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Research Article

Modeling and Estimation of Production Rate in Ornamental Stones Sawing Based on Brittleness Indexes

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As for estimating the cost and planning the process of the rock sawing plants, it is significant to predict the production rate of ornamental stones sawing. To promote the efficiency in planning these rock sawing projects, scholars have been trying to find a high-accuracy method of production rate estimation. Moreover, targeting at the 28 granite and carbonates stone in the nature, this study examined the connection between two various brittleness indexes in statistics, including the ratio of compressive strength to tensile strength (B_1) and places below the line of compressive strength and the line of tensile strength (B_2) in rocks and production rate had been studied. Through the results of cross plots analysis, it was indicated that there existed a strong connection between production rate and the brittleness B_1 and B_2. Finally, in this thesis, through adding B_1 factor, it has improved the estimation model for production rate which Mikaeil et al. (2013) have established. What's more, by virtue of brittleness about B_1 and B_2, this production rate estimation model has been established successfully for natural stone sawing. Actually, the way of estimating the production rate of 28 rock samples is to utilize the two kinds of models described before. Through the result, it is showed that the production rate estimated by the improved model corresponds to the value of production rate of rock testing. Meanwhile, the precision has been greatly improved with comparison to the model of estimating the production rate designed by Mikaeil et al. (2013). Thus, on the basis of the new model, a dependable prediction for ornamental stones production is put forward in this paper. And it is required to do a further study involving different rock types since limited rock types were used in this study.

1. Introduction

As is known to us, the stone factories generally tend to use the circular diamond saws. It is of great importance for predicting the performance in circular diamond saw to estimate the cost and plan the process of stone factory. Actually, there are different types of effective parameters classified according to the typical stone feature, sawing and operational portrayal about machine, and abilities to operate and working state. Meanwhile, it is this complicated interaction of such effective parameters that affects this performance in circular diamond saws. Moreover, during sawing process, the sawing characteristics and operating skills are controllable except the stone characteristics amid these parameters [1]. Besides, when it comes to the relationship of sawability and rock features of stone sawing, numerous studies [2–5] have been conducted about it. Indeed, as for this relation of stone quality and performance in circular saw, it has been studied before by the researchers [6–10]. According to [11], two models of empirical performance prediction have been put forward, in which Schmidt hammer rebound values and Cerchar abrasivity index are employed for predicting. A comparison between these predicted and real areal slab production rates of circular diamond saws was exploited to verify the reliability of the models. Based on the samples gathered among 5 various marble quarries in Mugla province of Turkey, a number of statistical models have been suggested by [12]. In these models, the slab production rate each hour and surface hardness and mineral grain size are connected. Through the investigation of the performance of circular diamond saws on eight distinct carbonate rocks, it has been found by [13] that there exists the strong linear connection between areal slab production rate in large diameter saws and indentation hardness index.

Table 1: Most of the previous researches on the performance of circular diamond saws.

Main directions of research	Stone characteristics	Sawing and operational characterization of machine	Operating skills and working conditions
Researchers	[1]; [2]; [3]; [4]; [5]; [6]; [7]; [8]; [10]; [11]; [12]; [13]; [16]; [17]; [18]; [19]; [20]; [21]; [22]; [23]; [24]; [25]; [26]; [27]; [28]; [29]; [30]; [31]; [32]; [33]; [34]; [35]; [36]; [37]; [38]; [39]; [40]; [41]; [42]; [43]; [44]; [45]; [46]; [47]; [48]; [49]; [50]; [51]; [52]; [53];	[9]; [15]; [54]; [55]; [56]; [57]; [58]; [59]; [60]; [14]; [61]; [62]; [63]; [64];	[65]; [66]; [67]; [68];

As is known to us, it is obvious that brittleness is a member of the crucial mechanical rocks features. However, there are just small numbers of researches which are conducted on the relation of rock sawability plus rock brittleness. Within the researches, with the help of the regression analysis, [7] paid much attention to the investigation of the connection of rock sawability plus various brittleness indexes. Moreover, by virtue of the optimum data gained through these studies in experiments, a connection among brittleness, destruction-specific energy, and both sawability and drillability has been evaluated statistically by [15]. Paper [1] conducted a discussion about the connection between different brittleness indexes and rock sawability and proposed that B_3 (places below the line of compressive strength and the line of tensile strength) indexes should be regarded as a standard to predict production rate of rock sawing. At present, many scholars have done a lot of researches in stone processing and a number of related academic papers have been published. The previous research works can be classified in three major categories as shown in Table 1.

In the investigation of this study, the application of rock brittleness is seen as a standard to predict production rate of rock sawing. What's more, collecting the specimens in various stone processing plants and conducting relevant experiments can make a contribution to the generation of a data base. Eventually, a new prediction model based on brittleness indexes is obtained and the efficiency of the proposed models in this study is analyzed in detail.

2. Sawing Mechanism and Brittleness Indexes

2.1. Sawing Mechanism. Through the diamond circular saw, chip formation of rock sawing serves to destruct workpiece substance. Besides, the saw revolves at a kind of angular cutting speed and cut the workpiece at a stable traverse rate. By damaging and breaking the surface of the workpiece, the material is removed by these diamond particles on the outer side of segment. Meanwhile, there is a cut produced in two mechanisms in these processes, which is given in Figure 1.

Indeed, it is the tangential forces that influence the stress in front of a grain involved in this process. Meanwhile, the tensile and compressive stresses are able to process the swarf, which is a kind of mechanism named the primary chip formation. Besides, the proof around the grain can force out the swarf which is generally abrasive and small in size. When it is displayed that the elastic quality of the rock has reached its final stress, reaching the relative minimum grinding thickness through cutting can be necessary. Actually, this compressive stress under a diamond can deform a rock cut. It is in the secondary chip formation that a process influenced by the tensile stresses is described. And the process denotes that an elastic revision results in the critical tensile stress when the load is removed, which produces the brittle fracture. And the coolant fluid makes the swarf disappear [14].

2.2. Brittleness Indexes. Brittleness, one of the crucial rock properties, has been exploited for judging the fracture toughness and evaluating the cutability of coal, the sawability of rocks, the drillability, and borability of rocks [6, 7, 18–21]. Furthermore, brittleness of rock plays a key part in developing these tight oil gas reservoirs in which a kind of implication about a potential for hydraulic fracturing has been given.

Actually, many authors take different opinions on the definition, notion, or measurement of brittleness. Thus, there is a growing number of various measurements for rock brittleness which were proposed and employed for various research aims [18, 19, 21–42, 61–64, 68]. According to previous studies, it is observed that the brittleness approaches are determined by mechanical experiments [30, 41], mineral contents [69, 70], and elastic parameters [43–45]. Generally, brittleness measures a related susceptibility in an article to two mechanical responses in competition including deformation and breaking. The ductile-brittle transition has been successfully expounded by [41]. In this study, the two employed brittleness indexes are given as follows [30, 41]:

$$B_1 = \frac{\sigma_c}{\sigma_t} \tag{1}$$

$$B_2 = \frac{\sigma_c \cdot \sigma_t}{2} \tag{2}$$

in which B_1 and B_2 refer to brittleness, σ_c means the uniaxial compressive strength (MPa), and σ_t refers to the Brazilian tensile strength (MPa).

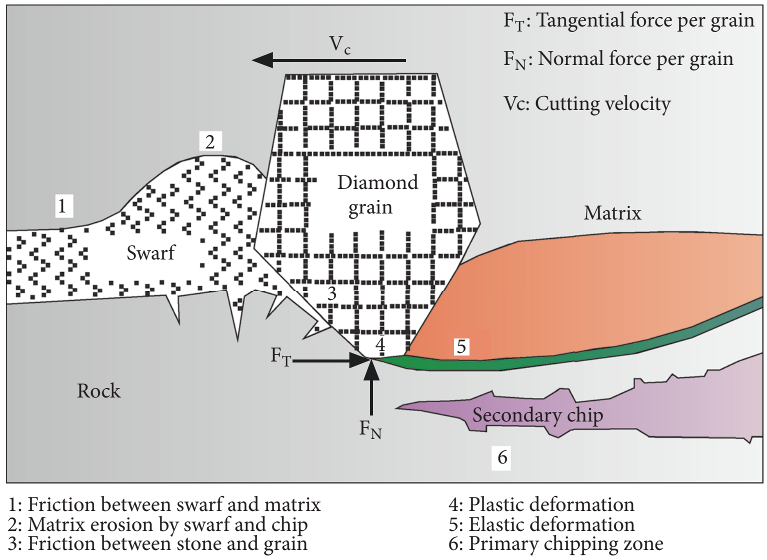


Figure 1: Mechanical connection of saw and stone in cutting process (modified after [14]).

Some authors frequently talk about equations (1) and (2), like Walsh and Brace [46], Niwa and Kobasayashi [47], Beron et al. [48], Chiu and Johnston [49], Kim and Lade [50], Vardoulakis [71], Koulikov [72], Inyang and Pitt [36], Goktan [63], Inyang [37], Andreev [51], Kahraman [21], Atici and Ersoy [15], and Mikaeil et al. [1]. Limited rock types including granite and carbonate were tested since the purpose of this paper is to reveal the predictability about production rate in ornamental stone from brittleness. In the future, the study will be deepened and extended by reaching various rock types.

3. Data Preparation and Analysis

3.1. Laboratory and Field Studies. This study will use two sets of rock experimental data: one comes from [1] and the other is from [11, 52]. A group of 17 data points were obtained from [1]. In Shamsabad of Iran, several stone factories were visited. Besides, targeting at 17 various granite and carbonate rocks, production rates in diamond circular saws have been calculated. Meanwhile, there were the rocks blocks selected among these factories which target at doing experiments. Among the block samples, each one has been examined carefully in terms of the macroscopic defects in order to offer the test specimens without breakings, partings, and change areas. Besides, on the basis of ISRM suggested methods [53], standard test samples have been selected among the block specimens. Moreover, the Brazilian tensile strength and the uniaxial compressive strength have been decided. Table 2 presents these results about field and experimental researches and these calculated brittleness values on every rock [1]. For simplicity and reader's preference, the detailed introduction of the experimental tests was omitted. More detailed studies about experiment are provided in relevant literatures and reviews which readers can refer to [1, 11]

According to these results on conducted experiments, uniaxial compressive strength (*UCS*) values change from 53 to 218 MPa, Brazilian tensile strength (*BTS*) values change from 4.3 to 24.6 MPa, B_1 ranges from 8.86 to 16.9, B_2 ranges from 114 to 2681, and production rate values vary between 3 and 11 m^2/h. Table 3 includes the basic descriptive statistics.

In addition, another group of 11 rock block samples were gathered from natural stone factories. From International Society for Rock Mechanics criteria [53], the mechanical property tests were conducted involving the carbonate rocks, including Afyon tigerskin marble, Afyon white marble, Karacabey black limestone, Manyas white marble, Marmara white marble, Milas white marble, Eskisehir supreme limestone, Karahallı white marble, Karahallı gray marble, Mustafa Kemal Pasa white marble, and Sivaslı purple marble. Among these grinded NX (54.7 mm) specimens which possess the length to diameter ratio of about 2.5-3, these uniaxial compressive strength (*UCS*) experiments have been conducted. The stress rate has been limited in a specific rank 0.5-1.0 kN/s. Moreover, among the grinded NX samples which possess the length to diameter ratio of about 0.5-1.0, these Brazilian tensile strength (*BTS*) experiments have been conducted. And the applied stress rate has been required as 0.25 kN/s. Actually, the *UCS* and *BTS* tests are duplicated ten times on every stone specimen. Table 4 summarizes these results about field and experimental researches and these calculated brittleness values about every rock.

According to these results about conducted experiments, it is displayed that uniaxial compressive strength (*UCS*) values change from 63.8 to 108 MPa, Brazilian tensile strength (*BTS*) values change from 3.9 to 7.9 MPa, B_1 ranges from 13.11 to 17.17, B_2 varies between 127.34 and 426.6, and production rate values vary between 7.04 and 16.22 m^2/h. Table 5 includes the basic descriptive statistics.

3.2. Analyzing Data. Generally, according to a number of readings, a connection has been discovered between brittleness index of natural stones and production rate. Thus, as is shown in Figure 2, the cross plot of B_2 versus B_1 which

Table 2: The results about field and experimental researches and these calculated brittleness values (Mikaeil et al. [1]).

Sample no.	Rock type	*UCS* (MPa)	*BTS* (MPa)	B_1	B_2	Production rate (m^2/h)
1	Granite (Toyserkan)	218	24.6	8.86	2681	3
2	Granite (Nehbandan-K)	146	10.6	13.8	773.8	5
3	Granite (Piranshahr)	176	18	9.78	1584	4.5
4	Granite (Birjand)	126.5	8.52	14.8	538.9	6.5
5	Granite (Ouromie)	129	10.3	12.5	664.4	6
6	Granite (Chayan)	173	14.5	11.9	1254	5
7	Granite (yazd)	142	8.52	16.7	604.9	5.5
8	Granite (Nehbandan-S)	145	9.2	15.8	667	5
9	Granite (Khoramdare)	133	8.3	16	552	6
10	Granite (Mashhad)	125	7.4	16.9	462.5	6.5
11	Marble (Harsin)	71.5	6.8	10.5	243.1	8.5
12	Marble (Anarak)	74.5	7.1	10.5	264.5	9
13	Marble (Salsali)	73	6.3	11.6	230	9
14	Marble (Haftoman)	74.5	7.2	10.3	268.2	8
15	Travertine (Darehbokhari)	63	5.4	11.7	170.1	10
16	Travertine (Hajiabad)	61.5	5.6	11	172.2	10
17	Travertine (Azarshahr)	53	4.3	12.3	114	11

UCS: Uniaxial compressive strength, *BTS*: Brazilian tensile strength.

Table 3: The basic descriptive statistic for the original dataset of the 17 rocks.

Descriptive statistics	*UCS* (MPa)	*BTS* (MPa)	B_1	B_2	Production rate (m^2/h)
Minimum value	53	4.3	8.86	114	3
Maximum value	218	24.6	16.9	2681	11
Average	116.74	9.57	12.64	661.45	6.97
Standard deviation	48.3	5.14	2.55	652.74	2.29

UCS: Uniaxial compressive strength, *BTS*: Brazilian tensile strength.

Table 4: Summary of mechanical properties and these calculated brittleness values about natural stone samples (Tumac, [11]).

Sample no.	Rock type	*UCS* (MPa)	*BTS* (MPa)	B_1	B_2	Production rate (m^2/h)
1	Afyon tigerskin marble	81.3	5.1	15.94	207.32	11.28
2	Afyon white marble	88.6	6.0	14.77	265.80	7.28
3	Karacabey black limestone	70.8	5.4	13.11	191.16	8.23
4	Manyas white marble	65.3	3.9	16.74	127.34	15.33
5	Marmara white marble	70.4	4.1	17.17	144.32	16.22
6	Milas white marble	97.3	7.1	13.70	345.42	8.63
7	Eskisehir supreme limestone	89.0	5.3	16.79	235.85	12.32
8	Karahallı white marble	63.8	4.6	13.87	146.74	11.85
9	Karahallı gray marble	70.2	4.7	14.94	164.97	13.38
10	Mustafa Kemal Pasa white marble	77.8	5.1	15.25	198.39	12.25
11	Sivaslı purple marble	108.0	7.9	13.67	426.60	7.04

UCS: Uniaxial compressive strength, *BTS*: Brazilian tensile strength.

Table 5: The fundamental descriptive data about these original datasets of the 11 rocks.

Descriptive statistics	*UCS* (MPa)	*BTS* (MPa)	B_1	B_2	Production rate (m^2/h)
Minimum value	63.8	3.9	13.11	127.34	7.04
Maximum value	108	7.9	17.17	426.6	16.22
Average	80.23	5.38	15.09	223.08	11.26
Standard deviation	14.13	1.21	1.42	92.1	3.13

UCS: Uniaxial compressive strength, *BTS*: Brazilian tensile strength.

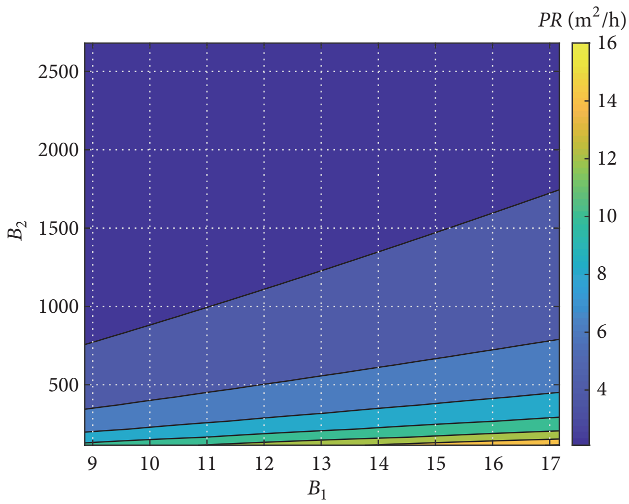


Figure 2: Cross plot of B_2 versus B_1 showing change in production rate (*PR*) for limited rock types in this study.

shows the change in production rate for the total of 28 rock samples in this paper was carried out to study the correlation between brittleness index of natural stones and production rate. In Figure 2, it can be seen that a positive correlation is produced between B_1 and production rate, while negative correlation exists between B_2 and production rate. However, this figure does not show a clear degree of correlation between brittleness index and production rate. And it also does not show a global range for the brittleness values of natural stones which could be used for other case researches as well.

In addition, to evaluate simple relation of rock brittleness indexes and observed production rate data, one analysis technique was taken to feature the sensitivity of production rate values to brittleness indexed values. An extremely simple linear regression experiment (cross plotting) has been carried out. Besides, correction coefficient (R^2) has been exploited for an important signal to indicate a kind of investigation of the influence of various rock brittleness indexes about these lab-observed production rate values.

According to the lithology of the rock, the first group of 17 rock samples were divided into marble and carbonate groups in this study. There was a statistical analysis targeting at each group separately. In order to analyze the performance results and rock brittleness indexes, the least squares regression method was exploited. By virtue of the "Origin" software, a connection has been discovered between these production rate values and the brittleness indexed values. Mikaeil et al. [1] showed that brittleness about B_1 and that about B_2 are two significant factors affecting the estimation of production rate. Figures 3 and 4 demonstrate how production rate is related to B_1 and B_2.

Cross plots of observed production rate and the brittleness indexes for the 17 rock samples can be seen from Figure 3. It is discovered that a negative relation exists between B_2 and production rate within linear regression, which possesses the highest correction coefficient of 0.8157 for granite rocks and of 0.8971 for carbonate rocks. Although the B_1 appears to have a positive connection with production rate, it has the correction coefficient of 0.5218 for granite rocks and of 0.6532 for carbonate rocks, respectively. Cross plots of observed production rate and the brittleness indexes for the 11 rock samples are shown in Figure 4. Similar to 17 rock samples, the B_2 has a negative connection with production rate, with correction coefficient of 0.5448 in linear regression, while the B_1 appears to have a positive relationship with production rate, with correction coefficient of 0.5742 (see Figure 4).

What can be shown from the above comparison is that the brittleness of B_1 and B_2 shows a sufficiently good relation with production rate according to linear regression analysis. Thus, we can safely conclude that brittleness about B_1 and B_2 could be regarded as the good and independent variables to estimate production rate in rock cutting studies.

4. Results and Discussion

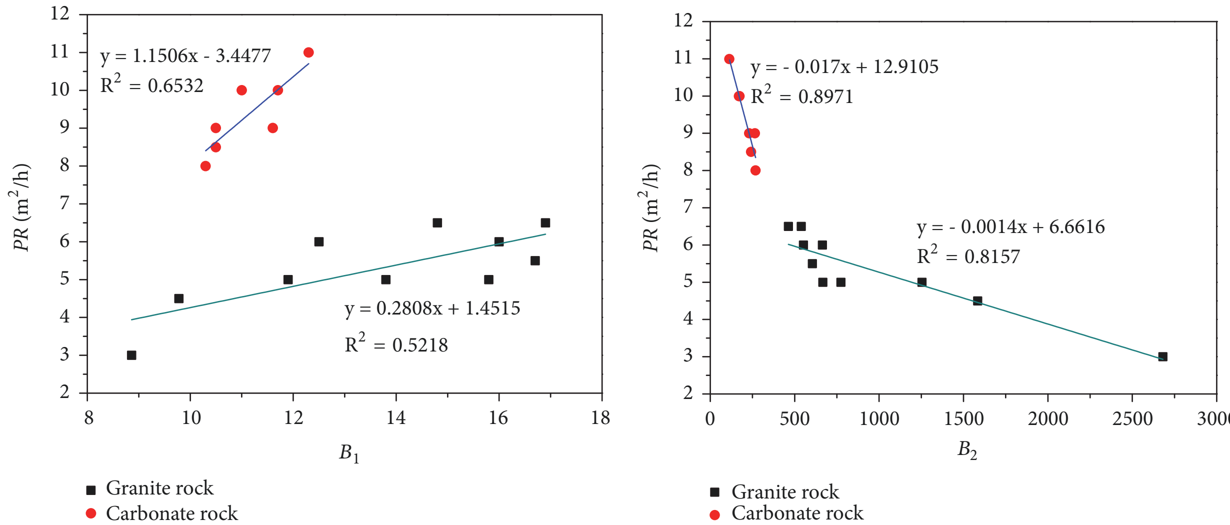
4.1. Establishment and Effect Analysis of Production Rate Model. After analyzing the 17 data points measured from rock analysis concerning granite and carbonate rock, it has been observed by [1] that the brittleness of B_2 is closely connected with the production rate of ornamental stone. And it is the production rate equation suggested by [1] that meets the need of the following model which is expressed as follows:

$$PR = a\left(B_2\right)^b \tag{3}$$

where *PR* refers to production rate, m^2/h; B_2 means brittleness index of ornamental stone, calculated by (2); *a* and *b* are undetermined constants.

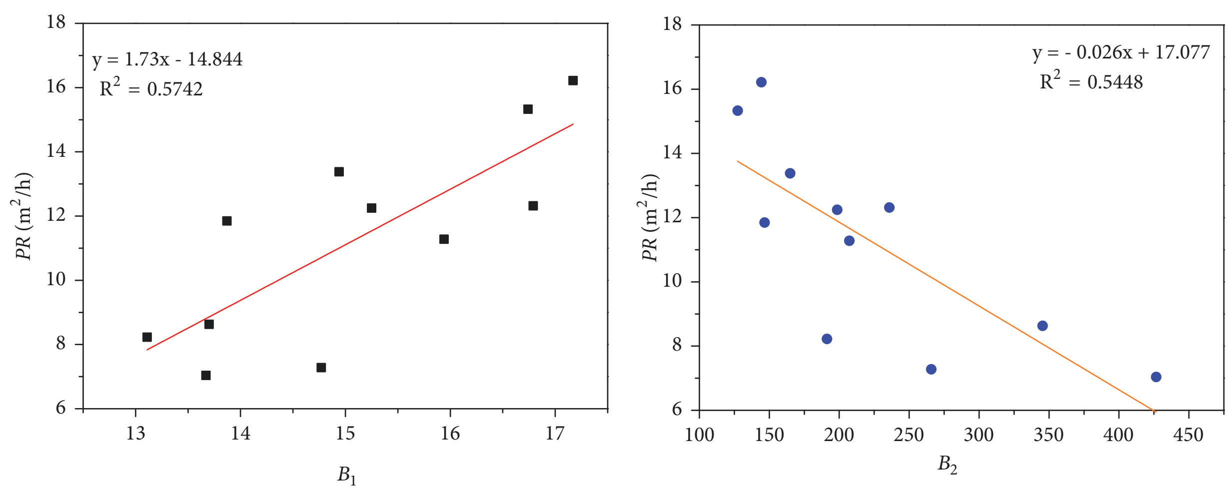
As is mentioned before, it has been demonstrated that the brittleness of B_1 can also reflect the production rate of ornamental stone. Therefore, a new model is put forward, adding the factor of B_1, which is expressed as follows:

$$PR = a\left(B_1\right)^b \times \left(B_2\right)^c \tag{4}$$



(a) Production rate versus B_1 (b) Production rate versus B_2

Figure 3: Cross plots of observed production rate and the brittleness indexes for the 17 rock samples (a): production rate versus B_1; (b): production rate versus B_1.



(a) Production rate versus B_1 (b) Production rate versus B_2

Figure 4: Cross plots of observed production rate and the brittleness indexes for the 11 rock samples (a): production rate versus B_1; (b): production rate versus B_1.

where PR denotes production rate, m^2/h; B_1 and B_2 calculated by (1) and (2), respectively, are brittleness indexes of ornamental stone; a, b, and c are undetermined coefficients.

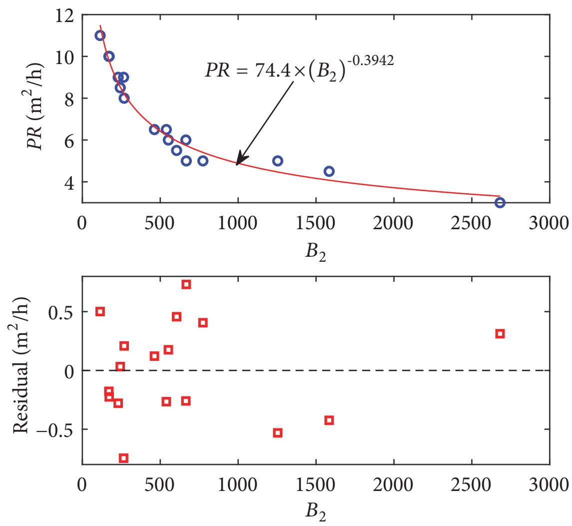
The final results are as follows:

$$PR = 74.4 \times (B_2)^{-0.3942} \quad (5)$$

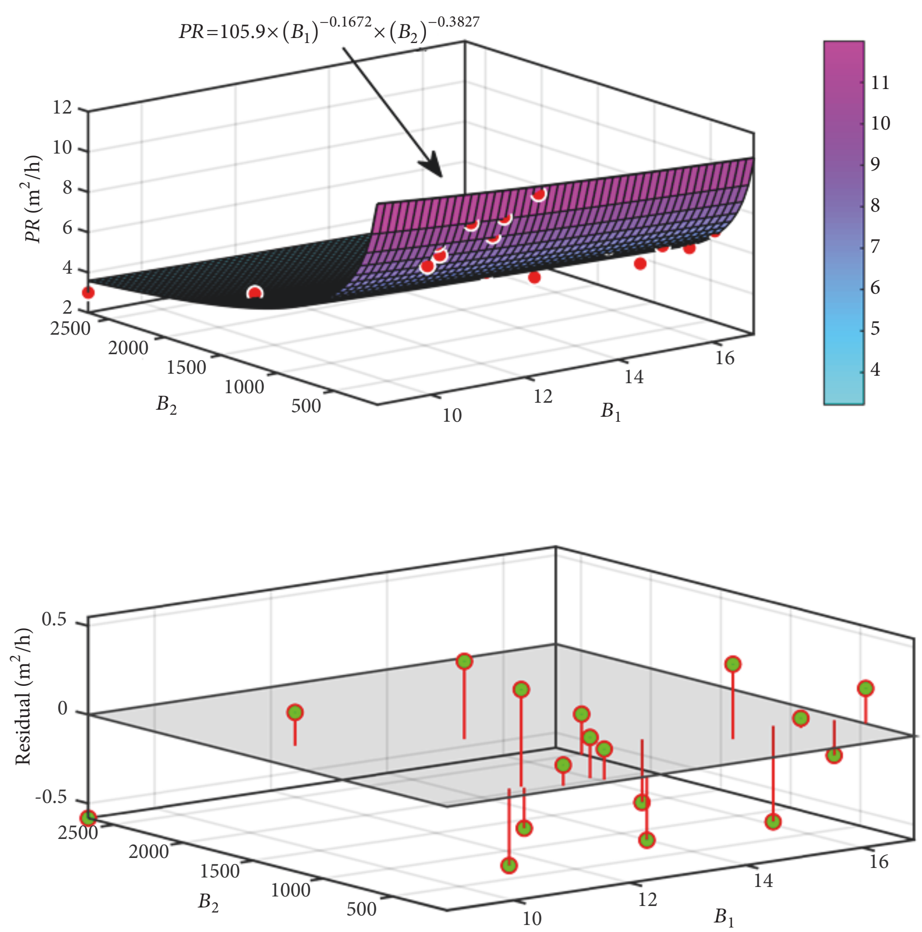
$$PR = 105.9 \times (B_1)^{-0.1672} \times (B_2)^{-0.3827} \quad (6)$$

In addition, the visualized results of production rate model establishment are shown in Figure 5. From Figure 5, what can be clearly shown is that residual of B_2 based model in the prediction of production rate for each rock sample is within the range of [-0.5 m^2/h, 0.5 m^2/h] for most data points, while residual of B_1 and B_2 based model in prediction of production rate for each rock sample is within the range of [-0.5 m^2/h, 0.5 m^2/h] for almost all data points. Eventually, the residual results of two models mentioned before indicate that the B_1 and B_2 based model has better accuracy compared with the B_2 based model in the estimation of production rate of ornamental stone.

Table 6 shows the estimation results of proposed models and the relative errors, and Figure 6 shows the relations between predicted production rate of two types of models and observed production rate of rock samples. It can be seen that the brittleness of B_2 based model with the factor of B_1 mentioned in this thesis has superiority to B_2 based model in production rate of ornamental stone prediction. From the two figures, it can be concluded that, except a few points, the



(a) B_2 based model



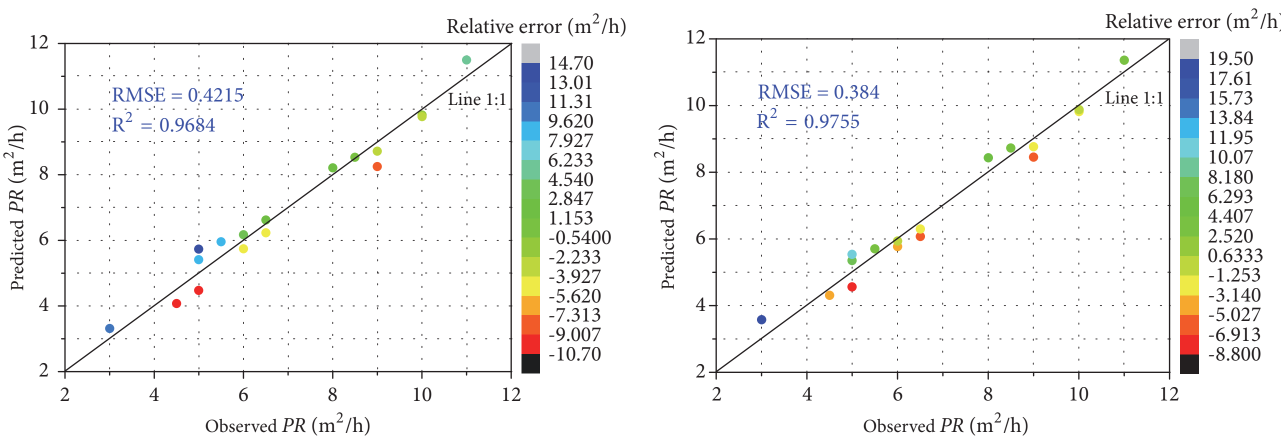
(b) B_1 and B_2 based model

Figure 5: The visualized results of production rate model establishment (a): B_2 based model; (b): B_1 and B_2 based model.

Table 6: The relative error analysis of estimated production rate of two types of models for the 17 rock samples.

Sample no.	Rock type	PR (m^2/h)	B_2 based model PR (m^2/h)	B_1 and B_2 based model PR (m^2/h)	B_2 based model relative error (%)	B_1 and B_2 based model relative error (%)
1	Granite (Toyserkan)	3	3.3123	3.5834	10.4086	19.4474
2	Granite (Nehbandan-K)	5	5.4058	5.3536	8.1165	7.0724
3	Granite (Piranshahr)	4.5	4.0758	4.3111	-9.4261	-4.198
4	Granite (Birjand)	6.5	6.2345	6.0771	-4.0852	-6.506
5	Granite (Ouromie)	6	5.7406	5.7699	-4.3233	-3.8349
6	Granite (Chayan)	5	4.469	4.5621	-10.62	-8.758
7	Granite (yazd)	5.5	5.9569	5.698	8.3071	3.5999
8	Granite (Nehbandan-S)	5	5.7318	5.5399	14.6355	10.7982
9	Granite (Khoramdare)	6	6.1757	5.9435	2.9286	-0.9416
10	Granite (Mashhad)	6.5	6.6217	6.3019	1.873	-3.048
11	Marble (Harsin)	8.5	8.5326	8.7285	0.384	2.6884
12	Marble (Anarak)	9	8.2535	8.4512	-8.2941	-6.098
13	Marble (Salsali)	9	8.721	8.7682	-3.0999	-2.5756
14	Marble (Haftoman)	8	8.2085	8.4335	2.6057	5.4182
15	Travertine (Darehbokhari)	10	9.8224	9.8272	-1.7762	-1.7278
16	Travertine (Hajiabad)	10	9.775	9.8826	-2.2502	-1.1737
17	Travertine (Azarshahr)	11	11.5008	11.3583	4.5528	3.2571

PR: Production rate.



(a) B_2 based model results vs. *PR* of rock samples

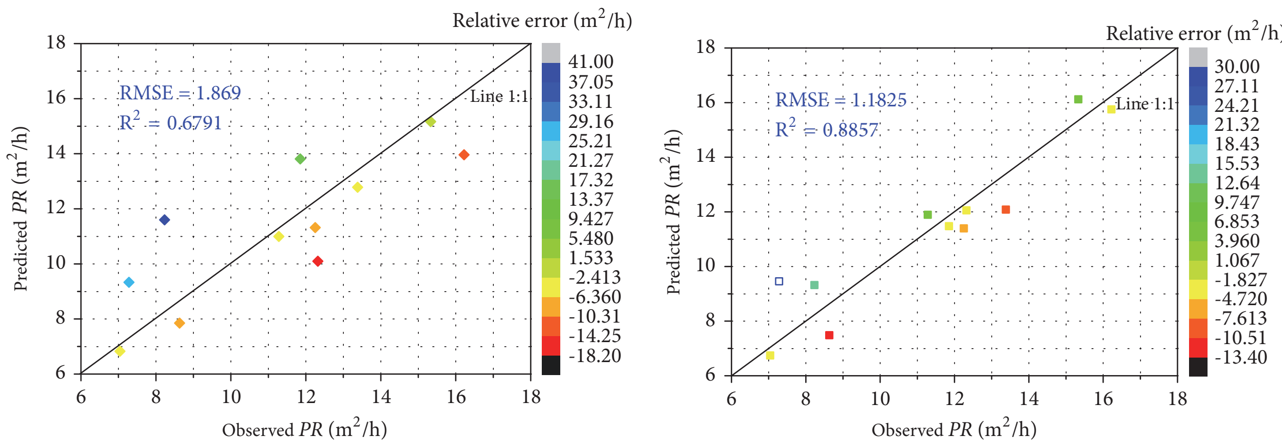
(b) B_1 and B_2 based model results vs. *PR* of rock samples

Figure 6: Comparison of the production rate (*PR*) prediction results and laboratory observed of the 17 rock samples (a): B_2 based model results vs. *PR* of rock samples; (b): B_1 and B_2 based model results vs. *PR* of rock samples.

predicted production rate fundamentally corresponds to the target values of rock samples.

4.2. Model Validation. In the latter stage of this study, to provide validity of these proposed models, 11 data points from another rock group mentioned before were employed for the assessment of proposed models. Table 7 shows the estimation results of proposed models and the relative errors, and Figure 7 shows the relations between predicted production rate by two kinds of models and the target values. It can be seen that the brittleness of B_2 based model with the factor of B_1 mentioned in this paper has superiority to B_2 based model in production rate of ornamental stone prediction.

Two statistical concepts, that is, coefficient of determination (R^2) and root mean square error (*RMSE*), were utilized to compare the prediction performance. Figure 7(a) shows the cross plot of B_2 based model derived production rate results and observed values where correlation coefficient of the predicted and discovered production rate values can be 0.6791. Figure 7(b) shows the cross plot of B_1 and B_2 based model derived production rate results and discovered values where correlation coefficient of the predicted and discovered production rate values can be 0.8857. Once R^2 becomes



(a) B_2 based model results vs. *PR* of rock samples

(b) B_1 and B_2 based model results vs. *PR* of rock samples

FIGURE 7: Comparison of the production rate (*PR*) prediction results and laboratory observed of the 11 rock samples (a): B_2 based model results vs. *PR* of rock samples; (b): B_1 and B_2 based model results vs. *PR* of rock samples.

TABLE 7: The relative error analysis of estimated production rate of two types of models for 11 rock samples.

Sample no.	Rock type	*PR* (m^2/h)	B_2 based model *PR* (m^2/h)	B_1 and B_2 based model *PR* (m^2/h)	B_2 based model relative error (%)	B_1 and B_2 based model relative error (%)
1	Afyon tigerskin marble	11.28	10.9944	11.8944	-2.5317	5.4473
2	Afyon white marble	7.28	9.3316	9.4584	28.1814	29.9235
3	Karacabey black limestone	8.23	11.5993	9.3213	40.9391	13.2599
4	Manyas white marble	15.33	15.1658	16.1219	-1.0711	5.1656
5	Marmara white marble	16.22	13.9634	15.7515	-13.9127	-2.8884
6	Milas white marble	8.63	7.8498	7.4839	-9.0401	-13.2806
7	Eskisehir supreme limestone	12.32	10.0976	12.055	-18.0387	-2.1514
8	Karahallı white marble	11.85	13.811	11.4772	16.5482	-3.1458
9	Karahallı gray marble	13.38	12.7839	12.0826	-4.4555	-9.6967
10	Mustafa Kemal Pasa white marble	12.25	11.3186	11.3948	-7.6035	-6.9808
11	Sivaslı purple marble	7.04	6.8291	6.7433	-2.996	-4.215

PR: Production rate.

over 0.9, this model performance will serve for premium. Generally, only B_1 plus B_2 based model can get correlation coefficient which is over 0.85, demonstrating that predicted production rate has succeeded. *RMSE* can convey that the advantage of the performance about the predictive model can be connected with factual value. As is seen from Figure 7, the lowest *RMSE* belongs to the B_1 and B_2 based model, implying a better prediction performance than B_2 based model.

According to the results of the comparison among the two kinds of models proposed in the study, it is demonstrated that the model based brittleness indexes of B_1 and B_2 outperform the other method owing to the higher R^2 and *RMSE*.

To evidently show the validity of the model proposed in this study, as shown in Figure 8, a boxplot showing the distribution of the differences in relative errors of each model was made to compare the relative errors of the models and their estimation performance. Figures 8(a) and 8(b) show the model's estimation performance in its training part and testing part, respectively. According to Figure 8, it is evident that the model based on B1 and B2 is superior to the one based on B1 for its higher precision in both model construction and testing part, especially in the testing part, and its better estimation because its absolute value of the relative error is controlled fewer than 5%. Moreover, with the comparison between the testing results, the model proposed in this study shows its advantage in estimation accuracy contributing to a more stable estimation and better extensive application. Therefore, it can be applied in related

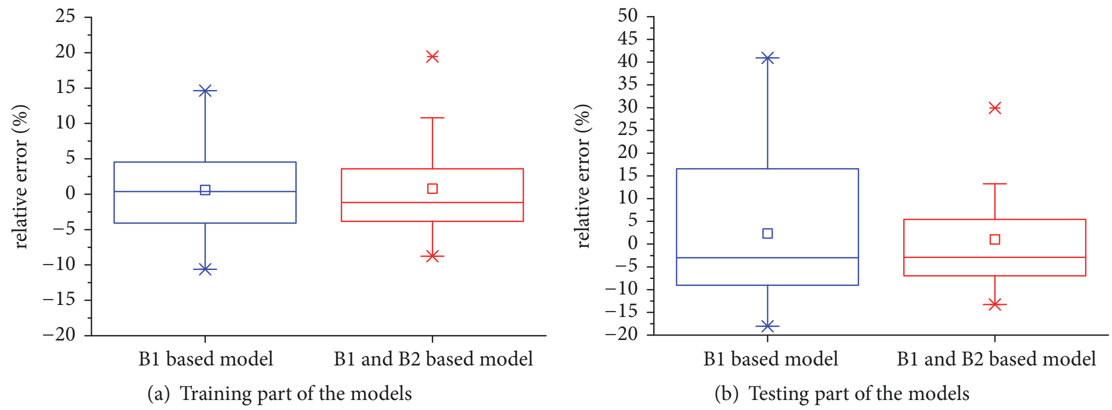


Figure 8: Boxplot showing the differences in relative errors of each model (a): Training part of models; (b): Testing part of models.

industrial production as a more reliable empirical model to make rapid, effective estimation of the production rate. In addition, this study is implemented preliminarily with limited rock types. The samples and rock types are expected to be extended to improve the model's precision and wide application. Therefore, what is expected is that this model can be applied in the industrial production with wide tests and be improved gradually to make it be an inexpensive and simple method with high precision for production rate estimation.

5. Conclusions

According to the extremely inspiring results, the paper gives a precise identification and explanation on estimating sawability performance in diameter circular saw with the help of the brittleness indexes of natural stones. Brittleness parameters B_1 and B_2 of granite and carbonate rock samples have a good connection with production rate. In this paper, there is a new model put forward for the estimation about production rate of rock sawing according to the brittleness parameter and production rate of two groups of rock samples in total of 28 rock blocks. In reality, the new model is better than B_2 based model in estimation performance. What can be shown through the practice is that the production rate estimated by the improved model and the production rate values by core testing are in good agreement, and the accuracy is improved with comparison to the previous B_2 based model, which demonstrates that this method plays a key role in resolving production rate of rocks within ornamental stones sawing. In addition, what can be concluded is that B_1 and B_2 indexes are able to be regarded as a standard to predict production rate of rock sawing. In this study, based on the detailed analysis of the connection between brittleness index and production rate, a model based on brittleness index is constructed for production rate estimation. This model takes a more stable performance and better precision and the relative error of the estimation results is generally kept in 5% contributing to the fact that such a rapid, effective model can be applied to decrease the cost of ornamental stones sawing. Therefore, it is verified that the use of the new empirical method can be seen as an efficient technique to predict sawability performance in the diameter circular saw during natural stones sawing.

Data Availability

The experimental data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare no conflict of interest.

Authors' Contributions

Pan Wang designed research, performed research, and analyzed data; Pan Wang wrote the paper.

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