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ORIGINAL PAPER

An Investigation into the Rock Properties Influencing the Strength in Some Granitoid Rocks of KwaZulu-Natal, South Africa

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Abstract The uniaxial compressive strength (UCS) of rocks is a critical parameter required for most geotechnical projects. However, it is not always possible for direct determination of the parameter. Since determination of such a parameter in the lab is not always cost and time effective, the aim of this study is to assess and estimate the general correlation trend between the UCS and indirect tests or indexes used to estimate the value of UCS for some granitoid rocks in KwaZulu-Natal. These tests include the point load index test, Schmidt hammer rebound, P-wave velocity (V_p) and Brazilian tensile strength (σ_t). Furthermore, it aims to assess the reliability of empirical equations developed towards estimating the value of UCS and propose useful empirical equations to estimate the value of UCS for granitoid rocks. According to the current study, the variations in mineralogy, as well as the textural characteristics of granitoid rocks play an important role in influencing the strength of the rock. Simple regression analyses exhibit good results, with all regression coefficients R^2 being greater than 0.80, the highest R^2 of 0.92 being obtained from UCS versus σ_t. Comparison of equations produced in the current study as well as empirical equations derived by several researchers serves as a validation. Also illustrate that the reliability of such empirical equations are dependent on the rock type as well as the type of index tests employed, where variation in rock type and index tests produces different values of UCS. These equations provide a practical tool for estimating the value of UCS, and also gives further insight into the controlling factors of the strength of the granitoid rocks, where the strength of a rock is a multidimensional parameter.

Keywords Uniaxial compressive strength · Point load index · Brazilian tensile strength · Schmidt hammer rebound · Ultrasonic velocity

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1 Introduction

Rock engineering properties such as the uniaxial compressive strength (UCS) of intact rocks is a significant mechanical property for engineering projects (Yesiloglu-Gultekin et al. 2013; Singh et al. 2013; Torabi et al. 2013; Momeni et al. 2015; Armaghani et al. 2016). The UCS can be determined experimentally through direct or indirect methods (ISRM 2007), or it can be estimated from empirical equations proposed in literature. At the preliminary stage of a project, direct measurement of the UCS requires high-quality samples and considerable time (Shalabi et al. 2007; Cai 2010; Yagiz 2011; Basu et al.

2012; Ersoy and Kanik 2012; Azadan and Ahangari 2013; Ozcelik et al. 2013). Therefore, direct testing of UCS may not always be possible to conduct at the preliminary design stages of underground structures, as a result of representative rock samples not being obtained (Yesiloglu-Gultekin et al. 2013). Empirical equations can assist scientists with the estimation of such strength parameters for practical solutions. Indirect tests such as the Point Load Index (PLI), Schmidt hammer rebound (SHR), P-wave velocity (V_p), and Brazilian tensile strength (σ_t) are often conducted to predict the values of UCS (Cargill and Shakoor 1990; Aydin and Basu 2005; Kilic and Teymen 2008; Heidari et al. 2011; Minaeian and Ahangari 2011; Karaman and Kesimal 2012).

According to Bewick et al. (2015), the UCS simply records the load at failure during uniaxial testing of a cylindrical core. Therefore, the UCS value is not the same as the Hoek–Brown parameter σ_{ci}, where the mean UCS is often considered to represent a reliable rock material property. The UCS value can therefore only be regarded as a proxy for rock strength which is dependent on many factors such as the loading rate (Bieniawski 1967), specimen geometry (Hudson et al., 1971), specimen size (Bieniawski 1968), and mineralogy. As a result, the UCS cannot be used to replace the Hoek–Brown criterion parameter σ_{ci}, and differentiation between the two parameters is required (Bewick et al. 2015). Besides being an important parameter for the assessment of failure criterions (Hoek and Brown 1980) for intact rocks and rock masses under triaxial conditions, the UCS has significant importance as it is employed in geotechnical classification of rock masses such as the rock mass rating (RMR) (Bieniawski 1989), Q-system (Barton et al. 1974), as well as in tunnelling durability, and bearing capacity assessment of foundations (Moomivand 2011).

The expression of correlations among engineering properties has long been the scope of experimental research. This is aroused by the need to represent the actual behaviour of rocks and to calculate the design parameters accurately. In this paper we consider the UCS from unconfined compressive strength tests and differentiate between the properties influencing this strength parameter, with specific focus on granitoid rocks. Considering the spatial distribution of granitoid rocks in KwaZulu-Natal, there is limited knowledge concerning the behaviour of this type of material. We investigate the strength properties affecting the UCS, and utilize indirect methods of strength testing to predict the UCS of granitoid rocks in Kwa Zulu-Natal. An evaluation of previously published correlation equations is conducted, followed by simple regression to produce useful and practical equations for estimating the value of UCS from the PLI, SHR, V_p, and σ_t.

2 Literature Review

The PLI has long been regarded as the best intermediary for the UCS (Cargill and Shakoor 1990; Ghosh and Srivastava 1991; Chau and Wong 1996; Tugrul and Zariff 1999). It is relatively easy to conduct and economical, and thus widely applied both in the field and laboratory. Several authors have conducted PLI and UCS tests for various lithologies to determine the most effective conversion factor which converts the PLI to the representative UCS value (Brook 1985; Cargill and Shakoor 1990; Ghosh and Srivastava 1991; Chau and Wong 1996; Tugrul and Zariff 1999; Basu and Aydin 2006) (Table 1). It is evident from literature that the equations published exhibit a wide range, varying from linear to quadratic, and power laws. One of the problems commonly encountered is with the vast range of correlation equations offered in literature, there is often no agreement between authors on a specific conversion factor. Given the great variability of rock properties, even within the same rock type, it is consequently difficult, and often not very meaningful, to cite specific values for specific rocks (Jaeger et al. 2007).

The Schmidt hammer is a handheld device which is commonly used to assess the strength of rocks and concrete (Kahraman 2001). It has also been used as a tool to predict the amount of weathering a rock has been subjected to since the rebound is related to the strength of the rock (Deere and Miller 1964; Yesiloglu-Gultekin et al. 2013; Tandon and Gupta 2013). There is a variety of equations (Table 2) estimating the value of UCS from the measured SHR (Ghose and Chakraborti 1986; Deere and Miller 1966; Beverly et al. 1979; Aydin and Basu 2005; Selçuk and Yabalak 2015).

The P-wave velocity has been successful as a non-destructive test for the prediction of mechanical properties of rocks (Vasconcelos et al. 2007; Tandon and Gupta 2013; Azimian et al. 2013), where the

Table 1 Empirical equations correlating Uniaxial Compressive Strength (UCS) and Point Load Index (PLI)

No.	Author	Lithology	Empirical equation	R^2
1	D'Andrea et al. (1964)	Schistose	UCS = 15.3PLI + 16.3	–
2	Deere and Miller (1966)	Granitic gneiss, slate, limestone, granitoid, taconite, synenite, pegmatite, anorthosite, basalt, serpentinite, rhyolite, dolomite, slate, greenstone, gabbro, quartzite, peridotite, marble schist, chalk	UCS = 20.7(PLI) + 4.299	0.92
3	Broch and Franklin (1972)	Igneous, sedimentary, metamorphic	UCS = 24PLI	–
4	Bieniawski (1975)	Sandstone, quartzite, norite	UCS = 23PLI	–
5	Hassani et al. (1980)	Sedimentary	UCS = 29PLI	–
6	Singh (1981)	Basalt, andesite, granodiorite, granitoid, volcanic bomb, marble, serpentinite, gneiss, schist, migmatite, limestone, dolomitic limestone, sandstone, travertine	UCS = 18.7PLI − 13.2	–
7	Forster (1983)		UCS = 14.5PLI	–
8	Gunsallus and Kulhawy (1984)		UCS = 16.5PLI + 51.0	–
9	ISRM (1985a, b)	Various rock types	UCS = (20–24)PLI	–
10	Norbury (1986)		UCS = 8–54PLI	–
11	Cargill and Shakoor (1990)		UCS = 23PLI + 13	–
12	Ghosh and Srivastava (1991)	Granite	UCS = 16PLI	–
13	Tsidzi (1991)		UCS = (14–82)PLI	–
14	Grasso et al. (1992)		UCS = 9.30PLI + 20.04	–
15	Singh and Singh (1993)		UCS = 23.37PLI	–
16	Ulusay et al. (1994)	Sandstone	UCS = 19PLI + 12.7	–
17			UCS = 15.25(PLI)	–
18	Chau and Wong (1996)		UCS = 12.5PLI	0.73
19	Tugrul and Zariff (1999)	Granite	UCS = $3.86(\text{PLI})^{2+5.65(\text{PLI})}$	–
20	Kahraman (2001)	Basalt, andesite, granodiorite, metagabbro, granitoid, volcanic bomb, marble, quartzite, gneiss schist, migmatite, limestone, serpenite anhydrite, travertine	UCS = 8.41PLI + 9.51	0.85
21	Kahraman 2001	Igneous, sedimentary, metamorphic	UCS = 23.6(PLI) − 2.7	0.85
22	Quane and Russel (2003)	Pyroclastic	UCS = 24.4PLI	–
23	Tsiambaos and Sabatakakis (2004)	Sedimentary rocks	UCS = 23PLI	–
24	Fener et al. (2005)	Igneous, sedimentary, metamorphic	UCS = 9.08(PLI) + 39.2	–
25	Kahraman et al. (2005)	Igneous, sedimentary, metamorphic	UCS = 10.91PLI + 27.41	0.84
26	Kahraman et al. (2006)		UCS = 24.83(PLI) − 39.64 (for rocks with $n < 1$) UCS = 10.22(PL) + 24.31 (for rocks with $n > 1$)	–
27	Kahraman and Gunaydin (2009)	Granitic rocks	UCS = 10.92(PLI) + 24.2	0.56
28	Diamantis et al. (2009)	Igneous and metamorphic	UCS = $17.81(\text{PLI})^{1.06}$	–
29	Basu and Kamran (2010)		UCS = 11.03(PLI) + 37.657	–

Table 1 continued

No.	Author	Lithology	Empirical equation	R^2
30	Karaman and Kesimal (2012)	Igneous, sedimentary, metamorphic	UCS = 20.42PLI − 5.146	–
31	Heidari et al. (2011)	Gypsum	UCS = 5.557(PL) + 23.68	0.92

Table 2 Empirical equations correlating Uniaxial Compressive Strength (UCS) and Schmidt Hammer Rebound (SHR)

No.	References	UCS equation	R^2
1	Deere and Miller (1966)	$UCS = 6.9 \times 10^{(0.16 + 0.0087(R\rho))}$	–
2	Beverly et al. (1979)	$UCS = 12.74e^{0.0185(R\rho)}$	–
3	Singh et al. (1983)	$UCS = 2R$	0.72
4	Haramy and De Marco (1985)	$UCS = 0.994(R) - 0.383$	0.70
5	Tugrul and Zariff (1999)	$UCS = 8.36(R) - 416$	0.87
6	Katz et al. (2000)	$UCS = 2.208e^{0.067(R)}$	0.96
7	Yasar and Erdogan (2004)	$USC = 4 \times 10^{-6}(R)^{4.2917}$	0.89
8	Aydin and Basu (2005)	$UCS = 1.4459e^{0.0706(R)}$	0.92
9	Kilic and Teymen (2008)	$UCS = 0.0137R^{2.2721}$	0.96

R rebound, ρ density

velocity of pulses traveling in the solid material depends not only on mineral composition, pore structure, fluid properties, but also vary with stress and tempareture (Jaeger et al. 2007). The measurement of the velocity of pulses can be used to indicate the elastic strength of the rock specimens (Tandon and Gupta 2015), and thus, the relationship between UCS and V_p has been investigated by a variety of researchers (Kahraman 2001; Yasar and Erdogan 2004a; b; Entwisle et al. 2005; Sharma and Singh 2008; Cobanglu and Çelik 2008; Moradian and Behnia 2009; Khandelwal and Singh 2009; Diamantis et al. 2009; Dehghan et al. 2010; Kurtulus et al. 2011; Khandelwal and Ranjith 2010; Yagiz 2011; Sharma et al. 2011; Khandelwal 2013). Table 3 lists selected publications of equations correlating the UCS to V_p.

The Brazilian tensile strength has been widely used as an indirect test to measure tensile strength (σ_t). It has also been employed to produce estimates of UCS strength as these two parameter are commonly required and determined in most geotechnical projects (Karaman and Kesimal 2012; Farah 2011; Altindag 2012). As σ_t can be easily determined from the Brazilian tensile strength, due to sample preparation requirements being less than UCS testing, it is useful to find strong conversion factors between these two parameters. Furthermore, Farah (2011) indicated that indirect tensile strength may have a better correlation with UCS than PLI, which is also confirmed in the current study. Table 4 shows selected regression equations for estimation of UCS through σ_t measurement.

The correlation of UCS-E (tangent modulus of elasticity) is usually referred to as the modulus ratio (MR) which generally constitutes a common tool for rock material (Deere and Miller 1966) and rock mass (Hoek and Diederichs 2006) classification. Torabi-Kaveh et al. (2014) aimed to predict UCS and E using physical properties of Asmari limestones. They conducted tests on 150 rock samples from two different dam sites. Strong correlations were identified between the UCS and physical properties. However, there were no strong correlations between the predicted E and the measured E. Vasconcelos et al. (2007) evaluated the suitability of the ultrasonic pulse velocity method for describing the mechanical and physical properties of granites, and for the assessment of its weathering state. Vasconcelos et al. (2007) confirmed that ultrasonic pulse velocity can be effectively used as a simple and economical, non-destructive method for a preliminary prediction of mechanical and physical properties. Young's modulus (E) can also be estimated from empirical equations listed in Table 5. Additionally, Bell (1992) outlines a number of equations that relate the Young's modulus, Poisson's ratio and ultrasonic pulse velocity.

Table 3 Empirical equations correlating Uniaxial Compressive Strength (UCS) and P-wave velocity (V_p)

No.	References	UCS equation	R^2
1	Freyburg (1972)	$UCS = 35.0V_p - 31.5$	–
2	Militzer and Stoll (1973)	$UCS = 2.45V_p$	–
3	Golubev and Rabinovich (1976)	$\log UCS = 0.358V_p - 0.283$	–
4	McNally (1987)	$UCS = 1277e^{-117/Vp}$	–
5	Goktan (1988)	$UCS = 36.0V_p - 31.2$	–
6	Tugrul and Zariff (1999)	$UCS = 35.54V_p - 55$	0.80
7	Kahraman (2001)	$UCS = 9.95V_p^{1.21}$	0.83
8	Yasar and Erdogan (2004)	$UCS = 31.5V_p - 63.7$	0.81
10	Sousa et al. (2005)	$UCS = 22.032V_p^{1.247}$	–
11	Sharma and Singh (2008)	$UCS = 0.0642.V_p - 117.99$	0.90
12	Kilic and Teymen (2008)	$UCS = 2.304V_p^{2.4315}$	–
13	Cobanglu and Çelik (2008)	$UCS = 56.71V_p - 192.93$	0.81
14	Yagiz (2009)	$UCS = 0.258V_p^{3.43}$	0.92
15	Diamantis et al. (2009)	$UCS = 110V_p - 515.56$	–
16	Khandelwal and Singh (2009)	$UCS = 133.3V_p - 227.19$	–
17	Sharma and Singh (2010)	$UCS = 36V_p - 45.37$	–
18	Diamantis et al. (2011)	$UCS = 0.14V_p - 899.33$	–
19	Kurtulus et al. (2011)	$UCS = 0.0675V_p - 245.13$	0.92
		$UCS = 0.0188V_p - 71.054$	0.83
20	Yagiz (2011)	$UCS = 49.4V_p - 167$	0.92
21	Sarkar et al. (2012)	$UCS = 0.038V_p - 50$	–
22	Altindag (2012)	$UCS = 0.258V_p^{1.194}$	–
23	Khandelwal (2013)	$UCS = V_p - 34.83$	–

Table 4 Recent correlations between Uniaxial Compressive Strength (UCS) and Brazilian Tensile Strength (σ_t)

No.	References	Equation	R^2	Lithology
1	Altindag (2012)	$UCS = 12.38 \times \sigma_t^{1.02725}$	0.89	Different rock types
2	Farah (2011)	$UCS = 5.11 \times \sigma_t - 133.86$	0.68	Weathered limestone
3	Kahraman (2012)	$UCS = 10.61 \times \sigma_t$	0.50	Different rock types

The reliability of E for estimating the value of UCS has been investigated by several researchers (Bradford et al. 1998; Horsrud 2001; Golubev and Rabinovich 1976; Colwell and Frith 2006), with results indicating that the UCS can be estimated from E. Bradford et al. (1998) and Horsrud compiled test results on the North Sea sandstone and shale respectively. The equations typically take a power form, except for Bradford (1998). Table 6 lists selected empirical equations correlating UCS—E. Equations with no specified author are those which are unpublished.

It has been observed (Maji 2011), that failure modes of a rock under compression will affect the strength of the sample. Thus, as the compressive strength of the rock material increases with an increase in confining pressure, the UCS will provide a minimum strength that the rock can withstand under compression. As a result, the failure modes of the rock under uniaxial compression can provide useful information for safe and economic design of various engineering structures (Basu et al. 2013).

However, failure modes are typically complex and difficult to predict (Basu et al. 2013). At a laboratory scale, mineralogy and geometric arrangement of grains and voids, and fractures/microcracks, typically control the rock mechanical behaviour (Sammis and

Table 5 Empirical equations to estimate the value of Young's Modulus (E)

No.	References	Equation	R^2
1	Vasconcelos et al. (2007)	$E = 19.87V_p - 27{,}813$	0.84
2	Khandelwal and Singh (2009)	$E = 4.9718V_p - 7151$	0.97
3	Diamantis et al. (2011)	$E = 0.041V_p - 264.15$	0.81
4	Kurtulus et al. (2011)	$E = 0.0015V_p - 2.516$	0.74
5	Yagiz (2011)	$E = 20.1V_p - 53$	0.95
6	Altindag (2012)	$E = 0.919V_p^{1.9122}$	0.79

Table 6 Empirical equations correlating Uniaxial Compressive Strength (UCS) and Young's Modulus (E)

No.	Equation	References	lithology
1	$UCS = 46.2\exp(0.027E)$	–	–
2	$UCS = 2.28 + 4.1089E$	Bradford et al. (1998)	All rock types
3	$UCS = 25.1E^{0.34}$	–	Dolomite with 60–100 UCS (MPa)
4	$UCS = 13.8E^{0.51}$	–	Limestone with 10–300 UCS (MPa)
5	$UCS = 4.1141E^{0.9176}$	Colwell and Frith (2006)	–
6	$UCS = 7.97E^{0.91}$	Horsrud (2001)	Shales
7	$UCS = 7.22E^{0.712}$	–	Shales

Ashby 1986; Akesson et al. 2004; Basu and Aydin 2006; Szwedzicki 2007; Basu et al. 2009, 2013). Quantification or prediction of failure modes is therefore a complex and difficult task (Santarelli and Brown 1989; Basu et al. 2013).

3 Methodology

As per the widely recognized high strength of granitoid rocks, sampling proved rather difficult, where serious complications about extracting suitable samples were encountered. Even were weathering had advanced, a limited number of samples were extracted due to the hard rigid structure of granitoid rocks. As such, the limited number of rock samples tested for UCS and of which are used to define the relation among properties is employed as an indicator to estimate the general correlation trends of the granitoid rocks. The sample locations are within KwaZulu-Natal, South Africa viz., Scottburgh, Botha's Hill, Jolivet, and White Mfolozi (Fig. 1).

The Scottsburgh granitoids are restricted to the coastline, which lies within the Granitic Zone of the eastern sector of the Natal-Namaqua Mobile belt (Matthews 1985). These samples are weathered, with the rock mass having an overall blocky structure (Fig. 2a). The White Mfolozi River has incised a large valley into the pre-Karoo rocks, exposing the Pongola Supergroup and basement granitoids and gneisses. (Matthews 1972), allowing the sampling of fresh granitoid samples (Fig. 2b). The granitoids in this area are intrusive igneous rocks and form part of the Natal Metamorphic Province Granitoids, and part of the Kaapvaal Craton Basement Granitoids. The rocks of the Fafa pluton are restricted to the southern most part of the Mzumbe terrane. They extend north and south inland from the village of Jolivet, to west of Mtwalume village. Two sample localities (F1 and F2) were selected to provide a good representation of this type of rock. The granitoids from these localities typically form the basement granitoids. Within these outcrops there is the constant presence of cracks, with smaller fractures radiating from the crack (Fig. 2c). There is a shear zone which is represented in Fig. 2d. The foliation can be defined by the direction of the mafic minerals. The granitoids at this second locality are typically megacrystic.

Eleven large blocks (Fig. 3) were collected from the four localities. This allowed for reasonable spatial distribution as to provide representative samples. The granitoid rocks were cored using a 54.7 mm diameter

Fig. 1 Sampling locations in the study area

Fig. 2 **a** Scottsburgh outcrop with block structure, **b** White Mfolozi granitoid outcrop forming part of the basement rock, **c** Fafa granitoid exhibiting tension crack, **d** Fafa granitoid exhibiting a shear zone

diamond coring bit. Samples were cut to the appropriate size for each test according to the ISRM (2007) suggested methods. The core samples were ground and lapped parallel to achieve an accuracy of ±0.2 mm. Each core sample prepared was carefully investigated for macroscopic defects so that testing

Fig. 3 Field samples collected for index testing

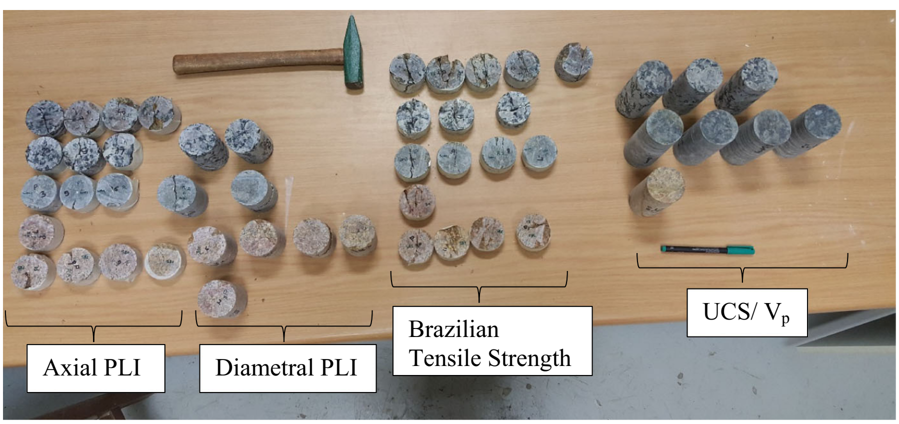


Fig. 4 Core test specimens used in the study

would be free from fractures, cracks and fissures, which may have occurred due to the coring and/or cutting process. A total of 49 cores and 22 blocks (Fig. 4) were prepared for index testing purposes. The rocks employed in the current study are classified within the granite group according to the Streckeisen classification (1991) (Fig. 5).

The petrographic examination of the granitoid rocks under investigation was conducted using an optical Leica Olympus BX41 microscope. Twelve thin

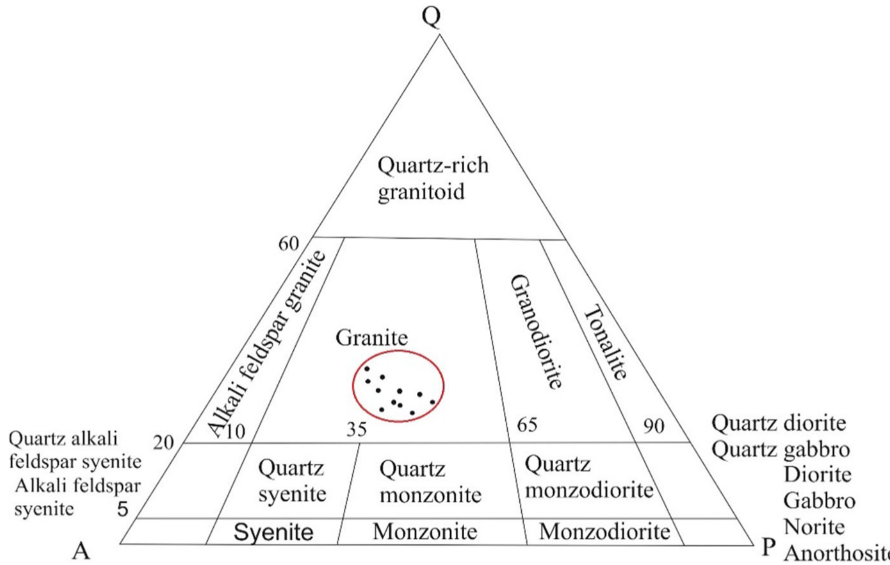


Fig. 5 Classification of rocks according to IUGS Le Bas and Streckeisen (1991)

sections for the granitoid rocks were prepared and examined for the study. The volumetric percentages of minerals present in the samples were determined by X-ray diffraction (XRD). A detailed petrographic description of the examined granitoid samples is discussed in the impending section.

The physical properties of the granitoid rocks such as porosity, density and water absorption were determined in accordance to the ISRM (2007) suggested methods. The UCS of the granitoid rocks was determined using a servo-controlled compression testing machine, which has a load capacity of 2000 kN. Each sample was prepared with a length of ±110 mm and diameter of 54 mm. The UCS machine applied a load at a rate of 0.5–1.0 MPa/s to a core sample (Brown and Hoek 1980).

Young's modulus was estimated with empirical equations developed by Vasconcelos et al. (2007) and Torabi-Kaveh et al. (2014). The modulus ratio (MR) is calculated as the Young's modulus (E) divided by the UCS (Deere and Miller 1966). The range of MR values represent the boundary and expresses the ratio of E and UCS of the intact rock. Poisson's ratio was calculated from the frequency of P-waves according to Bell (1992).

The PLI was conducted on NX-size cores as well as block/irregular lumps of the rock samples using a point load testing machine in accordance to the ISRM (2007) standard. Three different tests were conducted to determine the PLI: axial, diametral and block/irregular lump. The corrected index, $Is_{(50)}$, is applied to obtain the unique Point Load Strength Index (PLI).

The P-wave velocity (V_p) test was conducted on 8 core samples of NX size and in accordance to the ISRM (2007) recommendations. The core ends were polished and lubricated to create good coupling. The PUNDIT Pulse Generator Unit with two transducers (diameter of 50 mm and frequency of 0.5 MHz) was utilized. The pulse transmission technique (ISRM 2007), where the transmitter is placed opposite to the plane on which the receiver is placed, was employed. To attain accurate results, the PUNDIT unit was reset and calibrated with metal cores before each consecutive test. The average V_p was determined for each sample and used for analysis.

The Schmidt hammer rebound number (SHR), ranges from 0 to 100. The N-type Schmidt hammer has an impact energy of 2.207 Nm (Kahraman 2001) and was used in the current study. Each test was conducted in accordance to the ISRM (2007) suggested methods. The rebound height is recorded on a linear scale which provides an indication of the strength of the material. In order to obtain reliable results, the hammer is placed perpendicular to the surface, and was conducted by a single individual to allow a consistent amount of force to be applied.

Tensile strength (σ_t) was measured indirectly by means of the Brazilian tensile strength. Each sample was wrapped around its periphery with one layer of masking tape and mounted in the apparatus in such a way that the curved platens loaded the sample diametrally. This allows analysis of the orientation in which failure occurs.

The weathering classification of the studied granitoid rocks is based on the ISRM (Brown 1981) weathering grade classification. The granitoid rocks are classified as "moderately weathered" to "fresh" rocks. The samples indicate less than half of the rock material disintegrates, whereas in some cases slight discoloration indicates weathering of the rock material and discontinuity surfaces, with the majority of the rock maintaining its original structure and being intact.

4 Results

4.1 Petrographic Analysis

The granitoid samples employed are light coloured, medium to coarse grained, and hypediomorphic to allotriomorphic in nature (Fig. 6a). The petrographic analysis revealed that in cases, the imprints of brittle deformation are indicated by the undulating extinction in quartz grains, with a moderately well-developed foliation present. The major constituent minerals are quartz, plagioclase, microcline, with minor proportions of biotite in interstitial spaces of the major constituents. The minerals are typically fractured and

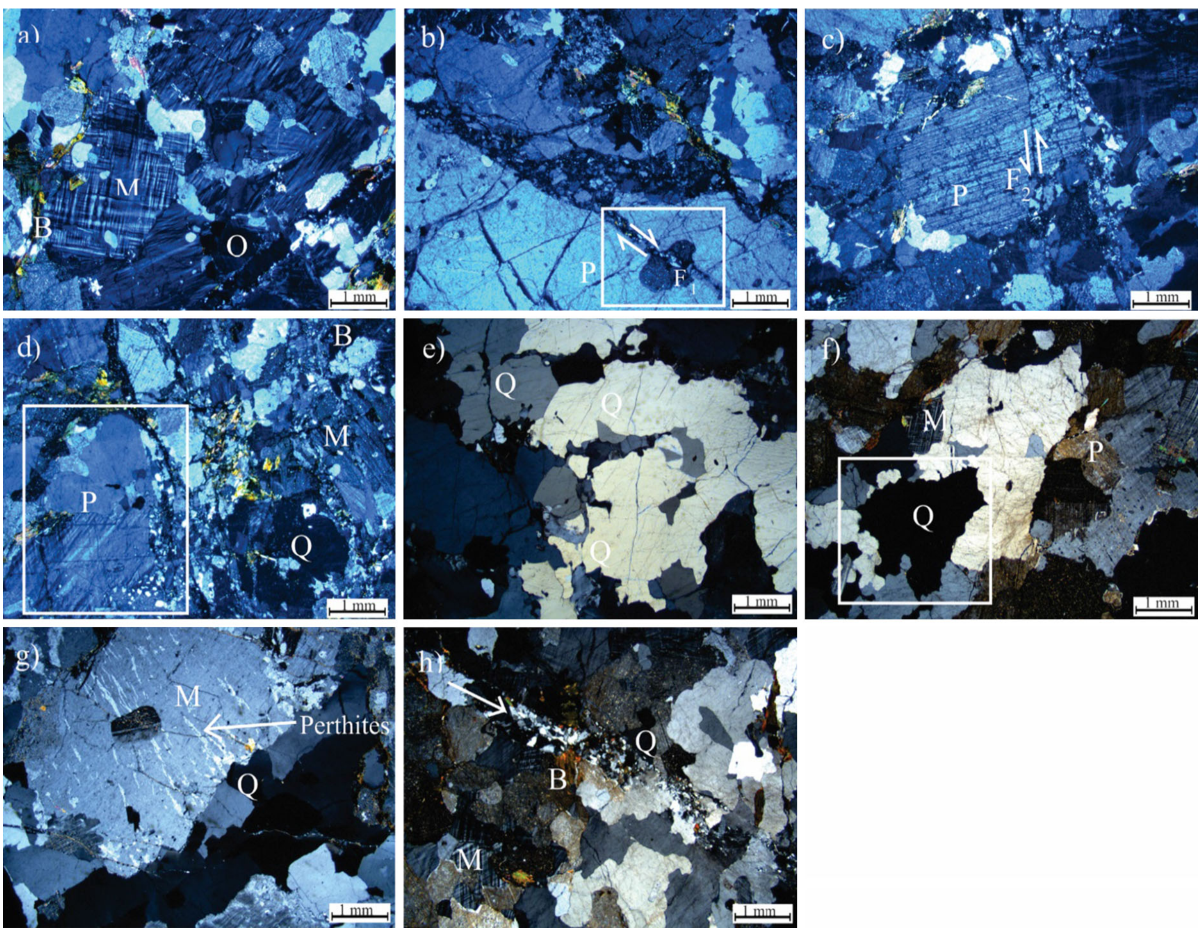


Fig. 6 **a** Medium to coarse grained, hypediomorphic to allotriomorphic texture of granitoid, **b** fracturing of granitoid (see F_1 in figure) with granulations along the fracture plane, **c** twin lamellae in plagioclase showing displacement along the fracture (F_2); and **d** prismatic plagioclase grains partially altered to sericite, **e** strained quartz exhibiting polygonal structure, **f** polygonal quartz showing dendritic sutured contact with adjacent grains, **g** sting perthites within microcline, **h** injection of apilitic veins within coarse grained granites. *Q* quartz, *P* plagioclase, *M* microcline, *B* biotite

granulated (Fig. 6b). The plagioclase occurs as subhedral laths with well-developed albite twins, where in some cases, the twin lamellae exhibits displacement due to fracturing (Fig. 6c). In cases, the granitoid rocks contain megacrysts of K-feldspar, where these prismatic plagioclase grains are up to 7 mm in length, and partially replace by sericite at the margins (Fig. 6d). However, the prismatic, tabular shape of the plagioclase is still present. The quartz grains are anhedral in shape, and are either shown as strained quartz with polygonal shapes (Fig. 6e), or anhedral grains with dendritic sutured contacts with adjacent quartz grains (Fig. 6f). However, majority of the quartz grains exhibit undulous extinctions. There are large grains of potash feldspar set within the granular matrix, with the smaller, more rounded grains surrounding the larger ones, indicative of the brittle behaviour of the granitoids under study. The microcline grains are anhedral (size 0.5–3 mm), and show perthitic structure where the perthitic intergrowths are sting shaped (Fig. 6 g). The microcline also displays the signature of alteration. The flaky biotite is mostly unaltered and occur in interstitial spaces between quartz, plagioclase and microcline, where in cases, bleached interstitial biotite is present. The hornblende is the mafic mineral present in the rock and is typically altered to biotite. The studies rocks have also been subjected to aplitic vein injection (Fig. 6h). The volumetric percentage of minerals present in selected samples is shown in Table 7.

4.2 Statistical Analysis

The basic descriptive statistical variables from the laboratory tests are shown in Table 8. According to the histograms, the mean PLI is 4.37 MPa (Fig. 7a), σ_t is 9.73 MPa (Fig. 7b), SHR is 44.45 (Fig. 7c) V_p 7049.02 m/s (Fig. 7d), and UCS 113.23 MPa (Fig. 7e). Young's Modulus was estimated to be in the range of 69–79 GPa. MR values range between 56.38 and 117.03, with a standard deviation of 23.46. Poisson's Ratio was calculated to have a mean of 0.22. The standard deviation values are relatively high, except for V_p. The low value of standard deviation of V_p indicate the dependant and independent variables employed in the present study are controlled by the difference in mineralogical content. Therefore, V_p is affected much less when compared to the other variables.

4.3 Regression Analysis and Prediction Performance Assessment

The raw data (Table 9) obtained from laboratory testing was subjected to curve fitting analysis, whereby linear ($y = ax + b$), logarithmic ($y = a + lnx$), exponential ($y = ae^x$), and power approximations ($y = ax^b$) were used to produce the best correlation. Linear equations were produced for all correlations in the current study (Table 10). A comparative assessment of previous empirical equations was conducted to verify the acceptability with regards to the current study granitoid rocks. Furthermore, the regression coefficient value between the measured and predicted values are calculated, as it is a good indicator of the performance of the proposed relationship. The relationship between PLI and UCS is depicted in Fig. (8a). The regression coefficient for the point load test is $R^2 = 0.82$, given a linear form:

$$UCS = 15.939\left(Is_{(50)}\right) + 37.235;\ R^2 = 0.82 \qquad (1)$$

From the 35 empirical equations used to estimate the value of UCS from the PLI, only seven such equations produced values close to that measured in the lab. The relationship between the UCS and PLI is compared well with other studies, and the results of this relationships were close to the results obtained by Deere and Miller (1966), ISRM (1985a, b), and D'Andrea et al. (1964) (Fig. 8b).

Table 7 Volumetric percentage of minerals in selected samples

Sample	Quartz (%)	Albite (%)	Microcline (%)	Biotite (%)
SB	22	30	34	4
BH	30	25	41	4
WM	34	24	30	2
F1	30	38	26	2
F2	26	36	24	4

Table 8 Statistic parameters

	Density (g/cm^3)	n%	UCS (MPa)	PLI (MPa)	V_p (m/s)	SHR (R)	σ_t (MPa)	MR (GPa)
N	29	18	8	70	29	58	22	8
SD	0.25	0.75	40.48	2.12	2057.44	5.91	3.48	23.46
Mean	2.65	1.47	113.23	4.23	6155.47	43.08	9.87	77.42
Min	2.23	0.57	58.41	1.06	4862.39	32.00	5.06	56.38
Max	3.48	2.91	167.67	8.55	9814.81	54.00	16.63	117.03

The regression coefficient for the UCS versus V_p is $R^2 = 0.82$ (Fig. 9). The correlation equation produced is given a linear form:

$$UCS = 0.0673\left(V_p\right) - 257.39;\ R^2 = 0.82 \quad (2)$$

None of the empirical equations outlined in Table 3 accurately estimate the UCS value tested in the lab. The closest values to that tested is produced by Kurtulus et al. (2011). Both equations are only applicable to rock types with a $V_p > 3700$ m/s. However, Kurtulus et al. (2011) overestimates the moderately weathered granitoid samples UCS by ±40 MPa, but estimates the fresh granitoid samples within ±5–10 MPa. Therefore, these equations should only be used where fresh samples are available.

The regression coefficient for UCS versus σ_t is $R^2 = 0.92$, and takes a linear form (Fig. 10a). The regression equation of the current study is within bounds of previous empirical equations, with the estimated values from Kahraman (2012) being the closest to that tested in the lab (Fig. 10b). The correlation equation produced is given by:

$$UCS = 11.564\sigma_t - 13.1; R^2 = 0.92 \quad (3)$$

The regression equation for UCS versus SHR is given by power law equation with a regression coefficient of $R^2 = 0.86$ (Fig. 11a).

$$UCS = 0.0142(SHR)^{2.3559};\ R^2 = 0.86 \quad (4)$$

A total of seven equations correlating the SHR to the UCS was tested in the current study (Fig. 11b). The Deere and Miller (1966) equation produced the most reliable estimation for the value of UCS with a variation between 1 and 5 MPa.

Since the Young's modulus values are not obtained through direct measurements, but obtained by empirical equations, direct correlation with UCS is not suggested. Therefore a range of MR values are provided for the granitoid samples. MR values range from 58.19 to 117.0 GPa, which is consistent with those reported in literature (Hoek and Diederichs 2006).

In the current study, the failure modes are adopted after Basu et al. (2013) (Fig. 13). The dominant failure mode for UCS testing is shown in Fig. 12. For the granitoids of the current study, failure modes up to a UCS of 60 MPa corresponds to axial splitting (single extensional plane or multiple plane). Shearing and axial splitting occurred at UCS range of 65–100 MPa. Shearing along a single plane manifested at higher UCS values, typically between 135 and 150 MPa. Therefore, as the UCS increases, the failure mode changes from axial splitting to shearing along a single plane.

5 Discussion

Granitoids are intrusive igneous rocks which are commonly felsic and are subdivided on the basis of relative proportion of quartz, alkali feldspar and plagioclase feldspar (Nesse 2009). In order for a rock to be classified as a granitoid, it must contain 20–60% quartz and 5–65% feldspar. As such, the strength of the granitoid rocks of the current study is highly dependent on mineralogy of the rock.

The essential minerals found in the granitoids of the current study are quartz, feldspar, biotite, microcline and hornblende. The strength of the rock is influenced by the grain size and modal mineralogy, in particular, the size of phenocryst present in the granitoid rocks. The UCS values of the investigated rocks depend more on grain size, rather than modal mineralogy. This is exhibited by the samples with similar mineralogical composition but different phenocryst size having different values of UCS. The granitoid with medium to coarse grained phenocrysts is stronger than the granitoid with very coarse grained phenocrysts. Thus,

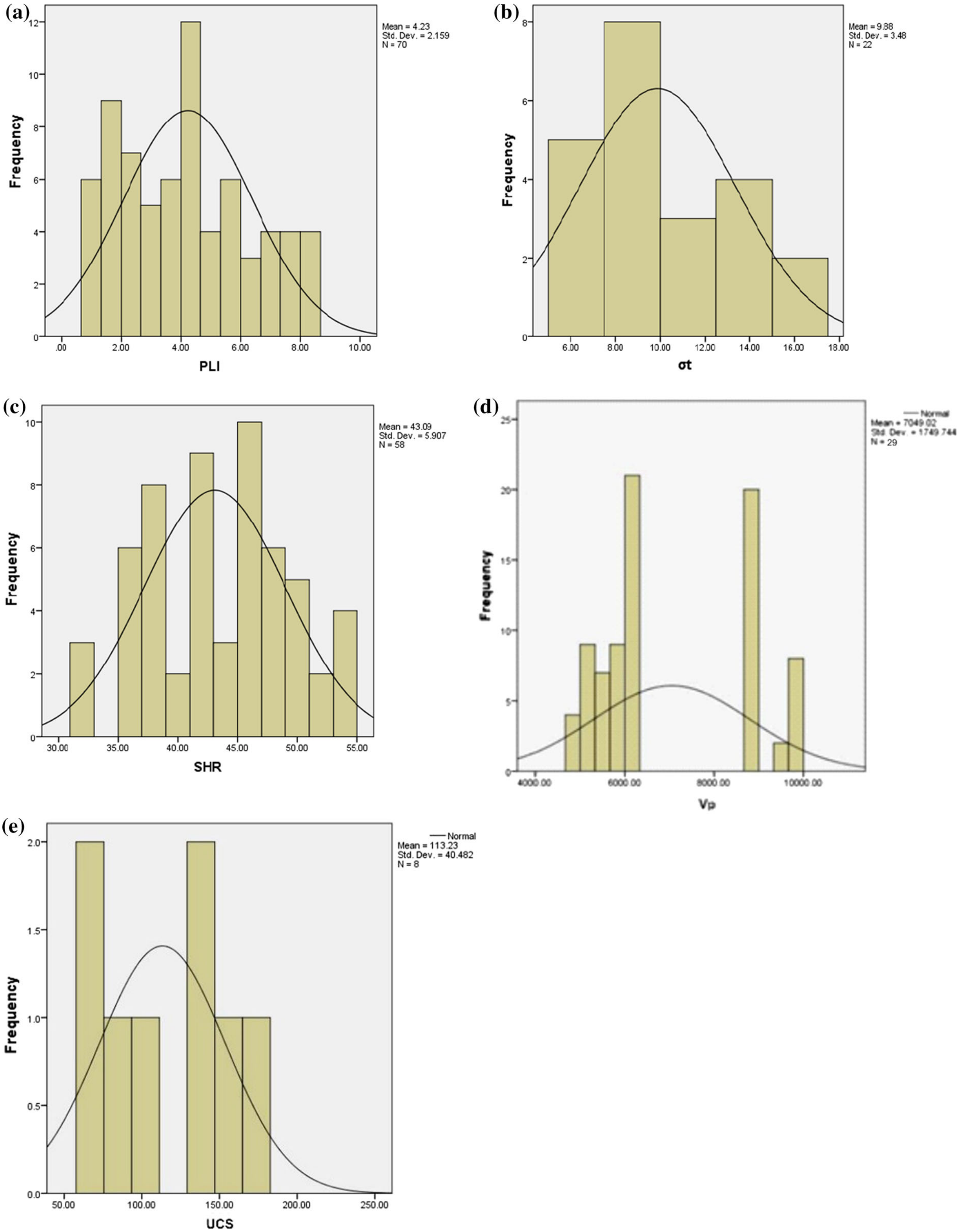


Fig. 7 Histograms of **a** Point Load Index, **b** Tensile Strength (σ_t), **c** Schmidt Hammer Rebound (SHR), **d** P-wave velocity (V_p), **e** Uniaxial Compressive Strength (UCS)

Table 9 Experimental data base

No.	Sample	UCS (MPa)	DiPLI (MPa)	AxPLI (Mpa)	Blck/irrg PLI (MPa)	σ_t (MPa)	Di SHR (MPa)	Ax SHR (MPa)	V_p (m/s)	n%	p (g/cm^3)	MR (GPa)
1	SB1a	58.41	1.88	3.97	1.37	8.22	41	36	5071.77	2.5	2.48	117.03
2	F1a	64.39	1.91	4.22	1.32	10.8	35	35	5023.7	1.49	2.60	110.35
3	F1b	91.85	1.06	4.09	3.27	8.83	39	37	4976.53	1.47	2.61	76.12
4	F1c	99.71	2.61	4.16	1.74	5.31	38	32	5047.62	1.46	2.70	73.65
5	F1d	134.67	1.21	4.34	3.68	5.06	42	38	5023.7	0.61	2.77	56.38
6	WM1a	139.4	7.79	8.29	5.53	16.63	46	43	5000	0.6	2.80	64.76
7	WM1b	149.74	8.55	5.65	2.66	12.9	49	46	4953.27	0.59	2.80	62.90
8	WM1c	167.67	6.23	4.64	3.16	13.81	48	45	4862.39	0.57	2.93	58.19
9	SB2a		1.88	3.97	1.37	8.22	32	38	5071.77	2.18	2.68	23.46
10	SB2a		1.91	4.22	1.32	10.8	36	41	5023.7	2.91	2.52	
11	SB2b		1.06	4.09	3.27	8.83	38	41	4976.53	2.1	2.23	
12	SB3a		2.61	4.16	1.74	5.31	45	42	5047.62	2.62	2.30	
13	BH		1.21	4.34	3.68	5.06	46	48	5023.7	1.46	2.55	
14	F1d		6.23	5.11	5.53	8.11	48	49	5023.7	1.63	3.00	
15	F1e		5.85	4.3	2.66	7.02	50	53	4976.53		2.74	
16	F1f			3.71	3.16		51	54	5047.62		2.92	
17	F2a			7.12	2.12	11.4	35	35	5023.7	1.00	2.88	
18	F2b			6.67	6.26	9.69	39	37	9814.81	1.20	3.48	
19	F2c			7.29	5.33	9.79	38	32	9724.77	1.14	2.62	
20	F2d			7.68	1.57	8.2	42	38	9636.36	1.08	2.83	
21	WM2a		7.79	8.29	2.05	16.63	46	43	9814.81		2.75	
22	WM2b		8.55	5.65	5.11	12.9	49	46	9724.77		2.93	
23	WM3			4.64	2.45	13.81	48	45	9814.81		2.61	
24	WM4			4.95	7.24		41	48	9636.36		2.51	
25	SB4a				3.24		53	50	5071.81		2.49	
26	SB4a				4.37		54	51	5071.81		2.30	
27	SB5a				7.53		42	46	5023.7		2.49	
28	SB5b				3.72		44	42	4953.27		2.45	
29	SB5c				5.86		48	45	5047.62		2.44	

N number of samples, *SD* standard deviation, *n%* porosity, *PLI* point load index, V_p P-wave velocity, *SHR* Schmidt hammer rebound, σ_t Brazilian disk, *MR* modulus ratio

the fresh granitoid samples show the highest strength, in terms of petrography, mainly because:

- It contains roughly more quartz and less mica minerals;
- Has a low fracture intensity;
- The grain size of the groundmass is in contrast to the grain size of that of the minerals, especially the phenocrysts present;
- The shape of the minerals, specifically the phenocrysts, are highly irregular

There is a clear correlation between weathering and density, weathering and SHR, and weathering and V_p. The values obtained from laboratory tests indicate a decrease in SHR and V_p with an increase in weathering. The granitoids with a lower degree of weathering have high V_p values which is consistent with the values obtained in previous studies (Tandon and Gupta 2015) on granitic rocks that are not weathered.

Density is one of the most fundamental properties of a rock and is influenced by mineral composition and the amount of void spaces (Bell 1987). The density of

Table 10 Proposed simple regression equations for granitoid rocks

No.	Correlation	Equation	R^2	Comment
1	SHR-UCS	$UCS = 0.0142(SHR)^{2.3559}$	0.86	SHR > 20
2	PLI-UCS	$UCS = 15.939(Is_{(50)}) + 37.235$	0.82	
3	σ_t-UCS	$UCS = 11.564\sigma_t - 13.1$	0.92	
4	V_p-UCS	$UCS = 0.0673(V_p) - 257.39$	0.82	$V_p > 3700$ m/s

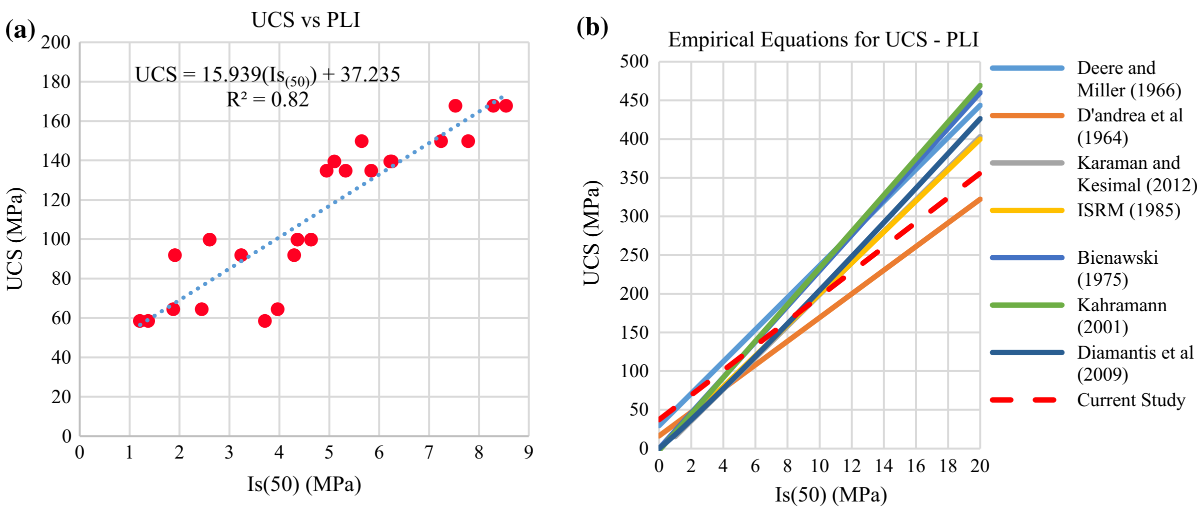


Fig. 8 **a** Uniaxial Compressive Strength (UCS) versus Point Load Index (PLI), **b** Comparison between empirical equations and derived equations for Uniaxial Compressive Strength (UCS) versus Point Load Index (PLI)

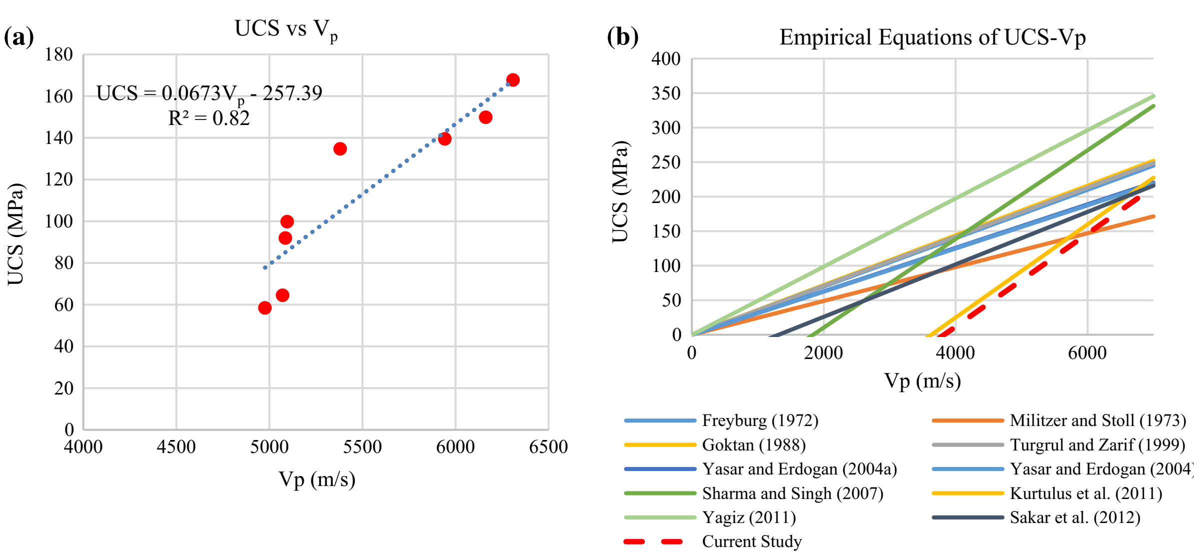


Fig. 9 **a** Uniaxial compression stress (UCS) versus P-wave velocity (V_p), **b** Comparison between empirical equations and derived equation for UCS versus V_p

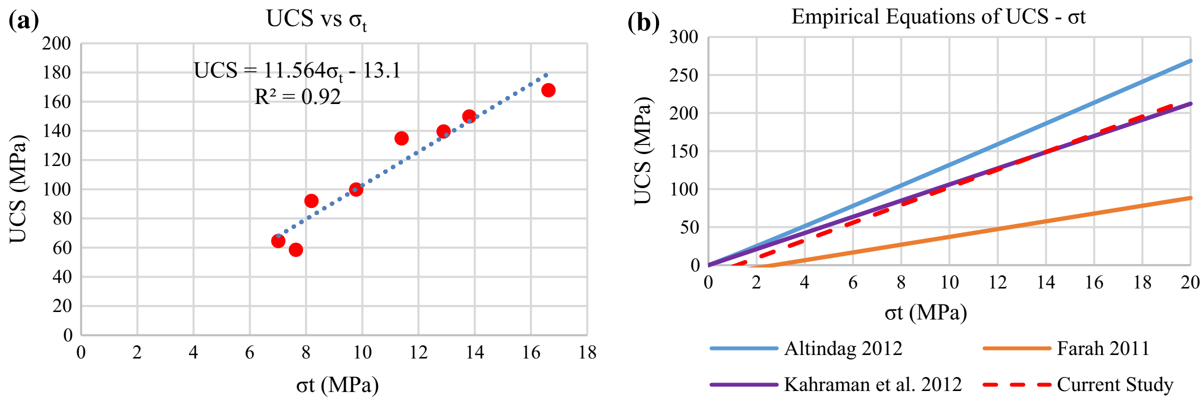


Fig. 10 **a** UCS versus σ_t, **b** Comparison between empirical and derived equation for UCS versus σ_t

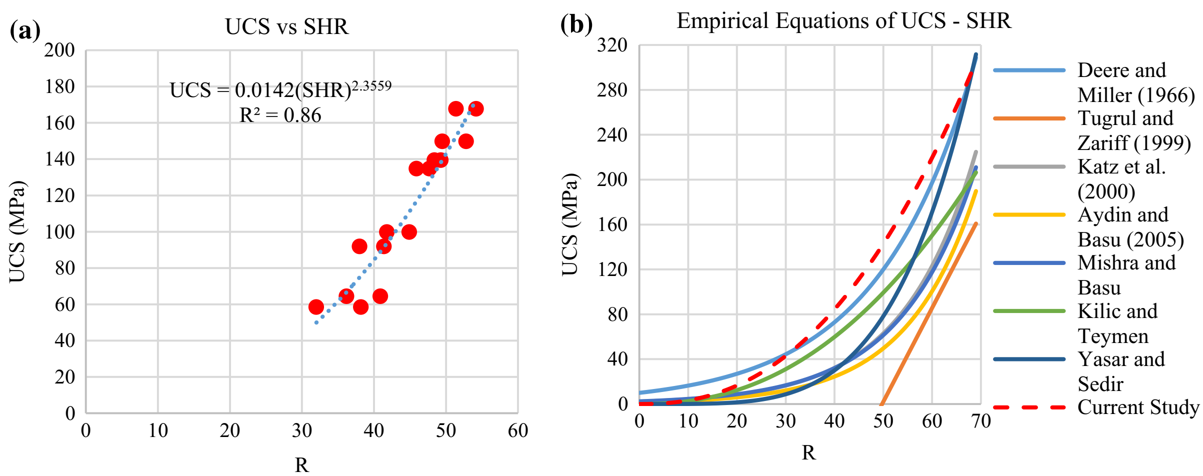
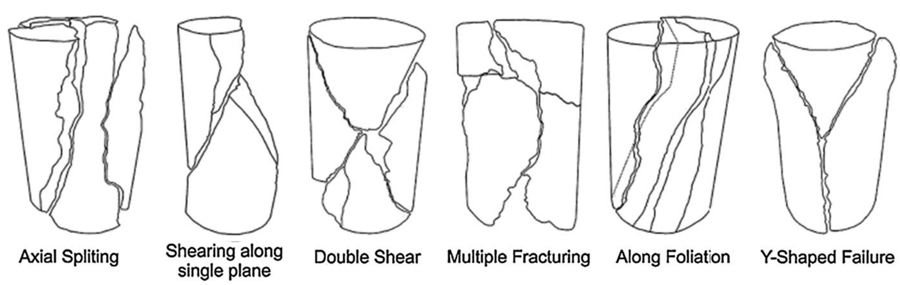


Fig. 11 **a** UCS versus SHR, **b** Comparison between empirical and derived equation for UCS versus SHR

Fig. 12 Schematic representation of modes of failure in UCS test (After Basu et al. 2013)



a rock allows insight into the UCS. However, the study shows that even though the granitoids of the current study have similar values of density, the density alone cannot be a reliable index for estimation of the UCS. This can be attributed to the mineralogical composition not changing significantly (Sousa 2014). Only when the weathering has advanced does it lead to a significant reduction in the bulk density.

An additional factor influencing the strength of these granitoids is the variation in crack intensity across different rock samples, which may affect the UCS, PLI, V_p and SHR values (Tandon and Gupta

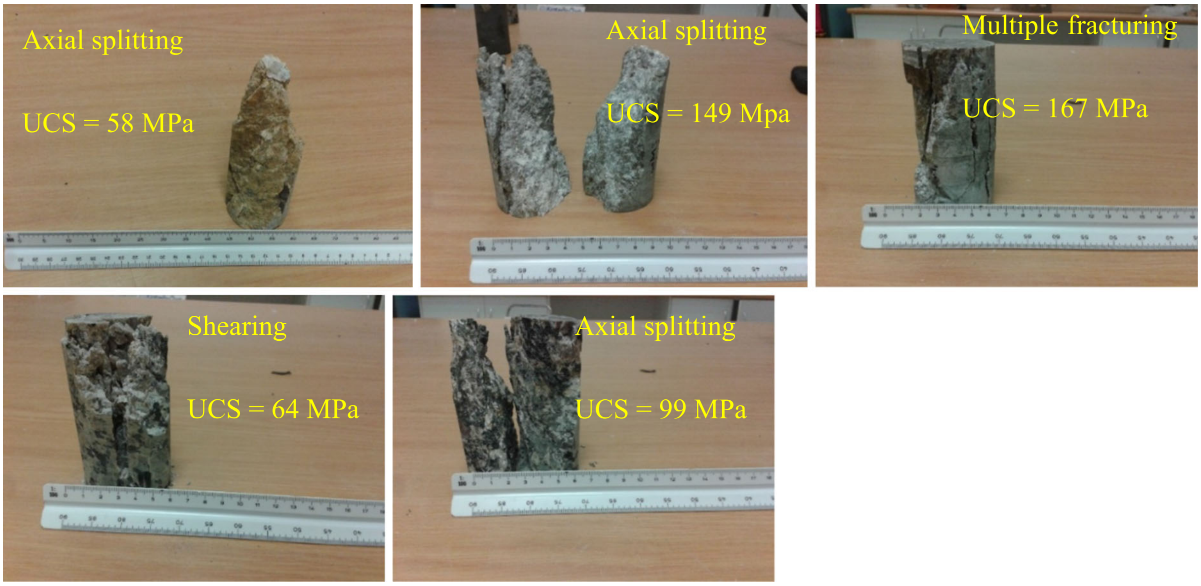


Fig. 13 Modes of failure under UCS test

2015). It may be possible that the amount and the intensity of the preferred alignment of mica minerals mainly control the UCS, PLI, V_p and SHR values, which is examined by the alignment of minerals in relation to fractures that lead to failure of the rock specimen.

Three types of point load tests were conducted and plotted against the corresponding UCS values. Broch and Franklin (1972) proposed that for axial testing, specimen length and diameter both influence the results, where there is a "shape" effect in addition to the "size" effect experienced in the diametral tests. For the diametral test, the failure load is independent of the length of the core, provided that the length of the sample is sufficiently large. The strength index is therefore not influenced by irregular geometry of the end faces (Broch and Franklin 1972). The PLI produced a regression coefficient of 0.82, indicating the index tests to be a reliable tool for the estimation of UCS, where care is taken when conducting the specific tests.

The SHR is frequently used, because it is a fast and reliable method for obtaining values of strength since the rebound is related to other rock properties (Tugrul and Zariff 1999). There is a slight tendency for the SHR value and UCS to change simultaneously, as has been observed by previous researchers (Yilmaz and Sendir 2002; Yasar and Erdogan 2004). However, many factors could influence the values of SHR. These include the orientation of the hammer, or the surface upon which the testing was conducted. Thus, the Schmidt hammer may not always be a reliable tool for the estimation of the UCS, if care is not taken when conducting the test.

A strong regression coefficient for the UCS versus V_p was produced in the current study. However, propagation of V_p is a complex process which depends on various factors which include, the amount of minerals present, mineral shape, mineral size, orientation, fluids present, cracks, porosity, pore shape and size (Tandon and Gupta 2015). Tandon and Gupta (2013) reported that there are one or two main factors that control the velocity, and these will depend on the rock type.

Tensile strength exhibits a strong regression coefficient with UCS for the granitoid rocks of this study. These two parameters are commonly required for geotechnical projects and as such, it is a good idea to find strong conversion factors for these two parameters, to allow the prediction of UCS from the indirect tensile tests. Comparatively, UCS versus σ_t produced the highest regression coefficient. As such, estimation of the UCS from the indirect tensile strength test provides a better proxy than the PLI with regards to the granitoid rocks of the current study.

Regression analysis exhibits strong correlation coefficients, with all index tests producing R^2 values greater than 80%. The results of the study clearly indicate that regression analysis can be successfully employed as a predictive tool for the estimation of UCS. The PLI has long been regarded as the best proxy for the estimation of UCS, however, the highest correlation is produced by UCS versus σ_t, which is concurrent with the findings of Farah (2011). Furthermore, critical information about the rock of study can be obtained by conducting V_p test, allowing a better understanding of the structure and behaviour of the rock. As such, where critical information is required, estimation of the UCS should not be relied on a single index tests, but rather, several index tests should be conducted to provide a better understanding of the behaviour of the rock, and as such the UCS. The equations produced in the current study can therefore be used to predict the value of UCS for granitoid rocks of KwaZulu-Natal.

Although there are numerous empirical equations that have been proposed in previous studies which have strong correlations, from the 65 equations used to estimate the value of UCS, only 11 were able to estimate UCS values that were close to that tested in the lab. The reasons for this are that these equations were developed in terms of the conditions of the specific study and specific rock type. This indicates that empirical equations should be used to allow estimates of the UCS at the preliminary stages of a project to allow estimates of the requirements for the project. Thereafter the appropriate detailed testing should be conducted.

6 Conclusion

There are many factors that influence the strength of a rock. Subjecting it to the influence of a single property or parameter may result in erroneous values, especially when reliable representative results are required. The UCS can be sufficiently estimated with the aid of simple index tests. However, the subject of estimation is dependent on the in situ conditions and the rock type, with various rock types producing a range of UCS value. Thus, the geological origin and type of rock (mineralogical composition) influences the strength and should be taken into consideration when estimating the strength of granitoid rocks, especially with regards to the relationship between UCS and V_p. Furthermore, the study shows that the shape of samples and direction of testing will affect calculated estimates. Therefore, each test should be adopted with care and an understanding of the potential accuracy risks associated with each index test.

None of petrographic characteristics of the rock individually control the strength of the granitoid rocks. Each sample exhibited similar mineralogical compositions, but differed in mineralogical volumetric percentage, grain size and texture, in some cases on a microscopic scale. Therefore, it is a combination of factors which appear to collectively contribute to determine the rock strength.

Although the rocks have different volumetric percentages of minerals, and thus may be subdivided into different forms of granitoid rocks based on various classification schemes, the UCS values fall within the range of those that are characterized as "high strength" rocks when classified according to the ISRM (2007) UCS strength classification. The charts and equations produced in the study follow the trends of published literature. It therefore provides additional validation curves for the adopted testing methods and adds to the existing correlations in literature.

It is suggested that the equations derived from this study can be used during the preliminary stage of design where detailed data is not easily accessible. The proposed equation could serve as an indicator to estimate the general correlation trend of UCS. Yet, the results of the current investigation give further insight into the controlling factors of the strength of the granitoid rocks, where the strength of a rock is a multidimensional parameter.

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