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Petrographic characteristics and mechanical properties of rocks from Khagram-Razagram area, Lower Dir, NWFP, Pakistan

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Abstract

The Khagram-Razagram area, consists of rocks of the Kamila amphibolite belt, which constitutes the southern portion of the intra-oceanic Kohistan island arc. Field observations and detailed petrographic studies of representative samples reveal that the area largely consists of two major rock types, namely epidote amphibolite and gabbro-norite. The epidote amphibolites are sub-equigranular, fine to coarse-grained, xenoblastic, and foliated along shear zones. They consist of abundant hornblende, plagioclase, epidote, quartz and accessory amounts of sphene, apatite and ore minerals. The gabbro-norites are sub-equigranular, medium- to coarse-grained, hypidiomorphic to idiomorphic and massive, i.e. without any preferred orientation of grains. They essentially consist of plagioclase, orthopyroxene and clinopyroxene with accessory amounts of epidote and quartz. Some of the engineering properties of the petrographically investigated epidote amphibolite and gabbro-norite were also determined in the course of this study. These include unconfined compressive strength, unconfined tensile strength, shear strength, specific gravity and water absorption. The values of specific gravity and water absorption of both the epidote amphibolite and gabbro-norite are within the range permissible for their use as dimension stones and construction material. Comparison of the petrographic characteristics of the two rock types with their respective strengths reveals that modal mineralogy, grain size and shapes, degree of alteration and foliation have a significant effect on the strength of these rocks.

Keywords: Petrography; Mechanical Properties; Amphibolites; Gabbronorites; Dir; Pakistan

1. Introduction

Engineers are concerned with mechanical properties of artificial and natural materials, specially their behavior under stress. The stress analysis of rocks and area is of great importance in designing buildings and engineering structures. Petrographic characteristics known to affect mechanical properties of rocks include grain size, shape of grains, fabric (arrangement of mineral grains and degree of interlocking), type of contacts, mineralogical composition and the weathering state (Irfan, 1996). For a typical fresh igneous rock, the mineralogy and texture combine to give high strength and excellent elastic deformation characteristics (Johnson and De Graff, 1988). Onodera and Asoka Kumara (1980) reported that the strength decreased significantly as the grain size increased in igneous rocks. They determined a linear relationship between the grain size and strength, that is, as the grain size of the granite decreased, the strength increased. The strength of rocks is also highly affected by the process of alteration and weathering. Arif et al. (1999) have worked on the mechanical properties of Mansehra granite and revealed that the investigated rocks have very low values of compressive strength as compared to granitic rocks from elsewhere in northern Pakistan due to their older age, coarser texture and weathered character. Din et al. (1993) have determined shear and triaxial strengths of various types of rocks used as building materials in northern Pakistan.

The purpose of the present study is to quantify the relationship between petrographic characteristics and engineering properties of rocks from Khagram-Razagram area located in the middle of Dir district, NWFP, Pakistan. Geologically, the district of Dir constitutes a part of the Kohistan Island Arc. A preliminary petrographic account of the rocks around Khagram was presented by Chaudhry and Chaudhry (1974). The Khagram-Razagram area largely consists of amphibolites and gabbro-norites of the Kamila amphibolite belt that extends eastward into Swat and westward into Bajaur (Fig. 1). The main Malakand-Dir-Chitral road passes through the area. Malakand is linked with Peshawar. The area lies between latitude 35^0 to $35^0$51'30"N and longitude 72^0 to $72^0$9'30"E.

The engineering properties, which are determined in the course of the present study include unconfined compressive strength, unconfined tensile strength, shear strength, specific gravity and water absorption. These properties are analyzed to (i) predict the response of the investigated rocks when subjected to load thereby assessing their suitability for use as dimension stone and/ or construction material, and (ii) see the possible relationship between them and petrographic details.

2. Tectonic setting

The area under investigation is part of Kohistan Island Arc. The Kohistan Island Arc is located in northern Pakistan and is bounded to the north by Shyok suture or MKT (Main Karakorm Thrust) and to the south by Indus suture or MMT (Main Mantle Thrust) (Fig. 1). Tahirkheli et al. (1979) suggested that the entire Kohistan sequence represents the crust and mantle of a complete island arc. Further work (Jan, 1980; Bard et al., 1980; Coward et al., 1982; Khan et al., 1998) supported the idea that it is an obducted island arc turned on end during the Himalayan orogeny.

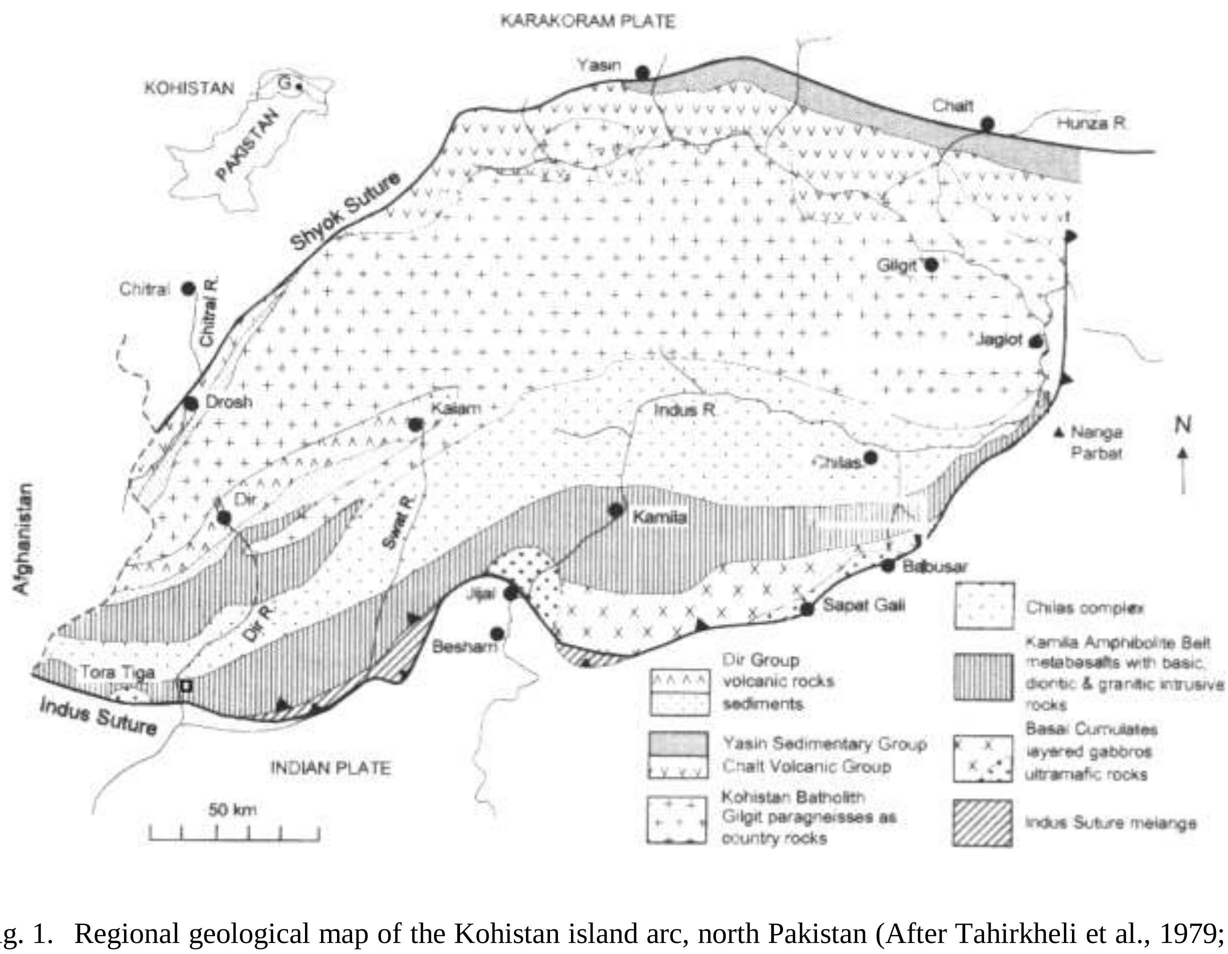

Fig. 1. Regional geological map of the Kohistan island arc, north Pakistan (After Tahirkheli et al., 1979; Khan et al., 1993; Searle and Khan, 1996).

MMT marks the entire southern and eastern boundaries of the Kohistan Island arc (DiPietro et al., 2000). MMT was described as extending eastward from Afghanistan through Swat to Babusar and then northward around the Nanga Parbat-Harmosh massif to Ladakh where it is connected with Indus suture zone (DiPietro et al., 2000).

The intra-oceanic crust of Kohistan consists of five units extending from the Indus suture in south to the Shyok suture in north (Khan et al., 1997): i) Basic ultramafic cumulates (Jijal ultramafites); ii) Kamila amphibolites; iii) Chilas complex of mafic to intermediate plutonic rocks; iv) Early bimodal suite of intrusive rocks (Stage 1 of Petterson and Windley, 1985) and Gilgit Gneisses; and v) Chalt volcanics (Khan et al., 1993).

The Asian or Karakoram plate, immediately north of MKT, consists mostly of slates intruded by Karakoram Batholith and related intrusive rocks. To the south of MMT occur rocks of the Indo-Pakistan plate mostly comprising Pre-Cambrian to Mesozoic metasediments and Cambrian Granite and Gneisses. The three major rock units constituting the Indian plate in the lower Swat area include Pre Cambrian to Cambrian Manglaur Formation, the Cambrian to Early Ordovician Swat Gneisses, and the late Paleozoic to early Mesozoic Alpurai group (DiPietro, 1990; DiPietro et al., 1993).

The Kamila amphibolites extend E-W across the southern part of the arc, and have been studied in detail in the Indus and swat valleys of central Kohistan (Jan, 1977, 1980; Treloar et al., 1990, 1996) and in the south-east Kohistan in Thak Valley (Khan et al., 1998). The Kamila amphibolite belt is a composite mass dominated by amphibolite-facies metaplutonic and metavolcanic rocks (Khan et al., 1997). Two types of amphibolites are identified (Khan et al., 1997): (i) fine- to medium-grained amphibolites either homogeneous or banded, and (ii) homogeneous, medium- to coarse-grained amphibolites (Jan, 1988; Treloar et al., 1990). The former are thought to be metamorphosed mafic to intermediate volcanics, whereas the latter are interpreted as metamorphosed gabbros and diorites. In the study area, gabbro-norite and hornblendite are present in the form of patches within the surrounding epidote amphibolites. Felsic intrusions and veins of epidosite also occur at places.

3. Petrography

Geologically, the area under discussion is occupied by medium (to high) grade metamorphic rocks of mafic (to ultramafic) composition. Petrographically the rocks are divided into epidote amphibolite, gabbro-norite and hornblendite. The lack of sharp contacts between these lithologies makes it difficult to show them as separate bodies. At places, these rock units are cut by felsic intrusions, which have sharp contacts with the surrounding rocks.

The area under investigation largely consists of epidote amphibolites. Detailed observations of the samples in thin sections reveal that the epidote amphibolites from the study area are sub-equigranular, fine- to coarse-grained and xenoblastic to hypidioblastic. Mineralogically, they are more or less uniform and consist of abundant hornblende (45-50 modal %), plagioclase (15-20 modal %), quartz (10-15 modal %), epidote (8-10 modal %) and accessory amounts of biotite, muscovite, sphene, apatite, rutile, ilmenite, monazite and opaque ore(s). The grains of hornblende are anhedral to subhedral and mostly medium to large in size. Some of the hornblende grains are variably altered and chlorite, biotite, sericite, muscovite, epidote and clays are the most common products of alteration. Most of the plagioclase grains appear cloudy or dusty due to alteration. The alteration products include clays, epidote, clinozoisite, white mica and quartz. Hence the process of alteration is largely saussuritization. Variable amounts of quartz also occur in the epidote amphibolites. Mostly, it occurs as inclusions within the grains of hornblende showing the metamorphosed character of the host rocks but discrete anhedral deformed quartz grains are also present. Some of the studied samples also contain variable but accessory amounts of garnet mostly as small to large porphyroblasts. Some of the garnet porphyroblasts are also visible megascopically.

Gabbro-norite occurs in the form of small to large patches within the epidote amphibolite. These rocks are sub-equigranular, medium- to coarse-grained and hypidiomorphic to idiomorphic. Mineralogically, they are more or less uniform and consist of plagioclase, orthopyroxene and clinopyroxene as essential minerals. In addition to these, accessory amounts of hornblende, epidote, clay mineral(s) and opaque ore(s) also occur. Furthermore, some of the samples contain accessory amounts of quartz (1 to 2 modal %). The modal compositions of the studied samples are listed in table 1 and plotted on the relevant IUGS classification diagram in figure 2. Plagioclase is the most abundant mineral occurring in the studied samples of gabbro-norite. Its modal abundance ranges from 55 to 70 %. Most of the plagioclase grains are large, subhedral to euhedral and cloudy. The cloudy appearance of plagioclase grains is because of their partial alteration to clay mineral(s) and epidote. Orthopyroxene occurs as euhedral, medium- to large-sized grains. Its modal abundance ranges from 20 to 25 %. Some of the larger orthopyroxene grains show extensive alteration and are almost totally transformed into bastite. They also show alteration to a mixture of hornblende, chlorite and quartz such that a symplectitic intergrowth is produced. Tiny reddish brown lamellae of hematite occur in the form of regular disseminations in almost all the orthopyroxene grains. Clinopyroxene also occurs in these rocks and ranges from 10 to 15 modal %. It is medium-grained and mostly subhedral to euhedral in form. Larger clinopyroxene grains show alteration to amphibole along their margins.

Hornblendites occur in the form of patches within the associated epidote amphibolite. In the field, they are easily distinguishable from the surrounding epidote amphibolites by their dark black color. The rocks under discussion are subequigranular, medium to coarse grained and hypidiomorphic. In terms of mineralogical composition, they are more or less uniform and almost totally consist of hornblende with only accessory amounts of quartz and clay mineral(s). The modal abundance of hornblende ranges from 80 to 90 %. Most of the hornblende grains show the effects of alteration. Chlorite, epidote and clays seem to be the most common alteration products.

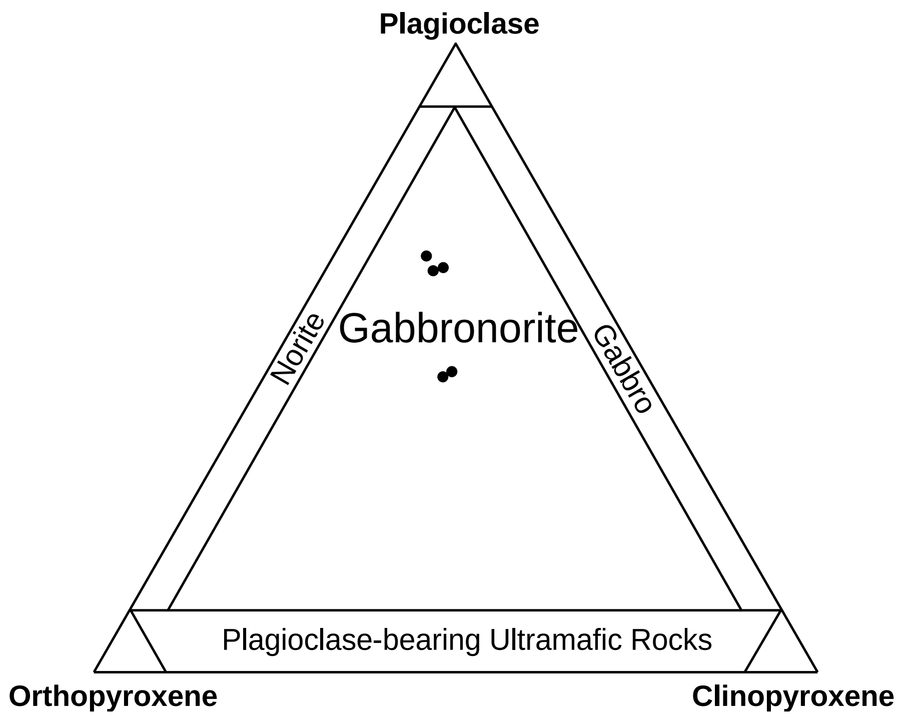

Fig. 2. Modal composition of the studied gabbro-norite plotted on the IUGS classification diagram (from Le Maitre, 2002).

The epidote amphibolites of the Khagram area are intruded by felsic dykes. These are regarded as intrusions because of their undoubtedly intrusive relationship with the enclosing rocks and irregular or tongue shape. The rocks constituting the felsic intrusions are subequigranular and medium- to coarse-grained. Mineralogically, they consist of abundant quartz, plagioclase as essential minerals and biotite, muscovite, sericite, epidote and clay in accessory amounts. Relatively larger grains of garnet also occur in the rock under discussion.

4. Mechanical properties

Among the mechanical properties of rocks, those related to their strength are of prime importance. The mechanical properties of rocks govern their behavior in response to the applied load. Strength of a material is its ability to resist the externally applied load and is oftenly measured in the laboratory, rather than in the field, for greater accuracy and more satisfactory results. In the present study, the following tests on the petrographically investigated rocks (epidote amphibolite and gabbro-norite) were carried out in the laboratory.

4.1. Unconfined compressive strength (UCS)

The UCS does allow comparisons to be made between rocks and affords some indication of rock behavior under more complex systems (Tsiambaos and Sabatakakis, 2004). Generally the UCS of the rock is the function of specimen size, shape, confining pressure, height to diameter ratio, rate of loading, porosity and moisture content (Jumikis, 1983).

The UCS of the studied rock types was measured with the help of strength testing machine. Bulk samples of the rocks were collected from their outcrops in the field and cylindrical core samples were obtained from them by using core drilling machine. To clear drill cuttings and cool the bit, water was admitted through a swivel into the core barrel. First the samples were dried at 90-100°C as the moisture content of the specimen at the time of test can have a significant effect upon the indicated strength of rock (ASTM-D3976). As per requirement, a grinding machine was used for making the faces of the cores smooth. The cylindrical cores thus obtained were cut at right angles to the longitudinal axis for getting the required length to diameter ratio (L/D), which is 2.0 to 2.5 (ASTM-D2938). Three specimens from each rock type were tested for the UCS. For this purpose, the cylindrical cores were loaded in the testing machine and load was applied continuously and without shock. The load at the time of failure was noted.

4.2. Unconfined tensile strength (UTS)

The tensile strength of rocks is found to be much lower than their compressive strength (Bell, 2007). The direct determination of tensile strength frequently has proved difficult because it is not easy to grip the specimen without introducing bending stress (Bell, 2007). So the splitting tensile test or Brazillian test appears to be a desirable alternative as it is much simpler and inexpensive (ASTM- D3976). As per requirement, a disc-shaped specimen with thickness to diameter ratio of approximately 0.5 was selected from the core. As for UCS, three specimens for each rock type were used for the UTS test by loading the specimens in the testing machine. The load at the time of failure of the specimen was noted.

The resulting UCS and UTS values of all the investigated rock samples are listed in tables 2, 3, 4 and 5. The average UCS to UTS ratios of the studied epidote amphibolite and gabbro-norite are 6.02 and 9.30, respectively (Table 6). Rocks with compressive strength values of ~35 MPa are regarded suitable for usual building and construction purposes (Bell, 2007). As the compressive strengths values of the investigated epidote amphibolite and gabbro-norite are well above 35 MPa, they can be utilized as building and dimension stones.

Table 1. Modal composition of gabbro-norite.

Sample Identity	29	31	34	35	36
Plagioclase	44.3	42.1	60.7	54.5	61.0
Orthopyroxene	24.7	25.3	18.4	*24.1	20.3
Clinopyroxene	23.8	22.3	15.4	10.7	14.5
Quartz	1.0	0.5	0.4	0.3	0.9
Ore	4.0	4.3	2.5	0.6	2.0
Hornblende	1.5	1.8	1.7	2.6	1.3
Clay	0.0	3.2	0.9	6.6	0.2
Apatite	0.5	----	----	----	----
Chlorite	----	----	----	0.5	----
Epidote	0.3	----	----	----	----

*Includes 6.8 modal % bastite.

Sums are 97 to 96%
What makes the remainder?

Table 2. Results of UCS test of epidote amphibolite.

S. No.	Diameter (meters)	Length (meters)	Area (m^2)	Load (KN)	Strength (MPa)
1.	0.0441	0.101	0.00152	104	68.42
2.	0.0441	0.105	0.00152	122	80.26
3.	0.0441	0.104	0.00152	108	71.05

Table 3. Results of UTS test of epidote amphibolite.

S. No.	Diameter (meters)	Thickness (meters)	Load (KN)	Strength (MPa)
1.	0.045	0.0259	23	12.56
2.	0.045	0.0259	22	12.02
3.	0.045	0.0238	20	11.90

Table 4. Results of UCS test of gabbro-norite.

S. No.	Diameter (meters)	Length (meters)	Area (m^2)	Load (KN)	Strength (MPa)
1.	0.045	0.101	0.00158	74	46.39
2.	0.045	0.101	0.00158	86	54.43
3.	0.045	0.102	0.00158	64	45.50

Table 5. Results of UTS test of gabbro-norite.

S. No.	Diameter (meters)	Thickness (meters)	Load (KN)	Strength (MPa)
1.	0.045	0.0251	11	6.21
2.	0.045	0.0259	8	4.38
3.	0.045	0.0248	9	5.14

Table 6. Average values and ratios between UCS and UTS, and values of specific gravity and water absorption of the studied samples.

Rock Type	UCS (MPa)	UTS (MPa)	UCS:UTS	Specific Gravity	Water Absorption (%)
Epidote amphibolite	73.24 ± 6.22	12.16 ± 0.35	6.02	2.82	0.211
Gabbro-norite	48.77 ± 4.92	5.24 ± 0.92	9.30	2.81	0.371

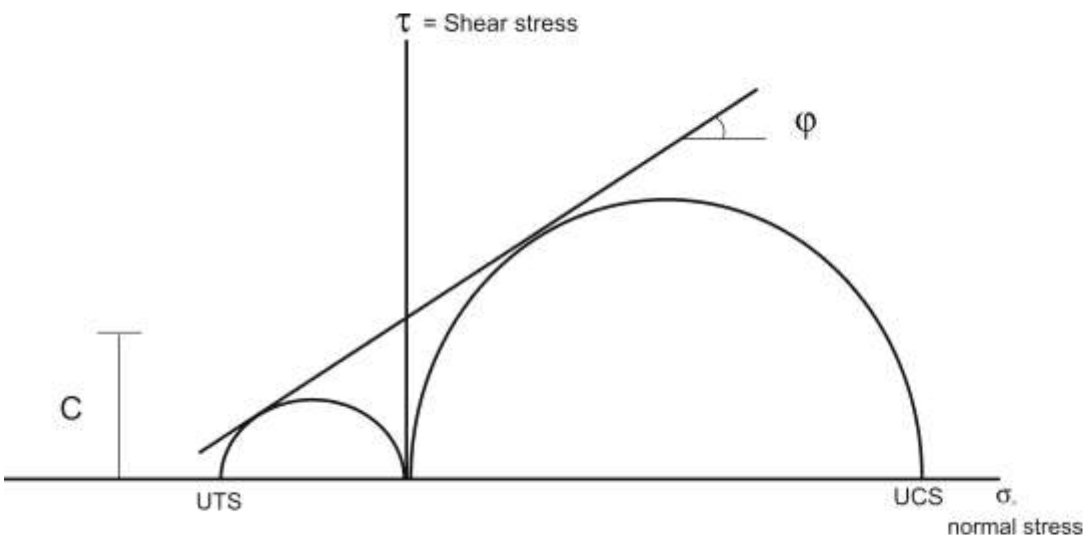

Fig. 3. Measurement of shear strength from UCS and UTS.

4.3. Shear strength

"The shear strength of a rock is its maximum resistance to deformation by a continuous shear displacement upon the action of a shear" (Jumikis, 1983). Shear strength of the rock specimen is usually measured with torsion test in the laboratory. In case of the present study, shear strength was not measured directly; rather it was indirectly measured using the values of UCS and UTS.

UCS reading of the specific rock type was taken on the positive x-axis and UTS reading for the same rock was taken on the negative x-axis according to scale. Separate Mohr circles were drawn for both the UCS and UTS readings (Fig. 3). A common tangent to the resulting two Mohr circles was drawn. The two parameters for measuring the shear strength are cohesion (C) and angle of internal friction (Φ). The angle of tangent with the horizontal axis gives us the value of Φ. The distance between the point of intersection between the x and y axes and the point at which the tangent cuts the y-axis gives us the value of C. Several values of C and φ were calculated for each sample by changing the UCS and UTS values and the average was then worked out. The average C and Φ values are, respectively, 14.5 MPa and 44.42^0 for the epidote amphibolite and 8.2 MPa and 50.8^0 for the gabbro-norite.

4.4. Specific gravity

Morgenstern and Eigenbrod (1974) carried out a series of compressive softening tests on engineering materials and found that the rate of softening of rock specimens on immersion in water depends on their origin. However, they swell slowly hence decreasing density and strength. The resulting loss in strength is very significant in controlling the engineering properties of rocks.

The specific gravity of the epidote amphibolite and gabbro-norite samples was determined in the laboratory. The values so obtained are 2.82 and 2.81, respectively (Table 6). The rocks having specific gravity ≥2.55 are considered to be suitable for heavy construction work (Blyth and de Freitas, 1974). This suggests that, in terms of their specific gravity, the tested rocks are suitable for use as raw material in heavy construction projects.

4.5. Water absorption

It refers to the quantity of water that can be readily absorbed by a rock and is designated as water absorption test. Most of the rocks are weakened by the addition of water through absorption. Pressure, known as pre-water pressure, is developed that influences the strength of the rock. Greater the content of water absorbed, the greater will be the loss in strength of the rock. A low absorption value in turn means that the given rock has high resistance to weathering. Such rocks have very low disintegration effect from frost action and chemical weathering (Blyth and de Freitas, 1974). Hence water absorption is a useful property in evaluating the durability of different rocks as building materials (Shakoor and Bonelli, 1991). The plutonic rocks having absorption value less than 1% by weight can be used as dimension stone because of their high resistance to weathering (Blyth and de Freitas, 1974).

The measured water absorption values for the studied epidote amphibolite and gabbro-norite are 0.211 % and 0.371 %, respectively (Table 6). Thus the absorption capacities of both the studied rock types are well within the range of values permissible for use as dimension stone and engineering material.

5. Discussion

According to Brady and Brown (2004), UCS of rocks is eight times their UTS and cohesion is two times UTS. However, Farmer (1983) proposed the ratio between UCS and UTS to be 10:1. Putting the two findings together, the UCS to UTS ratios of rocks fall in the range of 8 to 10. For the studied gabbro-norite, the UCS is 9.3 times UTS and hence in accordance with the stated relationship. However, the cohesion of gabbro-norite is low, i.e. 1.56 times its UTS. For the investigated epidote amphibolite, the UCS is 6.02 times its UTS, which is low and, therefore, falls below the expected range, mentioned above. Similarly, the value of its cohesion is low, i.e. 1.19 (rather than 2) times its UTS. The lower than 'normal' UCS to UTS ratio of the epidote amphibolite could be either because (i) the UCS is underestimated or (ii) the value of UTS is overestimated. Since the value of cohesion not only of the epidote amphibolite but also that of the gabbro-norite (having a 'normal' UCS to UTS ratio) is low, the lower UCS to UTS ratio is most probably because the value of UTS is higher and therefore overestimated. Alternatively, the UTS values are not overestimated and hence the UCS to UTS ratio of the tested epidote amphibolite is real. If supported with ample evidence, such an argument would suggest an extension in the lower limit of the range for the UCS to UTS ratios to at least 6. However, proposal for such an extension on the basis of very limited amount of data presented here cannot be defended.

A number of techniques were developed by Willard and McWilliams (1969) in an attempt to gain a better understanding of the mechanical behavior of rocks in relation to their micro-structure (petrographic characteristics). They reported that microfractures, grain boundaries, mineral cleavages and twinning planes influence the ultimate strength of a rock and may act as surfaces of weakness, which control the direction in which failure occurs. The strength of a rock is related to the presence of discontinuities, where cracks can be initiated at the time of failure (Lindqvist et al., 2007). Fine grained rock varieties are generally stronger than the coarse grained ones. It is not only the grain size but also the grain size distribution that is important, with the effect that a large size range gives higher strength and better resistance to fragmentation and wear compared to a more equigranular or idioblastic rock (Lindqvist et al., 2007).

Euhedral mineral grains may act as discontinuities where cracks may initiate in the structure (Lindqvist et al., 2007). On the other hand, an increased complexity in the grain shape and grain boundary geometry increases the strength of the material. This may be due to sub-grains occurring at the grain boundaries. Going from an idioblastic texture, in which the shape of the grains is largely defined by straight surfaces, to xenoblastic texture with more irregular grain boundaries, increases the strength and resistance to mechanical fragmentation (Åkesson et al., 2003).

The strength of a rock undergoes a notable reduction on weathering (Bell, 2007). Generally the alteration product of plutonic rocks has high clay content. Clays are mechanically weak and their abundance has a deleterious effect on the durability aspects of a rock (Lindqvist et al., 2007).

Metamorphic rocks are characterized by certain textures that have a marked preferred orientation. Such rocks are appreciably stronger across than along the lineation (Bell, 2007). Shape-preferred orientation may form planes of weakness in a structure. A foliation defined by micas or clay minerals has a stronger influence on the mechanical properties than foliations without micas. Randomly oriented micas have a considerably less significant effect. This is because micas act as a large discontinuity in the foliation where cracks can initiate and propagate easily. The total amount of mica in a rock is in itself not as important as foliations defined by micas (Lindqvist et al., 2007).

In terms of chemical composition, the studied epidote amphibolite and gabbro-norite are closely similar, i.e. both are basic. The repetitive intimate spatial association between the two and examples from elsewhere strongly suggest that the former is derived from the latter (Arif et al., 1983; Sajid, 2008). Hence these two rock types are expected to have comparable values of strength and thus should belong to the same category of rocks distinguished on the basis of strength (Hoek and Brown, 1997). Yet there is a marked difference in the mechanical strength between these two chemically similar and genetically related rocks. That is, both the unconfined compressive strength (UCS) and unconfined tensile strength (UTS) of the epidote amphibolite are higher than that of the gabbro-norite. This difference can only be attributed to difference in mineralogy, texture, degree of metamorphism and weathering/ alteration.

Whereas the epidote amphibolite is fine to coarse-grained, the associated gabbro-norite is medium to coarse-grained. In other words, the overall grain size is finer and its range wider in case of the former than the latter. This factor also most probably accounts for the observed difference in their strength. According to Tugrul and Gurpinar (1997) and Aggistalis et al. (1996), the mean UCS of basalt from Turkey and Greece is 120.1 MPa and 74.2 MPa, respectively, which is considerably greater than that of the studied gabbro-norite (48.8 MPa). Despite the fact that gabbro-norite is plutonic and hence coarse grained, it is a basic rock and its chemical (and mineralogical) composition is broadly similar to that of basalt. The difference in strength between the gabbro-norite under discussion and basalt, referred to above, lends further support to the thesis that fine grained rocks are stronger than chemically similar coarse grained rocks.

The grains of constituent minerals in the epidote amphibolite are more irregular in shape than those in gabbro-norite. Accordingly, the gabbro-norite can be classified on the basis of its texture as one intermediate hypidiomorphic and idiomorphic, i.e. most of the constituent mineral grains are subhedral (have somewhat regular shapes) and euhedral (having highly regular outlines), respectively. On the other hand, the epidote amphibolite is classifiable between xenomorphic, i.e. most of the constituent gains are anhedral (having highly irregular forms) and hypidiomorphic. As mentioned above, the hypidiomorphic to xenomorphic texture is expected to be much resistant to the applied load than hypidiomorphic to idiomorphic texture of gabbro-norite. That is perhaps why the studied epidote amphibolite gives higher strength value than gabbro-norite.

Whereas the studied gabbro-norite is characteristically massive, the epidote amphibolite is somewhat foliated at places. The possible effect of foliation on the strength of the epidote amphibolite was eliminated by placing it across the direction of the applied load during the testing of the core samples. That is why despite displaying foliation, the epidote amphibolite yields higher strength values. Micas occur in the epidote amphibolite but in very small amounts and without any preferred orientation, i.e. they are randomly distributed and hence their presence does not affect the strength of the rock.

The presence of a larger amount of quartz in epidote amphibolite than the gabbro-norites has probably also contributed to the higher strength of the former. On the other hand, the gabbro-norite essentially contains pyroxenes (including both clino- and orthopyroxenes). Being higher-temperature and relatively less hard, these ferro-magnesian (mafic) minerals are much more susceptible to alteration (chemical weathering) and physical disruption than the hornblende, epidote and quartz of the epidote amphibolite. Hence the low strength values of the gabbro-norite may partly be due to its modal mineralogical composition, i.e. essentially containing less resistant mafic minerals. Furthermore, plagioclase is the essential and most abundant constituent of the studied gabbro-norite. As is almost always the case, most of the plagioclase grains display twinning. Besides, the optical properties, notably the extinction angle suggest that the plagioclase is moderately calcic in composition. Both these features of plagioclase, i.e. the presence of twinning and calcic composition are detrimental to its strength as the former makes it physically less resistant and the latter renders it more vulnerable to chemical attacks (weathering). Hence the low strength value of gabbro-norite relative to epidote amphibolite is partly because of the occurrence of abundant plagioclase in the former.

6. Conclusions

The following broad conclusions can be drawn from the discussion presented above:

1. Both the epidote amphibolite and gabbro-norite have high mechanical strength and specific gravity and low values of water absorption. Hence they are suitable for use as dimension stones and construction material.
2. The UCS to UTS ratio of the gabbro-norite falls within the recommended range for rocks, however, that for the epidote amphibolite is low and therefore falls below the lower limit for the range.
3. The epidote amphibolite is stronger than gabbro-norite in terms of both the UCS and UTS. A detailed comparison reveals that the difference in strength between rocks with broadly similar chemical composition is strongly related to differences in their texture (grain size, grain shapes, etc.) and modal mineralogical composition.

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