditional clustering methods, such as K-means, which assign each data point to a single cluster, fuzzy clustering allows data points to belong to multiple clusters with varying degrees of membership. This flexibility makes fuzzy clustering particularly more useful in cases where class boundaries are not well-defined or when dealing with datasets that exhibit significant overlap between categories (Shafi et al., 2024).

The most widely used fuzzy clustering method is the Fuzzy C-means (FCM) algorithm, originally proposed by Bezdek et al. (1984). FCM assigns membership values to each data point based on its relative distance from cluster centres. This approach

Table 2 Laboratory test results.

Location	Rock property	min	mean	max	Std dev.	n
Konya	γ_d (kN/m^3)	12.07	16.9	21.48	2.69	9
	n_e (%)	9.84	35.46	35.46	8.88	
	V_p (km/s)	1.56	2.52	3.19	0.54	
	UCS (MPa)	6.19	21.56	32.21	9.93	
Aksaray	γ_d (kN/m^3)	14.52	17	20.7	2.04	6
	n_e (%)	12.3	22.16	35.46	7.26	
	V_p (km/s)	1.79	2.83	3.9	0.65	
	UCS (MPa)	10.55	38.42	96.7	29.36	
Niğde	γ_d (kN/m^3)	11.18	12.64	13.73	0.85	5
	n_e (%)	25.88	33.9	42.79	5.93	
	V_p (km/s)	1.68	2.15	2.5	0.29	
	UCS (MPa)	5.2	8	13.2	2.75	
Nevşehir	γ_d (kN/m^3)	10.99	13.87	18.05	2.12	25
	n_e (%)	17.4	28.64	38.02	4.98	
	V_p (km/s)	1.58	2.42	3.01	0.36	
	UCS (MPa)	3.14	11.88	39.1	8.6	
Kayseri	γ_d (kN/m^3)	12.1	14.95	19.91	2.04	35
	n_e (%)	12.67	26.54	38.43	5.65	
	V_p (km/s)	1.59	2.45	3.05	0.45	
	UCS (MPa)	6.95	22.45	59.71	12.83	

Explanations: γd: Dry unit weight, ne: effective porosity, Vp: pulse wave velocity, UCS: Uniaxial compressive strength.

Table 3 FCM classification proposed for the investigated rocks.

Class	γ_d (kN/m^3)	n_e (%)	V_p (km/s)	UCS (MPa)	Durability assessment	Rating point, RP
I	< 12.00	> 36.37	< 1.77	< 7.74	VLD	1
II	12.00 – 14.23	36.37 – 30.21	1.77 – 2.29	7.74 – 17.18	LD	2
III	14.24 – 17.49	30.20 – 24.54	2.30 – 2.68	17.19 – 32.69	MD	3
IV	17.50 – 20.12	24.53 – 15.03	2.69 – 3.10	32.70 – 55.62	HD	4
V	> 20.12	< 15.03	> 3.10	> 55.62	VHD	5

VLD: Very low durability, LD: Low durability, MD: Moderate durability, HD: High durability, VHD: Very high durability

provides a more balanced representation of complex datasets. Because of this reason, it can be successfully applied in medical imaging, remote sensing, mineral exploration, and geochemical modelling (Masulli and Schenone, 1999; Chaira, 2011; Ghosh et al., 2011; Zhong et al., 2013; Sepúlveda et al., 2018; Torppa et al., 2019; Daviran et al., 2020; Benjumea et al., 2011; Ghezelbash et al., 2025). FCM can be easily implemented in MATLAB, which provides built-in functions and toolboxes for efficient execution. The *"fcm"* function in MATLAB's Fuzzy Logic Toolbox allows researchers to apply the algorithm with minimal effort. Due to its ability to handle overlapping clusters and uncertainty in data classification, the FCM remains a valuable tool in various scientific and industrial applications.

In this context, the database listed in Table 2 was classified using the FCM method in the MATLAB environment (Table 3). To clarify this process, each class in Table 3 is assigned a rating point (RP) that reflects the relative quality of the investigated rocks. In this approach, the minimum and maximum RPs range between 5 and 20. The sum of the RPs is regarded as a solid measure of revealing the overall quality of the investigated rock types. Table 4 presents examples of how RPs are changed based on various rock properties. The total RPs (RP_T) are correlated with rock types previously used in dimension stone applications. In this way, a systematic background can be established to identify significant correlations between varying rock properties and their potential application areas.

5. RESULTS AND DISCUSSION

The durability assessment of the investigated rock types was carried out using the rock material classification systems proposed by Anon (1979). This evaluation depends on the fundamental physical and mechanical properties of the rocks, namely γ_d, n_e, V_p, and UCS. Based on these parameters, the rock materials were classified into five classes: very high (VH), high (H), moderate (M), low (L), and very low (VL). According to the γ_d values, the tuffs were categorised as L-VL in quality (Fig. 4a).

Table 4 Some cases for determining RPs.

Location	γ_d (kN/m^3)	n_e (%)	V_p (km/s)	UCS (MPa)	RP (γ_d)	RP (n_e)	RP (V_p)	RP (UCS)	RP_T
Konya	17.27	27.11	2.95	32.10	3	3	4	3	13
	12.07	34.89	2.04	11.02	2	2	2	2	8
	18.74	26.06	2.79	30.70	4	3	4	3	14
Aksaray	18.05	19.11	2.95	39.62	4	4	4	4	16
	17.17	23.89	2.95	48.63	3	4	4	4	15
	14.52	35.46	1.79	14.43	3	2	2	2	9
Niğde	11.18	42.79	1.68	5.20	1	1	1	1	4
	13.15	25.88	2.16	6.36	2	3	2	1	8
	13.73	34.90	2.39	13.20	2	2	3	2	9
Nevşehir	11.97	30.14	1.70	5.44	1	3	1	1	6
	17.17	21.09	2.45	16.86	3	4	3	2	12
	17.95	22.38	2.92	30.96	4	4	4	3	15
Kayseri	13.86	30.93	1.75	11.11	2	2	1	2	7
	19.72	12.67	2.57	42.13	4	5	3	4	16
	12.85	30.17	2.56	17.65	2	3	3	3	11

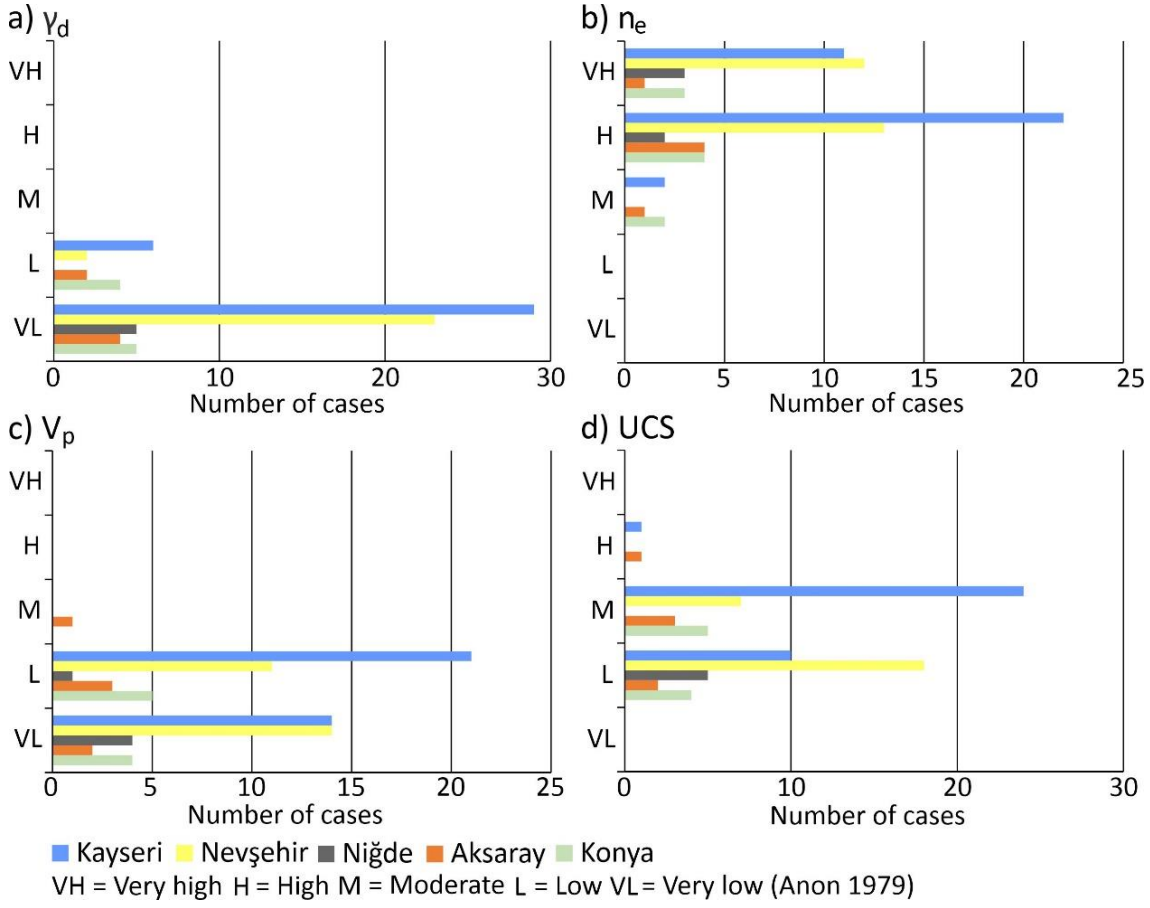

Fig. 4 Durability assessment of the investigated tuffs: a) ρ_d, b) n_e, C) V_p, d) UCS.

This classification suggests that the tuffs are relatively poorly compacted and weakly consolidated, which can significantly impact their long-term durability and mechanical integrity, especially under natural weathering conditions. In contrast, the n_e values of the rocks were predominantly classified as H to VH (Fig. 4b), indicating a high degree of pore space within the rock matrix, which further contributes to their susceptibility to weathering and degradation. When examining the V_p values, the rocks were mostly found within the L to VL categories (Fig. 4c). These values reflect a lack of structural continuity, often associated with materials of low mechanical strength and high porosity. Lastly, the UCS values showed that most samples fall into the L-M strength classes (Fig. 4d).

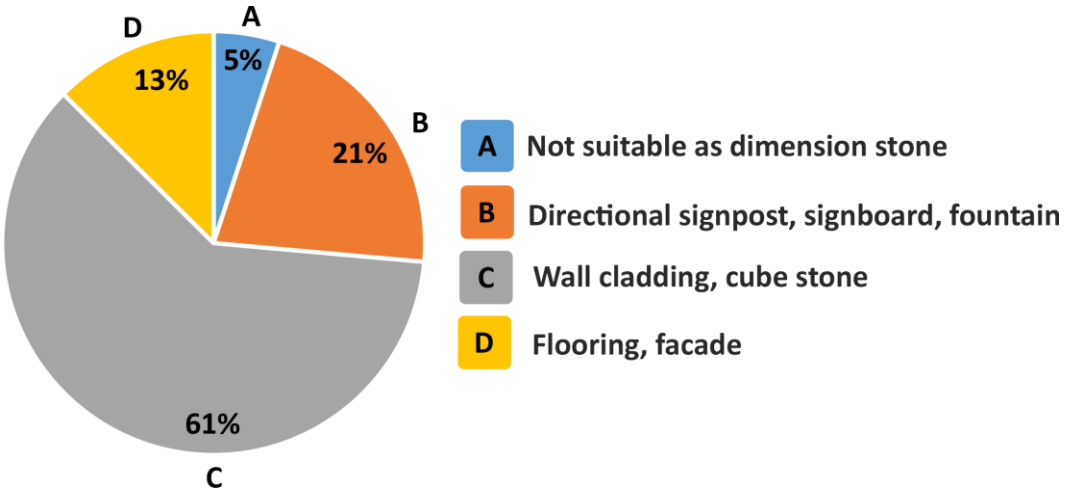

Fig. 5 Statistical distribution of the tuffs with respect to their potential use.

Table 5 Examples of correlations between RPT and the previous usage areas of some tuffs.

Location	γ_d (kN/m^3)	n_e (%)	V_p (km/s)	UCS (MPa)	RP_T	Previous usage area
Konya	17.27	27.11	2.95	32.10	13	Wall cladding
	12.07	34.89	2.04	11.02	8	Signboard
	18.74	26.06	2.79	30.70	14	Cube stone
Aksaray	18.05	19.11	2.95	39.62	16	Flooring
	17.17	23.89	2.95	48.63	15	Wall cladding
	14.52	35.46	1.79	14.43	9	Fountain
Niğde	11.18	42.79	1.68	5.20	4	NA
	13.15	25.88	2.16	6.36	8	Signboard
	13.73	34.90	2.39	13.20	9	Fountain
Nevşehir	11.97	30.14	1.70	5.44	6	NA
	17.17	21.09	2.45	16.86	12	Wall cladding
	17.95	22.38	2.92	30.96	15	Wall cladding
Kayseri	13.86	30.93	1.75	11.11	7	Directional signpost
	19.72	12.67	2.57	42.13	16	Facade
	12.85	30.17	2.56	17.65	11	Signboard

NA: Not applicable.

Utilising the comprehensive database (Table 2), an extensive FCM analysis was conducted to establish a classification system that reveals the specific usage areas of the tuffs. The calculated total RPs were further correlated with various dimension stone applications. Table 5 lists several types of tuffs and their corresponding rock properties, which have been previously employed in a range of dimension stone applications. Based on their retrospective usage, these rock types have been utilized for wall cladding, facades, signboards, fountains, and flooring purposes.

Adopting the proposed method (Table 3), the rock properties were systematically matched with various dimension stone applications, enabling a more objective and informed material selection process. As a result of this analysis, a novel classification system (Table 6) provides a structured, scientific approach to evaluating tuffs for their potential in the dimension stone industry. This classification framework aims to optimise material selection by ensuring that rock properties align with specific industry requirements, including durability and structural integrity. The application of Table 6 is based on quantifying the rock properties using the criteria outlined in Table 3. This approach connects empirical data with practical applications, thereby supporting more efficient and targeted use of tuffs in architectural and construction projects. This research, in this manner, establishes a comprehensive framework for linking rock properties with potential uses by integrating data-driven clustering techniques with practical application insights. This systematic methodology enhances the accuracy and reliability of rock classification systems, facilitating more informed decision-making in selecting proper dimension stones.

The established classes (A–D) were also analysed statistically (Fig. 5), and the results indicate that most of the investigated tuffs (61 %) are identified in Class C. This classification suggests that these tuffs are most suitable for use as wall cladding and cube stone. In other words, they are better suited for non-load-bearing applications.

Table 6 Proposed classification system.

Class	RP_T	Recommended usage area
A	< 7	Not suitable as a dimension stone
B	7 – 11	Directional signpost / Signboard / Fountain
C	11 – 15	Wall cladding / Cube stone
D	> 15	Flooring / Facade

Table 7 Comparison of the durability classification systems.

Konya	Durability classification Ertaş-Deniz (2016) *				Proposed classification (Table 3)	Nevşehir	Durability classification Ertaş-Deniz (2016)				Proposed classification (Table 3)
	γ_d	n_e	V_p	UCS			γ_d	n_e	V_p	UCS	
VLD	–	–	–	–	–	VLD	–	–	–	–	1
LD	1**	2	3	4	1	LD	13	3	4	18	8
MD	2	4	1	5	4	MD	8	17	11	6	10
HD	6	3	5	–	2	HD	4	5	10	1	5
VHD	–	–	–	–	2	VHD	–	–	–	–	1
Total	9	9	9	9	9	Total	25	25	25	25	25
Aksaray	Durability classification Ertaş-Deniz (2016)				Proposed classification (Table 3)	Kayseri	Durability classification Ertaş-Deniz (2016)				Proposed classification (Table 3)
	γ_d	n_e	V_p	UCS			γ_d	n_e	V_p	UCS	
VLD	–	–	–	–	–	VLD	–	–	–	–	–
LD	–	1	1	2	–	LD	10	2	10	9	6
MD	3	1	1	1	2	MD	18	23	7	20	12
HD	3	4	4	3	2	HD	7	10	18	6	14
VHD	–	–	–	–	2	VHD	–	–	–	–	3
Total	6	6	6	6	6	Total	35	35	35	35	35
Niğde	Durability classification Ertaş-Deniz (2016)				Proposed classification (Table 3)						
	γ_d	n_e	V_p	UCS							
VLD	–	–	–	–	1						
LD	4	3	2	5	2						
MD	1	2	3	–	2						
HD	–	–	–	–	–						
VHD	–	–	–	–	–						
Total	5	5	5	5	5						

* See Table 1 for more details.
** Number of case studies by durability class.

VLD: Very low durability
LD: Low durability
MD: Moderate durability
HD: High durability
VHD: Very high durability

The proposed method (Table 3) was also validated using Ertaş-Deniz's study (2016) as a benchmark. The tuffs examined in this study were reevaluated based on the criteria outlined in Table 1. In this context, the number of case studies for each durability class was determined considering each sampling location, as shown in Table 7.

This comparative analysis demonstrates that the proposed classification system (Table 6) is well-balanced and more comprehensive than the system employed by Ertaş-Deniz (2016). The refined classification enhances both the accuracy and reliability of rock property evaluations, establishing a stronger scientific foundation for linking geological characteristics with real-world applications. Moreover, the highlighted methodology encourages a data-driven and standardised approach to selecting dimension stone, ensuring that selected materials meet industry standards for structural integrity and durability. By integrating empirical data with practical application potential, the proposed system supports more informed decision-making in different industrial applications. From this perspective, this study provides valuable insights for geologists, architects, and industry professionals seeking to optimise the use of tuffs in construction and design. By introducing a systematic approach, this study contributes to advancing better practices in material selection. It supports the development of sustainable applications of the investigated rock types in the dimension stone industry.

Nevertheless, while the proposed methodology and the final evaluation framework (Table 6) show significant agreement with the classification established by Ertaş-Deniz (2016), the proposed method's broader applicability requires further validation.

To enhance the generalizability and robustness of this approach, the proposed classification should be applied to a broader range of tuffs from diverse geological settings. In its current form, the framework is specifically validated for tuffs exposed in and around central Anatolia, Turkey.

To improve clarity and ease of use, a user-friendly MATLAB-based software package was developed to automate classification and support the practical implementation of the proposed methodology (Appendix A). The software is available upon reasonable request and enables users to input basic rock properties to receive a direct classification result based on the framework outlined in this study. Furthermore, the software provides visual summaries of different classification outcomes. This capability not only supports practical use in laboratory and field settings but also serves as an educational and demonstration resource for researchers and students analysing rock property assessment and classification techniques.

6. CONCLUSIONS

The present study employs a comprehensive assessment and proposes a classification approach to evaluate the suitability of the tuffs in and around central Anatolia, Turkey, as dimension stones. The durability of the investigated rock types was initially assessed based on their fundamental physical and mechanical properties.

Using a comprehensive dataset, detailed FCM analyses were conducted to develop a new classification framework for addressing various dimension stone applications of the investigated tuffs. By correlating total RPs with historical and practical usage examples, the proposed classification system enables systematic, scientific matching of rock properties to different dimension stone applications. Validation of the proposed classification system using a well-established methodology for tuffs further demonstrates its reliability and comprehensiveness. In this context, it can be claimed that the developed methodology demonstrates improved accuracy and objectivity in rock evaluation, thereby promoting a more standardised, quantitative approach to material selection in the dimension stone industry. Additionally, a user-friendly MATLAB-based software was also developed to implement the proposed methodology more effectively. By reducing the potential for human error, the software enhances the accessibility and repeatability of the classification system, making it a valuable tool for researchers, industry professionals, and decision-makers involved in evaluating and selecting dimension stones.

The findings and the developed classification system are believed to enhance the accuracy, objectivity, and standardization of rock evaluation, overcoming limitations of traditional, subjective material selection methods in the dimension stone industry. Overall, the study encourages informed material selection, supports the optimal use of tuffs in construction and decorative applications, and advances methodologies in dimension stone assessment.

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DATA AVAILABILITY

Enquiries about data availability should be directed to the authors

DECLARATIONS

CONFLICT OF INTEREST

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

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APPENDIX A

GRAPHICAL USER INTERFACE OF THE DEVELOPED SOFTWARE

