



ORIGINAL PAPER

PETROGRAPHIC AND PHYSICO-MECHANICAL CHARACTERISTICS OF THE BIBIOR GRANITOIDS USING GEOTECHNICAL AND STATISTICAL ANALYSIS AT THE NORTHWESTERN MARGIN OF THE KOHISTAN ISLAND ARC

Izhar ULLAH ¹⁾, Syed Mamoon SIYAR ²⁾*, Mumtaz Ali KHAN ¹⁾, Fahad ALSHEHRI ³⁾, Sadaf Fida KHAN ⁴⁾, Sattam ALMADANI ³⁾, Muhammad ZAFAR ¹⁾, Azmat Ullah ORAKZAI ⁵⁾, Muhammad SHAHAB ³⁾*, Taqweem Ul Haq ALI ⁶⁾, Izaz AZIZ ⁷⁾ and Farhat ULLAH ⁸⁾

¹⁾ Department of Earth and Environmental Sciences, Bahria School of Engineering and Applied Sciences, Bahria University, Islamabad 44000, Pakistan

²⁾ Department of Geology, University of Malakand, Chakdara, Dir (L), KP, 18800, Pakistan

³⁾ Abdullah Alrushaid Chair for Earth Science Remote Sensing Research, Geology and Geophysics Department, College of Science, King Saud University 11451, Riyadh, Saudi Arabia

⁴⁾ Department of Geology, University of Peshawar, Peshawar, 25120, Pakistan

⁵⁾ Department of Geology, Shaheed Benazir Bhutto University Sheringal, KP, 18050, Pakistan

⁶⁾ Department of Geology, Bacha Khan University Charsadda 24420, Pakistan

⁷⁾ Mineral Testing Laboratory Minerals Development Department, KP, Pakistan

⁸⁾ Department of Earth Sciences, Quaid-i-Azam University, Islamabad 45320, Pakistan

*Corresponding author's e-mail: mamoon@uom.edu.pk; shahabgeo07@gmail.com

ARTICLE INFO**Article history:**

Received 9 November 2024

Accepted 24 April 2025

Available online 21 May 2025

Keywords:

Granitoid rocks

Petrography

Physico-mechanical properties

Upper Dir

Khyber Pakhtunkhwa

Pakistan

ABSTRACT

The porphyritic granite, coarse-grained foliated granite, and fine-grained granite around the Bibior area were studied to establish the relationship between their petrographic features and physico-mechanical properties. Field observations revealed that the granitoid rocks were generally coarse-grained and porphyritic in texture, with fine-grained equigranular and coarse-grained foliated varieties. Petrographic examination indicates that these granitoids are essentially composed of quartz, plagioclase, and alkali feldspar, which also occurred as groundmass in some of the analyzed samples. The accessory mineral assemblage consists of biotite, muscovite, and hornblende with a trace amount of sericite, chlorite, opaque-ore minerals, zircon, titanite, epidote, apatite, garnet, and hematite. Quartz grains predominantly exhibit undulose extinction, indicating deformation and strained conditions. The behavior and durability of the granitoids as construction materials using physical and mechanical properties were studied, including water absorption, specific gravity, porosity, unconfined compressive strength (UCS), and unconfined tensile strength (UTS). Three different texture varieties were studied, which revealed that these rocks had average values of water absorption 0.25-0.32 %, bulk specific gravity 2.68-2.71 kg/cm³, porosity 0.67-0.87 %, UCS 72.3-129 MPa, and UTS 5.74-13.45 MPa. The statistical analysis of petrographic and physio-mechanical properties shows that the mineral composition, texture, and lower amount of flaky minerals made these rocks stronger, followed by fine-grained granitoid rocks having higher strength values compared to the porphyritic rocks. The overall physio-mechanical assessment suggests that the Bibior Granitoids can be used in construction applications, particularly as dimension stone and embankment fill material.

1. INTRODUCTION

The physical and mechanical properties of the rocks having similar chemical signatures largely depend on the texture and model mineralogical composition. Texture describes the size, shape, and relationship between the mineral grains in a rock (McPhie et al., 1993; Bucher and Frey, 1994). The engineering capabilities of rocks can be ascertained by their intrinsic properties, such as their mineralogy and grain-to-grain interaction (Lundquist and Goransson, 2000; Lindqvist et al., 2007). Many scholars have examined the relationships between the petrographic features of various rock types and their mechanical properties (Shakoor and Bonelli, 1991; Tugrul and Zarif, 1999., Alshehri et al., 2025). The use of a scanning electron microscope (SEM) and polarizing

microscope for computerized image analysis to identify the texture of rocks that correlates with their various mechanical characteristics has been documented by many authors (Akesson et al., 2003). The distribution of grain sizes, the degree of interlocking of grain boundaries in minerals, and the availability of fine-grained minerals all significantly affect mechanical characteristics (Li et al., 2024). Granitic rocks make up a significant portion of northwest Pakistan, and the mechanical properties of granites from Ambela and Malakand have been thoroughly investigated (Din and Rafiq, 1997).

In the current study, three distinct textural types of the Bibior Granitoids, including Bibior Porphyritic Granite (BPGt), Bibior Foliated Granite (BF'Gt), and Bibior Fine-grained Granite (BFGt) were selected

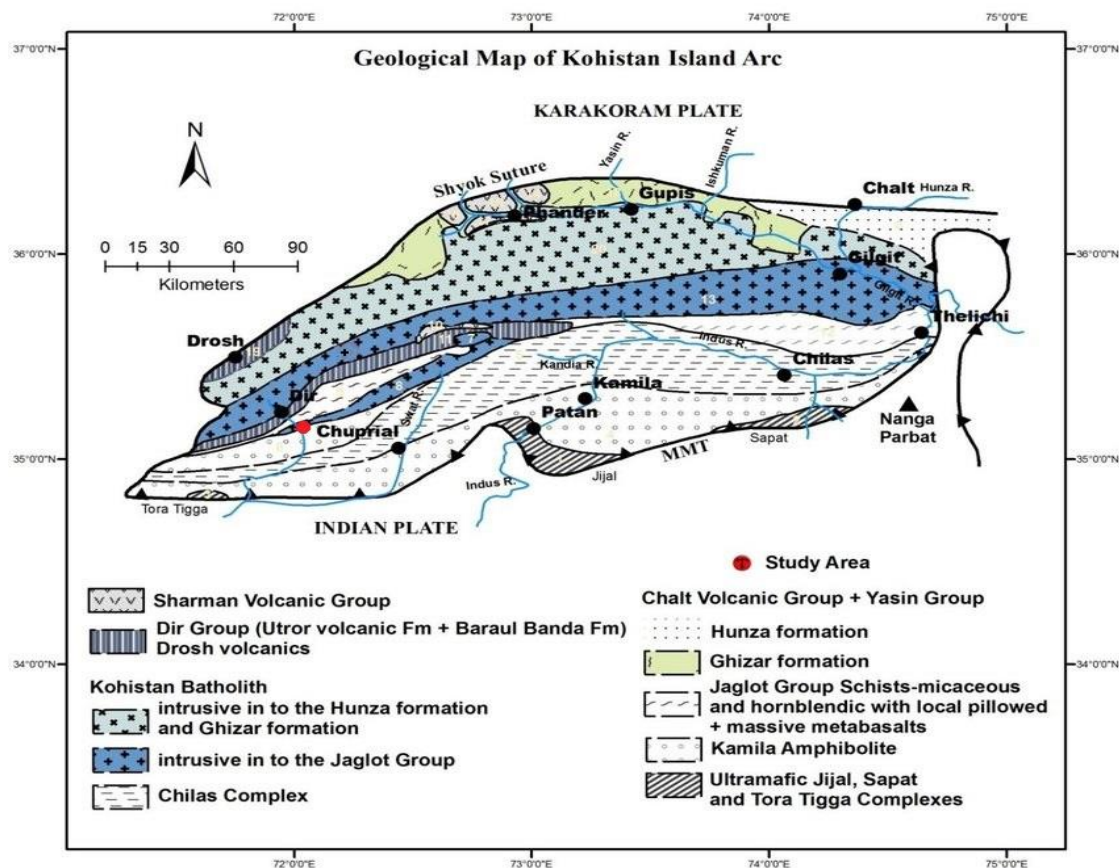


Fig. 1 Geological map of the Kohistan Island Arc, showing the study area (after Arif et al., 2015).

from the Bibior area, District Upper Dir, Pakistan (Fig.1). This study aimed to establish the relationship between the petrographic and mechanical characteristics of the Bibior Granitoids in the Upper Dir District of Pakistan. The relationship between the mechanical and physical characteristics and petrographic factors, such as grain size, distribution, modal mineralogy, and mineral alignment, was ascertained using regression analysis.

2. GEOLOGICAL SETTING

In Northern Pakistan, granitic rocks can be found as minor to massive intrusions (Tahirkheli, 1979). According to Bignold et al. (2006) and Haq et al. (2013), the Barawal Banda meta-sediments cover the Kamila Amphibolite Belt, which extends into Dir Valley. Kamila Amphibolites in the valley have been invaded by the Chilas Complex, a continuous sequence of intrusive igneous rocks (Ullah et al., 2025; Shahab et al., 2025; Treloar et al., 1996;). The Chaudhry et al. (1974) reported the intermixing association of granodiorite and amphibolite rocks as a result of granitic magma acting on pre-existing amphibolites as hornfels, Hyden (1915) termed the rocks granites. They also investigated schist, gneiss, and quartzite rocks. The Bibior area has small bodies of meta-sedimentary rocks, granites, gneisses, syenites, diorite, and granodiorite (Bakr and Jackson, 1964). The diorite resembles those of Kalam

and Khwazakhela, which are close to the study region. Bibior Diorite has intruded these meta-sediments, which also contain quartzite, phyllites, and slate (Sullivan et al., 1993).

The rocks in the Bibior area are composed of granodiorite, with granite, aplite, and pegmatite dykes and stocks intruding the country rocks. According to Chaudhry et al. (1974, 1987), amphibolites are an obducted melange of metamorphosed sequences. The region was further separated into main lithological units by Chaudhry et al. (1974, 1987). (a) Calcareous schists with calcite and quartz veins, whereas Assilina and Nummulite fossils exhibiting Eocene deposits are held by a marly bed. (b) Epidote, quartz, granite, and pegmatite veins can be found in some locations in leuco amphibolites. (c) Mela Amphibolites with veins of granite, pegmatite, quartz-o-feldspar, and epidote (d) Granodiorite (e) Epidote, quartz-o-feldspar, granite veins, and hornblende patches make up the mixed zone. (f) Garnet-bearing quartz-o-feldspathic rock that has been sliced by tiny granite intrusions. (g) Epidote, quartz-o-feldspar veins, pegmatites, and tonalites are all found in hornblendites. (h) Pegmatites and (i) Tonalites.

According to Chaudhry and Chaudhry (1974), the Norite Complex includes gabbro, pegmatites, pyroxenites, hornblende dykes, and quartz-o-feldspathic dykes and veins. Amphibolite, granite, and tonalite rocks are all in contact with the trondhjemite

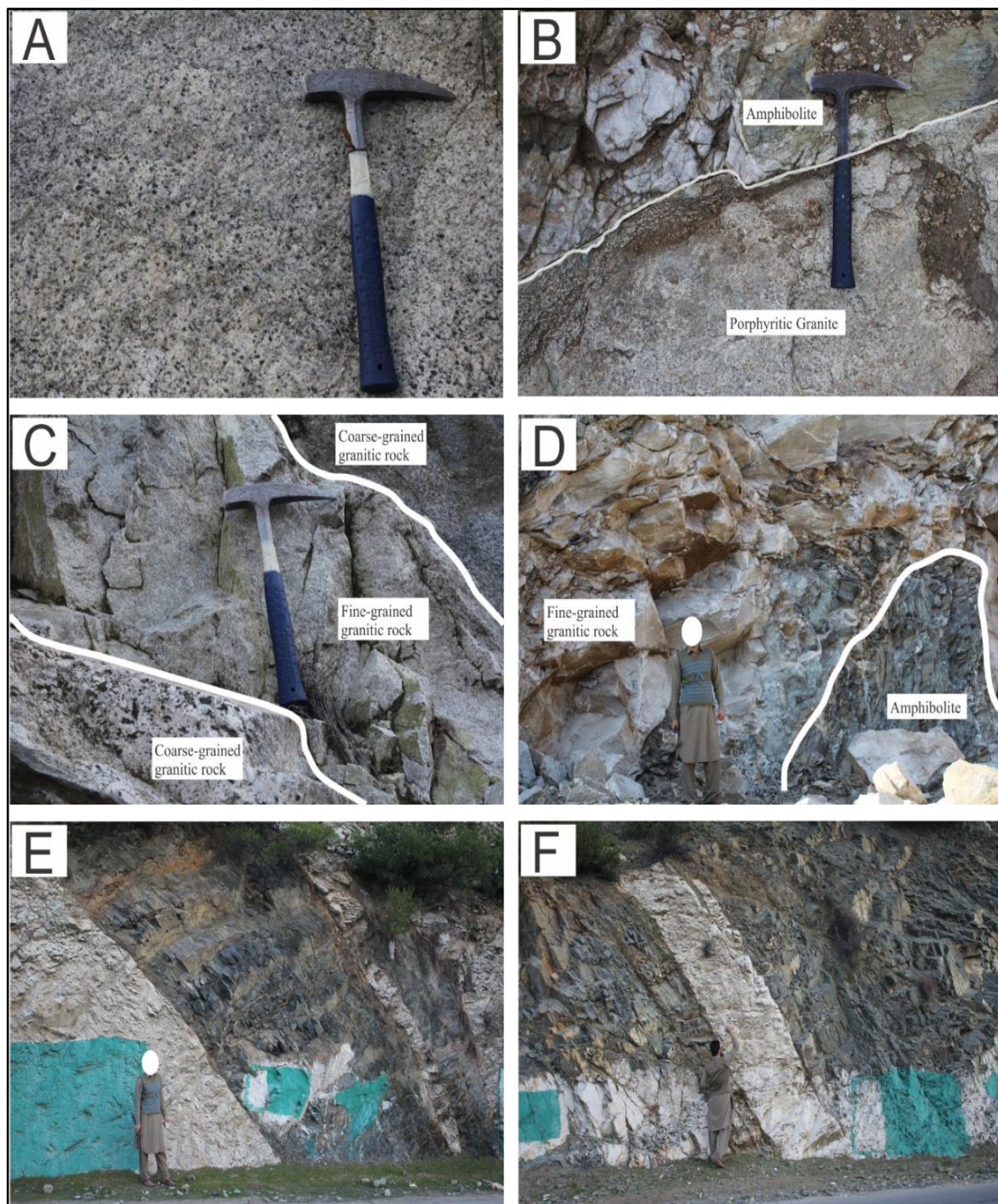


Fig 2 Field photographs: (A) The porphyritic Bibior Granitoids (B) Contact between amphibolite and granitic rocks exposed along the mixed zone in Bibior area (C) Fine-grained granitic intrusion in amphibolite rocks (D) Contact between fine-grained and porphyritic granitic rocks in the study area. (E) Amphibolite dyke cross-cutting the granitic intrusion (F) A small dyke of quartz cross-cutting the amphibolite in the study area.

intrusion. The Complex of Diorite: the primary diorite body, which includes amphibolite, xenoliths, granite, tonalite, mela-diorite, pegmatites, epidosite veins, and quartz-o-feldspathic veins, granite and pegmatite dykes, quartz-o-feldspathic veins, and the assimilation zone are all parts of the amphibolites (epidote mela-amphibolite and plagioclase mela-amphibolite).

3. METHODOLOGY

3.1. FIELD OBSERVATION

The Bibior area is primarily covered by large exposures of igneous and metamorphic rocks. Based on detailed field observations, the major rocks exposed in the area can be divided into two categories: granites and amphibolite, as shown in Figure 2 (A-F). These rocks also contribute as small bodies in the form

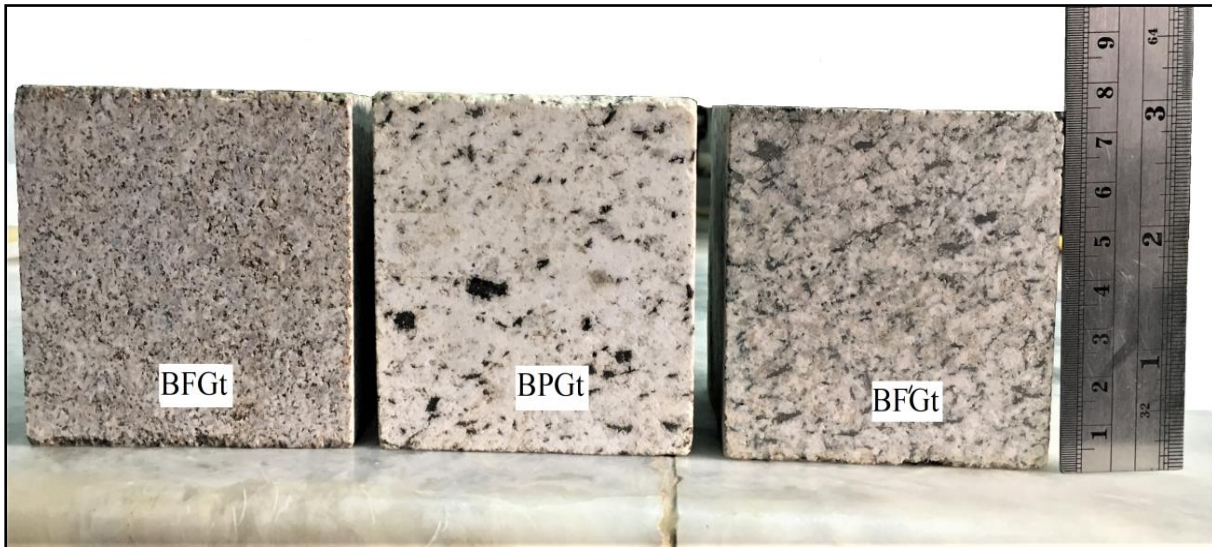


Fig. 3 Cube samples of the different rock textural varieties from the Bibior area. BFGt; Bibior Fine-grained Granite, BPGt; Bibior Porphyritic Granite, and BF'Gt; Bibior Foliated Granite.

of dykes. Igneous rock units are present in large to minor intrusions, and there are igneous intrusion veins and dykes throughout the area. The igneous intrusions vary in lithology and texture, and the rocks are primarily granodiorite, granite, and diorite in nature, with quartz veins present. The rocks color variation is caused by weathered surfaces and can be identified from their fresh bodies. Rocks exhibit deformations along the shear zones and contacts. Both textual and photographic documentation of the most genetically essential field characteristics were identified. Texturally, the Bibior granitic rocks are porphyritic in nature (Fig. 2A). But some varieties are foliated and fine-grained. Amphibolites and granites are closely related in the region. The locations where amphibolite comes into close contact with these granites, they produce dykes. The granitic rocks from the mixed zone have seen significant deformation due to close contact with amphibolite rocks (Fig. 2B). Amphibolite in the study area is intruded by the fine-grained granitic dykes (Fig. 2C). The coarse-grained granitic rock marks close contact with fine-grained igneous rocks at some places (Fig. 2D). Massive amphibolite rocks can also be found in dykes where they have intruded into granitic rocks (Fig. 2E). The region is dotted with quartz veins and dykes (Fig. 2F).

3.2. LABORATORY WORK

A total of 18 representative samples of porphyritic, fine-grained and foliated granites were collected from the study area for petrographic and physico-mechanical analyses. These samples encompass various textural types, including Bibior Fine-Grained Granite (BFGt), Bibior Foliated Granite (BF'Gt), and Bibior Porphyritic Granite (BPGt). To determine the unconfined compressive strength (UCS), 18 cubic specimens, each with dimensions of 3 × 3 inches, were prepared following the guidelines

outlined in ASTM C170 as shown in Figure 3. The physical properties of the samples, including specific gravity, porosity, and water absorption, were assessed using the water saturation method as per ISRM (2007) standards. The obtained UCS values were statistically analyzed in relation to the petrographic characteristics of the samples.

The petrographic thin sections were prepared at the Rock Cutting Laboratory of the Department of Geology, University of Peshawar. The thin sections were studied at the Petrographic Laboratory of the Department of Earth and Environmental Sciences, Bahria University, Islamabad. The physico-mechanical tests were performed at the Geotechnical Laboratory of the National Center of Excellence in Geology, University of Peshawar, and the Material Testing Laboratory at the University of Engineering and Technology, Peshawar, Pakistan.

4. RESULTS AND DISCUSSION

4.1. PETROGRAPHY

The essential minerals in the studied granitic rocks are primarily quartz, alkali feldspar (orthoclase and microcline), and plagioclase, with trace amounts of biotite, muscovite, hornblende, and chlorite. Accessory minerals are sericite, tourmaline, titanite, zircon, epidote, apatite, garnet, and hematite. The modal composition of the investigated granitoid rocks is shown in Table 1. The modal abundance of essential minerals is plotted on the IUGS classification triangle, and the majority of them fall in the compositional field of granite (Fig. 4). The petrographic details for each rock variety are presented in the following paragraphs.

FINE- GRAINED GRANITIC ROCKS

The representative samples of the fine-grained granitic rocks of the Bibior Granitoids were studied for petrographic observations. The petrographic

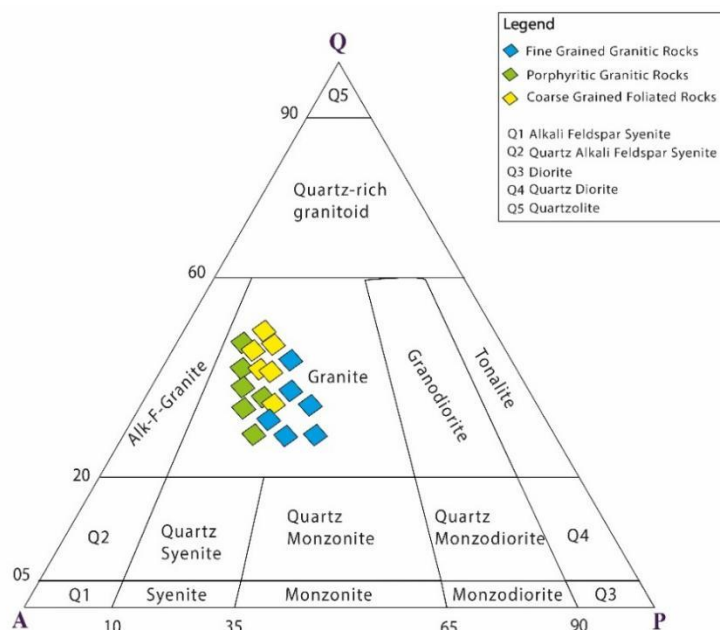


Fig. 4 QAF classification diagram for the studied granitoids from Bibior area (after Le Maitre, 2002).

Table 1 Modal mineralogical composition of the Bibior Granitoid.

S.no	Qtz	Afs	Pl	Bt	Ms	Tur	Opq	Ep	Chl	Hbl	Ser	Grt	Hem	Zrn	AP
Fine-Grained Granitic Rocks															
BFGt-1	38	33.8	10.5	3.6	4	--	3.6	0.5	2	2.8	1.2	--	--	--	--
BFGt-2	39	31	18	5.8	2.8	--	1	--	1.4	1	--	--	--	--	--
BFGt-3	38	36	14	5.4	3	--	2.4	--	1.2	--	--	--	--	--	--
BFGt-4	37	32.5	17.8	5.2	5	0.8	1.7	--	--	--	--	--	--	--	--
BFGt-5	39	34.4	13	6	4	--	2	--	--	1.6	--	--	--	--	--
BFGt-6	37.5	37	13	5.7	3.8	--	1.25	0.05	1.7	--	--	--	--	--	--
Porphyritic Granitic Rocks															
BPGt-1	33.5	26	21.4	9.8	2.28	--	3.6	0.5	3	1	--	--	0.02	--	--
BPGt-2	34	29	19	8	1.8	--	1	--	2.3	--	1.6	0.3	--	--	--
BPGt-3	34	30.6	20.5	4.5	0.8	--	2.4	--	3	2	1.2	--	--	--	--
BPGt-4	36.5	25.5	17	11	3.6	--	1.7	--	1.8	1.8	--	--	--	--	--
BPGt-5	32	26	21	9	3.7	--	2	--	2.2	1.2	--	0.1	--	--	--
BPGt-6	34	26	19	10	3.8	--	1.25	0.05	2.1	--	--	--	0.03	--	--
Coarse-Grained Foliated Rocks															
BF [*] Gt-1	35	22	18	9	3.18	--	5	--	3	--	--	--	4.6	0.2	0.02
BF [*] Gt-2	31.5	27	16.5	11	3.2	1.8	4	--	1.2	--	--	--	3.8	--	--
BF [*] Gt-3	33	27	19	9	3	0.6	5.2	--	1.2	--	--	--	2	--	--
BF [*] Gt-4	33.5	23.6	18	12	4.8	--	6	--	2.02	--	--	--	--	0.08	--
BF [*] Gt-5	29.8	28	21	10	3	1.2	5	--	2	--	--	--	--	--	--
BF [*] Gt-6	32.5	26	19	9	5	--	5.4	--	3.04	--	--	--	--	--	0.06

Key: Qz: Quartz, Afs: Alkali feldspar, Pl: Plagioclase, Bt: Biotite, Ms: Muscovite, Opq: Opaque, Chl: Chlorite, Ser: Sericite, Grt: Garnet, Hem: Hematite, Hbl: Hornblende

observations reveal that quartz, alkali feldspar, plagioclase, biotite, and muscovite are the dominant minerals, with trace amounts of hornblende, tourmaline, epidote, chlorite, sericite, and opaque ore minerals (Figs. 5A-5C, Table 1). The majority of the grains are fine-grained and subhedral to anhedral in shape. Quartz is the most abundant mineral and their modal composition ranges from 37 % to 39 % with an

average of 38.08 %. Majority of the grains are anhedral in shape and display strong undulose extinction (Fig. 5A). The presence of strained quartz, commonly exhibiting undulose extinction, indicates tectonic deformation likely associated with the Himalayan Orogeny. These microstructural features suggest that the granitoids experienced tectonic stress, with quartz responding through internal strain as seen

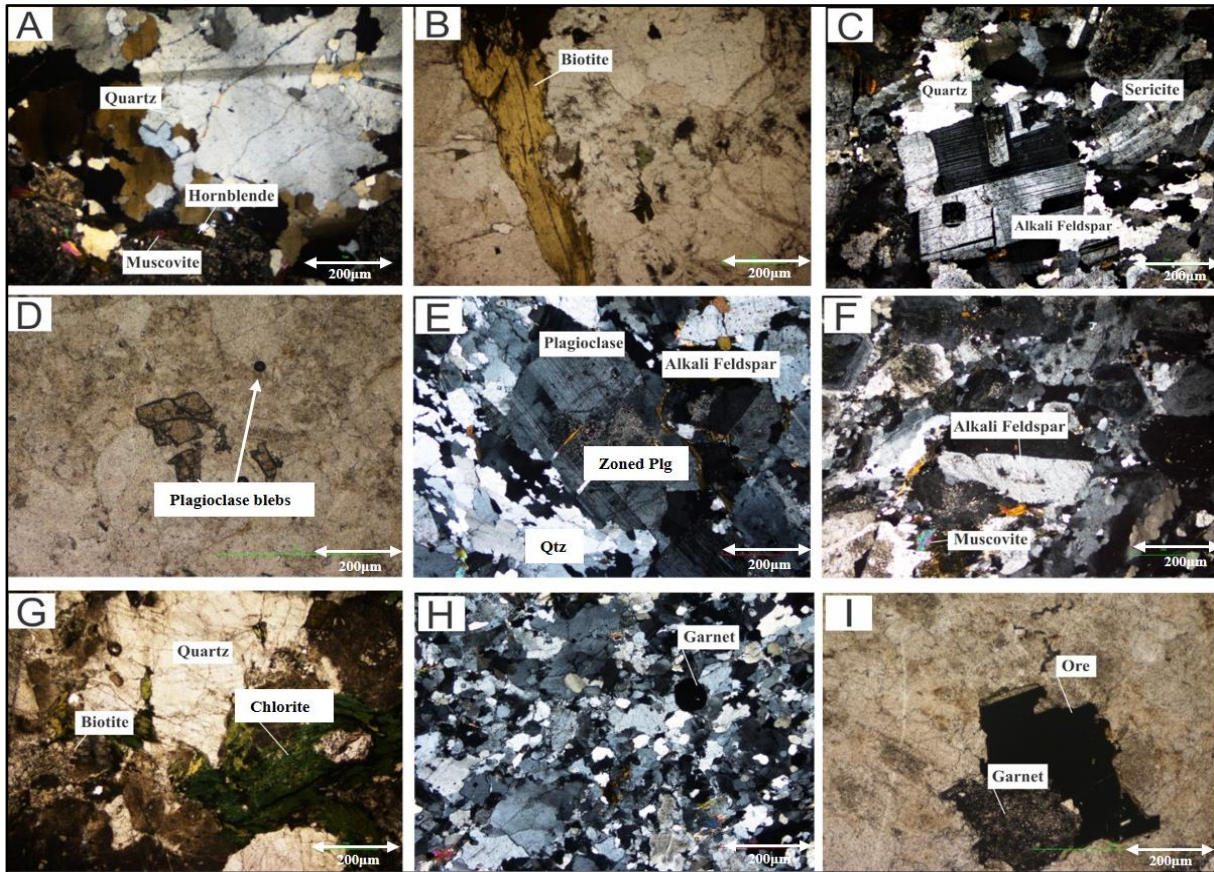


Fig. 5 Photomicrographs: (A, XPL) Unstrained fine-grained quartz grains around a strained (fractured) quartz grain, (B, PPL) Flaky biotite grain, (C, XPL) Blebs of zoned plagioclase, (D, PPL) Titanite (E, XPL) Plagioclase phenocrysts resulted in alteration with sericitization in the core and having fresh boundaries (F, XPL) Alkali feldspar showing simple twinning, (G, PPL) Fully chloritized grain of biotite associated with quartz and muscovite grain, (H, XPL) Garnet grain in fine-grained quartz, (I, PPL) An opaque ore mineral having association with high relief garnet grain.

in undulose extinction pattern (Fig. 5A). The alkali feldspar is next in abundance to the quartz among the essential minerals, and their modal abundance ranges from 31 % to 37 % with an average of 34.12 %. The alkali feldspar is mainly microcline, having inclined extinction and subhedral to anhedral crystal form in association with quartz and plagioclase (Fig. 5C).

Plagioclase is next in abundance to the alkali feldspars, having model compositions from 10.5 to 18 % with an average of 14.38 %. Majority of the crystals are euhedral to anhedral having alteration products of muscovite, sericite, and epidote. Sericitization is the most common hydrothermal alteration product in these rocks (Fig. 5C). The large crystals of biotite are next in abundance to alkali feldspars, with model compositions of 3.6 % to 6 % with an average of 5.28 % (Fig. 5B). The muscovite flakes are next in abundance to the biotite, having model compositions from 2.8 % to 5 % with an average content of 3.76 % (Fig. 5A). The opaque minerals form the well-sufficient portion of these fine-grained granitic rocks, having concentrations ranging from 1 % to 3.6 % with an average content of 1.99 %, followed by the minor contents of chlorite,

hornblende, tourmaline, and sericite.

PORPHYRITIC GRANITIC ROCKS

The porphyritic granitic rocks of the Bibior Granitoids are mainly consist of quartz, alkali feldspars, plagioclase, biotite, and muscovite with trace amount of hornblende, chlorite, hornblende and opaque, epidote, sericite, garnet and hematite. Quartz is the most abundant mineral and their modal composition ranges from 32 % to 36.5 % with an average of 34 %. (Fig. 5E). Majority of the grains are fine-grained and subhedral to anhedral in shape. The alkali feldspar is next in abundance to the quartz among the essential minerals and their modal abundance ranges from 25.5 % to 30.6 % with an average of 27.18 % as shown in Table 1. The alkali feldspar and quartz intergrowth thereby producing a graphic texture, while in other examples, plain twinning is observed in Figure 5E.

Plagioclase, is next in abundance to the alkali feldspars, having model compositions from 17 to 21.4 % with an average of 19.65 %. Majority of the

Table 2 Water absorption, specific gravity, and porosity analysis of the studied samples from the Bibior area of District Upper Dir, Pakistan.

S. No.	Weight in air (g)	Weight in water (g)	Oven dry weight (g)	Water absorption (%)	Specific Gravity	Porosity (%)
Standard Specifications	-	-	-	Max. 1%	>2.5K g/cm ³	
Fine Grained Granitic Rocks						
BFGt -1	1129	705	1125	0.36	2.679	0.94
BFGt -2	1116	698	1112	0.36	2.686	0.96
BFGt -3	1116	698	1113	0.27	2.682	0.72
BFGt -4	1126	703	1123	0.27	2.674	0.71
BFGt -5	1122	701	1119	0.27	2.678	0.71
BFGt -6	1125	702	1121	0.36	2.684	0.94
Porphyritic Granitic Rocks						
BPGt -1	1122	701	1120	0.18	2.673	0.48
BPGt -2	1120	699	1117	0.27	2.672	0.71
BPGt -3	1114	696	1111	0.27	2.677	0.72
BPGt -4	1114	696	1110	0.36	2.693	0.96
BPGt -5	1124	702	1122	0.18	2.672	0.47
BPGt -6	1122	701	1119	0.27	2.668	0.71
Porphyritic Foliated Rocks						
BF'Gt -1	1157	729	1154	0.26	2.715	0.70
BF'Gt -2	1152	726	1149	0.26	2.716	0.70
BF'Gt -3	1125	707	1121	0.36	2.708	0.96
BF'Gt -4	1152	727	1148	0.36	2.712	0.94
BF'Gt -5	1136	718	1132	0.36	2.708	0.96
BF'Gt -6	1129	711	1125	0.36	2.704	0.96

crystals are euhedral to subhedral exhibits pericline and Carlsbad-albite polysynthetic twinning (Fig. 5E). Plagioclase phenocrysts have zonal plagioclase blebs (Fig. 5D). The alteration products of plagioclase are muscovite, sericite, and epidote. Sericitization is mostly present in these minerals. Nevertheless, some of the plagioclase grains have new edges, but their centers exhibit typical zoning due to sericitization (Figs. 5E, 5F). Biotite is next in abundance to the plagioclase having modal composition from 4.5% to 11 % with an average of 8.71%. Biotite mostly occurs as a flake yielding chlorite in response to partial alteration. The chlorite is next in abundance to the biotite having model composition 1.8% to 3% with an average of 2.4%. The chlorite exhibits a flaky to fibrous texture, resulting from the partial alteration of biotite. The muscovite flakes are next in abundance to the biotite having model composition from 0.8% to 3.8% with an average of 2.66%. The epidote, opaque, hornblende, sericite, garnet and hematite recorded their minor concentrations in the porphyritic granitic rocks as shown in Table 1.

FOLIATED GRANITIC ROCKS

The foliated granitic rocks are mainly consisting of quartz, Alkali feldspars, plagioclase, biotite, muscovite, and opaque are the dominant minerals with trace amount of hematite, chlorite, and tourmaline, epidote, sericite, garnet and hematite. Quartz is the most abundant mineral and their modal composition ranges from 29.8 % to 35 % with an average of 32.55 %. Quartz is mostly fine to medium grained present in the groundmass Figure 5H. The foliated variety of granite is composed of large subhedral to

euhedral crystals of plagioclase and alkali feldspar, as shown in Figure 5I. The alkali feldspar is next in abundance to the quartz having modal composition ranges from 22 % to 28 % with an average concentration of 25.8 %. The is next in abundance to the alkali feldspars having modal composition ranges 16.5 % to 21 % with an average of 18.58 %. Plagioclase and alkali feldspar show a cloudy appearance of sericitization in some grains, while poor oscillatory zoning is noticed in plagioclase grains (Fig. 5H). The flakes of biotite are next in abundance to the plagioclase having modal composition ranges 9 % to 12 % with an average of 10 %. The biotite shows partial alteration to chlorite (Fig. 5G). The alteration follows a topotaxial intergrowth pattern, where chlorite preferentially replaces biotite along its cleavage planes as shown in Figure 5G. The epidote, hornblende, sericite, garnet, and hematite recorded their minor concentrations in the foliated grained granitic rock as shown in Table 1.

4.2. PHYSICAL PROPERTIES

WATER ABSORPTION

The water absorption values were determined by using the caliper method and water saturation. The examined samples had water values of less than 1 % and 0.4 % by weight (g). Hence, they can be used as building materials and as dimension stones. The water absorption values of Bibior fine-grained granite (BFGt) range from 0.36 to 0.27 % (Table 2). As the values are less than 1 % and according to the ASTM-C97 method with ASTM C615 standard maximum limit of 0.4 %, these rocks are suitable for construction and building works and can be used as

Table 3 The unconfined compressive strength (UCS) analysis of the studied samples from Bibior Granitoids in the study area.

S. No.	Area (in)	Load (N)	Strength (Psi)	Strength (MPa)
Fine Grained Granitic Rocks				
BFGt -1	9.0	172439	19160	132
BFGt -2	9.0	175183	19465	134
BFGt -3	9.0	149625	16625	115
BFGt -4	9.0	163618	18180	125
BFGt -5	9.0	182242	20249	140
BFGt -6	9.0	166521	18502	128
Porphyritic Granitic Rocks				
BPGt -1	9.0	96381	10709	74
BPGt -2	9.0	94942	10549	73
BPGt -3	9.0	93578	10398	72
BPGt -4	9.0	93943	10438	72
BPGt -5	9.0	95318	10590	73
BPGt -6	9.0	91582	10176	70
Porphyritic Foliated Granitic Rocks				
BF'Gt -1	9.0	164466	18274	126
BF'Gt -2	9.0	136341	15149	104
BF'Gt -3	9.0	138188	15354	106
BF'Gt -4	9.0	129678	14409	99
BF'Gt -5	9.0	146832	16315	112
BF'Gt -6	9.0	162174	18019	124

embankment fill and dimension stones. Similarly, the water absorption values for Bibior porphyritic granite (BPGt) and Bibior foliated granite (BF'Gt) ranges between 0.18 %-0.36 % and 0.36 %-0.26 %, respectively. The values depict that these rocks are suitable for embankment fill material and dimension stones.

BULK SPECIFIC GRAVITY

The specific gravity of the Bibior Granitoids was determined following the ASTM C97 standard practice. The results indicate that Bibior Fine-Grained Granite (BFGt) ranges from 2.674 to 2.686 kg/cm³, Bibior Porphyritic Granite (BPGt) varies between 2.668 and 2.693 kg/cm³, and Bibior Foliated Granite (BF'Gt) exhibits values from 2.704 to 2.716 kg/cm³ as illustrated in Table 2. The values of the studied samples are greater than 2.5 kg/cm³, so these rocks are suitable for construction as embankment fill and dimension stone (Khan et al., 2025).

POROSITY

The porosity of the analyzed Bibior granitic rocks varies across different lithologies. Bibior Fine-Grained Granite (BFGt) exhibits porosity values ranging from 0.96 % to 0.71 %, while Bibior Porphyritic Granite (BPGt) ranges from 0.96 % to 0.47 %, and Bibior Foliated Granite (BF'Gt) falls between 0.96 % and 0.70 %, as shown in Table 4. The relatively low porosity values suggest that these rocks are suitable for use as embankment fill and dimension stones in construction sites.

4.3. MECHANICAL PROPERTIES

UNCONFINED COMPRESSIVE STRENGTH

A universal testing machine was used to conduct the unconfined compressive strength (UCS) tests on cube samples of Bibior Granitoids in accordance with the ASTM-C170 standard (ASTM, 2017). The Bibior Fine-Grained Granite (BFGt) shows high strength values ranging from 115 MPa to 140 MPa (Table 3; Fig. 6). The International Society for Rock Mechanics (ISRM) and the American Geological Society (AGS) divide these rocks into "high" and "very strong" categories, respectively. The strength values of Bibior Porphyritic Granite (BPGt) range from 70 to 74 MPa showing a lower strength value than fine-grained granites because of porphyritic texture. According to the AGS and ISRM classifications, the analyzed rocks fall within the "strong" and "high" strength categories, respectively. Bibior Foliated Granite (BF'Gt) exhibits strength values ranging from 99 MPa to 126 MPa, classifying it as "very strong" and "high," except for sample PFG-4, which has a strength of 99 MPa (Table 3) and remains within the "strong" and "high" categories.

UNCONFINED TENSILE STRENGTH

The Brazilian or splitting tensile strength (UTS) tests were conducted in accordance with the ASTM D3967 standard (ASTM, 2016) and interpreted using the methodology of Bieniawski and Hawkes (1978). The results indicate that UTS values are consistently 8–10 times lower than UCS values (Table 4). All Bibior granitic varieties meet the minimum strength

Table 4 The unconfined tensile strength (UTS) analysis of the studied samples from Bibior Granitoids in the study area.

S. No.	Length (m)	Diameter (m)	Load (N)	UTS (MPa)
Fine-Grained Granitic Rocks				
BFGt-1	0.025	0.044	18940.840	13.271
BFGt-2	0.025	0.044	17672.235	12.382
BFGt-3	0.024	0.044	16428.510	11.050
BFGt-4	0.025	0.044	15138.594	12.046
BFGt-5	0.025	0.044	16905.00	13.452
BFGt-6	0.025	0.044	12430.010	9.902
Porphyritic-Granitic Rocks				
BPGt-1	0.020	0.044	7680.451	4.305
BPGt-2	0.024	0.044	8478.629	5.703
BPGt-3	0.024	0.044	10722.334	7.212
BPGt-4	0.024	0.044	9520.840	6.496
BPGt-5	0.020	0.044	8901.276	5.526
BPGt-6	0.024	0.044	10210.790	6.866
Foliated Granitic Rocks				
BF'Gt-1	0.024	0.044	16782.781	11.288
BF'Gt -2	0.022	0.044	12870.286	7.935
BF'Gt -3	0.021	0.044	14621.610	8.605
BF'Gt -4	0.022	0.044	13892.416	8.245
BF'Gt -5	0.024	0.044	15250.327	9.105
BF'Gt -6	0.022	0.044	14180.773	8.474

requirements specified by ASTM D3967, making them suitable for use as dimension stone and construction materials, except for sample BPGT-1, which exhibits a lower UTS value (Table 4).

Mineralogical analysis reveals that Bibior Fine-Grained Granite (BFGt) contains an average quartz content of 38 %, while Bibior Porphyritic Granite (BPGt) and Bibior Foliated Granite (BF'Gt) have average quartz concentrations of 34 % and 32.6 %, respectively (Table 5). Compared to the BFGt variety, which shows a decrease in UCS and UTS values, the BPGt and BF'Gt varieties exhibit a lower quartz content and a higher proportion of flaky minerals. This difference arises from the greater abundance of quartz matrix and fewer micaceous minerals (biotite and muscovite) in BFGt. The presence of micaceous minerals in BPGt and BF'Gt contributes to foliation, making these rocks more prone to deformation along foliation planes (Lindqvist et al., 2007).

Additionally, an increase in grain size leads to the expansion of pore spaces. As a result, fine-grained Bibior granite exhibits higher water absorption and porosity values compared to the coarser-grained porphyritic and foliated varieties. The high UCS and UTS values of Bibior granitic rocks (Tables 3, 4) further confirm their suitability for load-bearing structural applications.

5. CORRELATION BETWEEN GEOTECHNICAL AND PETROGRAPHIC CHARACTERISTICS

The petrographic and physico-mechanical properties data have been plotted against each other to examine their relationship in the investigated three textural varieties of Bibior Granitoids i.e. BFGt, BPGt, and BF'Gt (Table 5, Figs. 6A-6O). The UCS values of

each sample are plotted against their relative quartz to feldspar ratios in order to evaluate the relationship between the rocks' strength and mineral abundance. This reveals a direct correlation between the two variables. Quartz is thought to be stronger and more resistant to changes. Shakoor and Bonelli (1991) assert that grain contact rather than the percentage of quartz is more crucial in determining the strength of a rock. However, the shape has an impact on the strength of the rocks, because anhedral-shaped quartz fills in the gaps and makes substantial contact with other grains (Tugrul and Zarif, 1999).

The porosity values of each textural type are shown against their quartz to feldspar ratio (Figs. 6I-6J), demonstrating a significant link between these parameters. This is why the UCS values are plotted against the porosity and water absorption values to illustrate their relationship, which yields data that indicate an inverse relationship (Figs. 6M-6O). Moreover, a plot of each sample's UCS and mica content reveals noteworthy findings, indicating that a rock's strength values may be impacted by its mica content. Plotting the unconfined compressive strength (MPa) of fine-grained granite against the ratio of quartz to feldspar reveals that the MPa of the sample increased as the ratio increased (Figs. 6A-6C). This positive behavior is because quartz is stronger and shows more resistance to grain weathering.

The correlation between unconfined compressive strength and the ratio of quartz to feldspar in coarse-grained porphyritic foliated granite reveals that the sample's unconfined compressive strength (MPa) shows an increasing tendency as the ratio increases. The quartz-feldspar ratio directly influences UCS, indicating the sample's growing strength.

Table 5 Plot showing the combined values of minerals content against physico-mechanical properties.

S. No.	Qtz	Afs	Pl	Bt	Ms	Absorption	Specific Gravity	Porosity	UCS
BFGt-1	38	33.8	10.5	3.6	4	0.36	2.679	0.94	132
BFGt-2	39	31	18	5.8	2.8	0.36	2.686	0.96	134
BFGt-3	38	36	14	5.4	3	0.27	2.682	0.72	115
BFGt-4	37	32.5	17.8	5.2	5	0.27	2.674	0.71	125
BFGt-5	39	34.4	13	6	4	0.27	2.678	0.71	140
BFGt-6	37.5	37	13	5.7	3.8	0.36	2.684	0.94	128
BPGt-1	33.5	26	21.4	9.8	2.28	0.18	2.673	0.48	74
BPGt-2	34	29	19	8	1.8	0.27	2.672	0.71	73
BPGt-3	34	30.6	20.5	4.5	0.8	0.27	2.677	0.72	72
BPGt-4	36.5	25.5	17	11	3.6	0.36	2.693	0.96	72
BPGt-5	32	26	21	9	3.7	0.18	2.672	0.47	73
BPGt-6	34	26	19	10	3.8	0.27	2.668	0.71	70
BF'Gt-1	35	22	18	9	3.18	0.26	2.715	0.7	126
BF'Gt-2	31.5	27	16.5	11	3.2	0.26	2.716	0.7	104
BF'Gt-3	33	27	19	9	3	0.36	2.708	0.96	106
BF'Gt-4	33.5	23.6	18	12	4.8	0.36	2.712	0.94	99
BF'Gt-5	29.8	28	21	10	3	0.36	2.708	0.96	112
BF'Gt-6	32.5	26	19	9	5	0.36	2.704	0.96	124

Plotting the unconfined compressive strength of coarse-grained porphyritic granitoid against the ratio of quartz to feldspar reveals that the sample's unconfined compressive strength (MPa) increased as the ratio increased, meaning that the graph indicates an increase in strength and resistance. Results comparing the unconfined compressive strength (MPa) and mica content in fine-grained granite indicate that the MPa decreased as the mica content rose. This demonstrated an indirect influence when compared to the quartz-feldspar ratio status in the same sample. In coarse-grained porphyritic foliated granite, results comparing the unconfined compressive strength (MPa) and mica content show that the MPa stayed constant as the mica content increased, indicating that the mica content did not signal a change in the sample's strength. In coarse-grained porphyritic granite, the relationship between mica content and unconfined compressive strength reveals that the unconfined compressive strength (MPa) decreased as the mica content rise or increasing strength as the mica content in the sample increased (Figs. 6D-6F).

The relationship between porosity and unconfined compressive strength in fine-grained granite revealed that unconfined compressive strength (MPa) values would decrease as sample porosity rose. Porosity would widen the space between the material's particles, resulting in less interaction between them and a reduction in strength. The relationship between porosity and unconfined compressive strength in coarse-grained porphyritic foliated granite revealed that unconfined compressive strength (MPa) values would decrease as sample porosity rose. As the sample's porosity rose, the sample's strength was found to decrease. The findings comparing the porosity and unconfined compressive strength of coarse-grained porphyritic granite demonstrated that the unconfined compressive strength (MPa) values would drop with increasing porosity in the sample,

signifying a sharp decline in the material's strength. In fine-grained granite, the findings of the study comparing porosity and the ratio of quartz to feldspar revealed that the samples' strength dropped as their porosity rose. Findings comparing porosity and the ratio of quartz to feldspar in coarse-grained porphyritic foliated granite revealed that the ratio of quartz to feldspar declined as sample porosity rose, indicating a less resilient material to weathering processes. A plot of the porosity and quartz-feldspar ratio of coarse-grained porphyritic granite revealed that the index of sample strength dropped as the samples porosity rise (Figs. 6J-6L). The graph illustrating the relationship between water absorption and unconfined compressive strength in fine-grained granite demonstrates that these two parameters exhibited a reversal trend, meaning that as the former rose, the latter would correspondingly fall. Porosity is essentially equivalent to increasing water absorption percentage.

A graph illustrating the relationship between water absorption and unconfined compressive strength in coarse-grained porphyritic foliated granite demonstrates that the two variables exhibited a reversal trend, meaning that as the former rose, the latter would correspondingly fall. Its strength would diminish as its porosity grew due to its improved ability to absorb water.

In coarse-grained porphyritic granite, the relationship between water absorption and unconfined compressive strength is depicted graphically. It demonstrates a reversal tendency, whereby as the former rose, the latter would correspondingly decrease. The sample's ability to absorb water and its porosity determine its strength. The specimen's UCS increases as the latter two get smaller. This graph indicates that the chemical would result in a drop in UCS as the percentage of water absorption increased (Fig. 7).

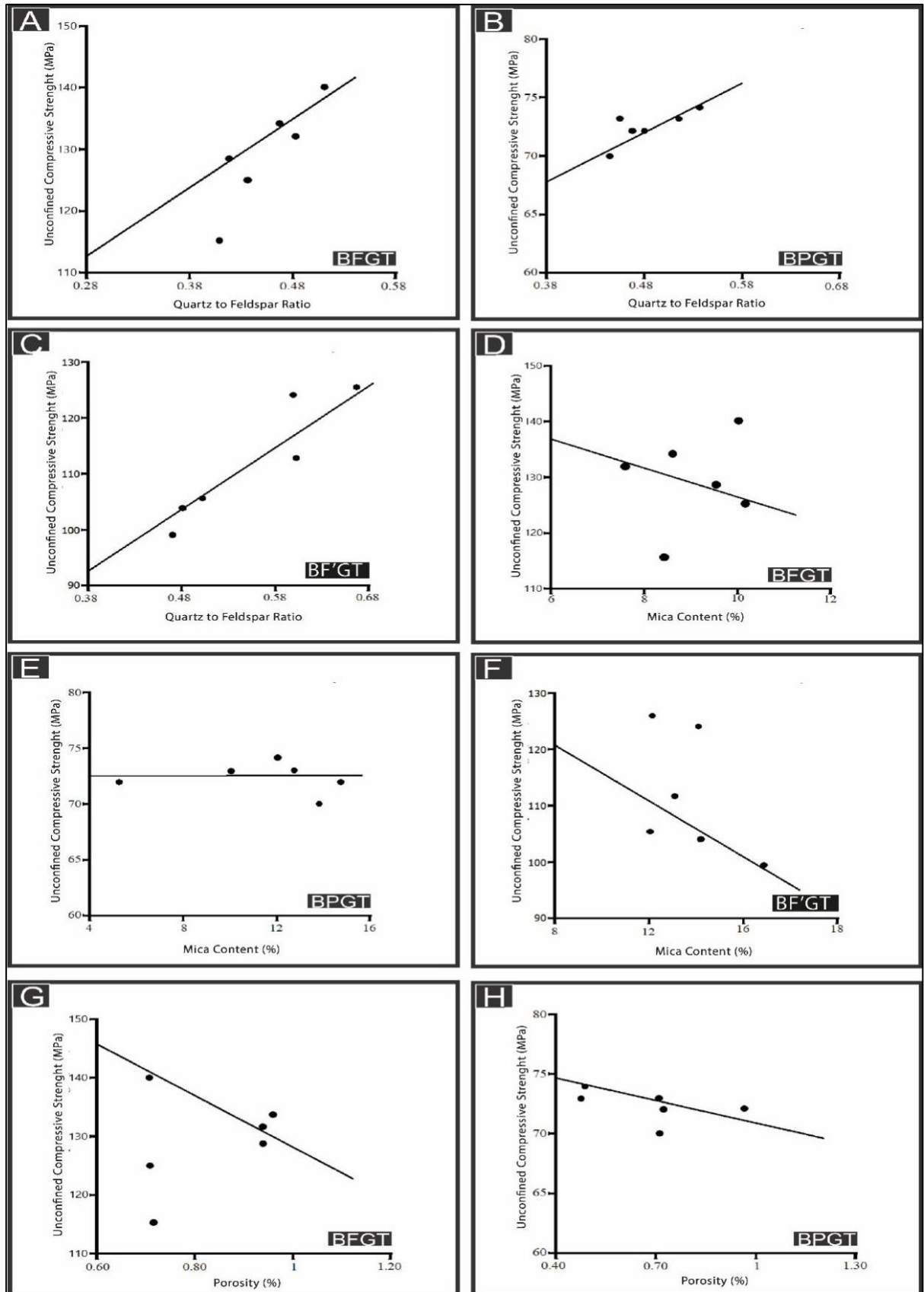


Fig. 6 Relationship between the parameters and rock types. (Separate plot for similar parameter of each rocks 1st plot of the same parameter shows BFGT, 2nd plot of similar parameters BPGT, 3rd plot BF'GT.

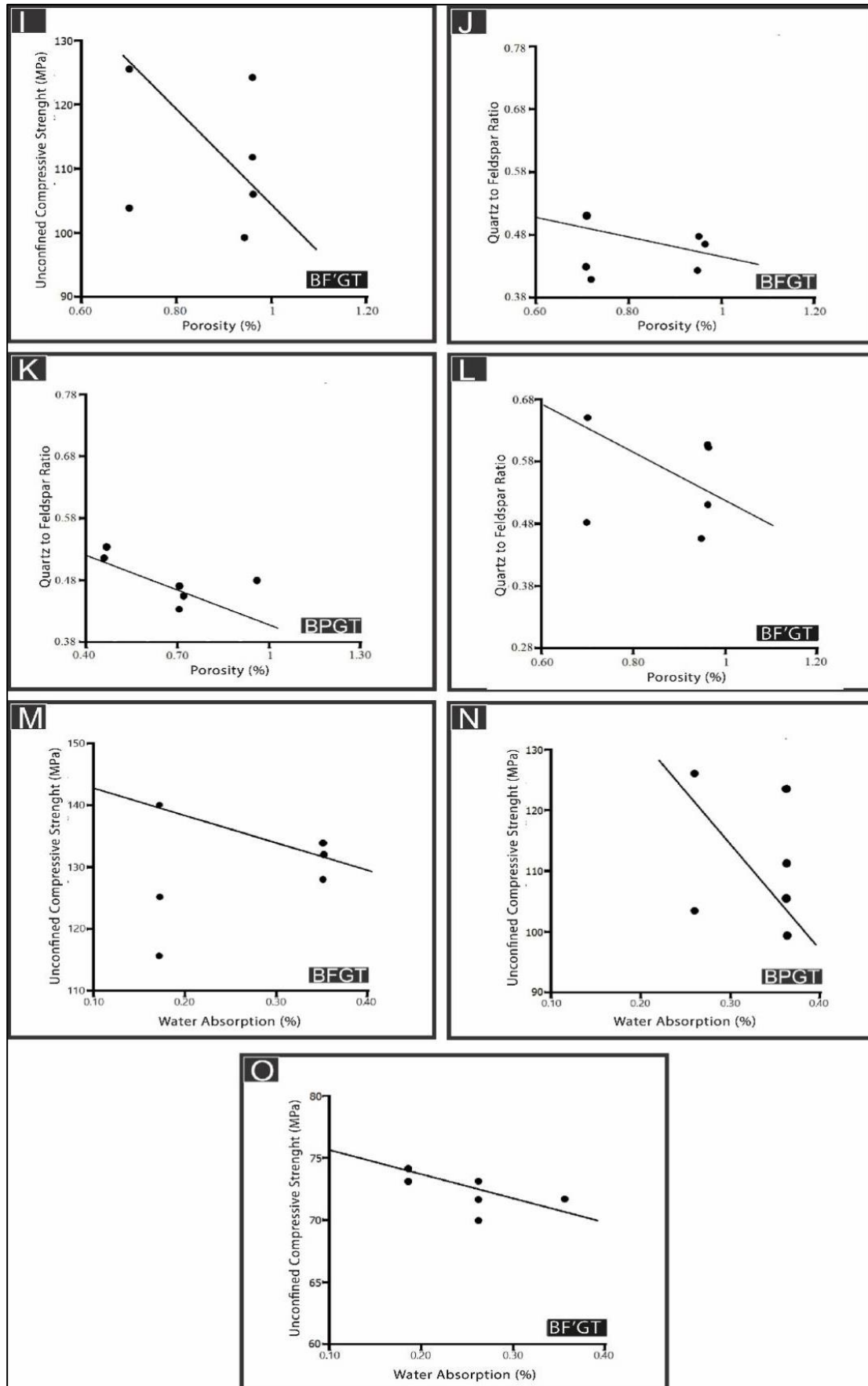


Fig. 6 continued - Relationship between the parameters and rock types. (Separate plot for similar parameter of each rocks 1st plot of the same parameter shows BF'GT, 2nd plot of similar parameters BPGT, 3rd plot BF'GT.

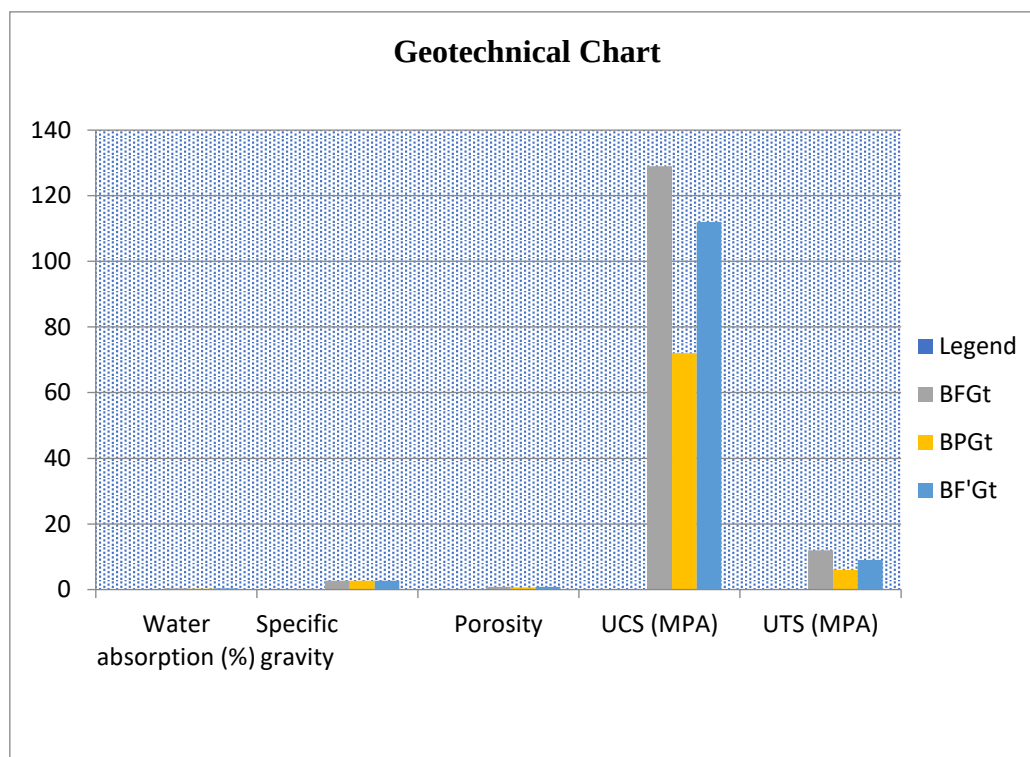


Fig. 7 Geotechnical analyses of texturally variable granitic rocks i.e. Bibior Porphyritic Granite (BPGt), Bibior Foliated granite (BF'Gt) and Bibior Fine-grained Granite (BFGt).

6. CONCLUSIONS

The mineral composition, grain sizes and pore arrangement, texture, weathering, deformation, and mica content are petrographic elements that affect the mechanical and physical characteristics of the granitoids from Bibior area in the Upper Dir District of Khyber Pakhtunkhwa, Pakistan. The petrographic and physico-mechanical properties of the Bibior granitoids indicate that their strength is primarily influenced by mineral composition, grain size, texture, and the presence of micaceous minerals. Fine-grained granite (BFGt) exhibits the highest strength due to its high quartz content, dense mineral packing, and minimal mica content, while porphyritic (BPGt) and foliated (BF'Gt) granites show relatively lower strength due to the presence of flaky minerals and increased porosity. The strong interlocking of quartz and feldspar in BFGt enhances its unconfined compressive strength (UCS) and unconfined tensile strength (UTS), making it highly durable. The lower porosity and water absorption of these rocks further contribute to their suitability as load-bearing materials. Overall, the Bibior granitoids meet ASTM standards for construction materials and can be effectively used as dimension stones and embankment

fill in engineering applications.

ACKNOWLEDGMENTS

The authors extend their appreciation to Abdullah Alrushaid Chair for Earth Science Remote Sensing Research at King Saud University for funding.

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