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A Comparative Investigation on the Brazilian Tensile Strength (BTS) of the Various Rocks and Development a BTS-Based Rock Classification

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Abstract

Brazilian tensile strength (BTS) is an important parameter in mining activities, particularly in conditions that rocks are under tensile stresses. This test measures the indirect tensile strength of rocks, which is crucial for understanding the mechanical behavior and quality of rocks in the mining context, including slope stability analysis, blast design, rock support systems, excavation and equipment selection, fracture propagation, and hydraulic fracturing and drilling. So far, no classification of tensile strength of rock for mining applications has been presented. In the present study, a new rock classification based on BTS for the various rocks was proposed. To achieve this purpose, by a reviewing previous studies, uniaxial compressive strength (UCS) and BTS of various rock classes, including igneous, sedimentary, and metamorphic were collected. For each rock class, the correlation equations between UCS and BTS were developed using simple regression analysis. Using data analyses, the rocks was categorized into to seven BTS classes. The findings revealed that igneous, sedimentary, and metamorphic rocks have a wide range of BTS values, and subsequent fall into the different BTS classes. The validity of BTS classification was verified using data of BTS and UCS of various rock classes published in the literature, and results showed that BTS can be as a suitable indicator for preliminary assessment of rock quality. This can lead to a better understand from the strength behavior of the rock under tensile stresses in site a mining activity, and therefore, a more accurate design of a mining project.

1. Introduction

In some mining activities, such as rock slope, tunnel, and excavation, rocks can be under both compressive and tensile stresses. However, mechanical behavior of rock subjected to each of these stresses is different [1–5]. Tensile strength is a key indicator to assess mechanical behavior of rocks subjected to tensile stresses in the mining activities [6–8], and on the other hand, it has a critical role on the durability of the rocks exposed to weathering processes in site a mining project [9,10]. It is evident under conditions where the stresses governing the rock are primarily tensile, the tensile strength than the compressive strength can provide a better assessment of the mechanical behavior of the rock. Therefore, incorporating the tensile strength of rock in designing a mining activity, where rock is under tensile stresses, can lead to a better assessment of the rock mechanical behavior and subsequently, a more accurate design of the mining project.

Although, the tensile strength in controlling some failure mechanisms is an importance factor, it is often overlooked as an input parameter in mining activities due to difficulties with obtaining reliable data [11]. The findings of the many researchers such as Griffith [12], Stacey [13], Myer et al. [14], and Haimson and Cornet [15] indicated that the initiation of fractures in brittle materials can be a tensile phenomenon. Thus, the tensile strength is a critical parameter that affects the resistance of a rock to failure under tensile stresses. For instance, Diederichs and Kaiser [16] stated that

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tensile strength is an important controlling property in critical span stability of underground openings. However, in many mining studies, focus was often on the uniaxial compressive strength (UCS) of the rock, and this has resulted in challenges for the safety of mining project.

There are two common laboratory methods to determine the tensile strength of rock, including direct tensile strength (DTS) and Brazilian tensile strength (BTS) of rock, also known as indirect tensile strength. DTS test is rarely carried out because of the difficulties in preparing the rock specimen; many poorly-prepared specimens fail invalidly (not through the middle of the specimen) and thus must be discarded [11]. In contrast, BTS test is widely employed by researchers due to it is relatively simple, cost-effective, and provides consistent results for assessing the tensile strength of brittle materials like rocks. The BTS is an important parameter in mining activities, particularly in understanding the mechanical properties of rocks. This parameter is crucial for several reasons in the mining context. Some applications of BTS in various mining domain are presented in Table 1.

Table 1. Some applications of BTS in various mining domain [17]

Domain	Application
Slope stability analysis	In open-pit mines and underground mines, understanding the tensile strength of rock helps assess the risk of slope failure or collapse. Tensile failure often initiates rock fractures, so having accurate BTS data can guide decisions on slope design, ensuring stability and safety
Blast design	BTS is used to optimize blast patterns and minimize damage to surrounding rock structures. By knowing the rock's tensile strength, mining engineers can design blasts that are powerful enough to fracture the rock efficiently without causing excessive overbreak or underbreak, leading to more controlled and safer operations
Rock support systems	In underground mining, BTS data helps determine the appropriate support systems such as rock bolts, shotcrete, or other reinforcements. This ensures that the openings in mines remain stable and safe for workers
Excavation and equipment selection	Knowledge of the rock's BTS allows for the selection of appropriate excavation methods and machinery. For example, in weaker rocks, more precise cutting tools may be used, while in stronger rocks, heavier-duty equipment is necessary. It optimizes operational efficiency and reduces wear on machinery
Fracture propagation	BTS is often lower than compressive strength in rocks, so fractures are more likely to initiate in tension. Understanding BTS helps in predicting how cracks and fractures will propagate through rock during mining, which is critical for ensuring controlled rock breakage
Geotechnical risk Management	Accurate BTS data assists in evaluating risks associated with rockfalls, ground subsidence, and other geotechnical hazards. This helps in developing safety measures and designing mine layouts that minimize the risk of accidents or operational disruptions
Hydraulic fracturing and drilling	In certain mining activities like hydraulic fracturing or when drilling for ore, BTS is vital for understanding how rock will behave under stress. It provides insights into how fractures will develop, influencing drilling patterns and the success of resource extraction

Rocks typically have much lower tensile strength than compressive strength, so understanding their tensile strength helps predict how they might fracture or break in mining, construction, and other engineering applications. Overall, BTS is critical for ensuring safety, optimizing operational efficiency, and minimizing environmental impact in mining activities [18,19]. So far, no classification of tensile strength of rock for mining applications has been presented. Thus, the present study was conducted to address this gap. In this context, a new classification for various rock classes, including igneous, sedimentary, and metamorphic, based on their BTS is proposed. The BTS-based rock classification can lead to a better understand from the strength behavior of the rock under tensile stresses in site a mining activity, and therefore, a more accurate design of a mining project. In addition, various rocks were compared in a systematic way from the perspectives of their BTS values.

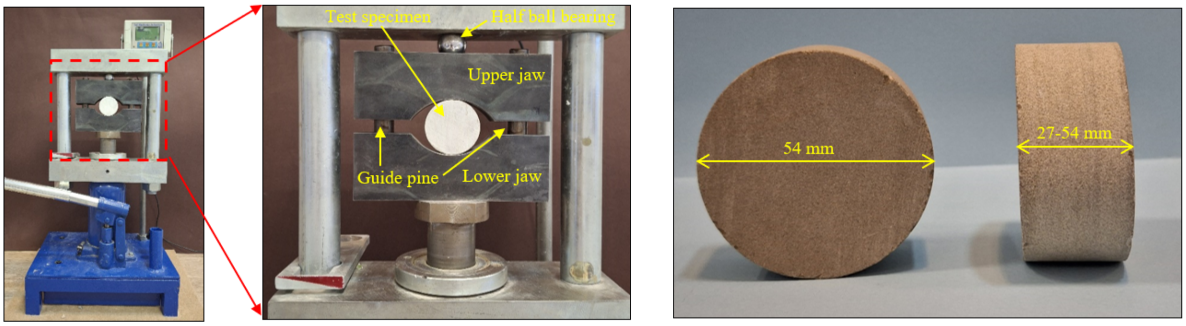
2. Brazilian tensile strength

There are some techniques to determine the tensile strength of rock, including laboratory tests and predictive experimental equations reported in literature, which are known among the mining engineers as direct and indirect tools, respectively. Among the laboratory tests, the BTS test is a common method used to determine the tensile strength of rock materials. It is widely employed because it is relatively simple, cost-effective, and provides consistent results for assessing the tensile strength behavior of brittle materials like rocks [20–23].

To perform the BTS test, a cylindrical rock specimen is prepared, typically with a diameter of 54 mm and a thickness of between 27 to 54 mm, giving it a disc shape. The ends of the specimen are flattened and parallel to ensure even loading [24]. The specimen is placed in a compression testing machine between two flat loading platens. The loading is applied along the diameter of the specimen, creating tensile stresses along the loading plane (Figure 1). The load is increased continuously and uniformly until the specimen fails. The applied load is measured at the moment of failure. Finally, the BTS of specimen can determined using follows equation:

$$BTS = \frac{2P_f}{\pi DT} \quad (1)$$

where P_f is the load at the moment of failure, and D and T are diameter and thickness of the specimen, respectively.



(a) (b)

Figure 1. a) The ISRM [24] suggested apparatus for BTS test, and b) disk-shaped rock specimen

Due to the small size of the test specimen and the simplicity of performing the test, BTS is in high demand among mining and geotechnical engineers. However, in some laminated sedimentary rocks (such as shale, mudstone, sandstone), metamorphic rocks containing schistosity (such as slate, schist), and highly igneous weathered rocks, it is impossible to prepare test specimens with appropriate dimensions according to the guidelines suggested by the ISRM [24]. In this situation, indirect methods can be used as alternative tools for quick and inexpensive assessment of BTS. Regression analysis is one of the oldest indirect methods for predicting BTS through the use of several rock parameters, such as density, porosity, point load index, P-wave velocity, and Schmidt hardness [7,23,25–27]. Table 2 presents some correlation equations between BTS and other rock parameters developed in literature. Besides, in recent decades, soft computing and probabilistic-based techniques have been introduced as newer tools for the smart prediction of the BTS of rocks [37–40]. Some artificial intelligence approaches to predict the BTS are given in Table 3.

Table 2. Correlation equations by previous studies to predict BTS using physical and mechanical parameters

Researcher/s	Rock class	Correlation equation	r
Zheng et al. [23]	Sedimentary	$BTS = -0.78n + 14.12$	0.80
	Sedimentary	$BTS = -1.34Wa + 15.80$	0.76
	Sedimentary	$BTS = 20.86\rho - 44.10$	0.71
Kiliç and Teymen [28]	Various	$BTS = 7.51Ln(PLI) + 2.22$	0.96
Altindag and Guney [29]	Various	$BTS = 0.0423SH^{1.2799}$	0.81
Heidari et al. [30]	Sedimentary	$BTS = 1.36PLI + 2.06$	0.96
Karakul and Ulusay [31]	Various	$BTS = 0.45Vp^{1.87}$	0.87
Karaman et al. [32]	Various	$BTS = 3.34PLI - 3.4$	0.95
Jamshidi et al. [33]	Sedimentary	$BTS = 8.44Ln(Vp) - 66.2$	0.96
	Sedimentary	$BTS = 6.26Ln(SH) - 17.99$	0.85
Harandizadeh et al. [34]	Igneous	$BTS = 1.132PLI + 3.008$	0.82
Li et al. [35]	Igneous	$BTS = 0.2182SH - 0.5659$	0.84
	Igneous	$BTS = 0.0146\rho^{6.6245}$	0.83
Parsajoo et al. [36]	Igneous	$BTS = 0.0015Vp - 0.3164$	0.80

* *r* correlation coefficient, *Wa* water absorption, ρ density, *n* porosity, *PLI* point load index, *Vp* P-wave velocity, *SH* Schmidt hardness

3. Data collection

The data utilized in the present study were gathered from documents published by various researchers. These data are from 1972 to 2024, encompassing a timeframe of 52 years. The UCS and BTS values for three main classes of rocks, namely igneous, sedimentary, and metamorphic, were extracted from these documents. In Tables 4–6, the sources, rock types, and the range of UCS and BTS values are presented. For a more depth analysis of the results, each of the classes of igneous, sedimentary and metamorphic rocks was categorized into subclasses according to Table 7. Moreover, each subclass includes a set of various rocks types. It can be seen from Table 7 that a wide range of rock types have been used in the present study, including 25, 16, and 11 types of igneous, sedimentary, and metamorphic rocks, respectively.

Table 3. Artificial intelligence techniques by previous studies to predict BTS using physical and mechanical parameters

Researcher/s	Rock class	Model	Input parameters	r
Gurocak et al. [7]	Various	MLPN	ρ, SH, PLI	0.92
Zheng et al. [23]	Sedimentary	SVR	ρ, n, Wa, Vp, PLI	0.96
Li et al. [35]	Igneous	ANFIS	ρ, Vp, SH	0.95
Fang et al. [40]	Sedimentary	BPANN	ρ, n, Vp, SH	0.99
Çanakci et al. [41]	Igneous	ANN	ρ, Wa, Vp, SH	0.99
Ceryan et al. [42]	Sedimentary	LS-SVM	n, SDI, Vp	0.93
Huang et al. [43]	Igneous	IWO-ANN	ρ, PLI, SH	0.96
Mahdiyar et al. [44]	Igneous	PSO-ANN	ρ, PLI, SH	0.96

* *ANN* artificial neural network, *MLPN* multilayer perceptron network, *LS-SVM* least-squares support-vector machines, *IWO* invasive weed optimization, *PSO* particle swarm optimization, *ANFIS* neurofuzzy inference system, *SVR* support vector regression, *BPANN* backpropagation artificial neural network

** *Wa* water absorption, *ρ* density, *n* porosity, *PLI* point load index, *Vp* P-wave velocity, *SH* Schmidt hardness, *SDI* slake durability index

Table 4. Database of the igneous rocks

Researcher/s	Rock type	No of data	UCS range (MPa)	BTS range (MPa)
Wei et al. [3]	Granite	5	88.1–128.7	2.4–5.6
Altindag and Guney [29]	Andesite, Anorthosite, Basalt, Dacite, Diabase, Diorite, Gabbro, Granite, Tuff	39	5.7–375.2	0.20–30.3
Schmidt [45]	Anorthosite, Basalt, Gabbro, Granite	10	89.6–374.7	8.7–28.3
Bilgin [46]	Granite	1	179.1	10.8
Clark [47]	Anorthosite, Basalt, Gabbro, Granite	10	123.2–296.8	7.3–15.4
Howarth [48]	Basalt, Granite, Syenite, Trachyte	4	137.1–234.0	8.0–15.2
Bilgin and Shahriar [49]	Andesite, Tuff	7	27.9–53.0	2.3–6.2
Bilgin et al. [50]	Tuff	1	43.4	4.0
Gupta and Rao [51]	Granite	8	2.5–132.8	0.88–16.1
Bearman [52]	Andesite, Diorite, Granite	4	128.8–274.8	10.6–18.4
Kahraman [53]	Diabase, Tuff	2	10.1, 110.9	0.90, 10.1
Tugrul and Zarif [54]	Granite	19	109.2–193.3	14.9–28.0
Ersoy et al. [55]	Andesite, Dacite, Gabbro, Granite, Syenite, Tuff	10	6.4–168.0	0.50–8.7
Ersoy and Atici [56]	Andesite, Dacite, Tuff	4	6.4–65.3	0.50–4.8
Dwivedi et al. [57]	Granite	5	112.8-133.7	8.9–10.9
Atici and Ersoy [58]	Andesite, Dacite, Diorite, Gabbro, Granite, Syenite, Tuff	12	6.0–375.0	0.50–30.3
Erguler and Ulusay [59]	Tuff	6	1.3–12.9	0.00–1.8
Yagiz [60]	Andesite, Basalt, Diabase, Gabbro, Granite, Granitoid, Syenite	17	47.0–327.0	4.2–17.8
Yilmaz et al. [61]	Granite	3	11.8–131.4	10.4–11.4
Karaca et al. [62]	Granite	2	111.8-131.4	10.4–11.4
Fener [63]	Andesite, Basalt, Granite, Ignimbrite, Tuff	6	3.9–121.8	1.3–9.5
Yarali and Kahraman [64]	Andesite, Basalt, Diabase, Granite, Granodiorite, Syenite	18	28.6–182.1	2.6–16.5
Ghobadi and Rasouli Farah [65]	Granite, Granodiorite, Monzogranite, Tonalite	21	18.6–123.0	3.0–14.6
Kahraman et al. [66]	Andesite, Basalt, Gabbro, Granite, Granodiorite	13	77.5–202.9	7.6–14.8
Khanlari et al. [67]	Granodiorite, Monzogranite	10	12.4–135.7	0.46–11.4
Yavuz [68]	Tuff	2	6.9, 14.9	0.43, 1.4
Basu et al. [69]	Granite	20	91.5–201.7	10.5–19.8
Heidari et al. [70]	Granite, Granodiorite	10	3.8–150.1	0.46–17.6
Karakus and Akatay [71]	Basalt	18	17.2–145.2	1.1–12.2
Khandelwal [72]	Diabase, Granite	2	89.5, 121.5	6.9, 9.0
Mikaeil et al. [73]	Granite	10	125.0–218.0	7.4–24.6
Heidari et al. [74]	Granite, Tuff	2	122.0–124.3	9.96–11.2
Fener and Ince [75]	Andesite	6	44.3–60.3	4.0–5.05
Majeed et al. [76]	Diabase	17	154.6–258.5	15.5–22.2
Ribeiro et al. [77]	Andesite, Diabase, Granite, Granodiorite, Monzogranite	8	103.7–223.0	8.9–18.8
Sajid and Arif [78]	Granite	21	17.3–63.3	1.2–6.4
Ghobadi et al. [79]	Tuff	48	55.0–245.0	3.7–25.7

Continuous of Table 4

Ince and Fener [80]	Tuff	10	7.6–48.6	1.1–4.8
Momeni et al. [81]	Granite	3	90.7-164.0	8.7–14.7
Ronmar [82]	Basalt, Tuff	2	212.0, 87.6	14.2, 8.3
Akinbinu [83]	Anorthosite, Granite, Norite, Troctolite	12	129.6–276.3	9.2–16.9
Almasi et al. [84]	Andesite, Diorite, Gabbro, Granite, Syenite	11	91.0–193.0	6.3–15.0
Bozdağ and İnce [85]	Andesite, Basalt, Granite, Spilite, Tuff	23	7.6–144.1	1.0–11.5
Jaques et al. [86]	Syenogranite	5	1.2–160.6	0.19–9.7
Teymen and Mengüç [87]	Andesite, Aplite, Basalt, Dacite, Diabase, Dunite, Gabbro, Granite, Granodiorite, Ignimbrite, Rhyolite, Spilite, Syenite, Trachyte, Tuff	52	6.6–330.7	1.1–21.3
Xue et al. [88]	Granite	7	104.0–137.0	4.4–6.4
Zalooli et al. [89]	Granodiorite, Monzogranite	2	124.3, 145.8	11.1, 13.0
Akbay and Altindag [90]	Andesite, Diabase, Granite	3	102.4–154.0	10.0–11.6
Hamzaban et al. [91]	Andesite, Basalt, Granite	8	33.8–80.0	2.8–7.5
Jamshidi [92]	Granite, Granodiorite, Monzogranite, Syenogranite	16	68.0–123.0	5.3–13.3
Fereidooni [93]	Diorite, Gabbro, Granite, Granitoid, Monzogranite, Monzonite, Syenite, Tonalite	16	69.7–129.5	2.3–4.3
Pötzl et al. [94]	Tuff	21	4.0–73.7	0.60–6.7
Ajalloeian et al. [95]	Granite, Granodiorite, Monzogranite, Syenogranite	10	67.9–112.3	5.2–12.1
Diamantis et al. [96]	Peridotite	70	52.3–241.6	9.7–24.9
Kahraman et al. [97]	Andesite, Basalt, Diabase, Granite, Granodiorite, Syenite, Tuff	27	3.6–204.9	0.40-13.5

Table 5. Database of the sedimentary rocks

Researcher/s	Rock type	No of data	UCS range (MPa)	BTS range (MPa)
Minaeian and Ahangari [26]	Conglomerate	1	6.8	0.82
Altindag and Guney [29]	Breccia, Claystone, Dolomite, Gypsum, Limestone, Sandstone, Siltstone	58	7.0–216.4	1.0–18.06
Heidari et al. [30]	Gypsum	15	29.0–37.4	3.8–5.5
Wei et al. [34]	Sandstone	10	28.5–79.2	0.82–4.4
Schmidt [45]	Claystone, Dolomite, Limestone	3	97.0–220.7	4.2–18.4
Bilgin [46]	Limestone, Sandstone	3	55.8–183.9	3.1–16.5
Clark [47]	Limestone	2	121.8, 34.2	4.7, 2.5
Howarth [48]	Sandstone	3	35.1–44.1	2.4–3.3
Bilgin and Shahriar [49]	Limestone, Marl, Sandstone	4	17.1–62.0	0.77–3.7
Bilgin et al. [50]	Limestone, Marl	11	7.9–88.7	0.80–6.5
Bearman [52]	Limestone, Sandstone	7	47.8–226.3	3.8–15.4
Kahraman [53]	Dolomite, Limestone, Marl, Sandstone	18	11.4–123.8	0.90–16.1
Ersoy and Atici [56]	Limestone	4	49.7–87.2	5.5–8.5
Atici and Ersoy [58]	Breccia, Limestone, Mudstone, Sandstone, Siltstone	13	28.0–175.0	2.9–14.5
Erguler and Ulusay [59]	Siltstone, Mudstone, Marl	53	1.9–136.1	0.1–12.8
Yagiz [60]	Limestone, Mudstone, Sandstone, Shale, Siltstone	18	21.0–159.0	2.3–6.9
Karaca et al. [62]	Limestone, Travertine	6	23.0–93.6	3.5–11.8
Fener [63]	Dolomite, Limestone, Travertine	3	13.7–85.2	3.5–5.7
Yarali and Kahraman [64]	Dolomite, Limestone, Marl, Sandstone, Siltstone	13	31.6–91.4	4.1–11.2
Kahraman et al. [66]	Anhydrite, Limestone, Sandstone, Travertine	17	30.4–175.0	2.2–10.2
Basu et al. [69]	Sandstone	20	12.8–172.0	2.0–14.3
Khandelwal [72]	Limestone, Sandstone, Shale	5	45.0-99.2	4.4–9.3
Mikaeil et al. [73]	Travertine	3	53.0-63.0	4.3–5.6
Heidari et al. [74]	Gypsum, Sandstone, Travertine	3	32.1–65.8	4.5–9.4
Ribeiro et al. [77]	Conglomrate, Gypsum, Limestone, Mudstone, Sandstone, Shale, Siltstone	18	5.2-147.7	0.30–10.7
Ronmar [82]	Sandstone	1	43.9	4.16
Akinbinu [83]	Sandstone	2	35.2, 40.3	2.6, 2.9
Teymen and Mengüç [87]	Aragonite, Breccia, Claystone, Gypsum, Limestone, Sandstone, Shale, Siltstone, Travertine	27	14.1–236.2	1.7–16.6
Akbay and Altindag [90]	Limestone	3	64.2–110.6	8.0–8.9
Hamzaban et al. [91]	Sandstone, Travertine	6	25.5–47.0	2.0–6.8
Fereidooni [93]	Limestone	9	12.5–61.9	1.0–2.4
Kahraman et al. [97]	Limestone	5	113.7–136.5	5.9-9.3
Phillips [98]	Sandstone	2	41.0, 49.2	1.9, 2.6
Bilgin [99]	Anhydrite, Gypsum	2	112.9, 45.0	5.5, 2.8
Singh [100]	Coal	3	18.4–24.5	1.4–1.5
Harris [101]	Coal	5	7.0–24.8	1.4–1.8
Kahraman et al. [102]	Limestone, Travertine	13	45.4–175.0	2.2–10.2
Goktan and Yilmaz [103]	Limestone, Mudstone, Sandstone	26	7.0–170.0	1.0–8.9
Hecht et al. [104]	Conglomerate, Sandstone	6	21.0–135.0	2.5–10.4
Vásárhelyi [105]	Limestone	90	0.63–26.5	0.07–4.2
Kayabali et al. [106]	Gypsum	8	6.2–16.6	0.77–2.8

Continuous of Table 5

Tiryaki [107]	Sandstone	19	6.2–122.7	1.0–8.9
Hoseini [108]	Lomashell	41	2.0–10.2	0.05–1.71
Ahmadi [109]	Sandstone	18	29.8–105.2	1.1–7.6
Yavuz et al. [110]	Limestone, Travertine	6	20.0–100.0	2.5–8.0
Kumar et al. [111]	Chalk, Limestone, Marl, Sandstone, Shale	6	15.2–71.8	2.0–8.9
Tahir et al. [112]	Limestone	30	26.6–61.8	4.0–7.9
Rajabzadeh et al. [113]	Limestone	16	32.9–138.6	5.0–14.2
Tumac [114]	Limestone	2	70.1, 89.0	5.4, 5.3
Ghobadi and Naseri [115]	Limestone	41	10.1–16.6	1.8–4.4
Jamshidi et al. [116]	Travertine	15	33.6–65.7	3.7–6.4
Masoumi et al. [117]	Sandstone	25	11.0–49.2	1.7–5.0
Naseri and Khanlari [118]	Travertine	80	20.1–103.5	3.3–10.1
Fereidooni and Khajevand [119]	Travertine	6	18.5–32.0	4.2–7.7
Jamshidi et al. [120]	Sandstone	21	46.6–77.3	5.1–9.4
Ashtari et al. [121]	Marl	10	23.4–71.1	3.0–7.2
Torabi-Kaveh et al. [122]	Limestone	1	115.6	11.2
Zalooli et al. [123]	Travertine	4	33.6–61.5	3.9–6.4
Jamshidi et al. [124]	Sandstone	10	32.1–69.0	4.5–7.4
Lakirouhani et al. [125]	Dolomite	32	9.2–83.8	1.6–10.0
Arman [126]	Gypsum	1	24.6	2.8
Jamshidi et al. [127]	Sandstone	5	38.0–70.8	3.9–7.1
Kolapo and Munemo [128]	Sandstone	5	34.0–56.1	1.2–2.1
Tripathi et al. [129]	Sandstone	9	15.0–27.0	1.4–3.8
Sadeghi et al. [130]	Limestone	13	42.5–88.0	5.7–10.9
Cun et al. [131]	Coal	5	1.6–12.2	0.60–2.1
Fadhil et al. [132]	Claystone, Limestone, Sandstone	60	31.0–102.0	1.8–12.5
Khajevand [133]	Conglomerate, Limestone, Sandstone, Travertine	30	10.8–51.5	2.3–7.9
Khajevand [134]	Conglomerate, Limestone, Sandstone, Travertine	44	13.3–53.5	2.2–9.7
Pathan et al. [135]	Claystone, Coal, Sandstone, Siltstone	7	0.57–2.5	0.22–0.42
Qiang et al. [136]	Sandstone, Shale	2	36.2, 65.1	6.9, 9.4

Table 6. Database of the metamorphic rocks

Researcher/s	Rock type	No of data	UCS range (MPa)	BTS range (MPa)
Altindag and Guney [29]	Marble, Quartzite, Serpentine, Slate	18	38.1–301.2	3.1–20.3
Schmidt [45]	Marble, Quartzite	4	127.6–307.2	7.0–20.8
Clark [47]	Marble	2	183.4, 172.9	8.5, 10.1
Howarth [48]	Hornfels, Marble	3	49.9–100.5	3.0–13.5
Bearman [52]	Quartzite	1	138.6	13.0
Atici and Ersoy [58]	Marble	1	85.0	7.8
Yagiz [60]	Gneiss, Quartzite, Marble, Schist	10	68.0–227.0	5.4–12.7
Karaca et al. [62]	Marble	2	57.7–110.3	6.6–10.1
Yarali and Kahraman [64]	Quartzite	1	164.8	17.1
Kahraman et al. [66]	Gneiss, Migmatite, Marble, Quartzite, Schist, Serpentinite	15	24.1–203.6	4.9–17.2
Khandelwal [72]	Marble, Quartzite	4	42.3–133.5	4.7–8.7
Mikaeil et al. [73]	Marble	4	71.5–74.5	6.3–7.2
Heidari et al. [74]	Hornfels, Marble	2	84.0–149.0	9.6–10.4
Ribeiro et al. [77]	Gneiss, Mylonite, Phyllite, Quartzite, Schist	12	87.1–215.5	11.2–15.5
Akinbinu [83]	Marble, Quartzite	2	76.8, 249.9	5.6, 15.7
Teymen and Mengüç [87]	Marble, Quartzite, Serpentinite	13	24.7–230.2	2.4–15.9
Akbay and Altindag [90]	Marble	1	72.1	8.5
Fereidooni [93]	Marble	3	58.1–61.4	1.7–2.6
Kahraman et al. [97]	Marble	3	78.6–89.7	6.3–7.2
Yavuz et al. [110]	Marble	5	54.0–126.0	4.8–8.2
Rajabzadeh et al. [113]	Marble	10	45.9–101.8	4.4–10.6
Tumac [114]	Marble	5	65.3–97.3	3.9–7.1
Qiang et al. [136]	Marble	1	93.6	12.7
Yavuz et al. [137]	Marble	14	61.7–155.5	2.8–12.7
Yavuz and Topal [138]	Marble	12	58.4–134.3	3.5–9.2
Fereidooni [139]	Hornfels	8	99.2–272.8	3.8–20.5
Singh and Murthy [140]	Gneiss	3	35.0–65.0	3.5–8.0
Tumac [141]	Marble	4	63.8–108.0	4.6–7.9
Singh et al. [142]	Gneiss, Phyllite, Quartzite	6	41.2–112.2	5.1–12.3
Jafari et al. [143]	Schist	10	19.7–70.4	2.3–9.7
Zalooli et al. [144]	Schist	2	47.4, 68.2	8.2, 4.1

Table 7. Class, subclass, and type of the rocks used in the present study

Rock class	Rock subclass	Rock type
Igneous	Plutonic	Anorthosite, Aplite, Diorite, Dunite, Gabbro, Granite, Granitoid, Granodiorite, Monzogranite, Monzonite, Norite, Peridotite, Syenite, Syenogranite, Tonalite, Troctolite
	Subvolcanic	Diabase, Spilite
	Volcanic (flow)	Andesite, Basalt, Dacite, Rhyolite, Trachyte
	Pyroclastic	Ignimbrite, Tuff
Sedimentary	Carbonate	Dolostone, Limestone, Travertine
	Detrital	Berccia, Conglomerate, Sandstone
	Argillaceous	Claystone, Marl, Mudstone, Shale, Siltstone
	Evaporates	Anhydrite, Gypsum
	Organic	Chalk, Coal, Lomashell
Metamorphic	Foliated	Amphibolite, Gneiss, Migmatite, Mylonite, Phyllite, Schist, Serpentinite, Slate
	Nonfoliated	Hornfels, Marble, Quartzite

A huge amount of data has been used to achieve the objectives of this study. According to the Figure 2, the total number of data for igneous, sedimentary, and metamorphic rocks are 699, 1083, and 181, respectively. In igneous rocks, the subclasses of plutonic, subvolcanic, volcanic (flow), and pyroclastic include 412, 35, 112, and 140 data, respectively. In subclasses belong to sedimentary rocks, number of data used for carbonate, detrital, argillaceous, evaporates, and organic were 553, 300, 142, 31, and 57, respectively. Finally, metamorphic rocks are categorized into two subclasses: foliated and nonfoliated, comprising 48 and 133 data, respectively.

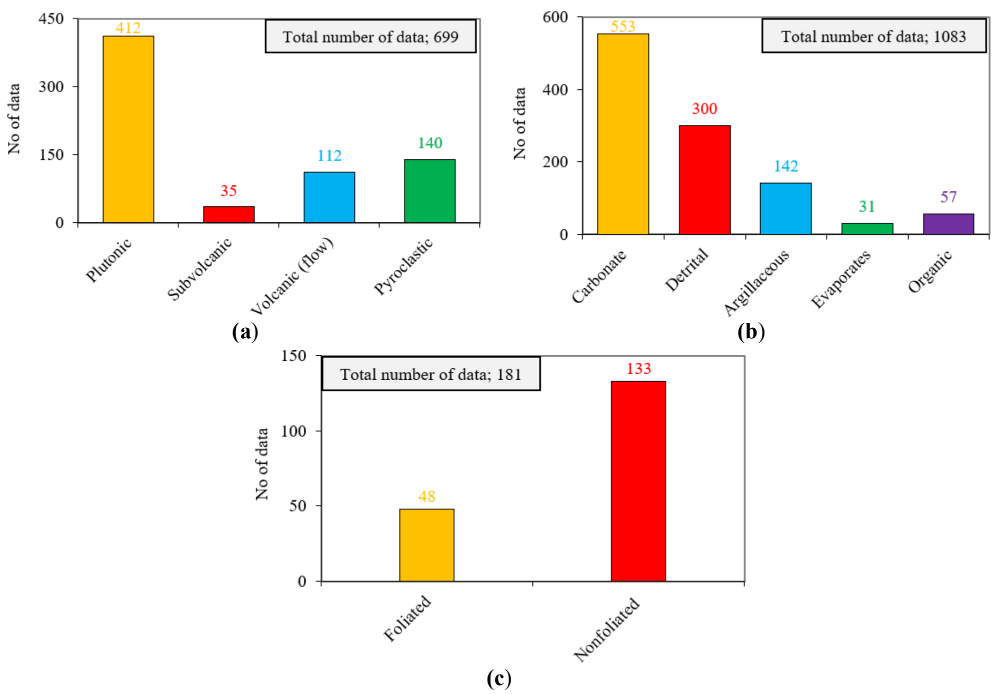


Figure 2. No of data each subclass for (a) igneous rocks (b) sedimentary rocks, and (c) metamorphic rocks

4. Data analysis and results

4.1. Comparison of BTS values of various rocks

The average and range of BTS values for rock types belonging to igneous, sedimentary and metamorphic classes are depicted in Figure 3. In class of igneous rocks, an average of BTS equal to 6.40, 7.80, 11.18, and 15.67 MPa was obtained for subclasses of pyroclastic, volcanic (flow), plutonic, and subvolcanic, respectively. These results showed that extrusive igneous rocks, i.e., pyroclastic, volcanic (flow), have lower average BTS compared to those obtained for intrusive igneous rocks, i.e., plutonic and subvolcanic. Difference in BTS values can be attributed to variety of mineralogical composition and textural characteristics (such as grains size and shape) between extrusive and intrusive igneous rocks. In this regard, the findings of Momeni et al. [81] and Ajalloeian et al. [95] on the BTS of igneous rocks are in good agreement with the results of the present study. It is obvious from Figure 3 that igneous rocks have a wide range of BTS between 0.19–30.30, 6.45–24.96, 1.02–28.26, and 0.00–25.70 MPa for subclasses of plutonic, subvolcanic, volcanic (flow), and pyroclastic, respectively.

The subclasses of sedimentary rocks including organic, evaporates, detrital, carbonate, and argillaceous revealed average BTS values equal to 0.86, 3.62, 4.83, 5.19, and 5.41 MPa, respectively. According to these values, among the sedimentary rocks, organic (chalk, coal, and lomashell) and argillaceous (claystone, marl, mudstone, shale, and siltstone) exhibited the lowest and highest BTS on average, respectively. Due to the various processes of sedimentary rocks formation (i.e., detrital, chemical, or biochemical), these rocks have a wide range of constituent components including grains, cement, and matrix. On the other hand, the conditions of formation of sedimentary rocks usually gives to them a porous nature. Overall, these factors play a prominent role in the mechanical behavior of sedimentary rocks, such as BTS [93,145,146].

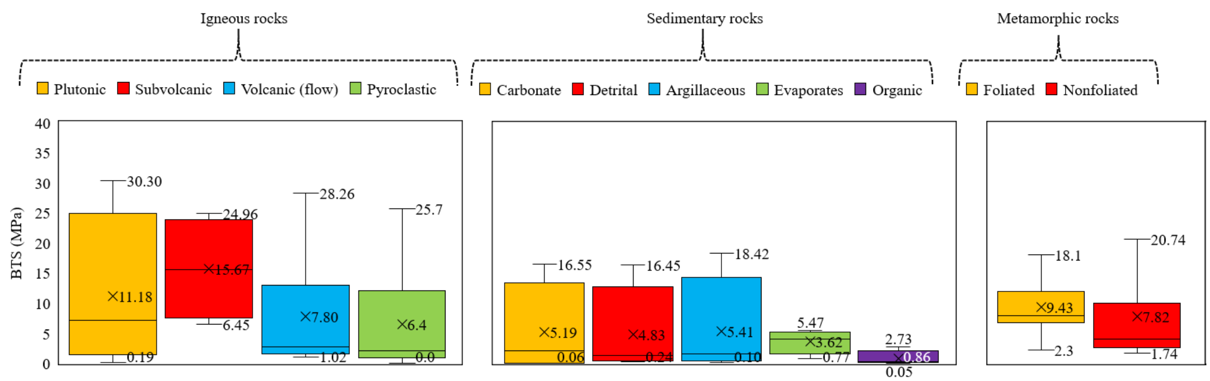


Figure 3. Average and range of BTS values for rock types (According to rock classification given in Table 7)

As presented in Table 7, metamorphic rocks categorized into two subclasses; foliated and nonfoliated. According to data of Figure 3, the BTS of foliated metamorphic rocks ranging from 2.3 to 18.1 MPa with an average 9.43 MPa, whereas, nonfoliated types revealed a range of BTS between 1.74 and 20.74 MPa, on average 7.82 MPa. These values showed that nonfoliated rock subclasses, including hornfels, marble, and quartzite, have a higher range and average of BTS than foliated subclass, such as amphibolite, gneiss, migmatite, schist, etc. In the previous studies carried out by researchers such as Debecker and Vervoort [147], Chao et al. [148], and Ma et al. [149] it found that BTS of metamorphic rocks is strongly affected by schistosity planes as the weakness surfaces. According to the results of Yavuz and Topal [138] and Fereidooni [139], the presence or lack of schistosity planes is one of the factors controlling the strength of metamorphic rocks.

The average and range of BTS values for all igneous, sedimentary, and metamorphic rock types are shown in Figure 4. The data analysis indicated that the highest average BTS was obtained to igneous rock class with a value equal to 9.91 MPa, followed by metamorphic and sedimentary rock classes with the average BTS of 8.24 and 4.85 MPa, respectively. Furthermore, these results showed that there is a considerable different between values of BTS in sedimentary rock class with those obtained for igneous and metamorphic rock classes. One of the reasons for this issue can be attributed to difference in formation nature of rocks. Igneous and metamorphic rocks have a dense and interlocking texture from crystallized minerals, while sedimentary rocks often exhibit a porous texture, from low to high degree, due to the conditions of their formation. In the previous studies, it was found that porosity as function a pore media of a rock play a significant role on strength behavior of the rocks such as BTS. Overall, findings of various researchers revealed an inverse correlation between BTS and porosity of various rock types [71,93,113,130,150]. In addition to porosity, it should be noted that some other inherent characteristics of a rock, especially the mineralogical composition and texture parameters, can also affect the BTS [95,146].

Besides difference in average BTS of various rock classes, it can be seen from Figure 4 that the BTS values for igneous rocks varies in a wide range from 0.00 to 30.30 MPa, while sedimentary and metamorphic rocks have a narrow range of BTS, compared with igneous rocks, between 0.05–18.42 MPa and 1.74–20.74, respectively.

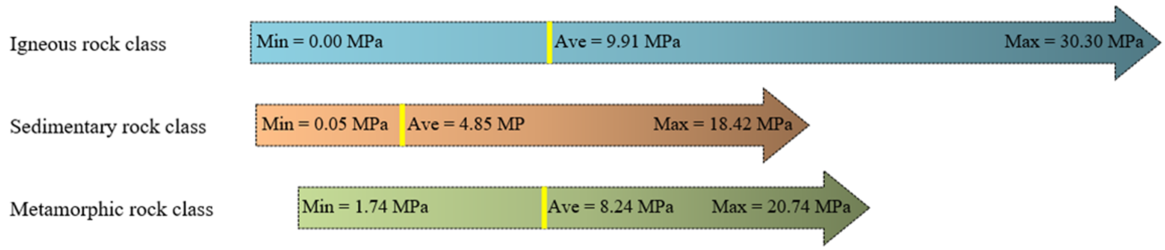


Figure 4. Comparison of BTS values (minimum, maximum, average) of the igneous, sedimentary, and metamorphic rocks

4.2. Correlation between BTS and UCS

The relationship between BTS and UCS was established using simple regression analysis. This type of analysis is one of the most common statistical methods to develop the relationship between two strength variables of the rocks (one dependent and the other independent) [151–153]. To perform simple regression analyses, each rock class, i.e., igneous, sedimentary, and metamorphic, was separately investigated. The regression analyses were undertaken with 95% confidence level, and the best fit curves were obtained between BTS and UCS using the least squares method. The plots of the BTS as a function UCS for each rock class are shown in Figure 5. From this figure can be seen that there are good linear relationships between BTS and UCS in all regressions. Moreover, the figure denotes that with increasing the UCS, BTS is increased correspondingly.

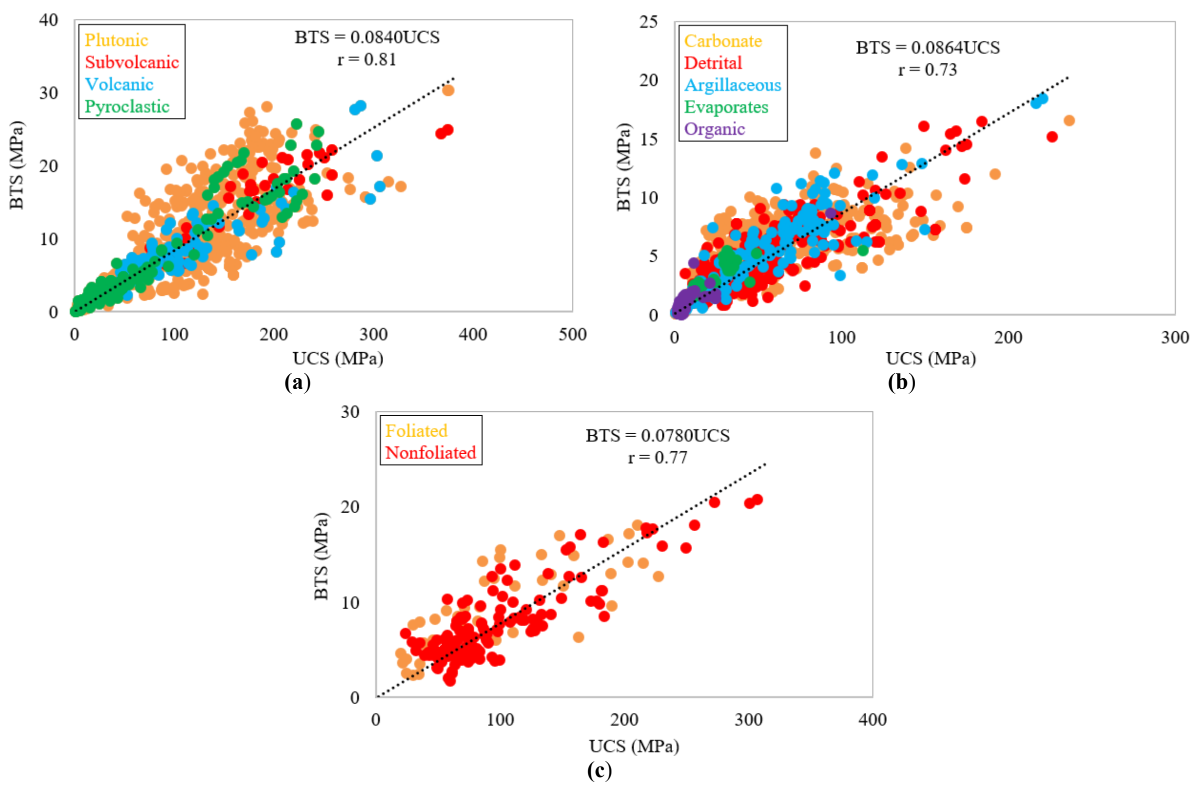


Figure 5. Relationship between BTS and UCS for (a) igneous rocks, (b) sedimentary rocks, and (c) metamorphic rock

As two common numerical measures, the correlation coefficient (r) and standard error of estimate (SEE) were used as to investigate the accuracy of the correlation relationships developed between the BTS and UCS. The degree of fit to a curve can be measured by r and SEE. The r measures the proportion of variation in the dependent variable. On the other hand, SEE indicates how close the real data points fall to the estimated values on the regression curve. It is of note that a correlation relationship with a high r and a small SEE can be more accurate in estimating an unknown parameter of rock. The r and SEE values of correlation relationships between BTS and UCS are presented in Table 8. According to this table, the r values of correlation relationships between BTS and UCS are 0.81, 0.73, and 0.77 for igneous, sedimentary, and metamorphic, respectively. These values are in the acceptable levels (r > 0.73), indicating significant correlations between BTS and UCS with the good accuracies. This result indicated that equations of 2–4 can be accepted as reliable models for estimating the BTS from UCS. By comparing the values of r obtained from these equations, it can concluded that the correlation relationship between BTS and UCS for igneous rocks was somewhat stronger (highest r = 0.81) compared with those obtained for sedimentary and metamorphic rocks (r of 0.73 and 0.77, respectively). As other numerical measure, SEE values obtained from regression analyses developed between UCS and BTS of igneous, sedimentary, and metamorphic are 3.72, 1.82, and 2.47, respectively, which are acceptable values, indicating good accuracy of correlation relationships in estimating the BTS using UCS. According to r and SEE values, the correlation relationships can be accepted as a reliable estimate for the BTS from UCS for all rock classes, including igneous, sedimentary, and metamorphic.

Table 8. Results of the regression analyses

Equation no.	Rock class	Regression equation	r	SEE	F- ratio		Sig.
					Computed	Tabulated	
2	Igneous	BTS = 0.0840UCS	0.81	3.72	1389	3.85	0.000
3	Sedimentary	BTS = 0.0864UCS	0.73	1.82	1978	3.85	0.000
4	Metamorphic	BTS = 0.0780BTS	0.77	2.47	364	3.89	0.000

The literature reports many correlation relationships between BTS and UCS of various rock classes. Table 9 provide some these relationships for igneous, metamorphic, and sedimentary rocks. It can be seen from this Table that there are different correlation relationships with correlation coefficients (r) ranging from 0.67 to 0.97 and different equation forms, including linear and non-linear. The correlation relationships between BTS and UCS developed in the present study have been compared with those reported in the previous studies. According to Table 9, previous studies revealed that the linear correlation relationship was the most frequency than other correlation relationships (i.e., power, logarithmic, and exponential) established between BTS and UCS. Besides, the frequency distribution of r values attained from the correlation relationships indicated that the r between 0.80–1 and 0.60–0.80 were the most frequent (Figure 6). It can be seen from Figure 6 that there are no r values in the ranges of 0.00–0.20, 0.20–0.40, and 0.40–0.60. However, in the present study, the linear correlation relationships between BTS and UCS, as the most accurate equations, with r values equal to 0.81, 0.73, 0.77 was obtained for igneous, sedimentary, and metamorphic rocks, respectively.

It is worth noting there are differences in correlation relationship type and r value obtained by various researchers. These differences could be due to differences in the rock class (i.e., igneous, metamorphic, and sedimentary), range of physico-mechanical characteristics of the rocks (e.g., density, porosity, UCS, and BTS), mineralogical composition and textural parameters of the rocks, the sample conditions under test (i.e., dry or fully-saturated), number and dimensions of tests samples, and rate of loading on the sample during BTS and UCS tests.

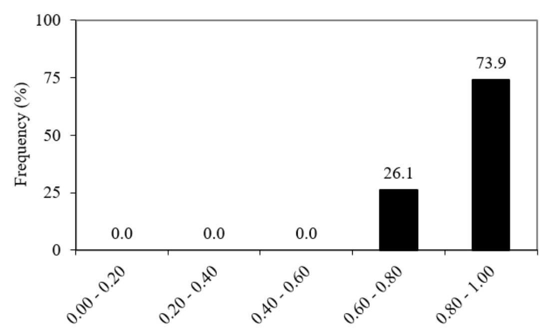


Figure 6. The frequancy of r values of the correlation relashionships between BTS and UCS established in the previous studies (Based on data of Table 9)

Variance analysis (ANOVA) was conducted to investigate the significance and validity of regression relationships. The F statistical test is widely used for variance analysis. The null hypothesis for this test is H0: $\alpha = 0$. Additionally, the alternative hypothesis is H1: $\alpha \neq 0$. The results of the variance analysis for correlation relationships are shown in Table 8. At a significance level of 0.05, the values of tabulated F-ratio for correlation relationships developed on the data igneous, sedimentary, and metamorphic are 3.85. 3.85, and 3.59, respectively. If the computed F-ratio is greater than the F-tabulated obtained from the F distribution table, the null hypothesis is rejected; therefore, the regression is significant [163]. Since the computed F–ratios for the correlation relationships are much greater than the tabulated F–ratios, the null hypothesis is rejected. So, it can be concluded that correlation relationships established in the present study are appropriate for estimating the BTS from UCS.

Table 9. Correlation relationships between BTS and UCS

Researcher/s	Rock class	Predictive Equation	r
Bell and Lindsay [20]	Sedimentary	UCS = 6.71BTS + 36.0	0.78
Altindag and Guney [29]	Various	$UCS = 2.38BTS^{1.073}$	0.89
Tugrul and Zarif [54]	Igneous	UCS = 6.67BTS + 0.73	0.96
Kahraman et al. [66]	Various	UCS = 10.61BTS	0.73
Basu et al. [69]	Sedimentary	UCS = 10.53BTS − 10.23	0.91
Ribeiro et al. [77]	Sedimentary	UCS = 13.70BTS	0.82
Teymen and Menguc [87]	Various	$UCS = 7.73BTS^{1.197}$	0.95
Tahir et al. [112]	Sedimentary	UCS = 7.53BTS	0.67
Masoumi et al. [117]	Sedimentary	UCS = 9.29BTS + 3.91	0.82
Khajevand [124]	Sedimentary	UCS = 40.09ln(BTS) − 36.14	0.97
Arman [126]	Sedimentary	UCS = 4.233BTS + 13.64	0.73
Sadeghi et al. [130]	Sedimentary	UCS = 7.26BTS	0.97
Fereidooni [139]	Metamorphic	UCS = 10.03BTS + 55.19	0.96
Iyare et al. [150]	Sedimentary	$UCS = 5.31BTS^{1.06}$	0.93
Chatterjee and Mukhopadhyay [154]	Sedimentary	$UCS = 10.33BTS^{0.89}$	0.97
Gokceoglu and Zorlu [155]	Sedimentary	UCS = 6.8BTS + 13.5	0.81
Farah [156]	Sedimentary	UCS = 7.86BTS − 447.63	0.96
Nazir et al. [157]	Sedimentary	$UCS = 9.25BTS^{0.947}$	0.95
Yesiloglu-Gultekin et al. [158]	Igneous	UCS = 7.22BTS + 40.08	0.78
Kallu and Roghanchi [159]	Igneous	$UCS = 6.75BTS^{1.08}$	0.89
Karman et al. [160]	Various	UCS = 4.87BTS + 24.30	0.95
Mohamad et al. [161]	Various	UCS = 15.361BTS – 10.303	0.91
Aliyu et al. [162]	Sedimentary	UCS = 10.4BTS + 18.2	0.79

4.3. BTS classification of the rock

According to Table 10, rock is classified to seven classes based on its UCS values, as suggested by Bieniawski [11], with each rock class having lower and upper limits for UCS values. For developing BTS classification, seven BTS classes corresponding to UCS classes were introduced. For this purpose, the lower and upper limits each UCS class were placed in equations of 2–4 (Table 8), and the corresponding BTS values were determined. The classification of rock BTS was analyzed separately for igneous, sedimentary, and metamorphic rocks. As shown in Table 10 and graphically in Figure 7, several classes of BTS were suggested for each of igneous, sedimentary, and metamorphic rocks. These classes are in accordance with the UCS classification of rock proposed by Bieniawski [164]. In BTS classification there are seven classes from weak to strong, including extremely weak, very weak, weak, medium, strong, very strong, and extremely strong. The lower and upper limits of BTS for a given class showed a slight difference among the igneous, sedimentary, and metamorphic rocks. For example, extremely strong class has BTS values higher 21.0, 21.6, and 19.5 MPa for igneous, sedimentary, and metamorphic rocks, respectively. However, from extremely weak class to extremely strong class difference between lower and upper limits of BTS values showed a decreasing trend. It is evident from Figure 7 that for all rocks, the lower and upper limits of BTS values for extremely weak and very weak classes are lesser 0.1 and 0.1–0.4 MPa, respectively.

Table 10. Suggested BTS classification for the various rocks

Qualitative description		UCS (MPa)[a]	BTS (MPa)		
			Igneous rocks[b]	Sedimentary rocks[c]	Metamorphic rocks[d]
Strong	Extremely strong	> 250	> 21.0	> 21.6	> 19.5
	Very strong	100–250	8.4–21.0	8.6–21.6	7.8–19.5
	Strong	50–100	4.2–8.4	4.3–8.6	3.9–7.8
Medium	Medium	25–50	2.1–4.2	2.2–4.3	2.0–3.9
Weak	Weak	5–25	0.4–2.1	0.4–2.2	0.4–2.0
	Very weak	1–5	0.1–0.4	0.1–0.4	0.1–0.4
	Extremely weak	< 1	< 0.1	< 0.1	< 0.1

[a] According to Bieniawski [164]
[b,c,d] BTS values of the igneous, sedimentary, and metamorphic rocks were obtained using equations of 2, 3, and 4, respectively (Table 8), based on UCS values proposed by Bieniawski [164]

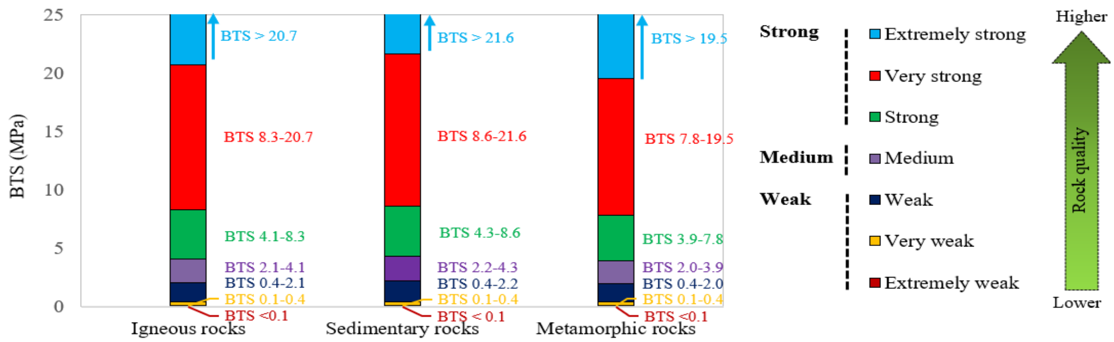


Figure 7. A schematic chart for BTS classification of the rock as an indicator for preliminary assessment of rock quality

Using BTS classification proposed in Figure 7, by shifting the BTS class from extremely weak to extremely strong, a rock can showed a better strength behavior and, as a result, more suitable quality at the site of a mining activity. To investigate the quality a rock, its BTS can determined using laboratory test or indirect methods such as experimental equations, and artificial intelligence techniques. Next, rock is categorized according BTS value using BTS classification proposed in Figure 7. In a site of mining activity containing various rock types, a rock that falls into a BTS class with a higher strength can exhibit better mechanical behavior in terms of tensile strength. The validity of BTS classification was examined using data published in literature. In Figure 8, UCS and BTS data obtained by researchers on some rocks was plotted on BTS classification chart proposed in the present study. A data point that fall into a same class of UCS and BTS indicates to validation of the BTS classification. It can be seen from Figure 8 that all data points classified into same classes of UCS and BTS. For example, basalt in study of Graue et al. [167] and travertine in study of Ebdali et al. [168], are classified as rocks with strong and medium classes, respectively, based on both the UCS and BTS values. It can be seen from Figure 8 that a same pattern was also found for studied rocks by other researchers. These results verified validity of BTS classification suggested in the present study.

The igneous, sedimentary, and metamorphic rocks was compared based on BTS classes using BTS classification. To this end, data reported in the previous studies on BTS of various rock types was used (Tables 4–6). The frequency of each BTS class for various rock types, including igneous, sedimentary, and metamorphic, is presented in Figure 9. The highest (79.51%) and lowest (9.31%) frequencies of BTS classes in the igneous rocks belong to the strong (sum: strong + very strong + extremely strong) and weak (sum: weak + very weak + extremely weak) classes, respectively. Also, medium BTS class has a frequency of 11.17%. For sedimentary rocks, BTS class of strong has highest frequency with the 55.04%, followed by weak and medium classes with the frequencies equal to 23.59 and 21.37%, respectively. Finally, metamorphic rocks exhibit a considerable frequency of 90.65% for BTS class of strong, while BTS classes of medium and weak have frequencies of 8.29 and 1.10, respectively. according to data given in Figure 9, a comparison between results indicate to tendency of igneous and metamorphic rocks to BTS classes of strong. In contrast, although frequency of strong BTS class in sedimentary rocks reveal a good value of 55.04%, a significant proportion of these rocks fall into the BTS classes with medium and weak strengths (a sum of 54.96%).

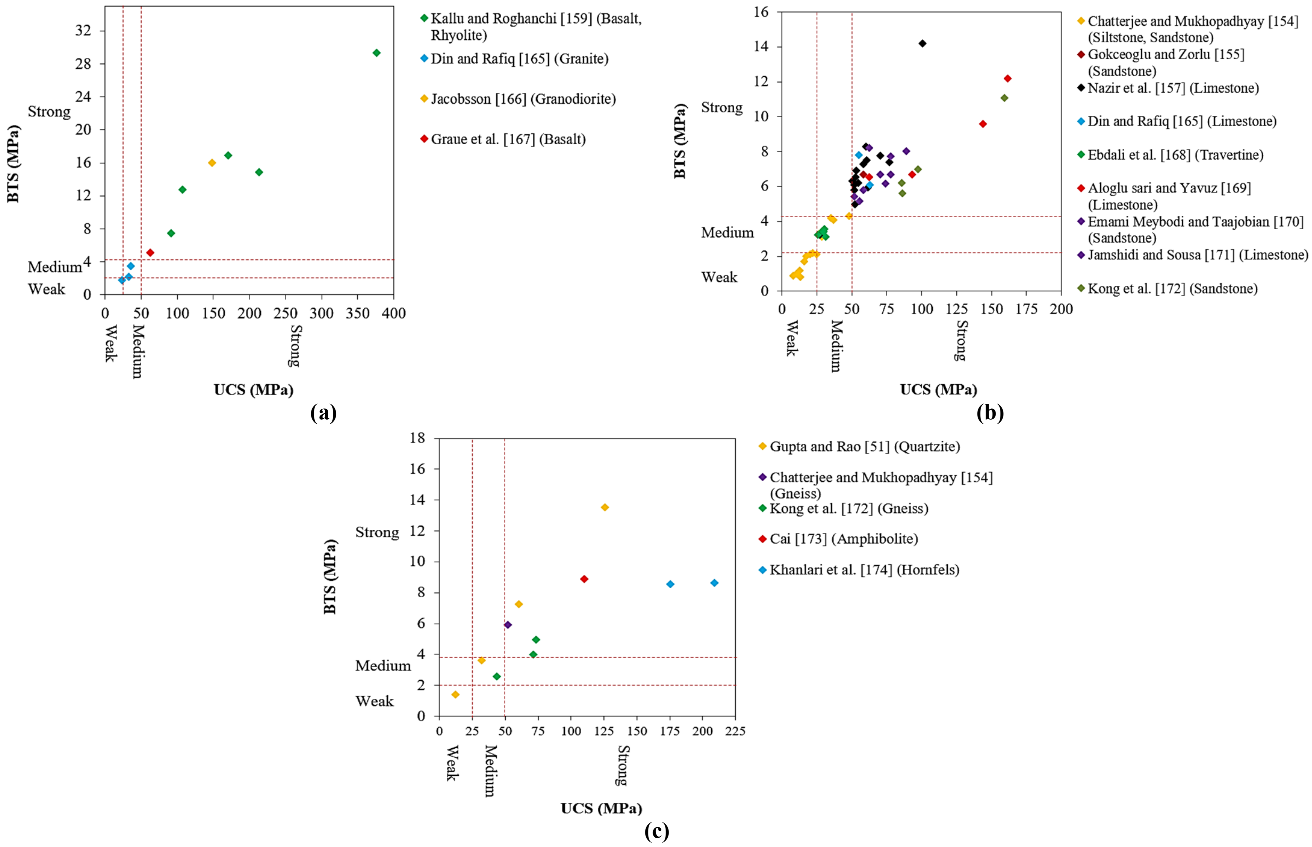


Figure 8. The validity of BTS classification by data published by various researchers a) Igneous rocks b) sedimentary rocks, and c) metamorphic rocks

* According to Table 10: weak (sum: extremely weak + very weak + weak), medium, strong (sum: strong + very strong + extremely strong)

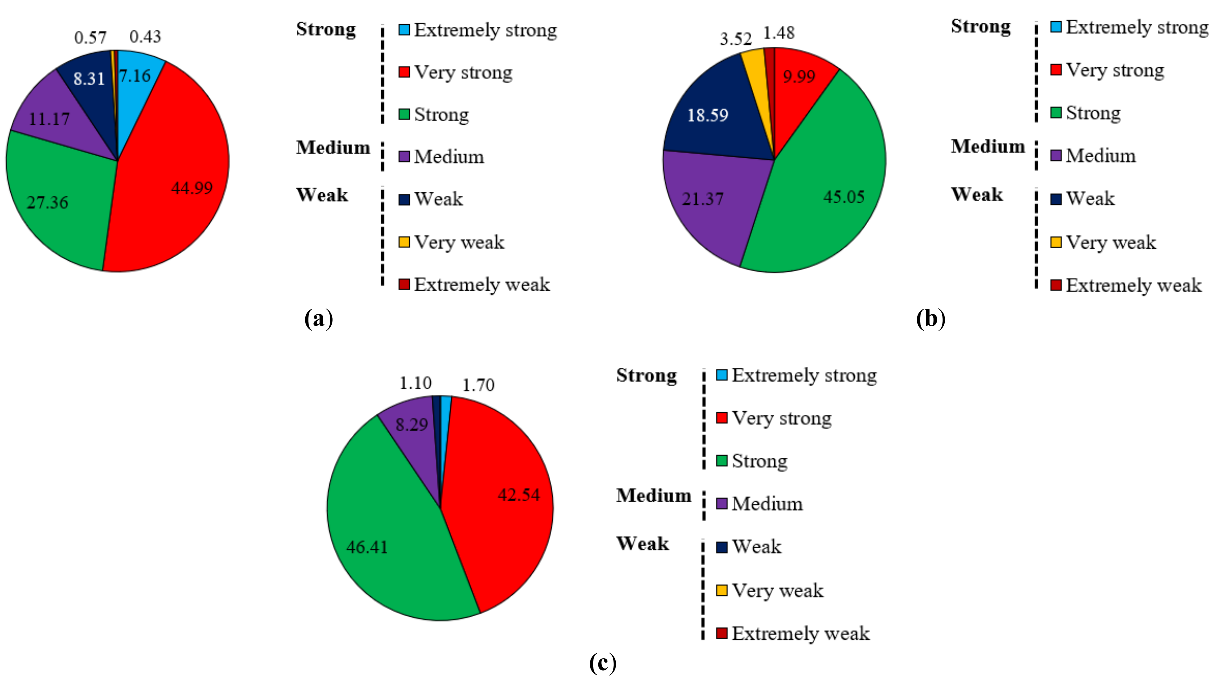


Figure 9. The frequency of BTS classes (a) igneous rocks, (b) sedimentary rocks, and (c) metamorphic rocks

5. Conclusions

Based on a review on the previous studies, a large number of uniaxial compressive strength (UCS) and Brazilian tensile strength (BTS) data of various rock types, including igneous (25 types, 699 data), sedimentary (16 types, 1083 data), and metamorphic (11 types, 181 data), were collected. Next, by analyzing the data, two objectives were pursued; a comparative study between various rocks in terms of BTS values and the development of a new classification for the strength of rocks based on BTS. The main findings of the present study are as follows.

– According to the results of regression analyses, it was found that there is the acceptable correlation relashioships between the BTS and UCS of the various rocks. However, comparing the values of correlation coefficient (r) indicated that the accuracy of the correlation relationship between BTS and UCS is highest for igneous rocks, followed by metamorphic and sedimentary rocks, respectively.

– Overall, igneous rocks showed higher average BTS (9.91 MPa) than metamorphic and sedimentary rocks (8.24 and 4.85 MPa, respectively). Furthermore, the BTS range of igneous rocks varies from 0.00 to 30.30 MPa, while metamorphic and sedimentary rocks have a limited range between 1.74–20.74 MPa, and 0.05–18.42 MPa, respectively.

– According to the BTS values, the rocks categorized into the seven strength classes, namely extremely weak, very weak, weak, medium, strong, very strong, and extremely strong. The validity of the BTS classification developed in the present study was verified using data published in the literature.

– The BTS classification can be used as a suitable indicator for the preliminary assessment of rock quality at the site of a mining activity. In this regard, a rock categorized into a BTS class with a higher strength can exhibit better mechanical behavior in terms of BTS.

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Conflict of interest/Competing interests

The authors declared that they have no known competing financial interests or personal relationships that could have appeared to influence the study reported in this paper.

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بررسی مقایسه‌ای مقاومت کششی برزیلین سنگ‌های مختلف و توسعه طبقه‌بندی مبتنی بر مقاومت کششی برزیلین برای سنگ‌ها

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چکیده:

مقاومت کششی برزیلین یک پارامتر مهم در فعالیت‌های معدنکاری بویژه برای سنگ‌های در معرض تنش کششی است. آزمایش برزیلین برای اندازه‌گیری مقاومت کششی غیرمستقیم سنگ‌ها استفاده می‌شود به طوری که در شناخت رفتار مکانیکی و کیفیت سنگ‌ها در حوزه معدنکاری مانند آنالیز پایداری دامنه، طراحی انفجار، سیستم‌های نگهدارنده ، حفاری و انتخاب ابزار آن، گسترش شکست، شکست هیدرولیکی و حفاری مفید است. تاکنون طبقه‌بندی مقاومت کششی سنگ برای کاربردهای معدنکاری ارائه نشده است. در مطالعه حاضر، یک طبقه‌بندی جدید بر اساس مقاومت کششی برزیلین برای سنگ‌های مختلف پیشنهاد شده است. برای رسیدن به این هدف، بر اساس بررسی مطالعات پیشین، مقاومت فشاری تک‌محوری و مقاومت کششی برزیلین رده‌های سنگ مختلف شامل آذرین، رسوبی و دگرگونی جمع‌آوری شدند. برای هر رده سنگ، معادلات همبستگی بین مقاومت فشاری تک‌محوری و مقاومت کششی برزیلین با استفاده از آنالیز رگرسیون ساده توسعه داده شد. بر اساس آنالیز داده‌ها، سنگ‌ها به هفت رده مقاومت کششی برزیلین طبقه‌بندی شده‌اند. نتایج نشان داد مقدار مقاومت کششی برزیلین سنگ‌های آذرین، رسوبی و دگرگونی در دامنه گسترده‌ای متغیر است که در نتیجه آن سنگ‌ها در رده‌های مختلف طبقه‌بندی مقاومت کششی برزیلین قرار می‌گیرند. صحت طبقه‌بندی مقاومت کششی برزیلین بر اساس داده‌های منتشر شده مقاومت فشاری تک‌محوری و مقاومت کششی برزیلین در مطالعات پیشین تایید شد و نتایج حاکی از این است که مقاومت کششی برزیلین می‌تواند به عنوان یک شاخص مناسب برای ارزیابی مقدماتی کیفیت سنگ استفاده شود. این موضوع می‌تواند منجر به شناخت بهتر از رفتار مقاومتی سنگ‌های در معرض تنش کششی در ساختگاه فعالیت معدنکاری شود و بنابراین طراحی دقیق‌تر پروژه معدنکاری را در پی داشته باشد.

کلمات کلیدی: مقاومت کششی برزیلین، طبقه‌بندی سنگ بکر، کیفیت سنگ، فعالیت معدنکاری.