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Predictive Models for Uniaxial Compressive Strength of Dry and Saturated Marble: An Empirical Approach

Naeem Abbas[1], Kausar Sultan Shah*[2], Javed Akhter Qureshi[3], Hawas Khan[3], Jibran Hussain[3] and Amjad Ali[3]

[1]Department of Mining Engineering Karakoram International University (KIU), Gilgit

**[2]Department of Mining Engineering and Mineral Resources Engineering, NUST Balochistan Campus*

[3]Department of Earth Science, KIU, Gilgit

**Corresponding Author: Kausar Sultan Shah (Kausarsultanshah@gmail.com)*

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Abstract

In this study, marble samples were collected from a quarry near the Karakoram Highway, and core samples were prepared for direct compressive strength, indirect strength, pulse velocity, and Schmidt hammer value testing. The study revealed a strong linear relationship between the point load index (PLI) and uniaxial compressive strength (UCS) for both dry and saturated samples, demonstrating the predictive value of PLI, especially in dry conditions. However, it is important to note the reduced reliability of this relationship in saturated samples, which is likely due to factors such as pore water pressure. An exponential relationship was also observed between ultrasonic pulse velocity (Vp) and UCS, with most samples exhibiting lower Vp values than the typical marble average. This suggests variations in the subsurface structure of the marble and warrants further investigation to understand its mechanical implications. The linear correlation between the degree of weathering and Schmidt hammer readings offers a practical method for assessing weathering conditions. Grade I marble exhibited Schmidt hammer rebound values greater than 45, while values ranged between 35 and 45 for Grade II and were less than 35 for Grade III. The stress-strain curve revealed a decrease in peak stress (from 60 MPa to 32 MPa) with saturation. These results enhance the understanding of Ghulmet marble's mechanical behavior and its suitability for diverse applications, emphasizing the importance of considering varying conditions and characteristics in geotechnical assessments.

Keywords: *Uniaxial compressive strength, Ultrasonic pulse velocity, correlation, saturation.*

1. Introduction

Uniaxial compressive strength (UCS) is an essential parameter for rock mass classification and geotechnical projects. Determining UCS is time-consuming and expensive due to sample preparation and the high cost of universal testing machines (Shah et al., 2021, Khan et al., 2022, Shah et al., 2022). The Schmidt hammer rebound value (N), ultrasonic pulse velocity (Vp), and point load index (PLI) have been used to predict uniaxial compressive strength (UCS). The Schmidt hammer, initially developed to assess concrete hardness, is now widely used as an indicator of rock hardness . The Schmidt hammer is a simple, portable, quick, and affordable method for predicting rock hardness . Numerous correlations between Schmidt hammer rebound number and UCS have been developed, revealing that UCS is highly dependent on rock type. Several studies have also explored the specific applications of the Schmidt hammer. These include mine roof control road header and tunnel boring machine performance , determination of rock weathering , assessing rock discontinuities , predicting the uniaxial compressive strength of rock , joint wall strength , drilling machine penetration rate and rock mass excavatability classification . Other indirect techniques, such as the point load index and ultrasonic pulse velocity, have also been correlated with UCS, showing either linear or nonlinear relationships. determined that the size correction factor for granite has a power of 0.44. In a study of 48 different rock types, the author found a strong correlation between PLI and UCS for rocks of the same type, but a weaker correlation for rocks of different types.

Water saturation significantly affects the relationship between indirect and direct strength determination methods. Therefore, it is necessary to investigate how saturation and porosity affect this correlation. Moisture content decreases the elastic limit and increases the propagation of microcracks, which implies that saturation has a relatively minimal effect after the elastic limit is reached. Beyond the lowered elastic limit due to saturation, plastic strain has a more pronounced impact on saturated rock samples compared to dry rock samples .

Several correlations between compressive strength and various indirect techniques have been established in the literature for a wide range of rock types. However, due to the dependence of compressive strength on the specific rock type, separate empirical models must be developed for each distinct rock type. This study aims to develop empirical UCS models for marble using Schmidt hammer rebound value, ultrasonic pulse velocity, and point load index. Additionally, the effects of saturation on the material's elastic limit have been explored by analyzing the stress-strain curve. Understanding the implications of saturation is of paramount importance given the extensive use of marble in both indoor and outdoor tile applications. This research also examines the effects of saturated samples on the correlation of UCS with other parameters.

2. Regional Geology

Hunza and Gilgit, situated in the northern part of Pakistan within the western Himalayas, are defined by their intricate regional geology formed by ongoing tectonic activity. The collision of the Indian Plate with the Eurasian Plate has led to the uplift of the Himalayan and Karakoram Mountain ranges, resulting in a diverse range of rock types, including sedimentary, metamorphic, and igneous rocks, as well as complex folding, faulting, and the formation of striking anticlines and synclines. Glacial processes have significantly contributed to the rocky terrain and the creation of deep valleys. The region is renowned for its mineral resources, including precious gemstones like rubies and sapphires. This tectonic activity, while contributing to the area's geological significance, also makes it seismically active.

3. Experimental setup and the methodology

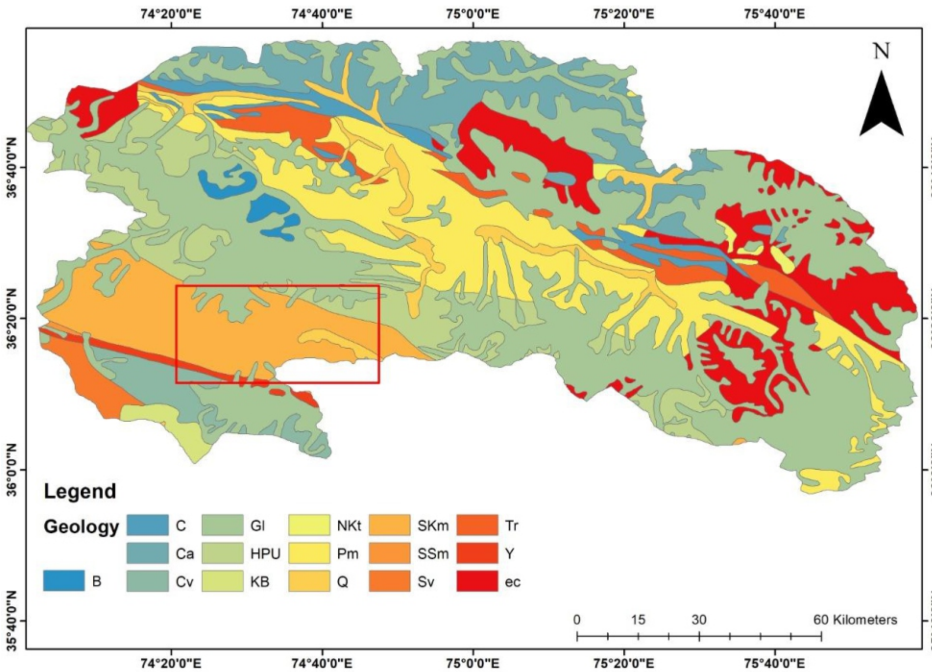
Marble boulders from a quarry near Karakoram Highway in Ghulmet Nagar, Pakistan (Fig. 2), were collected for direct and indirect UCS testing. Schmidt hammer (N-Type) readings were taken at various locations, considering different weathering conditions. A detailed geological field survey of the study area was conducted. Schmidt hammer rebound number tests were performed in the field and laboratory following standard guidelines (Aydin, 2008). The methodology flowchart is provided in Fig. 3. To conduct the rebound number test, a smooth rock surface was prepared, and ten values were recorded at each point. The lowest and highest values were excluded, and the average of the remaining values was recorded as the N value for that specific point.

The ISRM suggested method was followed to determine UCS of core samples in the laboratory (Hatheway, 2009). For the direct determination of uniaxial compressive strength, the length-to-diameter ratio of the specimens was 2.5. The tests were conducted on both dry and fully saturated specimens using an Eagle Scientific Universal Testing Machine model No. TEST-1000E (Fig. 4a). To study the saturation effect, specimens were immersed in water for 2 hours, following the guidelines outlined in the revised ISRM method (Ulusay, 2015). The variation of rebound value with the degree of saturation was also calculated. Some core samples broke during the hammer test, primarily due to the presence of microcracks.

The ISRM suggested method (Eberhardt, 2009) is used to determine porosity, density, water content, and degree of saturation. According to the ISRM, the degree of saturation is determined using Equation 1.

$$S_r(\%) = \frac{V_w}{V_v} \times 100 \qquad (1)$$

Where S_r is degree of saturation, V_w is volume of pore water and V_v is the volume of pore.



C=Cretaceous sandstone	SSm= Shyok Suture melange
GI=Ghamu bar unit	Y= Yaseen Sediments
NKt=Northern Karakoram terrain	B= Batura Plutonic Unit
SKm=Southern Karakoram Metamorphic	Cv= Chalt volcanic
Tr=Triassic Rock	KB= Kohistan Batholith
Ca= Cat calcite	Q= Quaternary
HPU= Hunza Plutonic Unit	Sv= Shmaran Volcanic
Pm=Permian massive	ec= Eclogites

Fig. 1. Geological Map showing different geological features.

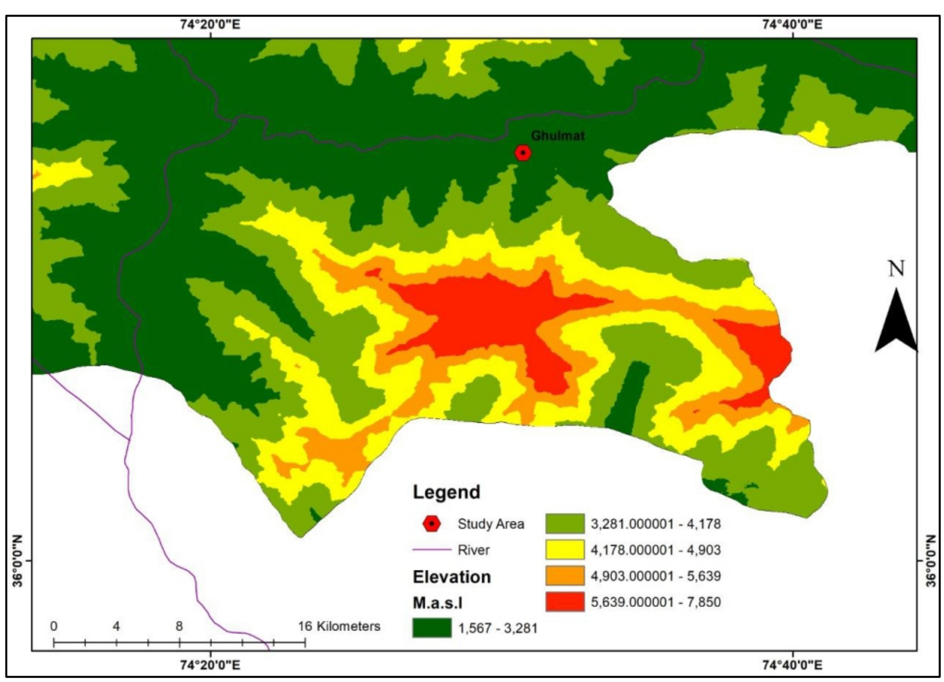


Fig. 2. The Location map of study area

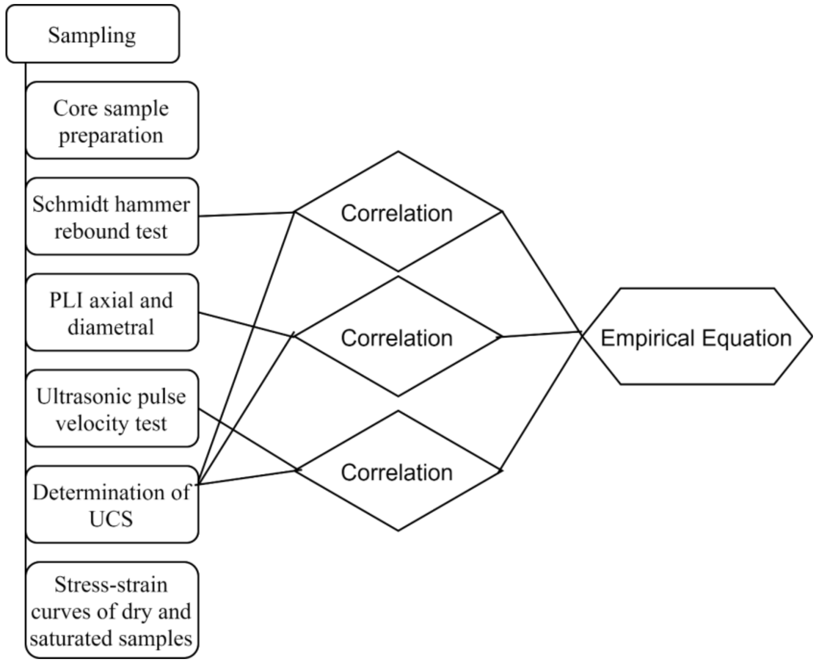


Fig. 3. Schematic of experimental setup

Fig. 4. Experimental setup (a) Universal testing machine (b) Ultrasonic pulse velocity tester (c) Marble sample (d) Point load index

4. Results and discussions

Core samples with a length-to-diameter ratio of 2.5 were carefully prepared for direct uniaxial compressive strength testing. A constant loading rate of 5 kN/s was applied to the samples until failure. Notably, a significant proportion of the samples exhibited tensile failure during testing. The uniaxial compressive strength and Schmidt hammer results for both saturated and dry marble samples are presented in Figure 5. A decreasing trend in UCS was observed in saturated specimens. The UCS of dry samples ranged from 20 to 59 MPa, while the UCS of saturated samples ranged from 9 to 42 MPa. Table 1 summarizes the maximum and minimum values of the tested parameters for marble.

4.1 The effect of saturation on uniaxial compressive strength

The results indicate that uniaxial compressive strength (UCS) decreases with the degree of saturation. Karakul and Ulusay (2013) investigated this decreasing trend and suggested that it may be attributed to the mineralogical composition and porosity of the rock. The decrease in UCS with saturation is more pronounced in clay-rich rocks than in other rock types . In the case of Ghulmet marble, the majority of the samples broke during the laboratory Schmidt hammer test, indicating the presence of microcracks within the deposit. These cracks may also contribute to increased saturation, which could explain the decrease in UCS (Abbas, 2022). also found that porosity and clay content have a combined effect on UCS.

Porosity is another factor that contributes to the decrease in rock mass strength due to the saturation effect, in addition to clay content, as shown in equation 2 (Shah et al., 2021).

$$ECC = n \times cl(\%) \qquad (2)$$

Whereas, ECC is effective clay content, n is porosity, and cl is clay content.

The experimental results of this study also revealed that the saturation effect is more significant in highly porous samples than in low porous samples, and the decreasing trend in UCS is more pronounced in highly porous samples (Shah et al., 2023). Similar results were also predicted by Abbas et al. (2023), who found that samples with low porosity exhibit higher UCS values. Some of the highly porous samples in this study exhibited low values of saturation, which may be due to the disconnection of pores. Figure 6 shows the stress-strain curve for both dry and saturated marble. The curve's nonlinearity increases with saturation, and the peak stress value of saturated samples is significantly lower than that of the dry samples. The peak strain of saturated samples (5.5×10^{-3}) is greater than dry samples (2.9×10^{-3}).

4.2 Correlation of N value and UCS for dry and saturated marble

Figure 7 shows the correlations between UCS and porosity (N) for both dry and saturated marble samples. Linear, quadratic, and exponential models were fitted to the data, and the exponential model showed the highest correlation coefficients, 0.86 for dry samples and 0.79 for saturated samples. Equations 3 and 4 show the empirical correlations for dry and saturated marble, respectively. It is important to note that these equations may only be valid for the marble deposit studied, as UCS is rock-dependent.

$$UCS = 4.0712e^{0.0552N} \qquad (3)$$

$$UCS = 6.67e^{0.049N} \qquad (4)$$

4.3 Correlation of UCS an PLI

The linear correlation between the point load index (PLI) and uniaxial compressive strength (UCS) of marble, shown in Figure 8, is a significant finding. Equations 5 and 6 provide empirical correlations for dry and saturated samples, respectively. These equations provide a practical and reliable method for estimating UCS from PLI measurements. The high correlation coefficient of 0.9 for dry samples highlights the strength and predictive power of this linear relationship, making it a valuable parameter for geotechnical applications. However, the reduced correlation coefficient of 0.6 for saturated samples suggests that the relationship is weaker under saturated conditions, likely due to the influence of factors such as pore water pressure and microcracks (Shah et al., 2023; Hashim et al., 2022). This result highlights the need to consider variable conditions when applying the PLI-UCS correlation, emphasizing its significance in dry conditions while acknowledging its limitations in saturated settings. While multiple linear correlations have been reported in the literature (Kahraman et al., 2003; Abbas et al., 2022), the UCS is rock-dependent, meaning that a single relationship may not be suitable for all rock types.

$$UCS = 19PLI - 26 \tag{5}$$

$$UCS = 6.64PLI - 17.5 \tag{6}$$

4.4 Correlation of pulse velocity with marble strength

The exponential relationship between uniaxial compressive strength (UCS) and ultrasonic pulse velocity (Vp) for marble samples, as shown in Equation 7, is similar to the equation suggested by Kahraman et al. (2003). This relationship indicates that changes in Vp have an exponential impact on UCS, reflecting the material's mechanical properties. Notably, most of the samples exhibit Vp values ranging from 2.5 km/s to 3 km/s, significantly lower than the typical average Vp value for marble (approximately 5 km/s). This observation has implications for the mechanical behavior and applications of marble. The lower Vp values suggest variations in the marble's structure, possibly linked to factors such as porosity, microcracks, or mineralogical composition. These deviations in Vp values may signify reduced sound wave velocity due to an altered subsurface structure, potentially affecting the marble's strength and stability.

$$UCS = 2.6e^{0.96Vp} \tag{7}$$

Upon a comprehensive examination of the strength parameters discussed above for marble, it is evident that all derived values are consistently lower than the standard values proposed for marble in the existing literature (Han et al., 2017). This discrepancy can be attributed to the geological characteristics of the study region, situated over the Main Karakorum Thrust (MKT). The prevailing tectonic activities in this area serve as the primary drivers behind the formation of microcracks. Consequently, the strength parameters may not align with the established standards for marble (Yilmaz, 2006; Shah et al., 2023). The statistical analysis results conducted through SPSS software are presented in Tables 2 and 3 for dry and saturated marble samples, respectively.

A multivariate linear regression analysis was used to assess the impact of saturation on the relationship between UCS and N. In this analysis, UCS was the dependent variable, and N and Sr (saturation ratio) were the independent variables. The results of this analysis are shown in Equation 8, which has a correlation coefficient of 0.9, indicating a strong correlation.

$$UCS = 14.1 + 0.609N - 7.55S_r \ (\mathrm{R}^2 = 0.899) \tag{8}$$

4.5 The weathering and Schmidt hammer rebound number

The determination of weathering grade employed the ISRM suggested method (Pasamehmetoglu, 1981). Laboratory and in-situ tests were conducted across various locations within the marble quarry using the N-type Schmidt hammer. Prior to the Schmidt hammer test, meticulous preparation of rock surfaces ensured smoothness, with ten readings taken on a single plane and the average value considered as the N value. The relationship between weathering grade and Schmidt hammer readings is visually represented in Figure 10. Fresh marble rocks exhibited N values exceeding 45, whereas slightly weathered rocks fell within the range of 35 to 45. Moderately weathered rocks displayed N values less than 33, showcasing a linear correlation between the degree of weathering and N values. This correlation serves as an indirect method for assessing the weathering condition of marble. Such an assessment holds implications for the material's suitability across various applications and its mechanical behavior under diverse weathering conditions.

Table 1. The maximum and minimum values of strength parameters of marble

	Dry		Saturated		Degree of saturation
	Uniaxial compressive strength (MPa)	Schmidt hammer rebound value	Uniaxial compressive strength (MPa)	Schmidt hammer rebound value	
Maximum	59	49	42	38	0.6
Minimum	20.5	31	9	11	0.1913

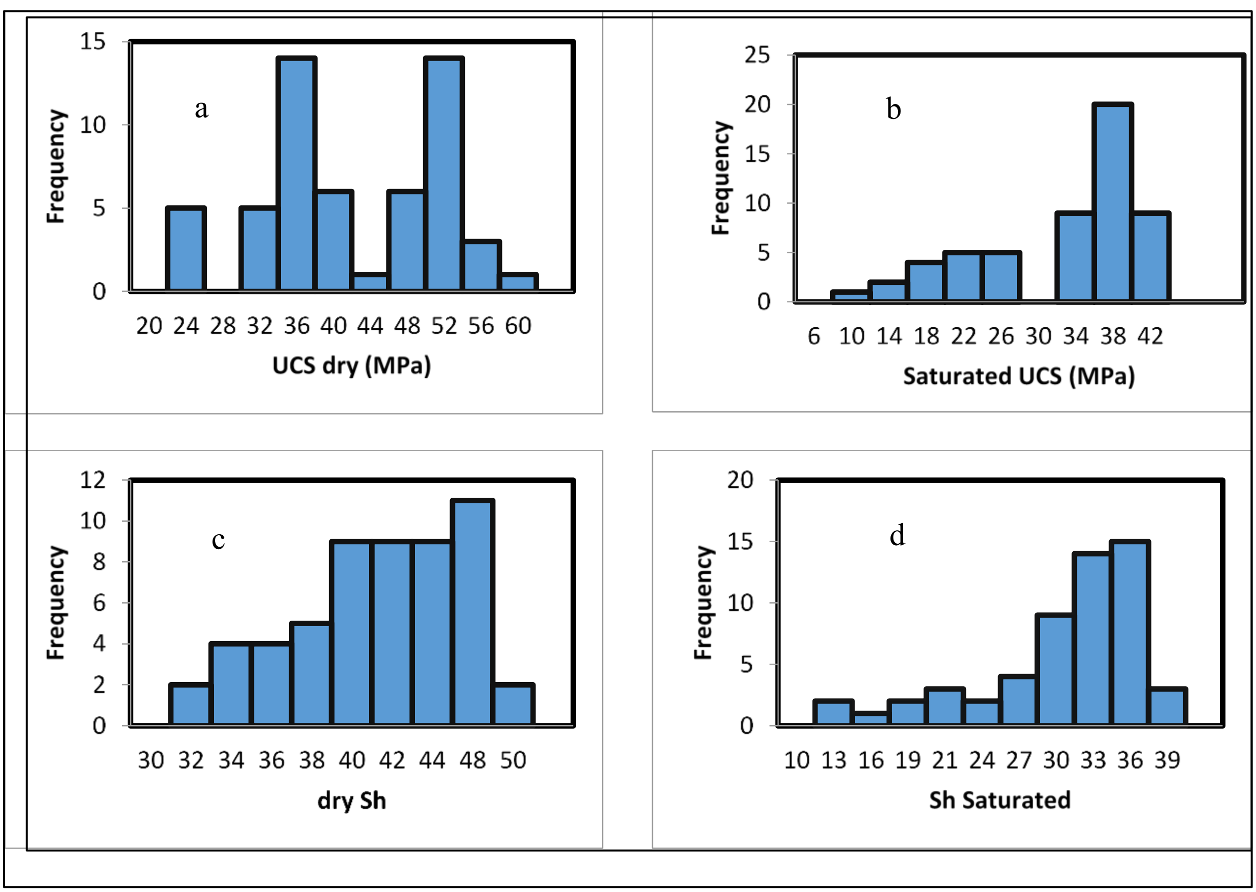


Fig. 5. The UCS and Schmidt hammer: (a) UCS of dry samples; (b) UCS of saturated samples; (c) Schmidt hammer reading of dry samples; (d) Schmidt hammer readings of saturated samples

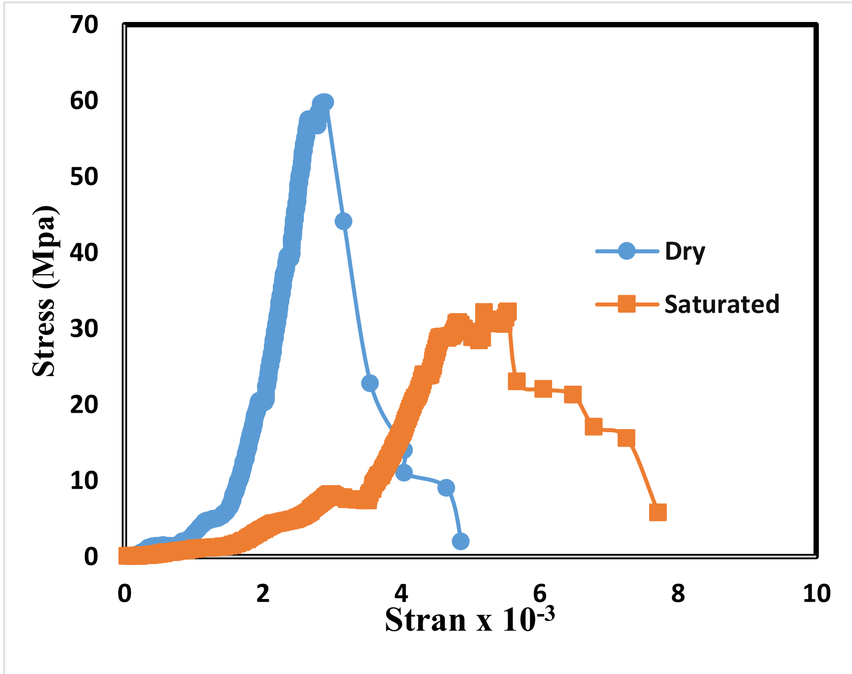


Fig. 6. Stress-strain behavior of dry and saturated marble

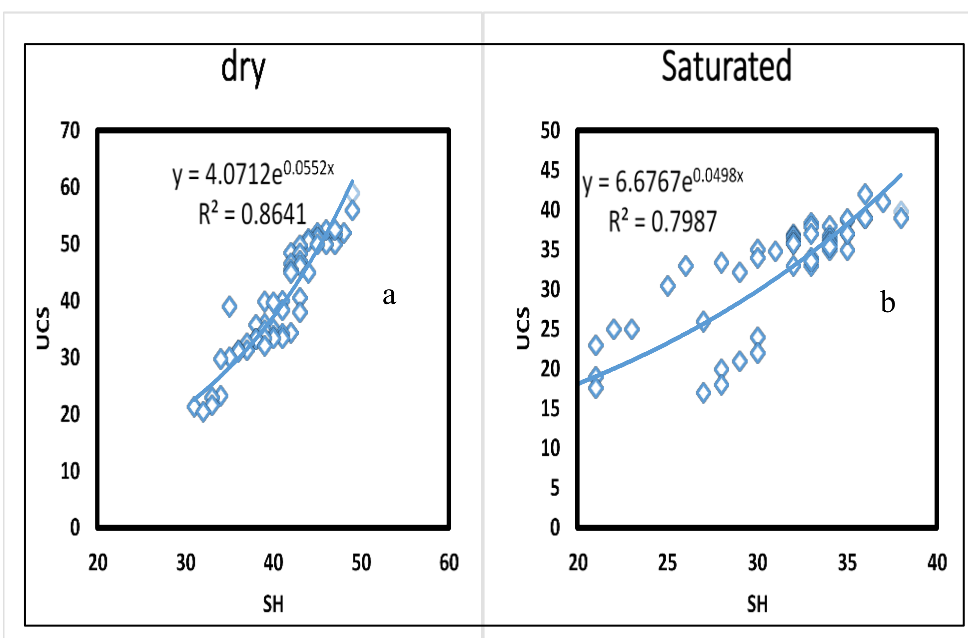


Fig. 7. Correlation of UCS and Schmidt hammer rebound (a) dry samples (b) Saturated samples

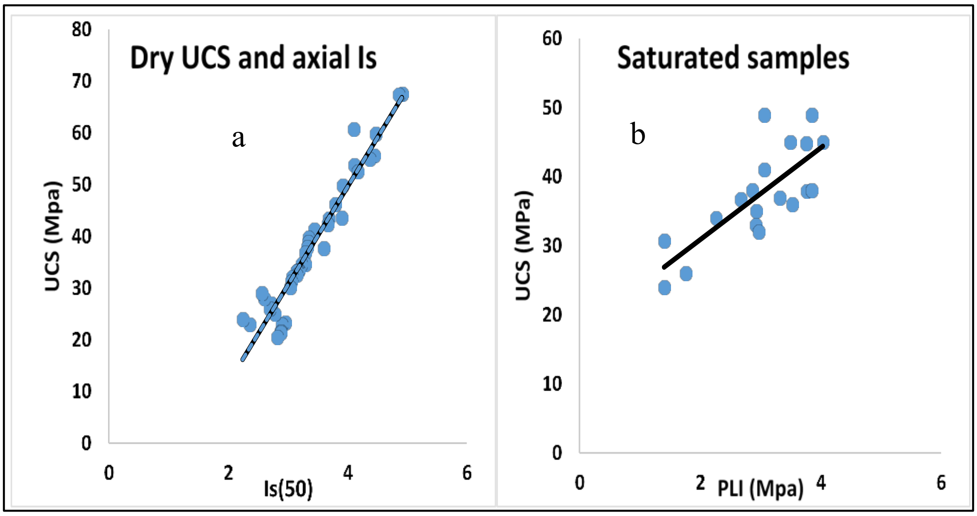


Fig. 8. The correlation of UCS and PLI (a) dry samples and (b) saturated samples

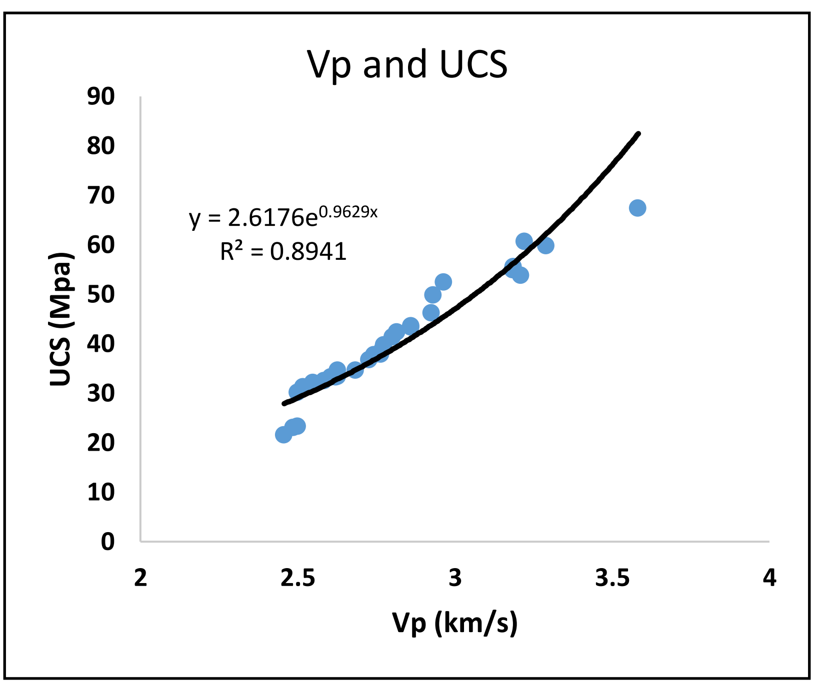


Fig. 9. Correlation of Vp and UCS for marble samples

Table 2. Statistical analysis of empirical models of dry samples

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
UCS	-44.09	4.51	-9.77	1.90E-13	-53.14	-35.03
SH	2.07	0.11	18.81	4.13E-25	1.84	2.29

Table 3. Statistical analysis of empirical models of saturated samples

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
UCS	-4.80	2.58	-1.87	0.07	-9.97	0.36
SH	1.20	0.08	14.22	1.00E-19	1.03	1.37

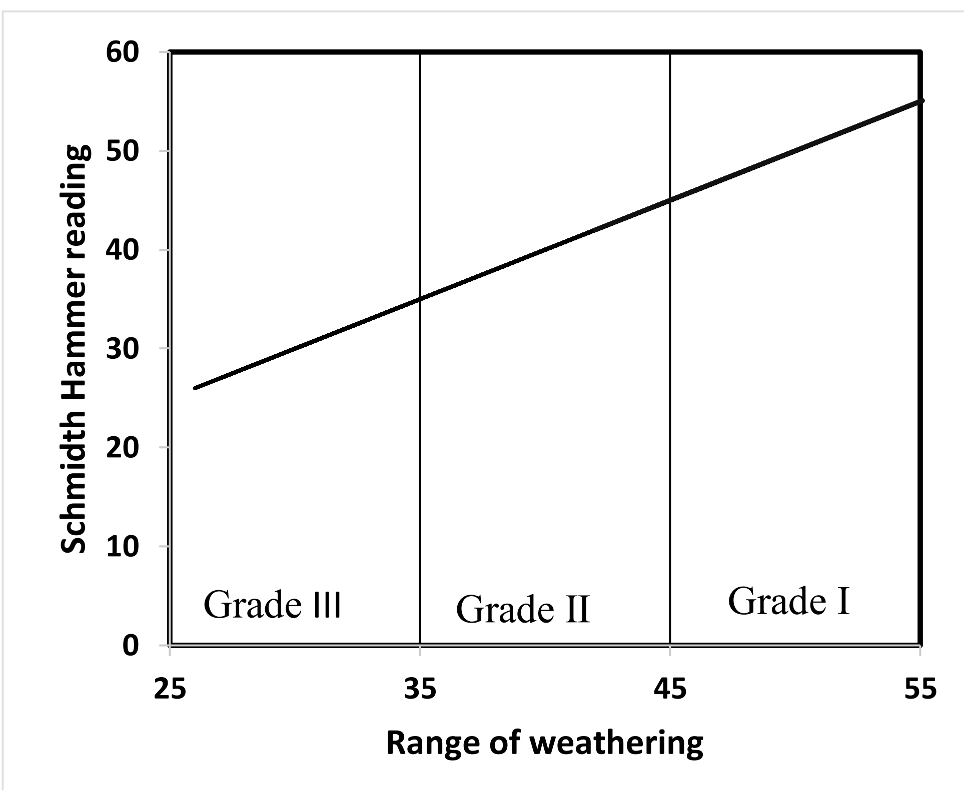


Fig. 10. Weathering grade and Schmidt hammer reading

5. Conclusions

Marble samples were collected from a quarry near the Karakoram Highway, and core samples were prepared for direct compressive strength, indirect strength, pulse velocity, and Schmidt hammer value testing. The study revealed a strong linear relationship between the point load index (PLI) and uniaxial compressive strength (UCS) for both dry and saturated samples, demonstrating the predictive value of PLI, especially in dry conditions. However, it is important to note the reduced reliability of this relationship in saturated samples, which is likely due to factors such as pore water pressure.

An exponential relationship was also observed between ultrasonic pulse velocity (Vp) and UCS, with most samples exhibiting lower Vp values than the typical marble average. This suggests variations in the subsurface structure of the marble and warrants further investigation to understand its mechanical implications. The linear correlation between the degree of weathering and Schmidt hammer readings offers a practical method for assessing weathering conditions. Grade I marble exhibited Schmidt hammer rebound values greater than 45, while values ranged between 35 and 45 for Grade II and were less than 35 for Grade III. The stress-strain curve revealed a decrease in peak stress (from 60 MPa to 32 MPa) with saturation. The recommended correlations of UCS with other marble properties are presented below. These results enhance the understanding of Ghulmet marble's mechanical behavior and its suitability for diverse applications. The importance of considering varying conditions and characteristics in geotechnical assessments is emphasized.

Correlations	Empirical relations
UCS, N and Sr	$UCS = 14.1 + 0.609N - 7.55Sr$
UCS and UPV	$UCS = 2.6e^{0.96vp}$
UCS and PLI of dry samples	$UCS = 19PLI - 26$
UCS and PLI of saturated sample	$UCS = 6.64PLI + 17.5$
Dry samples	$UCS = 4.0712e^{0.0552N}$
Saturated samples	$UCS = 6.67e^{0.049N}$

Authors' Contribution

Naeem Abbas and Kausar Sultan Shah, proposed the main concept and involved in write up. Javed Akhter Qureshi assisted in establishing sequence stratigraphy of the section. Hawas Khan, collected field data. Jibran Hussain, did provision of relevant literature, and review and proof read of the manuscript. Amjad Ali, did technical review before submission and proof read of the manuscript. Amjad Ali and Naeem Abbas, did collection of field data. Kausar Sultan Shah and Jibran Hussain, was involved in 14 assistance in preparation of illustration and plates of figures.

References

Abbas, N., 2022.The size correction and correlation of point load index with compressive strength of dimension stones from north Pakistan. Scientific Mining Journal, 61(4), 185-191. DOI: 10.30797/madencilik.977231.

Abbas, N., Li, K. G., and Ali, R., 2022. Correlation of Schmidt Hammer Rebound Number and Point Load Index with Compressive Strength of Sedimentary, Igneous and Metamorphic Rocks. Journal of Mining Science, 58(6), 903-910. doi:10.1134/S1062739122060047.

Altindag, R., and Güney, A., 2006. ISRM suggested method for determining the Shore hardness value for rock. International Journal of Rock Mechanics and Mining Sciences, 43(1), 19-22.

Aydin, S., 2008. An investigation on the language anxiety and fear of negative

evaluation among Turkish EFL Learners. Asian EFL Journal, 30, 421-444.
Bilgin, N., Seyrek, T., Erding, E., and Shahriar, K., 1990. Roadheaders plean valuable tips for Istanbul metro. Tunnels and Tunnelling, 22(10), 29-32.
Eberhardt, E., 2009. The Complete ISRM Suggested Methods for Rock Characterization, Testing and Monitoring: 1974–2006, Resat Ulusay, John A. Hudson (Eds.). Commission on Testing Methods, International Society for Rock Mechanics. 628pp.
Gokceoglu, C., and Aksoy, H., 2000. New approaches to the characterization of clay-bearing, densely jointed and weak rock masses. Engineering Geology, 58(1), 1-23.
Goodman, R. E., 1989. Introduction to rock mechanics, Wiley New York.
Goudie, A.S., 2016. The Schmidt Hammer in geomorphological research. Progress in Physical Geography, 30(6), 703-718.
Han, J., Wang, Y., Wang, S., Yu, H., Rong, K., Zhang, W., Cai, H., An, G., Wang, H., Xue, L., and Zhou, J., 2017. Mode filling factor of a laser with end-pumped configuration. Journal of Laser Applications, 29, 031501. 10.2351/1.4990655.
Hatheway, A., 2009. The Complete ISRM Suggested Methods for Rock Characterization, Testing and Monitoring; 1974-2006. Environmental and Engineering Geoscience, 15, 47-48. 10.2113/gseegeosci.15.1.47.
Huang, S., and Yu, S., 2022. Effect of water saturation on the strength of sandstones: experimental investigation and statistical analysis. Bulletin of Engineering Geology and the Environment, 81(8), 323.
Kahraman, S., Bilgin, N., and Feridunoglu, C., 2003. Dominant rock properties affecting the penetration rate of percussive drills. International Journal of Rock Mechanics and Mining Sciences, 40(5), 711-723.
Karakul, H., and Ulusay, R., 2013. Empirical correlations for predicting strength properties of rocks from P-wave velocity under different degrees of saturation. Rock Mechanics and Rock Engineering, 46(5), 981-999.
Karpuz, C., 1990. A classification system for excavation of surface coal measures. Mining Science and Technology, 11(2), 157-163.
Khan, N.M., Cao, K., Yuan, Q., Mohd Hashim, M.H.B., Rehman, H., Hussain, S., Emad, M.Z., Ullah, B., Shah, K.S., and Khan, S., 2022. Application of machine learning and multivariate statistics to predict uniaxial compressive strength and static Young's modulus using physical properties under different thermal conditions. Sustainability, 14(16), 9901.
Kidybiński, A., 1968. Rebound number and the quality of mine roof strata. International Journal of Rock Mechanics and Mining Sciences and Geomechanics Abstracts, Elsevier.
Masoumi, H., Horne, J., and Timms, W., 2017. Establishing empirical relationships for the effects of water content on the mechanical behavior of Gosford sandstone. Rock Mechanics and Rock Engineering, 50, 2235-2242.
Miller, R.P., 1965. Engineering classification and index properties for intact rock, ProQuest Dissertations Publishing.
Mishad, A., Mohd Hashim, M.H.B., Ibrahim, A., Lian, O.C., Zainal, A.H., and Raizamzamani, M., 2022. FEM on Short-Term Chloride Penetration on Carbon Fibre Reinforced Polymer (CFRP) Strengthened to RC Beam, Green Materials and Electronic Packaging Interconnect Technology Symposium, Springer Nature Singapore Publisher, 233-246.
Pasamehmetoglu, A.G., Karpuz, C., and Irfan, T.Y., 1981. The Weathering Characteristics of Ankara Andesites from the Rock Mechanics Point of View. Paper presented at the ISRM International Symposium, Tokyo, Japan, September 1981.
Shah, K.S., Abbas, N., Kegang, L., Mohd Hashim, M. H. B., Rehman, H.U., and Jadoon, K.G., 2023. Analysis of Granite Failure Modes and Energy Conversion Under Uniaxial Compression at Various Temperatures. Journal of Mining and Environment, 14(2), 493-506.
Shah, K.S., Mohd Hashim, M.H.B., Rehman H.U., and Ariffin, K.S.B., 2021.

Application of stochastic simulation in assessing effect of particle morphology on fracture characteristics of sandstone. Journal of Mining and Environment, 12(4), 969-986.

Shah, K.S., Mohd Hashim, M.H.B., Rehman, H., and Ariffin, K.S.B., 2023. Loading rate-induced failure characteristics and fracture classification of various weathering grade sandstone. Arabian Journal of Geosciences, 16(6), 384.

Shah, K.S., Mohd Hashim, M.H.B., Rehman, H.U., and Ariffin, K.S.B., 2022. Evaluating microscale failure response of various weathering grade sandstones based on micro-scale observation and micro-structural modelling subjected to wet and dry cycles. Journal of Mining and Environment, 13(2), 341-355.

Ulusay, R., 2015. The ISRM Suggested Methods for Rock Characterization, Testing and Monitoring: 2007-2014. 10.1007/978-3-319-07713-0.

Yagiz, S., 2009. Predicting uniaxial compressive strength, modulus of elasticity and index properties of rocks using the Schmidt hammer. Bulletin of Engineering Geology and The Environment, 68(1), 55-63.

Yilmaz, S., Eryilmaz, A., and Geban, O., 2006. Assessing the Impact of Bridging Analogies in Mechanics. School Science and Mathematics, 106, 220-230. https://doi.org/10.1111/j.1949-8594.2006.tb17911.x

Yin, J.-H., Wong, R.H., Chau, K.T., Lai, D.T., and Zhao, G.-S., 2017. Point load strength index of granitic irregular lumps: Size correction and correlation with uniaxial compressive strength. Tunnelling and Underground Space Technology, 70, 388-399.

Young, R., and Fowell, R., 1978. Assessing rock discontinuities. Tunnels and Tunnelling International, 10(5), 45-48.