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The Brazilian tensile strength as an alternative for point load index in the Rock Mass Rating system

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Abstract
The Rock Mass Rating (RMR) system is widely used to assess rock mass quality and the its mechanical parameters including cohesion, internal friction angle, and elasticity modulus. The uniaxial compressive strength (UCS)/point load index (PLI) of intact rock is one of the input parameters in RMR. Rocks in some geotechnical works, such as rock slopes, tunnels, and some foundations are under tensional stresses. In these conditions, the tensile strength of the rocks may be a suitable strength parameter in RMR system to assess mechanical behavior of the rock mass in site a geotechnical work. One of the weaknesses of RMR is that it does not take into account the tensile strength of intact rock. In this paper, a new rock classification is introduced based on Brazilian tensile strength (BTS) as an alternative for point load index (PLI) in RMR. To achieve this purpose, BTS and UCS values for diverse rock types including igneous, sedimentary, and metamorphic were collected through a comprehensive review of existing literature. For each rock type, the correlation equations between BTS and UCS were developed using simple regression analysis. Using data analyses, the intact rock was categorized into seven BTS classes. The BTS classification suggested in the present study can be used as a novel approach in RMR for a rock mass outcropped at the site of a geotechnical project. This can lead to a more comprehensive assessment of the mechanical behavior of the rock mass, and therefore, a more accurate design of a geotechnical project.

Keywords: Brazilian Tensile Strength, Uniaxial Compressive Strength, Point Load Index, Rock Classification, Rock Mass Rating.

Introduction

The Rock Mass Rating (RMR) system or geomechanics classification, proposed by Bieniawski (1973), was initially developed at the South African Council of Scientific and Industrial Research (CSIR) based on experiences in shallow tunnels in sedimentary rocks. Subsequently, it has been applied to the preliminary design of foundations and rock slopes, as well as to an indirect assessment of the cohesion, angle of internal friction, modulus of deformation, and shear strength of rock masses (Kendorski et al. 1983; Laubscher and Page 1990; Rose et al. 2001; Hoek and Diederichs 2006; Isik et al. 2008; Ajalloeian and Mohammadi 2014; Rehman et al. 2019; Hassanpour et al. 2022; Jaiswal et al. 2024). The RMR has used six parameters including uniaxial compressive strength (UCS)/point load index (PLI) of intact rock, rock quality designation (RQD), joint spacing, joint conditions, groundwater conditions, and joint orientations. RMR is calculated as an algebraic sum of ratings for the aforementioned

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parameters. Based on RMR value, the rock mass in site-specific geotechnical project is sorted into five quality classes: very good (RMR 100–81), good (RMR 80–61), fair (RMR 60–41), poor (RMR 40–21), and very poor (RMR <20).

Among the parameters used in RMR, UCS/PLI of the intact rock with a rating range of 0 to 15 has a share 0 to 15% of the final value of RMR (Table 1). In some conditions (such as laminated sedimentary rocks, metamorphic rocks containing schistosity, and highly weathered igneous rocks), it is impossible to prepare cylindrical core specimens from intact rock to UCS testing. In this regard, the PLI can serve as an alternative for UCS in RMR. Although the PLI test has several advantages such as simplicity, quickness, and portability of PLI device (Singh and Singh 1993; Basu and Aydin 2006; Azimian and Ajalloeian 2015; Xue et al. 2022), some previous studies have revealed that depending on the geometric shape of the test specimen (i.e., cylindrical core, block, or irregular lump), the PLI of intact rock is accompanied by measurement errors (Heidari et al. 2012; Jamshidi 2022; Akbay 2023). Therefore, using PLI of intact rock as an input key parameter in RMR can result in a less accurate assessment of rock mass and thus, design errors for a geotechnical project

Another critical issue in RMR is the type of strength parameter considered for intact rock. In some geotechnical projects such as rock slopes, tunnels, and some foundations, rocks can be under both compressive and tensile stresses. However, the mechanical behavior of rock mass subjected to each of these stresses is different (Diederichs 1999; Dan et al. 2013; Wei et al. 2021; Zhou et al. 2022; Qiu and Zhou 2023). It is evident under conditions where the stresses governing the rock mass are primarily tensile, the tensile strength, as opposed to compressive strength, can provide a better assessment of the mechanical behavior of the rock mass. Among tensile strength tests, Brazilian tensile strength (BTS) is the most common method. One of the practical advantages of BTS testing is its ability to overcome key limitations associated with UCS, including difficulties in sample preparation for weak or fractured rocks and the need for complex, high-capacity equipment, offering a simpler, more practical solution for field applications. Moreover, BTS more accurately represents rock mass behavior in shear and brittle fracture, critical for assessing failure along discontinuities like joints and bedding planes, while its heightened sensitivity to microcracks, weathering, and mineralogical changes makes it a superior indicator of long-term rock degradation. By addressing the RMR system's historical neglect of tensile strength, this research provides a standardized, empirically validated approach to enhance design accuracy in tensile-critical projects, ensuring safer and more reliable geotechnical assessments. Therefore, incorporating the tensile strength of intact rock into the RMR system can lead to a more accurate assessment of the rock mass' mechanical behavior under tensile stresses in geotechnical projects. So far, no classification of the tensile strength of intact rock for RMR applications has been presented. Thus, the present study was conducted to address this gap. In this context, an attempt has been made to propose a new classification for intact rock based on its Brazilian tensile strength (BTS) is proposed, which can be used as an input parameter in RMR.

Table 1. Strength classification of intact rock material in RMR (Bieniawski1989)

UCS (MPa)	PLI (MPa)	Rating
> 250	> 10	15
100–250	4–10	12
50–100	2–4	7
25–50	1–2	4
5–25	Use of UCS test	2
1–5	is preferred	1
< 1		0

Brazilian tensile strength

Tensile strength is one of the key parameters of intact rocks for evaluating their mechanical behavior during geotechnical activities such as rock drilling, blasting in mines, slope cutting, tunnels, dams, and foundations (Hassanpour et al. 2009; Gurocak et al. 2012; Mohammed et al. 2022). In addition, this parameter plays an important role in the durability of the rocks against processes of freezing-thawing in site a geotechnical project site (Zalooli et al. 2017; Ur Rehman et al. 2022). There are various methods to measure the tensile strength of rocks, among which the BTS is the most indirect common and widely used by previous researchers (Bell and Lindsay 1999; Kilic and Teymen 2008; Huang et al. 2019; Zheng et al. 2023).

To conduct the BTS test, the cylindrical core specimens having a diameter of 54 mm and a thickness of between 27 and 54 mm are placed in a BTS test machine (ISRM 1981). Next, loading on the specimens applied by two opposed concave loading jaws (Fig. 1). Finally, the BTS can calculated by the following equation:

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

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

Data collection

The data utilized in the present study were gathered from documents published by previous researchers. These data are from the 1972 to 2024 and they encompass a timeframe of 52 years. The BTS and UCS values for three main classes of rocks including igneous, sedimentary, and metamorphic were extracted from these documents. In Tables 2–4, 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 5. Moreover, each subclass includes a set of various rock types. It can be seen from Table 5 that a wide range of rock types have been used in the present study.

A huge amount of data has been used to achieve the objectives of this study. According to Fig. 2, the total amount 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. Similarly, in subclasses belonging to sedimentary rocks, the 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 namely foliated and non-foliated, comprising 48 and 133 data, respectively.

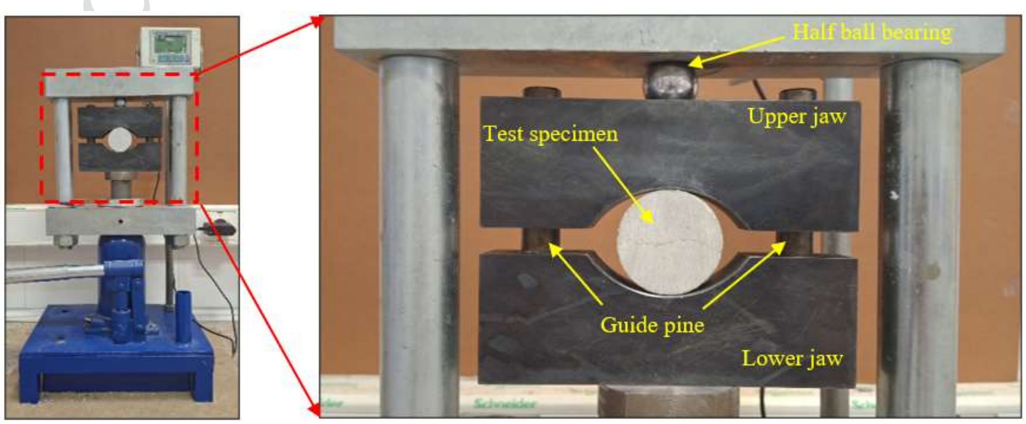

Figure 1. The apparatus for the BTS test

Table 2. Database of the igneous rocks

Researcher/s	Rock type	No of data	UCS range (MPa)	BTS range (MPa)
Schmidt (1972)	Anorthosite, Basalt, Gabbro, Granite	10	89.6–374.7	8.7–28.3
Bilgin (1977)	Granite	1	179.1	10.8
Clark (1979)	Anorthosite, Basalt, Gabbro, Granite	10	123.2–296.8	7.3–15.4
Howarth (1987)	Basalt, Granite, Syenite, Trachyte	4	137.1–234.0	8.0–15.2
Bilgin and Shahriar (1988)	Andesite, Tuff	7	27.9–53.0	2.3–6.2
Bilgin et al. (1993)	Tuff	1	43.4	4.0
Gupta and Rao (1998)	Granite	8	2.5–132.8	0.88–16.1
Bearman (1999)	Andesite, Diorite, Granite	4	128.8–274.8	10.6–18.4
Kahraman (1999)	Diabase, Tuff	2	10.1, 110.9	0.90, 10.1
Tugrul and Zarif (1999)	Granite	19	109.2–193.3	14.9–28.0
Ersoy et al. (2005)	Andesite, Dacite, Gabbro, Granite, Syenite, Tuff	10	6.4–168.0	0.50–8.7
Ersoy and Atici (2007)	Andesite, Dacite, Tuff	4	6.4–65.3	0.50–4.8
Dwivedi et al. (2008)	Granite	5	112.8-133.7	8.9–10.9
Atici and Ersoy (2009)	Andesite, Dacite, Diorite, Gabbro, Granite, Syenite, Tuff	12	6.0–375.0	0.50–30.3
Erguler and Ulusay (2009)	Tuff	6	1.3–12.9	0.00–1.8
Yagiz (2009)	Andesite, Basalt, Diabase, Gabbro, Granite, Granitoid, Syenite	17	47.0–327.0	4.2–17.8
Yilmaz et al. (2009)	Granite	3	11.8–131.4	10.4–11.4
Karaca et al. (2010)	Granite	2	111.8-131.4	10.4–11.4
Fener (2011)	Andesite, Basalt, Granite, Ignimbrite, Tuff	6	3.9–121.8	1.3–9.5
Yarali and Kahraman (2011)	Andesite, Basalt, Diabase, Granite, Granodiorite, Syenite	18	28.6–182.1	2.6–16.5
Ghobadi and Rasouli Farah (2012)	Granite, Granodiorite, Monzogranite, Tonalite	21	18.6–123.0	3.0–14.6
Kahraman et al. (2012)	Andesite, Basalt, Gabbro, Granite, Granodiorite	13	77.5–202.9	7.6–14.8
Khanlari et al. (2012)	Granodiorite, Monzogranite	10	12.4–135.7	0.46–11.4
Yavuz (2012)	Tuff	2	6.9, 14.9	0.43, 1.4
Basu et al (2013)	Granite	20	91.5–201.7	10.5–19.8
Heidari et al. (2013)	Granite, Granodiorite	10	3.8–150.1	0.46–17.6
Karakus and Akatay (2013)	Basalt	18	17.2–145.2	1.1–12.2
Khandelwal (2013)	Diabase, Granite	2	89.5, 121.5	6.9, 9.0
Mikaeil et al. (2013)	Granite	10	125.0–218.0	7.4–24.6
Heidari et al. (2014)	Granite, Tuff	2	122.0–124.3	9.96–11.2
Fener and Ince (2015)	Andesite	6	44.3–60.3	4.0–5.05
Majeed et al. (2015)	Diabase	17	154.6–258.5	15.5–22.2
Ribeiro et al. (2015)	Andesite, Diabase, Granite, Granodiorite, Monzogranite	8	103.7–223.0	8.9–18.8
Sajid and Arif (2015)	Granite	21	17.3–63.3	1.2–6.4
Ghobadi et al. (2016)	Tuff	48	55.0–245.0	3.7–25.7
Ince and Fener (2016)	Tuff	10	7.6–48.6	1.1–4.8
Momeni et al. (2016)	Granite	3	90.7-164.0	8.7–14.7
Ronmar (2016)	Basalt, Tuff	2	212.0, 87.6	14.2, 8.3
Akinbinu (2017)	Anorthosite, Granite, Norite, Troctolite	12	129.6–276.3	9.2–16.9
Almasi et al. (2017)	Andesite, Diorite, Gabbro, Granite, Syenite	11	91.0–193.0	6.3–15.0
Altindag and Guney (2017)	Andesite, Anorthosite, Basalt, Dacite, Diabase, Diorite, Gabbro, Granite, Tuff	39	5.7–375.2	0.20–30.3
Bozdağ and İnce (2018)	Andesite, Basalt, Granite, Spilite, Tuff	23	7.6–144.1	1.0–11.5
Jaques et al. (2020)	Syenogranite	5	1.2–160.6	0.19–9.7
Teymen and Mengüç (2020)	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. (2020)	Granite	7	104.0–137.0	4.4–6.4
Zalooli et al. (2020)	Granodiorite, Monzogranite	2	124.3, 145.8	11.1, 13.0
Akbay and Altindag (2021)	Andesite, Diabase, Granite	3	102.4–154.0	10.0–11.6
Hamzaban et al. (2021)	Andesite, Basalt, Granite	8	33.8–80.0	2.8–7.5
Jamshidi (2021)	Granite, Granodiorite, Monzogranite, Syenogranite	16	68.0–123.0	5.3–13.3
Wei et al. (2021)	Granite	5	88.1–128.7	2.4–5.6
Fereidooni (2022)	Diorite, Gabbro, Granite, Granitoid, Monzogranite, Monzonite, Syenite, Tonalite	16	69.7–129.5	2.3–4.3
Pötzl et al. (2022)	Tuff	21	4.0–73.7	0.60–6.7
Ajalloeian et al. (2024)	Granite, Granodiorite, Monzogranite, Syenogranite	10	67.9–112.3	5.2–12.1
Diamantis et al. (2024)	Peridotite	70	52.3–241.6	9.7–24.9
Kahraman et al. (2024)	Andesite, Basalt, Diabase, Granite, Granodiorite, Syenite, Tuff	27	3.6–204.9	0.40-13.5

Table 3. Database of the sedimentary rocks

Researcher/s	Rock type	No of data	UCS range (MPa)	BTS range (MPa)
Schmidt (1972)	Claystone, Dolomite, Limestone	3	97.0–220.7	4.2–18.4
Phillips (1975)	Sandstone	2	41.0, 49.2	1.9, 2.6
Bilgin (1977)	Limestone, Sandstone	3	55.8–183.9	3.1–16.5
Clark (1979)	Limestone	2	121.8, 34.2	4.7, 2.5
Bilgin (1982)	Anhydrite, Gypsum	2	112.9, 45.0	5.5, 2.8
Singh (1986)	Coal	3	18.4–24.5	1.4–1.5
Howarth (1987)	Sandstone	3	35.1–44.1	2.4–3.3
Bilgin and Shahriar (1988)	Limestone, Marl, Sandstone	4	17.1–62.0	0.77–3.7
Bilgin et al. (1993)	Limestone, Marl	11	7.9–88.7	0.80–6.5
Bearman (1999)	Limestone, Sandstone	7	47.8–226.3	3.8–15.4
Kahraman (1999)	Dolomite, Limestone, Marl, Sandstone	18	11.4–123.8	0.90–16.1
Harris (2002)	Coal	5	7.0–24.8	1.4–1.8
Kahraman et al. (2004)	Limestone, Travertine	13	45.4–175.0	2.2–10.2
Goktan and Yilmaz (2005)	Limestone, Mudstone, Sandstone	26	7.0–170.0	1.0–8.9
Hecht et al. (2005)	Conglomerate, Sandstone	6	21.0–135.0	2.5–10.4
Vásárhelyi (2005)	Limestone	90	0.63–26.5	0.07–4.2
Kayabali et al. (2006)	Gypsum	8	6.2–16.6	0.77–2.8
Tiryaki (2006)	Sandstone	19	6.2–122.7	1.0–8.9
Ersoy and Atici (2007)	Limestone	4	49.7–87.2	5.5–8.5
Hoseini (2007)	Lomashell	41	2.0–11.7	0.05–4.4
Ahmadi (2008)	Sandstone	18	29.8–105.2	1.1–7.6
Yavuz et al. (2008)	Limestone, Travertine	6	20.0–100.0	2.5–8.0
Atici and Ersoy (2009)	Breccia, Limestone, Mudstone, Sandstone, Siltstone	13	28.0–175.0	2.9–14.5
Erguler and Ulusay (2009)	Siltstone, Mudstone, Marl	53	1.9–136.1	0.1–12.8
Yagiz (2009)	Limestone, Mudstone, Sandstone, Shale, Siltstone	18	21.0–159.0	2.3–6.9
Karaca et al. (2010)	Limestone, Travertine	6	23.0–93.6	3.5–11.8
Fener (2011)	Dolomite, Limestone, Travertine	3	13.7–85.2	3.5–5.7
Kumar et al. (2011)	Chalk, Limestone, Marl, Sandstone, Shale	6	15.2–71.8	2.0–8.9
Tahir et al. (2011)	Limestone	30	26.6–61.8	4.0–7.9
Yarali and Kahraman (2011)	Dolomite, Limestone, Marl, Sandstone, Siltstone	13	31.6–91.4	4.1–11.2
Heidari et al. (2012)	Gypsum	15	29.0–37.4	3.8–5.5
Kahraman et al. (2012)	Anhydrite, Limestone, Sandstone, Travertine	17	30.4–175.0	2.2–10.2
Rajabzadeh et al. (2012)	Limestone	16	32.9–138.6	5.0–14.2
Basu et al. (2013)	Sandstone	20	12.8–172.0	2.0–14.3
Khandelwal (2013)	Limestone, Sandstone, Shale	5	45.0-99.2	4.4–9.3
Mikaeil et al. (2013)	Travertine	3	53.0-63.0	4.3–5.6
Heidari et al. (2014)	Gypsum, Sandstone, Travertine	3	32.1–65.8	4.5–9.4
Ribeiro et al. (2015)	Conglomrate, Gypsum, Limestone, Mudstone, Sandstone, Shale, Siltstone	18	5.2-147.7	0.30–10.7
Tumac (2015)	Limestone	2	70.1, 89.0	5.4, 5.3
Ghobadi and Naseri (2016)	Limestone	41	10.1–16.6	1.8–4.4
Jamshidi et al. (2016)	Travertine	15	33.6–65.7	3.7–6.4
Ronmar (2016)	Sandstone	1	43.9	4.16
Akinbinu (2017)	Sandstone	2	35.2, 40.3	2.6, 2.9
Altindag and Guney (2017)	Breccia, Claystone, Dolomite, Gypsum, Limestone, Sandstone, Siltstone	58	7.0–216.4	1.0–18.06
Masoumi et al. (2017)	Sandstone	25	11.0–49.2	1.7–5.0
Minaeian and Ahangari (2017)	Conglomerate	1	6.8	0.82
Naseri and Khanlari (2017)	Travertine	80	20.1–103.5	3.3–10.1
Fereidooni and Khajevand (2018)	Travertine	6	18.5–32.0	4.2–7.7
Jamshidi et al. (2018)	Sandstone	21	46.6–77.3	5.1–9.4
Ashtari et al. (2019)	Marl	10	23.4–71.1	3.0–7.2
Torabi-Kaveh et al. (2019)	Limestone	1	115.6	11.2
Zalooli et al. (2019)	Travertine	4	33.6–61.5	3.9–6.4
Jamshidi et al. (2020)	Sandstone	10	32.1–69.0	4.5–7.4
Lakirouhani et al. (2020)	Dolomite	32	9.2–83.8	1.6–10.0
Teymen and Mengüç (2020)	Aragonite, Breccia, Claystone, Gypsum, Limestone, Radiolarite, Sandstone, Shale, Siltstone, Travertine	27	14.1–236.2	1.7–16.6
Akbay and Altindag (2021)	Limestone	3	64.2–110.6	8.0–8.9
Arman (2021)	Gypsum	1	24.6	2.8

Hamzaban et al. (2021)	Sandstone, Travertine	6	25.5–47.0	2.0–6.8
Jamshidi et al. (2021)	Sandstone	5	38.0–70.8	3.9–7.1
Kolapo and Munemo (2021)	Sandstone	5	34.0–56.1	1.2–2.1
Tripathi et al. (2021)	Sandstone	9	15.0–27.0	1.4–3.8
Wei et al. (2021)	Sandstone	10	28.5–79.2	0.82–4.4
Fereidooni (2022)	Limestone	9	12.5–61.9	1.0–2.4
Sadeghi et al. (2022)	Limestone	13	42.5–88.0	5.7–10.9
Cun et al. (2023)	Coal	5	1.6–12.2	0.60–2.1
Fadhil et al. (2023)	Claystone, Limestone, Sandstone	60	31.0–102.0	1.8–12.5
Khajevand (2023a)	Conglomerate, Limestone, Sandstone, Travertine	30	10.8–51.5	2.3–7.9
Khajevand (2023b)	Conglomerate, Limestone, Sandstone, Travertine	44	13.3–53.5	2.2–9.7
Pathan et al. (2023)	Claystone, Coal, Sandstone, Siltstone	7	0.57–2.5	0.22–0.42
Qiang et al. (2023)	Sandstone, Shale	2	36.2, 65.1	6.9, 9.4
Kahraman et al. (2024)	Limestone	5	113.7–136.5	5.9-9.3

Table 4. Database of the metamorphic rocks

Researcher/s	Rock type	No of data	UCS range (MPa)	BTS range (MPa)
Schmidt (1972)	Marble, Quartzite	4	127.6–307.2	7.0–20.8
Clark (1979)	Marble	2	183.4, 172.9	8.5, 10.1
Howarth (1987)	Hornfels, Marble	3	49.9–100.5	3.0–13.5
Bearman (1999)	Quartzite	1	138.6	13.0
Yavuz et al. (2005)	Marble	14	61.7–155.5	2.8–12.7
Yavuz and Topal (2007)	Marble	12	58.4–134.3	3.5–9.2
Yavuz et al. (2008)	Marble	5	54.0–126.0	4.8–8.2
Atici and Ersoy (2009)	Marble	1	85.0	7.8
Yagiz (2009)	Gneiss, Quartzite, Marble, Schist	10	68.0–227.0	5.4–12.7
Karaca et al. (2010)	Marble	2	57.7–110.3	6.6–10.1
Yarali and Kahraman (2011)	Quartzite	1	164.8	17.1
Kahraman et al. (2012)	Gneiss, Migmatite, Marble, Quartzite, Schist, Serpentinite	15	24.1–203.6	4.9–17.2
Rajabzadeh et al. (2012)	Marble	10	45.9–101.8	4.4–10.6
Khandelwal (2013)	Marble, Quartzite	4	42.3–133.5	4.7–8.7
Mikaeil et al. (2013)	Marble	4	71.5–74.5	6.3–7.2
Heidari et al. (2014)	Hornfels, Marble	2	84.0–149.0	9.6–10.4
Ribeiro et al. (2015)	Gneiss, Mylonite, Phyllite, Quartzite, Schist	12	87.1–215.5	11.2–15.5
Tumac (2015)	Marble	5	65.3–97.3	3.9–7.1
Fereidooni (2016)	Hornfels	8	99.2–272.8	3.8–20.5
Singh and Murthy (2016)	Gneiss	3	35.0–65.0	3.5–8.0
Tumac (2016)	Marble	4	63.8–108.0	4.6–7.9
Akinbinu (2017)	Marble, Quartzite	2	76.8, 249.9	5.6, 15.7
Altindag and Guney (2017)	Marble, Quartzite, Serpentine, Slate	18	38.1–301.2	3.1–20.3
Singh et al. (2017)	Gneiss, Phyllite, Quartzite	6	41.2–112.2	5.1–12.3
Teymen and Mengüç (2020)	Marble, Quartzite, Serpentinite	13	24.7–230.2	2.4–15.9
Akbay and Altindag (2021)	Marble	1	72.1	8.5
Jafari et al. (2021)	Schist	10	19.7–70.4	2.3–9.7
Fereidooni (2022)	Marble	3	58.1–61.4	1.7–2.6
Qiang et al. (2023)	Marble	1	93.6	12.7
Kahraman et al. (2024)	Marble	3	78.6–89.7	6.3–7.2
Zalooli et al. (2024)	Schist	2	47.4, 68.2	8.2, 4.1

Data analysis

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) (Fener et al. 2005; Azimian and Ajalloeian 2015; Akbay 2023). To perform simple regression analyses, each rock class, including igneous, sedimentary, and metamorphic, was separately investigated. The regression analyses were undertaken with a 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 Fig. 3. 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.

Table 5. 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	Breccia, Conglomerate, Sandstone
	Argillaceous	Claystone, Marl, Mudstone, Shale, Siltstone
	Evaporates	Anhydrite, Gypsum
	Organic	Chalk, Coal, Lomashell, Radiolarite
Metamorphic	Foliated	Amphibolite, Gneiss, Migmatite, Mylonite, Phyllite, Schist, Serpentinite, Slate
	Nonfoliated	Hornfels, Marble, Quartzite

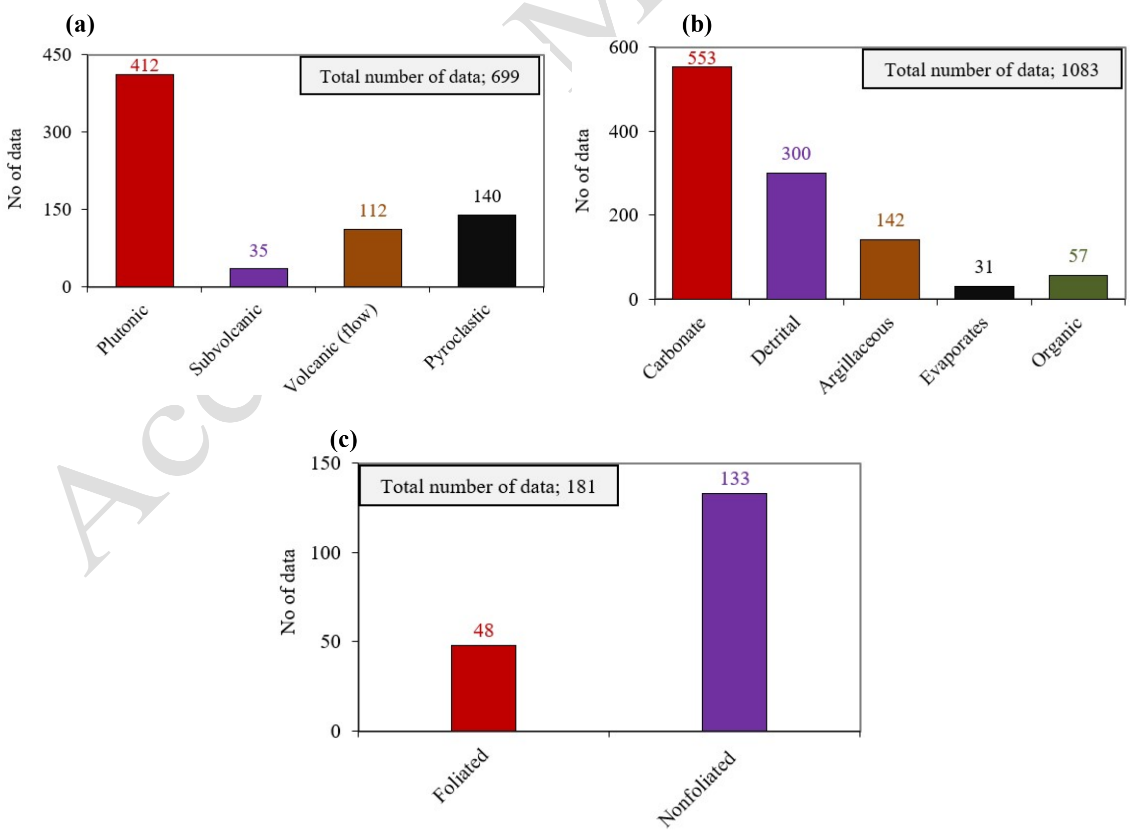

Figure 2. No. of data in each subclass for a) igneous rocks b) sedimentary rocks, and c) metamorphic rocks

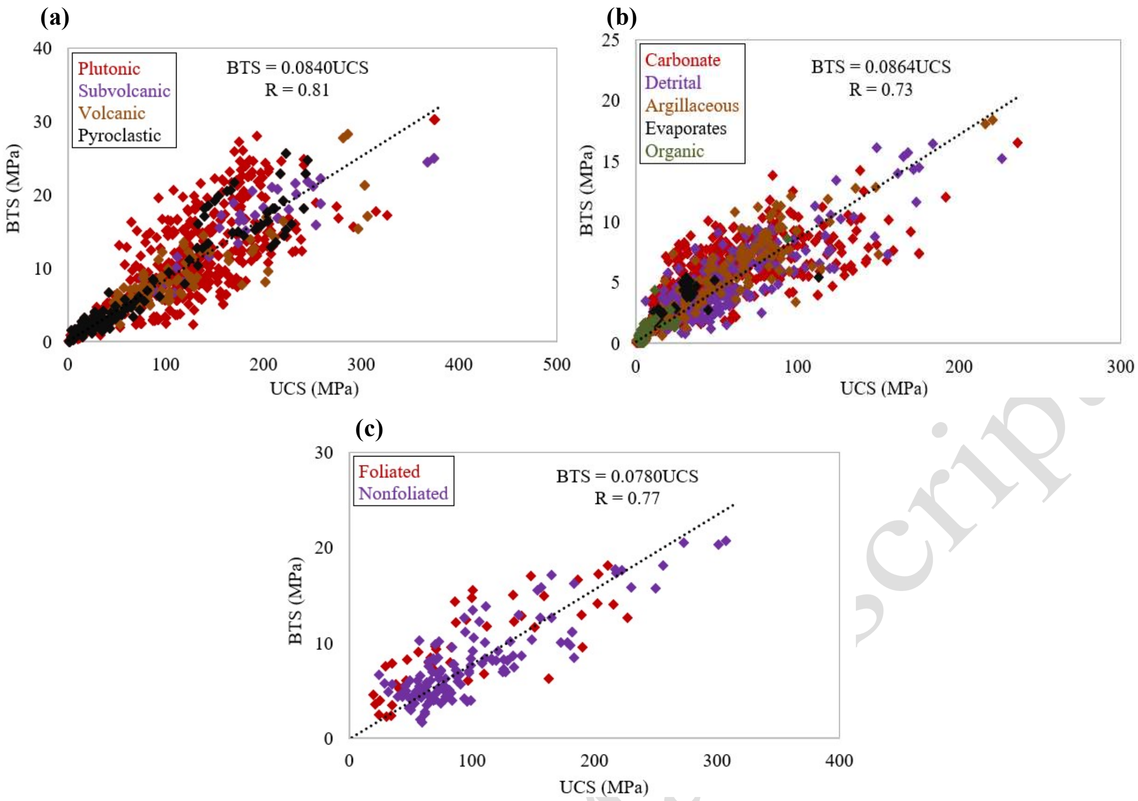

Figure 3. Relationship between BTS and UCS for a) igneous rocks b) sedimentary rocks, and c) metamorphic rocks

As two common numerical measures, the coefficient of correlation (R) and standard error of estimate (SEE) were used to investigate the accuracy of the correlation relationships developed between the BTS and UCS. A correlation relationship with a high R and a small SEE can be more accurate in estimating an unknown parameter of rock. According to Table 6, 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 at acceptable levels (R > 0.73), indicating significant correlations between BTS and UCS with good accuracies. This result indicated that Eqs. 2–4 presented in Table 6 can be accepted as reliable models for estimating the BTS from UCS. By comparing the values of r obtained from these equations, it can be 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 measures, SEE values obtained from regression analyses developed between BTS and UCS of igneous, sedimentary, and metamorphic are 3.72, 1.82, and 2.47, respectively (Table 6), which are acceptable values, indicating good accuracy of correlation relationships in estimating the BTS from 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.

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 H_0: $\alpha = 0$. Additionally, the alternative hypothesis is H_1: $\alpha \neq 0$. The results of the variance analysis for correlation relationships are shown in Table 6. 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 (Stoodley et al. 1980). 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 are appropriate for estimating the BTS from UCS.

Classification of the intact rock based on Brazilian tensile strength

According to Table 1, intact rock in the RMR system is classified to into seven classes based on its UCS values, 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 Eqs. 2–4 (Table 6), 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 7 and graphically in Fig. 4, several classes of BTS were suggested for rocks with the given ratings. These classes and their ratings are following the UCS classification of intact rock proposed by Bieniawski (1989). In BTS classification there are seven classes including the extremely strong (rating 15), very strong (rating 12), strong (rating 7), medium (rating 4), weak (rating 2), very weak (rating 1), and extremely weak (rating 0). 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 than 21.0, 21.6, and 19.5 MPa for igneous, sedimentary, and metamorphic rocks, respectively. However, from the extremely strong class to the extremely weak class difference between the lower and upper limits of BTS values showed a decreasing trend. It is evident from Fig. 4 that for all rocks, the lower and upper limits of BTS values for very weak and extremely weak classes are 0.1–0.4 MPa and lesser 0.1 MPa, respectively. To rate the intact rock BTS as an input parameter in the RMR system, it is necessary first to determine the rock mass type (i.e., igneous, sedimentary, or metamorphic) at site of a geotechnical project. Then, the rock specimens are prepared and their BTS are measured through a Brazilian test. Finally, based on Fig. 4, the BTS rating is determined according to the rock mass type. In situations that performing the UCS test is not possible, and on the other hand, due to some errors in PLI results (Heidari et al. 2012; Jamshidi 2022; Akbay 2023), BTS classification can be an alternative parameter, resulting in a more accurate rating for intact rock strength in the RMR system and, thus, a better assessment of the mechanical behavior of rock mass.

Table 6. 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 = 0.0780UCS	0.77	2.47	364	3.89	0.000

Table 7. Suggested BTS classification of the intact rock for application in the RMR system

Qualitative description	UCS (MPa)[a]	PLI (MPa)[a]	BTS (MPa)			Rating[a]
			Igneous rocks[b]	Sedimentary rocks[c]	Metamorphic rocks[d]	
Extremely strong	> 250	> 10	> 21.0	> 21.6	> 19.5	15
Very strong	100–250	4–10	8.4–21.0	8.6–21.6	7.8–19.5	12
Strong	50–100	2–4	4.2–8.4	4.3–8.6	3.9–7.8	7
Medium	25–50	1–2	2.1–4.2	2.2–4.3	2.0–3.9	4
Weak	5–25	Use of UCS test is preferred	0.4–2.1	0.4–2.2	0.4–2.0	2
Very weak	1–5		0.1–0.4	0.1–0.4	0.1–0.4	1
Extremely weak	< 1		< 0.1	< 0.1	< 0.1	0

[a] According to Bieniawski (1989)
[b,c,d] BTS values of the igneous, sedimentary, and metamorphic rocks were obtained using Eqs. 2, 3, and 4, respectively, based on UCS values in the RMR system (Bieniawski 1989)

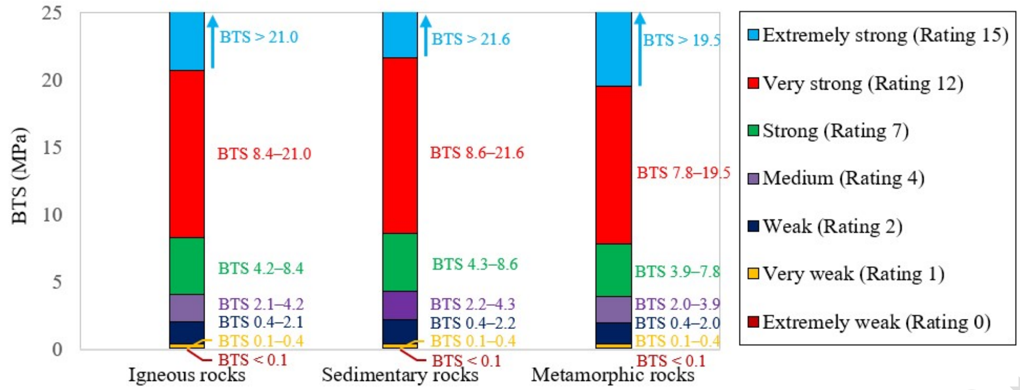

Figure 4. A schematic pattern of BTS classification of the intact rock and rating of each class in the RMR system

Conclusion

In the present study, a new classification was proposed based on the BTS for the igneous, sedimentary, and metamorphic intact rocks. This classification not only provides a quantitative-qualitative description of intact rock BTS but also offers practical and easy integration into the RMR system. Through comprehensive analysis of 1,963 test results spanning 52 years of research across igneous, sedimentary, and metamorphic rock types, there was established robust correlations between BTS and UCS with correlation coefficients of 0.81, 0.73, and 0.77 respectively. The proposed classification introduces seven distinct BTS categories (extremely strong to extremely weak) with rock-type specific thresholds, providing the more information and insights to traditional UCS-based ratings in RMR when evaluating rock masses under tensile stress conditions. Key findings demonstrate that the tensile strength characteristics vary significantly by lithology, with igneous rocks showing the strongest BTS-UCS correlation (R=0.81) and metamorphic rocks exhibiting the most pronounced deviation from compressive strength behavior. Rating to intact rock strength based on its BTS, as an input parameter in the RMR system, will lead to a more comprehensive assessment of the mechanical behavior of the mass rock. As a result, the design parameters of geotechnical projects will be more accurate leading to the construction of safer civil structures on or into the rock mass.

Conflict of interest

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.

Authors' contributions

Conceptualization, Amin Jmashidi; methodology, Amin Jamshidi; validation, Amin Jamshidi, Luís Sousa and Davood Fereidooni; formal analysis, Amin Jamshidi; investigation, Amin Jamshidi, Luís Sousa and Davood Fereidooni; writing-original draft preparation, Amin Jamshidi; writing-review and editing, Luís Sousa and Davood Fereidooni; visualization, Amin Jamshidi, Luís Sousa and Davood Fereidooni. All authors have read and agreed to the published version of the manuscript.

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