Research, Society and Development, v. 11, n. 12, e478111234956, 2022
(CC BY 4.0) | ISSN 2525-3409 | DOI: http://dx.doi.org/10.33448/rsd-v11i12.34956

Quality index of dimension stones for application in building industry using technological characterization lab tests

Índice de qualidade de rochas ornamentais para aplicação na indústria de construção civil usando ensaios de caracterização tecnológica em laboratório

Índice de calidad de piedra natural para utilización en construcción con base en ensayos de laboratorio de caracterización tecnológica

Received: 09/05/2022 | Reviewed: 09/11/2022 | Accept: 09/13/2022 | Published: 09/21/2022

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Abstract
Dimension stones have been used in many different environments, like airports, shopping malls, commercial buildings and houses, due to their beauty and quality. However, the choice of the ideal material for application in a given environment is a challenging decision. Esthetic patterns determine the choice in most of the cases, instead of the physical and mechanical properties, which can cause damages and even accidents. Thus, this research aims to propose a quality index using technological characterization lab tests established by international and national regulations. This index can be used to help practitioners in the choice of the proper dimension stone for a given environment, minimizing pathologies. An extensive database encompassing many lab tests for technological characterization of dimension stones was used in this research.
Keywords: Dimension stones; Quality index; Technological characterization lab tests; Building industry.

Resumo
Rochas ornamentais têm sido utilizadas em muitos ambientes diferentes, como aeroportos, shoppings, edifícios comerciais e residências, devido à sua beleza e qualidade. Entretanto, a escolha do material ideal para aplicação em determinado ambiente é um desafio. Padrões estéticos determinam essa escolha na maioria dos casos, em vez das características físicas e propriedades mecânicas; o que pode causar danos e até acidentes. Assim, este trabalho tem como objetivo propor um índice de qualidade utilizando os ensaios de caracterização tecnológica estabelecidos por normas internacionais e nacionais. Este índice pode ser utilizado para auxiliar os profissionais na escolha de uma rocha ornamental apropriada para aplicação em determinado ambiente, minimizando patologias. Um expressivo banco de dados contendo ensaios de laboratório para caracterização tecnológica de rochas ornamentais foi utilizado nessa pesquisa.
Palavras-chave: Rochas ornamentais; Índice de qualidade; Ensaios de caracterização tecnológica em laboratório; Construção civil.

Resumen
La piedra natural se emplea en muy distintos entornos, como aeropuertos, centros comerciales, oficinas y residencias, debido a su belleza y calidad. Sin embargo, es un desafío seleccionar el material ideal para su utilización en un determinado ambiente. La estética, en lugar de las propiedades físicas y mecánicas, determina la piedra escogida en la mayoría de los casos, lo que puede causar una serie de daños e incluso accidentes. Por consiguiente, este trabajo pretende proponer un índice de calidad a partir de ensayos de laboratorio de caracterización tecnológica establecidos en normas internacionales y nacionales. Este índice puede ser utilizado para ayudar a los profesionales en la elección

de la piedra más adecuada para cada ambiente, reduciendo al mínimo las patologías. En esta investigación se ha empleado una extensa base de datos de resultados de caracterización tecnológica de piedra natural.
Palabras clave: Piedra natural, Índice de calidad, Ensayos de laboratorio de caracterización tecnológica, Construcción civil.

1. Introduction

According to the American Society for Testing and Materials (ASTM) (2012), a dimension stone is defined as any rocky material that can be sawed or cut in slabs, which may have a mechanical finishing or not, excluding artificial products consisting of aggregates, fragments and ground or broken stones.

The main types of dimension stones are granite, limestone, marble, sandstone, quartzite and slate, even though a great variety of igneous, metamorphic or sedimentary rocks can also be used. However, according to Alade & Olayinka (2012), not all dimension stones are eligible to be applied in the building industry.

From a commercial point of view, the Marble Institute of America (MIA) (2016), dimension stones are classified into three major groups: granites (which may include other igneous and metamorphic rocks), marble (limestone, travertine and onyx) and quartzite (sandstones, metaconglomerates and other quartz-rich rocks).

The building industry and the architecture have intensively used dimension stones for building cladding, due to their durability, ease of maintenance and cleaning, beauty and flexibility. Basic requirements for their application are the color, texture and grain pattern. Other important selection criteria are durability (essentially related to mineral composition, hardness and performance), strength and ability to be processed (Dolley, 2004).

According to Frascá (2010), despite the intensive use of dimension stones, the incorrect applicability or the lack of adequate maintenance can cause pathologies, which are changes in the characteristics of the rocks that occur during or after the execution of a construction. Some of the main pathologies are the detachment of slabs, failure by compression and/or tension, loss of brightness in a short exposure time, excessive superficial damage and stains.

This work aims to propose a quality index for dimension stones, using the results of the technological characterization lab tests established by international and national regulations. This proposal intends to help practitioners in the choice of a dimension stone for a given environment, not only considering their aesthetic characteristics, but especially their strength and durability, avoiding the development of pathologies.

An extensive database containing many lab tests for technological characterization of dimension stones encompassing many different Brazil regions was used in this research.

2. Characterization Technological Tests for Dimension Stones

The technological properties and physical characteristics of dimension stones are obtained by lab tests and descriptions, according to regulations established by national and international rules.

The regulations for the characterization lab tests of dimension stones are given by ABNT NBR 15.844, ABNT NBR 15.012 and their international equivalent norms (ASTM and CEN), Table 1.

Table 1: Standard tests for technological characterization of dimension stones.

Tests	Brazilian regulations	International regulations
Petrographic description	ABNT NBR 15.844 - 1	CEN 12407:2019 ASTM C 1721 - 21
Bulk Specific Gravity, apparent porosity and water absorption	ABNT NBR 15.844 - 2	ASTM C 97/C 97M - 18 ASTM C 121/C121M – 20 (slate) CEN 1936:2006
Linear Thermal Expansion	ABNT NBR 15.844 - 3	CEN 14581:2004 ASTM 228 - 17
Durability of rock under freezing and thawing conditions	ABNT NBR 15.844 - 4	ASTM D5312 - 12 CEN 12371:2010
Uniaxial compressive strength	ABNT NBR 15.844 - 5	ASTM C170/C170M-17 CEN 1926:2006
Modulus of Rupture	ABNT NBR 15.844 - 6	ASTM C99/C99M - 18 CEN 12372:2006
Flexural strength	ABNT NBR 15.844 -7	ASTM C880/C880M - 18 ASTM C120/C120M – 19 (slate) CEN13161: 2008
Rupture energy	ABNT NBR 15.844 - 8	CEN 14158:2004
Amsler Abrasion Resistance	ABNT NBR 12.042	ASTM C1353 / C1353M - 20

Source: Adapted from Chiodi Filho et.al. (2020).

The tests of dimension stones presented in Table 1 yield parameters that guide practitioners to specify these rocks for their potential applications. Reference values for dimension stone properties of each rock type were proposed by many authors, like ASTM, C-615, ABNT NBR 15844 and Frazão & Farjallat (1995, 1996) for granites and Chiodi Filho (2002) for granites and marbles.

It is also essential to consider the loading conditions of each environment in the selection of a dimension stone. Frascá *et al.* (2019) suggest which technological characterization tests are recommended for a given application.

3. Quality Indices for Dimension Stones

A good quality index for a dimension stone must rank the available rocks according to their properties, like durability and strength.

Table 2 presents some quality indices proposed in the literature, based on physical-mechanical characteristics of dimension stones.

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Table 2: Quality indices of dimension stones.

Authors	Variables	Quality index
Smith *et al.* (1970)	*DAP:* absorption quality index *I*: amsler abrasion resistance in wet samples	DAP= I/1+ (water absorption)
Farjallat (1971)	$K_{\Delta t}$: quality index *F*: sum of the losing material percentage of intact rock after test (abrasion, uniaxial compressive strength etc) *I*: sum of the losing material percentage of intact rock after test in weathered sample	$K_{\Delta t}$=1-(200-F) / (200-I)
Yoshida (1972)	R_f: resistance quality index *P*: losing percentage of material due to weathering R_i: mechanical resistance of intact material R_f: mechanical resistance of weathered material	R_f= (100-P)xΔR/100 where: ΔR= (R_i- R_f) /R_i
Tourenq & Archimbaud (1974)	IQ_V – quality index (%); V_P – wave longitudinal propagation velocity in a dried sample (m/s) V_P * – theoretical wave longitudinal propagation velocity for zero porosity (m/s)	IQ_v= V_p/(V_p*) x 100
Formaintraux (1976)	IQ_P – quality index (%); 1.6 – a constant ρ – total porosity of sample (%)	IQ_p= 100-1.6 x ρ
Irfan & Dearmam (1978)	I_P: quality index *A*: percentage of primary minerals *B*: percentage of secondary minerals + percentage of voids + percentage of fissures	I_P= A/B
CRB (1982)	*SMC*: index of secondary minerals *S*: percentage of secondary minerals, voids and microfissures *M*: percentage of minerals (primary and secondary).	SMC= S/M x 100
Urmeneta (1997)	I_c: quality index *DA*: apparent density (g/cm^3) *PA*: porosity (%) *MD*: strain in uniaxial compressive strength *DC*: uniaxial compressive strength (Kg/cm^2) *RT:* tension strength (Kg/cm^2) *RD*: friction abrasion (mm)	I_C= (V_{DA}+V_{PA}+V_{MD}+V_{RC}+V_{RT}+V_{RD}) /6 Where: V_{DA}= 1000/6 (DA-2) V_{PA}= 25/6 (8-PA) +100 V_{MD}= 1/3500 (MD-100000) V_{RC}= 1/10 (DC-100) V_{RT}= 100/85 (RT-15) V_{RD}= 25/2 (2-RD) +100
Perrier & Bouineau (1997), adapted from Moura & Carvalho (2001)	Q: quality factor A: flexural strength in three points A': flexural strength in three points after accelerated weathering test	Q= 1/ (log A- log A')
Shohda *et al.* (2016)	CS_w: weight for the uniaxial compressive strength CS_r: rating for the uniaxial compressive strength H_w: weight for the toughness	$QI=CS_wCS_r+H_wH_r+A_wA_r+W_wW_r+P_wP_r+D_wD_r$

H_r: rating for the toughness
A_w: weight for abrasion
A_r: rating for abrasion
W_w: weight for water absorption
W_r: rating for water absorption
P_w: weight for porosity
P_r: rating for porosity
D_w: weight for durability
D_r: rating for durability

Source: Modified and adapted from Maia, (2001); Simão *et al.*; (2010); Rocha, (2016).

Quality indices presented in Table 2 aim to represent the behavior of dimension stones using technological properties measured in lab tests. Most of these indices quantify the influence of weathering on the loss of quality in these rocks. Although the effect of weathering is quite important in the quality of dimension stones used in external environments, lab tests in weathering material are rarely available. Moreover, only one parameter is used for measuring quality in the proposals that quantified the effect of weathering (Table 2).

Many other authors use only one parameter to measure the quality of a dimension stone (Table 2). Smith *et al.* (1970) proposed a quality index based on the abrasion resistance test. Additionally, Tourenq & Archimbaud (1974) used only the wave longitudinal propagation velocity and Formaintraux (1976), the porosity.

Urmeneta (1997) proposed a quality index based on six parameters, which includes resistance, physical indices and abrasion. However, some of these parameters are rarely available, like the strain in uniaxial compressive strength and the tension strength. Furthermore, the index was proposed as the arithmetic mean of all the parameters; but as they have different units and scale this mean seems to be biased.

Shohda *et al.* (2016) proposed the most complete quality index. These authors established a system of weights and ratings for the variables considered. The weights vary according to the environment (outdoor or indoor). For the outdoor environment, the weights vary between 6 and 1; being 6 for the first term of Shohda's equation (CS_w in Table 2), decreasing for the other terms up to D_w, which receives a weight equal to 1. For the indoor environment, the weights are: 2 for the first term of Shohda's equation (CS_w in Table 2) and 1,3,5,6 and 4 for the other terms up to D_w.

The ratings in Shohda's equation are attributed to a range of values for each property considered in Table 2. These ratings and their respective ranges of values of properties can be found in Shohda *et al.* (2016). They vary between 1 and 5; being 1 for the worst situations (very low values of uniaxial compressive strength, toughness, abrasion and durability; very high values of porosity and water absorption) and 5 for the best situations (very high values of uniaxial compressive strength, toughness, abrasion and durability; very low values of porosity and water absorption).

Applying the weights and ratings in Shohda's equation (Table 2), the dimension stones are classified according to their quality (Table 3).

Table 3: Quality classification of dimension stone.

Class	Quality Index (IQ)	Quality of dimension stone
I	> 100	Excellent
II	80-100	Very Good
III	60-80	Good
IV	40-60	Fair
V	20-40	Poor
VI	< 20	Very Poor

Source: Shohda *et al.* (2016).

3.1 Classification of technological parameters

Table 4 shows a proposal of a dimension stone classification, based on the main lab tests for technological characterization. The quality of the dimension stones increases with columns. It can be used as a guide for their use in building industry, from a technological point of view.

Table 4: Classification of technological parameters for use in building industry, according to the results of lab tests.

Water absorption (WA) (%)	Linear thermal expansion (LTE) (mm/m x °C x 10^{-3})	Amsler abrasion resistance (AAR) (mm)	Rupture energy (RE) (m)	Uniaxial compressive strength (UCS) (MPa)	Flexural strength (FS) (MPa)
very high > 3	very high > 12	very high > 6	very low < 0.3	very low < 40	very low < 4.5
high 3 - 1	high 12 - 10	high 6 - 3	low 0.3 – 0.5	low 40- 70	low 4.5 – 7.5
medium < 1 – 0.4	medium < 10 - 8	medium < 3 – 1.5	medium > 0.5 – 0.7	medium > 70 - 130	medium > 7.5 – 11.5
low < 0.4 – 0.1	low < 8 - 6	low < 1.5 – 0.7	high > 0.7 – 0.95	high > 130 - 180	high > 11.5 - 15
very low <0.1	very low < 6	very low < 0.7	very high > 0.95	very high > 180	very high > 15

Source: Modified from Chiodi Filho *et al.*, (2020).

It is important to highlight that some rocks may not have a high quality in this classification due to their structure, composition or texture; but are still acceptable for some applications in building industry.

4. Materials and Methods

4.1 Database organization

A database containing the results of technological characterization lab tests of dimension stones was organized from information collected of enterprises of the sector, the catalogs of Dimension Stones of Espírito Santo state (Brazil, Sardou Filho *et al.*, 2013), São Paulo state (Brazil, Braga & Caruso, 1990, Frascá *et al.*, 2000), Bahia state (Brazil, Azevedo & Costa, 1994, SGM, 1997 and CBPM, 2002), Ceará state (Brazil, FUNCAP; SECITECE, 2002) and the catalog of Brazil Dimension Stones, version 2 (ABIROCHAS; CETEM, 2002).

From these sources, 285 samples were selected, including 200 granites, 61 quartzites and 24 marbles of all Brazil regions. The names of these dimension stones refer to their commercial designations. The selected samples comprise all the lab test results needed for this study; those samples where some of these tests were missing were discarded.

4.2 Quality index proposal for dimension stones

This work presents a proposal of a technological quality index for dimension stones, based on Table 4. A system of weights varying between 2 and 10 is proposed for each parameter, according to the classification presented in Table 4. This system is presented in Table 5.

Table 5: System of weights for quality attributes.

WA, DA and AAR	Weights	UCS, FS and RE.
very low (VL)	10	very high (VH)
low (L)	8	high (H)
medium (M)	6	medium (M)
high (H)	4	low (L)
very high (VH)	2	very low (VL)

Source: Authors (2022).

The quality index is calculated by the sum of weights assigned to each lab test of Table 4. Thus, the higher the quality index, the better the quality of the dimension stone (Equation 1).

$$QI= W_{WA}+W_{LTE}+W_{AAR}+W_{RE}+W_{UCS}+W_{FS} \quad (1)$$

Where:

QI is the quality index

W_{WA}: weight assigned to the result of the water absorption test;

W_{LTE}: weight assigned to the result of the linear thermal expansion test;

W_{AAR}: weight assigned to the result of the Amsler abrasion resistance test;

W_{RE}: weight assigned to the result of the rupture energy test;

W_{UCS}: weight assigned to the result of the uniaxial compressive strength test;

W_{FS}: weight assigned to the result of the flexural strength test.

It is important to observe that for the variables water absorption, linear thermal expansion and Amsler abrasion resistance, and the rock quality increases as their values decrease. The opposite happens to the values of the variables rupture energy, uniaxial compressive strength and flexural strength.

The quality index proposal presented in this research shows some similarities with Shohda *et al.* (2016) index, especially considering the idea of attributing weights to the variables. However, the variables considered are different to adapt the index to the classification proposed by Chiodi Filho *et al.* (2020), Table 4. It is important to highlight that water absorption and porosity are very similar and they both were considered in Shohda *et al.* (2016) index. In this research only the water absorption was considered.

The quality index classification was determined by applying the Sturges' rule, which gives the number of classes in a histogram (Equation 2).

$$k=1+3.3*\log_{10}(N) \quad (2)$$

Where:

k is the number of classes and N is the number of samples.

Total data amplitude is equal to 48, which is the difference between 60 (upper limit of the sum of weights) and 12 (lower limit of the sum of weights). Thus, the class amplitude is given by Equation 3. Total data amplitude is equal to 48, which is the difference between 60 (upper limit of the sum of weights) and 12 (lower limit of the sum of weights). Thus, the class amplitude is given by Equation 3.

$$A=AT/k \quad (3)$$

Where:

A is the class amplitude;

AT is the total data amplitude;

k is the number of classes (Equation 2).

Applying Equation 2 and Equation 3, k=9 and A=5. Based on these results, the quality index classification would be given by Table 6.

Table 6: Initial proposal for quality index classification.

QI	Class	Classification
60-55	A1	excelent
54-49	A2	
48-43	B1	good
42-27	B2	
36-31	C1	fair
30-25	C2	
24-19	D1	poor
18-13	D2	
12	E	inadequate

Source: Authors (2022).

In order to simplify the quality index classification, the divisions between classes were disregarded. Therefore, final quality index classification is given in Table 7.

Table 7: Quality index classification.

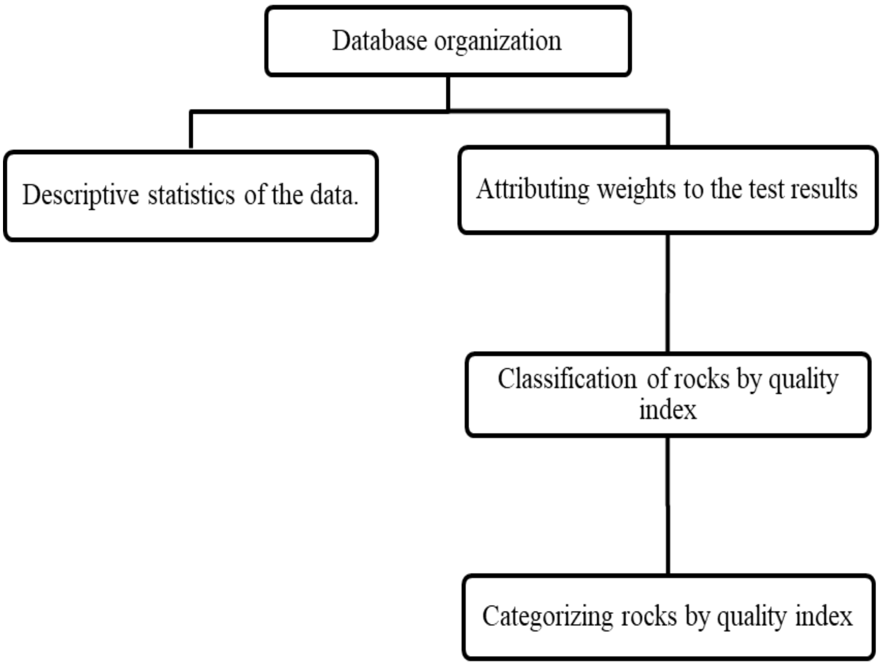
QI	Classification
60-49	excellent
48-37	good
36-25	fair
24-13	poor

Source: Authors (2022).

With this simplification, the interpretation for the application of the quality index becomes simpler and more direct.

Figure 1 shows the flowchart of the methodology.

Figure 1: Methodology flowchart.



Source: Authors (2022).

Figure 1 represents in a simplified way the methodology applied in this research.

5. Results and Discussion

The quality index was calculated for all database samples, using Equation 1. Descriptive statistics of the quality index is presented in Table 8.

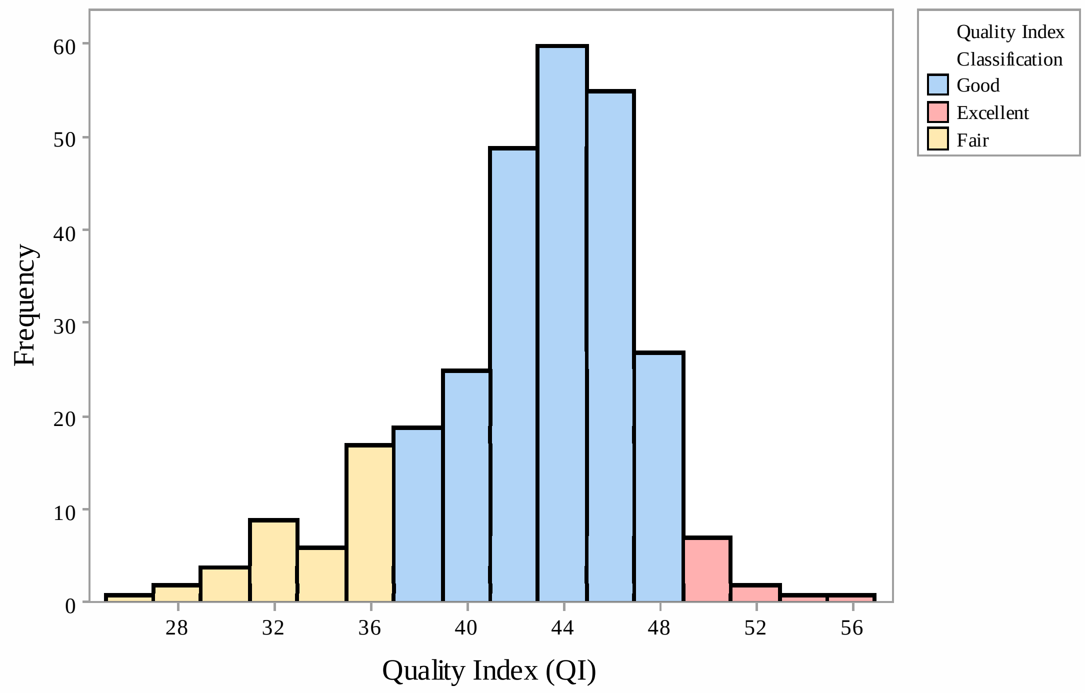
Table 8: Descriptive statistics of the quality index.

variable	m	sd	min	q1	md	q3	max	mo
QI	42.50	4.79	26.00	40.00	44.00	46.00	56.00	44.00

Notes: m: mean; sd: standard deviation; min: minimum value; q1: first quartile; md: median; q3: third quartile; max: maximum value; mo: mode.
Source: Authors (2022).

The majority of rocks in the database have a quality index equal to good, in the range 42-46. Most of rocks classified as fair have a quality index equal to 36 and most of rocks classified as excellent have a quality index equal to 50. None of the rocks is classified as poor or inadequate. The database histogram of the quality index is presented in Figure 2.

Figure 2: Data histogram of quality index.

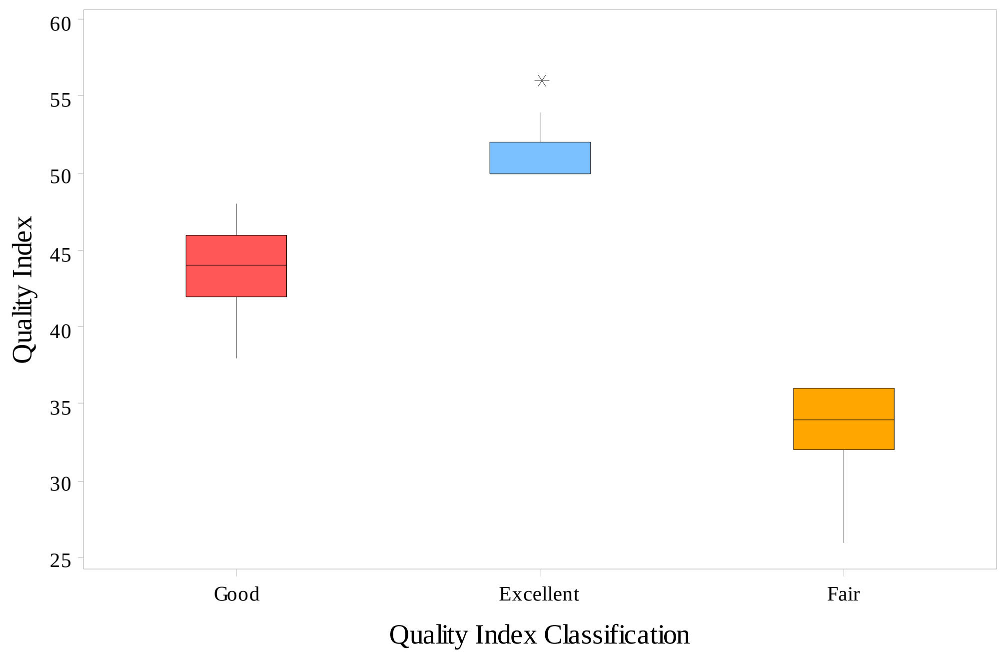


Source: Authors (2022).

The group of rocks classified as fair is in the upper limit of this class, which shows that rocks in the database are quite good to apply in building industry.

The boxplot of the quality index is presented in Figure 3.

Figure 3: Data boxplot of quality index.



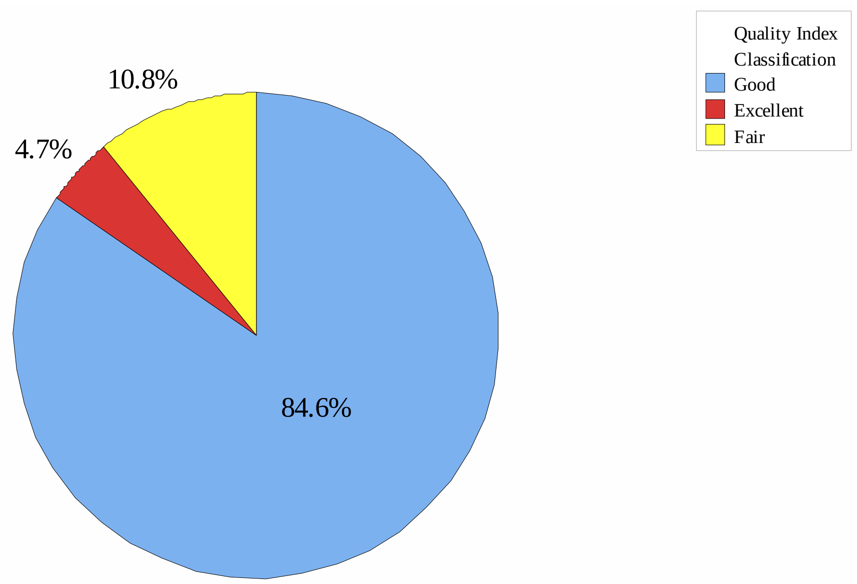
Source: Authors (2022).

Only 11 rocks of the 285 samples of the database are classified as excellent. The majority of samples (235) are classified as good and 39 are classified as fair.

The low interquartile range of quality indices in the database is notable. Also the prevalence of a good quality index is a remarkable characteristic of the database. Extreme values for quality indices are rare. It is interesting to highlight that there are not poor or inadequate rocks in the database.

Figure 4 presents the percentage of rocks in each quality index classification.

Figure 4: Percentage of rocks for the quality index classification.

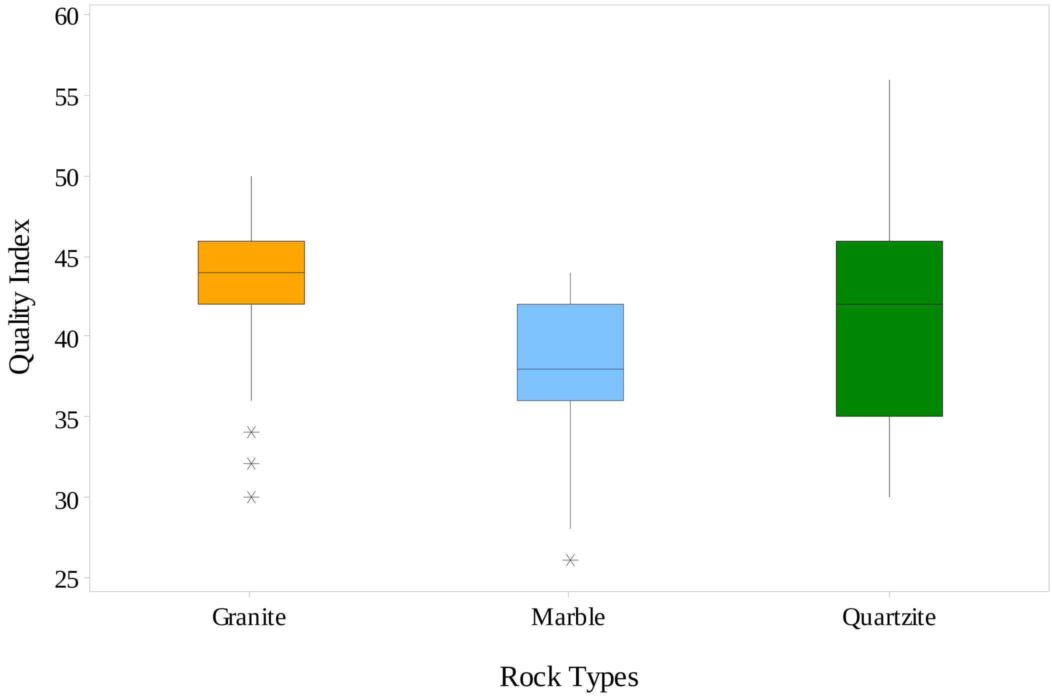


Source: Authors (2022).

This figure confirms the low incidence of quality index extreme values in the database. 95.4% of rocks are classified as good and fair and only 4.7 of rocks are excellent.

Figure 5 presents the boxplot of the quality index for rock types of the database.

Figure 5: Boxplot of quality index for rock types.



Source: Authors (2022).

The quartzites have the greatest variability of the quality index and the granites the least. A small number of outliers can be seen in the group of granites.

The granites are the rocks with better quality compared to marbles.

6. Conclusion

The proposed quality index is simple and useful to indicate the quality of a dimension stone. It can be used to help practitioners in the choice of an adequate rock for the building industry. It is also useful to indicate a rock with poor quality or inadequate, considering its technological properties, precluding its application in a given environment.

The properties used for the quality index proposal are always available, as the characterization tests are mandatory. Physical indices, resistance and durability properties were used to construct the quality index.

This research shows that most of the rocks classified as granites have a good quality and a low dispersion in the quality index; therefore their choice can be adequate for the majority of applications. On the other hand, the quartzites presented the largest dispersion in the quality index; so their choice must be carefully evaluated, especially for environments exposed to high risks of damage.

The authors suggest as future research and article the insertion of quantitative mineralogical parameters to calculate the quality index.

Acknowledgments

The authors acknowledge the institutions that provided the results of the technological characterization lab tests, the Graduate Program of Mineral Engineering (Federal University of Ouro Preto, UFOP) and the Federal Institute of Education, Science and Technology of Espírito Santo for supporting this work. The authors also thank to Nuria Fernández Castro from the

Centre for Mineral Technology (CETEM/MCTI) and PhD Professor Tatiana Barreto do Santos from the Engineering Mining Department of the Federal University Federal of Ouro Preto (DEMIN/UFOP) for their collaborations in translating the title, abstract, and keywords into the Spanish language.

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