The control of composition, texture and weathering on the physical and strength properties of selected intrusive igneous rocks from North Pakistan

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Abstract

This work characterizes intrusive igneous rocks from north Pakistan in terms of their mineralogy, texture and weathering grades and their effect on the physical and strength properties. The mafic and intermediate rocks showed a low cumulative percentage of quartz, feldspar and plagioclase with high specific gravity, strength (i.e. UCS and R-value) and UPV values compared to the felsic rocks. Likewise, samples with anhedral grain shape, irregular boundaries, fine to medium grain size (UD, ANS, CGN) showed higher strength values, that is, 121, 118 and 91 MPa compressive strength and 11, 9, and 12 MPa tensile strengths, respectively. The weathering grades assigned to the investigated samples, such as fresh (WG-I), slightly weathered (WG-II) and highly weathered (WG-III) corresponded well with the physical and strength properties, that is, as the grade increased from WG-I to WG-III, the porosity and water absorption increased (0.28% and 0.72% respectively), whereas the specific gravity, compressive strength and tensile strength decreased (2.04, 20 MPa and 2.5 MPa, respectively, for CGA). The presence of quartz affects rock strength; however, no significant correlation was observed for strength and maximum and mean grain sizes of different minerals.

1. Introduction

Rocks, whether igneous, sedimentary, or metamorphic, have been used as a construction material throughout human history. Strength and durability of rocks are the two key parameters that require evaluation before their selection as construction material and dimension stone. Studies have shown that in addition to the composition, several petrographic features control rock strength and the stress and strain behavior of rock, such as modal abundance, texture and grain size distribution (Arif et al. 1999; Sajid et al. 2016; Sousa 2013). Moreover, weathering and alteration also influence the rock strength and durability (Coggan et al. 2013; Tuğrul 2004).

The mechanical properties of different textural varieties of Utla granites from north-west Pakistan were investigated (Sajid and Arif 2015). It was observed that reduction in the strength is linked to the extensive recrystallization and associated mineralogical changes. Altered parts of minerals and petrological features such as exsolution in mineral phases can induce compressional fractures under loading (Coggan et al. 2013). As a general trend, fine-grained rocks show higher strength compared to their coarse-grained counterparts. However, with increasing complexity in texture (variation in grain size, shape and boundary), the strength also increases (Åkesson et al. 2003; Lindqvist et al. 2007; Tuğrul and Zarif 1999). Lindqvist et al. (2007) noticed that minerals with euhedral grains (regular boundaries) serve as discontinuities in a rock structure that facilitates fracture growth. The textural variations affect other properties such as resistance to drilling penetration and thermal wear (Howarth and Rowlands 1986). Studies show that micro-textures and fractures affect rock weathering and are primarily responsible for the changes in the physical and mechanical properties (Coggan et al. 2013; Rigopoulos et al. 2010; Sajid and Arif 2015; Sajid et al. 2016).

The northern part of Pakistan consists of Indian Plate, Kohistan Island Arc (KIA) and Eurasian Plate (Coward et al. 1986; Tahirkheli 1979). The Indian Plate consists of several intrusive igneous rocks that can be proposed as quality construction materials such as Mansehra Granite, Malakand Granite, Utla Granite, Ambela Granite, Chakdara Granite, Swat Granite and some dolerites in the form of dykes. The textural and weathering controls on mechanical behavior for a particular rock type have been elaborated in detail (Rigopoulos et al. 2010; Sajid et al. 2016). This study, in contrast, highlights the effects of common textural observation, derived from various rock units, on the mechanical nature of rocks. For this purpose, the geochemically and texturally different intrusive rocks from north Pakistan were investigated and the role of texture and weathering on their physical and strength properties was discussed. Petrography, physical tests (specific gravity, water absorption, porosity, Ultrasonic Pulse Velocity-UPV) and strength tests (compressive, tensile, Schmidt hammer rebound-R-value) were performed. Finally, the relationships of petrographic and engineering properties of these rocks were also statistically modeled and evaluated.

2. Materials And Methods

Fieldwork was conducted to collect bulk samples from Utla Dolerite (UD), Nepheline Syenite (ANS), Chilas Gabbronorite (CGN), Ambela Granite (AG), Chakdara Granite (CGB), Swat Granite (SG), and Chakdara Granite (CGA) (Fig. 1). The samples were collected based on texture, weathering-grade and mesoscopic structures (Table 1). The weathering condition was assessed, based on a careful examination of rocks in terms of the original texture preserved, the color of the fresh and weathered surfaces and impact sound produced by the geologic hammer (Borrelli et al. 2007; Irfan and Dearman 1978). Indicators of weathering, such as fractures, recrystallization and alteration of different minerals were also noticed. Figure 2 shows cylindrical core specimens (50-mm diameter) obtained from the investigated rock types to perform the physical and strength tests. The tests were conducted on three core specimens from each rock sample and average results are reported. Thin-sections were prepared from small chips of cores (size 40 x 20 mm) for the petrographic study. The petrographic examination included both the naked eye and microscopic observations. Thin-sections from each sample were studied under the polarizing microscope (Nikon Eclipse LV100ND). Minerals were identified based on their optical properties (MacKenzie and Guilford 2014). The modal abundance was determined (based on visual estimation) and grain shape, size and arrangements were noted for textural identification.

The physical property tests such as specific gravity and water absorption were determined in the laboratory according to standard test methods for absorption and bulk-specific gravity of dimension stone (ASTM, DC97 / C97M-18). The porosity of the investigated rocks was obtained using the saturation method (Franklin 1979). The UPV was determined using the ultrasonic pulse velocity test instrument from MS CONTROLS Italy. A pitch-catch technique was used that involves a pair of transducers i.e. transmitter and receiver (Aydin 2013). The frequency of $10s^{-1}$ was used to acquire the transit travel time of the core samples at two conditions i.e. saturated surface dry (UPV_{SSD}) and the oven-dry (UPV_{OD}) at 110 °C for 24 h. To obtain better correlations, all the tests were conducted on the same specimen that was later used for the strength tests.

The Unconfined Compressive Strength, (UCS) test was conducted according to the standard test methods for compressive strength and elastic moduli of intact rock core specimens under varying states of stress and temperatures (ASTM, D7012-14e1). Unconfined Tensile Strength (UTS) test was performed using a Brazilian test method according to the standard test method for splitting tensile strength of intact rock core specimens (ASTM, D3967-16). The Schmidt hammer rebound test (R-value) is a nondestructive method for determining the strength and was conducted according to the standard test method for determination of rock hardness by a rebound hammer method (ASTM, D5873-14). The R-value was obtained using N-type Schmidt Hammer (SH) equipment having impact energy 0.735 Nm

3. Results

3.1 Petrography and Weathering Grades:

Figure 3 shows the selected microphotographs of the investigated rocks and Table 1 shows their petrographic description. Table 2 shows the modal mineralogy and average grain size. Based on the modal mineralogy, the rocks are classified as mafic (UD, CGN) intermediate (ANS,) and felsic (AG, CGB, SG, CGA). Tables 3 presents weathering grades (WG) assigned to the investigated rocks based on field and microscopic observations. The rocks were classified as fresh, WG-I (UD, ANS and CGN), slightly weathered, WG-II (AG, CGB and SG) and highly weathered, WG-III (CGA).

3.2 Physical Properties

Table 4 enlists the average results of physical properties. Fresh, WG- I samples (UD, ANS and CGN) showed higher specific gravity, and UPV_{sat} (3.08 and 5573.17 m/sec respectively for UD), and lower WA (0.13% for CGN) and porosity (0.12% for ANS). The highly weathered sample, WG-III, (CGA) showed the minimum specific gravity (2.04) and UPV_{dry} (1526.26 m/sec), and the maximum water absorption (WA) (0.28%) and porosity (0.72%). The results of UPV displayed a slight decrease from UPV_{sat} to UPV_{dry}, except for CGA, that displayed a slight increase. These results agree with previous studies on weathering effects on granites that showed a material with high porosity can retain more water and thereby results in reduced UPV values (Sousa et al. 2005; Vasconcelos et al. 2008).

3.3 Strength Properties

The strength values of the investigated rocks followed the physical properties (Table 4), i.e. fresh, WG-I samples showed higher UCS (120 MPa for UD) and UTS values (12.40 MPa for CGN). Whereas highly weathered, WG-III sample showed lower UCS and UTS values (20 MPa and 2.5 MPa, respectively, for CGA). These results are comparable with those reported in previous studies from Pakistan (Arif et al. 1999; Rafiq et al. 1988; Sajid and Arif 2015; Sajid et al. 2016) and from various parts of the world such as (Basu et al. 2009; Sousa 2013; Tuğrul 2004). Likewise, high R-value was obtained for fresh, WG-I sample (53.78 for UD) and lowest for highly weathered, WG-III sample (13.67 for CGA).

3.4 Petrographic, Physical and Strength Properties

The petrographic, physical and strength properties of the investigated rock varieties are discussed.

- Sample UD contained a relatively high number of opaque minerals (5%-8%), that resulted in a higher specific gravity (3.08). Likewise, the higher porosity (0.37%) was attributed to the slight alteration of pyroxene mineral (Fig. 3a) and intergranular fractures. Among the investigated samples, fresh, WG-I sample, UD showed the highest UCS and UTS values (121 MPa and 11 MPa, respectively).
- The sample ANS showed a slight alteration of alkali feldspar and amphibole that resulted in relatively high water absorption and porosity values (0.19% and 0.12%, respectively). However, it also displayed high UCS and UTS values (i.e. 118 MPa and 9 MPa, respectively) and fresh weathering-grade (WG-I). This is attributed to the inequigranular, anhedral grains, irregular grain boundaries mainly of fine-grained feldspar surrounding the nepheline (Fig. 3b).
- The sample CGN showed a uniform grain size and regular boundaries. The twinning and slight alteration (Fig. 3c) resulted in moderate values of water absorption and porosity (i.e. 0.13% and 0.28%, respectively) and lower UCS and UTS values (i.e. 91 MPa and 12 MPa, respectively) compared with other fresh, WG-I samples.
- In sample AG, the water absorption and porosity were the lowest (0.06% and 0.14% respectively) among the investigated samples. The subhedral grain shape and the presence of large feldspar grains (up to 10 mm) having intra-granular fractures (Fig. 3d) contributed to its moderate UCS and UTS values (i.e., 60 MPa and 6 MPa, respectively) and slightly weathered, WG-II weathering-grade.
- The sample CGB showed relatively fresh grains of alkali feldspar, quartz and mica than CGA (Fig. 3e) and therefore resulted in lower water absorption and porosity (0.17% and 0.44% respectively), higher UCS and UTS values (i.e. 53 MPa and 6 MPa, respectively) and slightly weathered WG-II weathering-grade.
- The sample SG showed gneissosity in the form of aligned flaky mica (Fig. 3f). Besides, it showed gneissosity and slight weathering (WG-II) and resulted in moderate water absorption and porosity (0.12% and 0.26% respectively). The alteration as sericitization and fractures in alkali feldspar impacted its UCS and UTS values (i.e. 45 MPa and 6 MPa, respectively). Åkesson (2004)also made similar observations on microstructures in granites and marbles from Sweden.
- The sample CGA was highly sheared (WG-III) and showed sericitization, alteration and intense fracturing of alkali feldspar (Fig. 3g). As a result, high water absorption and porosity values were obtained (0.28% and 0.62%, respectively). It showed the lowest UCS and UTS values among the investigated samples (20 MPa and 3 MPa).

4. Discussion

Figure 4 shows the regression analysis to investigate the effect of mineralogy and weathering grades of the investigated rocks on the physical and strength properties. The cumulative percentage of quartz, feldspar and plagioclase (Q+F+P) is plotted against the specific gravity, UCS, R-value and UPV, and inverse correlations are obtained (Figs. 4a,b,c) with R^2 0.62, 0.81, and 0.90, respectively. Figure 4a shows the mafic and intermediate rocks, fresh (WG-I) having a lower cumulative percentage of Q+F+P resulted in a higher specific gravity (2.68 to 3.08). Whereas, the felsic rocks, slightly weathered to highly weathered (WG-II and WG-III) having a higher cumulative percentage of Q+F+P showed lower specific gravity (2.0 to 2.67). Rocks having higher specific gravity indicate heavy and high-strength minerals, which have a significant impact on the rock strength (Fig. 4d). These findings are in agreement to (Sajid et al. 2016), who correlated modal composition of quartz, plagioclase and feldspar against the UCS and found negative correlations for quartz and plagioclase but positive for feldspar. Similarly, compared to felsic rocks, mafic rocks showed higher UPV_{OD} values (Fig. 4e) with $R^2=0.90$, as also reported by (Behn and Kelemen 2003).

The ultrasonic pulse velocity (UPV) as an index of rock strength is well explained by (Aldeeky and Al Hattamleh 2018; Ercikdi et al. 2016; Gomez-Heras et al. 2020; Selçuk and Nar 2016). They argued that UPV with detailed petrography can evaluate fractures and compactness in rocks. Yılmaz et al. (2014) found a positive correlation between specific gravity and UPV and showed compact rocks have higher UPV values. Figure 5a plots UPV and specific gravity with $R^2=0.89$. The compressional waves of UPV show different results for different pore-filled fluids in the rocks and generally positive correlation are observed for UPV_{OD} and UPV_{SSD} (Kahraman 2007; Karakul and Ulusay 2013; Vasanelli et al. 2013). Figure 5b shows a positive correlation between UPV_{OD} and UPV_{SSD} ($R^2=0.87$). Figures 5c, and d plot of UPV_{OD} against UCS and R-value and show significant positive correlations, ($R^2=0.85$ and $R^2=0.82$ respectively). These results agree with the findings of Akoglu et al. (2020); Vasanelli et al. (2013); Vasconcelos et al. (2008) who derived similar positive relationships. Figure 5e shows a positive correlation between the R-value and UCS ($R^2=0.89$)

Figure 6 plots the modal composition and grain size on the rock strength against the UCS. The strength of the rock decreases as the composition changes from mafic to felsic along with the increase in weathering-grade (Fig. 6a). The presence of quartz also affects rock strength, which agrees with the results of (Sajid et al. 2016). The rock strength was plotted against maximum and mean grain sizes of different minerals (Fig. 6band c) and no significant correlation was observed which is in contrast to the previous studies by Sajid et al. (2016); Tuğrul (2004) and many others. It can be inferred from these plots that meaningful relationships derived by the previous workers cannot be generalized for any rock type.

5. Summary And Conclusions

The details of the field and petrographic observations, geochemical analyses, physical and strength properties of the selected intrusive rocks from north Pakistan are presented in this study. Based on the detailed laboratory testing, the investigated intrusive igneous rocks were categorized as fresh, WG-I (UD, ANS and CGN), slightly weathered, WG-II (AG, CGB and SG) and highly weathered, WG-III (CGA). Physical and strength properties showed a strong relationship with weathering grades. Fresh, WG- I samples (UD, ANS and CGN) showed higher specific gravity, and UPVsat (3.08 and 5573.17 m/sec respectively for UD), and lower WA (0.13% for CGN) and porosity (0.12% for ANS). Whereas the highly weathered sample, WG-III, (CGA) showed the minimum specific gravity (2.04) and UPV_{OD} (1526.26 m/sec), and the maximum water absorption (WA) (0.28%) and porosity (0.72%). Likewise, fresh, WG-I samples showed higher UCS (120 MPa for UD) and UTS values (12.40 MPa for CGN). While highly weathered, WG-III sample showed lower UCS and UTS values (20 MPa and 2.5 MPa, respectively, for CGA). The ultrasonic pulse velocity of UPV_{OD} slightly decreased compared to UPV_{SSD}. The rock strength decreased as the composition changed from mafic to felsic. The presence of quartz also affects rock strength; however, no significant correlation was observed for the rock strength and maximum and mean grain sizes of different minerals. It can be inferred from the results that relationships derived by previous workers cannot be generalized for any other rock type.

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Tables

Table 1 Details of samples collected during the fieldwork

Rock Name	Rock Designation	Grain Size	Petrographical description
Utla Dolerite	UD	Medium	Equigranular, euhedral to anhedral, ophitic to sub ophitic. Plagioclase was tabular and showed a typical polysynthetic twinning. Pyroxene (mostly clinopyroxene) was subhedral to anhedral and sericitized at places.
Nepheline Syenite	ANS	Fine	Inequigranular, anhedral to euhedral grains. Alkali feldspar appeared both as perthite and microcline. Nepheline was euhedral to subhedral. Amphibole was anhedral, mostly disseminated and altered.
Chilas Gabbronorite	CGN	Medium	Inequigranular, subhedral to anhedral grains. Plagioclase showed polysynthetic twinning and sericitization at places. Biotite was present along the margins of pyroxene grains.
Ambela Granite	AG	Coarse	Inequigranular with anhedral to subhedral grains. Alkali feldspar was perthitic having blebs of albite. Microcline feldspar was also present. Quartz showed undulose extinction.
Chakdara Granite-B	CGB	Fine to medium	Inequigranular, anhedral to subhedral grains. Alkali feldspar was perthitic where exsolution lamellae were present and contained inclusions of mica and zircon. Quartz showed undulose extinction.
Swat Granite	SG	Medium to coarse	Inequigranular, anhedral grains. Minerals alteration and sericitization were commonly observed. Alkali feldspar contained inclusions of muscovite and quartz. Mica was mostly in tabular form and aligned.
Chakdara Granite-A	CGA	Fine to medium	Equigranular, anhedral grains. Alkali feldspar contained inclusions of mica, mostly microcline and sericitized. Quartz was mostly recrystallized. Amphibole was altered to muscovite along the margins.

Table 2 Modal mineralogy of the studied rocks

	UD			ANS			CGN			AG			CGB			SG			CGA		
Sample	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
Afs	-	-	-	54	56	58	-	-	-	65	62	66	58	53	56	34	31	33	58	56	58
Qz	-	-	-	-	-	-	-	-	-	13	21	18	33	40	36	41	38	41	35	36	34
Pl	53	50	51	7	7	6	55	57	54	2	2	2	2	1	3	8	11	9	2	1	2
Bt	1	1	1	T	T	T	2	3	2	9	5	5	3	2	3	9	12	11	3	2	3
Amp	1	2	2	6	4	5	-	-	-	6	2	6	-	-	-	4	5	4	0	2	1
Opq	5	8	5	-	-	-	2	4	5	2	3	3	-	-	-	-	-	-	-	-	-
Cal	-	-	-	-	-	-	-	-	-	1	2	-	-	-	-	-	-	-	-	-	-
Chl	-	-	-	-	-	-	-	-	-	-	1	T	-	-	-	-	-	-	-	-	-
Rt	-	-	-	-	-	-	-	-	-	-	-	T	-	-	-	-	-	-	-	-	-
Spn	-	-	-	4	4	3	-	-	-	-	-	T	T	T	T	-	-	-	-	-	-
Nph	-	-	-	18	21	19	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Aeg	-	-	-	11	8	9	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Ap	-	-	-	T	T	T	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Zrn	-	-	-	T	T	T	-	-	-	-	-	-	T	T	T	-	-	-	-	-	-
Ms	-	-	-	-	-	-	-	-	-	-	-	-	5	4	4	4	3	2	3	3	2
OPx	-	-	-	-	-	-	23	20	21	-	-	-	-	-	-	-	-	-	-	-	-
CPx	40	39	41	-	-	-	18	17	18	-	-	-	-	-	-	-	-	-	-	-	-
Ol	-	-	-	-	-	-	T	T	T	-	-	-	-	-	-	-	-	-	-	-	-
Avg Grain Size (mm)	0.85			1.07			1.12			4.15			0.61			1.03			0.63		

Afs= alkali feldspar, Qz= quartz, Pl= plagioclase, Bt= biotite, Amp= amphibole, Opq= opaque minerals, Cal= calcite, RT= rutile and Spn= sphene, Nph= nepheline, Aeg= aegirine, Ap= apatite and Zrn= zircon, Ms= muscovite, CPx= clinopyroxene, T = trace

*Minerals abbreviations are according to Whitney and Evans, 2010.

Table 3 Weathering classification of the investigated rocks (after Irfan and Dearman, 1978; Borrelli et al., 2007)

Rock Designation	Outcrop observations	Microscopic observations	Descriptive term	Weathering Grade
UD	Dark grey to black in colour, uniform and fine-grained. Very compact and produced a sharp sound with a geological hammer	Ophitic to sub-ophitic texture, with polysynthetic twinning in plagioclase, was mostly fresh but slight alteration was observed in pyroxene.	Fresh	I
ANS	Fine to medium-grained, grey and no discolouration. Purely fresh and produced good sharp sound with a geologic hammer.	Major minerals such as feldspar and nepheline were fresh but a slight alteration of amphibole was observed.	Fresh	I
CGN	Greyish in colour on fresh while brown on the weathered surface, medium-grained. Very hard, having compact sound with a geologic hammer.	A slight alteration was observed in plagioclase and pyroxene at places but overall dominantly consisted of fresh mineral grains.	Fresh	I
AG	Milky white colour with dark greyish phenocryst, medium-grained, original texture was preserved. Produced a compact sound when struck with a geological hammer. The weathered surface colour was brownish-grey.	Minerals with a fresh appearance and no signs of prominent alteration. Some fractures in feldspar and quartz were present.	Slightly weathered	II
CGB	Light brown, fine to medium-grained. Slight discolouration and moderately foliated. Fairly compact sound with a geologic hammer.	Comparatively fresh mineral grains to CGA, however, alteration of feldspar was observed.	Slightly weathered	II
SG	White in colour, moderately gneissose and medium to coarse-grained. Slightly fresh, and produced dull sound with a geological hammer.	Alteration and sericitization were observed in both feldspar and micas. Feldspar was fractured and mica was mostly aligned.	Slightly weathered	II
CGA	Milky white in colour, fine-grained, having discolouration. Extremely sheared and foliated. Produced a dull sound and was easily breakable with a geologic hammer.	Thin sections appearance was dirty. Major minerals such as feldspar and quartz were highly fractured. Sericitization and alteration were commonly observed in feldspar and amphibole.	Highly weathered	III

AG = Ambela Granite, ANS= Nepheline Syenite, CGA= Chakdara Granite A, CGB= Chakdara Granite B, CGN= Chilas Gabbronorite, SG= Swat Granite, UD= Utla Dolerite

Table 4 Average results of physical and strength properties of the investigated rocks

Sample	Weathering Grade	Specific Gravity	Water Absorption (%)	Porosity (%)	UPV_{sat} (m/sec)	UPV_{OD} (m/sec)	UCS (MPa)	UTS (MPa)	R-Value
UD	I	3.08	0.16	0.37	5573.16	5142.38	120.70	10.50	53.78
ANS	I	2.68	0.19	0.12	4212.15	3629.84	118.07	9.33	47.44
CGN	I	2.92	0.13	0.28	4769.30	4558.54	91.35	12.40	44.33
AG	II	2.67	0.06	0.14	2896.05	2463.62	59.94	6.03	35.44
CGB	II	2.64	0.17	0.44	2360.35	2607.63	53.31	6.07	21.11
SG	II	2.64	0.12	0.26	3209.28	2453.99	45.02	5.60	32.78
CGA	III	2.04	0.28	0.72	1340.89	1526.26	20.43	2.50	13.67

Figures

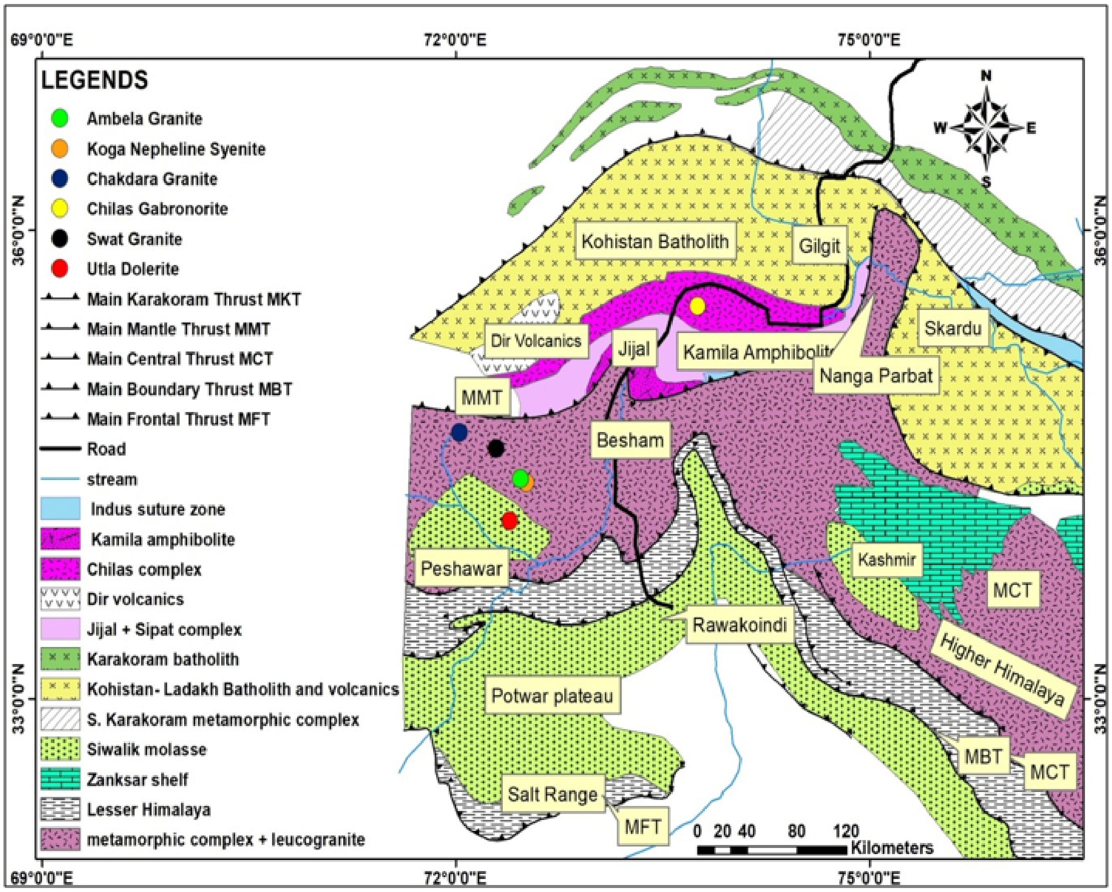


Figure 1

Geological map of North Pakistan, modified after Searle et al. (1999). Shaded circles show the locations of the collected samples.

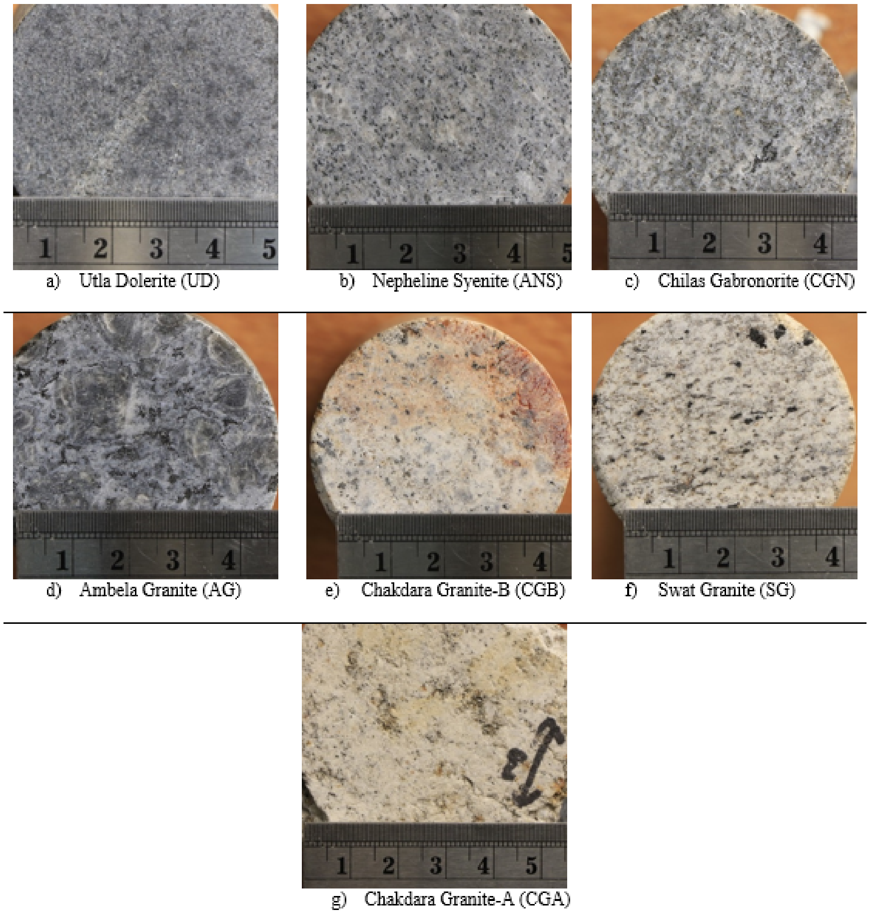
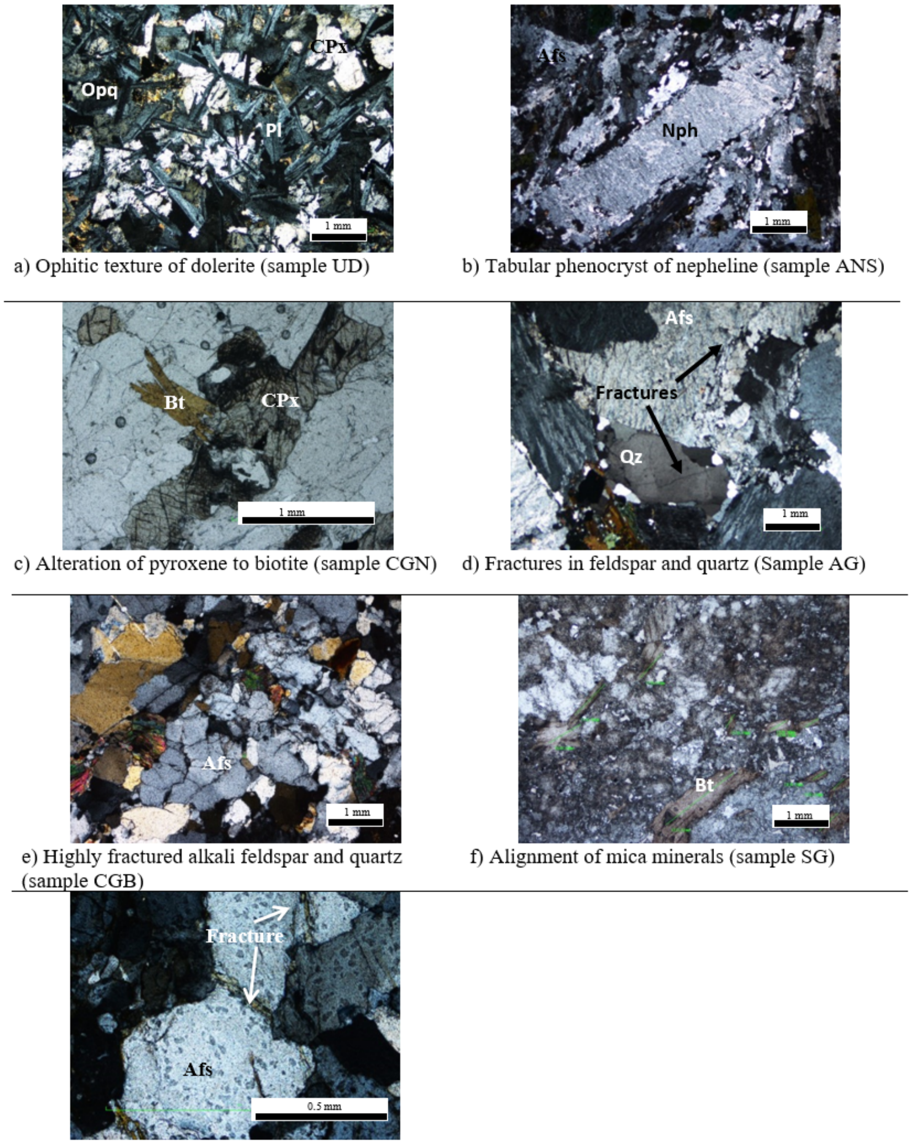


Figure 2

Photographs of the studied intrusive rocks



a) Ophitic texture of dolerite (sample UD)

b) Tabular phenocryst of nepheline (sample ANS)

c) Alteration of pyroxene to biotite (sample CGN)

d) Fractures in feldspar and quartz (Sample AG)

e) Highly fractured alkali feldspar and quartz (sample CGB)

f) Alignment of mica minerals (sample SG)

h) Fracture in feldspar (sample CGA)

Figure 3

Microphotographs of the investigated rocks. Afs= alkali feldspar, Qz= quartz, Pl= plagioclase, Bt= biotite, Opq= opaque minerals, Nph= nepheline, CPx= clinopyroxene,

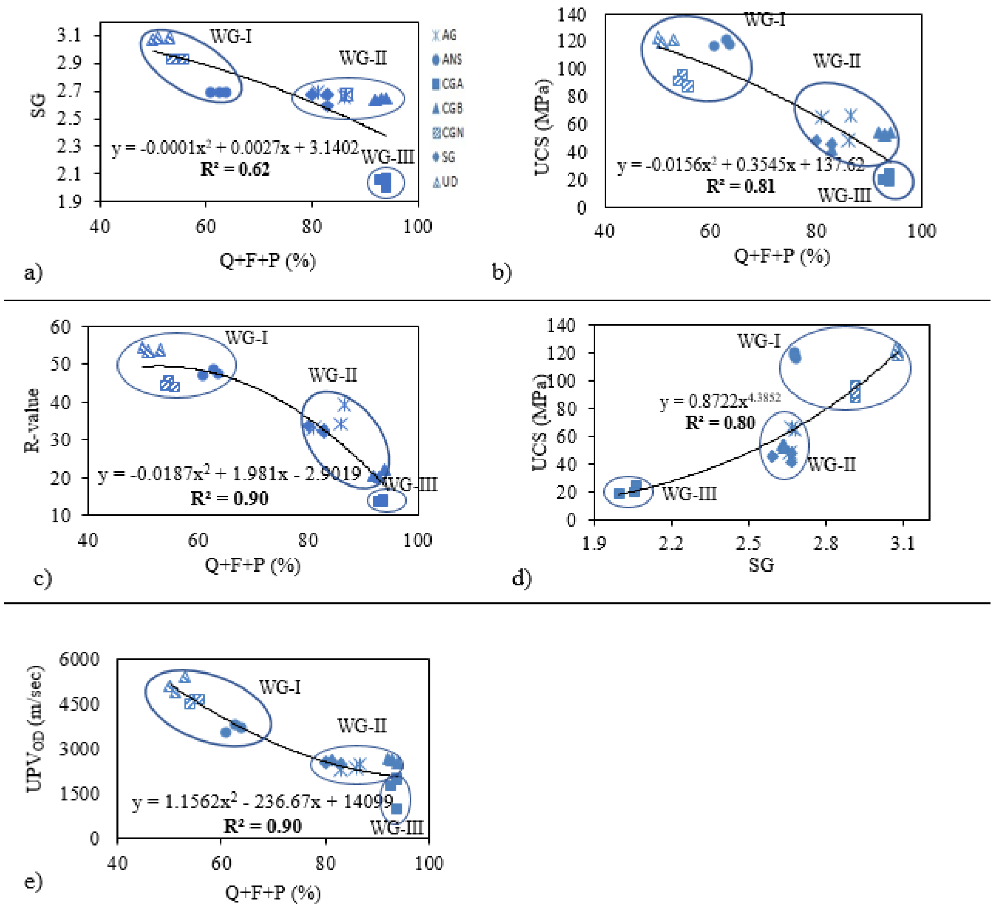


Figure 4

Correlation plots of (a) Cumulative percentage of Quartz, Feldspar and Plagioclase (Q+F+P) vs Specific gravity(SG) (Polynomial), (b) Q+F+P vs Unconfined compressive strength (UCS)(Polynomial), (c) UCS vs SG, (d) Q+F+P vs R-value (Polynomial), (e) Q+F+P vs Ultrasonic pulse velocity oven-dry (UPV OD) (Polynomial). Symbols given in (a) are the same for all figures.

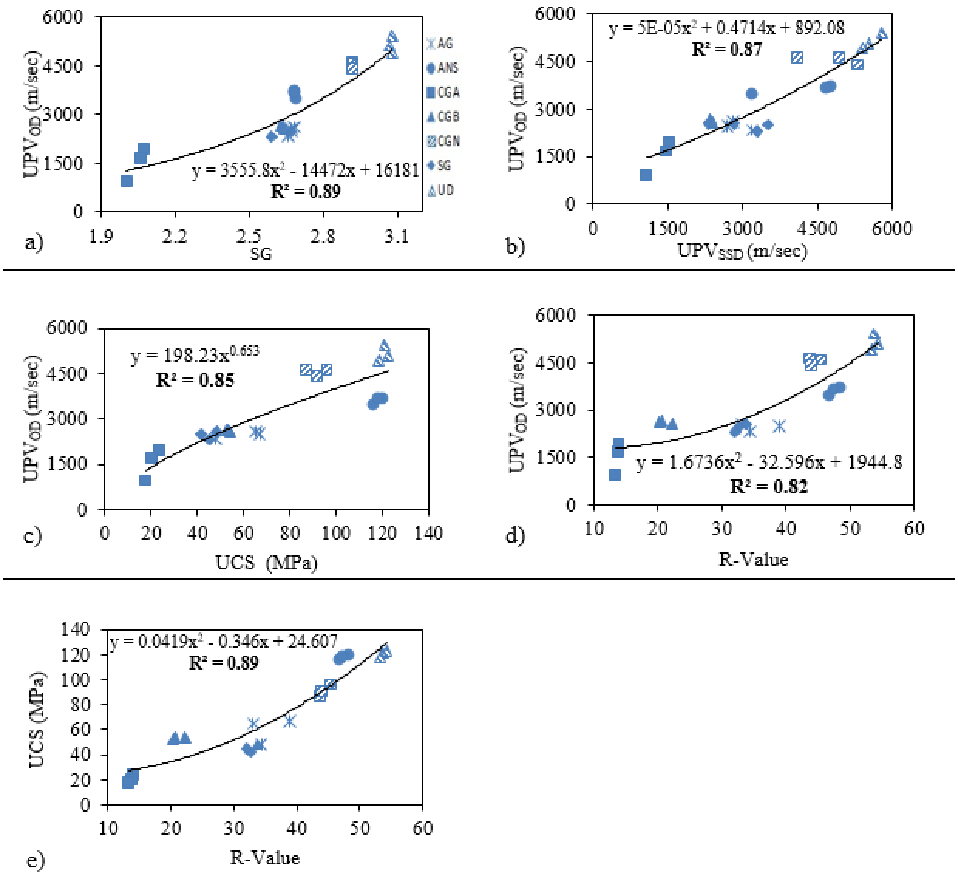


Figure 5

Correlation plots of (a) Ultrasonic pulse velocity oven-dry (UPV OD) vs Specific gravity (SG)(Polynomial), (b) UPV OD vs UPV SSD (Polynomial), (c) UPV OD vs UCS (Power) (d) UPV OD vs R-Value (Polynomial), (e) UPV OD vs R-Value (Polynomial). Symbols given in (a) are the same for all figures.

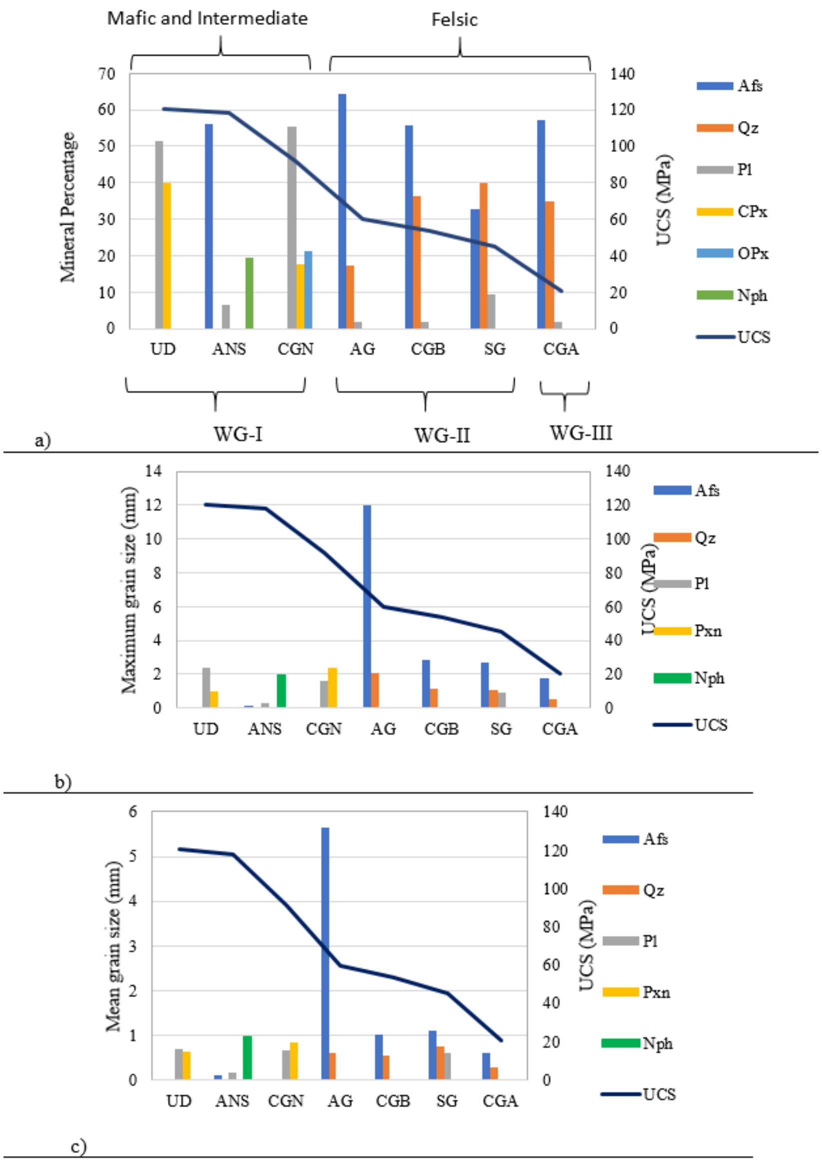


Figure 6

Relationship between the mineral grain size and the uniaxial compressive strength