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PHYSIO-MECHANICAL PROPERTIES OF MINAWAR GRANITE: IMPLICATIONS FOR BUILDING STONE IN GILGIT-BALTISTAN, PAKISTAN

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EXTENDED ABSTRACT

Il presente studio ha come scopo la valutazione delle proprietà fisico-meccaniche del granito Minawar, nella regione settentrionale del Gilgit-Baltistan (G-B), in Pakistan. Il granito, come pietra da costruzione, è stato apprezzato per secoli per la sua resistenza, durevolezza e proprietà estetiche.

L'obiettivo principale della ricerca è quello di fornire una comprensione approfondita delle caratteristiche fisico-meccaniche del granito Minawar per indirizzare la futura gestione della risorsa e lo sviluppo edilizio nella zona. Queste informazioni sono particolarmente importanti per le iniziative governative e private nel contesto del corridoio economico Cina-Pakistan (CPEC).

Quattordici campioni di roccia sono stati sottoposti a una serie di test standardizzati, tra cui assorbimento d'acqua, porosità, velocità di impulso ultrasonico (UPV), indice di carico puntuale (PLI), valori di rimbalzo del martello Schmidt, resistenza alla compressione monoassiale (UCS) e prova di trazione indiretta brasiliana (BTS). I valori UCS per i campioni di granito sono stati valutati in diverse condizioni. Le proprietà fisiche, porosità e assorbimento d'acqua, sono state misurate in tre condizioni di saturazione: asciutto, saturo e fresco. La bassa porosità è ampiamente apprezzata nei materiali da costruzione perché si traduce in un'integrità strutturale più efficace ed i bassi livelli di porosità di questo granito lo rendono estremamente durevole e resistente alle intemperie. Pertanto, rimane una scelta eccellente sia per uso interno che esterno.

Per i materiali esposti all'umidità è fondamentale un basso tasso di assorbimento dell'acqua perché riduce la probabilità di deterioramento nel tempo. Il minimo assorbimento d'acqua di questo granito lo rende quindi ideale per luoghi soggetti a esposizione all'acqua, come fondamenta e pareti esterne.

Le caratteristiche fisiche associate alle proprietà meccaniche del granito Minawar mostrano la sua validità per un'ampia gamma di usi edilizi. I nostri risultati rivelano come il granito Minawar soddisfi e superi le specifiche standard delle pietre dimensionali secondo gli standard ASTM, confermando la sua qualità superiore e la sua durata come materiale da costruzione per uso sia interno che esterno. Per la ricerca futura sul granito Minawar, lo studio ha raccomandato di indagare gli effetti della temperatura, poiché ciò potrebbe avere un impatto sostanziale sulla longevità del materiale.

Inoltre, tecniche avanzate come la diffrazione dei raggi X (XRD), la microscopia elettronica a scansione (SEM) e la spettrometria di massa al plasma accoppiato induttivamente (ICP-MS) consentiranno indagini approfondite sulle caratteristiche mineralogiche, chimiche e microstrutturali. Studi comparativi e modelli computerizzati aiuteranno a prevedere le prestazioni del granito Minawar, mentre la collaborazione con le parti interessate del settore garantirà soluzioni pratiche e innovative.

In conclusione questo studio evidenzia come il granito Minawar del Gilgit-Baltistan, grazie alle sue proprietà meccaniche e fisiche, è adatto a varie applicazioni architettoniche e ingegneristiche. Soddisfa gli standard delle pietre da costruzione, confermandosi un materiale affidabile e duraturo per diversi usi edilizi.

La nostra ricerca convalida il granito Minawar come una preziosa pietra da costruzione locale per l'edilizia in Gilgit-Baltistan e progetti in corso nell'ambito del CPEC, auspicando ulteriori studi avanzati necessari per convalidarne pienamente il potenziale.

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ABSTRACT

Granite, as a building stone has been valued for centuries due to its strength, durability, and aesthetic properties. Granitic rock deposits are abundant in Pakistan, mostly in the northern regions that include the Himalayas and Trans-Himalayas. The present study aimed to investigate the physio-mechanical properties of Minawar granite, located near Gilgit city in Gilgit-Baltistan, Pakistan to assess its suitability as a construction material. Various standardized tests were performed on 14 rock samples, including uniaxial compressive strength (UCS), Schmidt hammer rebound values, point load index (PLI), ultrasonic pulse velocity (UPV), Brazilian tensile strength (BTS), porosity, and water absorption. Results reveal that fresh granite samples had an average UCS of 138.9 MPa, whereas dry and saturated samples had lower UCS values. Schmidt Hammer testing conducted on-site with natural environmental conditions impacted rebound values to be higher than those obtained in laboratory experiments. PLI values (5.32 to 9.13 MPa) revealed granite's variability, although UPV measurements proved its high quality, with uniform density and few internal faults. The BTS tests showed an average tensile strength of 17.76 MPa. Moreover, the water absorption of the granite samples was very low - average of 0.21% for a fore mentioned commercial granites which is the reason to have an extremely good physical endurance considering material durability and resistance to weathering; low porosity and low water absorption make it ideal for moisture-rich conditions. Our results reveal that the Minawar granite meets and exceeds standard dimension stone specifications, confirming its superior quality and durability as a construction material for both indoor and outdoor use. These findings provide useful insights for future construction projects, demonstrating Minawar granite's ability to deliver higher performance and longevity.

Keywords: *minawar granite, physio-mechanical properties, building stone, Gilgit Baltistan, CPEC.*

INTRODUCTION

Globally (Fig. 1), granite is found across all continents in diverse tectonic settings and geological conditions (Migon, 2006). It is valued for centuries due to its exceptional durability, elegance, heat-resistance and weather resilience feature, making it an important building stone (Erdinç, 2023; Li & Ren, 2011; Vasconcelos *et alii*, 2008; Yaseen *et alii*). Granite quarrying is a constraint for building long-lasting roads, bridges, and structures (Shukla & Kaul, 2024), with growing global demand driven by its strength and increasing use in building decoration. Rocks that can be shaped into blocks and slabs, such as granite, marble, limestone, and sandstone, are ideal for construction due to their durability and availability (Walle *et alii*, 2000).

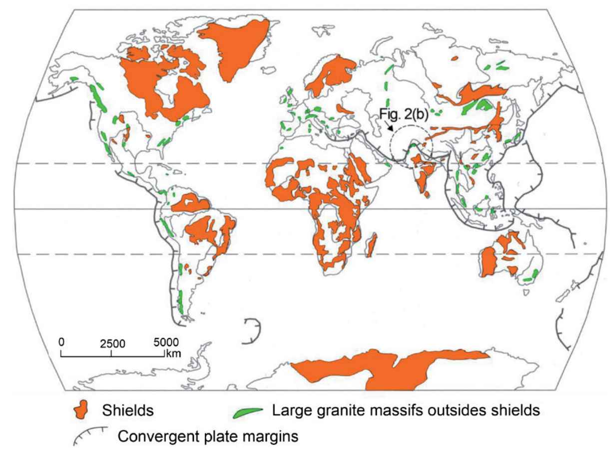

Fig. 1 - Global distribution of granite massifs, modified after (Migon, 2006), with the location of Figure 2(b) marked by a circle. Note: Within geological shields, granite usually coexists with other igneous and metamorphic rocks, but distinguishing them on this map is difficult due to scale limitations

As an under-developed country, Pakistan needs affordable and naturally occurring building stones. Besides being accessible and easy to quarry, the stone must meet requirements for strength, hardness, workability, porosity, durability, and appearance (Eren & Bahali, 2005). Characteristics like color, texture, and surface finish are normal requirement (Egesi & Tse, 2011). The occurrence of rock suitable as natural stone is influenced by the regional geological history of the area. Each region has its own geological potential for natural stone deposits (Selonen *et alii*, 2014). Before the 20th century, natural building stone was the predominant material used in construction (Eren & Bahali, 2005). However, with the production of modern cement and concrete, the use of natural building stone has decreased in mega structures and has almost disappeared in ordinary structures. Despite this decline, stones are still used in the construction of rock fill dams, retaining walls, as foundation material, armor stone, and especially as decorative and facing material (Mustafa *et alii*, 2015).

Hayden (1915) was the first geologist to report the presence of igneous rocks in the Gilgit Chitral area. After 1950, several scientists (Debon *et alii*, 1987; Khan *et alii*, 1996; Searle *et alii*, 1999; Sharma *et alii*, 1981) studied this region. Hunza and Gilgit districts were both extensively studied by (Guha *et alii*, 1956; Ivanac, 1956) and (Bakr & Jackson, 1964), which initially highlighted the potential of these regions as source of building stone. The physio-mechanical response of rocks utilized as building and dimension stones is frequently documented in the literature (Siedel & Siegesmund, 2014; Sousa, 2014; Vazquez *et alii*, 2018). These properties are influenced by numerous factors, with the mechanical behaviour of the rock typically resulting from various influencing factors such as weathering and porosity (Selonen *et alii*, 2014; Sousa & Gonçalves, 2013; Tuğrul & Zarif, 1999; Ündül, 2016). As rocks serve as construction materials, the industry strives to meet all physical and mechanical standards to ensure their suitability (Siedel & Siegesmund, 2014; Siegesmund & Török, 2010). Strength is a crucial property that impacts the mechanical quality of building stones. The Uniaxial Compressive Strength (UCS) of intact rock is a key parameter in almost all engineering projects (Zorlu *et alii*, 2008). It is the most vital parameter required and assessed for mechanical studies in most civil and mining projects (Dehghan *et alii*, 2010). Higher tensile strength is necessary for rocks used as facing stones (Bell, 2007). Besides the structural loading on masonry foundations, tensile strength is also essential for the stone to resist environmental stresses such as strong wind action causing suction on the outer masonry, vibrations, and warping of stone from insufficiently sized slabs (Kimura *et alii*, 1987). Durability is a key factor in determining the suitability of a rock for use as a building stone (Sims, 1991).

In Gilgit-Baltistan (GB), granite is highly valued for its durability and local availability, making it a first choice for building and dimension stones (Ahmed *et alii*, 2021; Malkani, 2020; Zahir *et alii*, 2022). Historically, it has been used for constructions such as Hunza's Altit and Baltit Forts, as well as the Shiger and kharpocho forts (Azeem *et alii*, 2024; Ovais *et alii*, 2023). Apart from these historical structures, granite is widely used in commercial and government facilities such as government and private buildings, schools, colleges, universities, and bridges (Ovais *et alii*, 2023). Despite its widespread use, the strength properties of granite from various places in GB have not been extensively studied. This oversight is important, as understanding these properties is essential in determining the material's suitability for building uses.

Therefore, present research aimed to fill in the lack of experimental data by studying the physical and mechanical characteristics of Minawar granite located at coordinates 35° 88' N latitude and 74° 38' E longitude (Fig. 3). This location is easily accessible from Gilgit city, and its proximity to the main road simplified fieldwork logistics. The Minawar District in GB holds strategic importance due to the Karakoram Highway, i.e., the only road link between China and Pakistan. It is the part of $65 billion China Pakistan Economic Corridor (CPEC) project (Afzal & Naseem, 2018; Ali, 2020; Khan & Khan, 2019), to facilitate trade and tourism between China, Pakistan, and other regions (Shahzad & Javaid, 2020). Our study will be helpful in opening new channels for economic exploitation and mega infrastructure development in the area, especially within the context of the CPEC.

GEOLOGICAL SETTING

Pakistan is one of the countries with significant granitic rock formations, particularly in the northern part (Sajid & Arif, 2015). These rocks are found in extensive geological belts extend through the Himalayas and Trans-Himalayas (Coward *et alii*, 1982; George *et alii*, 1993; Islam *et alii*, 2005; Zeitler, 1985). They include, from north to south, Khunjerab Pamir granitic belt, Karakoram belt, Kohistan granitic belt and Higher Himalayan granitic belt (Ali *et alii*, 2020; Searle, 1986). Generally, the GB in northern Pakistan comprises of three tectonostratigraphic units: the Nanga Parbat Haramosh Massif (NPHM) (Treloar *et alii*, 2000), the Kohistan Island Arc (KIA) (Searle *et alii*, 1999), and the Karakoram Block, separated by major thrusts and suture zones (Searle, 1986; Searle & Treloar, 2010) (Fig. 2).

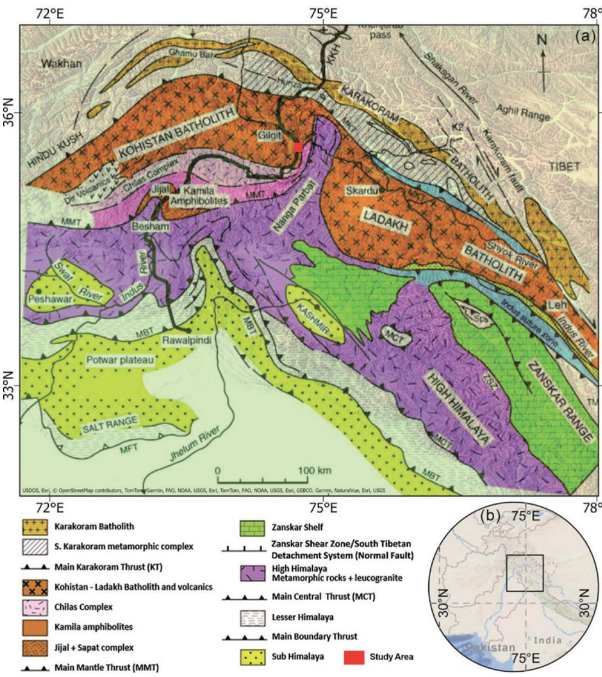

Fig. 2 - (a) Geological map of the NW Himalayan region, illustrating the tectono-geomorphic zones, major tectonic boundaries, modified after Searle and Treloar (2010)., with its location marked in (b). The location of the study area is shown by a red rectangle. The map highlights key features such as the Main Boundary Thrust (MBT), Main Central Thrust (MCT), and Indus Suture Zone (ISZ), providing insights into the complex tectonic and geological evolution of the area

The KIA includes igneous and sedimentary rocks from the Cretaceous period. The Kohistan Batholith, the main unit of the KIA, is made up of gabbro-diorites, trondhjemite, granites, and leucogranite sills and dykes. The South Karakoram Metamorphic Zone and Karakoram Batholith are part of the Karakoram Block (Searle, 1991). The Main Mantle Thrust in the south marks the contact between the metamorphosed rocks in the Indian plate and Calc-alkaline igneous rocks of KIA as shown in Figure 2. The Main Karakoram Thrust, located to the northern most thrust fault in Pakistan, marks the boundary between the KIA and southern metamorphic belt of the Eurasian Karakoram Block (Searle, 1986). The NPHM consists of a relic of metasedimentary rocks

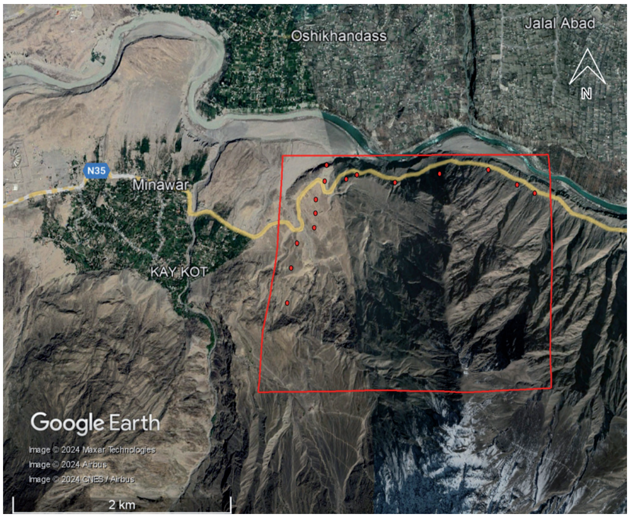

Fig. 3 - Location and accessibility map of the study area, depicting the sample collection site (Red rectangle) in the Minawar area and adjoining regions, with its location marked in Figure 1(a). Red circles represent the sample locations

from the Proterozoic basement of the Indian Plate (ZEITLER *et alii*, 2001). Comprising migmatite, quartz, and feldspathic gneisses with minor calcareous gneisses and amphibolite and is intruded by pegmatites and leucogranites formed by partial melting as a result of late Cenozoic uplift (QURESHI *et alii*, 2012).

MATERIAL AND METHODS

To achieve the desired goals, the following method was used, as shown in Figure 4. This study incorporated an organized and systematic procedure that includes several steps.

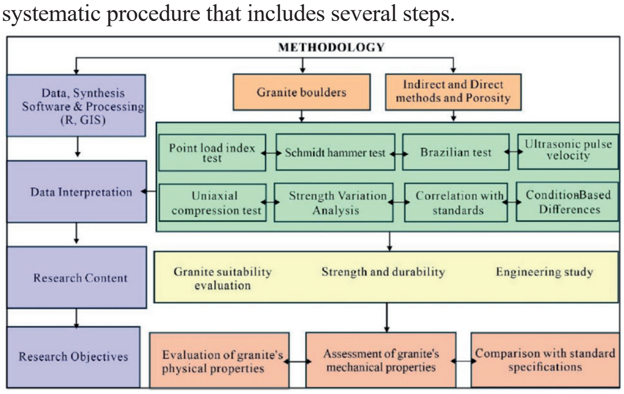

Fig. 4 - Flowchart explaining data acquisition, lab-based tests, and subsequent interpretations

Field surveys and data collection

Granite rock boulders were collected randomly from the outcrop. The granitic rock collected from the field is typically rough and rarely weathered (Fig. 5a). Additionally, a hand-held global positioning system (GPS) is used to provide accurate location information. In addition, Schmidt hammer readings were taken from intact granite rocks at the sampled locations to correlate these results with UCS destructive values. A rock classification hammer (45-D0561, L-type), non-destructive portable test device is used for this purpose. This process was carried out according to the ASTM standard. While taking the readings, weathered and rough surfaces affect rebound values (AYDIN & BASU, 2005), so we ensured that the rebound numbers were taken from smooth and fresh surfaces, as illustrated in Figure 5b. After the field test and evaluations were completed, the selected samples were sent to a laboratory for further geotechnical testing. Further analyses and tests were carried out on these samples in the laboratory.

Fig. 5 - (a) Granite outcropped in the study site; (b) Schmidt hammer test in outcrop

Laboratory tests

Core samples were extracted from the raw granite boulder using a core drilling machine in compliance with American Standard for Testing Materials (ASTM) and the International Society of Rock Mechanics (ISRM) standards, and all tests were conducted in the mining department laboratory at Karakoram International University, GB, Pakistan. Figure 6a shows some samples prepared for these tests. The following tests were performed on the prepared samples to assess the physical and mechanical properties of the rock in the study area.

- *Uniaxial compression test*

The uniaxial compression test (UCS) was performed with cylindrical specimens within a length to diameter (L/D) ratio between 2.0 and 2.5; a diameter of 43 mm and average length of 113 mm. A mechanical test was then performed on these specimens through Universal Testing Machine (UTM) by imposing constant Load on the specimen until failure. In accordance with ASTM D2938-95 or ASTM D4543-08E1, the peak load data was utilized to determine the UCS and the stress and strain data were electronically logged.

- *Schmidt hammer test*

For the Schmidt hammer test, a non-destructive method was used to determine the surface strength of the rock by getting rebound numbers (R) on core samples both in the laboratory and in situ (Figure 5b). These rebound numbers were converted to compressive strength using a Equation 1 (Miller, 1965) that includes the unit weight of the rock, providing an index value that indicates the surface hardness:

$$Log10JCS = 0.00088\ (\gamma)\ (R) + 1.01 \qquad (1)$$

here, *JCS* -joint compressive strength (MPa), γ - unit weight of rock (kN/m^3).

- *Point load index*

PLI test was used to calculate the UCS after subjecting fresh sample specimens to both diametric and axial testing under standard laboratory conditions. Table 1 reveals the values of UCS obtained from diametric and axial testing methods and the point load index (PLI) test assisted in the estimation of the UCS because both the methods were used on the specimens. Afterwards, the specimens were placed in the jaws of a point load tester and load was applied until the rock sample failed, whereby a shear (rupture) of failure immediately occurred, and the point load strength index was then calculated using the applied load and the geometric measurements of the sample (Fig. 6b).

- *Ultrasonic pulse velocity*

Ultrasonic Pulse velocity (UPV) test was carried out to find the quality of the rock specimens. An ultrasonic pulse velocity tester was used to examine rinsed fresh samples, which had a coupling agent applied and then had ultrasonic pulses sent through them. The pulse time of flight (TOF) was measured to calculate the wave velocity (Figure 6d).

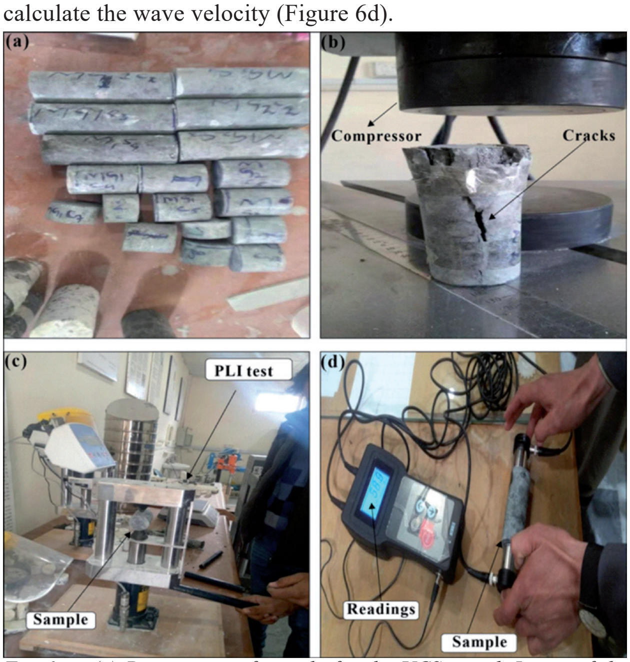

Fig. 6 - (a) Preparation of sample for the UCS test; b Image of the specimen after UCS testing procedure; c Showing the PLI test; d Showing the ultrasonic pulse velocity test

- *Brazilian test*

Fresh cylindrical specimens were subjected to the Brazilian test, which is used to assess the tensile strength of brittle materials and rocks. With flat or curved bearing blocks, these specimens were put within the testing apparatus. Tensile force was applied in the diametrical plane until failure, which caused a tensile crack. The tensile strength was estimated using the maximum load at failure. Equation 2 was used to determine Brazilian tensile strength:

$$\sigma_t = 2P\ /\ (\pi \cdot \mathrm{d} \cdot \mathrm{t}) \qquad (2)$$

here, σ_t - tensile strength in Pascals (Pa), *P* - denotes the maximum load at failure in Newtons (N), *d* - specimen diameter, (m); *t* - thickness of the specimen, (m);

- *Density*

The density of the samples was determined by calculating the weight and volume of each specimen. The density (ρ) was calculated by using following equation:

$$\rho = w\ /\ V \qquad (3)$$

here, ρ - density in kilograms per cubic meter (kg/m^3), *w* - weight of the specimen in kilograms (kg), *V* - specimen's volume in cubic metres (m^3).

- *Porosity and water absorption*

Rock pore structure is an essential factor for determining the parameter of porosity which was calculated by drying samples in an oven at 105°C until a constant weight was achieved and finding the difference between their masses. After dried, they were immersed in water for 48 hours, weighed again to find out the mass changes.

RESULTS

Mechanical Properties

The mechanical properties of the granite samples from the study area were determined through various standardized tests. The comprehensive testing and analysis of the fresh granite samples from Minawar region are summarized in (Table 1).

The UCS values for the granite samples were assessed under different conditions. Fresh granite samples exhibited an average UCS of 138.02 MPa. Dry samples showed a UCS of 122.48 MPa, while saturated samples exhibited a further decrease in UCS, with an average value of 106.6 MPa (Fig. 7). The UCS test stress-strain curves for fresh, dry, and saturated samples are shown in Figure 8.

The Schmidt hammer test results varied between field and laboratory conditions. In situ measurements yielded higher rebound numbers, with the highest value reaching 59, compared to the maximum laboratory value of 48 (Fig. 9). The overall field rebound number was consistently higher, indicating that the test results are affected by the rock surface's natural, undisturbed state. Although laboratory results were lower, they provided a controlled setting

Sample ID	UCS (MPa)	Schmidt Hammer (R)	BTS (MPa)	UPV (m/s)
MGS1	151	52	15.8	3521
MGS2	149	44	7.6	4112
MGS3	136.4	49	13.9	3990
MGS4	144.2	46	20.4	3451
MGS5	136.3	52	15.2	3952
MGS6	156.7	49	12.5	3621
MGS7	120.2	48	20	3454
MGS8	130.5	59	14.1	4211
MGS9	131	47	18.9	3288
MGS10	161.7	44	8.1	4151
MGS11	149.5	52	21	3660
MGS12	145.3	51	13	3544
MGS13	145	44	12.2	3612
MGS14	156	49	15.4	2912
MGS15	157.6	46	13.5	4140

Tab. 1 - Comprehensive testing and analysis of the mechanical properties of fresh granite samples

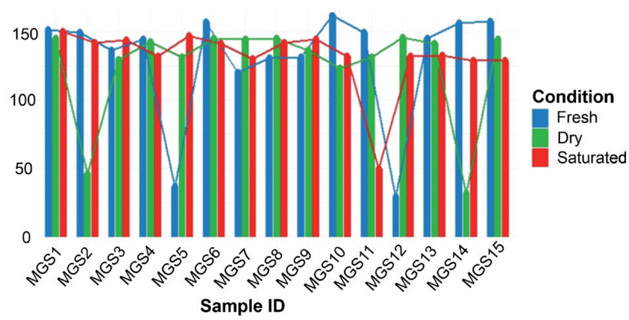

Fig. 7 - UCS values of granite samples under different conditions

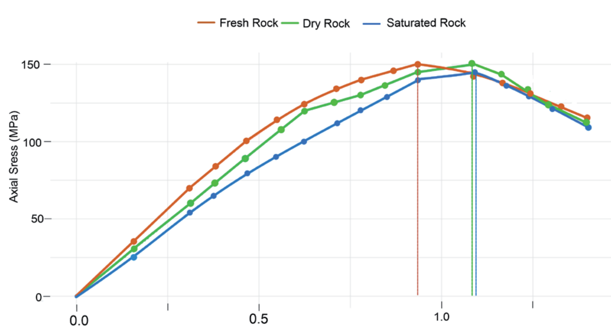

Fig. 8 - Stress-strain curves illustrating the pre-failure behaviour. The three vertical lines mark the resistance peak for each of the three specimen conditions

in which the data could be standardized. The observed variation highlights the need to take into consideration environmental conditions, including scale, when determining rock hardness.

The granite samples had PLI values ranging from 5.32 to 9.13 MPa, with an average of 6.24 MPa. The PLI test is essential for calculating the UCS and other mechanical characteristics of the rock. The variation in PLI values demonstrates the granite's heterogeneity, which is due to changes in mineral composition and particle size. Considering the variance, the PLI test has shown to be a reliable, non-destructive method for testing rock strength,

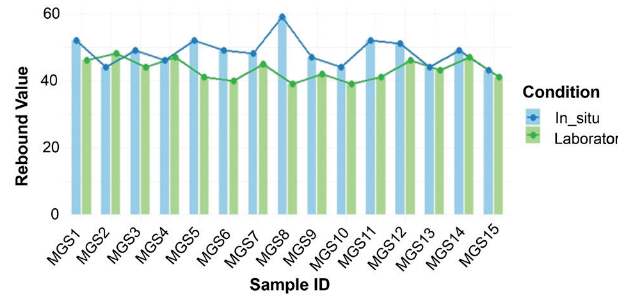

Fig. 9 - Schmidt hammer test results showing rebound values obtained in-situ and laboratory conditions

particularly in field circumstances when fast analyses are required.

The UPV is used to detect cracks, and identify voids within core samples, following ASTM standards (Soil & Rock, 2008). The 58-E4800 UPV tester, a portable, lightweight device with two 54 kHz transducers, was used for testing. In order to ensure effective energy transfer, the core faces were smoothed and a gel was used to form a tight seal against the sample surface. The calculated velocities vary from 3451 to 4211 m/s, showing high material quality with few intrinsic faults. Higher UPV readings indicate denser, more cohesive rock samples. The UPV results supported the findings of the UCS and Schmidt hammer tests, confirming granite's sustainability for construction and buildings. The BTS tests showed an average tensile strength of 17.76 MPa for the granite samples. This technique, utilizing a compressive force to produce tensile failure, provides useful information on the rock's stress behavior. The granite's relatively high tensile strength suggests that it can sustain significant tensile stresses, making it excellent for applications that require great durability and fracture resistance.Figure 10 presents a graphical representation of these results (a) PLI, (b)UPV, and (c) BTS test values.

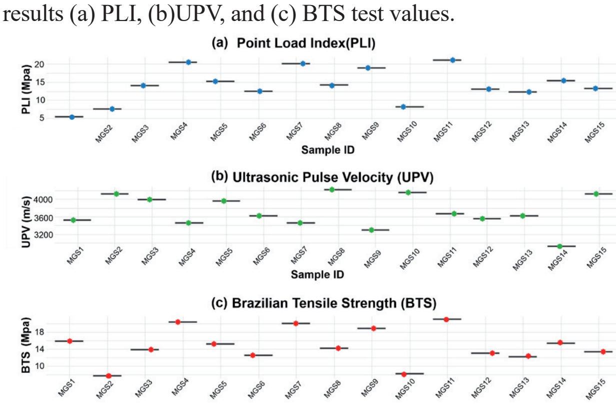

Fig. 10 - Results of test samples: (a) PLI, (b) UPV, (c) BTS

Physical Properties

The hydrostatic weighing method was used to determine the volume unit weight. Three saturation conditions dry, saturated, and fresh were used for the measurements. Measurements of porosity varied from 0.53 to 1.12%. The estimated average was 0.83%. Low porosity is widely valued in construction materials because it results in fewer gaps and, thus, more effective structural integrity. This granite's low porosity levels make it extremely durable and weather resistant. Thus, it remains an excellent choice for both indoor and outdoor use. The results of water absorption tests ranged from 0.11% to 0.33%, with an average of roughly 0.21%. Low water absorption rates are important for materials exposed to moisture because they lower the likelihood of deterioration over time. This granite's minimal water absorption makes it ideal for locations prone to water exposure, such as foundations and exterior walls. Minawar granite's physical characteristics, together with its mechanical properties, show its durability to a wide range of building uses. Table 2 presents a detailed analysis of these physical properties. This overview illustrates both the variety and the good quality of the granite. Furthermore, as shown in figure 10, graphical representations of the porosity, water absorption, and density tests demonstrate the uniformity and good quality of these granite samples. This further highlights their use for a wide range of construction applications.

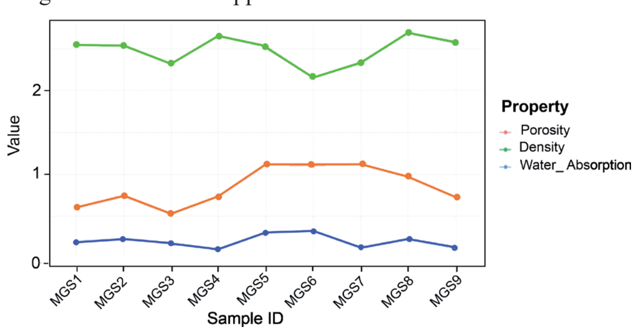

Fig. 11 - Graphical representation of porosity, water absorption, and density tests for granite samples

Sample ID	Porosity (%)	Density (g/cm³)	Water Absorption (%)
MGS1	0.61	2.54	0.21
MGS2	0.74	2.53	0.23
MGS3	0.53	2.32	0.19
MGS4	0.74	2.65	0.11
MGS5	1.12	2.52	0.31
MGS6	1.11	2.16	0.33
MGS7	1.13	2.33	0.13
MGS8	0.98	2.68	0.23
MGS9	0.73	2.57	0.13

Tab. 2 - Comprehensive testing and analysis of the physical properties of Minawar granite samples

DISCUSSION

Our study of Minawar granite samples from northern Pakistan, shows desirable physio-mechanical characteristics that make it suitable for various kinds of engineering purposes. The tests were carried out in accordance with ASTM and ISRM standards, ensuring that the results match with globally recognized standards for dimension stone. The physio-mechanical properties of targeted granite were understood by utilizing field and lab tests. UCS, PLI, and BTS tests indicate high compressive and tensile strength, which is important for its usage as a dimension stone. The low porosity and water absorption add to its durability, making it resistant to natural damage. The UCS results (Table 1 and Supplementary File 1) indicate that Minawar granite maintains a high compressive strength even under complex geological and environmental conditions of proposed study area. Furthermore, UCS values of Minawar granite are high compared to other granites of northern Pakistan (Ahmed *et alii*, 2024; Asif *et alii*, 2024; Yasir *et alii*, 2022). However, the unexpected trend in the stress-strain curve observed after peak value for fresh, dry, and saturated samples in figure 8 raises questions, as the failure behaviour for fresh, dry and saturated samples were anticipated to show significant differences. This inconsistency could be attributed to several factors influencing the anomaly, which includes sample variability, measurement conditions, and uneven moisture distribution within the rock matrix (Jiang *et alii*, 2021; Ojo & Brook, 1990; Stacey, 2008). These factors might account for the observed results, and further investigation is needed to better understand the underlying causes. Additional studies are suggested to explore these aspects in more detail. The Schmidt hammer test findings, both in situ and in the laboratory, provide a surface hardness index that is well correlated with UCS values. The PLI test provides an immediate and efficient approach for estimating UCS in the field, which supports results from the laboratory. The UPV test findings reveal strong internal integrity with slight faults, which increases the rock's reliability for building uses. BTS findings confirm the rock's capacity to endure tensile stresses, which is important for performance in applications involving bending forces or stretching.

The granite's physical characteristics, such as water absorption, porosity, and density, make it suitable for construction. Consistent density suggests a uniform composition and excellent material integrity. Low porosity means fewer voids and more strength, which improves durability and weather resistance. The low water absorption rates indicate durability under severe circumstances, which is important to outdoor structure maintenance. High UCS values show that it can take large loads, making it suitable for bridges, foundations, and walls. Schmidt hammer test results confirm surface hardness and suggest a non-destructive method for quickly determining compressive strength during on-site inspections. The BTS results show that granite has a high tensile strength. This indicates that the granite can sustain stretching stresses without breaking. It is essential for lintels, beams, and cladding that may bend or strain. Further, granite's capacity to endure freeze-thaw cycles with minimal deterioration ensures its ability to endure in hostile climates (Tan *et alii*, 2011). The GB, generally experiences extreme weather conditions (Ali *et alii*, 2024; Aslam *et alii*, 2023; Khan *et alii*, 2020), making granite an excellent choice for outdoor applications that don't require weather-resistant materials. Minawar granite in general, is excellent for a wide range of uses, including road-infrastructure, dam-constructions, decorative purposes and countertops.

For future research on Minawar granite, the study recommended to investigate the effects of temperature, as this may substantial impact on the material's longevity. Furthermore, advanced techniques such as X-ray diffraction (XRD), scanning electron microscopy (SEM), and inductively coupled plasma mass spectrometry (ICP-MS) will allow for extensive investigations of the mineralogical, chemical, and microstructural characteristics. Comparative studies and computerized modelling will assist in predicting the performance of Minawar granite, while collaboration with industry stakeholders will ensure practical and innovative solutions.

CONCLUSIONS

Fourteen rock samples of Minawar granite were studied for its physical and mechanical characteristics. Various field and lab tests were conducted to understand its potential as a building stone. UCS tests revealed that Minawar granite has an average of 130.9 MPa strength, confirming its toughness. However, its strength slightly decreased to 122.48 MPa in both dry and saturated samples due to moisture loss and the water presence. Schmidt hammer tests indicated greater rebound values on-site compared to laboratory conditions. Further, changes in the PLI values of Minawar granite indicate its heterogeneous composition, likely due to variations in mineral concentration and particle size. High UPV readings confirmed the high quality of the Minawar granite, aligning with results from other tests. The BTS results show that Minawar granite has high tensile strength, representing it as durable and break resistant. Physical characteristics i.e., low porosity and low water absorption indicate strong resistance to weathering and environmental impact. Overall, Minawar granite from GB is suitable for various architectural and engineering applications due to its mechanical and physical properties. It meets building stone standards, confirming it as a dependable and long-lasting material for diverse construction uses. Our research pioneer's future research by highlighting Minawar granite as a valuable locale building stone for construction in GB and ongoing projects under the CPEC, with further advanced studies needed to fully validate its potential.

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Declaration of Competing Interest

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

REFERENCES

Afzal S. & Naseem A. (2018) - *China Pakistan economic corridor (CPEC): Challenges and prospects.* Pakistan administrative review, **2**(1): 209-222.

Ahmed I., Basharat M., Sousa L. & Mughal M. S. (2021) - *Evaluation of building and dimension stone using physico-mechanical and petrographic properties: a case study from the Kohistan and Ladakh batholith, Northern Pakistan.* Environmental Earth Sciences, **80**: 1-17.

Ahmed I., Shang Y., Basharat M., Zada K. & Khan B. A. (2024) - *Influence of stress-induced fabric changes on the strength of granites: an insight from the Kohistan and Ladakh Himalayas, Northern Pakistan.* Bulletin of Engineering Geology and the Environment, **83**(9): 369.

Ali A., Jie Y., Ullah R. & Fei X. (2020) - *Geological Characteristics and Petrography of Granite of Baru Area, Malakand, Pakistan*. Pacific International Journal, **3**(1): 19-28.

Ali M. (2020) - *China–Pakistan economic corridor: prospects and challenges*. Contemporary South Asia, **28**(1): 100-112.

Ali N., Ali M. & Hashim H. (2024) - *Predictive model to minimize the effect of extreme temperature in Skardu and Astore, Gilgit Baltistan*. Journal of Mountain Area Research, **9**: 138-148.

Asif A. R., Sajid M., Ahmed W. & Nawaz A. (2024) -*Weathering effects on granitic rocks in North Pakistan: petrographic insights, strength classifications, and construction suitability.* Environmental Earth Sciences, **83**(11): 351.

Aslam M., Hayat R., Pari N., Sameen A. & Ahmed M. (2023) - *Climate Change, Flash Floods and Its Consequences: A Case Study of Gilgit-Baltistan.* In Disaster Risk Reduction in Agriculture. Springer: 293-310.

Aydin A. & Basu A. (2005) -*The Schmidt hammer in rock material characterization*. Engineering geology, **81**(1): 1-14.

Azeem M., Hameed M., Nadeem R., Bhatti W. & Ismat S. (2024) - *An Overview on the History and Architecture of Kharpocho Fort Baltistan*. Bulletin of Business and Economics (BBE), **13**(1).

Bakr M. A. & Jackson R. O. (1964) - *Geological map of Pakistan.* Government of Pakistan, Ministry of Industries and Natural Resources.

Bell F. G. (2007) - *Engineering geology.* Elsevier.

Coward M., Jan M., Rex D., Tarney J., Thirlwall M. T. & Windley B. (1982) - *Geo-tectonic framework of the Himalaya of N Pakistan*. Journal of the

Geological Society, **139**(3): 299-308.

Debon F., Le Fort P., Dautel D., Sonet J. & Zimmermann J. (1987) - *Granites of western Karakorum and northern Kohistan (Pakistan): a composite Mid-Cretaceous to upper Cenozoic magmatism.* Lithos, **20**(1): 19-40.

Dehghan S., Sattari G., Chelgani S. C. & Aliabadi M. (2010) - *Prediction of uniaxial compressive strength and modulus of elasticity for Travertine samples using regression and artificial neural networks.* Mining Science and Technology (China), **20**(1): 41-46.

Egesi N. & Tse C. (2011) - *Dimension stone: Exploration, evaluation and exploitation in southwest parts of Oban Massif Southeastern Nigeria.* Journal of Geology and Mining Research, **3**(4): 115-122.

Erdinç S. Y. (2023) - *A timeless journey of strength and beauty: The potentials of the use of stone in architecture.* Journal of Design for Resilience in Architecture and Planning, **4**(3): 317-338.

Eren Ö. & Bahali M. (2005) - *Some engineering properties of natural building cut stones of Cyprus.* Construction and Building Materials, **19**(3): 213-222.

George M. T., Harris N. B. & Butler R. W. (1993) - *The tectonic implications of contrasting granite magmatism between the Kohistan island arc and the Nanga Parbat-Haramosh Massif, Pakistan Himalaya*. Geological Society, London, Special Publications, **74**(1): 173-191.

Guha S., Madras G. G.-R., Press I., Sankar S. & Saedesai R. (1956) - 876 Bibliography of Asian Studies 1956. Geographical magazine, **273**: 88.

Hayden H. (1915). *Notes on the geology of Chitral, Gilgit and the Pamirs.* Rec. Geol. Surv. India, **45**(4): 1-30.

Islam R., Ahmad T. & Khanna P. (2005) - *An overview on the granitoids of the NW Himalaya*. Him. Geol, **26**(1): 49-60.

Ivanac J. (1956) - *The geology of the NW portion of the Gilgit Agency.* Rec. Geol. Surv. Pakistan, Quetta, **3**: 1-27.

Jiang L. Xu Y., Chen B. & Wu B. (2021) - *Effect of water content on the mechanical properties of an artificial porous rock.* Bulletin of Engineering Geology and the Environment, **80**(10): 7669-7681.

Khan M. Z. U. & Khan M. M. (2019) - *China-Pakistan economic corridor.* Strategic Studies, **39**(2): 67-82.

Khan S., Javed Z. H., Wahid A., Ranjha A. N. & Hassan M. (2020) - *Climate of the Gilgit-Baltistan Province, Pakistan*. International Journal of Economic and Environmental Geology, **11**: 16-21.

Khan T., Asif Khan M., Qasim Jan M. & Naseem M. (1996) - *Back-arc basin assemblages in Kohistan, Northern Pakistan*. Geodinamica Acta, **9**(1): 30-40.

Kimura T., Esaki T., Kameda, N. & Nishida T. (1987) - *Experimental and theoretical studies on strain softening behavior of rock*s. ARMA US Rock Mechanics/Geomechanics Symposium,

Li Y. & Ren S. (2011) - *Building decorative materials*. Elsevier.

Malkani M. S. (2020) - *Mineral resources of Gilgit Baltistan and Azad Kashmir, Pakistan: An Update*. Open Journal of Geology, **10**(6): 661-702.

Migon P. (2006) - *Granite landscapes of the world*. OUP Oxford.

Miller R. P. (1965) - *Engineering classification and index properties for intact rock.* University of Illinois at Urbana-Champaign.

Mustafa S., Khan M. A., Khan M. R., Hameed F., Mughal M. S., Asghar A. & Niaz A. (2015) - *Geotechnical study of marble, schist, and granite as dimension stone: a case study from parts of Lesser Himalaya, Neelum Valley Area, Azad Kashmir, Pakistan*. Bulletin of Engineering Geology and the Environment, **74**: 1475-1487.

Ojo O. & Brook N. (1990) - *The effect of moisture on some mechanical properties of rock*. Mining Science and Technology, **10**(2): 145-156.

Ovais H., Zaheer M. S., Sikandar F., Mobin S. A. & Talpur B. D. (2023) - *Changing architecture and construction practices in the Gilgit Baltistan region, Pakistan: case of hotel and tourism industry.* Sir Syed University Research Journal of Engineering & Technology, **13**(2): 55-66.

Qureshi A., Sultan A., Rashid A., Ali M., Waheed A., Manzoor S., Baloch M., Matiullah Batool S. & Khan H. (2012) - *Geological and radiological studies of the Mount Arafat, Mekkah, Saudi Arabia*. Journal of Radioanalytical and Nuclear Chemistry, **293**(3): 955-963.

Sajid M. & Arif M. (2015) - *Reliance of physico-mechanical properties on petrographic characteristics: consequences from the study of Utla granites, north-west Pakistan.* Bulletin of Engineering Geology and the Environment, **74**(4): 1321-1330. https://doi.org/10.1007/s10064-014-0690-9

Searle M., Khan M. A., Fraser J., Gough S. & Jan M. Q. (1999) - *The tectonic evolution of the Kohistan-Karakoram collision belt along the Karakoram Highway transect, north Pakistan.* Tectonics, **18**(6): 929-949.

Searle M. P. (1986) - *Structural evolution and sequence of thrusting in the High Himalayan, Tibetan—Tethys and Indus suture zones of Zanskar and Ladakh, Western Himalaya.* Journal of Structural Geology, **8**(8): 923-936. https://doi.org/https://doi.org/10.1016/0191-8141(86)90037-4

Searle M. P. (1991) - *Geology and tectonics of the Karakoram Mountains.* John Wiley & Sons Incorporated.

Searle M. P. & Treloar P. J. (2010) - *Was Late Cretaceous–Paleocene obduction of ophiolite complexes the primary cause of crustal thickening and regional metamorphism in the Pakistan Himalaya?* Geological Society, London, Special Publications, **338**(1): 345-359. https://doi.org/doi:10.1144/SP338.16

Selonen O., Ehlers C., Luodes H., & Härmä P. (2014) - *Exploration methods for granitic natural stones--geological and topographical aspects from case studies in Finland*. Bulletin of the Geological Society of Finland, **86**(1).

Shahzad M. K., & Javaid U. (2020) - *Strategic significance of CPEC: a game changer for Pakistan*. J. Pol. Stud., **27**: 107.

Sharma K. K., Sharma O., Choubey V. M. & Nagpaul K. (1981) - *Age of the Ladakh-Deosai granite batholith, Trans-Himalaya.* Current Science, **50**(18): 819-821.

Shukla S. K. & Kaul S. (2024) - *1 Advanced Building.* Thermal Evaluation of Indoor Climate and Energy Storage in Buildings, **1**.

Siedel H. & Siegesmund S. (2014) - Characterization of stone deterioration on buildings. In: *Stone in architecture: properties, durability*. Springer: 349-414.

Siegesmund S. & Török Á. (2010) - *Building stones. In Stone in architecture: properties, durability*. Springer: 11-95.

Sims, I. (1991). *Quality and durability of stone for construction.* Quarterly Journal of Engineering Geology and Hydrogeology, **24**(1): 67-73.

Soil A. C. D.-o. & Rock. (2008) - *Standard test method for laboratory determination of pulse velocities and ultrasonic elastic constants of rock*. ASTM International.

Sousa L. M. (2014) - *Petrophysical properties and durability of granites employed as building stone: a comprehensive evaluation*. Bulletin of Engineering Geology and the Environment, **73**: 569-588.

Sousa L. M. & Gonçalves B. M. (2013) - *Differences in the quality of polishing between sound and weathered granites.* Environmental Earth Sciences, **69**: 1347-1359.

Stacey D. (2008) - *Fundamentals of Rock Mechanics JC Jaeger, NGW Cook and RW Zimmerman (Eds.): book review*. South African Geographical Journal= Suid-Afrikaanse Geografiese Tydskrif, **90**(2): 147-148.

Tan X., Chen W., Yang J. & Cao J. (2011) - *Laboratory investigations on the mechanical properties degradation of granite under freeze–thaw cycles.* Cold Regions Science and Technology, **68**(3): 130-138.

Treloar P. J., Searle M. P., Khan M. A. & Jan M. Q. (2000) - *Tectonics of the Nanga Parbat syntaxis and the western Himalaya: an introduction*. Geological Society, London, Special Publications, **170**(1): 1. https://doi.org/10.1144/GSL.SP.2000.170.01.01

Tuğrul A. & Zarif I. (1999) - *Correlation of mineralogical and textural characteristics with engineering properties of selected granitic rocks from Turkey*. Engineering Geology, **51**(4): 303-317.

Ündül Ö. (2016) - *Assessment of mineralogical and petrographic factors affecting petro-physical properties, strength and cracking processes of volcanic rocks.* Engineering Geology, **210**: 10-22.

Vasconcelos G., Lourenço P., Alves C. & Pamplona J. (2008) - *Ultrasonic evaluation of the physical and mechanical properties of granites*. Ultrasonics, **48**(5): 453-466.

Vazquez P., Sánchez-Delgado N., Carrizo L., Thomachot-Schneider C. & Alonso F. (2018) - *Statistical approach of the influence of petrography in mechanical properties and durability of granitic stones.* Environmental Earth Sciences, **77**: 1-17.

Walle H., Heldal T. & Sintayehu Z. (2000) - *Building stone of central and southern Ethiopia: deposits and resource potential.* Norges geologiske undersøkelse Bulletin, **436**: 175-182.

Yaseen M., Anjum M. N., Ali Naseem A., Rehman G., Ali M., Inam W., Ali S. H. & Ahmad J. (2021) - *Physio-Mechanical Properties and Geological Features of the Gharam Chashma Granitic Batholith, Southern Margin of Asian Plate, Nw Pakistan: A Regional Geoheritage Diversity. Southern Margin of Asian Plate, Nw Pakistan: A Regional Geoheritage Diversity.* KeAi: International Journal of Geoheritage & Parks: 22 pp.

Yasir M., Ahmed W., Islam I., Sajid M., Janjuhah H. T. & Kontakiotis G. (2022) - *Composition, texture, and weathering controls on the physical and strength properties of selected intrusive igneous rocks from Northern Pakistan*. Geosciences, **12**(7): 273.

Zahir M., Ghani Khan A. & Farooq S. (2022) - *Enquiring the Rocks: Statistical Investigation of Buddhist Stupa Carvings at Chilas Bridge, Gilgit-Baltistan, Pakistan*. South Asian Studies, **38**(2): 116-140.

Zeitler P. K. (1985) - *Cooling history of the NW Himalaya, Pakistan*. Tectonics, **4**(1): 127-151.

Zeitler P. K., Koons P. O., Bishop M. P., Chamberlain C. P., Craw D., Edwards M. A., Hamidullah S., Jan M. Q., Khan M. A. & Khattak M. U. K. (2001) - *Crustal reworking at Nanga Parbat, Pakistan: Metamorphic consequences of thermal-mechanical coupling facilitated by erosion*. Tectonics, **20**(5): 712-728.

Zorlu K., Gokceoglu C., Ocakoglu F., Nefeslioglu H. & Acikalin S. (2008) - *Prediction of uniaxial compressive strength of sandstones using petrography-based models*. Engineering Geology, **96**(3-4): 141-158.

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