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# A NOVEL EVALUATION METHODOLOGY FOR DIMENSION STONE QUALITY

Ekin KÖKEN[1]*, Paweł STRZAŁKOWSKI[2]

[1] Nanotechnology Engineering Department, Engineering Faculty, Abdullah Gul University, 38100 Kayseri, Turkey, ORCID ID: 0000-0003-0178-329X

[2] Department of Mining, Faculty of Geoengineering, Mining and Geology, Wroclaw University of Science and Technology, Wybrzeże Wyspiańskiego 27, 50-370 Wrocław, Poland, ORCID ID: 0000-0002-2920-4512

**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 physicomechanical 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).

* Corresponding author: ekin.koken@agu.edu.tr (E. Köken)

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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 (Frascá 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 $\rho_d$ [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 mechanical 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 ($\rho_d$), 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 ($\rho_d$), 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.

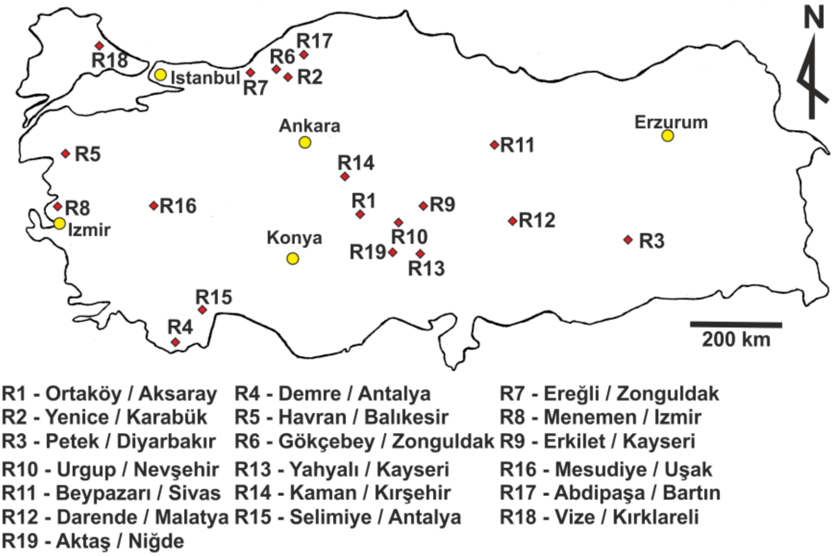


Fig. 1. Sampling location map of the investigated rocks

Table 3. Number of specimens used in different laboratory tests

| Rock type | Code | Location | Number of tests employed | | | | |
|---|---|---|---|---|---|---|---|
| | | | $\rho_d$ [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 × 70 × 70 mm) and prismatic (50 × 50 × 300 mm) rock samples were prepared to determine physicomechanical rock properties. The physical properties determined in this study are $\rho_d$ 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.

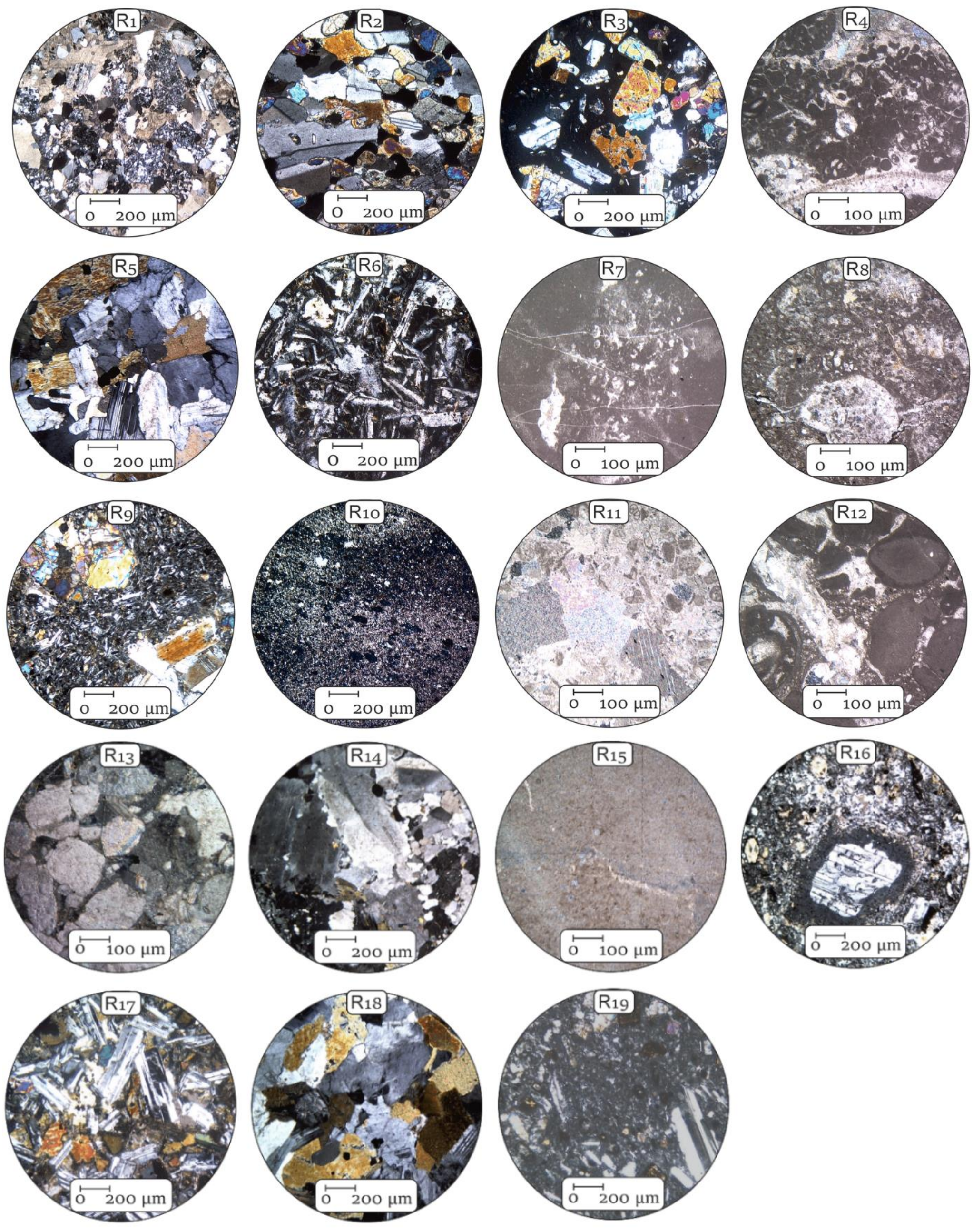


Fig. 2. Sampling location map of the investigated rocks

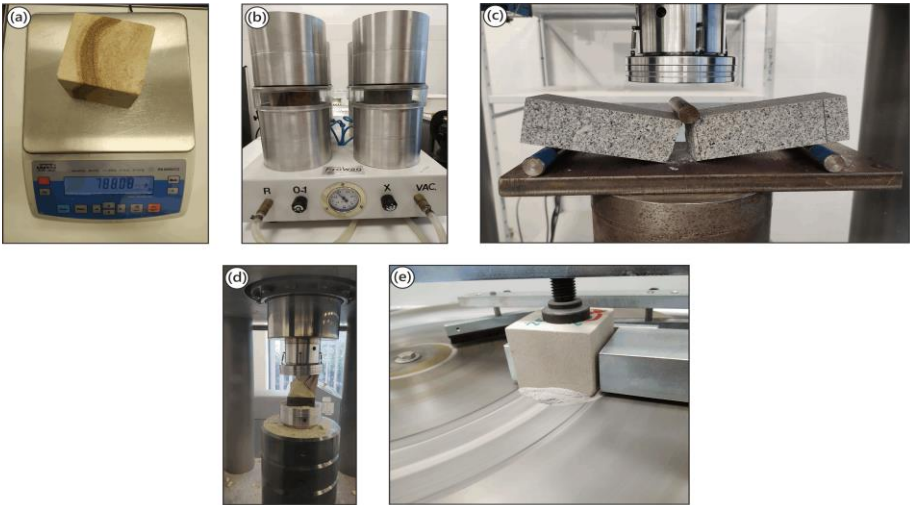


Fig. 3. Some of the laboratory studies: a) determination of the oven-dried weight for a cubical rock sample, b) Determination of $w_a$, c) *FS* test, d) *UCS* test, e) *BAV* test

Table 5. Laboratory test results

| Rock type | Code | $\rho_d$ [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, $\rho_d$ was selected) of dimension stones and some observations on mineralogical transformations. For example, the changes in the $\rho_d$ of dimension stones over time are referred to as "Loss of density". If the $\rho_d$ 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 physicomechanical 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, $\rho_d$, $w_a$, *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.

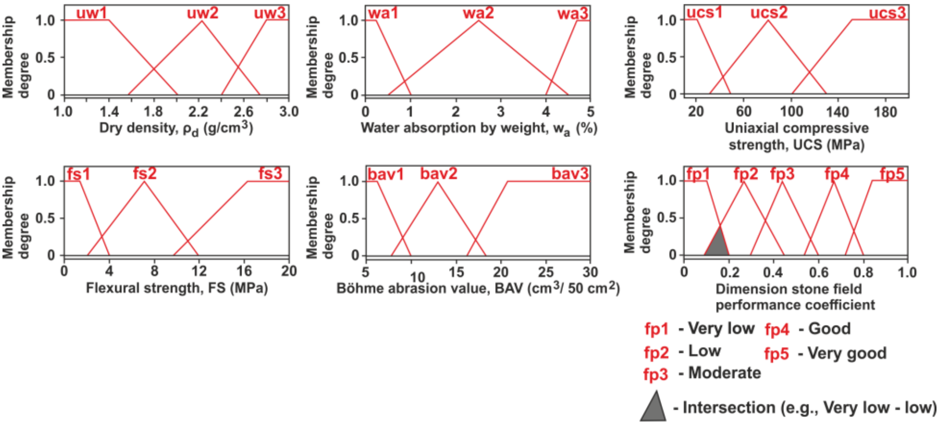


Fig. 4. Membership functions employed in the FIS analyses

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 $\rho_d$ 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 $fp_5$ |
| R2 | If $\rho_d$ is $uw_3$ and $w_a$ is $w_{a_1}$, and *UCS* is $ucs_3$, and *FS* is $fs_3$, and *BAV* is $bav_2$ then *FP* is $fp_5$ |
| R3 | If $\rho_d$ 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 $fp_4$ |
| R4 | If $\rho_d$ is $uw_3$ and $w_a$ is $w_{a_2}$, and *UCS* is $ucs_3$, and *FS* is $fs_3$ and *BAV* is $bav_1$ then *FP* is $fp_4$ |
| R5 | If $\rho_d$ is $uw_3$ and $w_a$ is $w_{a_2}$, and *UCS* is $ucs_3$, and *FS* is $fs_3$ and *BAV* is $bav_1$ then *FP* is $fp_5$ |
| R6 | If $\rho_d$ 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 $fp_3$ |
| R7 | If $\rho_d$ is $uw_3$ and $w_a$ is $w_{a_2}$, and *UCS* is $ucs_3$, and *FS* is $fs_2$ and *BAV* is $bav_2$ then *FP* is $fp_3$ |
| R8 | If $\rho_d$ is $uw_2$ and $w_a$ is $w_{a_2}$, and *UCS* is $ucs_1$, and *FS* is $fs_2$ and *BAV* is $bav_2$ then *FP* is $fp_2$ |
| R9 | If $\rho_d$ is $uw_3$ and $w_a$ is $w_{a_2}$, and *UCS* is $ucs_2$ and *FS* is $fs_2$, and *BAV* is $bav_2$ then *FP* is $fp_2$ |
| R10 | If $\rho_d$ is $uw_2$ and $w_a$ is $w_{a_1}$, and *UCS* is $ucs_3$, and *FS* is $fs_3$ and *BAV* is $bav_1$ then *FP* is $fp_4$ |
| R11 | If $\rho_d$ 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 $fp_4$ |
| R12 | If $\rho_d$ is $uw_2$ and $w_a$ is $w_{a_2}$, and *UCS* is $ucs_2$ and *FS* is $fs_2$, and *BAV* is $bav_3$ then *FP* is $fp_2$ |
| R13 | If $\rho_d$ 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 $fp_3$ |
| R14 | If $\rho_d$ is $uw_2$ and $w_a$ is $w_{a_2}$, and *UCS* is $ucs_2$ and *FS* is $fs_2$, and *BAV* is $bav_2$, then *FP* is $fp_3$ |
| R15 | If $\rho_d$ is $uw_3$ 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 $fp_4$ |
| R16 | If $\rho_d$ 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 $fp_1$ |
| R17 | If $\rho_d$ 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 $fp_1$ |
| R18 | If $\rho_d$ is $uw_2$ and $w_a$ is $w_{a_2}$, and *UCS* is $ucs_2$ and *FS* is $fs_2$, and *BAV* is $bav_2$ then *FP* is $fp_2$ |
| R19 | If $\rho_d$ is $uw_3$ and $w_a$ is $w_{a_2}$, and *UCS* is $ucs_2$ and *FS* is $fs_2$, and *BAV* is $bav_2$ then *FP* is $fp_2$ |
| R20 | If $\rho_d$ is $uw_2$ 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 $fp_2$ |

Table 7 continued

| | |
|---|---|
| R21 | If $\rho_d$ 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 $\rho_d$ 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 $\rho_d$ 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 $\rho_d$ 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 $\rho_d$ 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 $\rho_d$ 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 $\rho_d$ 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 $\rho_d$ 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 $\rho_d$ 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 $\rho_d$ 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 $\rho_d$ 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 $\rho_d$ 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 $\rho_d$ 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 | Beypınarı/Sivas | moderate | 0.33 | low-moderate |
| Limestone | R12 | Darende/Malatya | moderate | 0.32 | low-moderate |
| Dolomitic limestone | R13 | Yahyalı/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., $\rho_d$, $w_a$, *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 ($\rho_d$, $w_a$, 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 | $\rho_d$ | $w_a$ | *UCS* | *FS* | *BAV* | *DSFPC* |
|---|---|---|---|---|---|---|
| $\rho_d$ | 1 | | | | | |
| $w_a$ | −0.935 | 1 | | | | |
| *UCS* | 0.816 | −0.713 | 1 | | | |
| *FS* | 0.739 | −0.653 | 0.944 | 1 | | |
| *BAV* | −0.854 | 0.730 | −0.827 | −0.731 | 1 | |
| *DSFPC* | 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).

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

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., $w_a$, $\rho_d$, and *RRH*), multiple regression analyses were performed. As a result of the regression analyses, *DSFPC* can be estimated using Eq. (2).

$$DSFPC = -1.307 + 0.597\rho_d + 0.017w_a + 0.042RRH,\ R^2 = 0.73. \tag{2}$$

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 (R2) 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 $\rho_d$, $w_a$, *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).

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

where $x_{\text{norm}}$ 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 ($\rho_d$, $w_a$, *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.

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

$$A_1 = 1.4646\tanh\begin{bmatrix} 3.7451\rho_d^n - 2.805w_d^n + 1.816UCS^n + 3.2134FS^n \\ -2.8635BAV^n + 1.4295 \end{bmatrix}, \tag{5}$$

$$A_2 = -0.79143\tanh\begin{bmatrix} -0.7449\rho_d^n + 1.217w_a^n + 0.167UCS^n - 0.522FS^n \\ +2.0542BAV^n - 2.2584 \end{bmatrix}, \tag{6}$$

$$A_3 = -2.452\tanh\begin{bmatrix} -1.7337\rho_d^n - 3.4058w_a^n + 0.993UCS^n + 1.266FS^n \\ +1.469BAV^n - 1.4541 \end{bmatrix}, \tag{7}$$

$$A_4 = 3.1299\tanh\begin{bmatrix} 0.4704\rho_d^n 0.4750w_a^n + 0.4635UCS^n + 1.6762FS^n \\ +0.6654BAV^n + 0.8613 \end{bmatrix}. \tag{8}$$

Normalization equations:

$$\rho_d^n = 1.3793\rho_d - 3.0138, \tag{9}$$

$$w_a^n = 0.085w_a - 1.0068, \tag{10}$$

$$UCS^n = 0.0129UCS - 1.1322, \tag{11}$$

$$FS^n = 0.1248FS - 1.2545, \tag{12}$$

$$BAV^n = 0.0872BAV - 1.4605. \tag{13}$$

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.

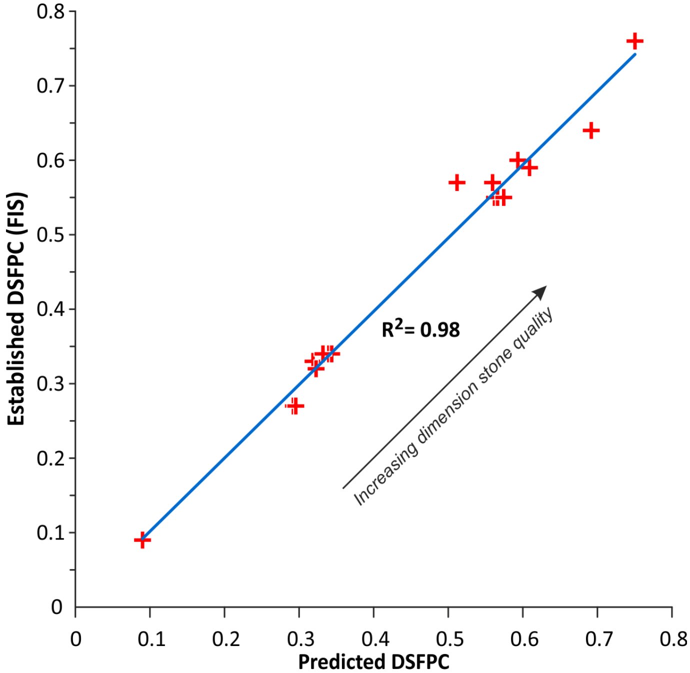


Fig. 5. Scatter plot of the developed ANN model

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 ($\rho_d$) | Criterion II ($w_a$) | 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 $\rho_d$ [g/cm$^3$] | Criterion II $w_a$ [%] | Criterion III *BAV* [cm$^3$/50 cm$^2$] | Criterion IV *UCS* [MPa] | Criterion V *FS* [MPa] | Classification | *DSFPC* |
|---|---|---|---|---|---|---|
| <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; Haileslassie 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 ($\rho_d$, $w_a$, *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

$\rho_d$ – 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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