

Textural Implications in Assessment of Physico-Mechanical behaviour of Metavolcanic Rocks from Dir Upper, north western Pakistan

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Abstract: The Dir-Utror meta-volcanics from the south western portion of the Kohistan arc in northern Pakistan are analyzed in term of their petrography, physico-mechanical properties. Field observations and petrography show the collected representative samples to be fine-grained meta-andesites (FMA), coarse-grained meta-andesites (CMA) and agglomerate (AG). The relationship between petrography and physico-mechanical properties has been investigated which inferred the grain size to be the major factor, alongside grains² shape, arrangement and size distribution as well as degree of mineral alteration significantly affecting the mechanical behavior of rocks. The CMA yield more strength (98 MPa) than FMA (93 MPa) due to its lesser degree of mineral alteration, inequigranular texture, lack of preferred mineral alignment, relatively low porosity and water absorption. The lower strength of agglomerate (57 MPa) corresponds to abundance of soft minerals (calcite), exotic rock fragments and coarse-grained texture. Based on physico-mechanical properties including specific gravity, bulk density, aggregate impact value, Los Angeles abrasion value and unconfined compressive strength (UCS), these rocks fall within permissible range to be utilized for multiple engineering purposes including dimension stones and foundation materials for other civil structures. However, petrographic investigations reveal excessive amount of reactive silica in these rocks making them prone to alkali-silica reactivity in concrete works with ordinary Portland cement (OPC). Hence these rocks are not recommended for use as sole aggregate material or low-alkali cement is recommended, if used.

Keywords: Petrography; physico-mechanical evaluation; metavolcanics rocks; upper Dir; Pakistan.

Introduction

Rocks are indispensable for construction and have wide applications ranging from use as building stones, dimension stones, decorative stones to aggregates in concrete, road pavements and railway ballast as well as used as mine opening supports in the form of pillars, fillings and linings. The resilience, strength and reliability of any engineering structure lie within the selection of right and durable rock material having suitable engineering properties. Many noted authors including Hartley (1974), Shakoor and Bonelli (1991), Irfan (1996), Arif et al., (1999, 2013, 2015), Al-Harathi (2001), Akesson et al., (2001, 2003), Lindqvist et al., (2007), Sajid et al., (2009, 2016), Rigopolous et al., (2010, 2013, 2014) and Sajid and Arif (2015) have evaluated physico-mechanical properties of different rocks and ascertained various geological factors affecting them with special emphasis on influence of mineralogy and petrographic characteristics. Mineralogical composition, textural features (e.g. size, shape, grain arrangement, nature of grain to grain contact and interlocking) and extent of alteration and deformation significantly influence the engineering character of rocks (Irfan, 1996; Tugrul and Zarif, 1999; Akesson et al., 2001; Miskovsky et al., 2004; Rigopolous et al., 2010; Sajid et al., 2016).

The negative effects of mineral alteration on strength of geochemically different rock types including granites and dolerites have been inferred (e.g. Sousa et al., 2005; Rigopolous et al., 2010; Coggan et al.,

2013). The modal mineralogical concentration, grain size of individual minerals, mean grain size of rock and distribution of grain size within a rock proved to be vital petrographic characteristics for controlling its mechanical behavior (Sajid et al., 2016). Fine-grained rock materials are believed to be stronger relative to coarse grained (Tugrul and Zarif, 1999; Lindqvist et al., 2007; Sajid et al., 2009; Yosuf and Zubaidi, 2016). Rocks having irregular shape (anhedral) of mineral grains tend to be stronger than those with regular shapes (euhedral) because boundaries between euhedral grains may act as discontinuities, where cracks may initiate in the structure (Akesson et al., 2003; Lindqvist et al., 2007; Arif et al., 2013; Sajid and Arif, 2015).

Pakistan is a developing country that is investing a certain proportion of its GDP in the infra structure development projects to improve living standards of its population by creating more jobs, connecting remote areas to big cities and overcoming energy crises to achieve its goal of becoming a developed nation. The major infrastructure projects include hydel power dams, major highways, tunnels, buildings etc. Therefore, availability of recommended construction material is important to ensure construction material supply chain and safety of the masses. The northern Pakistan is potential site of various small and large scale engineering structures including dams and associated tunneling. Hence, the physico-mechanical properties of rocks from different regions in north Pakistan are investigated in certain intervals including

Din et al., (1993), Din and Rafiq (1997), Arif et al., (1999, 2013, 2015), Sajid et al., (2009, 2016), Sajid and Arif (2015), Mustafa et al., (2015, 2016) and Wazir et al., (2015).

Major infrastructure projects including roads, dams and tunnels have been proposed in the Upper Dir region of northern Pakistan, mainly comprised of different types of volcanic rocks. In contrast to other rocks, volcanic rocks received very little attention not only in Pakistan but also at global level; hence excessive physical and mechanical data set is required to address their engineering behaviour and aggregate potential. This paper investigates the petrographic features (mineralogical composition and distinctive textural characteristics), assessment of physico-mechanical properties to address their aggregate suitability and correlation between petrographic and physico-mechanical features of certain varieties of volcanic rocks of late Paleocene-Eocene age (Fig. 1). The pertinent research literature and data sets of other rock types e.g. (Sajid et al., 2009, 2016; Rigopolous et al., 2010) have also been used for interpretation of the results. This study will not only aid the dearth of research on mechanical aspects of volcanic rocks but also support the ground investigation studies for the engineering projects in the region.

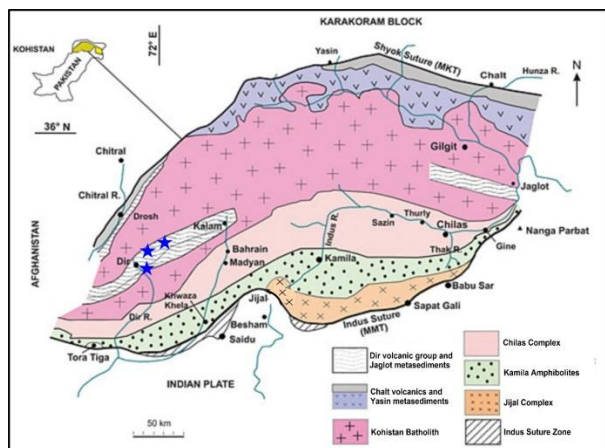


Fig. 1 Regional tectonic map of north Pakistan showing the study area (after Jagoutz et al. (2010)). Stars show location of analyzed samples.

Geological Setting

The Cretaceous north dipping intra-oceanic subduction in Neo-Tethys Ocean resulted the formation of Kohistan Island Arc (KIA) bounded by Main Karakoram Thrust (MKT) to the north and Main Mantle Thrust (MMT) to the south (Fig. 1) (Tahirkheli, 1979; Coward et al., 1986; Searle et al., 1999). The KIA consists six major units from south to north such as: (1) Jijal Complex (2) Kamila Amphibolites (3) Chilas Complex (4) Kohistan Batholith (5) Jaglot and Chalt group (6) Yasin meta-sediments (Tahirkheli, 1979; Khan et al., 1993; Bignold and Treloar, 2003; Jagoutz et al., 2007) (Fig. 1). For the region under investigation, Tahirkheli (1979) proposed the name

‘Dir Group’ for a sequence of Dir-Utror metavolcanics and Baraul Banda slates. Dir Utror metavolcanics is associated with Late Cretaceous to Paleogene Andean-type margin magmatism (Trealor et al., 1989; Sullivan et al., 1993; Danishwar et al., 2001). The Barawal Banda slates represent the last fore-arc marine sedimentation in Kohistan, also consist of rare limestone having marine nummulitic faunas (Eocene), sandstone and siltstone (Sullivan et al., 1993). Dir-Utror series dominantly comprised of intermediate to mafic metavolcanic rocks including andesites, basalts and basaltic andesites, felsic meta-volcanics (rhyolites, dacites) and pyroclastic flows, whereas the pyroclastic flows indicate the explosive nature of volcanism (Sullivan et al., 1993; Shah and Shervais, 1999). Based on geochemistry Shah and Shervais, (1999) suggested calc-alkaline trend for Dir-Utror metavolcanics. These metavolcanics are intruded by the stage 2 plutons of Kohistan batholith which are exposed in the Kumrat, Thall and Lamutai area of Dir valley (Searle and Cox, 1999). The deformation in metavolcanics is brittle and ductile in upper Swat and Dir valley respectively (Sullivan et al., 1993).

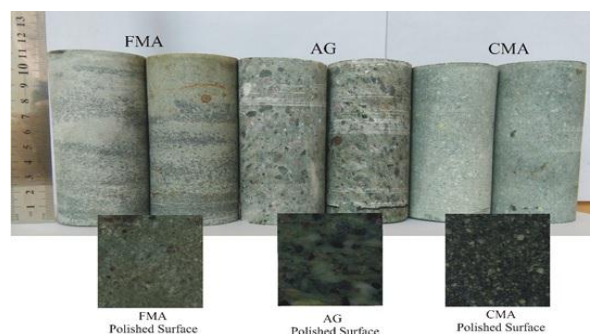


Fig. 2 Representative core samples and their respective polished slabs showing textural and mineralogical variations AG = Agglomerate, FMA = Fine-grained Meta-andesite, CMA = Coarse-grained Meta-Andesite.

Materials and Methods

1. Petrographic Study: Three fresh bulk samples from texturally distinct volcanic rocks (Fig. 2) were collected along Sheringal-Kumrat road, upper Dir north-west Pakistan. Two thin sections from each bulk sample were prepared. Small rock slabs cut from bulk samples were polished and adhered to thin glass slide. They were subsequently polished to make thin sections ready for petrographic studies via Nikon E600 polarizing microscope.

2. Mechanical Testing: The Unconfined Compressive Strength (UCS), Los Angeles abrasion and Impact value were conducted as per ASTM and British Standards Institute (BSI) standards. The cylindrical cores were extracted with the help of core drilling machine (55mm diameter) and cut to the required size (Length to diameter ratio = 0.5) (Fig. 2) as per standard requirements (ASTM-D2938) (Fig. 2). The samples are dried at 90-100° C temperature prior to testing as moistures can influence the

indicated strength. The UCS test was executed with the help of Universal Testing Machine (UTM).

3. Aggregate Testing: The remaining bulk sample were crushed with the help of jaw crusher machine to coarse aggregates for investigating their aggregate properties including Los Angeles abrasion (LAA) and Aggregate Impact Value (AIV) as per ASTM (C131-03) and BSI (1990) respectively. The aggregate physical properties investigated in the current study include bulk density, water absorption, porosity and specific gravity using saturation method (Harrison 1993).

quartz are euhedral to subhedral and amphiboles are subhedral to anhedral (Fig. 3D). The quartz grains exhibit undulose extinction indicating their strained nature. The abundance of fresh fine-grained quartz is due to segregation of silica during recrystallization accompanying metamorphism. The secondary phases like epidote and chlorite formed due to alteration of feldspar and amphiboles most probably by hydrothermal fluids. The deformation of rock during the process of metamorphism is indicated by the reduced grain size and foliated nature of minerals i.e. alignment of elongated amphibole grains without

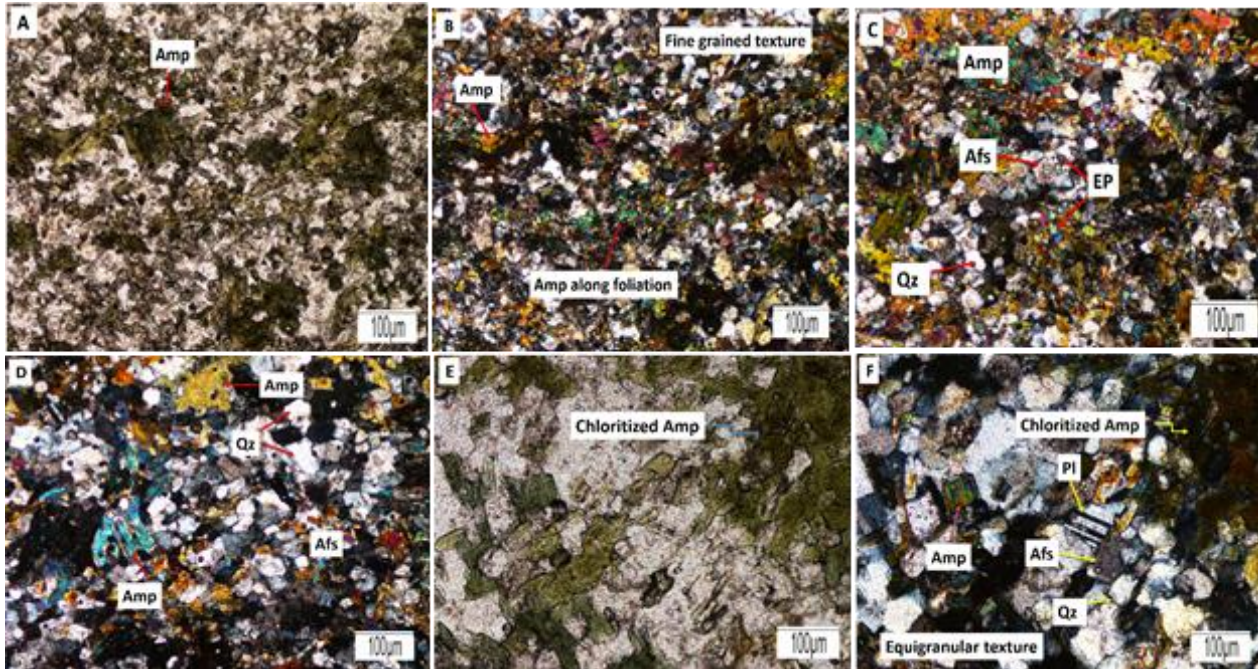


Fig. 3 Photomicrographs of Fine-grained Meta-Andesite illustrating (A: PPL, B: XPL) fine grained texture of rock and subhedral to anhedral aligned amphiboles, (C-D: XPL) equigranular texture of rock and euhedral feldspar and quartz grains, (E: PPL, F: XPL) Chloritized amphibole and plagioclase exhibiting twinning. Amp=Amphibole, Qz = Quartz, Afs = Alkali Feldspar, Pl = Plagioclase, Chl = Chlorite.

Results

Petrography

Petrography not only renders the petrogenetic and subsequent deformation history of a rock but in addition, it elaborates productive information about the strength and engineering characters of that rock (Rigopolous et al., 2010; Sajid et al., 2016). Based on detailed petrographic investigation the studied samples (Table 1) are divided into three types including fine-grained meta-andesite (FMA), coarse-grained meta-andesite (CMA) and Agglomerate (AG) (Fig. 2).

The FMA is fine-grained (Fig. 3A, B), equigranular and holocrystalline (Fig. 3C, D). The primary volcanic textures are not preserved which is mostly shaded during regional metamorphism as most of the minerals show signs of recrystallization. It mainly contains quartz (32 %), amphibole (22 %), feldspar (20 %) and chlorite (16 %) while plagioclase (5 %) and epidote (5 %) are relatively less (Table 1). The feldspar and

groundmass (Fig. 3A, B). The mineral assemblages indicate low to medium grade metamorphism of studied rock.

Table 1 Modal mineralogical composition of studied rocks.

Minerals	CMA (%) n=4	FMA (%) n=4	Agglomerate (%) n=4
Quartz	9	32	10
Amphibole	20	22	5
Chlorite	10	16	8
Epidote	7	5	-
Alkali Feldspar	8	20	-
Plagioclase	38	5	-
Clay minerals	8	-	8
Calcite	-	-	5
Chert	-	-	12
Ground mass	-	-	52

Table 2. Mean results of physico-mechanical properties of studied specimens

Sample	LA (%) n=2	Bulk Density (g/cm ³) n=2	Specific Gravity n=2	Water Absorption (%) n=2	Porosity (%) n=2	UCS (MPa) n=2	AIV (%) n=2
FMA	17.92	1.63	2.88 ± 0.02	0.5 ± 0.07	1.45±0.19	93.04 ± 8.6	10.75
CMA	16.18	1.54	2.81	0.44 ± 0.02	1.40±0.14	98.4 ± 11.4	8.42
AG	22.44	1.55	2.73	0.38 ± 0.18	0.54±0.19	57.2 ± 7.35	11.14

The CMA is mega-porphyritic with coarse-grained groundmass (Fig. 4D). The plagioclase (38%), amphibole (20 %) and chlorite (10 %) occur as major minerals while epidote (7 %) alkali feldspar (8 %)

alteration (Sajid et al., 2018) (Fig. 4A, B). The epidote present in rock represents liberation of calcium and aluminum from plagioclase at low temperature (Bucher and Grapes, 2010). Secondary quartz vein is

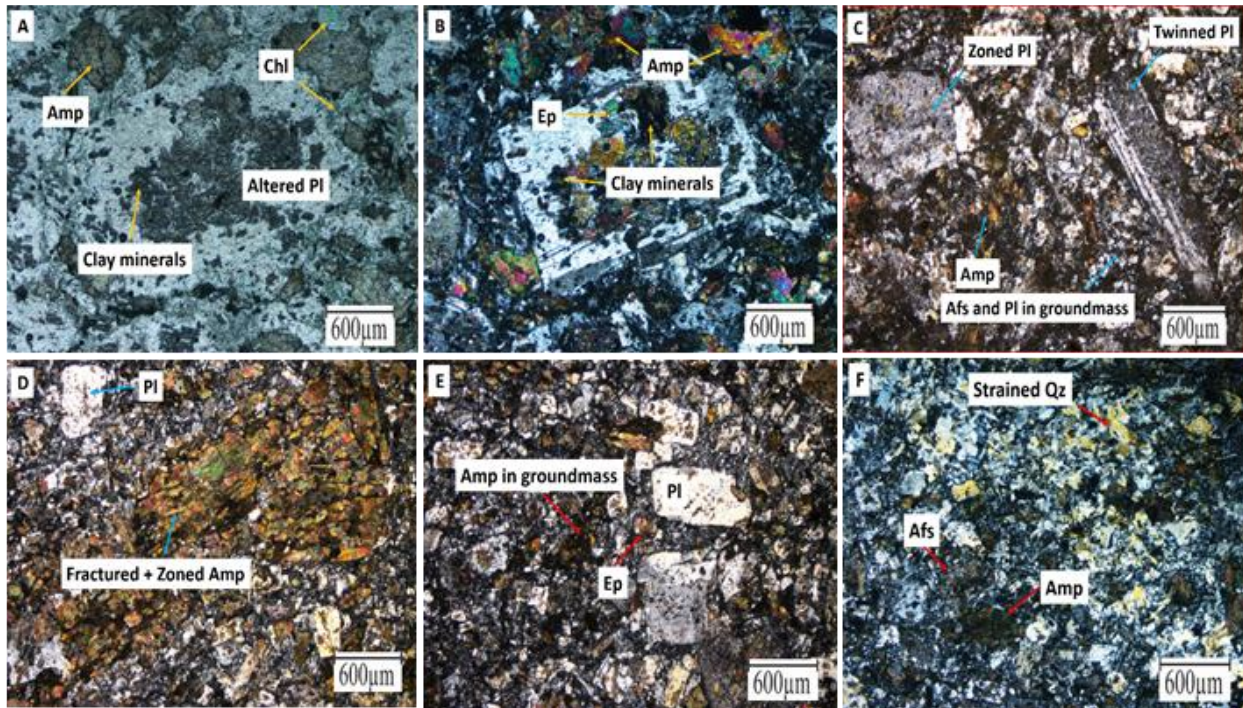


Fig. 4 Photomicrographs of Coarse-grained Meta-Andesite illustrating (A: PPL-B: XPL) zoning and alteration of plagioclase into epidote, clay minerals and chlorite in groundmass, (C: XPL) porphyritic texture, euhedral to subhedral plagioclase grains with zoning, and twinning, (D; XPL) subhedral to anhedral amphibole, (E: XPL) inequigranular texture. (F: XPL) recrystallized and strained Quartz vein. Amp=Amphibole, Chl = Chlorite, Ep = Epidote, Afs = Alkali feldspar, Pl = Plagioclase Qz = Quartz. Mineral abbreviations are given in accordance with Whitney and Evans, (2010).

quartz (9 %) and clay minerals (8 %) constitute the common accessory minerals (Table 1). The rock is generally inequigranular with subhedral to anhedral mineral grains (Fig.4D). The original porphyritic texture is preserved with well-developed phenocrysts of amphibole and plagioclase while indications of subtle recrystallization in groundmass is noted (Fig .4C). Plagioclase phenocrysts are euhedral to subhedral (Fig. 4C) in shape while amphiboles are subhedral to anhedral (Fig. 4D). Plagioclase phenocrysts are saussuritized resulting in the formation of mixture of clay minerals and epidote (Fig. 4A, B). The feldspar, plagioclase and amphibole phenocrysts show partial to complete alteration to epidote, chlorite and clay minerals. Some of plagioclase and amphibole grains show zoning (Fig. 5A and 5D respectively). The zoned plagioclase seems more calcic in core as interpreted from its altered nature i.e. calcic plagioclase is more prone to

observed being recrystallized during metamorphism, which is depicting its existence prior to metamorphism. The mineral assemblages show medium grade metamorphism of CMA.

The AG is mega-porphyritic (Fig. 5B) and comprised of 10% quartz (euhedral), 12% chert (euhedral), 5% calcite (subhedral to anhedral), 5% amphibole, 8% chlorite, 8% clay minerals, 52% groundmass (Fig. 5A, B) (Table 1). The presence of larger angular rock fragments designates the agglomerate as volcanic breccia (Vallejo et al., 2008). Calcite occurs both as larger grains, that might represent filled amygdales/vesicles, as well as fine grained ground mass (Fig. 5A, C).

Physico-Mechanical Properties of Rocks

The physical properties of the rocks are influenced by the presence of cracks and fractures; however, the

mechanical properties strongly depend on mineralogy, texture and degree of weathering (Ganesha et al., 2016). Among the physico-mechanical properties unconfined compressive strength (UCS), Los Angeles abrasion value (LAAV), aggregate impact value (AIV), specific gravity, water absorption, porosity and bulk density of the studied specimens are investigated. The corresponding results are presented in Table 2.

Discussion

Rocks Suitability for Construction Materials

The results of physico-mechanical properties obtained have been compared with various international standards i.e. ASTM, AASHTO and BSI to assess the potential of the studied rocks as construction material. Rocks with the specific gravity ≥ 2.5 are suitable for heavy construction (Blyth and Freitas, 1974) and the minimum range of specific gravity of any rock is 2.6 to use in cement concrete (ASTM-127). The studied rock samples have a specific gravity greater than these

absorption greater than 3% are more sensitive to freeze thaw damage (Shakoor et al., 1982) and enhance the hydrostatic pressure within concrete and crystallization of ice increase the volume of concrete aggregate therefore susceptible to destruction (Rahn, 1986).

According to ASTM C-131, rock samples with LAAV less than 40% are suitable for road aggregate, however, BSI-812 suggests this limit to be less than 30%. The studied rocks fulfill both criteria (FMA=17.92 %, CMA=16.18 % and AG=22.44 %) and are suitable for road and cement aggregates. The fine-grained meta-andesite and agglomerate fall in strong rocks, while coarse-grained meta-andesite is exceptionally strong based on AIV. The bulk density of fine-grained meta-andesite, coarse-grained meta-andesite and agglomerate is 1.63 gm/cm^3 (1630 kg/m^3), 1.54 gm/cm^3 (1540 kg/m^3) and 1.55 gm/cm^3 (1550 kg/m^3) respectively and all of them can be used in various engineering applications. On the basis of UCS, all the three rock samples fall in the category of strong rocks therefore can be used as

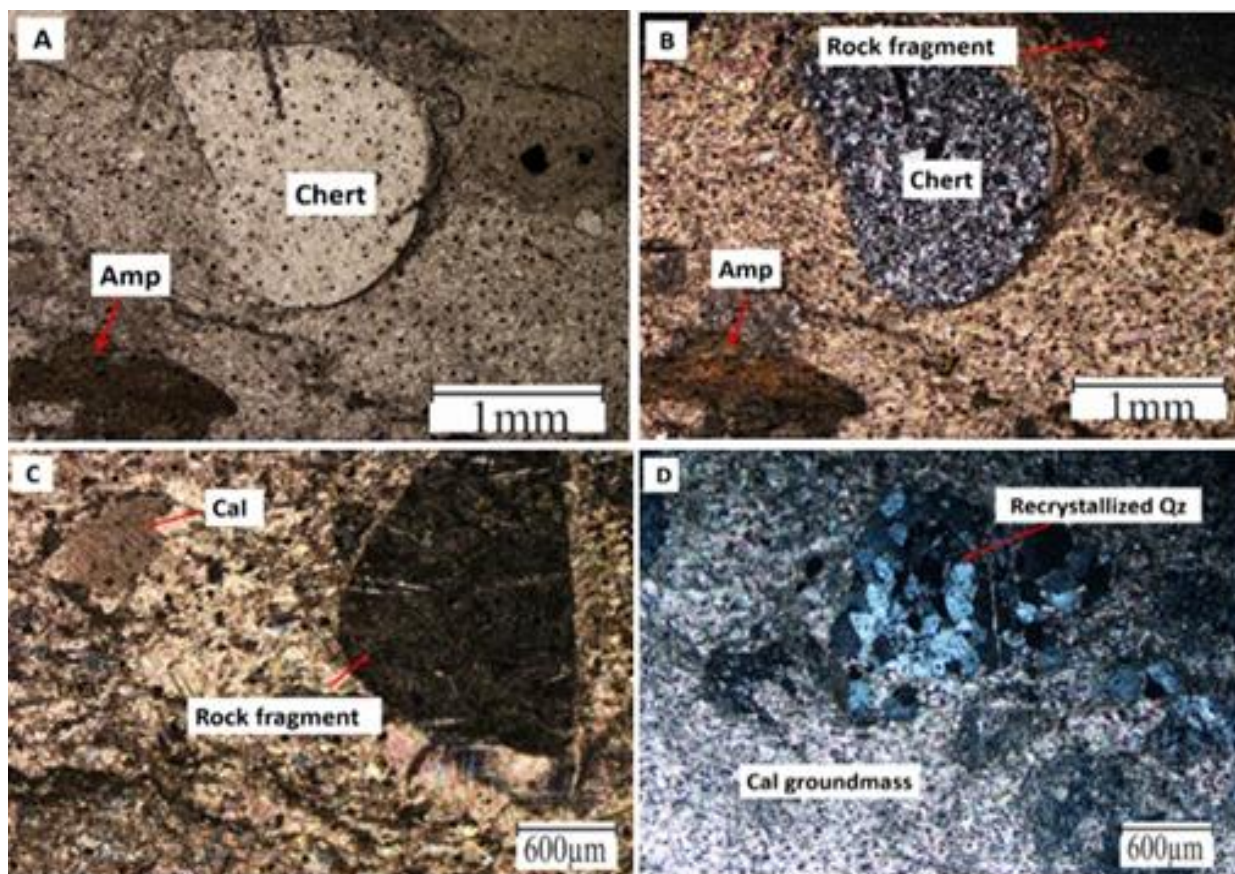


Fig. 5 Photomicrographs of agglomerate showing (A: PPL, B: XPL) chert and porphyritic texture of the rock. (C: PPL) rock fragment within calcite groundmass (D: XPL) recrystallized quartz in calcite groundmass. Amp=Amphibole, Cal = Calcite, Qz = Quartz.

values (Table 2). All the three samples can be used as dimension stone as water absorption is $<1 \%$ (Blyth and Freitas 1974) and can be used as aggregate in cement concrete. The aggregate with water absorption (W_a) $< 2.5 \%$ is recommended to be used in concrete for engineering works (ASTM-127). Rocks with water

dimension stones, foundation materials and other civil structures such as dam, bridge and highways (Bell, 2007).

These rocks are found suitable for concrete works in various construction purposes as mentioned, yet the

petrographic studies revealed enrichment of reactive form of silica (i.e. recrystallized microcrystalline quartz, strained/undulose quartz and chert. Hence, they are more likely susceptible to alkali silica reactivity (ASR) when used in concrete. Therefore, the studied rocks should either be avoided as sole aggregate source or if used, the low-alkali cement is recommended to be used in respective concrete rather than ordinary Portland cement (OPC) which will minimize the effects of ASR.

Effects of Petrographic features on Physico-Mechanical properties

Three rock types from Dir metovolcanics have been investigated with respect to their petrography and physico-mechanical properties. Petrographic investigations reveal division of samples into FMA, CMA and AG. Following the detailed petrographic studies, the physico-mechanical properties of these rocks were also determined. The CMA is porphyritic containing phenocrysts of plagioclase and amphibole while alkali feldspar, quartz and plagioclase occur in groundmass (Fig. 4). Recrystallization and alteration is widespread and chlorite, epidote, clay minerals occur as the alteration products. FMA is relatively equigranular and contains quartz, alkali feldspar, amphibole, chlorite as major minerals while plagioclase and epidote occur as accessory minerals (Fig. 3). Recrystallization as well as degree of alteration is considerably more in FMA than CMA. Their main evidences include reduced overall grain size, mineral alignment, no groundmass and abundance of chlorite (Fig.3). Evidences of low to medium-grade metamorphism is noticed in both FMA and CMA samples hence the prefix "meta" has been added to the name of the rock. Agglomerate contains euhedral to subhedral grains of quartz, chert, calcite as well as rock fragments and calcite-dominant matrix (Fig. 5).

The fine-grained rocks are generally found stronger than coarse-grained ones with similar composition (Onodera and Kumara, 1980; Krynine and Judd, 2005; Bell, 2007; Lindqvist et al., 2007), However, results of current study show opposite relation to this generalized concept. The UCS value of CMA is higher than FMA (Table 2), which seem anomalous, but this deviation can be explained with the high porosity and water absorption values, widespread alteration of minerals, grains alignment and overall uniform grain size of the fine-grained variety (FMA). Similar observations have also been made during investigations of granitic rocks by Sajid and Arif (2015).

The rocks with greater concentration of physically strong minerals are evidently strong, but their textural features and relationship with associated minerals may also affect the strength properties (Sajid and Arif, 2015). The overall concentration of quartz is more in FMA than CMA, however, low strength values of former is most probably due to its respective

uniformity in grain size. This is in accordance with the observation of Lindqvist et al. (2007) and Sajid and Arif (2015) that grain size distribution significantly affects the strength of rocks. The larger distribution in grain size of a rock significantly increases the strength of rock relative to more equigranular rocks (Lindqvist et al., 2007).

Fractures can easily propagate in euhedral mineral grains (Lindqvist et al., 2007) during compression as well as when the mineral grains are aligned (Sajid and Arif, 2015; Sajid et al., 2016). Abundance of euhedral quartz and feldspar grains as well as alignment of elongated mineral grains i.e. amphiboles in FMA are other potential reasons for their lesser strength (Fig. 3A-C). Similarly, higher porosity, water absorption and alteration adversely affect the strength of rocks (Krynine and Judd, 2005; Rigopolous et al., 2010; Coggan et al., 2013) which are also the vital factors for the lesser strength of FMA than CMA. The greater amount of minerals alteration, chlorite content and recrystallization (Rigopolous et al., 2010; Sajid and Arif, 2015) effectively increase the porosity and water absorption values of FMA.

The lower strength of agglomerate (i.e. 57.15 MPa) is attributed to its coarse-grained texture, high amount of relatively soft minerals e.g. calcite (Tugrul and Zarif, 1999) and presence of deleterious material like chert, rock fragments (Fig. 5). These interpretations are in accordance with the findings of Onodera and Asoka Kumara, (1980), Krynine and Judd, (2005), Bell, (2007), Lindqvist et al. (2007) and Mustafa et al., (2016). Relatively low water absorption and porosity of agglomerate can be explained due to its abundant fine matrix, less recrystallization and alteration (Fig. 5B, C).

Abrasion resistant rocks tend to have low porosity, high compressive strength, low proportion of soft minerals, reduced grain size and lack foliation (Hartley, 1974; Kazi and Al-Mansour, 1980; Yilmaz, 2011). Therefore, relatively high LAA and AIV value of FMA than CMA can be explained with all these characteristics. The increase in LAA value of agglomerate is also attributed to the abundance of soft minerals (calcite) and coarse-grained texture. The specific gravity of both FMA and CMA is higher than AG because of presence of heavy minerals (amphiboles, epidote) (Khalil et al., 2014). The relatively higher water absorption and porosity of FMA compared to the other two can be confidently explained with the presence of extensive recrystallization, more clay and chlorite content (Sajid and Arif, 2015; Khalil et al., 2014). The high bulk density of both FMA and AG is attributed to its fine-grained texture and fine-grained groundmass, respectively.

Conclusion

- a) The studied rocks were classified as fine-grained meta-andesite, coarse-grained meta-andesite and agglomerate based on petrographic studies. Fine-

grained meta-andesite is holocrystalline, equigranular, foliated while the coarse-grained meta-andesite is mega-porphyrific, inequigranular, contain coarse-grained recrystallized groundmass. Both fine-grained and coarse-grained meta-andesites contain evidences of metamorphism. The agglomerate is mega-porphyrific and is comprised of chert, quartz and soft calcite groundmass and exotic angular rock fragments.

- b) Mineralogy affect the physico-mechanical properties of rocks, as the presence of hard minerals like quartz, feldspar, amphibole, epidote and plagioclase impart high strength to both fine and coarse-grained meta-andesite while, agglomerate yield much lower strength due to greater abundance of chert (deleterious material) and soft calcite groundmass.
- c) The presence of larger angular rock fragments in agglomerate suggested the agglomerate as volcanic breccia (Vallego et al. 2008).
- d) Alteration products (chlorite, clay minerals, epidote, and chert) not always result mechanically weaker rocks as strength of the studied rocks fall in category of mechanically strong rocks.
- e) Fine-grained meta-andesite is mechanically weaker due its more euhedral grains, mineral foliation and equigranular texture than coarse grained meta-andesite (inequigranular) although both contain high proportion of harder minerals. It shows that that the textural relations of mineral grains are as significant in controlling the mechanical behavior of rocks as the mineralogical composition is considered.
- f) All studied samples fall in the category of strong rocks however, these are not recommended to be used as sole aggregate material for engineering purposes. The petrographic investigations reveal excessive amount of reactive silica in these rocks making them prone to alkali-silica reactivity, if used in concrete work.

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