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A NOVEL EVALUATION METHODOLOGY FOR DIMENSION STONE QUALITY

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Abstract: The physical and mechanical properties of natural stones are crucial factors in determining their quality, predicting their durability, and assessing their potential uses. In this study, a novel method is introduced to assess the quality of dimension stone using the Fuzzy logic inference system (FIS). The FIS analysis results are described as dimension stone field performance coefficient (*DSFPC*), which indicates the quality of dimension stones. The analysis results are also compared with different approaches, and it is concluded that the proposed FIS model can reliably be used to quantify the quality of dimension stones. The present study, in this manner, contributes to the natural stone industry by proposing a comprehensive predictive model used to quantify the dimension stone quality based on critical physico-mechanical rock properties.

Keywords: *fuzzy logic inference system, rock properties, dimension stone quality, soft computing*

1. INTRODUCTION

Dimension stone has been primarily used as a raw material for engineering projects related to civil, industrial, mining, and geological engineering disciplines. Due to its durability and ecological nature, high-quality dimension stone is in high demand across the globe. In addition to this, it can be fully recycled based on proper technologies (Selonen et al. 2000; Rana et al. 2016; Strzałkowski 2021).

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The durability of natural stones refers to their ability to withstand environmental factors, external loads, and rock weathering processes (Přikryl 2013), and it is closely related to their technical utilization (Turkington 1996). Physical, mineralogical, and mechanical rock properties are significant in evaluating the durability and initial use of dimension stones (Frasca and Yamamoto 2006; Figueiredo et al. 2010; Mustafa et al. 2015; Scrivano et al. 2018). In their studies, Přikryl (2013) and Salvini et al. (2023) provided an overview of various quantitative methods used to investigate the durability of dimension stones (Table 1).

The test methods mentioned in Table 1 reveal various physical and mechanical properties of dimension stones. In addition, there are also some technical specifications to evaluate the initial use of dimension stones. However, technical specifications are mainly established based on specific dimension stone applications, which vary in different countries. They are also built on specific rock units such as granites, marbles, basalts, etc. A typical technical specification for granitic dimension stones is explained in ASTM C615/C615M-18e1 (2018).

Table 1. Some quantitative approaches to measure the quality and durability of dimension stones (Přikryl 2013; Salvini et al. 2023)

Assessment method	Experimental procedure
Traditional laboratory tests	Water absorption, uniaxial compressive strength, flexural strength, Böhme abrasion value
Accelerated laboratory tests	Freeze-thaw cycling
	Wetting-drying
	Salt crystallization resistance
Complex environmental testing	Humidity, temperature, thermal shock measurements
Exposure site testing	Large-scale flexural and cutting tests

There are also international and national standards (TS 10835, 1993; TS 11137, 1993; ASTM C568/C568M, 2015; AS 3700, 2018; ASTM C503/C503M, 2022) for various dimension stones worldwide.

It is worth noting that while American standards establish some minimum requirements for dimension stones based on specific lithological units, European standards do not define any quantitative limits based on various physical and mechanical rock properties. In this context, Strzałkowski et al. (2023) put forward some evaluation criteria for assessing natural stone products (Table 2). In addition, the defined criteria provide guidance for engineers and designers in the selection of stone for its application.

It should be noted that the technical specifications for dimension stones only give an idea of their initial use and cannot be used to predict their long-term performance.

Because of this reason, retrospective analyses are necessary to predict and evaluate the performance of dimension stones.

The performance evaluation, in this manner, is based on the safety, durability and longevity of dimension stones. It should be kept in mind that since the performance evaluation of dimension stones can be somewhat subjective in different engineering applications, it should be defined based on specific engineering contexts.

In order to investigate the performance of dimension stones, several attempts have been made from different perspectives in previous studies. Regarding lithological variances, tuffs, and sandstones can be acknowledged as some of the most sensitive rocks to thermal decay (Fitzner 2004). Focusing on the physical and mechanical rock properties, porosity and pore structure are declared some of the most important rock parameters for the durability of historical monuments (Benavente et al. 2004).

Table 2. Some quantitative approaches to measure the quality and durability of dimension stones (Strzałkowski et al. 2023)

Criterion I ρ_d [g/cm ³]	Criterion II w_a [%]	Criterion III BAV [cm ³ /50 cm ²]	Criterion IV UCS [MPa]	Criterion V FS [MPa]	Classification
<1.5	>20	>55	<15	<4	very low
1.5–1.8	14.5–20	40–55	15–50	4–8	low
1.8–2.2	8.0–14.5	25–40	50–120	8–12	moderate
2.2–2.6	1.0–8.0	10–25	120–200	12–16	high
>2.6	<1.0	<10	>200	>16	very high

Rock texture is essential when working on the cutting performance of dimension stones (Ribeiro et al. 2007). Regarding the mineralogical variances, biotite is a very sensitive rock-forming mineral to the salt crystallization process for silicate rocks (Silva and Simão 2009). Martínez-Martínez et al. (2013) studied the effects of freezing-thawing cycles on the durability of carbonate dimension stones. Their laboratory test results indicated that the carbonate rocks with an effective porosity greater than 10% have a lower durability in their datasets. Sousa (2014) also emphasized rock texture and weathering as critical phenomena for evaluating dimension stone durability. Andriani and Germinario (2014) investigated the thermal decay of some carbonate dimension stones from southern Italy. In their study, the dimension stones were subjected to thermal cycles ranging from 100 to 700°C. Their laboratory test results indicated that the diagenetic fabric and mineralogical composition are found to be the most influential factors for evaluating the durability of carbonate dimension stones.

Germinario et al. (2017) considered the rate of decay for several dimension stones used in northern Italy. They revealed remarkable variations in several physical and me-

chanical properties under the domination of different environmental conditions based upon varying relative humidity.

Hosseini et al. (2020) investigated the cutting performance of dimension stones based on several cooling and lubricant fluid environments. Based on their laboratory test results, including uniaxial compressive strength (*UCS*), Mohs hardness, and Young modulus, the cutting performance of several dimension stones from Iran was estimated successfully using several soft computing techniques. Recently, Köken and Başpınar Tuncay (2022) proposed a probability-based evaluation method to quantify the quality of andesitic dimension stones from Turkey. In that study, dry density (ρ_d), effective porosity (n_e), pulse wave velocity (V_p), *UCS*, flexural strength (*FS*), and Böhme abrasion value (*BAV*) were adopted as input rock parameters for evaluating the quality of andesitic dimension stones.

The evaluation and interpretation of technical parameters on dimension stones require advanced mathematical methods due to their varying characteristics. One of the well-established mathematical methods to solve problems associated with engineering geology is the fuzzy logic inference system (FIS). This method has been adopted to solve many rock engineering and geomechanics problems (Aydin 2004; Taboada et al. 2006; Taboada et al. 2008; Hazrathosseini and Mahdevari 2018; Tao and Zheng 2020; Mikaeil et al. 2022).

More profoundly, Taboada et al. (2006) used FIS to assess the economic value and available deposits of ornamental slates in Spain. Taboada et al. (2008) developed a novel FIS-based method to estimate the reserve of ornamental granite deposits.

With the help of the advantages of FIS, Akkoyun and Fuat Toprak (2012) proposed a quantitative classification system used to assess the quality of natural stone blocks. In their classification system, rock color, texture and fossil content were used as input parameters. Hazrathosseini and Mahdevari (2018) also adopted FIS and developed an index used to assess the geometric quality of dimension stones.

The studies mentioned above put forward a solid basis for quantifying the performance and quality of several dimension stones. However, most of these studies focused on similar rock types or single lithological units. In addition, to the best of the authors' knowledge, there are no studies in the literature that provide a comprehensive evaluation methodology to assess dimension stone quality based on retrospective analyses.

For this reason, a comprehensive evaluation was conducted on different dimension stones used for cladding, decorative, and earthwork purposes in Turkey. The relative quality of dimension stones was first declared based on detailed retrospective inspections by field engineers who were responsible for the application and observation of related dimension stones. Later, systematic sampling was conducted for laboratory studies. Based on the laboratory test results, the quality of dimension stones was investigated and modelled using the FIS methodology.

The soft computing analysis results were compared with the actual field performances and those based on the classification by Strzałkowski et al. (2023). The details and keynotes on evaluating dimension stone quality through the FIS methodology can be found in this research paper.

2. MATERIALS AND METHODS

In this study, 19 rock types from several parts of Turkey were considered. The sampling location of the investigated rocks is given in Fig. 1. The investigated rock types have been mainly used for cladding, decorative, and earthwork purposes in different regions of Turkey.

During field sampling, only unweathered rock types were collected for laboratory testing. The unweathered rock types were selected based on the recommendations of the International Society of Rock Mechanics (ISRM 2007). The physical and mechanical properties of rocks determined in this study are dry density (ρ_d), water absorption by weight (w_a), uniaxial compressive strength (UCS), flexural strength (FS), and Böhme abrasion value (BAV).

The adopted rock properties were determined by adopting the standards of TS EN 1936 (2010), TS EN 1926 (2013), TS EN 13161 (2014), and TS EN 14157 (2017), respectively. The number of specimens used in the laboratory studies is listed in Table 3.

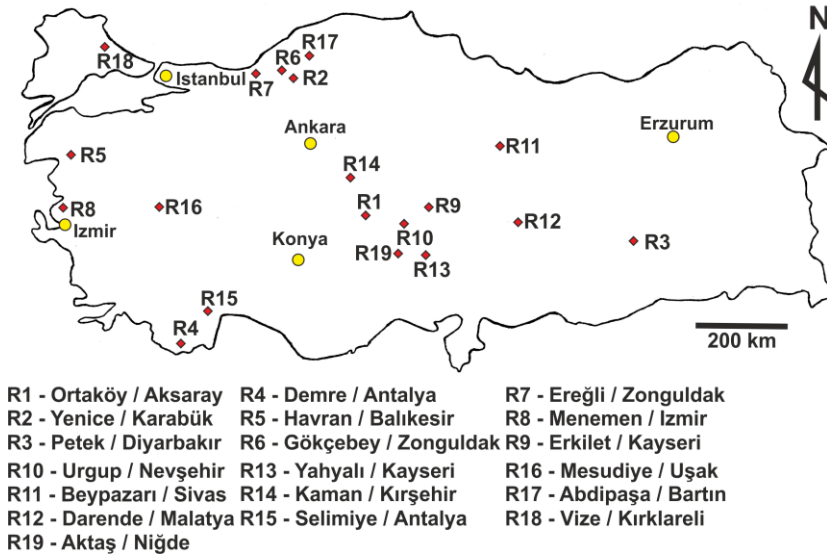


Fig. 1. Sampling location map of the investigated rocks

Table 3. Number of specimens used in different laboratory tests

Rock type	Code	Location	Number of tests employed				
			ρ_d [g/cm ³]	w_a [%]	UCS [MPa]	FS [MPa]	BAV [cm ³ /50 cm ²]
Granite	R1	Ortaköy/Aksaray	9	15	6	4	3
Gabbro	R2	Yenice/Karabük	12	8	5	4	3
Basalt	R3	Petek/Diyarbakır	6	9	5	4	3
Limestone	R4	Demre/Antalya	8	7	5	3	4
Granodiorite	R5	Havran/Balıkesir	10	6	4	5	5
Andesite	R6	Gökçebey/Zonguldak	8	14	7	4	4
Limestone	R7	Ereğli/Zonguldak	7	12	5	3	3
Limestone	R8	Menemen/Izmir	14	10	8	5	3
Basalt	R9	Erkilet/Kayseri	20	8	6	4	3
Tuff	R10	Urgup/Nevşehir	9	11	5	3	4
Limestone	R11	Beypınarı/Sivas	6	9	5	5	5
Limestone	R12	Darende/Malatya	11	6	4	4	3
Dolomitic limestone	R13	Yahyalı/Kayseri	7	9	6	4	3
Granite	R14	Kaman/Kırşehir	6	10	7	4	4
Limestone	R15	Selimiye/Antalya	5	8	8	3	5
Andesite	R16	Mesudiye/Uşak	5	7	5	3	3
Basalt	R17	Abdipaşa/Bartın	11	8	4	5	4
Granodiorite	R18	Vize/Kırklareli	14	11	8	4	3
Tuff	R19	Aktaş/Niğde	8	19	6	3	4

2.1. LABORATORY STUDIES

Laboratory studies include the determination of the mineralogical, physical, and mechanical properties of rocks. The mineralogical features of the investigated rock types were investigated through thin-section analyses. Using a polarized microscope, the investigated rocks were characterized from the mineralogical point of view (BS EN 12407, 2000).

For this purpose, thin sections were prepared for each rock type, and the quantities of rock-forming minerals were determined based on the point-counting method defined by Larrea et al. (2014). For each rock type, at least three thin sections were analyzed under a polarized microscope, and average quantities of rock-forming minerals were presented in this study. Typical thin sections of the investigated rock are illustrated in Fig. 2. According to the thin section analysis results, it was determined

that the mineralogical composition of the rocks is quite different due to the origins of the rock types. In this respect, the mineralogical composition of the rocks is listed in Table 4.

Table 4. Mineralogical composition of the investigated rock types

Constituent [%]	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12	R13	R14	R15	R16	R17	R18	R19
Qtz.	38	–	–	–	23	–	–	–	–	6	–	–	–	49	–	–	–	25	11
Qtz. (uncrystallized)	–	–	–	–	–	–	–	–	–	14	–	–	–	–	–	–	–	–	3
Orth.	19	–	–	–	10	–	–	–	–	–	–	–	–	11	–	–	–	13	–
Plg.	27	62	36	–	40	75	–	–	52	17	–	–	–	28	–	62	65	32	26
Pyrx.	–	16	8	–	10	3	–	–	23	–	–	–	–	3	–	6	24	15	10
Ol.	–	3	–	–	–	–	–	–	18	–	–	–	–	–	–	–	2	–	–
Horn.	5	4	4	–	5	1	–	–	1	–	–	–	–	2	–	–	–	2	–
Bt.	6	2	3	–	8	3	–	–	–	–	–	–	–	2	–	–	3	4	–
Mus.	1	–	–	–	–	–	–	–	–	1	–	–	–	–	–	–	–	1	–
Ep.	1	1	–	–	–	1	–	–	–	–	–	–	–	1	–	5	1	5	–
Clay min.	–	–	–	–	–	–	–	–	–	48	–	–	–	–	–	6	–	–	9
Lim.	–	–	–	–	–	–	–	2	–	–	–	–	–	–	–	–	–	–	–
Sid.	–	–	–	–	–	–	–	1	–	–	1	2	4	–	2	–	–	–	–
Cal.	–	–	–	49	–	–	91	88	–	11	87	48	76	–	96	–	–	–	–
Cal. mud.	–	–	–	9	–	–	4	3	–	2	1	18	5	–	1	–	–	–	–
Dol.	–	–	–	1	–	–	1	–	–	–	7	–	13	–	1	–	–	–	–
Opaque min.	3	12	4	–	4	7	2	1	4	1	1	–	3	4	–	11	2	3	1
Fossil rem.	–	–	–	41	–	–	2	5	–	–	3	32	–	–	–	–	–	–	–
Ground mass	–	–	45	–	–	10	–	–	2	–	–	–	–	–	–	10	3	–	40

Moreover, cubical ($70 \times 70 \times 70$ mm) and prismatic ($50 \times 50 \times 300$ mm) rock samples were prepared to determine physicommechanical rock properties. The physical properties determined in this study are ρ_d and w_a . On the other hand, the mechanical properties of the rocks consist of *UCS*, *FS*, and *BAV*, respectively. The laboratory studies were performed under oven-dried conditions, and some of them are illustrated in Fig. 3. Average values obtained from the laboratory studies are presented in Table 5. Based on the laboratory test results, it can be claimed that the considered rock types and their laboratory test results can be accepted as a comprehensive database for assessing dimension stone quality. From this point of view, detailed FIS analyses were conducted to evaluate dimension stone quality based on the database in Table 5.

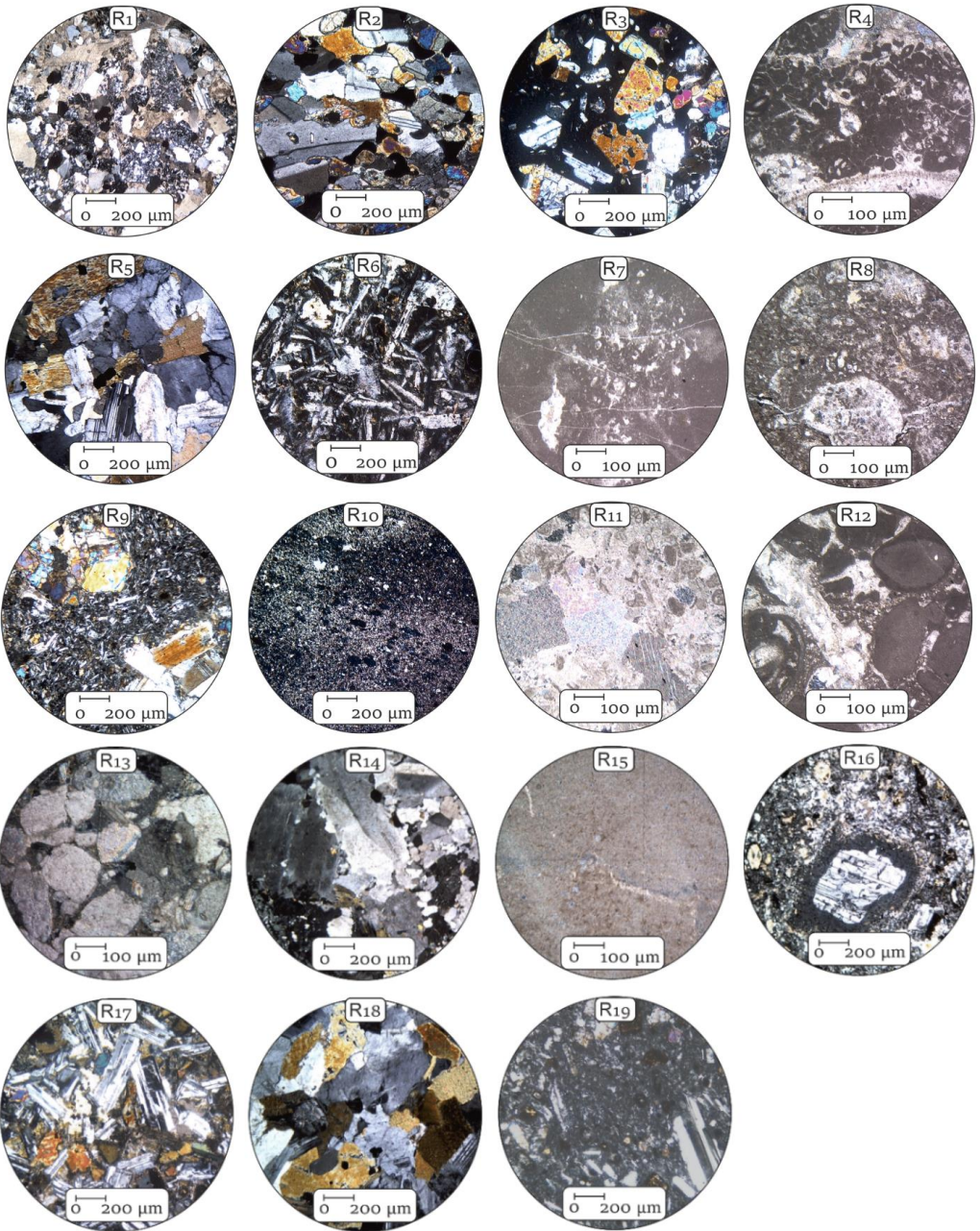


Fig. 2. Sampling location map of the investigated rocks

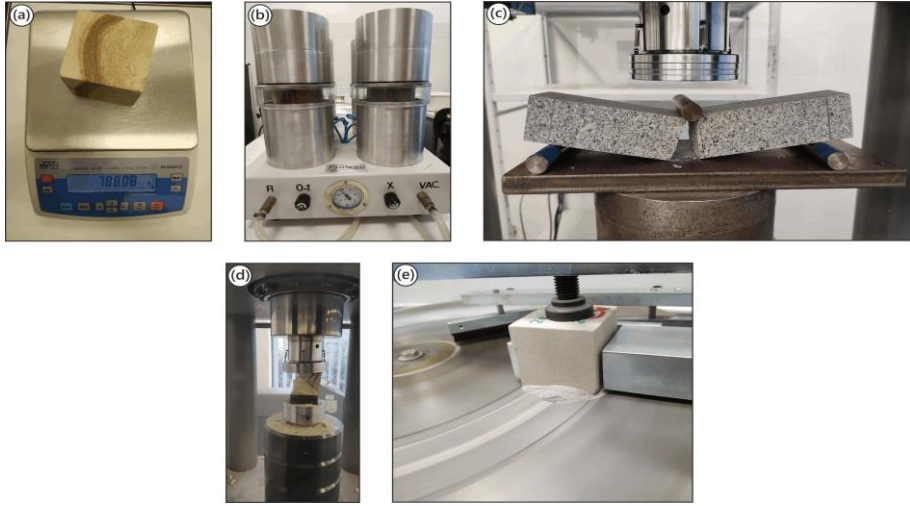


Fig. 3. Some of the laboratory studies: a) determination of the oven-dried weight for a cubical rock sample, b) Determination of w_a , c) FS test, d) UCS test, e) BAV test

Table 5. Laboratory test results

Rock type	Code	ρ_d [g/cm ³]	w_a [%]	UCS [MPa]	FS [MPa]	BAV [cm ³ /50 cm ²]
Granite	R1	2.62	0.35	126.05	16.51	7.21
Gabbro	R2	2.91	0.08	165.29	18.07	5.96
Basalt	R3	2.70	0.48	118.70	10.24	6.50
Limestone	R4	2.42	3.08	50.18	6.74	14.49
Granodiorite	R5	2.75	0.29	144.29	15.02	7.82
Andesite	R6	2.35	2.13	96.18	11.32	22.86
Limestone	R7	2.63	0.27	93.87	9.72	12.62
Limestone	R8	2.38	3.56	65.33	7.14	16.34
Basalt	R9	2.71	1.74	119.75	15.38	5.28
Tuff	R10	1.68	11.57	24.52	3.92	25.09
Limestone	R11	2.58	1.44	59.36	6.69	14.13
Limestone	R12	2.64	1.61	71.04	5.88	9.45
Dolomitic limestone	R13	2.68	0.18	122.51	13.72	7.38
Granite	R14	2.67	0.11	127.02	10.58	6.21
Limestone	R15	2.68	0.35	79.51	9.15	16.58
Andesite	R16	2.54	0.86	89.54	11.26	19.11
Basalt	R17	2.74	0.63	154.89	16.22	6.69
Granodiorite	R18	2.63	0.52	129.68	14.06	7.06
Tuff	R19	1.46	23.61	10.25	2.04	28.21

2.2. FIELD PERFORMANCE AND DETERMINING THE RELATIVE QUALITY OF DIMENSION STONES

The field performance of dimension stones is related to their durability and longevity during their usage. Unveiling of the relative quality of the dimension stones is based on the observations of relative engineers and technicians who were responsible for dimension stone applications. The inspections and observations are performed at regular intervals but undoubtedly, these intervals are not the same.

The observations are related to the occurrence of micro and macro cracks over time, variations in selected physical properties (in this study, ρ_d was selected) of dimension stones and some observations on mineralogical transformations. For example, the changes in the ρ_d of dimension stones over time are referred to as “Loss of density”. If the ρ_d decreases by up to 4% over time, this term is used to describe the relative quality of dimension stones. Other qualitative and semi-quantitative observations such as “slightly abraded”, “occurrence of micro-fissures”, “tight rock fabric” and “argillization” were based on macro- and micro-observations performed by field engineers and technicians. Furthermore, the conditions of relative abrasion and fragmentation of dimension stones are also reported by these people.

All these qualitative and semi-quantitative observations, which lasted at least two years, were documented, and objective engineering judgments were made in this direction.

In the light of the above explanations, field observations and the relative quality of the investigated dimension stones are listed in Table 6. Table 6 puts forward a solid basis for unveiling the relative quality of dimension stones based on qualitative and semi-quantitative observations. Accordingly, the relative quality of the studied rock types is quite different due to their mineralogical and physicommechanical properties. Nevertheless, it should be mentioned that the meteorological properties of the area where the dimension stones were used, and the possible surcharge loads acting on them could not have been measured due to the lack of opportunity.

Table 6. Field observations and performance of the investigated rocks

Rock type	Code	Location	Inspection time [year]	Brief explanation of the observations by field engineers	Qualitative field quality and performance
Granite	R1	Ortaköy/ Aksaray	2	Slightly abraded and no fragmentation	very good
Gabbro	R2	Yenice/ Karabük	2	Slightly abraded and occurrence of micro-fissures	good
Basalt	R3	Petek/ Diyarbakır	3	Slightly abraded, the occurrence of micro-fissures and mineral degradation, such as surface oxidation and hollow structure	moderate

Table 6 continued

Limestone	R4	Demre/ Antalya	2	Moderately abraded and fragmented, loss of density	moderate
Granodiorite	R5	Havran/ Balıkesir	2	Slightly abraded and fragmented, no degradation, stiff fabric and texture	good
Andesite	R6	Gökçebey/ Zonguldak	3	Highly abraded and fragmented, the occurrence of weathering signs such as oxidations and argillization	moderate
Limestone	R7	Ereğli/ Zonguldak	4	Slightly abraded, the occurrence of micro-fissures, slight dissolution of calcite veins	moderate
Limestone	R8	Menemen/ Izmir	2	Slightly abraded and fragmented. Surface oxidation. Stiff fabric and texture	moderate
Basalt	R9	Erkilet/ Kayseri	3	No abrasion and fragmentation. Slightly oxidated surfaces and hollow structures	good
Tuff	R10	Urgup/ Nevşehir	2	Highly abraded and fragmented. Apparent hollow structures in/on the rock surfaces. Sensitive to water-rock interactions	very low
Limestone	R11	Beypınarı/ Sivas	3	Moderately abraded and fragmented, slight loss of density. Occurrence of smooth discontinuity surfaces	moderate
Limestone	R12	Darende/ Malatya	3	Moderately abraded and fragmented. Occurrence of weathering signs of argillization and sericitization. Loss of density and slight dissolution of calcite veins	moderate
Dolomitic limestone	R13	Yahyalı/ Kayseri	3	Slightly abraded and no fragmentation. Occurrence of micro-fissures on the rock surfaces. No oxidated rock surfaces	good
Granite	R14	Kaman/ Kırşehir	4	Slightly abraded. No fragmentation. Tight rock fabric and texture. Occurrence of slight oxidation on rock surfaces	good
Limestone	R15	Selimiye/ Antalya	2	Highly abraded and slightly fragmented. Occurrence of micro and macro cracks in/on rock surfaces. Slight dissolution of calcite veins	moderate
Andesite	R16	Mesudiye/ Uşak	3	Highly abraded and fragmented. Occurrence of weathering signs such as sericitization, chloritization, and argillization in and on rock surfaces	moderate
Basalt	R17	Abdipaşa/ Bartın	3	Slightly abraded. Occurrence of slight micro fissures in/on rock surfaces. Slightly oxidated surfaces. Tight rock fabric and texture. No loss of density	good

Table 6 continued

Granodiorite	R18	Vize/ Kırklareli	4	Slightly abraded and fragmented. Surface oxidation and occurrence of micro-fissures in and on rock surfaces. Tight fabric and texture	moderate
Tuff	R19	Aktaş/ Niğde	2	Highly abraded and fragmented. Occurrence of hollow structures. Slight loss of density. Smooth rock surfaces	very low

Despite the absence of these unconsidered parameters, it seems logical to suppose that unveiling the relative quality of the investigated rock types depending on their mineralogical, physical and mechanical properties can provide a realistic and practical approach to selecting proper rock types for their possible use as dimension stones.

3. FUZZY INFERENCE SYSTEM (FIS) ANALYSES

In order to quantify the relative quality of dimension stones based on the information documented in Tables 5 and, several soft computing analyses are performed. In this study, FIS was adopted as a research methodology to establish a comprehensive predictive model for evaluating the dimension stone quality.

Fuzzy sets were first introduced by Zadeh (1965) as a mathematical way to represent linguistic vagueness. The advantage of the FIS comes from the fact that the opinions or experiences of users could be successfully integrated into such analyses by adopting fuzzy sets. Due to this advantage, a wide range of problems from social sciences to various engineering disciplines has been investigated in a detailed manner.

In FIS analyses, input and output parameters are mainly represented by membership functions (i.e., triangular, trapezoidal, gaussian, etc.). Then, if-then rules are defined based on previous experiences related to the engineering problem. Finally, a complete FIS model comprises three constituents: membership functions, if-then rules, and the output. In this study, detailed FIS analyses were performed to estimate the relative quality of investigated dimension stones. In the context of input parameters, ρ_d , w_a , UCS , FS , and BAV values were considered as trapezoidal and triangular membership functions (Fig. 4).

The intervals of the input parameters in membership functions (e.g., uw_1 , uw_2 , uw_3 , etc.) were determined by adopting a heuristic approach. More profoundly, these intervals were changed in every run of FIS analyses until the most optimal solution was rendered. Although it is a time-consuming data processing, it is one of the most confidential methods to identify the membership functions (Yun and Gen 2003; Gorsevski et al. 2006; Hamza et al. 2017). The if-then rules employed in the FIS analysis are also given in Table 7.

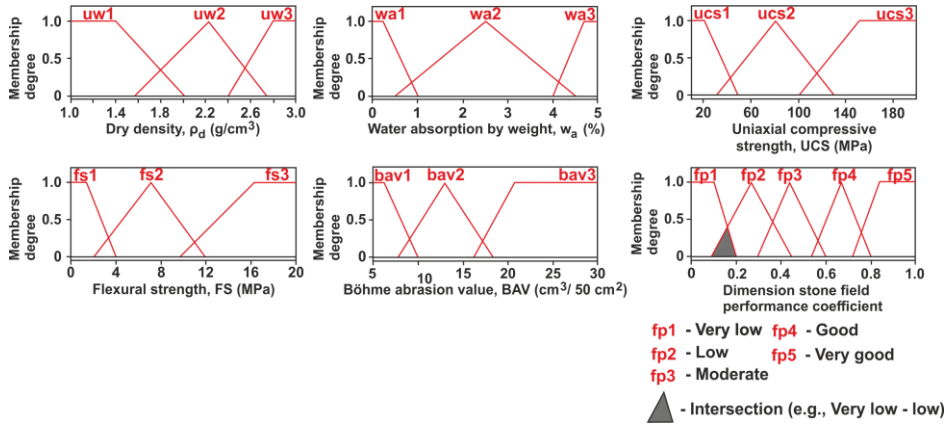


Fig. 4. Membership functions employed in the FIS analyses

By adopting the membership functions (Fig 4) and if-then rules (Table 7), each case was analysed based on the established methodology. As a result of soft computing analyses, a new term “dimension stone field performance coefficient (*DSFPC*)” was defined to quantify the relative quality of dimension stones.

Table 7. If-then rules employed in the FIS analyses

R1	If ρ_d is uw_2 and w_a is wa_1 , and UCS is ucs_2 and FS is fs_3 , and BAV is bav_1 then FP is fp_5
R2	If ρ_d is uw_3 and w_a is wa_1 , and UCS is ucs_3 , and FS is fs_3 , and BAV is bav_2 then FP is fp_5
R3	If ρ_d is uw_3 and w_a is wa_1 , and UCS is ucs_3 , and FS is fs_3 and BAV is bav_1 then FP is fp_4
R4	If ρ_d is uw_3 and w_a is wa_2 , and UCS is ucs_3 , and FS is fs_3 and BAV is bav_1 then FP is fp_4
R5	If ρ_d is uw_3 and w_a is wa_2 , and UCS is ucs_3 , and FS is fs_3 and BAV is bav_1 then FP is fp_5
R6	If ρ_d is uw_2 and w_a is wa_1 , and UCS is ucs_2 and FS is fs_2 , and BAV is bav_1 then FP is fp_3
R7	If ρ_d is uw_3 and w_a is wa_2 , and UCS is ucs_3 , and FS is fs_2 and BAV is bav_2 then FP is fp_3
R8	If ρ_d is uw_2 and w_a is wa_2 , and UCS is ucs_1 , and FS is fs_2 and BAV is bav_2 then FP is fp_2
R9	If ρ_d is uw_3 and w_a is wa_2 , and UCS is ucs_2 and FS is fs_2 , and BAV is bav_2 then FP is fp_2
R10	If ρ_d is uw_2 and w_a is wa_1 , and UCS is ucs_3 , and FS is fs_3 and BAV is bav_1 then FP is fp_4
R11	If ρ_d is uw_3 and w_a is wa_1 , and UCS is ucs_3 , and FS is fs_3 and BAV is bav_1 then FP is fp_4
R12	If ρ_d is uw_2 and w_a is wa_2 , and UCS is ucs_2 and FS is fs_2 , and BAV is bav_3 then FP is fp_2
R13	If ρ_d is uw_2 and w_a is wa_1 , and UCS is ucs_2 and FS is fs_2 , and BAV is bav_2 then FP is fp_3
R14	If ρ_d is uw_2 and w_a is wa_2 , and UCS is ucs_2 and FS is fs_2 , and BAV is bav_2 , then FP is fp_3
R15	If ρ_d is uw_3 and w_a is wa_2 , and UCS is ucs_2 and FS is fs_3 , and BAV is bav_1 , then FP is fp_4
R16	If ρ_d is uw_1 and w_a is wa_3 , and UCS is ucs_1 , and FS is fs_1 and BAV is bav_3 then FP is fp_1
R17	If ρ_d is uw_1 and w_a is wa_3 , and UCS is ucs_1 , and FS is fs_2 and BAV is bav_3 then FP is fp_1
R18	If ρ_d is uw_2 and w_a is wa_2 , and UCS is ucs_2 and FS is fs_2 , and BAV is bav_2 then FP is fp_2
R19	If ρ_d is uw_3 and w_a is wa_2 , and UCS is ucs_2 and FS is fs_2 , and BAV is bav_2 then FP is fp_2
R20	If ρ_d is uw_2 and w_a is wa_2 , and UCS is ucs_2 and FS is fs_2 , and BAV is bav_1 then FP is fp_2

Table 7 continued

R21	If ρ_d is uw_3 and w_a is w_{a_2} , and UCS is ucs_2 and FS is fs_2 , and BAV is bav_1 then FP is fp_2
R22	If ρ_d is uw_2 and w_a is w_{a_1} , and UCS is ucs_2 and FS is fs_3 , and BAV is bav_1 then FP is fp_3
R23	If ρ_d is uw_3 and w_a is w_{a_1} , and UCS is ucs_3 , and FS is fs_3 and BAV is bav_1 then FP is fp_3
R24	If ρ_d is uw_2 and w_a is w_{a_1} , and UCS is ucs_2 and FS is fs_2 , and BAV is bav_1 then FP is fp_4
R25	If ρ_d is uw_3 and w_a is w_{a_1} , and UCS is ucs_3 , and FS is fs_3 and BAV is bav_1 then FP is fp_4
R26	If ρ_d is uw_2 and w_a is w_{a_1} , and UCS is ucs_2 and FS is fs_2 , and BAV is bav_2 then FP is fp_2
R27	If ρ_d is uw_2 and w_a is w_{a_1} , and UCS is ucs_2 and FS is fs_2 , and BAV is bav_3 then FP is fp_2
R28	If ρ_d is uw_2 and w_a is w_{a_2} , and UCS is ucs_2 and FS is fs_3 , and BAV is bav_3 then FP is fp_2
R29	If ρ_d is uw_3 and w_a is w_{a_1} , and UCS is ucs_3 , and FS is fs_3 and BAV is bav_1 then FP is fp_4
R30	If ρ_d is uw_2 and w_a is w_{a_2} , and UCS is ucs_2 and FS is fs_3 , and BAV is bav_1 then FP is fp_3
R31	If ρ_d is uw_2 and w_a is w_{a_1} , and UCS is ucs_3 , and FS is fs_3 and BAV is bav_2 then FP is fp_3
R32	If ρ_d is uw_1 and w_a is w_{a_3} , and UCS is ucs_1 , and FS is fs_1 and BAV is bav_3 then FP is fp_1
R33	If ρ_d is uw_1 and w_a is w_{a_3} , and UCS is ucs_1 , and FS is fs_2 and BAV is bav_3 then FP is fp_1

4. RESULTS AND DISCUSSION

4.1. FIS ANALYSES RESULTS

Based on the above explanations, 627 FIS analyses were performed in total. The FIS analysis results are shown in Table 8. Accordingly, the $DSFPC$ values ranged from 0.09 to 0.76. In this respect, the higher the $DSFPC$ values, the higher the quality of the dimension stone. When the actual field performances were compared with those estimated from the proposed FIS model, it was concluded that this comparison seems in good agreement.

Table 8. FIS analysis results

Rock type	Code	Location	Reported field performance	$DSFPC$	Field performance estimation through FIS
Granite	R1	Ortaköy/Aksaray	very good	0.57	moderate-good
Gabbro	R2	Yenice/Karabük	good	0.55	moderate-good
Basalt	R3	Petek/Diyarbakır	moderate	0.64	good
Limestone	R4	Demre/Antalya	moderate	0.34	low-moderate
Granodiorite	R5	Havran/Balıkesir	good	0.55	moderate-good
Andesite	R6	Gökçebey/Zonguldak	moderate	0.27	low
Limestone	R7	Ereğli/Zonguldak	moderate	0.34	low-moderate
Limestone	R8	Menemen/Izmir	moderate	0.34	low-moderate
Basalt	R9	Erkilet/Kayseri	good	0.76	good-very good
Tuff	R10	Urgup/Nevşehir	very low	0.09	very low

Table 8 continued

Limestone	R11	Beyınarı/Sivas	moderate	0.33	low-moderate
Limestone	R12	Darende/Malatya	moderate	0.32	low-moderate
Dolomitic limestone	R13	Yahyalt/Kayseri	good	0.59	moderate-good
Granite	R14	Kaman/Kırşehir	good	0.60	good
Limestone	R15	Selimiye/Antalya	moderate	0.34	low-moderate
Andesite	R16	Mesudiye/Uşak	moderate	0.27	low
Basalt	R17	Abdipaşa/Bartın	good	0.57	moderate-good
Granodiorite	R18	Vize/Kırklareli	moderate	0.55	moderate-good
Tuff	R19	Aktaş/Niğde	very low	0.09	very low

Nevertheless, field performance estimation through FIS can be accepted as a flexible approach. It means that a significant number of the cases (13/19) was found to be between the intersections (e.g., moderate-good or low-moderate, etc.) of the membership functions given in Fig. 4.

In addition, the relationship between *DSFPC* and input rock parameters (i.e., ρ_d , w_a , *UCS*, *FS*, and *BAV*) was also investigated through Pearson's correlation analysis (Table 9). Accordingly, it can be claimed that *UCS* and *BAV* can be declared the most essential rock parameters to reveal the quality of dimension stones. On the other hand, the rest of the considered rock properties (ρ_d , w_a , and *FS*) are moderately correlated with *DSFPC*. All these rock properties determined in this study constitute a solid basis for estimating the dimension stone quality. Köken and Başpınar Tuncay (2022) also considered the adopted rock properties to reveal the cladding stone quality of some andesitic rocks from Turkey.

Table 9. Pearson's correlation matrix of the input parameters in the FIS analyses

Parameter	ρ_d	w_a	<i>UCS</i>	<i>FS</i>	<i>BAV</i>	<i>DSFPC</i>
ρ_d	1					
w_a	-0.935	1				
<i>UCS</i>	0.816	-0.713	1			
<i>FS</i>	0.739	-0.653	0.944	1		
<i>BAV</i>	-0.854	0.730	-0.827	-0.731	1	
<i>DSFPC</i>	0.772	-0.646	0.846	0.795	-0.928	1

4.2. ESTIMATING *DSFPC* BASED ON MINERALOGICAL FEATURES AND NON-DESTRUCTIVE TESTING METHODS

The relationship between *DSFPC* values and mineralogical features of the investigated rock types is revealed by a simple approach proposed by Oparin and Tanaino (2015). Using the Mohs hardness values of the rock-forming minerals, mineralogical features

were identified as relative rock hardness (RRH), which is determined by Eq. (1).

$$RRH = 0.01 \sum_{i=1}^n M_i \otimes R_i, \quad (1)$$

where M_i is the Mohs hardness value of the individual mineral (Federal Highway Administration, 1991), and R_i is the areal percentage of the related minerals observed in the thin section (Table 4).

Based on the calculated RRH values (Table 10), the correlation between $DSFPC$ and RRH values was found to be 0.555, which is statistically meaningful. For estimating varying $DSFPC$ values based on non-destructive testing methods (i.e., w_a , ρ_d , and RRH), multiple regression analyses were performed. As a result of the regression analyses, $DSFPC$ can be estimated using Eq. (2).

$$DSFPC = -1.307 + 0.597\rho_d + 0.017w_a + 0.042RRH, R^2 = 0.73. \quad (2)$$

Table 10. Calculated RRH values for each case

Rock type	RRH	Rock type	RRH	Rock type	RRH
R1	6.12	R8	3.01	R15	3.03
R2	5.96	R9	5.94	R16	5.42
R3	4.32	R10	3.71	R17	5.87
R4	2.76	R11	3.10	R18	6.06
R5	5.96	R12	2.77	R19	3.56
R6	5.58	R13	3.28	Note: RRH values were calculated using Eq. (1).	
R7	3.05	R14	6.43		

4.3. ESTIMATING DSFPC BASED ON ARTIFICIAL NEURAL NETWORKS (ANN)

In the previous section, a regression-based predictive model was introduced to estimate $DSFPC$ values (see Eq. (2)). However, the correlation of determination value (R^2) of the presented method is not satisfactory for precise estimations of $DSFPC$ values. For the sake of clarity, artificial neural networks (ANN) analyses were additionally performed to set forth a mathematical background in that $DSFPC$ values could be easily calculated using the input parameters of ρ_d , w_a , UCS , FS , and BAV .

In this respect, ANN analyses were performed in the MATLAB environment. Before performing ANN analyses, the dataset (Table 5) was normalized between $[-1, 1]$ using Eq. (3).

$$x_{\text{norm}} = \frac{2(x_i - x_{\min})}{x_{\max} - x_{\min}} - 1, \quad (3)$$

where x_{norm} is the normalized data, and x_i is the relevant data to be normalized, x_{\min} and x_{\max} are the minimum and maximum values in the dataset, respectively.

The ANN architecture is 5–4–1. It means that there are five inputs (ρ_d , w_a , UCS , FS , and BAV), four hidden layers, and one output ($DSFPC$). As a result of the ANN analyses, $DSFPC$ can be estimated using Eqs. (4)–(13). The performance of the above-mentioned predictive model is also illustrated through a scatter plot (Fig. 5). The R^2 for the established ANN model was found to be 0.98, which indicates the success of the ANN-based model.

$$DSFPC = 0.335 \tanh \left[\sum_{i=1}^4 A_i - 2.9391 \right] + 0.425, \quad (4)$$

$$A_1 = 1.4646 \tanh \left[\begin{array}{l} 3.7451\rho_d^n - 2.805w_a^n + 1.816UCS^n + 3.2134FS^n \\ -2.8635BAV^n + 1.4295 \end{array} \right], \quad (5)$$

$$A_2 = -0.79143 \tanh \left[\begin{array}{l} -0.7449\rho_d^n + 1.217w_a^n + 0.167UCS^n - 0.522FS^n \\ +2.0542BAV^n - 2.2584 \end{array} \right], \quad (6)$$

$$A_3 = -2.452 \tanh \left[\begin{array}{l} -1.7337\rho_d^n - 3.4058w_a^n + 0.993UCS^n + 1.266FS^n \\ +1.469BAV^n - 1.4541 \end{array} \right], \quad (7)$$

$$A_4 = 3.1299 \tanh \left[\begin{array}{l} 0.4704\rho_d^n + 0.4750w_a^n + 0.4635UCS^n + 1.6762FS^n \\ +0.6654BAV^n + 0.8613 \end{array} \right]. \quad (8)$$

Normalization equations:

$$\rho_d^n = 1.3793\rho_d - 3.0138, \quad (9)$$

$$w_a^n = 0.085w_a - 1.0068, \quad (10)$$

$$UCS^n = 0.0129UCS - 1.1322, \quad (11)$$

$$FS^n = 0.1248FS - 1.2545, \quad (12)$$

$$BAV^n = 0.0872BAV - 1.4605. \quad (13)$$

The quantitative approach based on the ANN methodology (Eqs. (4)–(13)) can be reliably used to estimate the quality of dimension stones. As stated previously higher *DSFPC* values indicate dimension stones with higher quality. However, *DSFPC* values should be classified to have a better understanding of how *DSFPC* reflects dimension stone quality. The following section presents a comparison of some quantitative approaches used to reveal dimension stone quality and the classification of *DSFPC* values.

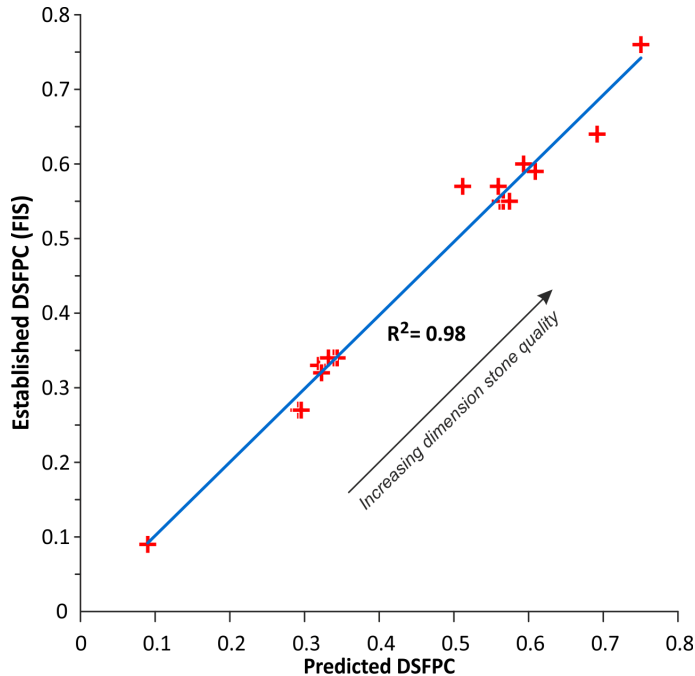


Fig. 5. Scatter plot of the developed ANN model

4.4. COMPARISON OF SOME QUANTITATIVE APPROACHES FOR THE EVALUATION OF DIMENSION STONE QUALITY

The comparison of some approaches used to estimate dimension stone quality was made by focusing on the quantitative classifications of natural stone products (Table 2), actual field performance evaluations (Table 6) and the FIS analysis results (Table 8). Table 11 shows that the actual field performances of the investigated rock types seem in good agreement with the FIS analysis results and the outputs found on the classification systems by Strzałkowski et al. (2023). It means that the dimension stone quality can be reliably assessed both by considering the quantitative classifications in Table 2 and the proposed FIS model.

In this regard, dimension stone quality can be quantified and classified by calculating DSFPC values. In order to have a general understanding of dimension stone quality, Eq. (2) can be considered. Nevertheless, for precise estimations, the ANN-based predictive model can be reliably adopted.

Table 11. Comparison of the dimension stone quality based on different approaches

Strzałkowski et al. (2023)						The present study	
Rock code	Criterion I (ρ_d)	Criterion II (w_d)	Criterion III (UCS)	Criterion IV (BAV)	Criterion V (FS)	Actual field performance	Field performance estimation through FIS
R1	very high	very high	high	very high	very high	very good	moderate-good
R2	very high	very high	high	very high	very high	good	moderate-good
R3	very high	very high	high	very high	moderate	moderate	good
R4	high	high	moderate	high	low	moderate	low-moderate
R5	very high	very high	high	very high	low	good	moderate-good
R6	high	high	moderate	high	moderate	moderate	low
R7	very high	very high	moderate	high	moderate	moderate	low-moderate
R8	high	high	moderate	high	low	moderate	low-moderate
R9	very high	high	high	very high	low	good	good-very good
R10	low	medium	low	moderate	very low	very low	very low
R11	very high	high	moderate	high	low	moderate	low-moderate
R12	very high	high	moderate	very high	low	moderate	low-moderate
R13	very high	very high	high	very high	high	good	moderate-good
R14	very high	very high	high	very high	moderate	good	good
R15	very high	very high	moderate	high	moderate	moderate	low-moderate
R16	very high	very high	moderate	high	moderate	moderate	low
R17	very high	very high	high	very high	very high	good	moderate-good
R18	very high	very high	high	very high	high	moderate	moderate-good
R19	very low	very low	very low	moderate	very low	very low	very low

When it comes to integrating varying DSFPC values into the quantitative classification in Table 2, a fuzzy-based clustering algorithm was adopted. This clustering analysis was performed in the MATLAB environment.

As a result of the clustering analyses, different DSFPC values can also be used to rank dimension stones by their relative quality (Table 12). In addition to the quality classifications by Strzałkowski et al. (2023), the proposed FIS model can be regarded as a practical tool to assess the dimension stone quality. With the help of this approach, quarry managers can save time and energy when investigating proper rock exposures for dimension stone manufacturing. However, in future studies, the number

of case studies should be increased to have a better classification system based on varying *DSFPC* values.

Table 12. Integration of *DSFPC* values to the quantitative classification by Strzałkowski et al. (2023)

Criterion I ρ_d [g/cm ³]	Criterion II w_a [%]	Criterion III <i>BAV</i> [cm ³ /50 cm ²]	Criterion IV <i>UCS</i> [MPa]	Criterion V <i>FS</i> [MPa]	Classification	<i>DSFPC</i>
<1.5	>20	>55	<15	<4	very low	<0.10
1.5–1.8	14.5–20	40–55	15–50	4–8	low	0.10–0.30
1.8–2.2	8.0–14.5	25–40	50–120	8–12	moderate	0.30–0.60
2.2–2.6	1.0–8.0	10–25	120–200	12–16	high	0.60–0.75
>2.6	<1.0	<10	>200	>16	very high	>0.75

Note: *DSFPC* values can be calculated by considering Eq. (2) and Eqs. (4)–(13).

4.5. FURTHER INVESTIGATIONS ON ASSESSING DIMENSION STONE QUALITY

As stated earlier, the meteorological properties of the area where the dimension stones were used, and the possible surcharge loads acting on the dimension stones could not have been integrated into the FIS analyses due to the lack of opportunity. Actually, meteorological variations and surcharge loads can be essential parameters influencing the occurrence of micro and macro cracks in/on rock surfaces over time (Tang and Kou 1998; Maurício et al. 2010; Nara et al. 2011; Wang et al. 2022).

Consequently, these micro and macro cracks make the rock more sensitive to thermal decay, salt crystallization, and freeze-thaw effects. The presence of these phenomena necessitates that the presented FIS model should be improved by adding the above-mentioned factors for specific regions. The present study in this regard can be declared a case study showing the applicability of FIS for evaluating dimension stone quality.

There is no doubt that the variations in dimension stone quality can also be specific to varying environmental and loading conditions. From this point of view, dimension stone quality can also be regarded not only for general purposes but also for specific areas of interest.

In addition, it should also be noted that geometric quality (Hazrathosseini and Mahdevari 2019) and stone aesthetics (Loudes et al. 2000; Akkoyun and Fuat Toprak 2012; Hailesslassie et al. 2019; Yarahmadi et al. 2019; Pereira et al. 2023) are the other critical concerns for the dimension stone industry, could be included when assessing dimension stones from the point of engineering economics. Unquestionably, all these considerations (i.e., strength, abrasion, fragmentation, geometric quality, aesthetic value) may constitute a full understanding of the technical and economic value of dimension

stones. The present study, in this respect, can contribute to the dimension stone industry by proposing a novel evaluation methodology based on critical physical and mechanical rock properties.

5. CONCLUSIONS

The assessment of dimension stones is a complex issue because of many factors (aesthetics, geometrical features, and physical and mechanical rock properties). However, when considering the industrial use of suitable rocks on a large scale, the technical parameters based on physical and mechanical rock properties become prominent. In this respect, the present study introduces an FIS-based method to assess the dimension stone quality. In the analyses, critical physical and mechanical rock properties (ρ_d , w_a , UCS , FS , and BAV) were used as input parameters. Based on the FIS analysis results, it is found that the higher the $DSFPC$ value, the higher the quality of the dimension stone. In addition, the relationships between $DSFPC$ and considered rock properties are investigated through Pearson's correlation analyses. Accordingly, UCS and BAV can be regarded as essential rock properties for rough estimations of dimension stone quality. On the other hand, for precise assessments, regression and ANN analyses are also performed to estimate $DSFPC$ values. As a result of these analyses, a novel ANN-based predictive model is developed, which can successfully estimate varying $DSFPC$ values.

The actual performances of the dimension stones are also compared by considering different approaches (Table 11) and it is concluded that the proposed FIS model can reliably be used to quantify the dimension stone quality. $DSFPC$ values are classified based on a fuzzy-based clustering algorithm (Table 12).

In conclusion, the proposed FIS model can be declared a flexible way of representing the dimension stone quality. It means that the proposed FIS model reflects the actual field performance of the investigated dimension stones. However, unconsidered parameters such as meteorological data, and possible surcharge loads should be integrated into the FIS analyses in future studies. Last but not least, the number of case studies should be increased to have a better classification of $DSFPC$.

ABBREVIATIONS

ρ_d	–	dry density [g/cm ³]
w_a	–	water absorption by weight [%]
n_e	–	effective porosity [%]
UCS	–	uniaxial compressive strength [MPa]
FS	–	flexural strength [MPa]
BAV	–	Böhme abrasion value [cm ³ /50 cm ²]
V_p	–	pulse wave velocity [km/s]

Qtz.	–	quartz
Orth.	–	orthoclase
Plg.	–	plagioclase
Pyrx.	–	pyroxene
Ol.	–	olivine
Horn.	–	hornblende
Bt.	–	biotite
Mus.	–	muscovite
Ep.	–	epidote
Clay min.	–	clay minerals
Lim.	–	limonite
Sid.	–	siderite
Cal.	–	calcite
Cal. mud.	–	calcite mud
Dol.	–	dolomite
Opaque min.	–	opaque mineral
ISRM	–	International Society of Rock Mechanics
FIS	–	Fuzzy inference system
ANN	–	artificial neural networks
DSFPC	–	dimension stone field performance coefficient

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