PETROGRAPHIC AND PHYSICO-MECHANICAL PROPERTIES OF GRANITOIDS FROM BIBIOR AREA, DISTRICT UPPER DIR, KHYBER PAKHTUNKHWA, PAKISTAN

IZHAR ULLAH

01-262182-015

BAHRIA UNIVERSITY, ISLAMABAD

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Committee Member	Name	Signature
Supervisor	Prof. Dr. M. Zafar	
Co-Supervisor	Mr. Sayed Mamoon Siyar	
Internal Examiner	Prof. Dr. Tehseenullah Khan	
External Examiner	Mr. Aqeel Gohar	
Post Graduate Coordinator	Dr. Muhsan Ehsan	
Head of Department (E&ES)	Dr. Said Akbar Khan	

Approval for Examination

Scholar’s name: IZHAR ULLAH
Registration No: 59452
Program of study: M.S. (Geology)

Thesis title: PETROGRAPHIC AND PHYSICO-MECHANICAL PROPERTIES OF GRANITOIDS FROM BIBIOR AREA, DISTRICT UPPER DIR, KHYBER PAKHTUNKHWA, PAKISTAN

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This thesis is dedicated to my parents. First and foremost, I have to thank my parents and siblings for their love and support throughout my life.

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Abstract

The Bibior area belongs to the western part of Kohistan Batholith in Kohistan Island Arc. Geographically the area is located at the south of the Dir Town, Upper Dir District, NW Pakistan. The rocks exposed in the study area are mainly granites, and amphibolites. The granitic rocks i.e., porphyritic granite, coarse-grained foliated granite, and fine-grained granitearound the Bibior area were study to determine their petrographic characteristics and mechanical properties. Field observations and petrographic examination revealed that the granitic rocks were broadly porphyritic in texture. However, fine-grained equigranular and coarse-grained foliated varieties were also found at places.

The petrographic examination showed that the porphyritic granite, foliated granite and fine-grained granite are essentially composed of quartz, plagioclase, and alkali feldspar which also contributed as ground-mass in some of the representative samples. The minor mineral assemblage is biotite, muscovite and hornblende with accessory amount of sericite, chlorite, opaque-ore minerals, zircon, titanite, epidote, apatite, garnet, and hematite. The quartz grains mostly display undulose extinction and are strained. To determine the behavior and durability of the granitic rocks as construction materials, 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 (fine-grained granite, coarse grained foliated and porphyritic granite) were study according to ASTM practices, and the tests revealed that these rocks had average values of water absorption 0.255-0.326%, specific gravity 2.680-2.710 kg/cm^3, porosity 0.675-0.87%, UCS 72.3-129MPa, andUTS 5.74-12.23MPa.The petrographic and physico-mechanical properties relationship through statistical analysis shows that the mineral composition, texture, and lower amount of flaky minerals make rocks stronger. The fine-grained granitic rocks from Bibior area having higher strength values due to their finer grain size compare to coarse-grained foliated and porphyritic varieties.The strength tests show that all

varieties from the area can be used in construction projectssuch as dimension stone and embankment fill.

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CHAPTER 1

INTRODUCTION

1.1 General Statement

Engineers are using natural geological materials for construction works.These geological materials are present in the earth's crust in different categories i.e. sedimentary, igneous, and metamorphic rocks. (Roberts et al. 1991) Sedimentary rocks have more importance and are majorly used in construction. Igneous and metamorphic rocks are also used in engineering works, depending on their locality, accessibility, durability and transportation. Among these, granitic rocks are used all over the world as embankment fill and dimension stone.Granitic rocks are exposed in different localities in Pakistan with varied mineralogy, texture, color and different mechanical behaviors. However, some of them are used as construction material and dimension stone. Engineers investigate these natural materials for their mechanical behaviors, especially under stress, because of their hardness, and lower porosity.In the construction industry, the rocks that meet the criteria of geotechnical investigations are used.Those rocks which attained the criteria of geotechnical investigations are used in construction projects. However, petrographic characteristics such as mineralogy, grain size, shape, texture, and weathering affect the mechanical features of rocks (Irfan, 1996).Abundance of strong minerals and texture give high strength to a typical fresh igneous rock (Johnson and De Graff, 1988). The strength is decreased markedly as the size of grain in igneous rocks increases (Onodera and Asoka Kumara, 1980). Rock strength is also greatly affected by the weathering and alteration process in mineral grains (Arif et al., 1999).

Igneous rocks are dominant and well-exposed in the research area (Bibior) having dykes and veins of different lithology and texture. Bibior granitic rocks (BG) may form a good source for construction material. Therefore petrographic characteristics, physical andmechanical properties werestudied for Bibior granitic rocks of different textures.

1.2 Location and Accessibility of the Study Area

Various igneous rocks are well-exposed in and around the Bibior area of Western Kohistan Island Arc (KIA). Geographically the area under study lies in the south-western part of Kohistan Batholith in Upper Dir district between latitude 35° 7' 32.3 N to 34° 57' 17.9" N and longitude 71° 55' 39.6" E to 72° 1' 25.6" E along Panjkurha River(Fig. 1.1). The study area can be easily approached through Malakand–Dir–Chitral all-weatherroad.

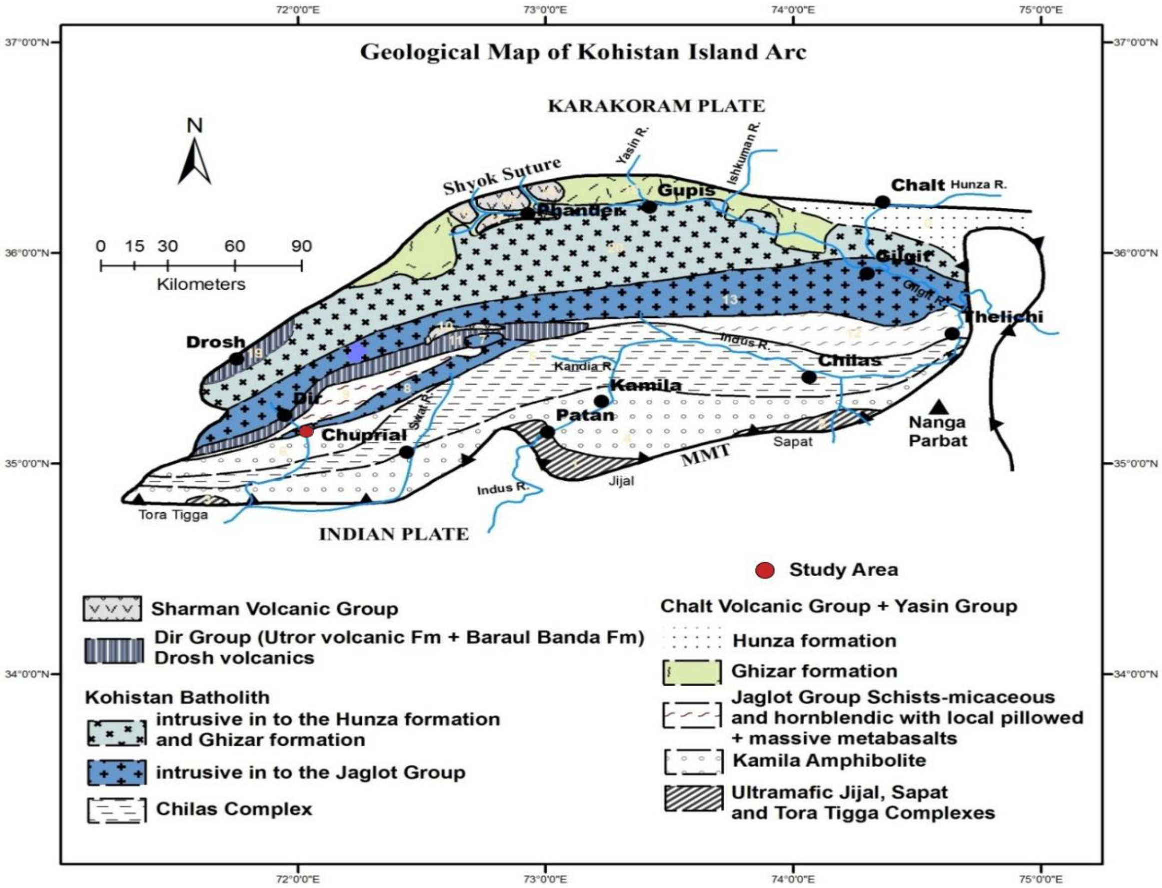

Figure 1.1: Geological map of the Kohistan Island Arc, showing the study area(after Arif et al., 2015).

1.3 Problem Statement

Granitic rocks are present in the Bibior area and easy to approach. Early workers have studied the petrographic details from the area rocks.The engineering properties of other rocks in the region have been determined and investigated. However, the Bibior granitic rocks are not yet studied for physico-mechanical properties and hence need to be studied for such details.

1.4 Aim and Objectives

The objectives of this investigation include:

i. To determine modal mineralogy of Bibior granitic rocks through their petrographic examination.
ii. To determine the physical and mechanical features of the Bibior granitic rocks to evaluate their appropriateness for use as construction material in the construction projects.
iii. To demonstrate a reasonable relationship between petrographic investigation and engineering properties of Bibior granitic rocks.

1.5 Geology and Tectonics of the Study Area

Granitic rocks are present in the form of small to large intrusions in Northern Pakistan (Tahirkheli, 1979). Bignold et al., 2006 and Haq et al., 2013, documented that the Kamila Amphibolite belt is extending towards Dir valley and overlying by Barawal Banda meta-sediments in the valley. The continuous series of intrusive igneous rocks of Chilas Complex intruded into Kamila Amphibolites in the valley (Chaudhry et al., 1974; Sullivan et al., 1993; Treloar et al., 1996).

The Bibior area rocks were first studied by Hyden (1915) as granites and Mixed-Zone (intermixing association of granodiorite and amphibolite rocks due to the action of granitic magma on preexisting amphibolites) (Chaudhry et al., 1974) as hornfels, and further documented schist, gneiss, and quartzite rocks in the area. The small bodies of diorite, granodiorite, granites, gneisses, syenites, and meta-sedimentary rocks are present in the Bibior area (Bakr and Jackson, 1964). The diorite is similar to the diorite of Khwazakhela and Kalam (Davies, 1965). Themeta-sediments contain slate, pyllites and quartzite, intruded by Bibior Diorite (Sullivan et al., 1993). The Bibior area rocks are granodiorite in composition where dykes/stocks of granite, aplite, and pegmatite intrude the country rocks. Amphibolites represent an obductedmelange of metamorphosed sequences (Chaudhry et al., 1974, 1987). Chaudhry et al., 1974, 1987 further divided the area into dominant lithological units; (a) Calcareous schists cut by calcite and quartz veins while Assilina and Nummulite fossils holding by a marly bed demonstrating Eocene deposits. (b) Leuco Amphibolites comprises epidote, quartz, granite, and pegmatite veins at places, (c) MelaAmphibolites consisting of epidote, quartz-o-feldspar, granite, and pegmatite veins, (d) Granodiorite (e) Mixed zone comprises epidote, quartz-o-feldspar, granite veins and hornblendite patches (f) Garnet bearing quartz-o-feldspathic rock cut by small granite intrusions (g) Hornblendites comprises epidote, quartz-o-feldspar veins (h) Pegmatites, and (i) tonalites.

Chaudhry and Chaudhry (1974) documented, The Norite Complex which comprises Quartz-o-feldspathic dykes and veins, pegmatites, pyroxenites, hornblendite dykes and gabbro, The Trondhjemite Intrusion, making contact with amphibolite, granite and tonalite rocks, The Diorite Complex: main diorite body, which comprises mela diorite, bojite, tonalite, granite, epidosite veins, pegmatites, Quartz-o-feldspathic veins, Amphibolite xenoliths, The Amphibolites (epidote mela amphibolite and plagioclase mela amphibolite) which comprises granite and pegmatite dykes, Quartz-o-feldspathic veins and, Assimilation Zone (a contact between norites, gabbro, and amphibolite). Sajid et al., (2009) worked on gabbro-norite, epidote-amphibolite, and hornblendite rocks from a nearby area in terms of petrographic and mechanical characterization.

1.6 Geology and Tectonics of Northern Pakistan

Northern Pakistan is mainly covered by three tectonic domains: Indo-Pakistan Plate, Kohistan Island Arc, and Karakoram Block. Kohistan Island Arc is sandwiched between Indo-Pakistan and Karakoram Plate, shearing two main sutures along their boundaries, Main Mantle Thrust(MMT)at the south with Indo-Pakistan Plate and Main Karakoram Thrust(MKT)or Northern Suture Zone at the north with Asian Plate (Tahirkheli, 1979, 1982; Bard, 1983) (Fig. 1.2). The developing matter of KIA and sutures along northern and southern boundaries is well addressed and researchers are agreeing but the timing of the collision with the major plates (Indo-Pakistan and Asian) is quite controversial. The collision timing of KIA has been suggested by two groups of geoscientists with Asian and Indo-Pakistan plates. One group of researchers are suggesting models of the collision 102-75Ma with Asian Plate first and 55-50Ma with Indo-Pakistan Plate later (Clift et al., 2002;Bignold and Treloar, 2003; Khan et al., 2007; Rehman et al., 2011). The other group of researchers is in the favor of collision 95-60Ma first with Indo-Pakistan plate before the collisin with Asian Plate (Ding et al., 2005; Yin, 2006; Khan et al., 2009; Chatterjee et al., 2013).

MMT formed as a result of the Indian Plate and Kohistan Island Arc collision in Early to Mid-Eocene resulted in obduction in rocks of the arc onto the Indian Plate rocks (Searle et al., 1999). This main suture extending from Afghanistan in the east direction joined Indus Suture Zone in Ladakh (DiPietro et al., 2000). The rocks of the Indian plate are divided into two main zones: Internal (northern zone of metamorphosed rocks) and external zone (southern zone of un-metamorphosed to low-grade metamorphic rocks). Main Boundary Thrust separates these zones from the Indus basin in the south (Treloar et al., 1989). Furthermore, rocks are divided into tecto-stratigraphic units from south all the way to north bounded by faults. These are Sub-Himalaya, Lesser-Himalaya, Higher-Himalaya, and Tibetan-Himalaya and these units are bounded by major sutures i.e., Main Frontal Thrust, Main Boundary Thrust, Main Central Thrust, and Indus Tsangpo Suture Zone (Gansser, 1981; Kazmi and Rana, 1982) (Figure 1.2).

Kohistan Island Arc (KIA)developed in the Late Jurassic-Early Cretaceous as a result of intra-oceanic subduction of neo-Tethys beneath Eurasian Plate, covering an extent of 3600km^2(Tahirkheli et al., 1979).

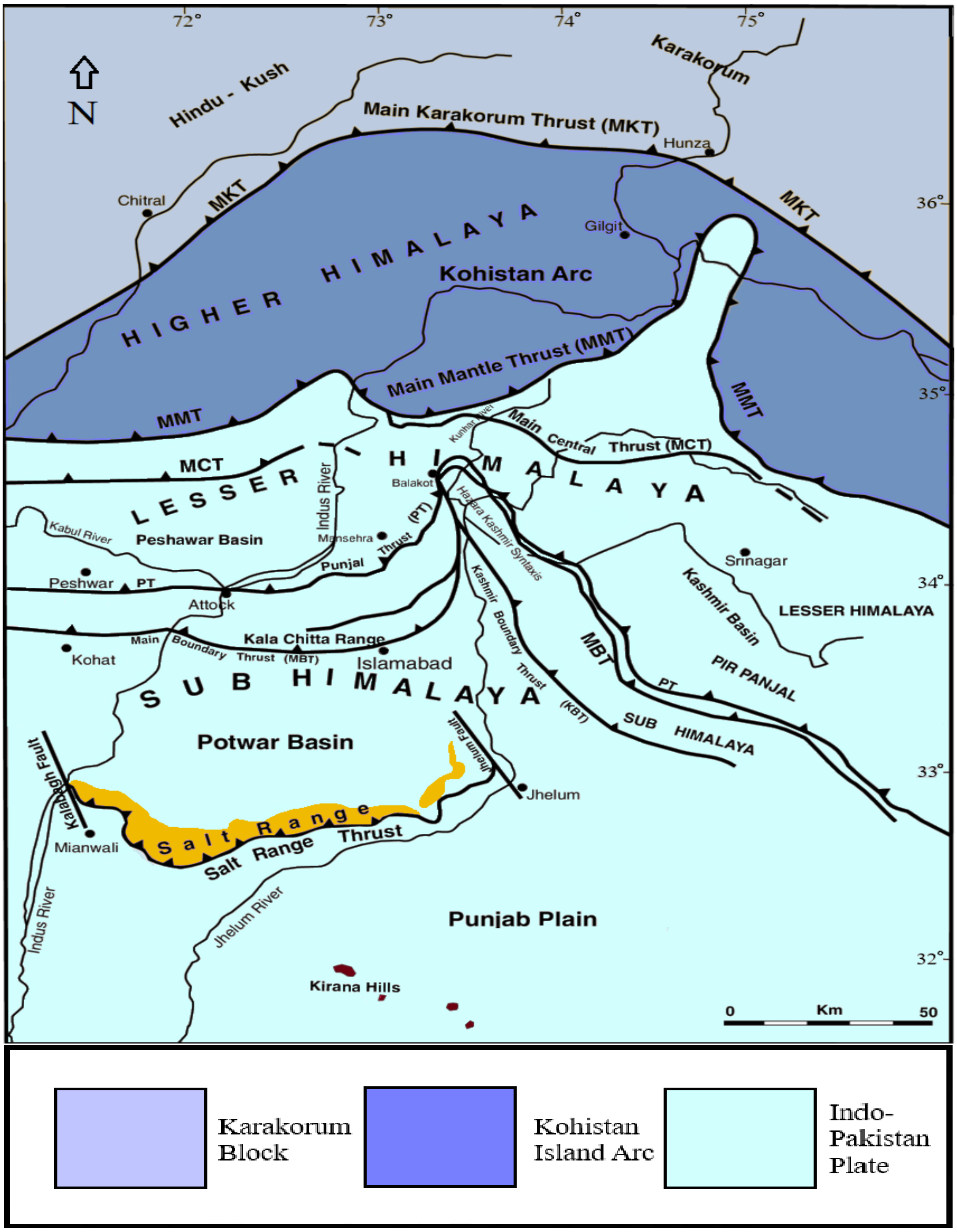

Figure 1.2: A generalized tectonic map, showing major sutures, Himalayas and tectonic domains of Northern Pakistan (Modified after Gansser, 1981; Kazmi and Rana, 1982; Ghazi et al., 2014).

The collision time of the KIA with Indian Plate is marked by Indus Suture Zone at south in Eocene age and with Eurasian Plate along Northern Suture Zone 100-75 Ma (Khan et al., 2007). Khan (1994) proposed an appropriate model of back-arc basin associated with KIA.KIA is separated from Eurasian Plate at the north by MKT and from Indian Plate separated by MMT on the southern side. From north to south KIA is composed of Yasin Group Sediments,Chalt Volcanic Group, Kohistan Batholith, Dir-Utror Volcanic Series, Chilas Complex, Kamila Amphibolite Belt, andJijal Mafic-Ultramafic Complex (Jan and Howie, 1981; Coward et al., 1982; Tahirkheli and Jan, 1984;Petterson and Windley, 1985;Khan et al., 1989; Shah et al., 1992; Sullivan et al., 1993; Shah and Shervais, 1999).

Yasin SedimentsGroup have the youngest Tethyan rocks comprising of sedimentary rocks along with volcano-clastic rocks, marked the northern portion of KIA bounded by Northern Suture Zone at the north and Chalt Volcanic Group at the south (Tahirkheli& Jan, 1984).Metamorphism caused by the collision of two major plates and changed the volcanic rocks of the group into greenschist. However, this group contains different lithologies along Northern Suture Zone at places. The group is composed of limestone, slates, basal conglomerates, volcanic, and volcano-clastics rocks. The fossils of Albian-Aptian age are the confirmation of Cretaceous age of the group (Pudsey, 1986).Chalt volcanic Group rocks are mainly composed of basalts, rhyodacites, and andesites. The rocks of the group are metamorphosed to green schists and are exposed in the south of the Northern Suture Zone. To the west of the group rocks liegreenschist and to the south are amphibolites formed by high deformation and metamorphism (Coward et al., 1982).

Kohistan Batholith (KB)is the main batholith of the arc that covers a large portion of KIA and comprises of granitic rocks at the northern portion of the arc (Tahirkheli and Jan, 1979). Petterson and Windley (1985) named it as Kohistan Batholith. This batholith covers 60 kilometer area from north to south and 300 kilometers from east to west. The batholith is mainly composed of granodiorites, leucogranite, diorite, hornblende gabbro, and hornblendites (Coward et al., 1986).KB developed in three magmatic intrusions. The first stage intrusion is characterized by two types of magmas and age assigned 120 ± 12 Ma, the first one magma is composed of medium to high potassium diorites while the other one is low potassium trondhjemites. The second stage magmatic intrusion of 85-40Ma covered two-third of the batholith within KIA. The rock samples from these plutons have medium to high potassium in composition and silica content is low to high while enriched in large ion lithophile respective to high field strength elements. The third stage magma is covering a comparatively minor part than the first and second stage intrusions in the batholith and the age assigned to this intrusion is 30 Ma due to formation after the development of MMT (Petterson and Windley, 1991).The igneous lithological units from Bibior show that these rocks are intrusions of the first and second stages.

The western KIA is composed of volcano-sedimentary rocks around Dir and Swat areas and named as Dir Group by Thahirkheli, 1982 and further divided the group into three units:Barawal Banda Slate, Dir-UtrorVolcanics, and Panakot Meta-arkose. Dir Group rocks are metamorphosed calc-alkaline and associated with meta-sediments. Rocks of this group are 90% mafic meta-volcanics including basalts, basaltic andesites, and andesites of almost porphyritic texture having epidote veins commonly (Shah and Shervais, 1999).

The Kamila amphiboite belt extends to the west into Dir valley (Bignold et al., 2006). The amphibolite belt is composed of two types of amphibolites and positioned at the south of the Chilas complex in the KIA. One type of amphibolites is coarse-grained homogeneous resulted from plutonic gabbroic-diorite and the other one is fine-grained banded resulted from a volcanic protolith (Shah et al., 1992). The age of these amphibolites is 83-80Ma suggesting that the deformation and metamorphism resulted before the collision with Indian Plate and KIA (Treloar et al., 1989). The Chilas Complex is a mafic-ultramafic, calc-alkaline intrusive body, which extends up to 300 km in east west direction (Khan et al., 1989). The Kamila amphibolites are intruded by Chilas Complex rocks in the west of the KIA in Dir valley (Treloar et al., 1996).The Dir area is mainly comprised of mafic-ultra mafic complex, meta-sediments, and Granitoids (Pudsey et al., 1985).

CHAPTER 2

METHODOLOGY

The present investigation of Bibior rocks is completed in three stages i.e., fieldwork and sampling, lab work, and write-up.

2.1 Field Work

A fieldwork was carried out in the study area located between latitude 35° 7' 32.3 N to 34° 57' 17.9" N and longitude 71° 55' 39.6" E to 72° 1' 25.6" E(Fig.2.1) to study and understand the lithological variations, field features, and relationships. The area is mainly covered by large exposures of igneous and metamorphic rocks. The main rocks exposed in the area are divided into two main categories based on detailed field observations:

i. Granitic rocks
ii. Amphibolite rocks

These rocks are also contributed as small bodies in the form of dykes. The igneous rock units are present in large to small intrusion. Dykes and veins of igneous intrusions are present in all over the area. The igneous intrusions have variations in lithology and texture. Igneous rocks are mainly granodiorite, granite, diorite in nature and quartz veins are also present. Color variation is found in the rocks due to weathered surfaces and can be differentiated from their fresh bodies. Deformations are found in the rocks along contacts and shear zones. The petrogenetically significant field features were documented in written and photographed.The granitic rocks from Bibior area are porphyritic. However, fine-grained and foliated variations occur too. Granitic rocks are closely associated with amphibolite rocks in the area. These granitic rocks are occurringin the form of dykes at places whichmake close contact with amphibolite rocks. The major portion of the igneous rocks is of coarse-grained and porphyritic (Fig. 2.1a). Close contact with amphibolite rocks have caused high deformation in the granitic rocks from the mixed zone. (Fig. 2.1b) The fine-grained granitic dykes are intruded into amphibolites in the area (Fig. 2.1c). The coarse-grained granitic rock mark close contact with fine-grained igneous rocks at places (Fig. 2.1d). Amphibolite rocks are massive and also found in dykes, intruded to granitic rocks (Fig. 2.2a). Quartz veins and dykes are common throughout the area (Fig. 2.2b).

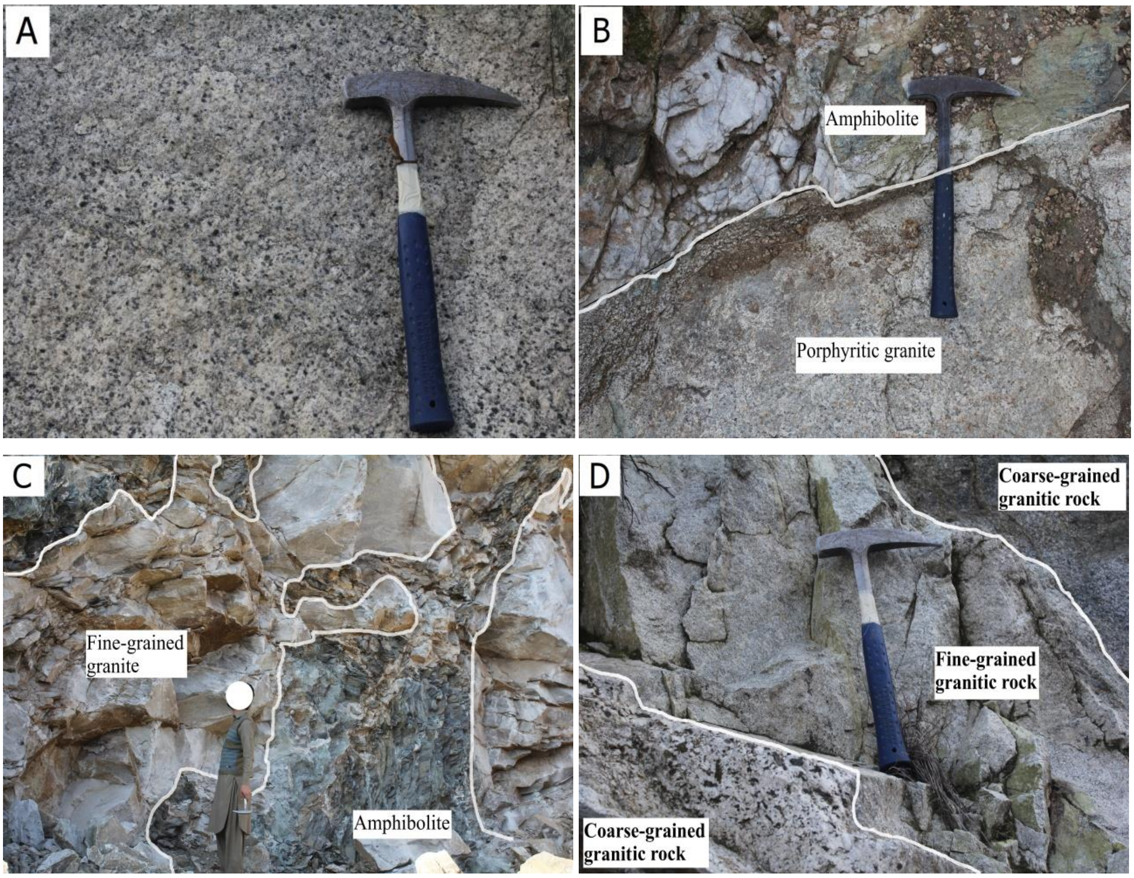

Figure 2.1: Field photographs: (A) The porphyritic Bibior Granite; (B) Contact between amphibolite and granitic rocksfrom the mixed zone in Bibior area; (C) Fine-grained granitic intrusion in amphibolite rocks; (D) Contact between fine-grained and porphyritic granitic rocks in the area.

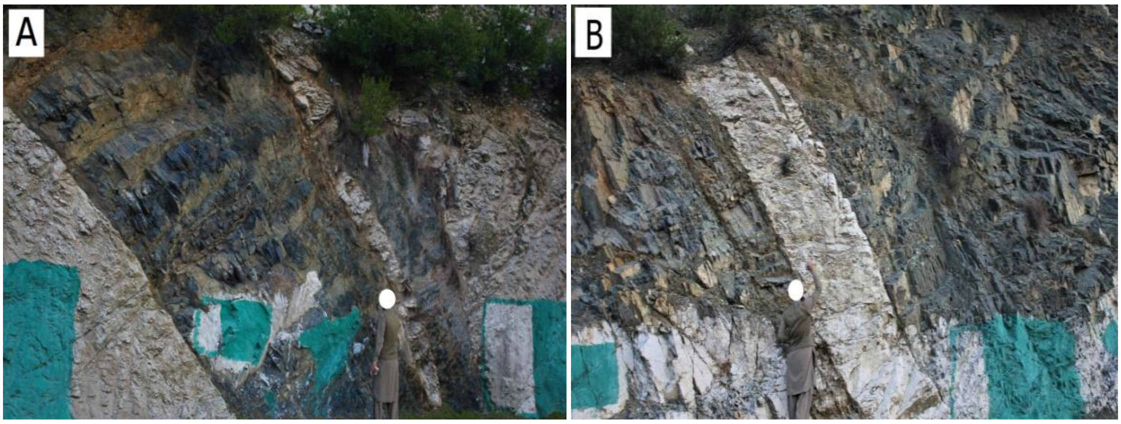

Figure 2.2: Field photographs: (A) Amphibolite dyke cutting the granitic body (B) A small dyke of quartz cutting the amphibolites in the area.

2.2 Samples and Methods

Methodology and sampling techniques were applied respectively for petrographic study and geotechnical properties.

2.2.1 Petrography

Twenty-one representative samples were collected from the study area for petrographic study. The accurate geographic coordinates of each specimen were recorded with the help of GPS (Fig. 2.1). These samples were consisted of granitic rocks both of coarse and fine-grained varieties. The rock sampleswere carried into the laboratory for thin section preparation in the Department of Geology, the University of Peshawar. Thin sections were studied in the Petrographic Lab, Department of Earth and Environmental Sciences, Bahria University Islamabad.

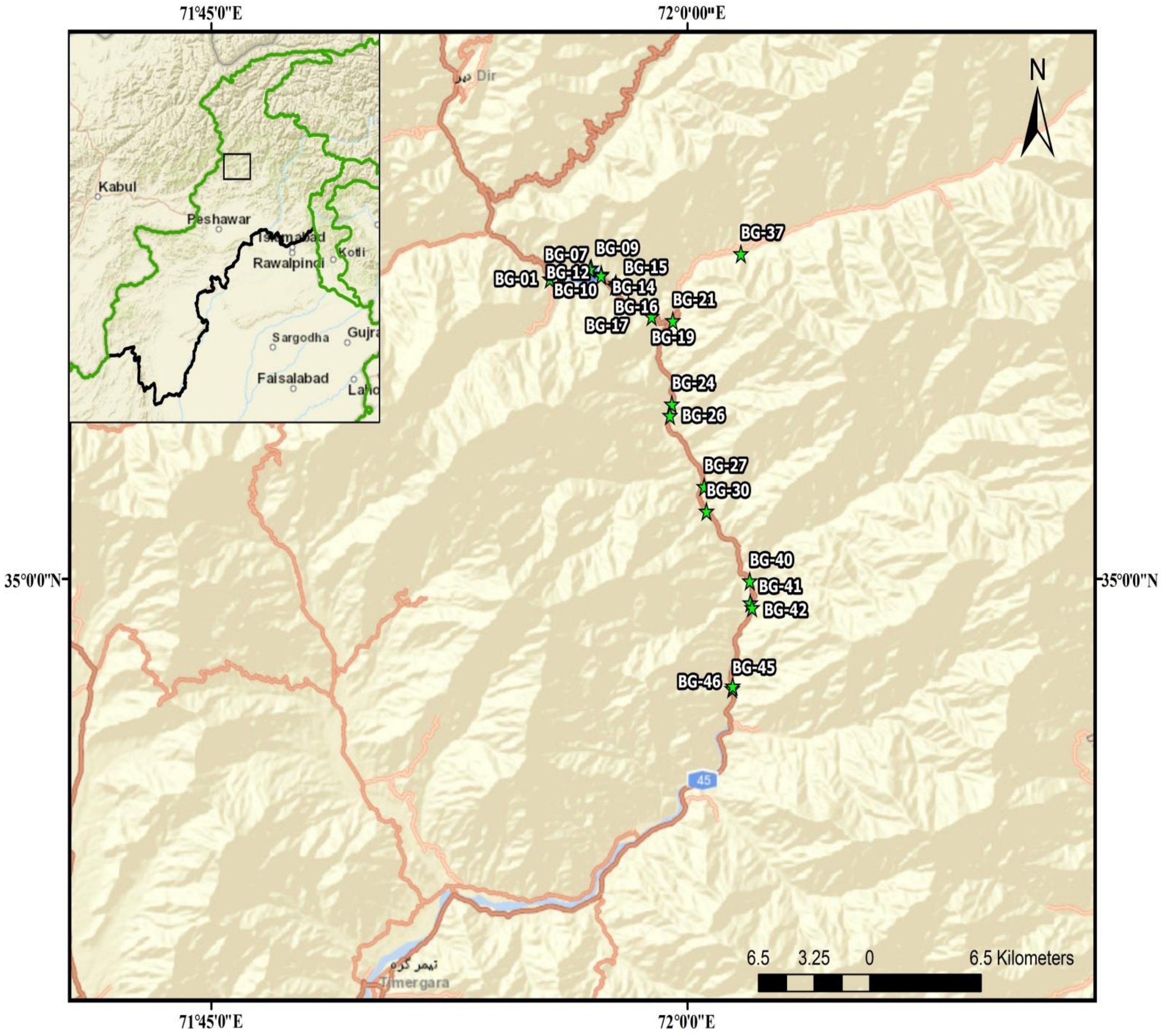

Figure 2.3: Map showing the locations of the studied samples.

2.2.2 Physical and Mechanical Properties

Three bulk samples were collected of different textural varieties in the Bibior area. These bulk samples were of porphyritic granite, coarse-grained foliated granite, and fine-grained granite. These samples were cut into 3/3 (in) cubes (fig.4.1) in Hamza Marble Factory, Warsak Road, Peshawar through a rock cutting blade machine. Six cubes were cut from each bulk sample and one thin section from each cube for petrographic study. These cubes were cut according to ASTM specifications(ASTM C170)to determine their unconfined compressive strength (UCS). The mechanical/strength tests and physical properties such as, water absorption, porosity and specific gravity of each sample were determined in the Geotechnical Laboratory, National Center of Excellence in Geology, University of Peshawar. The UTS tests were performed in the Material Testing Laboratory, University of Engineering and Technology, Peshawar. The values of these tests were correlated with their petrographic characteristics through statistical analysis.

CHAPTER 3

PETROGRAPHY

3.1 General statement

The petrographic study allows us to define the mineralogical composition and textural aspects of a specific rock. This involves observation of significant field features and thorough microscopic analysis. The granitic rocks from the Bibior area, NW Pakistan, are exposed at the south-west of Kohistan Batholith at Western KIA. Early workers studied the rocks around the area in appropriate detail, such as petrographic study, field features and observations.

Below are the petrographic details of BibiorGrantoidrocks.

3.3.1 Bibior Granitic rocks

The granitic rockshave minerals composition under the microscope, mainly quartz, alkali feldspar (orthoclase and microcline), plagioclase, with accessory to minor minerals of biotite, muscovite, hornblende, and accessory to trace amount of chlorite, sericite tourmaline, titanite, zircon, epidote, apatite, garnet, and hematite. The abundance of these minerals is displayed in table 3.1 and plotted on the relevant IUGS classification triangle (Fig. 3.1). Due to concentration of essential minerals, most of the compositional spots are all spread over granite field.However, one ofthem isspread over quartz monzonite based on modal composition(Fig. 3.1).

The most richly mineral in these granitic rocks is quartz (fine-medium-grained) which shows a modal proportion of 13-53% (Table. 3.1). Most of the quartz grains show undulose extinction (Fig. 3.2c). Some samples show mortar texture. The fine-grained unstrained assembled quartz grains also observed around strained quartz, alkali feldspar and plagioclase phenocrysts (Fig. 3.2a), which reveal tectonic activities and deformation in the area rocks.The second most abundantly occurring mineral in these rocks is alkali feldspar including orthoclase and microcline. Their modal proportion ranges from 15-38%.

Table 3.1: Visual estimates of mineral composition in volume % of granitic rocks from Bibior area

S. No.	Mineralogical percentage (%)															
	Qz	Afs	Pl	Bt	Ms	Tur	Ttn	Zrn	Ore	Ep	Chl	Ser	Ap	Grt	Hem	Hbl
BG-01	33	27	23	8	2	--	--	--	2.5	--	3	--	--	--	0.5	1
BG-07	48	16.5	18	1.5	3	--	--	--	1.5	--	2	9	--	--	--	0.5
BG-09	34	22	27	6	3	0.2	--	0.4	2,5	--	2	0.3	--	--	--	2.6
BG-10	36	15	27	10	1.3	--	--	0.2	3	--	1.5	5.8	0.2	--	--	--
BG-12	36	30	10	6	3.5	--	0.5	0.5	--	4	5	2	--	0.5	--	2
BG-14	31	34	22	5	2	0.5	--	--	--	0.5	1.5	2.5	--	--	--	1
BG-15	30	29	27	7	0.3	2.5	0.5	--	2	--	--	--	0.2	--	--	1.5
BG-16	53	26	12		1.6	--	2		1.6	0.8	3	--	--	--	--	--
BG-17	29	20	30	16	--	--	--	0.3	1.5	0.2	1	--	--	--	--	2
BG-19	13	27.8	38	6	1.5	0.8	3.5	--	--	0.6	2.8	--	--	--	--	6
BG-21	39	34	10	6	2	1.2	--	--	2.5	0.5	2	--	--	--	--	2.8
BG-24	23	35	30	1.6	1.6	0.5	--	--	1.5	--	0.8	--	--	--	--	6
BG-26	28	38	19	1	14	--	--	--	--	--	--	--	--	--	--	--
BG-27	39	36	15	--	1.5	0.5	--	--	3	--	1	--	--	--	--	4
BG-30	29	19	30	7	2.5	0.5	--	--	1.5	1	2	4	--	--	--	3.5
BG-37	26	23	36	4	1	0.2	--	--	0.5	--	2	--	0.3	--	--	7
BG-40	32	24	36	4	--	--	--	--	0.5	1	0.5	--	--	--	--	2
BG-41	31	22	34	2	--	--	--	--	1.5	--	2.5	--	--	--	--	7
BG-42	23	33	34	1.5	0.8	--	--	--	1	--	1.5	--	--	0.2	--	5
BG-45	27	35	31	0.8	0.6	--	--	--	--	--	0.6	--	--	--	--	5
BG-46	31	38	22	1	--	0.5	--	--	--	--	0.5	2	--	--	--	5

BG: BibiorGranitoid, Qz: Quartz, Afs: Alkali feldspar (Orthoclase and Microcline), Pl: Plagioclase, Bt: Biotite, Ms: Muscovite, Tur: Tourmaline, Ttn: Titanite, Zrn: Zircon, Ep: Epidote, Cht: Chlorite, Ser: Sericite, Apt: Apatite, Grt: Garnet, Hem: Hematite, Hbl: Hornblende

Some samples show intergrowth of alkali feldspar and quartz forming graphic texture andother samples show simple twinning (Fig. 3.5b). The next abundant mineral is plagioclase, which has modal proportion ranging 10-38%. The shape of plagioclase in these rocks is euhedral to subhedraland display pericline and Carlsbad-albite polysynthetic twinning. Sericite, epidote, and muscovite are the alteration product in plagioclase, but largely sericitization found in these minerals. However, some of the plagioclase grains have fresh margins but altered with sericitization their cores which show normal zoning. The margins of plagioclase grains are more resistant to alteration than their cores (Fig. 3.4b).Oscillatory zoning found in plagioclase grains in some of studied samples. Blebs of zoned plagioclase are present in plagioclase phenocrysts (Fig. 3.2d).

Biotite is present in flaky form in these rocks (Fig. 3.2b). Some are fully altered to chlorite (Fig. 3.3d) and some on their margins due to chloratization processes. Biotite encloses small flakes of muscovite in some of the studied specimens. Muscovite grains are present in tabular formbut also present in slightly folded form in some of the studied samples (Fig. 3.3a and b). Chlorite is present mostly with the association of biotite and hornblende showing alteration of biotite and hornblende (Fig. 3.4c and d). Hornblende grains show simple twinning in some samples (Fig. 3.4d) and in some have well-developed two sets of cleavages. Ore minerals are present in small-medium sized grains of black and dark colors in the form of opaques (Fig. 3.5a). Garnet grains occurring in the discrete form (Fig. 3.3c and 3.5a). Titanite is also present in some samples in small to mediumin size (Fig. 3.4a). Epidotegrains are present and some are associated with sericite. Epidote grains having zoning in some studied samples, show interference colors which reveal metamorphism in these granitoids. Discrete grains of apatite, hematite, and zircon are also found in some of the samples.

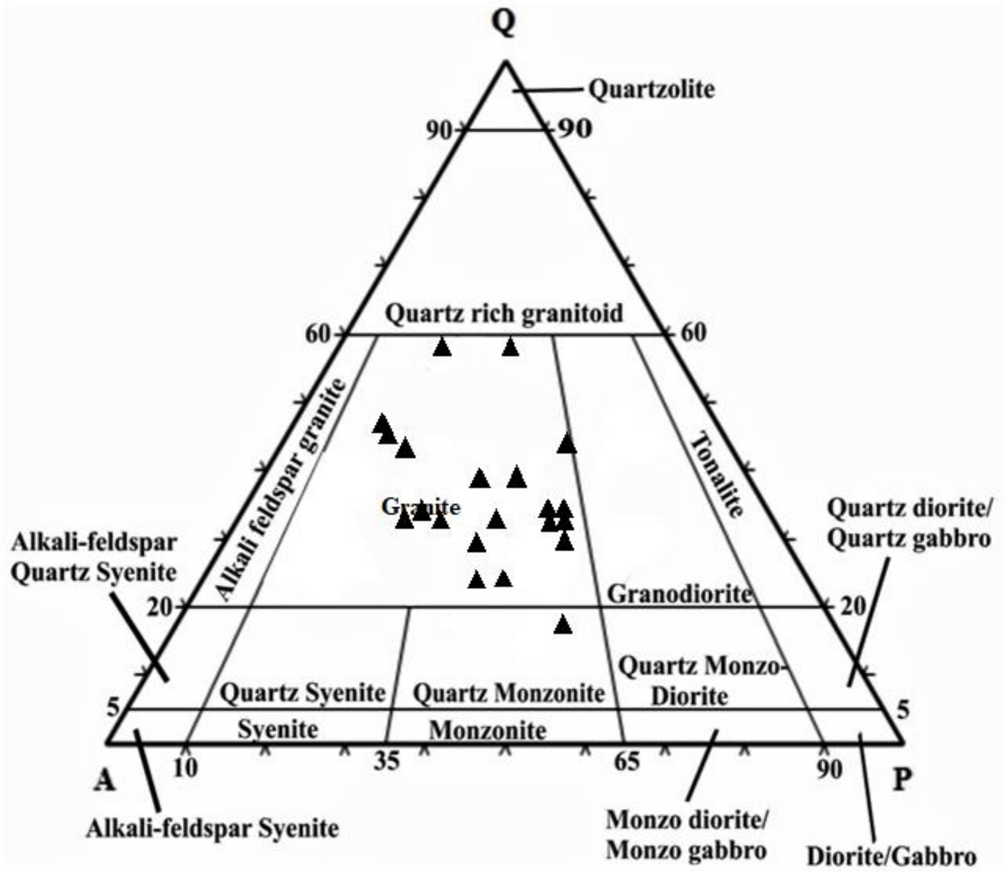

Figure 3.1: Modal composition of studied samples of granitic rocks from the Bibior area plotted on the IUGS classification diagram (from Le Maitre, 2002).

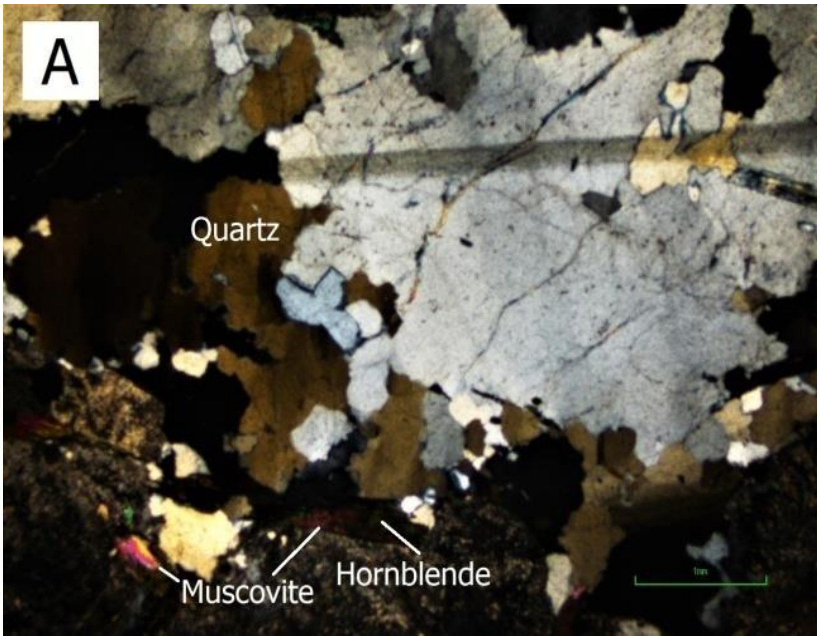

Figure 3.2: Photomicrograph: (A, XPL) Unstrained fine-grained assembled quartz grains around a strained quartz grain.

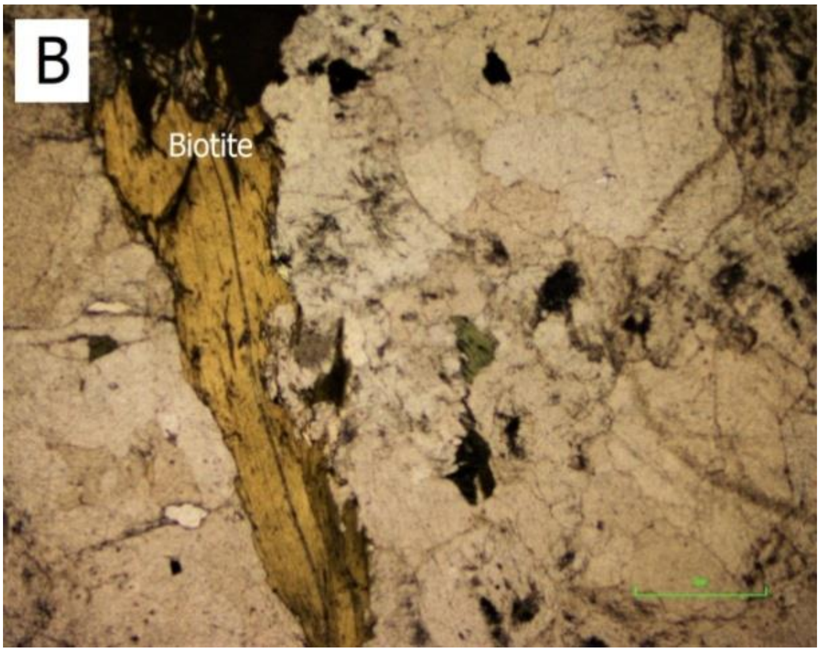

Figure 3.2: Photomicrograph: (B, PPL) Flaky biotite grain.

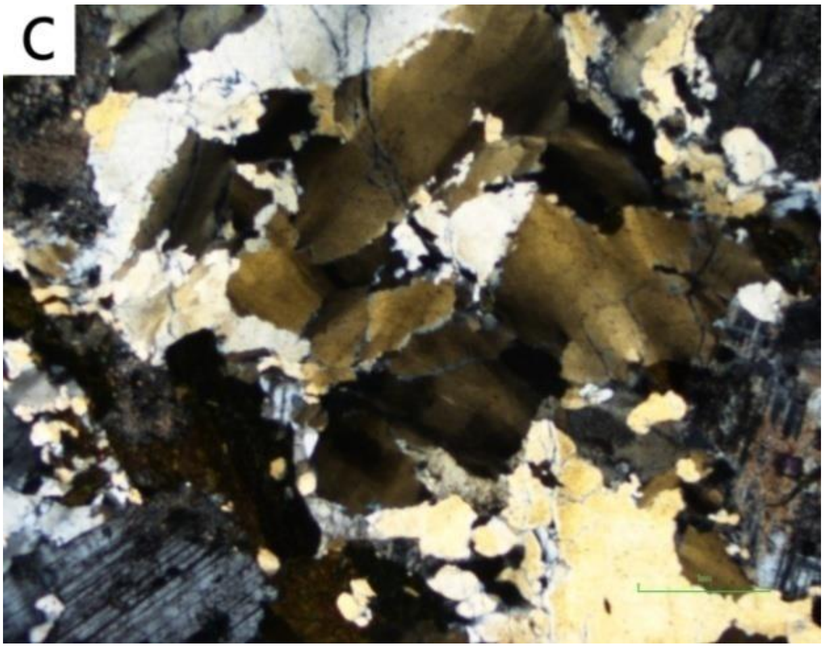

Figure 3.2: Photomicrograph:(C, XPL) Undulose extinction in quartz grains.

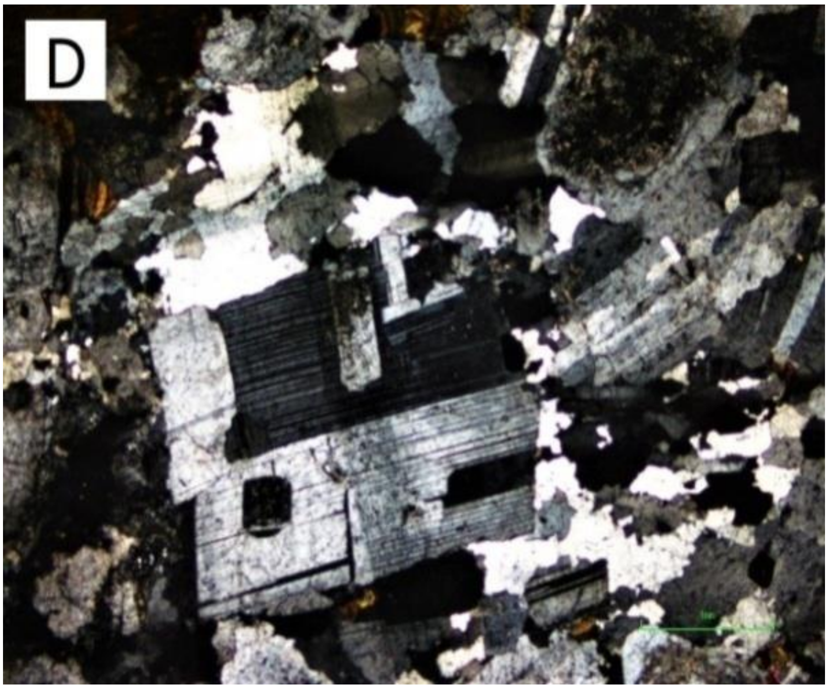

Figure 3.2: Photomicrograph: (D, XPL) Blebs of zoned plagioclase.

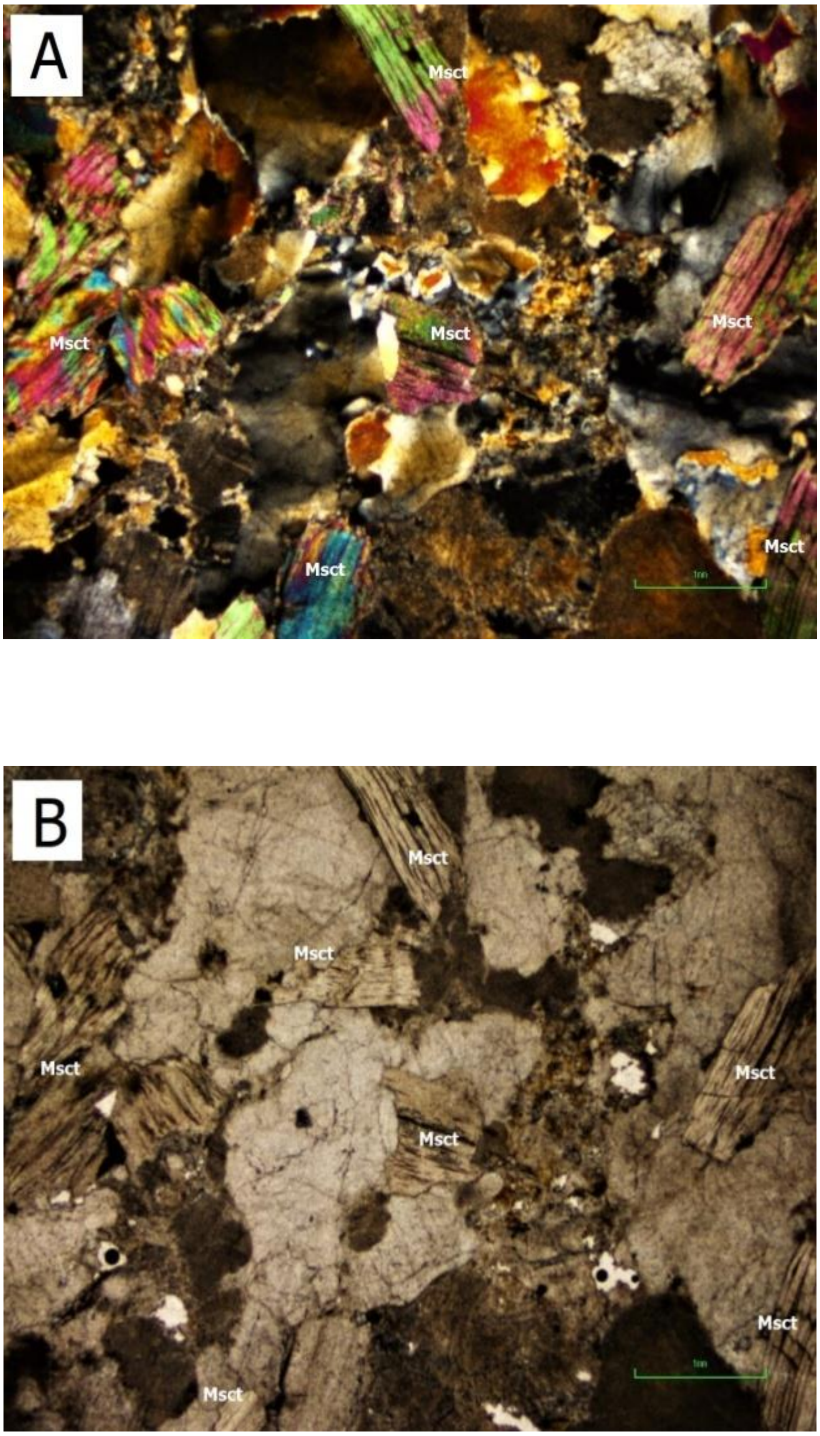

Figure 3.3: Photomicrographs: (A, XPL, and B, PPL) Large abundance of muscovite grains.

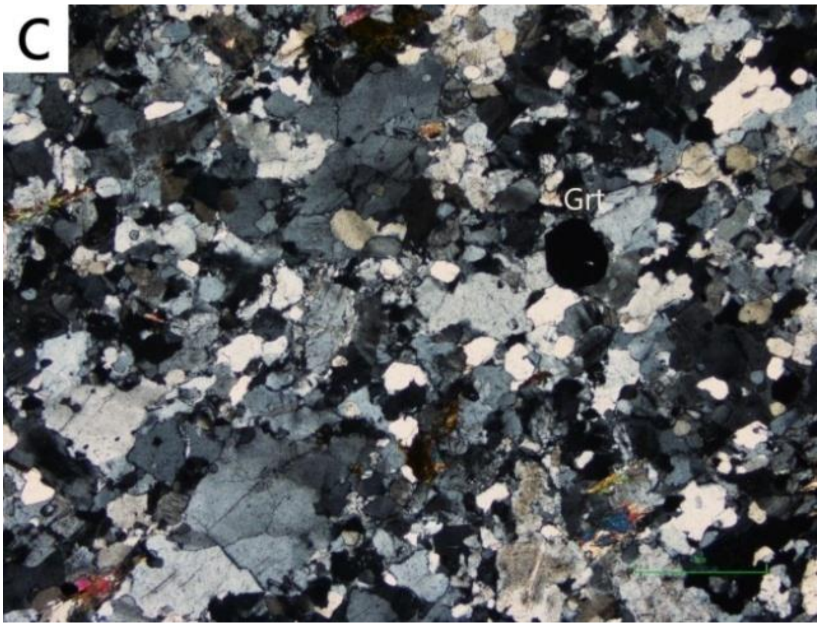

Figure 3.3: Photomicrograph: (C, XPL) Garnet grain in fined-grained quartz.

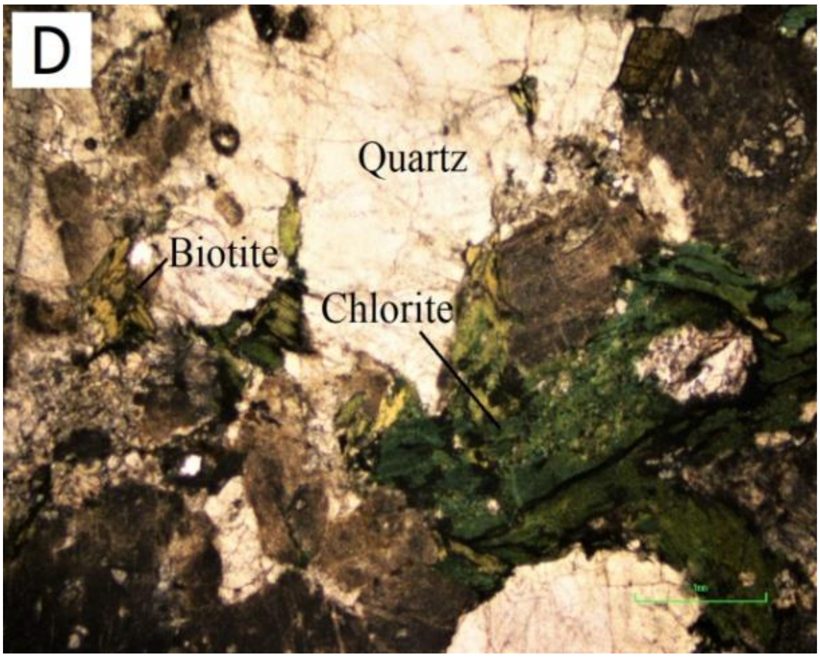

Figure 3.3: Photomicrograph:(D, PPL) Fullychloritized grain of biotite associated with quartz grain.

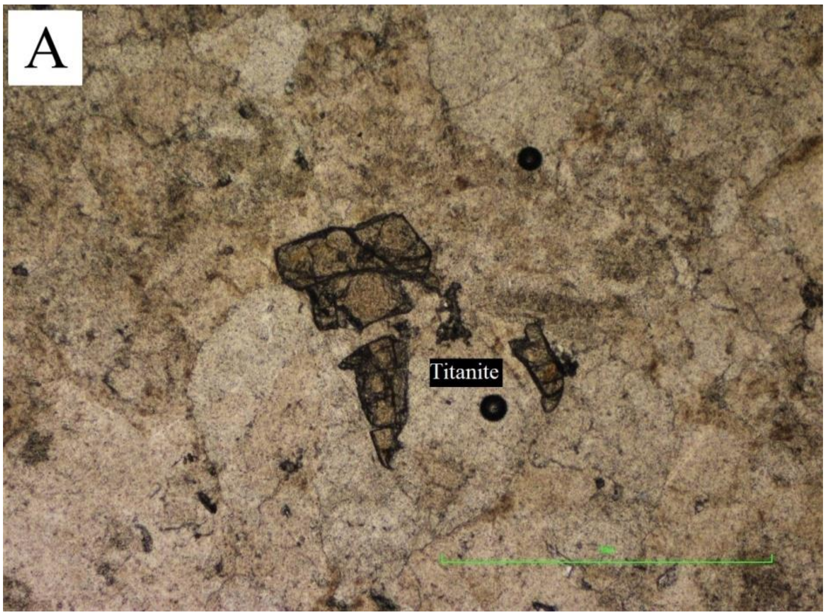

Figure 3.4: Photomicrograph: (A, PPL) Titanite.

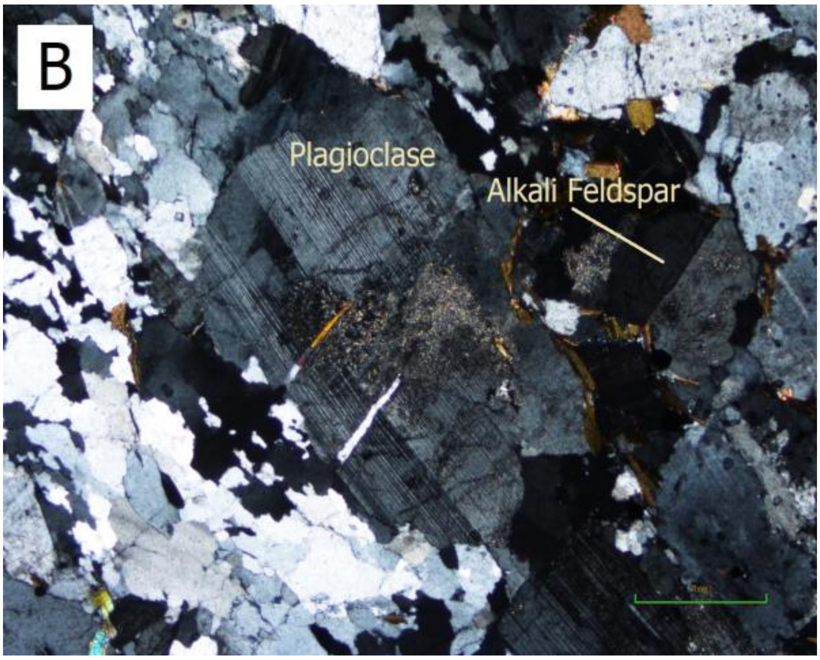

Figure 3.4: Photomicrograph: (B, XPL) Plagioclase phenocrysts resulted alteration with sericitization in the core and having fresh boundaries.

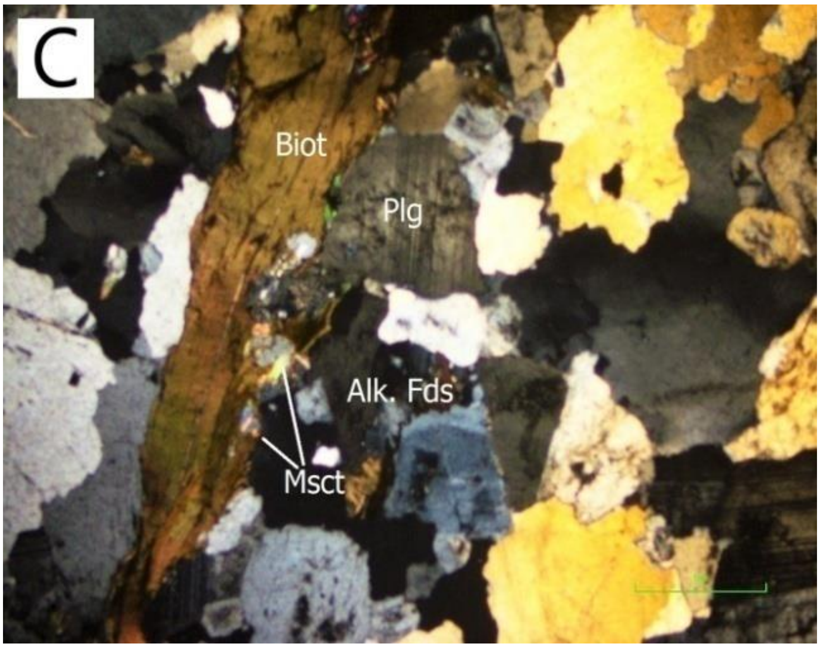

Figure 3.4: Photomicrograph: (C, XPL) Biotite grain having muscovite along margins.

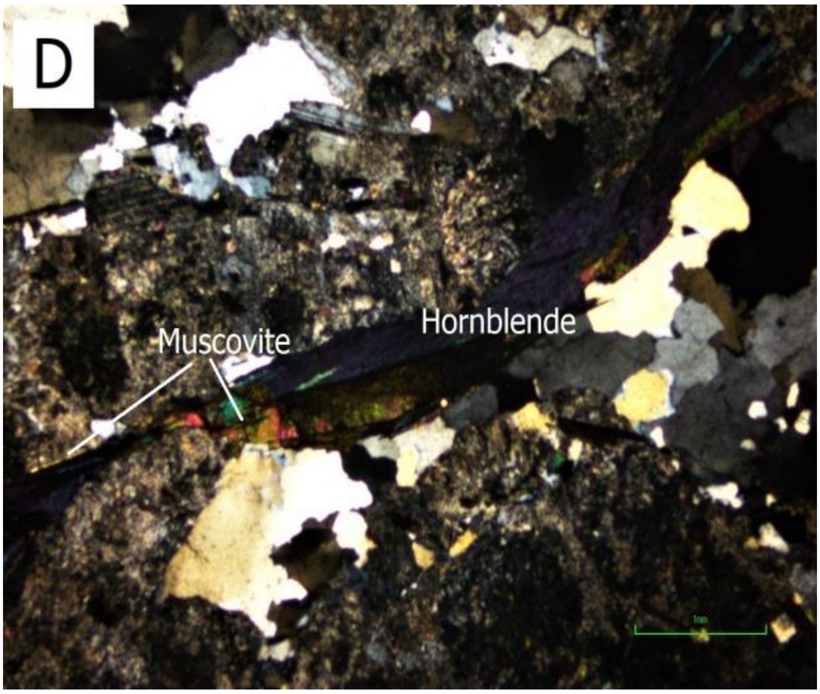

Figure 3.4: Photomicrograph: (D, XPL) Hornblende grain showing simple twinning and alteration to muscovite.

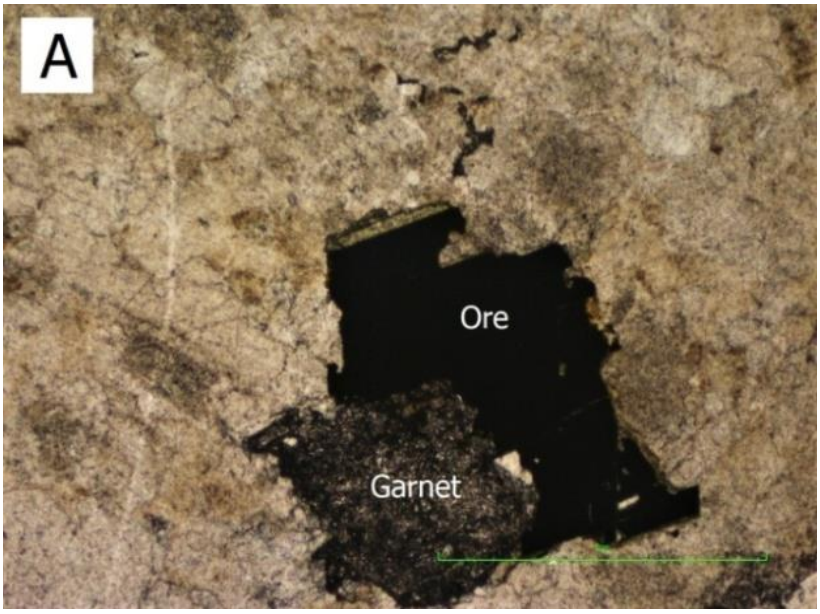

Figure 3.5: Photomicrograph: (A, PPL) An opaque ore mineral having association with high relief garnet grain.

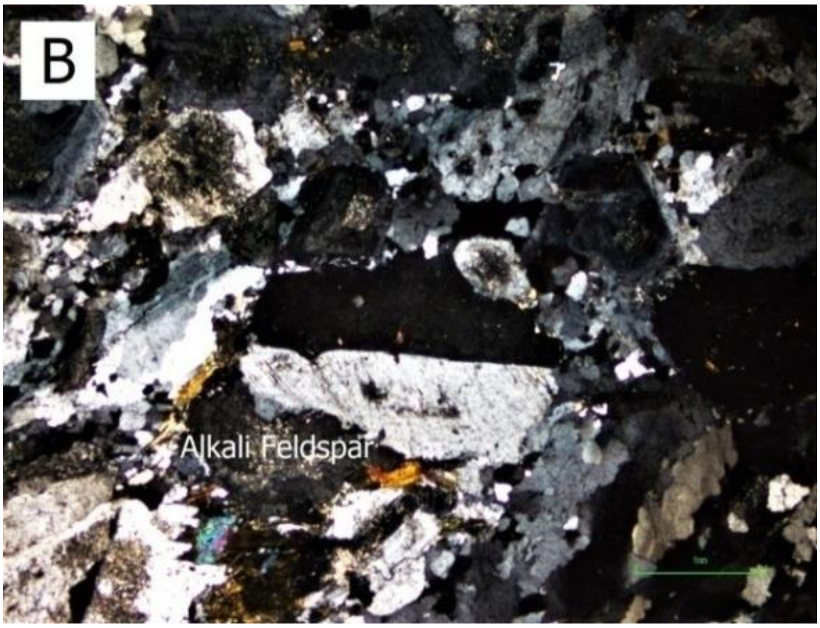

Figure3.5: Photomicrograph: (B, XPL) Alkali feldspar showing simple twinning.

CHAPTER 4

RESULTS AND DISCUSSIONS

Different type of rocks including sedimentary, metamorphic, and igneous depending on physical and mechanical properties are used in the construction works for designing, construction, engineering works, and maintenance because of their stability and suitability under various conditions. Same as other rocks granitic rocks show several engineering properties and chiefly used in different engineering projects as a dimension stone, concrete aggregate, flooring tiles, countertops, and paving materials. Some factors which affect the engineering properties of rocks are mineralogy, texture (size, shape, dimensions and arrangement of mineral grains), and degree/rate of weathering. Granitic rocks are exposed in Northern Pakistan at different locations and have been investigated for their physical and mechanical properties by a number of researchers earlier including Din et al. (1993), Din and Rafiq (1997), Arif et al. (1999), Sajid et al. (2009), Naeem et al. (2014) Sajid et al. (2014) and Arif et al. (2015).

4.1 Petrographic Study

The rock samples under study were classified based on their texture variations. These textural varieties were of porphyritic granite, foliated granite, and fine-grained granite.One thin section is prepared from each cube to study their petrographic characteristics. The Location and petrographic description of each class is described inthe following paragraphs.

i.Bibior Fine-grained Granite (BFGt) (35° 6' 29.4" N, 71° 59' 32.3" E): BFGt is a fine-grained variety of granitic rocks from Bibior area (Fig. 4.1). The grains are the same in size, almost subhedral, fine-grained quartz, plagioclase, and alkali feldspar in these rocks. Very low sericitization is noticed in the core of plagioclase grains. Hornblende and alkali feldspar shows simple twinning. Muscovite flakes and chlorite is present along biotite margins and hornblende and in some plagioclase minerals due to the alteration process. Minerals proportion is presented in table 4.1.

ii.Bibior Porphyritic Granite (BPGt)(35° 7' 32.304" N, 71° 55' 39.612" E): The porphyritic granite (Fig. 4.1)havinglarge phenocrysts of plagioclase, and alkali feldspar ofsubhedral to euhedral surrounded by a groundmass of fine-sized quartz grains. The large grains of quartz are strained/fractured shows syntectonic activities and also exhibit undulose extinction. Plagioclase grains have oscillatory zoning and sericitization in their centers and some of the grains are completely sericitized. Minerals proportion is presented in tables 4.2.

iii.Bibior Foliated Granite(BF´Gt) (35° 7' 47.3" N, 71° 56' 56.1" E): The foliated variety ofgranite (Fig. 4.1) is composed of large subhedral to euhedralphenocrysts of plagioclase and alkali feldspar. The groundmass is mostly fine to medium-grained quartz. Plagioclase and alkali feldspar show a cloudy appearance of sericitization in some grains while poor oscillatory zoning is noticed in plagioclase grains. Chloritizationis also noticed along biotite margins with muscovite flakes. Minerals proportion presented in table 4.3.

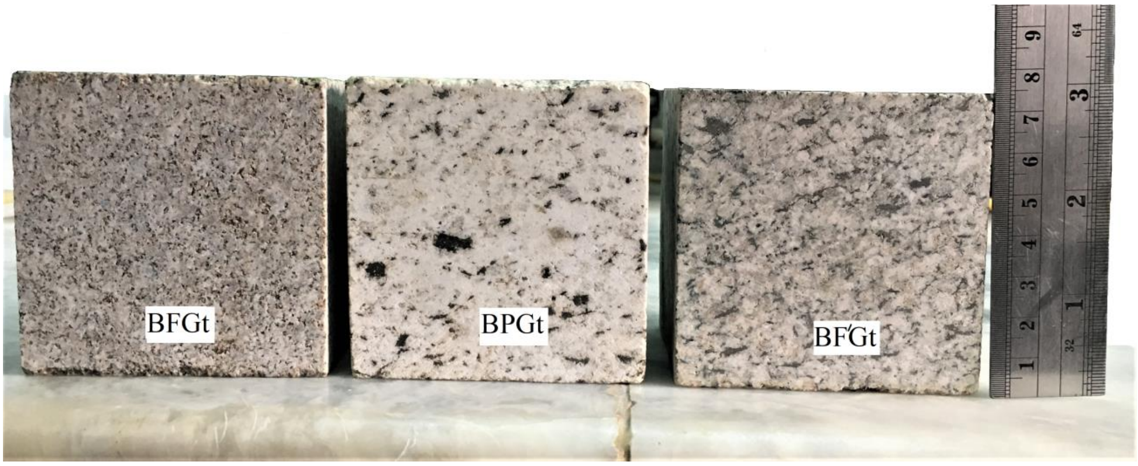

Figure 4.1: Cube samples of the different rock textural varieties from the Bibiorarea. BFGt; Bibior Fine-grained Granite, BPGt; Bibior Porphyritic Granite, and BF´Gt; Bibior Foliated Granite.

Table 4.1:Mineral composition of Bibior Fine-grained Granite.

S. No.	Qz	Afs	Pl	Bt	Ms	Tur	Opq	Ep	Cht	Hbl
BFGt-1	38	33.8	10.5	3.6	4	1.2	3.6	0.5	2	2.8
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	--

Qz: Quartz, Afs: Alkali feldspar, Pl: Plagioclase, Bt: Biotite, Ms: Muscovite, Tur: Tourmaline, Opq: Opaque, Ep: Epidote,Cht: Chlorite,Hbl: Hornblende.

Table 4.2: Mineral composition of Bibior Porphyritic Granite.

S.No.	Qz	Afs	Pl	Bt	Ms	Opq	Cht	Ser	Grt	Hem	Hbl
BPGt-1	33.5	26	21.4	9.8	2.28	3	3	--	--	0.02	1
BPGt-2	34	29	19	8	1.8	4	2.3	1.6	0.3	--	--
BPGt-3	34	30.6	20.5	4.5	0.8	3.4	3	1.2	--	--	2
BPGt-4	36.5	25.5	17	11	3.6	2.8	1.8	--	--	--	1.8
BPGt-5	32	26	21	9	3.7	4.8	2.2	--	0.1	--	1.2
BPGt-6	34	26	19	10	3.8	5.07	2.1	--	--	0.03	--

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

Table 4.3: Mineral composition of Bibior Foliated Granite.

S. No.	Qz	Afs	Pl	Bt	Ms	Tur	Zrn	Opq	Chl	Ser	Ap
BF´Gt-1	35	22	18	9	3.18	--	0.2	5	3	4.6	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	--	0.08	6	2.02	--	--
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

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

4.2 Physical Properties

The following physical properties ofthe BibiorGranitic rocks were determined.

i. Water Absorption

ii. Specific Gravity

iii. Porosity

These properties are important for rocks that are used as a construction material. Water absorption and porosity depend on weathering and grains arrangement in a rock. Physical properties were determined according to the ASTM-C127standard (ASTM, 2018).

4.2.1 Water Absorption

Igneous rocks of plutonic nature show more resistance to weathering that’s why their water absorption values always less than 1% (Blyth and de Freitas, 1974). Rocks from Bibior area were investigated for hydration and dehydration factors through water absorption test.Water absorption indicates the volume of water absorbed by a rock. This is one of the important properties to identify the rock behavior and stability used in engineering works (Shakoor and Bonelli, 1991). The water absorption values of Bibiorgranitic rocks are presented in table 4.4 and fig. 4.2, determined by water saturation and caliper method. These rocks showed water absorption results in less than 1% and 0.4% (ASTM-C127)by weight (g) therefore can be used as a dimension stone and as construction material in the construction works.

Table 4.4: Results of water absorption, specific gravity, and porosity of studied samples from the Bibior area.

S.No.	**Weight in air (g)**	**Weight in water (g)**	**Oven dry weight (g)**	**Water absorption (%)**	**Specific gravity Kg/m^3**	**Porosity (%)**
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
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
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

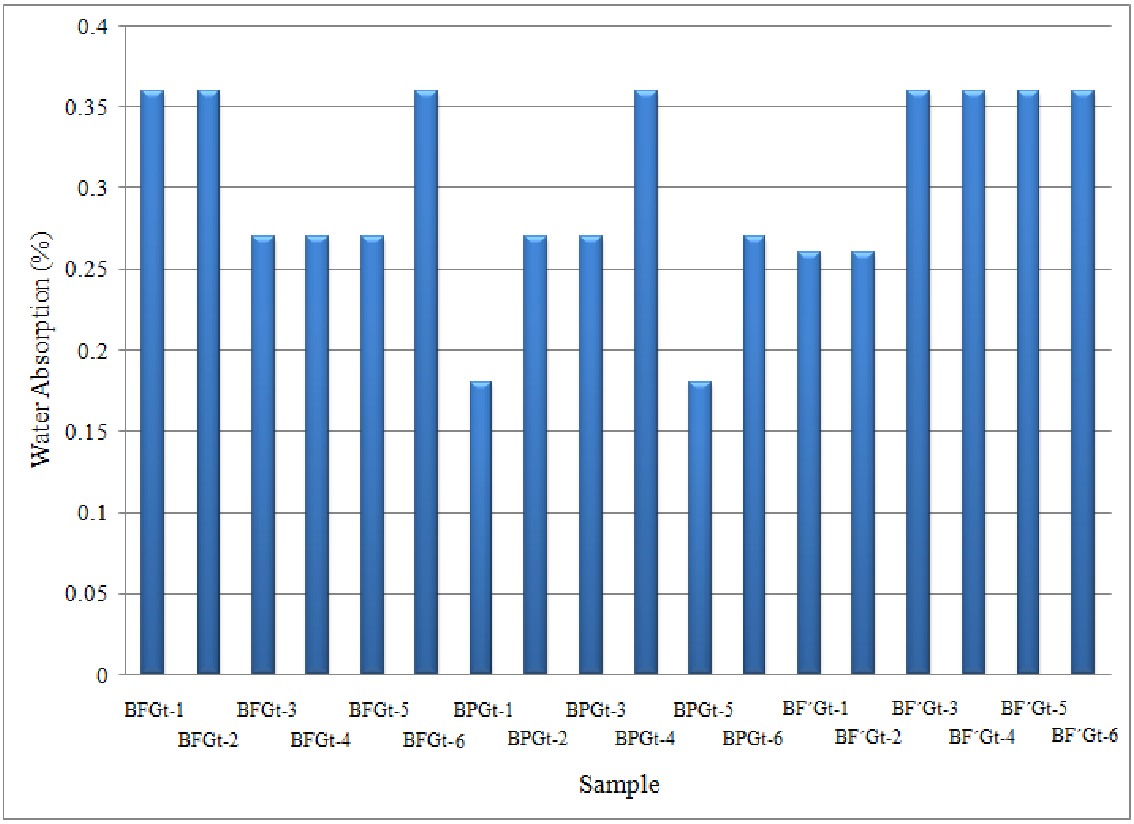

Figure 4.2: Water Absorption values of Bibior granitic rocks.

i. Bibior Fine-grained Granite (BFGt): This is a fine-grained variety of granitic rocks having 0.36-0.27 % water absorption values (Table 4.4). The values are less than 1 % (Blyth and de Freitas, 1974) and according to ASTM-C127 method maximum limit is 0.4% which shows that these rocks are suitable for construction and building works. The lower values indicate that these rocks can be used as embankment fill and dimension stones.

ii. Bibior Porphyritic Granite (BPGt):The Porphyritic granite having 0.18-0.36 % water absorption values (Table 4.4). Thevalues percentage isless than 1% (Blyth and de Freitas, 1974) and according to ASTM-C127 method maximum limit is 0.4%,shows that these rocks can be used as dimension stones, and embankment fill.

iii. Bibior Foliated Granite (BF´Gt):The foliated granite from Bibior having 0.36-0.26 % water absorption values. The values are less than 1% (Blyth and de Freitas, 1974) and according to ASTM-C127 methodmaximum limit is 0.4% show that these rocks are suitable embankment fill, and dimension stones.

4.2.2 Specific Gravity

The specific gravity of Bibior Granitic rocks was determined by using ASTM C127method. ASTM C127maximum limit is >2.77 kg/cm$^{3.}$ Those rocks which have specific gravity values equal to or greater than 2.55 kg/cm^{3} can be used in engineering projects (Blyth and de Freitas, 1974). The apparentspecific gravity of Bibior rocks attained the given criteria (Table 4.4) and can be used for construction purposes.

i. Bibior Fine-grained Granite (BFGt): The fine-grained granite having 2.674-2.686kg/cm^{3}apparent specific gravity values (Table 4.4). The values are greater than 2.55 kg/cm^{3}and suitable for construction works as embankment fill and dimension stone.

ii. Bibior Porphyritic Granite (BPGt):The porphyriticgranite having 2.668-2.693kg/cm^{3}apparentspecific gravity values (Table 4.4). The results show that these rocks can be used as embankment fill, and dimension stone.

iii. Bibior Foliated Granite (BF´Gt):The foliated granite having 2.704-2.716kg/cm^{3}apparent specific gravity values (Table 4.4). The values show that these rocks are suitable for embankment fill, and dimension stone.

4.2.3 Porosity

Porosity is the property of rocks measured as volume of the total voids in rocks and these voids play a significant role in the weathering process by holding water. The volume of voids in a rock increasing is lowering the mechanical/strength properties. The porosity of a rock is dependent on grain size, interlocking, shape, texture, and mineral composition (Bell, 1978). The saturation method (Harrison, 1993) was used to determine the porosity of Bibior rocks (Table 4.4), and the formula used is given below. The porosity percentage is presented in fig. 4.3.

$$P = \frac{\text{(Weight in air)(Dry weight)}}{\text{(Weigh in air) – (Weight in water)}} \times 100$$

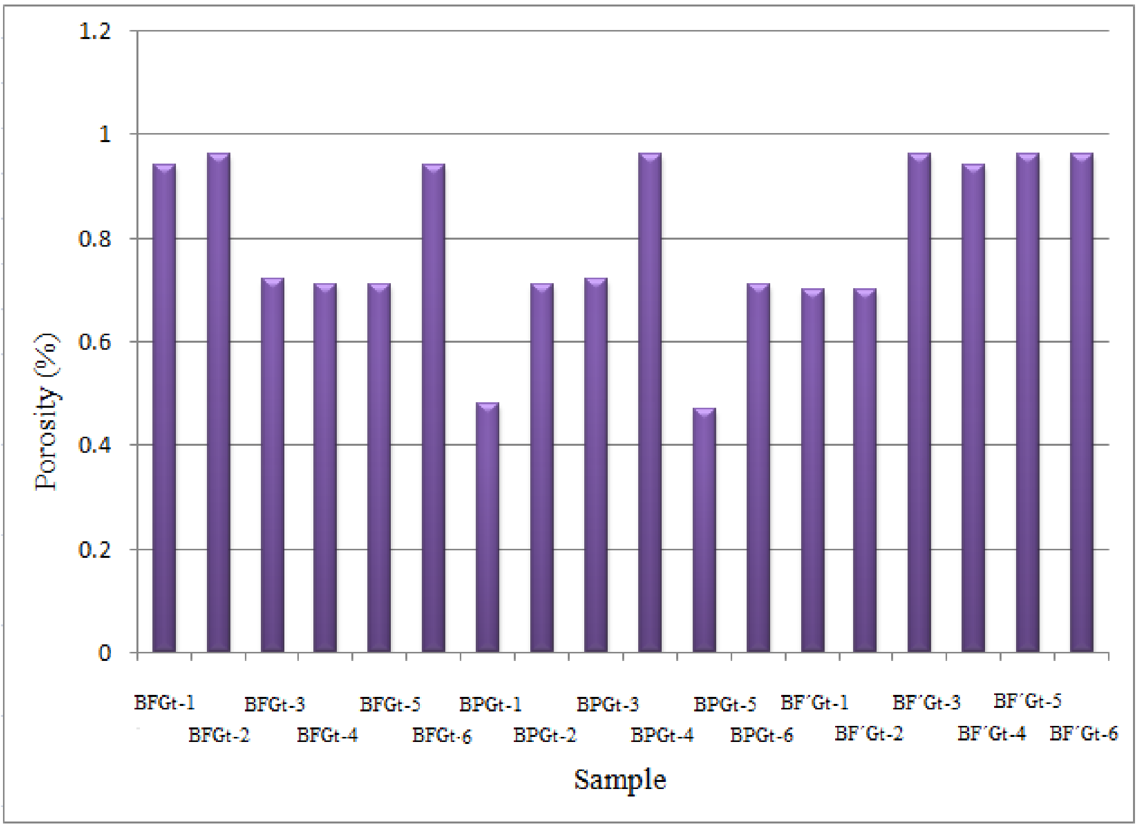

Figure 4.3: Porosity values of Bibior granitic rocks.

i. Bibior Fine-grained Granite (BFGt): The fine-grained granite having 0.96-0.71 % porosity values (Table 4.4). The lower values indicate that these rocks are suitable for embankment fill and dimension stone.

ii. Bibior Porphyritic Granite (BPGt):The porphyriticgranite having 0.96-0.47 % porosity values (Table 4.4). The results show that these rocks can be used as embankment fill, and dimension stone.

iii. Bibior Foliated Granite (BF´Gt):The foliated granite having 0.96-0.70 %values of porosity. Theselower values show that these rocks are suitable for embankment fill, and dimension stones in construction works.

4.4 Mechanical Properties

For mechanical properties determination, unconfined compressive strength (UCS) and unconfined tensile strength (UTS) tests were performed. The main purpose of mechanical properties is to determine the behavior of rocks under stress. Rocks show their strength under applied stresses. The determination of strength of rocks is too much important in the sense of their durability and suitability for construction woks. These conditions depend on engineering works in construction industry. For heavy construction works engineers always interested in high strength rocks. Granitic rocks are used around the globe in construction projects due to their high strength values and resistance to weathering. The strength tests were performed to identify the Bibior granitic rocks strength and to determine their use as a construction material such as dimension stone and embankment fill.The detailed and test results of UCS and UTS for the studied rocks are presented in table 4.5 and 4.7 respectively.

4.3.1 Unconfined Compressive Strength (UCS)

The UCS tests were performed according to the ASTM-C170 standard with minimum and maximum limits 60-200(ASTM, 2017) on cube samples of granitoids using a Universal testing machine.

i. Bibior Fine-grained Granite (BFGt): The fine-grained granite show high strength values ranges from 115-140 MPa (Table 4.5) (Fig. 4.5). According to the given criteria of ASTM-C170 with minimum and maximum limits 60-200MPa, these rocks show the appropriate strength values and classification values of the American Geological Society (AGS) and International Society for Rock Mechanics (ISRM), these rocks fall in the range of “very strong” and “high” categories respectively presented in table 4.6, fig. 4.5, and fig. 4.6.

ii. Bibior Porphyritic Granite (BPGt):The porphyriticgranite having 70-74 MPa strengthvalues (Table 4.5) (Fig. 4.5). The porphyritic texture affected the strength values, that why these rocks having lower strength valuesthan fine-grained rocks. According to the given criteria of ASTM-C170 with minimum and maximum limits 60-200MPa, these rocks show significant strength values and according to AGS and ISRM classifications these rocks fall in the range of “strong” and “high” categories respectively and presented in fig. 4.5 and 4.6.

iii.Bibior Foliated Granite (BF΄Gt): The foliated granite having 99-126 MPa strength values (Table 4.5) (Fig. 4.5). According to the given criteria of ASTM-C170 with minimum and maximum limits 60-200MPa, these rocks show the appropriate strength values and according to AGS and ISRM classifications these rocks fall in the range of “very strong” and “high” categories except PFG-4 of 99 MPa (Table 4.5) value placed in ‘strong’ and ‘high’ category and presented in fig. 4.5 and 4.6.

Table 4.5: Results of the unconfined compressive strength for studied granitic rocks

S. No.	**Area (in)**	**Load (N)**	**Strength (Psi)**	**Strength (MPa)**
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
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
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

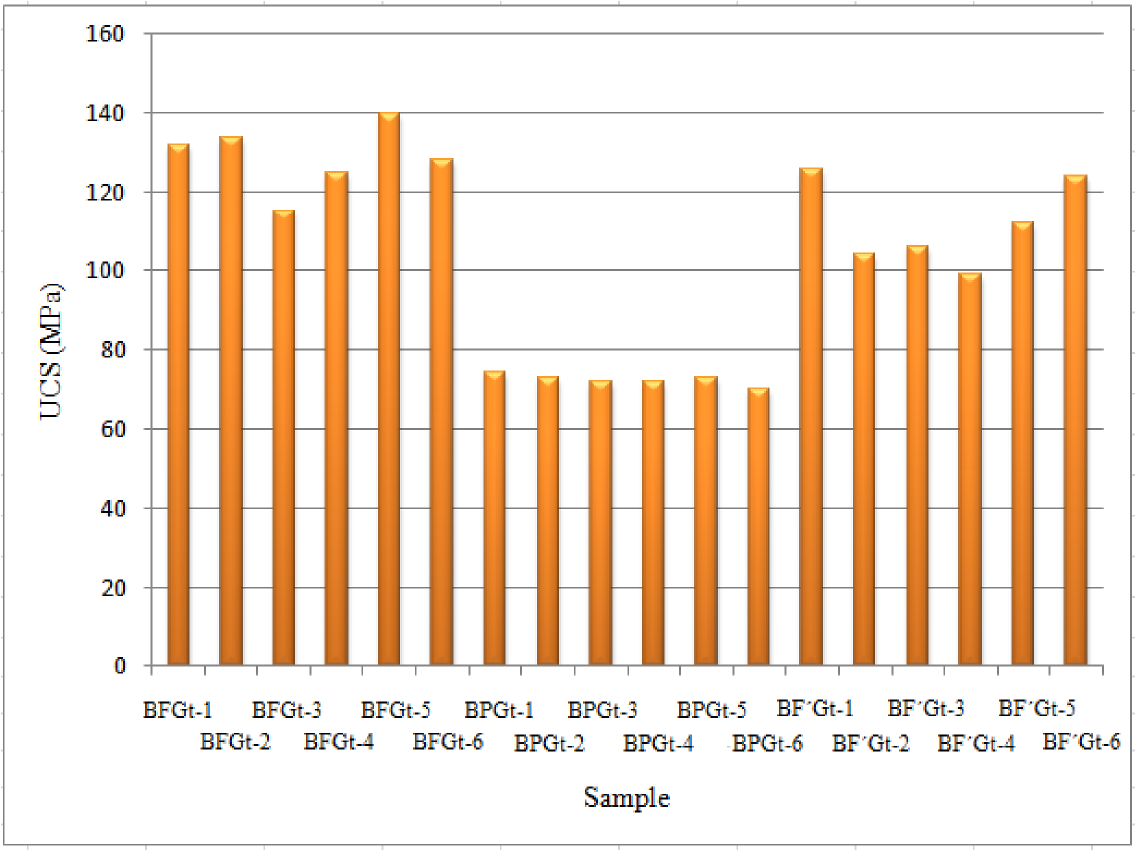

Figure 4.4: UCS values of Bibior Granitic rocksrocks.

Table 4.6: Categories of unconfined compressive strength

Geological Society (Anon, 1977)		**ISRM (Anon, 1981)**	
Category	**UCS (MPa)**	**Category**	**UCS (MPa)**
Very weak	< 1.25	Very low	< 6
weak	1.25-5	Low	6-10
Moderate weak	5-15.5	Moderate	20-60
Moderate strong	12.5-50	High	60-200
Strong	50-100	Very high	> 200
Very strong	100-200	---	---
Extremely strong	> 200	---	---

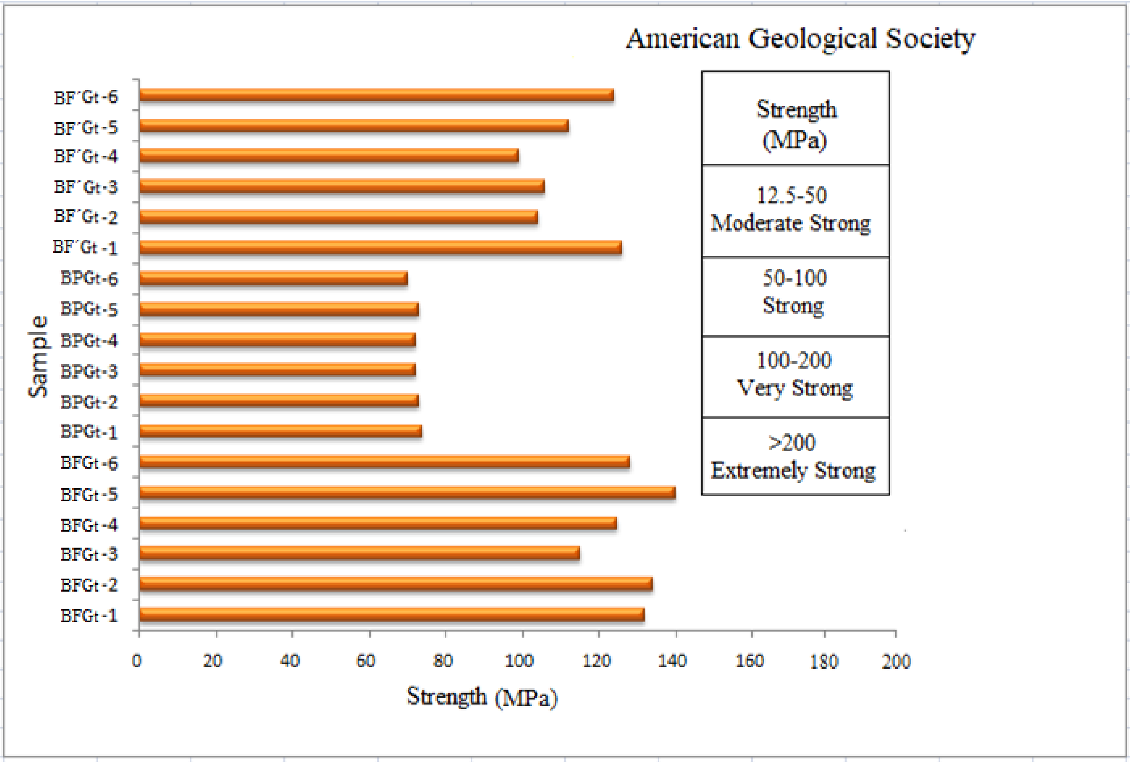

Figure 4.5: Rocks strength categories of Bibior Granitic rocks according to American Geological Society (Anon, 1977)

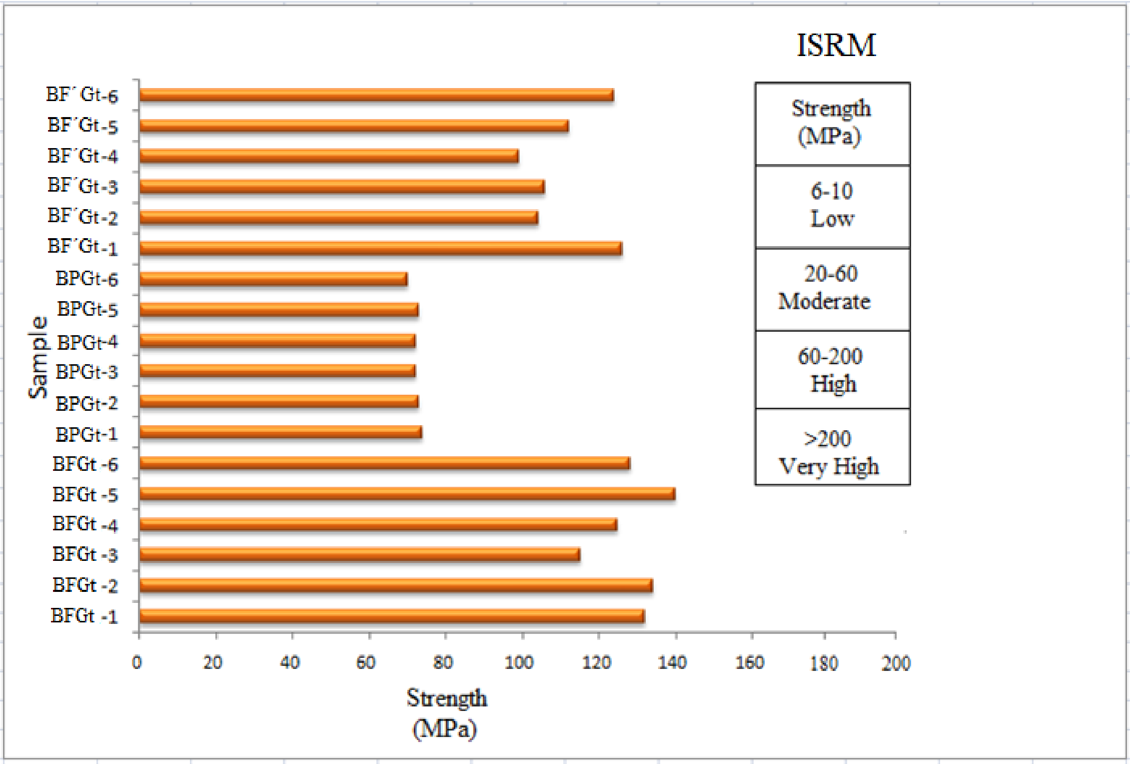

Figure 4.6: Rocks strength categories of Bibior granitic rocks according to ISRM (Anon, 1981)

4.3.2 Unconfined Tensile strength (UTS)

The UTS test results always 8-10 times less than UCS results.The Brazilian or splitting tensile test for sampleswas performed according to ASTM D3967 standard with maximum limit 4.8MPa (ASTM, 2016). The UTS values are presented in table 4.7. All the Bibior granitic varieties attained the minimum limit of the ASTM D3967 and can be used as dimension stone and construction material except BPGT-1 sample which has lower value of UTS (Fig. 4.7).

Table 4.7: Results of the unconfined tensile strength for studied granitic rocks.

S. No.	**Length (m)**	**Diameter (m)**	**Load (N)**	**UTS(MPa)**
BFGt-1	0.025	0.044	18940.84	13.27
BFGt-2	0.025	0.044	17672.23	12.38
BFGt-3	0.024	0.044	16428.51	11.05
BPGt-1	0.020	0.044	7680.45	4.30
BPGt-2	0.024	0.044	8478.62	5.70
BPGt-3	0.024	0.044	10722.33	7.21
BF΄Gt-1	0.024	0.044	16782.78	11.28
BF΄Gt-2	0.022	0.044	12870.28	7.93
BF΄Gt-3	0.021	0.044	14621.61	8.60

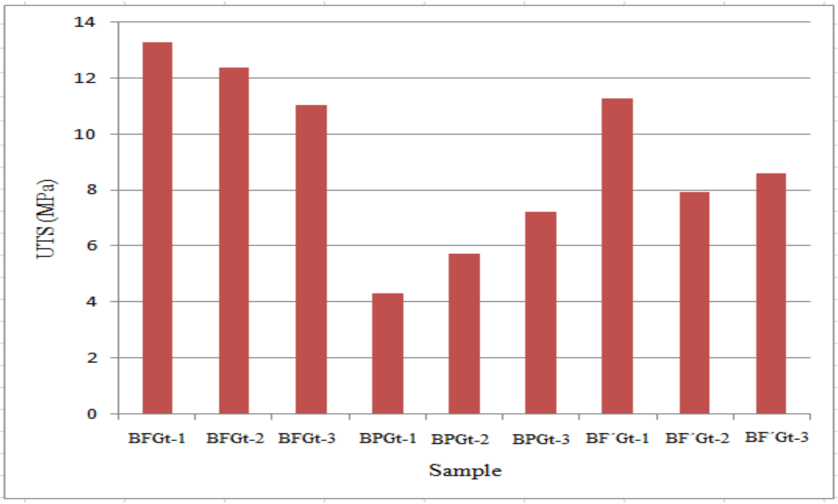

Figure 4.7: UTS values of Bibior granitic rocks.

The fine-grained rocks are stronger and tougher than their coarse-grained varieties(Bell, 2007). By comparison, the same is deducted from Bibiorgranitic rocks, where fine-grained variety rocks have higher strength values than coarse-grained rocks. The high strength rocks always depend on their strong minerals composition and strong durable matrix embedded in. The BFGtfrom Bibior area is composed of a quartz average value of ~38 %. The BPGtquartz average composition is ~34 % and the BF´Gtis composed of an average value of ~32.6 %. The fine-grained granite has a high composition of quartz matrix with lower micaceous minerals (biotite and muscovite) (Table. 4.1) show high UCS and UTS values while the porphyritic and foliated varieties have lower quartz concentration and greater abundance of flaky minerals (Table. 4.2 and 4.3) compare to BFGt variety show decrease in UCS and UTS values (Fig. 4.5).

The finer grain size and lower composition of mica content initiate the high strength values of fine-grained variety of Bibior granitic rocks.When number of grains increasing, it increased pore spaces in a rock.The fine-grained variety of Bibior area hasgreater values of water absorption and porosity comparative to porphyritic and foliated rocks. The micaceous minerals initiate foliation to the rocks and deform easily along foliation planes (Lindqvist et al., 2007).

The high values of UCS and UTS of Bibior granitic rocks (Table 4.5 and 4.7) reveal that these rocks can use as load bearing structures such as road construction, embankment fill and dimension stone.

4.4 Relationship between Petrographic, Physical, and Mechanical Characteristics

The petrographic and physico-mechanical properties data were plotted against each other to examine the relationship between petrographic, physical, and mechanical properties of three textural variants of Bibior rocks i.e. BFGt, BPGt, and BF´Gt. For that purpose, to assess the relationship between mineral abundance and strength of the rocks, UCS values of each sample are plotted against their quartz to feldspar ratio respectively (Fig. 4.6), which shows a direct relationship between these variables. Quartz is believed as more resistant to weathering and of high strength but according to Shakoor and Bonelli (1991), the total proportion of quartz is not so important in the strength of the rocks but grain contact is more important to the rock strength. However, the shape of the quartz grain is valuable because anhedral shaped quartz fills the spaces and make significant contact between other grains in a rock (Tugrul and Zarif, 1999). The quartz to feldspar ratio of each texture variety is plotted against their porosity values (Fig. 4.9), where the resulted graphs show a significance correlation between these parameters.Increase in the pore volume decreases the strength of the rocks. Due to that reason, the UCS values are plotted against water absorption and porosity values (Fig. 4.10 and 4.8) to demonstrate their relationship and it shows the inverse relationship in the resulted graphs. Furthermore, UCS and mica content of each sample are plotted against each other (Fig.4.7) and show significant results which mean that mica content in a rock can affect their strength values.

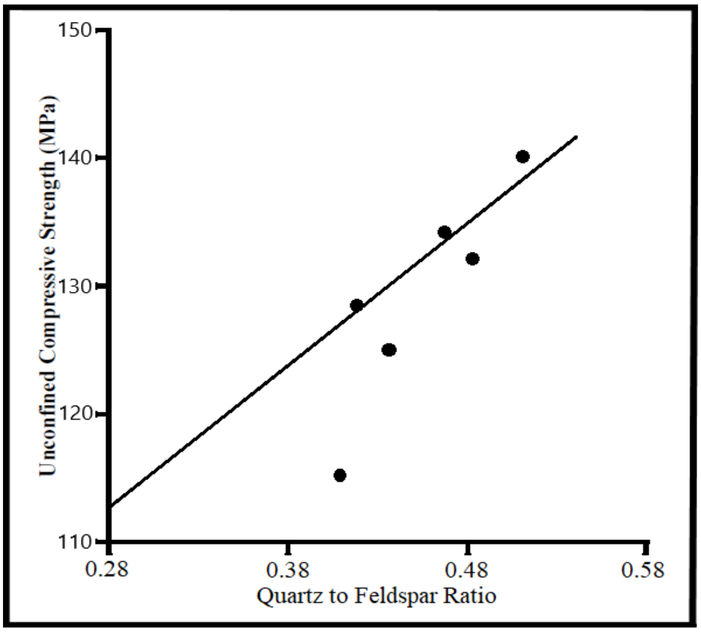

Figure 4.8(a):Graph between quartz to feldspar ratio and unconfined compressive strength for Fine-grained granite shows that with increasing quartz to feldspar ratio the unconfined compressive strength (MPa) of the sample showed an increasing trend. This positive behavior is due to the fact that quartz is stronger and shows more resistant to grain weathering.

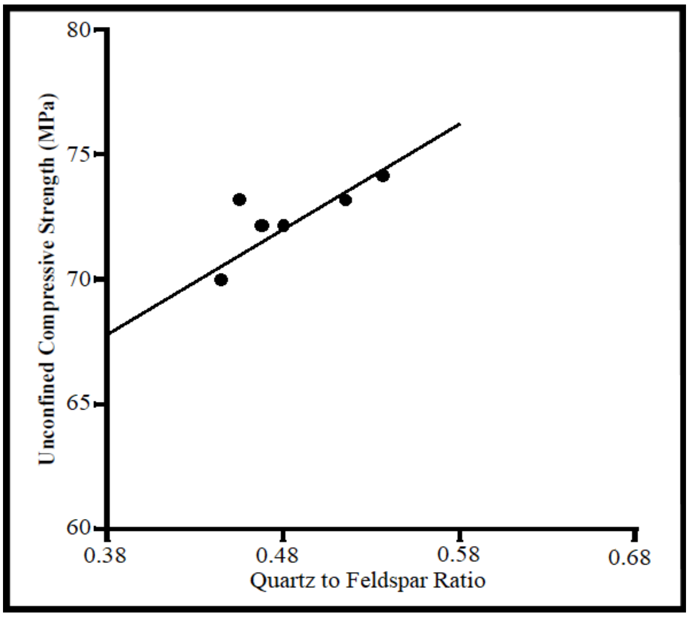

Figure 4.8(b): Relationship between quartz to feldspar ratio and unconfined compressive strength for foliated granite shows that with increasing quartz to feldspar ratio the unconfined compressive strength (MPa) of the sample showed an increasing trend. UCS is directly affected by quartz feldspar ratio showing increasing strength of the sample.

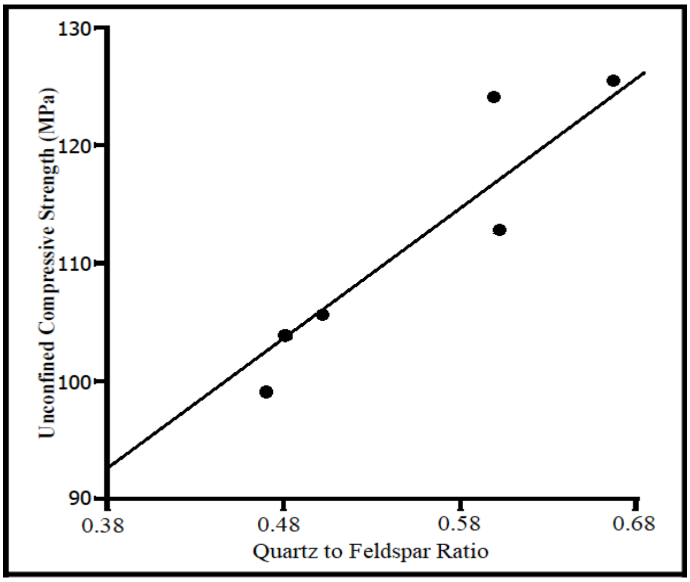

Figure 4.8(c): Graph between quartz to feldspar ratio and unconfined compressive strength for porphyritic granite shows that with increasing quartz to feldspar ratio the unconfined compressive strength (MPa) of the sample showed an increasing trend i.e.

the graph show increased in strength and resistance as the quartz feldspar ratio increased.

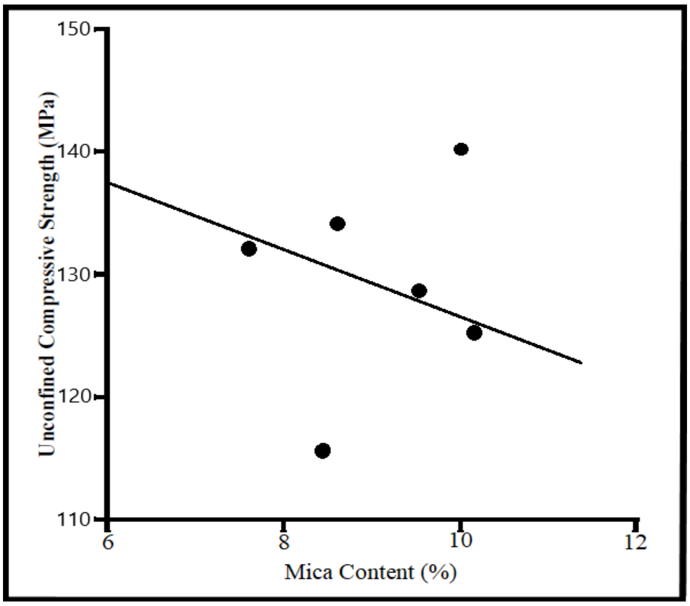

Figure 4.9(a): Graph between mica content and unconfined compressive strength in fine-grained granite shows that as the mica content increased the unconfined compressive strength (MPa) was observed to be decreasing. This showed an indirect effect as compared to the status of quartz feldspar ratio in the same sample.

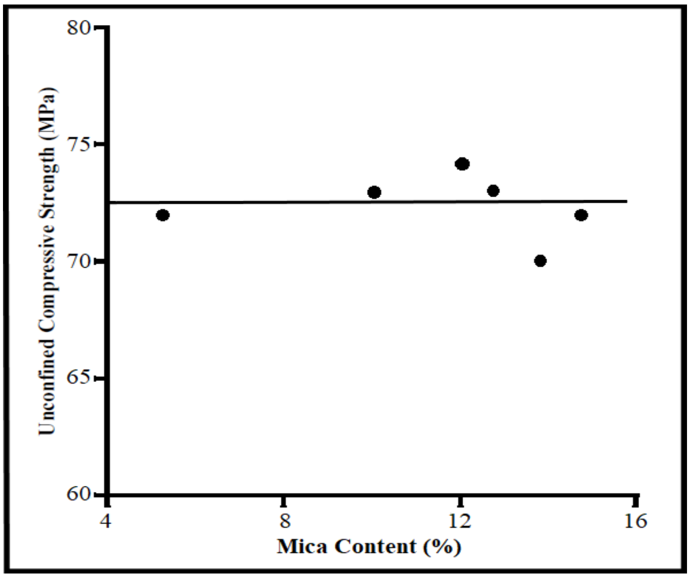

Figure 4.9(b): Graph between mica content and unconfined compressive strength in foliated granite shows that as the mica content increased the unconfined compressive

strength (MPa) was observed to be constant throughout i.e. the mica content didn't imply any change in the strength of the sample.

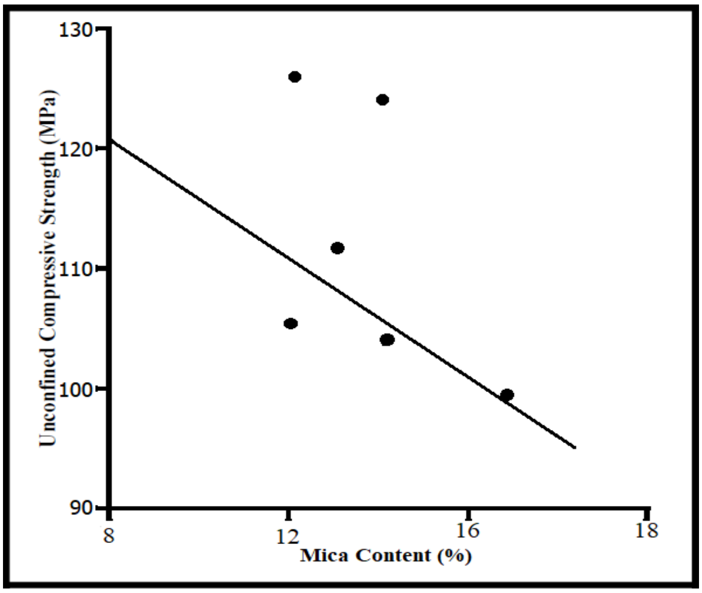

Figure 4.9(c): Graph between mica content and unconfined compressive strength in porphyritic granite shows that as the mica content increased the unconfined compressive strength (MPa) was observed to be decreasing which in other words means decreasing strength with more and more mica content in the sample.

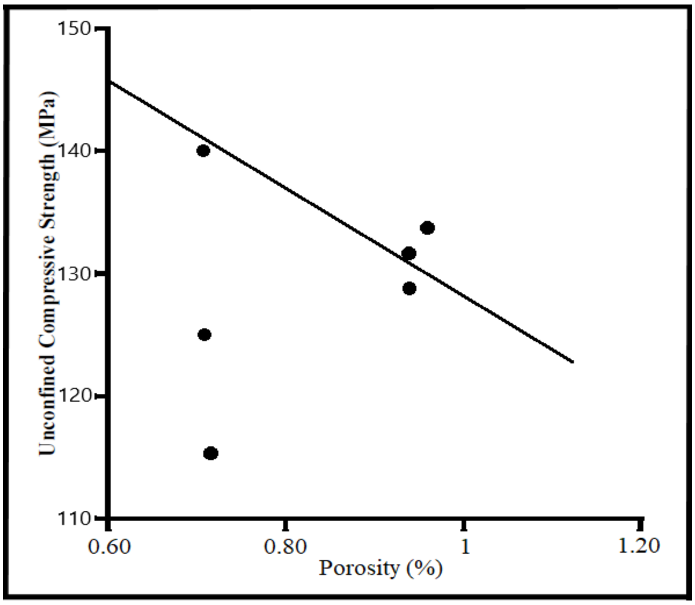

Figure 4.10(a): Graph between porosity and unconfined compressive strength of fine-grained granite showed that as porosity in the sample increased the values of unconfined compressive strength (MPa) would decrease. Porosity would increase gap between

particles of the substance and thus lesser interaction between the particles leading to decreased strength.

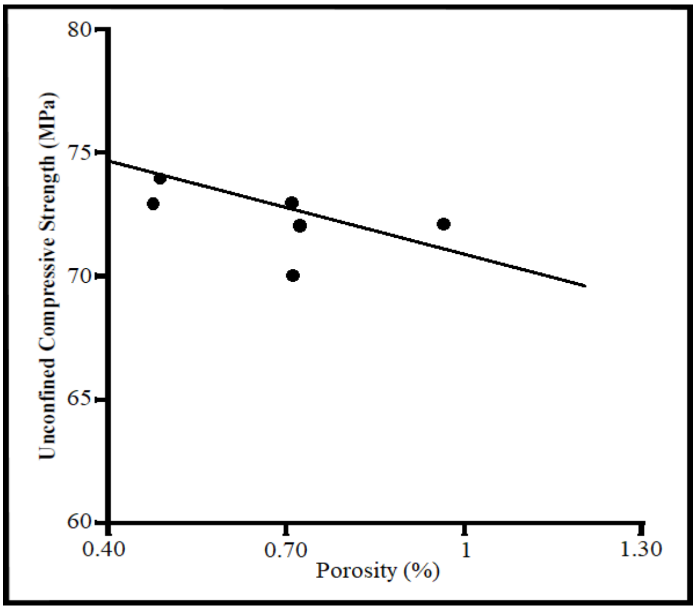

Figure 4.10(b): Graph between porosity and unconfined compressive strength of foliated granite showed that as porosity in the sample increased the values of unconfined compressive strength (MPa) would decrease. Strength of the sample was observed to be lesser as the porosity in the sample increased.

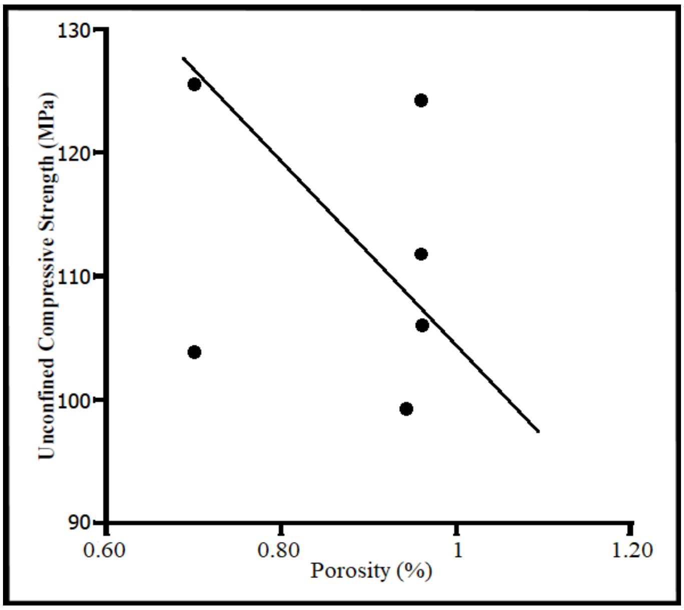

Figure 4.10(c): Graph between porosity and unconfined compressive strength of porphyritic granite showed that as porosity in the sample increased the values of

unconfined compressive strength.(MPa) would decrease indicating a drastic fall in the strength of the substance.

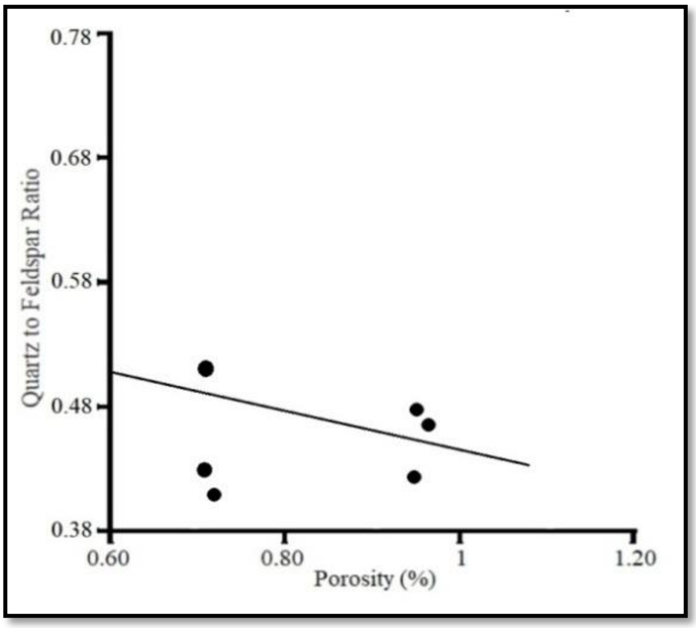

Figure 4.11(a): Graph plotted between porosity and quartz to feldspar ratio in fine-grained granite showed that as the porosity of the samples increased the quartz to feldspar ratio decreased ultimately marking lesser strength.

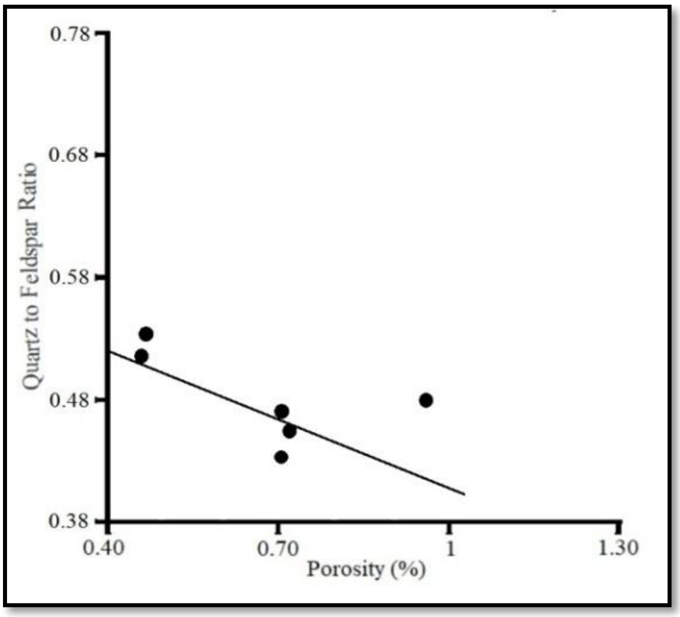

Figure 4.11(b): Graph plotted between porosity and quartz to feldspar ratio in foliated granite showed that as the porosity of the samples increased the quartz to feldspar ratio

decreased which in other words means decreased strength and resistance of the substance to weathering forces.

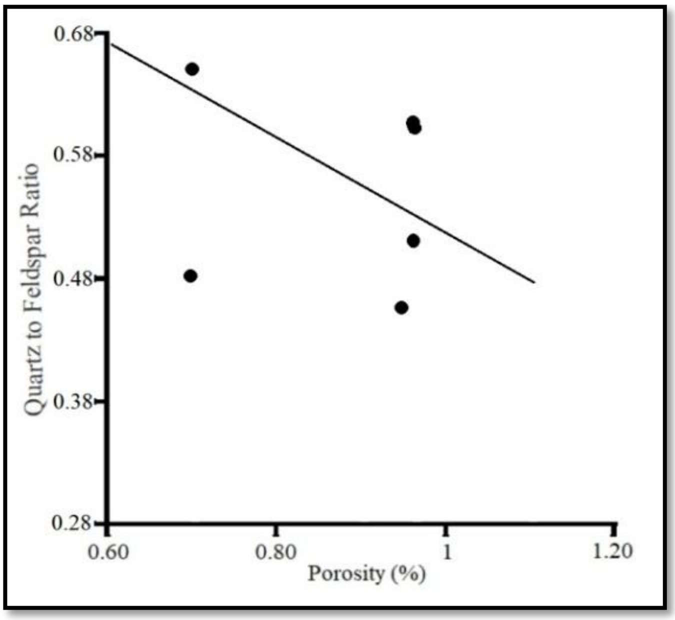

Figure 4.11(c): Graph plotted between porosity and quartz to feldspar ratio of porphyritic granite showed that as the porosity of the samples increased the quartz to feldspar ratio decreased i.e. the index of sample strength went low.

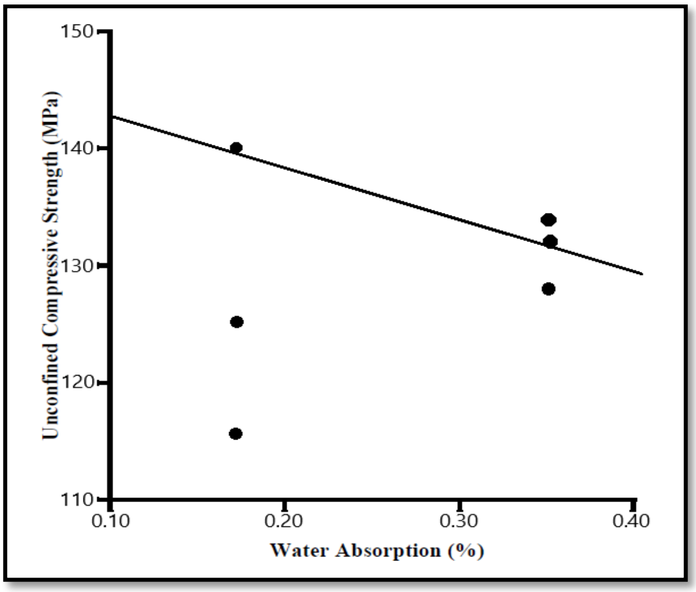

Figure 4.12(a): Relationship between water absorption and unconfined compressive strength in fine-grained granite shown with a graph shows that water absorption and unconfined compressive strength showed a reverse trend i.e. as the former increased the

later would consequently decrease. Increasing water absorption percent can also be roughly equated with porosity thus the same trend.

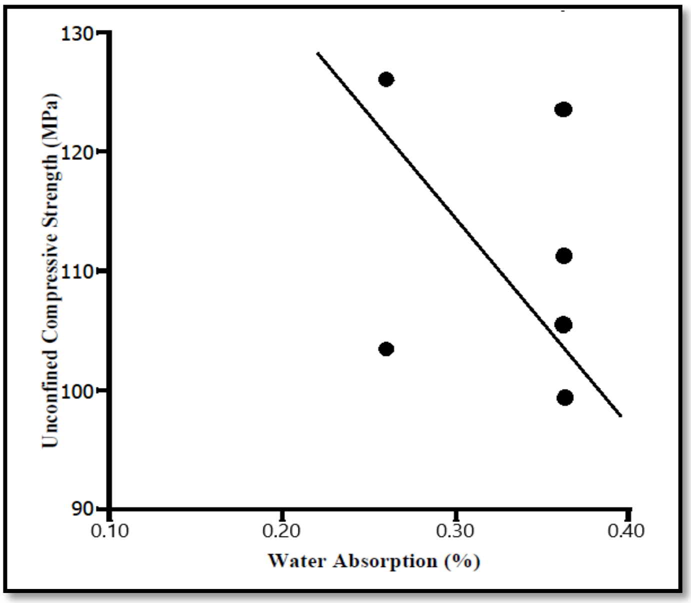

Figure 4.12(b): Relationship between water absorption and unconfined compressive strength in foliated granite shown with a graph shows that water absorption and unconfined compressive strength showed a reverse trend i.e. as the former increased the later would consequently decrease. The better it would absorb water meant its increased porosity and thus decreased strength.

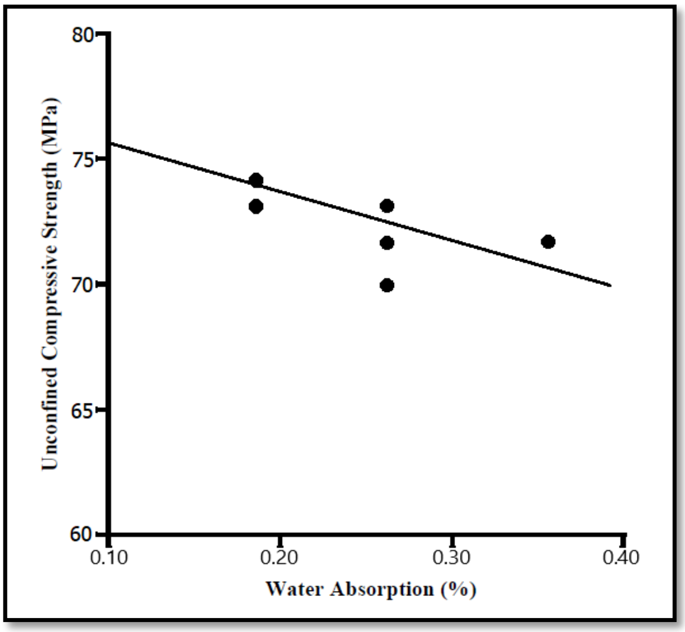

Figure 4.12(c): Relationship between water absorption and unconfinedcompressive

strengthin porphyritic granite shown with a graph shows that water absorption and unconfined compressive strength showed a reverse trend i.e. as the former increased the later would consequently decrease. Strength of the sample is dependent on its porosity and water absorption capacity. The smaller the latter two the greater is the UCS of the specimen. This graph shows that the substance, as would increase in water absorption % would decrease in UCS.

CONCLUSIONS

The detailed investigation of the present study based on field observations, petrographic study and geotechnical properties of the Bibior Granitoids from district Upper Dir are discussed in their respective chapters and the discussions are concluded in the following paragraphs:

1. Petrographically the rocks from Bibior area are divided into two groups;

   i.Granitic rocks: The granitic rocks from the area are mostly of porphyritic in texture and have close contact with amphibolite rocks. Fine-grained and foliated varieties of granitic rocks also present at places. These rocks are intruded into the amphibolites in the form of dykes. The massive intrusions of the granitoid rocksare cut over by amphibolite dykes at places.

   ii. Amphibolite rocks: By field observations amphibolite rocks are fine to medium-grained covered a major portion of the Bibior area and present in large volume. In some places small dykes of granitic composition and quartz-rich veins are intruded while on other hand small dykes of amphibolites cut over the granitic rocks from the area.

2. The physical and mechanical properties of granitic rocks from Bibior are influenced by petrographic factors of mineral composition, the arrangement of grains and pores, texture (including size and shape), weathering, deformation, and presence of mica content. The presence of strained quartz, these rocks may not be recommended for cement concrete aggregate because these may be susceptible to alkali silica reaction.

3. The Bibiorgranitic rocksarecomposed of strong minerals abundance which resulted high strength values and show less alteration in strong minerals.

4. The strength values of these rocks are significantly increasing toward fine-grained and decreasing toward coarse-grained varieties.

5. Fine grained Bibior granite having high strength because of fine-grainedsize and high proportion of quartz and feldspar minerals while foliated and porphyritic granitic rocks having less strength values compare to fine-grained granite.

6. Relationship between petrographic study and mechanical properties show that Bibior granitic rocks can be used as dimension stone and embankment fill in construction works.

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