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RESEARCH ARTICLE

Rock Mechanics

Quantifying the relationship between uniaxial compressive strength and slake durability index in gneiss rocks: an experimental approach

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Abstract: This study investigated the relationship between Uniaxial Compressive Strength (UCS) and slake durability index (SDI) in gneiss rocks collected from two aggregate quarry sites. The analysis revealed varying correlations between these two parameters depending on the grouping and categorisation of the data. Initially, a moderate correlation was observed between experimental and estimated UCS values when considering all the data together. However, further examination of the data by dividing it into two categories based on UCS values greater than or equal to 40 MPa and less than 40 MPa yielded insightful results. Within these divided categories, a robust correlation was found between experimental and estimated UCS values for cycles two and four of SDI. Moreover, this study reveals that fresh rock samples from the quarry locations maintained a durability of over 98% through four cycles of the slake durability test. Nonetheless, these same samples exhibited decreased strength, which can be attributed to their mineral composition and internal structural arrangements of the rock samples tested. Therefore, this study incorporated complementary testing methods such as Ultrasonic Pulse Wave Velocity (UPV) and Scanning Electron Microscope/Energy Dispersive X-ray Spectroscopy (SEM/EDX). These tests served as valuable tools for validating the results and enhancing the understanding of micro-scale changes within the gneiss rock samples. The comparison of test values and the exploration of underlying factors confirmed the reliability and usefulness of UPV and SEM/EDX as supporting tools for this study. The study also recommended that the developed equations can be useful for engineers and researchers in estimating rock strength quickly and inexpensively by replacing the laborious tasks involved in traditional laboratory testing.

Keywords: Correlation, EDX, gneiss rock, SEM, slake durability index, UCS.

INTRODUCTION

Engineering practices related to rocks involve studying their properties and behaviour to use them effectively in construction projects. Two critical tasks in this field are the characterisation of the strength of rocks and their appropriate application for various construction activities. The strength of rocks plays a crucial role in the stability and performance of structures built with them, both in the short and long term (Frenelus *et al*., 2021). Short-term stability refers to the ability of a structure to withstand the loads and stresses it is subjected to during construction, while long-term stability refers to its ability to maintain its integrity and performance over time (Frenelus *et al*., 2021). The uniaxial compressive strength (UCS) test is a commonly used method to determine the strength of rocks. This test involves applying a compressive force to a cylindrical rock sample until it fails. The maximum force the rock can withstand before it fails is its uniaxial compressive strength (Arman, 2021). The UCS test is used because it provides a relatively simple and standardised way to measure rock strength, which is important for designing structures that can withstand the expected loads and stresses. The strength of rocks also affects their behaviour under different loading conditions, such

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as tension, bending, or shear. Therefore, understanding the UCS value of rocks helps select the appropriate type of rock for a specific construction project and design structures that can withstand the expected loads and stresses.

The uniaxial compressive strength (UCS) test is a reasonably straightforward but costly and time-consuming method of assessing rock strength. The test involves preparing cylindrical rock samples of a specific size and shape, which must be carefully cut and prepared to ensure their accuracy and consistency (Kahraman *et al*., 2017). To obtain a typical strength value for a rock material, it is necessary to test multiple samples to obtain an average strength value. This is because rock strength can vary due to factors such as the geological composition, mineralogy, and structural features of the rock (Yılmaz & Sendır, 2002; Heidari *et al*., 2012; Kurtulus *et al*., 2018; Arman *et al*., 2019; Arman, 2021). This has led to the development of alternate tests and analytical/empirical correlations for calculating their strength characteristics. These methods are often used as supplements to the UCS test or when it is impossible to conduct the test due to practical or logistical reasons. In such cases, the slake durability index (SDI) test can be used as an alternative. This test is relatively easy and inexpensive to prepare and conduct (Arman, 2021). The Slake Durability Index (SDI) test was first developed by Franklin and Chandra (Franklin & Chandra, 1972) and then standardised by ISRM and ASTM standards. Some researchers have suggested that the index values at the end of the fourth cycle of the SDI test should be taken as a basis for estimating the strength parameters of the rock. This is because the first three cycles are considered primarily related to surface effects and do not necessarily provide an accurate representation of the internal strength of the rock. By the fourth cycle, the effects of weathering and erosion are supposed to have penetrated deeper into the rock, providing a more representative measure of its strength (Ulusay *et al*., 1995; Gökceoglu *et al*., 2000).

However, it is important to note that the use of the fourth-cycle SDI values as a basis for estimating rock strength is not universally accepted or standardised. Researchers have conducted various studies to establish analytical and empirical relationships between the slake durability index (SDI) and other properties of rocks, such as strength, weathering, and mineralogical-petrographical properties. These relationships can provide a means of estimating the strength parameters of rocks based on their SDI values or vice versa (Dhakal *et al*., 2002; Sharma & Singh, 2008; Sharma *et al*., 2011; Yagiz, 2011; Altindag, 2012; Sarkar *et al*., 2012).

In order to develop an estimation equation for UCS based on SDI, several researchers additionally looked into the relationship between the uniaxial compressive strength (UCS) and slake durability index (SDI) values of rocks. The goal of this approach is to provide a means of estimating the strength parameters of rocks based on the more easily measurable SDI values. (Cargill & Shakoor, 1990; Koncagül & Santi, 1999; Gökceoğlu *et al*., 2000; Dinçer *et al*., 2008; Yagiz, 2011; Yagiz *et al*., 2012; Kahraman *et al*., 2017; Arman, 2021). Consequently, it is possible to estimate the uniaxial compressive strength (UCS) values of rocks using a simple, fast, and inexpensive slake durability index (SDI) test. This can be achieved by applying an empirical equation that relates SDI values to UCS values.

In the context of Sri Lanka, there are only a few studies that have examined the relationship between uniaxial compressive strength (UCS) and slake durability index (SDI) for gneiss rocks. To address this gap, the current study aims to investigate the correlation between UCS and SDI for gneiss rocks from two quarry sites located around the Colombo area. The selected sites were identified based on their homogeneous geological traits, located within both the Highland and Wanni complexes, characterized by high-grade metamorphic rock primarily consisting of biotite gneiss or garnet-bearing biotite gneiss. This uniformity in geological composition facilitates a more precise examination of the correlation between Uniaxial Compressive Strength (UCS) and Slake Durability Index (SDI), specifically for gneiss rocks.

Existing correlations of UCS and SDI

Researchers have investigated the relationship between UCS and SDI to develop an estimation equation for UCS based on SDI, which will be described below in periodical order. The idea is to use SDI as a surrogate measure for UCS when direct measurement of UCS is not possible or practical. The exploration of the correlation between Uniaxial Compressive Strength (UCS) and Slake Durability Index (SDI) has been a focal point of research within the geotechnical field, especially concerning the mechanical properties of different rock types.

Cargill & Shakoor (1990) investigated various sedimentary rocks, analyzing the UCS-SDI relationship and contributing to the burgeoning body of empirical knowledge. The late 1990s saw further advancements, with studies specifically targeting the Breathitt shale in 1999 (Koncagül & Santi, 1999), aiming to establish a predictive model for UCS based on SDI measurements.

The turn of the millennium marked a continued exploration into this domain, with a 2000 study delving into the impact of mineralogy and mechanical strength on the durability of an array of weak and clay-bearing rocks in Turkey (Gökceoğlu *et al*., 2000). Despite challenges in identifying a universal correlation across all examined rock types, a focused analysis on marls yielded a promising equation for UCS prediction from SDI values.

The year 2008 witnessed the development of estimation formulas for UCS and Young's modulus, particularly for Quaternary caliche deposits, utilizing a variety of model types, including linear, logarithmic, power, and exponential correlations (Dinçer *et al*., 2008). This innovative approach underscored the potential for diverse modelling strategies in understanding UCS-SDI relationships.

Subsequent research in 2011 further reinforced the significance of these relationships within the context of carbonate rocks, uncovering a strong and direct correlation between UCS and SDI (Yagiz, 2011). This period also introduced more sophisticated analytical techniques, with a 2012 study employing both Artificial Neural Networks (ANN) and nonlinear multiple regression analysis to predict UCS values for different rock materials based on SDI values from both the second and fourth cycles of testing (Yagiz *et al*., 2012).

More recent investigations have continued to build on this foundation, with a 2017 study focusing on the UCS determination of pyroclastic rocks from fourth-cycle SDI values. This research underscored the nature of UCS-SDI relationships, generating separate predictive equations for data points below and above 20 MPa (Kahraman *et al*., 2017). Furthermore, a study conducted in 2021 aimed at empirically estimating UCS values of evaporitic rocks based on second-cycle SDI values (Arman, 2021) highlights the ongoing efforts to refine and expand empirical models for predicting rock strength and durability.

Table 1 presents the empirical equations relating to Uniaxial Compressive Strength (UCS) and Slake Durability Index (SDI) as derived by the aforementioned researchers, showcasing the evolution of predictive modeling across various rock types.

Table 1: Summary of the existing correlations of UCS and SDI

Year	Primary rock type	Types of Rocks	Equations		References
1990	Sedimentary and metamorphic rock	Sandstone Limestone Dolomite Marble Syenitic gneiss	$UCS = 60.34Id_2 - 5822$	r = 0.74	(Cargill & Shakoor, 1990)
1999	Sedimentary rock	Breathitt shale	$UCS = 0.658Id_2 + 9.081$	r = 0.63	(Koncagül & Santi, 1999)
2000	Sedimentary, volcano- sedimentary and metamorphic rock	Clay bearing rocks	$UCS = 2.54Id_4 - 202$	r = 0.70	(Gökceoğlu *et al*., 2000)
2008	Sedimentary rock	Quaternary caliche deposits	$UCS = 0.211Id_2 – 13.815$	r = 0.68	(Dinçer *et al*., 2008)
			$UCS = 13.636 \ln Id_2 – 69.552$	r = 0.65	
			$UCS = 4.9 \times 10^{-7} Id_2{}^{3.578}$	r = 0.74	
			$UCS = 0.084e^{0.45Id2}$	r = 0.76	
2011	Sedimentary rock	Carbonate rocks	$UCS = 29.63Id_4 - 2858$	r = 0.94	(Yagiz, 2011)
2012	Sedimentary rock	Carbonate rocks	$UCS = 0.7183 Id_2 − 0.0886$	r = 0.63	(Yagiz *et al*., 2012)
			$UCS = 0.7233 Id_2 − 0.0889$	r = 0.66	
			$UCS = 0.7856 Id_2 − 0.1171$	r = 0.71	
			$UCS = 0.531 Id_4{}^{1.454}$	r = 0.66	
			$UCS = 0.7454 Id_4 − 0.1122$	r = 0.67	
			$UCS = 0.6341 Id_4 − 0.0753$	r = 0.60	
2017	Volcanic rock	Pyroclastic rocks	$UCS = 0.047e^{0.065 Id_4}$	r = 0.92	(Kahraman *et al*., 2017)
			$UCS = 0.453 Id_4 − 26.22$	r = 0.82	
			$UCS = 7.75 Id_4 − 711.4$	r = 0.93	
2021	Sedimentary rock	Evaporitic rocks	$UCS = 17.792e^{0.0083 Id_2}$	r = 0.62	(Arman, 2021)

UCS - dry uniaxial compressive strength (MPa); Id_2 - second-cycle SDI (%); r - the correlation coefficient; Id_4 - fourth-cycle SDI (%)

This body of work illustrates a progressive enhancement in the understanding and prediction of UCS from SDI values across a diverse array of rock types, reflecting both the complexity of these properties and the evolving methodologies employed in their study.

While numerous studies have explored the relationship between the Slake Durability Index (SDI) and Uniaxial Compressive Strength (UCS) across a variety of rock types, metamorphic rocks have largely been overlooked in this research domain. Consequently, the primary objective of this study is to fill this gap by investigating the potential of predicting the strength parameter (UCS) of metamorphic rocks using the more accessible SDI test, which benefits from a simplified sample preparation process.

MATERIALS AND METHODS

Samples of gneiss rocks were collected from two different locations, Kaduwela and Kudayala, in the Colombo area, Sri Lanka. Strength and durability values were tested for those collected samples. Moreover, SEM, EDX, and ultrasonic pulse wave velocity were done to analyse the surface texture, elements present, and travel velocity, respectively.

Uniaxial compressive strength (UCS)

The specimens were transported to the laboratory, where they were cored to prepare NX-size samples to measure the UCS following the guidelines outlined by ASTM standards (ASTM D 2938, 2002). To maintain consistency and to reduce the influence of anisotropy, samples were cored in the direction perpendicular to the foliation planes because planes will easily slide over if the load is given parallel to the foliation plane and provides a minimal value of strength. To ensure accurate and reliable results, all core specimens intended for UCS testing underwent a thorough visual inspection and ultrasonic pulse wave velocity (UPV) measurements before testing. The inspection was conducted to detect any surface failures, such as macro cracks, fissures, or veins, that could impact the measurement results. Once the core specimens passed the inspection, nine rock core samples were selected for UCS testing. These samples were prepared by flattening their ends to ensure smooth and parallel surfaces that were normal to the long core axis. While maintaining the 2:1 length-to-diameter ratio of the samples, the end faces of the specimens were ground with a parallelism of 2/100. Subsequently, the UCS tests for the nine samples were performed under a constant loading rate of 40 kN/min, carefully controlled to ensure consistency across all measurements. This loading rate is typically determined based on the expected strength of the rock samples and the capabilities of the testing equipment being used. The results obtained from these tests were then used to determine the UCS of the rock samples being tested.

Slake durability index (SDI)

Following the guidelines outlined in the ASTM standard, slake durability tests were conducted using ten rounded rock lumps that were taken from the same boulder which was used to prepare the core samples, each with a mass ranging between 40 and 60 g (ASTM D 4644, 2004). The slake durability tests were conducted by taking the oven-dried rock lumps and placing them in a standard test drum that was then filled with tap water at a temperature of approximately 20°C. The drum was then rotated 200 times over 10 minutes. Following the test, the rock fragments inside the drum were carefully taken out and dried in an oven for 24 hours at 110°C. Once the rock pieces were completely dried, they were cooled to room temperature and weighed. To obtain a reliable measure of the slake durability of the rock samples, the process was repeated for four cycles, with the samples being subjected to the same conditions in each cycle. The four-cycle (I_{d4}) slake durability index was then calculated by dividing the weight of the rock pieces retained in the drum after the four cycles by the initial dry weight of the rock samples used in the test. The equation for the second cycle (I_{d2}) is given below;

$$Id_2 = [(WF - C)/(B - C)] \times 100 \qquad ...(1)$$

where:

Id_2 = Slake durability index (second cycle)
B = mass of drum plus oven-dried specimen before the first cycle (g)
WF = mass of drum plus oven-dried specimen retained after the second cycle (g)
C = mass of drum (g)

Ultrasonic pulse wave velocity

This typical laboratory method for characterising rock materials can be achieved non-destructively. The test involves sending ultrasonic waves through the rock aggregate and measuring the velocity of the waves as they travel through the material. The test measures the UPV value of the rock core, calculated based on the ratio of the distance between the two transducers to the time the ultrasonic waves travel between them (Chawre, 2018).

The results of the UPV test can also be used to detect defects or anomalies within the aggregate, such as cracks, voids, or inclusions, which may affect its elastic properties (Chai *et al*., 2011). These defects can cause stress concentrations within the aggregate, leading to localised failure and potentially compromising the overall strength and stability of the structure. Experimental readings of sonic velocity are typically lower than theoretical values, but it remains a sensitive parameter that correlates with other characteristics within the same rock type, making it valuable for standalone analysis or obtaining information about more complex parameters (ASTM D 2845, 2000). Since it is a non-destructive test, samples prepared for UCS testing were used for this analysis.

Table 2: Sample Identifier and Laboratory Testing Results

Sample No.	Sample Name	Location	Fresh/ Weathered	Image	Rock Description	Composition (EDX)	UCS (MPa)	Id$_2$ (%)	Id$_4$ (%)	UPV (m/s)
1	KW-FBG1	Kaduwela	Fresh		Biotite Gneiss	49.02% O, 32.06% Si, 8.84% Al, 5.00% K, 2.55% Na, 1.59% Ca, 0.48% Mg, 0.46% Fe	36.32	99.38	99.06	5925.72
2	KW-FBG2	Kaduwela	Fresh		Biotite Gneiss	45.85% O, 31.32% Si, 8.94% Al, 4.34% Fe, 2.84% K, 2.82% Na 2.11% Ca, 1.76% Mg, 0.02% C	31.45	99.78	99.58	5812.06
3	KW-FBG3	Kaduwela	Fresh		Biotite Gneiss	45.04% O, 28.40% Si, 9.45% Al, 6.01% Fe, 4.06% K, 2.81% Na, 2.47% Mg, 1.77% Ca	69.19	99.30	98.96	5114.24
4	KW-WBG1	Kaduwela	Weathered		Biotite Gneiss	47.70% O, 30.95% Si, 11.16% Al, 3.94% K, 2.97% Na, 1.71% Ca, 1.58% Fe	31.47	97.77	95.26	3398.75

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Sample No.	Sample Name	Location	Fresh/ Weathered	Image	Rock Description	Composition (EDX)	UCS (MPa)	Id_2 (%)	Id_4 (%)	UPV (m/s)
5	KY-FGBG1	Kudayala	Fresh		Garnet-bearing biotite gneiss	46.10% O, 29.33% Si, 8.62% Al, 5.43% Fe 4.12% K, , 2.02% Na, 1.89% Mg, 1.68% Ca, 0.80% Ti	90.50	99.66	99.08	5067.90
6	KY-FGBG2	Kudayala	Fresh		Garnet-bearing biotite gneiss	44.28% O, 31.07% Si, 10.50% Al, 7.50% K, 2.26% Na, 2.02% Fe, 1.75% Ca, 0.62% Mg	30.41	99.66	99.04	5075.62
7	KY-FGBG3	Kudayala	Fresh		Garnet-bearing biotite gneiss	51.62% O, 40.43% Si, 3.77% Al, 1.61% K, 0.90% Ca, 0.83% Na, 0.46% Fe, 0.38% Mg	52.99	99.40	98.76	4013.38
8	KY-WGBG1	Kudayala	Weathered		Garnet-bearing biotite gneiss	48.15% O, 23.69% Si, 10.94% C, 8.87% Al, 3.00% K, 2.58% Fe, 1.45% Na, 0.69% Ca, 0.63% Mg	16.54	94.39	85.02	1836.14
9	KY-WGBG2	Kudayala	Weathered		Garnet-bearing biotite gneiss	47.90% O, 27.38% Si, 12.89% Al, 6.39% K, 1.79% Na, 1.67% Fe, 0.77% Mg, 0.37% Ca, 0.29% Ti	18.51	91.73	82.71	3369.34

SEM and EDX

Scanning electron microscopy (SEM) is an imaging technique that employs an electron beam to scan the surface of a sample and generate high-quality images with exceptional resolution. SEM can be utilised to investigate various physical attributes, such as the surface morphology of a sample, and can be combined with elemental analysis using energy-dispersive X-ray spectroscopy (EDX) (Senarathna *et al*., 2021). This technology was instrumental in observing the micro crack system's evolution during scanning cycles. EDX, by identifying the components present in a sample and determining their relative concentrations, is an indispensable tool for material characterisation and analysis (Abd El Aal & Kahraman, 2017). The process involves first preparing the rock sample by hammering and removing dust on the surface. The sample is then loaded into the SEM chamber, where it is bombarded with a beam of electrons, generating high-resolution images of the sample's surface. During this process, the EDX detector collects and analyses X-rays emitted by the sample, providing information about its elemental composition.

Correlation analysis

Finally, the study analysed the correlation between SDI values obtained at the end of the second and fourth cycles and the measured UCS values. This also compared the experimental UCS values with the UCS values estimated from the developed empirical models. The results were further validated by SEM/EDX and Ultrasonic pulse wave velocity test results.

RESULTS AND DISCUSSION

UCS-SDI Regression Analysis

Table 2 represents the range of UCS and SDI values obtained from the tested rock samples. UCS values ranged from 16.54 to 90.50 MPa, indicating a wide range of rock strengths. The UCS value increased tremendously, especially with a high presence of quartz and feldspar, since their hardness is high, with 69.19 MPa in Kaduwela and 90.10 in Kudayala. SDI values ranged from 91.73% to 99.78% for the second cycle and from 82.71% to 99.58% for the fourth cycle. These values indicate the percentage of rock material broken down during the slake durability test. The higher the SDI value, the more durable the rock is. The range of SDI values suggests that the tested rocks have varying degrees of durability under slaking conditions.

The least squares regression method is used to fit a line or curve through a set of data points. This study employs a linear curve due to the limited number of data points. This study used the method to analyse the relationship between the second cycle SDI values and UCS values (Figure 1). The moderate level of correlation indicates a relationship between the two variables, but the strength of the relationship is not very strong. The linear function that was found shows that as the SDI values increase, the UCS values also tend to increase, but the relationship is not perfect. In other words, the UCS values are influenced by factors other than the SDI values, but there is a measurable correlation between the two. The equation of the curve is as follows;

$$UCS = 4.92\ Id_2 - 439.36 \qquad r = 0.58 \qquad ...(2)$$

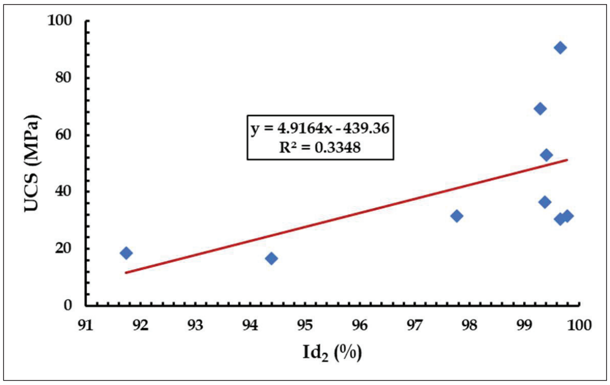

Figure 1: Correlation between UCS and Id_2

Figure 1 illustrates a common pattern of UCS values rising as SDI values increase. However, the data has some scatter, and the correlation coefficient is only moderate. This means that while there is a relationship between SDI and UCS, it is not a very strong one.

To assess the precision of the UCS prediction method using SDI values, Figure 2 displays a graph comparing the projected UCS with the actual UCS. The data points appear to be evenly spread around the diagonal line positioned below the UCS values of 40 MPa. This indicates that the estimated values for UCS are quite precise for rocks with lower strength. Nonetheless, when the UCS values exceed 40 MPa, the data points move away from the diagonal line and exhibit a different pattern. This indicates that the UCS-SDI correlation may not be as accurate for higher-strength gneiss rocks, and further testing may be needed to understand this relationship better.

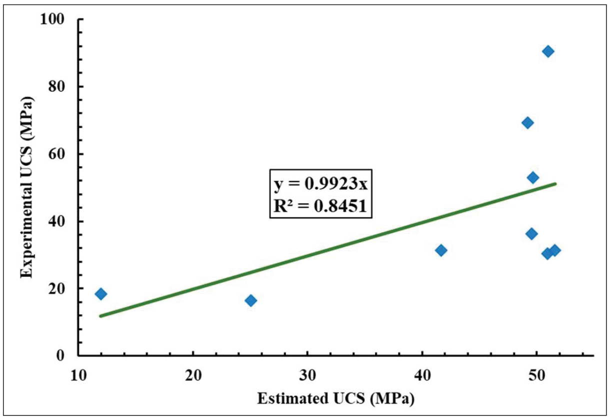

Figure 2: Correlation between experimental and estimated UCS for the Second cycle

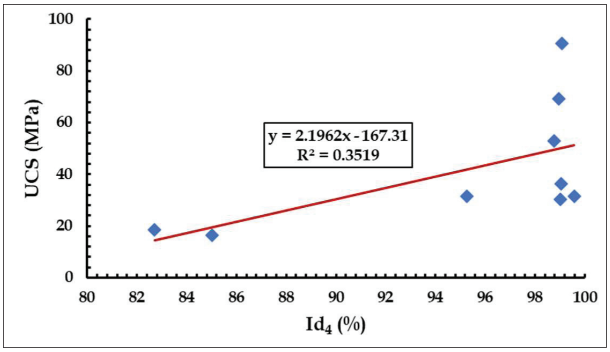

Figure 3: Correlation between UCS and Id_4

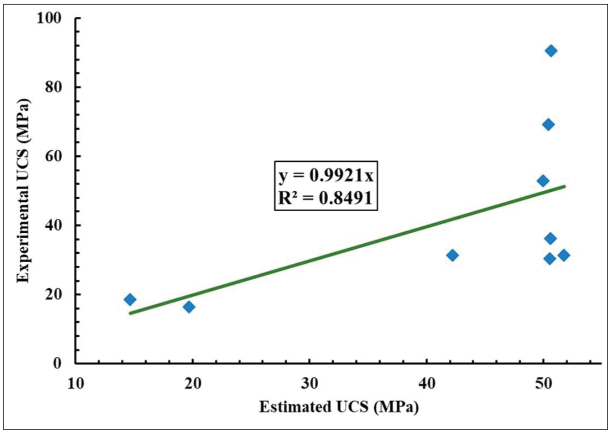

Figure 4: Correlation between experimental and estimated UCS for the Fourth Cycle

Moreover, the analysis was also conducted on the fourth cycle of SDI and UCS values, exhibiting a similar pattern to the second cycle (Figure 3 and Figure 4).

As a result of the different trends observed in the UCS-SDI correlation for gneiss rocks below and above the UCS values of 40 MPa, separate correlation plots were created for cycles two (Figure 5) and four (Figure 6). This 40 MPa was selected as the threshold for segmenting the data into two subsets based on its role as a statistically significant breakpoint. These plots were then used to derive equations for the two observed trends. The resulting equations are presented below;

For the second cycle of SDI and UCS,

$$UCS = 75.41Id_2 - 7428.80 \qquad r = 0.75 \qquad ...(3)$$

$$UCS = 2.14Id_2 - 180.22 \qquad r = 0.89 \qquad ...(4)$$

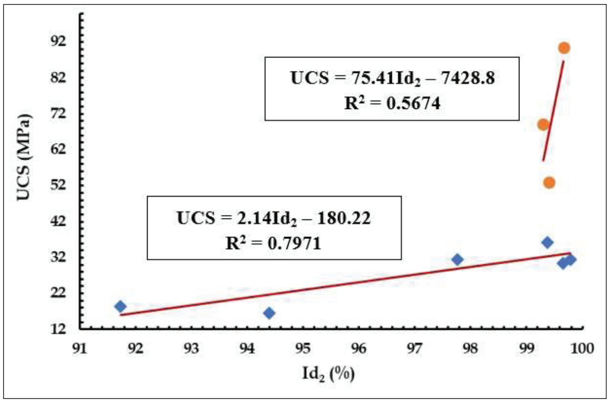

Figure 5: Correlation between UCS and Id_2

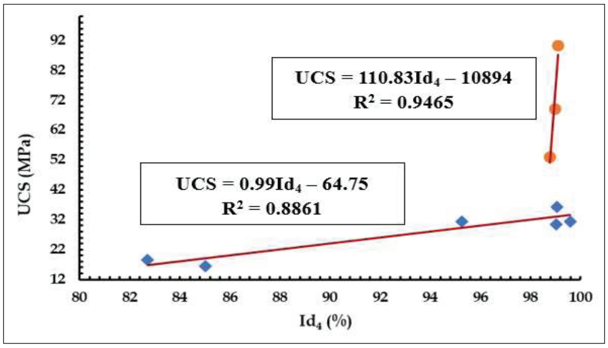

Figure 6: Correlation between UCS and Id_4

For the fourth cycle of SDI and UCS,

$$UCS = 110.83Id_4 - 10894 \qquad r = 0.97 \qquad ...(5)$$

$$UCS = 0.99Id_4 - 64.75 \qquad r = 0.94 \qquad ...(6)$$

This analysis showed different trends in the relationship between SDI and UCS depending on the UCS values. Therefore, the authors derived separate regression equations for UCS values above and below 40 MPa for cycles two and four. The strength of the correlation coefficients for the equations was significant, ranging from strong to very strong. This suggests that there is a positive relationship between SDI and UCS values. Kahraman *et al*. (2017) also found that by dividing the dataset into groups with UCS values above and below 20 MPa, the data points showed less scatter and exhibited a strong correlation as well.

It was observed that the inclinations of the regression lines were significantly dissimilar. When UCS values were analysed separately above and below 40 MPa, a robust connection between the experimental and estimated values was evident in cycle two (as illustrated in Figure 7) and cycle four (as shown in Figure 8). This indicates a high correlation between the predicted and estimated UCS values. This approach proved more effective than considering all the data points at once for this specific data points. This will improve the predictive accuracy and will help to understand the material behaviour under different threshold values.

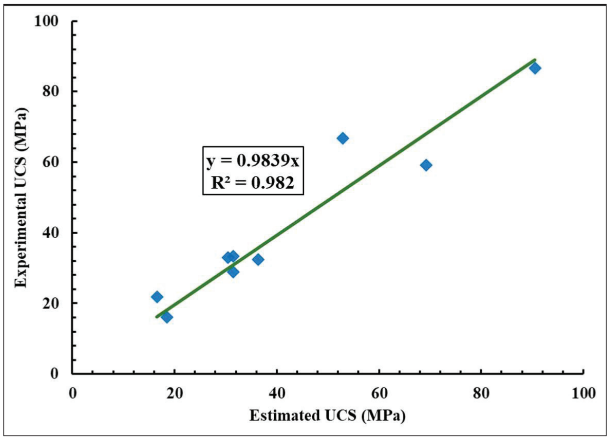

Figure 7: Correlation between Experimental and Estimated UCS for the Second cycle

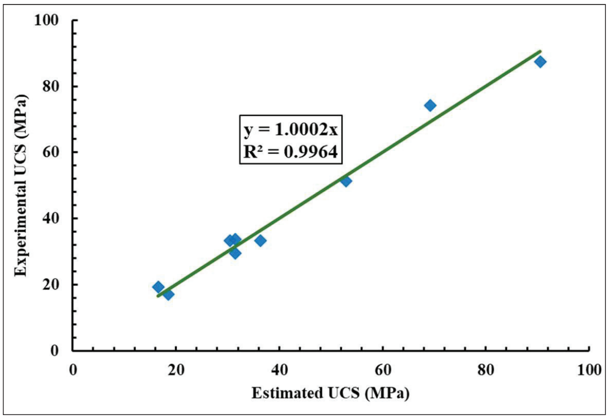

Figure 8: Correlation between Experimental and Estimated UCS for the Fourth cycle

Analysis of ultrasonic pulse wave velocity (UPV) results

The Ultrasonic pulse wave velocity results validated the estimated UCS results. For each lower value of UCS, especially below 30 MPa, the velocity was reduced except for sample Number KY-FGBG2 since it is a fresh rock sample and should contain fewer cracks and less porosity than weathered samples. Therefore, UPV is inversely proportional to the rock's strength. As the rock strength decreases, it becomes less resistant to deformation, leading to a slower propagation of ultrasonic waves. This decrease in strength can be caused by factors such as increased porosity, the presence of fractures or cracks, weathering, or alteration of mineral composition. With these factors, the estimated UCS values are in an acceptable condition.

Analysis of SEM / EDX results

The SEM/EDX analysis was conducted on the specimens listed in Table 2, with one sample, KY-WGBG1, being chosen for an in-depth explanation. The analysis was done by visual interpretation and based on the given information in Table 2 under the subheading "compositions (EDX)". The weight percentage of elements in the considered gneissic rock sample follows the order: Silicon (Si) > Aluminum (Al) > Potassium (K) > Iron (Fe) > Sodium (Na) > Calcium (Ca) > Magnesium (Mg). The focus is on assessing the effect of different elements on the rock's weathering behaviour (degradation of strength). Carbon (C) and oxygen (O) are present in the environment, and gold (Au) coating is done before conducting SEM/EDX analysis. Therefore, the weight percentages of C, O, and Au can be assumed to have minimal impact on assessing the effect of elements in weathering. Silicon (Si) is the most abundant element in the sample. It is a major component of many minerals in the gneissic rock, such as quartz, feldspar, and mica (Glover *et al*., 2012). Silicon-rich minerals are generally weather-resistant and can withstand environmental conditions, making them relatively stable (Velbel, 1999). However, with the presence of other elements such as Aluminium (Al), Iron (Fe), Calcium (Ca), Sodium (Na) and Magnesium (Mg), the rock sample is prone to weathering because Al compounds are susceptible to weathering, particularly through processes like hydrolysis (Coleman, 1962), which can result in the formation of secondary minerals like clays, while Fe (II) can undergo oxidation reactions when exposed to oxygen and water, leading to the formation of iron oxides or hydroxides (Bernal *et al*., 1959), which are commonly known as rust. This process can contribute to the weathering of the rock. Calcium-rich minerals can be susceptible to chemical weathering, particularly through processes like dissolution (Prestrud Anderson *et al*., 1997), and Na can be susceptible to weathering through processes like ion exchange and leaching (Guicharnaud & Paton, 2006). However, the overall impact of sodium on the weathering behaviour of the rock may be relatively lower than other elements. Mg in primary minerals is released during chemical weathering. This breaks the Mg-O bond in rock to form soluble Mg (Zhao *et al*., 2022).

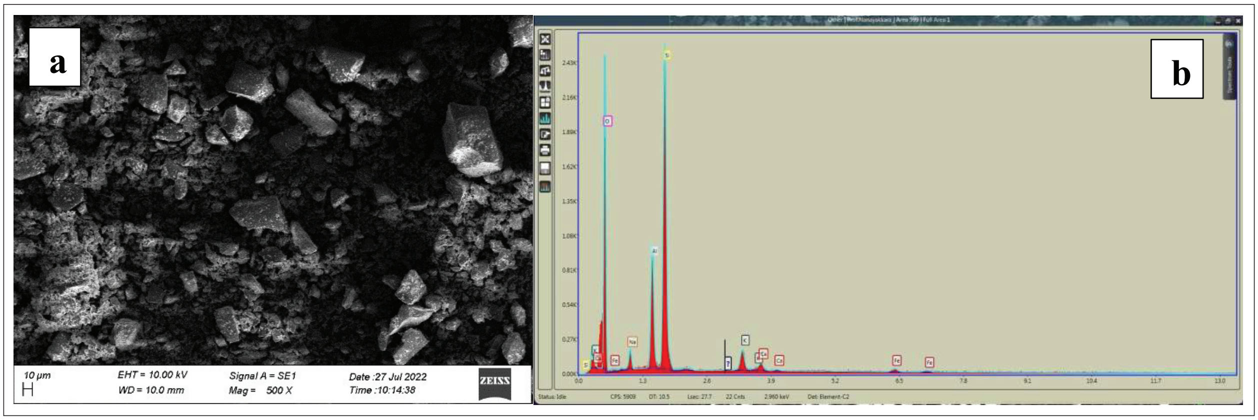

Figure 8: (a) SEM image (b) EDX elemental graph for the sample KY-WGBG1

The data highlighted in Table 2 distinctly show a variation in the weight percentages of elements like iron (Fe) and magnesium (Mg) between fresh and weathered rock samples. In this EDX experiment, chip samples from the UCS-tested specimens were analyzed to investigate the cause of strength parameter variations, which appeared to be linked to internal microstructures. This was pursued particularly because, despite satisfactory Slake Durability Index results, UCS values were not aligning. The findings revealed that the oxidation of Fe (II) to Fe (III) and Mg to Mg (II), indicative of weathering, significantly affects the rock's strength properties. This is evident as the weight percentages of Fe and Mg in weathered rocks are consistently lower due to the onset of weathering processes especially when they exposed to oxygen. Intriguingly, some fresh rock samples also exhibited lower values of Fe and Mg, signalling internal weathering, which consequently leads to a decrease in rock strength.

Even though it is a small-scale interpretation, it can be used as a secondary tool to further understand the changes in rock strength properties due to internal weathering and the validity of the results derived from the proposed equation. Furthermore, using the elemental distribution map, which can be derived during this analysis, and was utilised to examine element partitioning, the results can be further validated by assessing the elemental removal from the eroded areas. Since Sri Lanka is a tropical country with two monsoonal periods, the influence of especially chemical weathering will always be there in every field due to such elemental presence in the rock samples, which will induce weathering. So, EDX analysis is an important tool for assessing such elemental presence and distribution. Since this analysis was done by taking the sample from UCS-tested samples, these results helped to further confirm the variations of the derived UCS results due to different elemental variations. The information described above, which was based on Table 2, was further validated by overlaying the elemental distribution map onto the SEM image. This approach was used to gain a deeper understanding of the underlying mechanisms.

CONCLUSION

The proposed empirical equation to estimate UCS values from Id_2 and Id_4 values is more accurate for gneiss rocks with UCS values less than or greater than 40 MPa, as opposed to all UCS values combined. This approach will increase the prediction accuracy of UCS values. Therefore, it is concluded that the use of empirical equations (23), (24), (25) and (26) to estimate the uniaxial compressive strength (UCS) of gneiss rocks based on Id_2 and Id_4 is both affordable and straightforward. These equations will predict the maximum strength value a core specimen can provide since the equation was tested for the samples cored perpendicular to the foliation plane. However, it is recommended to use these equations with caution and only within the accuracy level limited to similar rocks at the preliminary analysis stage. The UPV and SEM/EDX tests provided valuable insights into micro-scale changes, thus enhancing the understanding of the sample characteristics and reinforcing the validity of the derived results. To ensure the generalizability and applicability of the findings, extending the investigation to encompass a broader range of rock types is recommended.

Conflict of interest statement

All authors disclose that they have no competing interests.

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