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Examining the effect of physico-mechanical and petrographical properties of granite building stones on the stone surface quality after polishing process

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ABSTRACT

The purpose of this study was to examine the effect of physico-mechanical and petrographic properties of building stones on their surface quality after the polishing process. To do this, a laboratory investigation was performed on 15 different types of Iranian granite building stones, including petrographic analyses, physico-mechanical evaluations, and polishing tests. Moreover, to assess the stone surface quality, surface roughness and gloss were measured before and after the polishing process, based of which three indices were proposed for quantifying the surface quality improvement, including gloss improvement index (GII), roughness improvement index (RII), and quality improvement index (QII). Then, the correlations between these three indices with the physico-mechanical and petrographic properties of stone were investigated. The results revealed that the Schmidt hammer hardness (SCH) is the main parameter that affects the proposed indices. Finally, non-linear regression analyses were applied for development of predictive equations for the GII, RII, and QII based on the SCH. Predictive equations presented very good performance with determination coefficient (R2) values between 0.747 and 0.826. These results suggest that the predictive equations are suitable for practical applications and can be employed for the rapid assessment of stone surface quality after polishing process.

Keywords: *Granites; Building stone properties; Polishing; Surface quality; Roughness; Gloss.*

1. Introduction

Polishing is the most commonly applied finishing process in stone processing plants. Polished stones are consistently in high demand and are preferred over other surface finishes. This process not only enhances the aesthetic appeal but also increases the stone's price by achieving a high gloss through the reduction of surface roughness. The stone polishing process involves the use of a machine equipped with multiple polishing heads (typically 12 to 26), which polish the stone at controlled speeds in the presence of water. A sequence of abrasive tools with varying grit sizes is employed, starting with coarse grit abrasives in the initial stages and progressing to finer grits in the final stages of the polishing process [1-5]. The high surface quality of the polished stones has paramount importance on marketing and customer satisfaction. Surface roughness (R) and gloss (G) are two common metrics for controlling the stone quality after the polishing process [1, 6-8]. The polishing process affects these two metrics directly. R typically describes the fine irregularities of a surface, representing the deviations of a real surface from its ideal form at a microscopic scale [9, 10]. G is defined as a specific light intensity reflectance on a surface with the incident angle equal and opposite to the reflectance angle [11].

The literature survey indicates that several factors affect the surface quality of polished stones which can be divided into four main categories [12]: (1) operating parameters of the polishing machine, such as the number of polishing head, polishing head pressure, head rotation speed, belt speed, water flow rate, and water quality, (2) stone properties, such as surface roughness of unpolished stone, physico-mechanical and petrographical properties, (3) properties of abrasive blocks, and (4) degradation due to environmental conditions, such as surface damage due to freeze-thaw and acid rain.

Recently, researchers have conducted many studies to evaluate the effect of various affecting parameters on the quality of polished stones. For example, Erdogan [13] studied the effect of porosity, distinct crystal boundaries, angular differences between cutting direction and crystal orientation, and joint filling materials on the surface gloss of various polished building stones and observed that these parameters affect surface gloss negatively. Furthermore, he mentioned that stones essentially made up of a single mineral show increasing values of surface gloss.

Ersoy and Kose [14] investigated the relationship between easiness of polishing and mechanical properties of marbles. Huang et al. [15] evaluated the surface roughness and gloss of two types of granite samples during the grinding process. They found that the prevailing mechanisms for the grinding of granite vary from brittle-mode removal to ductile-mode removal with reduction of diamond grit size. Karaca [16] studied the relationship between mechanical properties and the surface roughness of marble samples and found significant correlations between uniaxial compressive strength, tensile strength, and surface roughness. Gürkan et al. [17] evaluated the effect of mineralogical and microstructural properties on the surface roughness and gloss of polished marble stones. They observed that when the proportions of minerals other than calcite increases, a decreasing trend in the surface

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quality occures. Yavüz et al. [7] and Ersoy et al. [18] examined the effect of conveyor belt speed on surface quality by performing polishing tests at various constant rotational speed values and pressure levels of the polishing head. Ozcelik et al. [19] investigated the effects of freeze and thaw cycling on the gloss of various carbonate building stones from Turkey. The results revealed that with increase of freeze and thaw cycles, surface gloss decreases.

Careddu and Marras [20] assessed the effects of solar ultraviolet rays on the gloss values of polished surfaces of various carbonate building stones. Vázquez et al. [21] evaluated the changes in the surface quality of crystalline stones, such as granites and marbles, due to salt crystallization. Sousa and Gonçalves [22] studied the differences in the surface quality of polishing between sound and weathered granites. They found that sound and more textural homogeneous granites have a low surface roughness and high gloss, while weathered granite shows a higher surface roughness and lower gloss. Barbosa et al. [1] carried out polishing tests with a single-head laboratory-scale polishing machine to evaluate the influence of water flow and polishing head pressure on the polishing quality of Moleanos limestone, from Portugal. Cevheroğlu Çira et al. [23] examined the effects of polishing machine operating parameters (belt speed, rotational speed, and pressure of the polishing head) on marble surface quality using response surface methodology (RSM).

Sarici [24] determined the changes to the surface aesthetic properties of some Turkish marbles due to heat deterioration under thermal shock and thermal ageing cycles. They concluded that surface gloss values slowly decrease as thermal shock and thermal ageing cycles increase. Also, thermal shock cycles were more effective on gloss than thermal ageing. Cevheroglü et al. [8] investigated the effects of physico-mechanical properties of marble on surface roughness and gloss. They concluded that porosity, uniaxial compressive strength, and indirect tensile strength strongly affect the surface roughness and gloss of the studied marbles. Farhadian et al. [25] studied the effect of operating parameters of polishing machine on the wear of abrasive tools in the polishing stage of granitic building stones. Coelho et al. [2] investigated the effects of conveyor belt speed, polishing head transverse and rotational speeds on surface quality of product. The effects of types and series of abrasive tools on surface quality were studied by Görgülü and Ceylanoğlu [26], Gürcan and Oztürk [27], Huang et al. [28,29].

Sitzia et al. [30] investigated the effects of rainwater on the surface quality of polished limestones used for building cladding. They showed that, due to the presence of corrosive carbonic acid, rainwater induces micro-corrosion on the sample's surface, leading to colour modification, a reduction in gloss, and an increase in roughness after one month. Kelemen-Cserta and Gyurika [31] examined the effect of minerals composition in natural granite stones on surface roughness during machining. Rezaei et al. [12] investigated the effectiveness of wastewater treatment using flocculation process on surface quality and abrasive tool wear in polishing process of building stones. Çetintaş [32] studied the effect of different abrasives on the marble polishing performance. He concluded that polishing performance is highly affected by abrasive grain shape and grain distribution. Despite the practical importance of polishing performance in the building stone industry, a systematic understanding of how physico-mechanical and petrographic properties of granite influence surface quality improvement remains limited. Therefore, this study aims to address this research gap through a comprehensive experimental and statistical investigation.

The main contributions of this research are as follows. First, a controlled laboratory-scale polishing process was performed on fifteen different Iranian granite building stones to establish a consistent comparative framework. Second, the relationships between petrographic characteristics, physico-mechanical properties, and surface quality indicators (surface roughness and gloss) were quantitatively evaluated. Finally, novel predictive equations were developed to estimate surface quality improvement after polishing process using statistical analysis. The proposed equations provide a practical tool for predicting polishing performance and can support decision-making in stone selection, process optimization, and quality control in the stone processing industry.

2. Materials and methods

2.1. Materials

To do this study, fifteen types of commercial granite building stones from Iranian quarries with various mineralogical compositions were collected. The commercial and scientific names of studied stones with their Surface appearance are given in Table 1. For all stone types, the block samples with large enough dimensions were provided and were brought to the laboratory for sampling and testing. All samples were unweathered and free from any visible cracks or fractures to avoid the impact of anisotropy on the measurements. The collected stone samples were prepared for two sets of tests. The first involved preparing samples for physico-mechanical tests and creating thin sections for petrographic analyses. The second set included samples for polishing tests.

2.2. Sampling Procedure

2.2.1. Physico-mechanical properties tests

The physico-mechanical properties include apparent dry density (d), effective porosity (n), uniaxial compressive strength (UCS), Brazilian tensile strength (BTS), Schmidt hammer hardness (SCH) and P-wave velocity (Vp). To determine the d and n, the saturation and buoyancy methods suggested by ISRM [33] were used.

The UCS of samples was measured according to the ASTM C170 [34]. For this purpose, cubical shape samples with dimensions of 7×7×7 cm were prepared. To measure the Brazilian tensile strength (BTS), core samples of each stone type with a diameter of 54 mm and a thickness-to-diameter ratio of 0.5 were tested according to the ISRM suggested method.

The SCH was determined for each stone type on block specimens with approximate dimension of 30×30×20 cm using the N-type Schmidt hammer with an impact energy of 2.207 N.m according to the ISRM suggested method. All tests were made with the hammer held vertically downwards and at right angles to horizontal faces of the blocks. In order to avoid edge effects, the recordings were made at least two plunger diameters away from the edges of the specimen blocks.

The Vp for each stone type was measured on cubical shaped samples with the dimensions of 7×7×7 cm by direct transmission method using a Portable Ultrasonic Nondestructive Digital Indicating Tester (PUNDIT Lab+), equipped with two transducers (a transmitter and a receiver) operating at a frequency of 54 kHz, based on ISRM guidelines. The results of all the tests are summarized in Table 2. It should be mentioned that at least three samples of each stone type were tested and the average values were reported in Table 2.

2.2.2. Petrographic analyses

Petrographic analyses primarily focus on determining the mineral composition and grain size of stone samples. Toward this aim, thin sections were prepared from each sample and examined under a polarized microscope. Based on thin section analysis, quartz content (Q), cleavable minerals content (CLV), the ratio of quartz to cleavable minerals (Q/CLV), and mineral compositions were determined. Furthermore, the equivalent grain size (Gs), the equivalent quartz content (EQC), and overall Mohs hardness (MH) for each stone sample were calculated using following equations [3, 35, 36]:

$$G_s = S_q \times P_q + S_{kf} \times P_{kf} + S_{pl} \times P_{pl} \quad (1)$$

where S_q, S_{kf}, and S_{pl} are the mean grain size of quartz, K-feldspar and plagioclase minerals, respectively, and P_q, P_{kf} and P_{pl} are the corresponding percentage contents.

$$EQC = \sum_{i=1}^{n} P_i \times R_i \quad (2)$$

where P_i is the percentage content of minerals, R_i is the minerals' Rosiwal hardness, and n is the number of minerals.

$$MH = \sum_{i=1}^{n} P_i \times M_i \quad (3)$$

where M_i is the Mohs number for the mineral.

Stone textural property is a major factor in determining the performance of stone polishing process, and it is usually quantified using thin-section image analysis. One of the most widely used methods for quantifying the stone textural property is the texture coefficient (TC), introduced by Howarth and Rowlands [37].

Table 1. Stone samples used in this study.

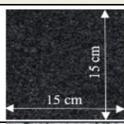
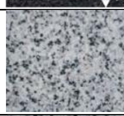
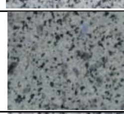
Sample ID	Surface appearance	Commercial name	Scientific name
S1		Meshki-Natanz	Diorite
S2		Sefid-Natanz	Granodiorite
S3		Khorramdarreh	Syenogranite
S4		Golpanbehi-Nehbandan	Granite
S5		Taibad	Syenogranite
S6		Borujerd	Granite
S7		Zahedan	Granite
S8		Germez-Yazd	Andesite
S9		Morvarid-Mashhad	Granite
S10		Shaghaegh-Nehbandan	Monzonite
S11		Sabze-Birjand	Granite
S12		Toosi-Astan	Granite
S13		Porteghali-Nehbandan	Granite
S14		Holoee-Zanjan	syenite
S15		Maraghe	Syenogranite

Table 2. Physico-mechanical properties of the studied stone samples.

Sample ID	d (g/cm^3)	n (%)	UCS (MPa)	BTS (MPa)	SCH	Vp (km/s)
S1	2.77	0.84	136.10	10.30	66.25	4.80
S2	2.66	1.33	124.80	9.06	58.64	4.65
S3	2.57	1.23	131.99	10.11	65.88	5.42
S4	2.62	1.06	139.94	11.78	64.26	5.45
S5	2.85	1.14	152.20	12.12	68.60	5.66
S6	2.58	1.39	118.30	8.53	56.11	4.25
S7	2.54	1.58	149.60	11.52	70.01	5.65
S8	2.56	2.09	127.50	8.82	58.00	5.00
S9	2.65	1.06	137.50	10.30	57.56	4.71
S10	2.61	1.10	143.27	10.36	63.16	5.18
S11	2.70	1.50	97.20	7.36	51.59	3.96
S12	2.61	1.41	147.23	12.46	64.26	5.50
S13	2.78	0.93	149.00	11.78	64.38	5.70
S14	2.56	3.26	131.80	10.35	61.90	4.65
S15	2.85	2.03	145.80	11.77	66.07	5.57

The TC quantifies aspects such as grain shape, orientation, degree of grain interlocking, and the relative proportion of grain to matrix [35]. In this study, the TC of all studied samples was determined, based on proposed Howarth and Rowlands formula. The obtained results of petrographic studies are given in Table 3.

2.2.3. Laboratory polishing tests

In this study, polishing tests were performed using a single-head laboratory-scale polishing rig, developed by Farhadian et al. [3], at the building stone laboratory of Isfahan University of Technology (IUT) (Figure 1). The main elements of device include a polishing head, an electro-gearbox, and a speed control unit. To implement the tests, stone samples with dimensions of 15×15×2 cm were prepared. For this purpose, the samples obtained from disc cutting were used. The appearance of disc cutting finish is matte and rough. Miniature abrasive pins 8 mm in diameter and 30 mm in length were used for polishing test. These pins were prepared from the magnesite abrasive blocks (flickers) employed in the industry with the grit number 120 (Figure1, c). During the test, two miniature pins polish the surface of the sample causing a trace on it (Figure 1, d). All polishing tests were performed based on the standard operational conditions proposed by Farhadian et al. [3], including polishing head pressure of 5 kg/cm2, water flow rate of 4 L/min and head rotation speed of 300 rpm, and testing time duration of 5 minutes. The details about this machine and the polishing test method have been described by Farhadian et al. [3].

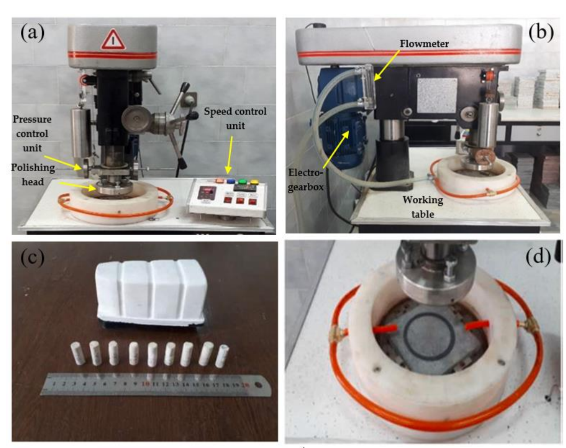


Figure 1. Laboratory polishing test rig: (a) front view, (b) side view, (c) industry abrasive block and miniature pins, and (d) a view of stone surface after the polishing test.

Table 3. Petrographic properties and mineral composition of studied stone samples.

Sample ID	Q (%)	CLV (%)	Q/CLV	G_S (mm)	EQC (%)	MH	TC	Mineral composition
S1	10	87.5	0.11	1.32	38.58	5.44	2.05	Quartz 10%, plagioclase 60%, amphibole 15%, biotite 5 %, opaque 7.5%, pyroxene 2.5%
S2	23	74	0.31	1.58	46.20	5.71	2.08	Quartz 23%, plagioclase 51%, k-feldspar 5%, amphibole 8%, biotite 10 %, opaque 3%
S3	20	73	0.27	1.71	48.97	5.88	2.33	Quartz 20%, plagioclase 15%, k-feldspar 50%, tourmaline 5%, biotite 8 %, opaque 2%
S4	28	72	0.38	1.55	49.83	5.95	2.96	Quartz 28%, plagioclase 26%, k-feldspar 35%, biotite 11%
S5	30	70	0.43	1.93	52.95	6.14	3.96	Quartz 30%, plagioclase 20%, k-feldspar 45%, biotite 5 %
S6	22	78	0.28	1.78	46.14	5.89	2.04	Quartz 22%, plagioclase 38%, k-feldspar 30%, biotite 8 %, chlorite 2%
S7	47.5	52	0.91	2.83	62.20	6.12	4.06	Quartz 47.5%, plagioclase 23%, k-feldspar 19%, muscovite 7.5%, biotite 3%
S8	20	78	0.26	0.42	41.17	5.79	0.94	Quartz 20%, plagioclase 15%, biotite 3%, opaque 2%, iron dioxide 60% (matrix)
S9	23.5	76.5	0.31	0.69	45.94	5.78	2.58	Quartz 23.5%, plagioclase 19%, k-feldspar 43.5%, muscovite 5.5%, biotite 8.5%
S10	19	79	0.24	1.03	47.29	5.94	3.68	Quartz 19%, plagioclase 33.5%, k-feldspar 36%, Biotite 4.5%, epidote 5 %, opaque 2%
S11	32	68	0.47	1.22	51.15	5.83	0.98	Quartz 32%, plagioclase 38%, k-feldspar 15%, muscovite 15%
S12	40	58	0.69	3.92	57.95	6.04	3.6	Quartz 40%, plagioclase 20%, k-feldspar 28%, biotite 5%, other 7%
S13	40	60	0.67	3.33	59.39	6.23	4.09	Quartz 40%, plagioclase 25%, k-feldspar 30%, biotite 3%, chlorite 2%
S14	8	89	0.09	2.06	39.75	5.89	2.00	Quartz 8%, plagioclase 8%, k-feldspar 75%, amphibole 6%, opaque 3%
S15	25	75	0.33	2.07	49.70	6.09	2.04	Quartz 25%, plagioclase 16%, k-feldspar 54%, biotite 3%, muscovite 2%

2.2.4. Gloss and roughness measurements

To assess the surface quality of the studied stone samples, roughness and gloss measurements were taken before and after polishing tests. It should be noted that prior to measurements, the surfaces of all samples were washed with water and dried at room temperature for 24 h to achieve a consistent dry state. In this study, the surface gloss of each sample, before and after polishing test, was measured using a TQC poly gloss meter (Figure 2) which has a measurement range of 0–100 gloss units (GU), at 60° light incidence and reflection angles relative to the vertical axis. Based on international standards, there are three types of angles used to measure a glossiness: 20°, 60° or 85°. The measurement at 60° is known to provide the best and the most comprehensive visual estimate while 20° and 85° are applied for high and low gloss measurements [38, 39]. The measurement was carried out in four selected positions on the sample, which are shown in Figure 3. The average of 4 measurements were considered as the gloss of stone sample before (G_1) and after (G_2) polishing test and have been reported in Table 4.

Another aspect that determines the stone's surface quality is roughness. The surface roughness measurements were performed using a stylus profilometer Mitutoyo SJ-210 (Figure 4) over a trace length of 2.5 mm, standard cutoff value being 0.8 mm. Surface roughness at selected points on a sample (see Figure 3) was measured in terms of the most commonly used parameter "average roughness (R_a)" before and after polishing. This parameter is defined as the arithmetic mean of the absolute departures of the roughness profile from the mean line [17]. The roughness values of all samples before (R_1) and after (R_2) polishing test are given in Table 4.

3. Result and discussion

In this study, three indices have been introduced for assessing the effectiveness of polishing process, including gloss improvement index (GII), roughness improvement index (RII), and quality improvement index (QII). These indices can be calculated using values of gloss and roughness before and after polishing test as follows:

$$GII=G_2/G_1 \quad (4)$$

$$RII=R_2/R_1 \quad (5)$$

$$QII=GII+1/RII \quad (6)$$

As mentioned before, polishing process simultaneously increases surface gloss and decreases surface roughness, so both indices GII and RII were considered for calculation of QII, as an overall index of surface quality. Since polishing leads to increase of surface quality and gloss, therefore the higher values of GII and QII indicate the more effectiveness of this process. On contrary, this process leads to decrease of roughness, so the lower values of RII indicates the more effectiveness of polishing.

Figure 2. The gloss meter used in this study.

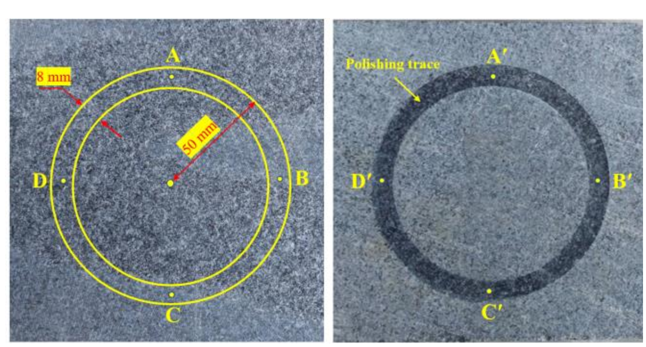


Figure 3. Position of measurement points: (a) before the polishing test, and (b) after the polishing test.

Table 4. Surface gloss and roughness of studied stone samples before and after the polishing test.

Sample ID	G_1 (GU)	G_2 (GU)	R_1 (µm)	R_2 (µm)	Measured			Predicted		
					GII	RII	QII	GII	RII	QII
S1	0.98	6.72	3.24	1.18	6.86	0.36	9.60	7.91	0.30	11.59
S2	1.44	7.93	2.64	1.05	5.51	0.40	8.02	4.97	0.41	7.62
S3	1.28	8.67	3.01	1.00	6.77	0.33	9.78	7.73	0.31	11.35
S4	1.46	8.10	2.26	0.80	5.55	0.35	8.37	7.00	0.33	10.38
S5	1.26	11.94	2.64	0.80	9.48	0.30	12.78	9.13	0.27	13.18
S6	1.38	5.50	2.53	1.30	3.99	0.51	5.93	4.26	0.45	6.63
S7	1.30	16.38	3.08	0.70	12.60	0.23	17.00	9.95	0.25	14.25
S8	1.40	6.58	2.60	1.03	4.70	0.40	7.23	4.78	0.42	7.36
S9	1.38	6.30	3.07	1.20	4.57	0.39	7.13	4.65	0.43	7.18
S10	1.28	8.75	2.83	0.88	6.84	0.31	10.06	6.55	0.34	9.77
S11	1.31	4.81	2.90	1.58	3.67	0.54	5.51	3.23	0.53	5.17
S12	1.80	10.70	1.99	0.81	5.94	0.41	8.40	7.00	0.33	10.38
S13	1.67	14.33	2.17	0.65	8.58	0.30	11.91	7.06	0.33	10.45
S14	1.14	7.78	3.03	0.95	6.82	0.31	10.01	6.07	0.36	9.12
S15	1.00	9.27	3.78	0.89	9.27	0.24	13.52	7.82	0.30	11.47

The values of GII, RII, and QII for all studied stones are presented in Table 4. There is an inverse power relationship between GII and RII (Figure 5) which indicates polishing process leads to increase of surface gloss and decrease of roughness. This is in accordance with that obtained by Yavus et al. [7] and Cevheroglü Cira et al. [8]. It can also be seen from Table 4 that the surface quality of the studied stones under polishing test increases with non-uniformly trend. S7 and S11 samples achieved highest and lowest quality after polishing process, respectively. Since the polishing tests were carried out under the same operational conditions, it can be concluded that difference in stone properties is the main reason of this non-uniformly trend. Thus, in the following, the effects of stone properties on quality improvement indices are examined.

Figure 4. Roughness tester device used in this study.

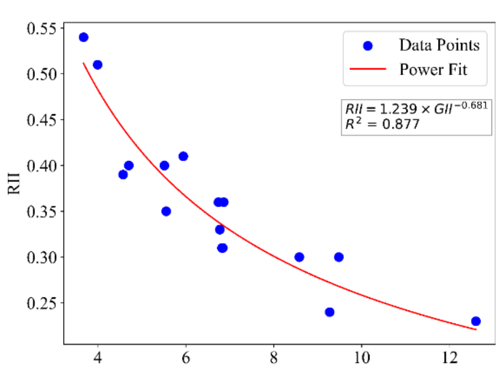


Figure 5. The relationship between GII and RII.

4. Statistical analysis and results

In this section, the main aim is development of three predictive equations for estimating GII, RII, and QII based on stone properties. In the other words, to develop these equations, GII, RII, and QII are dependent variables and petrological and physico-mechanical properties (including d, n, UCS, BTS, Vp, SCH, Q/CLV, Gs, EQC, MH, and TC) are independent or predictive variables. First, a series of simple regression analyses between the predictor variables and the dependent variable were performed to identify the most effective input variables. To do this, the relationships between GII, RII, and QII and the predictive variables were analyzed employing linear, power, logarithmic, and exponential functions. In this study, SPSS v. 16.0. computer package was used for all statistical analyses [40]. The results of simple regression analyses based on the best fit function are presented in Table 5. These results revealed that only four predictive variables, i.e. UCS, BTS, Vp, and SCH, have a significant effect on improvement indices and can be considered as input variables for developing the predictive equations using multiple regression analysis. While, the rest of predictor variables have poor correlations with improvement indices (R2 lower than 0.5). It should be mentioned that because of narrow variation range in the d and n of studied stones, no relationship between these variables and dependent variables was observed. As mentioned in Table 5, UCS, BTS, Vp, and SCH have a direct effect on improvement of surface gloss and quality. In the other words, stone surface gloss and quality after polishing process increase by increasing these stone properties. But these relationships are vice versa for RII (i.e. RII decrease by increasing UCS, BTS, Vp, and SCH). These findings are in accordance with that obtained by Cevheroglü Cira et al. [8, 23].

In multiple regression analysis, to increase the accuracy of the predictive equations, it is important to take into consideration the relationship observed between input variables. As can be seen in Figure 6, there are significant correlations between selected input variables. UCS, BTS, Vp, and SCH are closely related in practical rock mechanics engineering, these variables usually are as a function of the others. As well known, one of the strict conditions for multiple regression analysis is the requirement that all predictor variables should be independent. Multicollinearity occurs when independent variables in a regression model are correlated to each other [41]. To solve this problem, the stepwise regression method can be used in SPSS software to develop predictive equations [42]. The stepwise method takes into account the correlation between the variables, selects the most effective input variables to develop the equation, and removes the other (ineffective) variables. In this study, applying stepwise method, the SCH was determined as the main parameter that effects the GII, RII, and QII. Since the best relationships between SCH and improvement indices are non-linear and in the form of exponential and logarithmic (as can be seen in Table 5 based on simple regression analyses), so in order to

Table 5. The obtained results from simple regression analyses.

Dependent variable	Independent variable										
	D	N	UCS	BTS	V_P	SCH	Q/CLV	G_S	EQC	MH	TC
GII	Exp* +** 0.089***	Lin + 0.001	Exp + 0.631	Pow + 0.554	Exp + 0.631	Exp + 0.826	Lin + 0.257	Pow + 0.288	Lin + 0.300	Lin + 0.318	Exp + 0.411
RII	Exp - 0.048	Exp - 0.022	Lin - 0.681	Log - 0.583	Log - 0.659	Log - 0.747	Exp - 0.063	Pow - 0.121	Exp - 0.107	Exp - 0.249	Log - 0.296
QII	Exp + 0.080	Lin + 0.004	Exp + 0.643	Pow + 0.560	Exp + 0.641	Exp + 0.812	Lin + 0.222	Log + 0.248	Lin + 0.268	Lin + 0.319	Exp + 0.382

* Best fit function (Lin, Log, exp, and pow indicate linear, logarithmic, exponential, and power function, respectively)
** Relationship (+ and – represent direct and inverse relationships, respectively)
*** Determination coefficient (R^2)

develop more efficient predictive equations, the non-linear regression analysis was considered Using non-linear regression analysis, three equations were developed for predicting improvement indices as follows:

$$GII = 0.139e^{0.061SCH} \quad (7)$$

$$RII = -0.899\ln(SCH) + 4.071 \quad (8)$$

$$QII = 0.303e^{0.055SCH} \quad (9)$$

For above equations, the detailed results of analysis of variance (ANOVA) test are presented in Table 6. As can be seen in Table 6, the developed equations were statistically significant according to the student's t-test at a 95% level of confidence (Sig. level value⩽ 0.05). Furthermore, the variation explained by these equations is not due to chance based on the F values. For each equation, the F value is calculated by dividing the mean square of regression model by the mean square of the residual. The larger the F value, the more likely it is that the variation associated with the regression model is real and not due to chance. Hence, these derived equations can be reliably used, especially for predictive purposes.

The predicted values of GII, RII, and QII are presented in Table 4 based on Equations (7) to (9). The prediction performance of these equations is shown in Figure 7. It can be seen in Figure 7 that all three equations can predict improvement indices with acceptable accuracy for engineering purposes (with R2 values between 0.747 and 0.826). So, these equations can be applied to estimate the stone surface quality after polishing process based on properties of unpolished stones (initial surface gloss and roughness and SCH). Furthermore, in practical view, developed equations can be applied for the cheap and rapid assessment of polishability of building stone using Schmidt hammer.

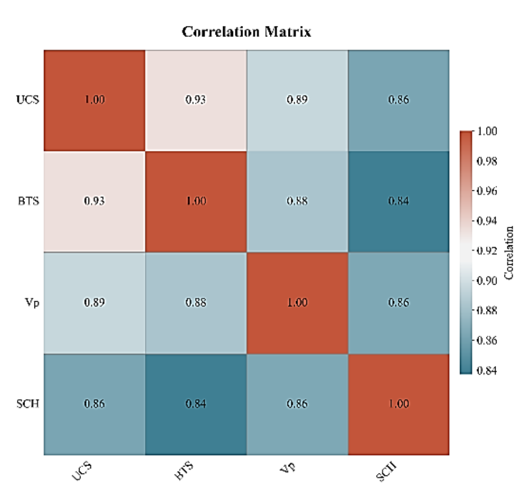


Figure 6. The correlations between selected input variables.

5. Performance of proposed predictive equations

In this section, the performance of proposed equations has been evaluated using three statistical metrics which are widely used in literature including the coefficient of determination (R^2), the normal root means square error (NRMSE), and the mean absolute error (MAE) (see Table 7). Theoretically, for a model to be considered excellent, the R2 value must be 1, the NRMSE value 0, and the MAE value 0 [43-46].

6. Conclusion

This study aimed to establish useful predictive equations for assessing surface quality of building stones after polishing process based on their physico-mechanical and petrographic properties. for this purpose, Comprehensive laboratory investigations were performed on 15 different types of granite stones. based on obtained results, three indices for evaluating improvement of stone surface quality were introduced and the correlation of these indices with petrographic and physico-mechanical properties of stones was examined. The findings indicated that the Schmidt hammer hardness (SCH) had the greatest impact on improvement indices and it is the most effective input variable for developing predictive equations. Consequently, three equations were established for predicting improvement indices based on SCH using non-linear regression analyses.

Table 7. Performance metrics used in this study.

Performance metric	Mathematical expression
R^2	$R^2 = 1 - \frac{\sum(y_i - f_i)^2}{\sum(y_i - \bar{y})^2}$
NRMSE	$NRMSE = \frac{\sqrt{\frac{1}{N}\sum(f_i - y_i)^2}}{\bar{y}}$
MAE	$MAE = \frac{1}{N}\sum\lvert f_i - y_i\rvert$

N: the total number of data, y_i: the i-th measured value, f_i: the i-th predicted value, and $\bar{y}$: the mean of all measured values.

Table 6. The detailed results of ANOVA test for developed equations.

Equation no.		Sum of squares	df*	Mean square	F	Sig.
7	Regression	1.356	1	1.356	61.543	0.000
	Residual	0.286	13	0.022		
	Total	1.642	14			
8	Regression	0.079	1	0.079	38.380	0.000
	Residual	0.027	13	0.002		
	Total	0.106	14			
9	Regression	1.084	1	1.084	56.190	0.000
	Residual	0.251	13	0.019		
	Total	1.335	14			

* df: degrees of freedom

The prediction performance of developed equations was assessed using statistical indicators, including the coefficient of determination (R^2), normalized root means square error (NRMSE), and mean absolute error (MAE). The performance assessment showed that the proposed equations are effective and practical tools for predicting GII, RII, and QII with an acceptable error margin. Based on these results, SCH can be used as a reliable in-situ, portable and nondestructive evaluation (NDE) tool to assess the surface quality of building stones after polishing process.

Finally, it is important to note that the validity of proposed equations is limited by the implementation conditions of polishing experiments, the data range and sample types which have been used to derive the equations. Therefore, it is strongly recommended that it is not assumed to be applicable to all types of building stones. More experiments can be performed on different stones to improve the reliability of developed equations and to develop more comprehensive equations.

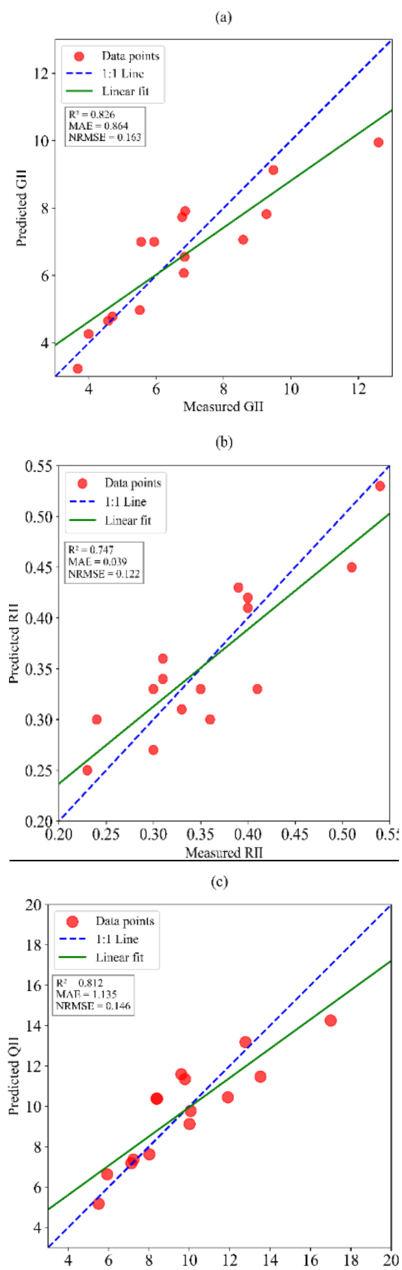


Figure 7. Prediction performance of proposed equations: (a) Equation (7), (b) Equation (8), and (c) Equation (9).

Declarations

Availability of data:

The data that support the findings of this study are available within the manuscript.

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Conflicts of interest/Competing interests

The authors declare no competing interests.

Authors' contributions:

Seyed Jalil Mousavi: Material preparation, data collection, methodology, software, writing — original draft. Ebrahim Ghasemi: Conceptualization, supervision, review, formal analysis. Ali Farhadian: Material preparation, discussion, formal analysis, review and editing. Ali Bameri: Writing—original draft, validation, software, visualization. All authors read and approved the final manuscript.

References

[1]. .Barbosa, A.R., Coelho, A., Fernandes, J.C., Amaral, P.M., Rosa, L.G. & Pereira, J.C. A contribution for an optimization of the polishing quality of stone slabs: simulation and experimental study using a single-head polishing machine. In Proceedings of the 3rd International Conference on Stone and Concrete Machining (ICSCM), Bochum, Germany, pp. 178-187 (2015). https://doi.org/10.13140/RG.2.1.4415.1769

[2]. Coelho, A., Pereira, J.C., Amaral, P.M. & Rosa, L.G. Gloss and modelling studies of stone polishing using linear polishing machines with rotating heads. Appl. Sci. 12, 7521 (2022). https://doi.org/10.3390/app12157521

[3.] Farhadian, A., Ghasemi, E., Hoseinie, S.H. & Bagherpour, R. Development of a new test method for evaluating the abrasivity of granite building stones during polishing process based on weight loss of abrasive tool. Constr. Build. Mater. 303, 124497 (2021). https://doi.org/10.1016/j.conbuildmat.2021.124497

[4]. Yang, H., Li, H., Zhu, C., Fang, H. & Li, J. A process parameters selection approach for trade-off between energy consumption and polishing quality. Int. J. Comput. Integr. Manuf. 31, 380–395 (2018). https://doi.org/10.1080/0951192X.2017.1407875

[5]. Saidi, M.N., Songmene, V., Kouam, J. & Bahloul, A. Rotational and translation-free polishing of granite: surface quality and dust particles emission and dispersion. Int. J. Adv. Manuf. Technol. 98, 289–303 (2018). https://doi.org/10.1007/s00170-018-2247-8

[6]. Sanmartín, P., Silva, B. & Prieto, B. Effect of Surface Finish on Roughness, Color, and Gloss of Ornamental Granites. J. Mater. Civ. Eng. 23, 1239–1248 (2011). https://doi.org/10.1061/(asce)mt.1943-5533.0000285

[7]. Yavuz, H., Ozkahraman, T. & Demirdag, S. Polishing experiments on surface quality of building stone tiles. Constr. Build. Mater. 25, 1707–1711 (2011). https://doi.org/10.1016/j.conbuildmat.2010.10.016

[8]. Cevheroğlu Çıra, S., Dağ, A. & Karakuş, A. Investigation of the effects of marble material properties on the surface quality. Adv. Mater. Sci. Eng. 2018, 6514785 (2018).

https://doi.org/10.1155/2018/6514785

[9]. Gadelmawla, E.S., Koura, M.M., Maksoud, T.M., Elewa, I.M. & Soliman, H.H. Roughness parameters. J. Mater. Process. Technol. 123, 133–145 (2002). https://doi.org/10.1016/S0924-0136(02)00060-2

[10]. Ruzova, T.A. & Haddadi, B. Surface roughness and its measurement methods-analytical review. Results Surf. Interf. 19, 100441 (2025). https://doi.org/10.1016/j.rsurfi.2025.100441

[11]. Alhassan, M., Maawadh, A., Labban, N., Alnafaiy, S.M., Alotaibi, H.N. & BinMahfooz, A.M. Effect of different surface treatments on the surface roughness and gloss of resin-modified CAD/CAM ceramics. Appl. Sci. 12, 11972 (2022). https://doi.org/10.3390/app122311972

[12]. Rezaei, N., Ghasemi, E. & Nasiri Sarvi, M. A laboratory investigation for assessing the effectiveness of wastewater treatment using flocculation process in building stone processing industry on stone surface quality and abrasive tool wear. Discov. Civ. Eng. 1, 57 (2024). https://doi.org/10.1007/s44290-024-00060-4

[13]. Erdogan, M. Measurement of polished rock surface brightness by image analysis method, Eng. Geol. 57, 65–72 (2000). https://doi.org/10.1016/S0013-7952(99)00148-9

[14]. Ersoy, M. & Kose, H. The relationship between easiness to polishing and mechanical properties of marbles. In Proceedings of the National Marble Symposium, Afyon, Turkey, pp. 337-349 (2011).

[15]. Huang, H., Li, Y., Shen, J.Y., Zhu, H.M. & Xu, X.P. Micro-structure detection of a glossy granite surface machined by the grinding process. J. Mater. Process. Technol. 129, 403–407 (2002). https://doi.org/10.1016/S0924-0136(02)00702-1

[16]. Karaca, Z. Relationship between the mechanical properties and the surface roughness of marble. Int. J. Mater. Res. 103, 633–637 (2012). https://doi.org/10.3139/146.110728

[17]. Gürcan, S., Goktan, R.M. & Yıldız, A. Effect of mineralogical and microstructural properties on surface roughness and gloss of some ornamental marbles subjected to polishing process. X-Ray Spectrom. 43, 70–78 (2014). https://doi.org/10.1002/xrs.2492

[18]. Ersoy, M., Yesilkaya, L., Celik, M.Y. & Gecer, G. Investigation of the belt conveyor speed effect to the surface quality in marble polishing process. J. Polytechnic. 17, 153–160 (2014).

[19]. Ozcelik, Y., Careddu, N. & Yilmazkaya, E. The effects of freeze–thaw cycles on the gloss values of polished stone surfaces. Cold Reg. Sci. Technol. 82, 49–55 (2012). https://doi.org/10.1016/j.coldregions.2012.05.007

[20]. Careddu, N. & Marras, G. The effects of solar UV radiation on the gloss values of polished stone surfaces. Constr. Build. Mater. 49, 828–834 (2013). https://doi.org/dx.doi.org/10.1016/j.conbuildmat.2013.09.010

[21]. Vázquez, P., Luque, A., Alonso, F.J. & Grossi, C.M. Surface changes on crystalline stones due to salt crystallisation. Environ. Earth Sci. 69, 1237–1248 (2013). https://doi.org/10.1007/s12665-012-2003-6

[22]. Sousa, L.M.O. & Gonçalves, B.M.M. Differences in the quality of polishing between sound and weathered granites. Environ. Earth Sci. 69, 1347–1359 (2013). https://doi.org/10.1007/s12665-012-2035-y

[23]. Cevheroğlu Çıra, S., Dağ, A. & Karakuş, A. Application of response surface methodology and central composite inscribed design for modeling and optimization of marble surface quality. Adv. Mater. Sci. Eng. 2016, 2349476 (2016). https://doi.org/10.1155/2016/2349476

[24]. Sarici, D.E. Thermal deterioration of marbles: Gloss, color changes. Constr. Build. Mater. 102, 416–421 (2016). https://doi.org/10.1016/j.conbuildmat.2015.10.200

[25]. Farhadian, A., Ghasemi, E., Hoseinie, S.H. and Bagherpour, R. Investigating the effect of operating parameters on the wear of abrasive tools in the polishing stage of granitic building stones. Lubricants 10, 321 (2022). https://doi.org/10.3390/lubricants10110321

[26]. Görgülü, K. & Ceylanoğlu, A. Evaluation of continuous grinding tests on some marble and limestone units with silicon carbide and diamond type abrasives. J. Mater. Process. Technol. 204, 264–268 (2008). https://doi.org/10.1016/j.jmatprotec.2007.11.039

[27]. Gürcan, S. & Oztürk, E. Effect of different abrasives on polishing of some limestones. AKU J. Sci. 14, 025801 (2014). https://doi.org/10.5578/fmbd.7494

[28]. Huang, S., Lu, J., Chen, S., Huang, H., Xu, X. & Cui, C. Study on the surface quality of marble tiles polished with Sol-Gel derived pads. J. Sol-Gel Sci. Technol. 91, 485–495 (2019). https://doi.org/10.1007/s10971-019-05041-z

[29]. Huang, S., Lu, J., Xu, X. & Cui, C. Surface evolution and potimizing strategy for polishing natural heterogeneous marble using Sol-Gel diamond pad. Appl. Sci. 14, 8314 (2024). https://doi.org/10.3390/app14188314

[30]. Sitzia, F., Lisci, C. & Mirao, J. The interaction between rainwater and polished building stones for flooring and cladding-Implications in architecture. J. Build. Eng. 52, 104495 (2022). https://doi.org/10.1016/j.jobe.2022.104495

[31]. Kelemen-Cserta, E. & Gyurika, I.G. Influencing effect of minerals composition in natural granite rocks on surface roughness. Results Mater. 21, 100504 (2024). https://doi.org/10.1016/j.rinma.2023.100504

[32]. Çetintaş, S. Polishing Performance of Muğla White Marble with Different Abrasives. Geoheritage 17, 23 (2025). https://doi.org/10.1007/s12371-025-01064-x

[33]. International Society for Rock Mechanics. Rock characterisation, testing and monitoring. In: Brown E.T. (ed) ISRM suggested methods. Pergamon, Oxford (1981).

[34]. ASTM C170. Standard test method for compressive strength of dimension stone. ASTM International (2017).

[35]. Ersoy, A. & Waller, M.D. Textural characterisation of rocks. Eng. Geol. 39, 123–136 (1995). https://doi.org/10.1016/0013-7952(95)00005-Z

[36]. Sousa, L.M.O. The influence of the characteristics of quartz and mineral deterioration on the strength of granitic dimensional stones. Environ. Earth Sci. 69, 1333–1346 (2013). https://doi.org/10.1007/s12665-012-2036-x

[37]. Howarth, D.F. and Rowlands, J.C. Quantitative assessment of rock texture and correlation with drillability and strength properties. Rock Mech. Rock Eng. 20, 57–85 (1987). https://doi.org/10.1007/BF01019511

[38]. Linke, B. & Das, J. Aesthetics and gloss of ground surfaces: a review on measurement and generation. J. Manuf. Sci. Eng. 138, 064501 (2016). https://doi.org/10.1115/1.4032587

[39]. Grymak, A., Aarts, J.M., Ma, S., Waddell, J.N. & Choi, J.J.E. Comparison of hardness and polishability of various occlusal splint materials. J. Mech. Behav. Biomed. Mater. 115, 104270 (2021). https://doi.org/10.1016/j.jmbbm.2020.104270

[40]. SPSS 16.0. Statistical analysis software (Standard Version). SPSS Inc (2007).

[41]. Jang, H., Topal, E. & Kawamura, Y. Unplanned dilution and ore loss prediction in longhole stoping mines via multiple regression and artificial neural network analyses. J. South. African Inst. Min. Metall. 115, 449–456 (2015).

[42]. Bahri, M., Ghasemi, E., Kadkhodaei, M.H., Romero-Hernández, R. & Mascort-Albea, E.J. Analysing the life index of diamond cutting tools for marble building stones based on laboratory and field investigations. Bull. Eng. Geol. Environ. 80, 7959–7971 (2021). https://doi.org/10.1007/s10064-021-02381-5

[43]. Yurdakul, M. & Akdas, H. Modeling uniaxial compressive strength of building stones using non-destructive test results as neural networks input parameters. Constr. Build. Mater. 47, 1010–1019 (2013). https://doi.org/10.1016/j.conbuildmat.2013.05.109

[44]. Amirkiyaei, V., Ghasemi, E. and Faramarzi, L. Estimating uniaxial compressive strength of carbonate building stones based on some intact stone properties after deterioration by freeze–thaw. Environ. Earth Sci. 80, 352 (2021). https://doi.org/10.1007/s12665-021-09658-8.

[45]. Duan, X. Assessment of resilient modulus of soil using hybrid extreme gradient boosting models. Sci. Rep. 14, 31706 (2024). https://doi.org/10.1038/s41598-024-81311-3

[46]. Chen, Y., Khandelwal, M., Onifade, M., Zhou, J., Lawal, A.I., Bada, S.O. and Genc, B. Predicting the Hardgrove grindability index using interpretable decision tree-based machine learning models. Fuel 384, 133953 (2025). https://doi.org/10.1016/j.fuel.2024.133953