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Geotechnical and Petrographic Assessment of Mafic Rocks from Tarbela Alkaline Complex, NW Pakistan

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ABSTRACT

The mafic rocks of Tarbela Alkaline Complex are excavated in the intake area of the Tarbela Dam for raising of Tunnel 3 and 4. These rocks are studied in terms of their petrographic characteristics and geotechnical properties. The bulk samples were collected at different elevations both from open and underground excavations. The petrographic study reveals that rocks are medium to coarse grained with euhedral to subhedral grains texture. These rocks essentially contain pyroxene, amphibole, plagioclase and accessory amount of chlorite, olivine, biotite and opaque phases. Modal mineralogical analysis categorized them as plagioclase bearing hornblende pyroxenite. The parameters investigated during current research for geotechnical assessment include unconfined compressive strength, Los Angeles abrasion, specific gravity, water absorption, porosity, soundness using sodium sulfate, flakiness/ elongation index and alkali-silica reactivity. Comparison with standard results revealed that the studied mafic rocks are suitable to use both as aggregate source or foundation material for construction of small- and large-scale civil structures. The regression analysis shows strong negative linear relationship of strength with weight loss during Los Angeles Abrasion, Porosity and water absorption. Due to the positive geotechnical results, the studied rocks are recommended to use as primary raw material for Tarbela 5th Extension Hydropower project.

1. Introduction

The rock aggregate is either used as crushed (both fine and coarse) or dimension stone. To ensure that the production of construction aggregate from naturally occurring rock mass is appropriate for the purpose and accommodate the requirements of the end-uses, it is essential to understand the geotechnical aspects of rocks to evaluate their suitability. The physical and mechanical properties are greatly influenced by the petrographic characteristics of a rock such as size, shape, intergranular spaces, mineralogical composition, and percentage of cement/matrix, degree of weathering and interlocking of mineral grains (Shakoor and Bonelli, 1991; Tugrul and Zarif, 1999; Miskovsky et al., 2004; Al-Oraimi et al., 2006; Sajid and Arif, 2015; Sajid et al., 2016).

Rock aggregate is typically sourced from all the three types of rocks i.e. igneous, metamorphic and sedimentary. Igneous rocks such as granite, dolerite/diabase and gabbro, sedimentary rocks such as sandstone and limestone and metamorphic rocks such as gneiss and marble are being proved to be a good source of aggregates (Bell, 2007).

The mafic rocks are part of belonging to the Tarbela Alkaline Complex (TAC) in Peshawar Basin (Fig. 1) and well exposed after the excavation for raising intakes of tunnels during the Tarbela 4th Extension Hydropower Project (T4th Ext. HPP). The cost and time effective measures are always of prime concern from the project management perspective during the construction of mega projects. Keeping same in view, engineers always prefer nearby or in-situ suitable rock sources to be used as primary construction aggregates in order to bring down the overall project cost. Likewise, for the construction of T4th Ext. HPP, the mafic rocks of TAC mined during the open and underground excavations (Fig. 2) have been proposed for use as a crushed aggregate for concrete and riprap material in the switchyard.

The proposed study area lies at the right bank of the Tarbela dam (Fig. 2). The geology and petrography of TAC revealed that it is a part of Peshawar Plain Alkaline Igneous Province (PPAIP) (Kempe, 1986). The rocks of the TAC have been studied in reasonable detail in the past regarding the petrography and geochemical aspects (e.g. Jan et al., 1981), however, their geotechnical aspects have received no attention. The current research is organized to furnish field, petrographic and geotechnical details of the excavated mafic igneous rocks of TAC. The statistical analysis has also been carried out to investigate the potential relationship among the geotechnical parameters. A comparison of these rocks with the other potential aggregate sources of the region e.g. granites, has also been investigated to assess their mechanical suitability. Such comparison will be helpful to locate a more potential resource of aggregates for the construction of other mega projects in this region e.g. Tarbela 5th Extension Hydropower Project.

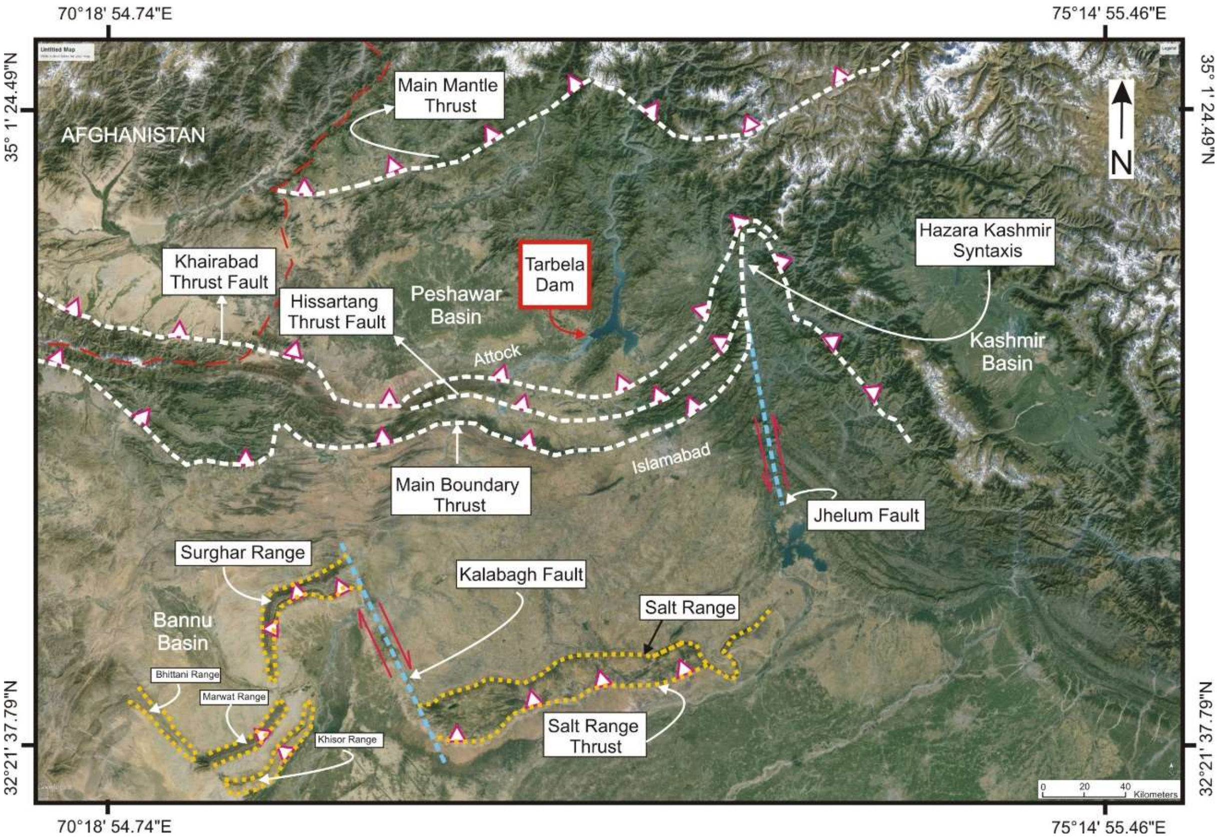

Fig. 1. Annotated Landsat image showing Regional Thrust Faults around the Tarbela Area (after Ali et al., 2015). The red box shows the location of the study area

2. Tectonic Setup of the Region

The Tarbela Dam is located in the southern part of the Hazara Hills forming the parts of Lesser Himalaya. The Hazara Hills are composed of crystalline and metamorphic rocks together with non-fossiliferous sedimentary formations and gabbroic intrusions, all ranging in age from Precambrian to Quaternary (Calkin et al., 1975; Qasim et al. 2014; Sajid et al. 2018a). The detailed geology and mapping of the region was reported in Calkin et al. (1975) wherein a major strike slip Darband Fault had been reported. The petrographic and geochemical investigations of the region have been executed by several authors (e.g. Kemp and Jan, 1970; Jan et al., 1981; Rafiq and Jan 1988; Pogue et al., 1992; Sajid et al., 2018a). Tectonically, it is bounded by MMT in the north, Khairabad-Panjal thrust in the south, Hazara-Kashmir Syntaxis in the east and the Peshawar basin in the west (Fig. 1). The surrounding tectonic settings impact the study area which developed a complex geological structure as a consequence of intense faulting, shearing and folding (Pogue et al., 1995).

The general orientation of the bedding of both the banks of the river reveals that they are the limbs of an anticline, the axis of which has been eroded by the Indus River. The variation in lithologies on both banks, delineates a strike-slip structural offset, running beneath the western abutment of the dam. This major offset is oblique north striking left lateral Darband Fault (Calkins et al., 1975).

Stratigraphically, there are four distinct geological formations at the Tarbela Dam Region (Fig. 3), the Salkhala Formation forming the right bank, the Hazara Formation forming the bedrock foundation of the Indus river, and the Tanawal and Abbotabad Formations forming the Left bank (Calkins et al., 1975; Qasim et al., 2014). The country rocks consist of the Precambrian Salkhala Formation and the Tanawal Formation (Fig. 3) (Hussain et al., 2004; Sajid et al., 2018b) cut across by middle to late Paleozoic intrusions including gabbros, albitites, granites and dolerites rocks collectively referred as the TAC (Jan et al., 1981; Kempe, 1986). The presence of PPAIP was first revealed by Kempe and Jan (1970), which extend from TAC at the right bank of the Tarbela Dam in the east to the Durand line (Pak-Afghan border) in the west..

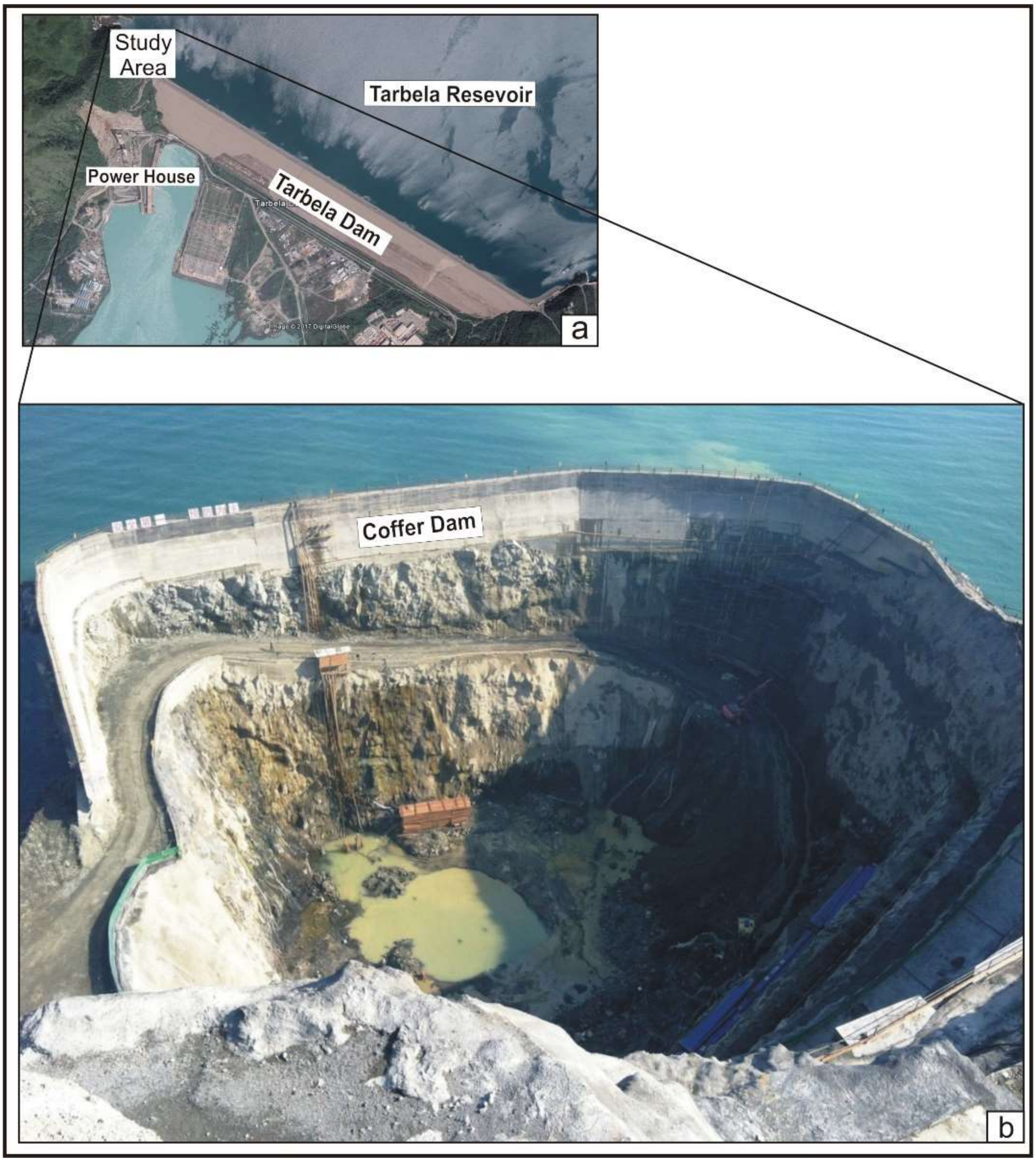

Fig. 2. a) Annotated Landsat image showing the Tarbela Dam and location of study area and b) An aerial image shows the open excavation of intake area of Tarbela Dam

3. Methodology

Geological fieldwork was conducted in the intake area of the project and eight bulk samples were collected for petrographic analyses as well as for geotechnical investigation at different elevations both from open and underground excavations. Crush samples of same rock units were also collected from the T4th Ext. HPP crushing plant for investigation.

Thin sections from each sample were prepared for detailed mineralogical composition and investigation of other petrographic characteristics. The different mechanical and aggregate tests executed on the collected sampled samples according to American Society for Testing and Material (ASTM) standard specifications i.e. strength (ASTM 1991, 1995), water absorption (ASTM, 2012), specific gravity (ASTM, 2012), Los Angeles abrasion (ASTM 2006), Soundness (ASTM, 2010), Alkali-Silica Reactivity (ASR) (ASTM, 2007) and Flakiness and Elongation (FnE) Index.

4. Petrographic Observations

The petrographic examination is useful in determining modal mineralogy and textural relationships within a rock. It also determines the durability of rock in terms of presence or absence of deleterious material in the rock. The samples were collected during the excavation of mafic rock for shaft installation (Fig. 2). The composition of the rock apparently looks same with little variation in the color from dark green to greenish black.

The studied specimens are medium to coarse grained with euhedral to subhedral grains. Pyroxene, amphiboles and plagioclase occur as essential minerals while biotite, olivine, chlorite and opaque minerals are noted as accessory minerals.

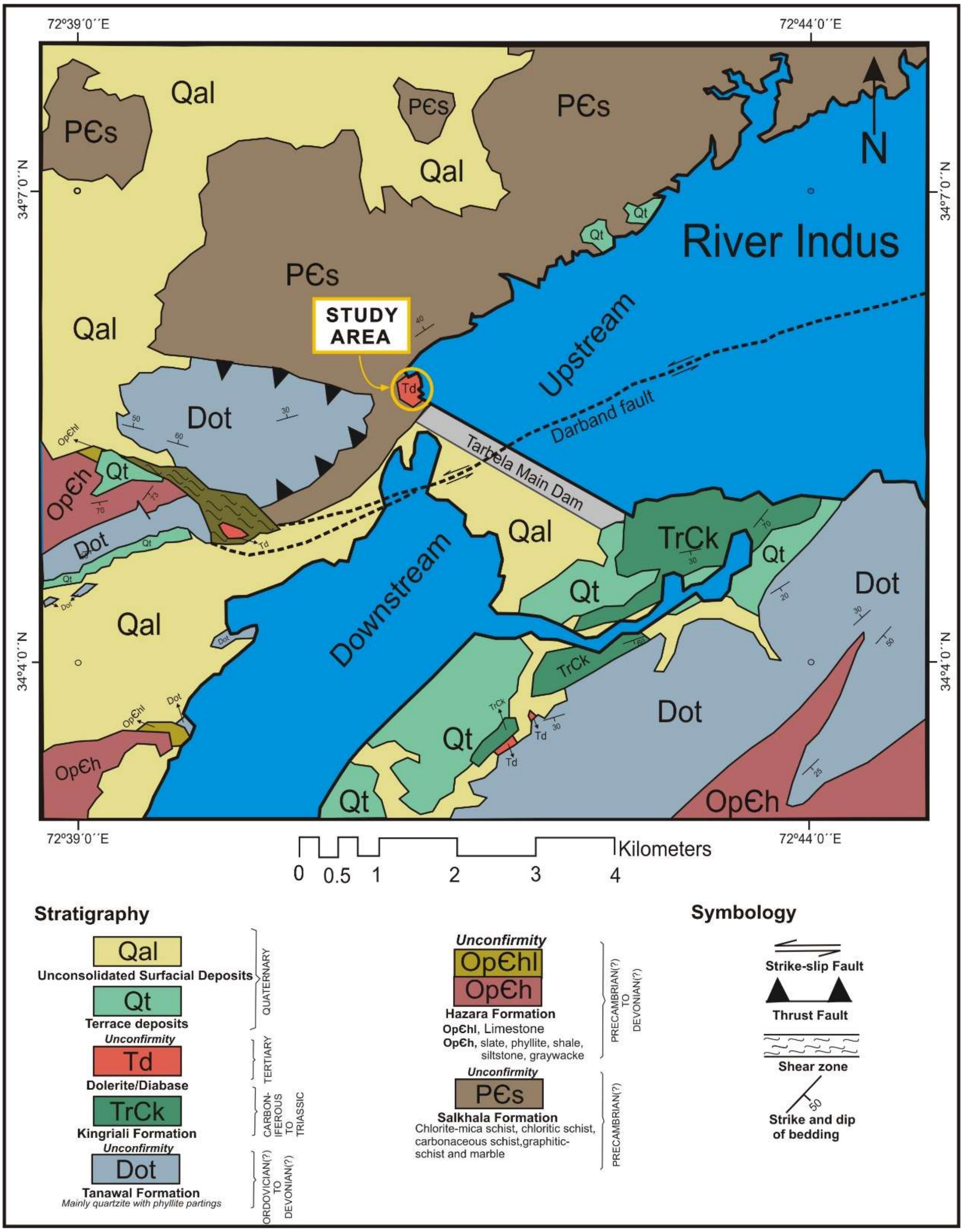

Fig. 3. Geologic map of Tarbela Dam site area (after Calkins et al. 1975), study area location is highlighted

The Plagioclase display poikilitic and sometimes sub-ophitic textures whereby its grains are enclosed in clinopyroxene. The olivine grains are subhedral with mostly fractured appearance. Biotite is present in small proportions showing altered nature. The modal abundances of the essential minerals are examined (Table 1) and subsequently plotted on the relevant "The International Union of Geological Sciences" (IUGS) ternary diagram. Most of the samples fall is field of plagioclase bearing hornblende pyroxenite (two plotted in plagioclase hornblende pyroxenite) except one sample which is categorized as plagioclase bearing pyroxene hornblendite (Fig. 4).

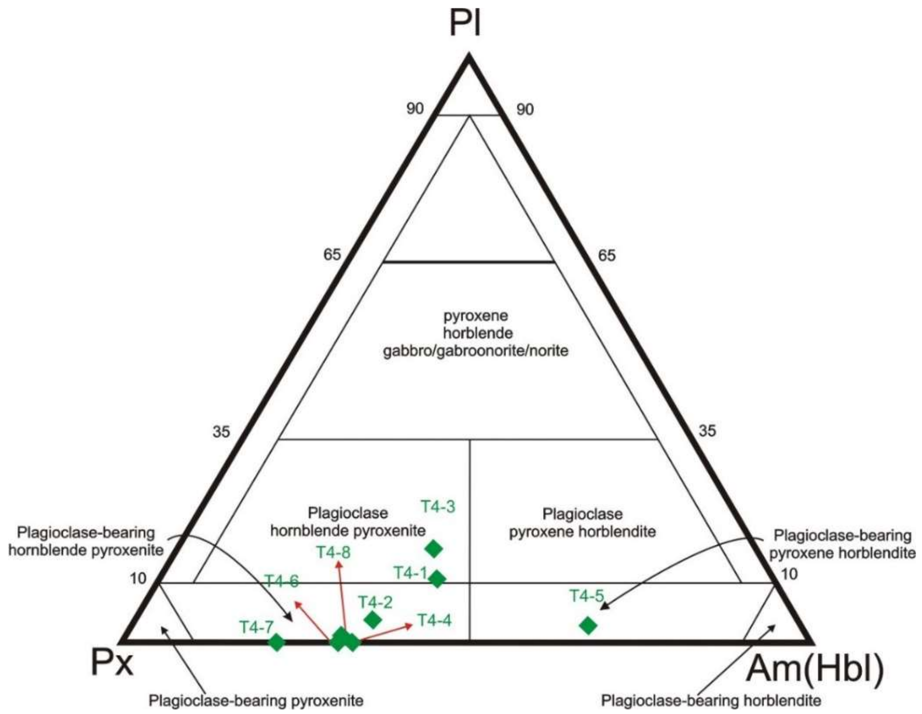

Fig. 4. Modal mineralogical composition plotted on the IUGS classification diagram (Streckeisen, 1976). Mineral abbreviations are according to Siivola and Schmid (2007)

Table 1. Average modal mineralogical composition of studied samples

Samples	Clinopyroxene	Orthopyroxene	Amphibole	Plagioclase	Biotite	Chlorite	Opaque	Olivine
T4-1	42	-	35	10	8	1	3	-
T4-2	55	-	30	3	3.5	-	3	-
T4-3	45	-	35	15	0.1	0.1	-	4
T4-4	60	2	30	-	4.3	-	-	0.1
T4-5	28	-	60.5	3.5	4.5	-	1.2	-
T4-6	60	-	28	-	4	0.5	2	-
T4-7	70	-	20	-	4.3	0.5	1.5	-
T4-8	60	2	30	-	4.3	-	-	0.1

Both clinopyroxene and orthopyroxene are present, however, orthopyroxene is limited in concentration (noted in two samples only) relative to clinopyroxene. The grains are subhedral showing altered appearance mostly along outer margins and fractured zones. At some places reaction texture are also formed with adjacent grains i.e. biotite. In certain places clinopyroxene bear sharp contact with biotite without any reaction rim which shows that both these phases are in equilibrium (Figs. 5A-B). The irregular opaque minerals occur as inclusions in clinopyroxene crystals.

The amphibole crystals are medium to coarse grained having subhedral to euhedral grains. At places, it also shows prismatic growth (Fig. 5C). Fresh and unaltered contact of amphibole with biotite and pyroxene in certain samples show the thermodynamic equilibrium between these phases in primary state. However, some amphiboles are totally pseudomorphed by secondary biotite (Fig. 5D). Plagioclase grains are subhedral to anhedral and mostly have sharp boundary contact with associated minerals displaying granular texture (Fig. 5E). Biotite exists in two petrographic domains, a) as primary biotite mostly in equilibrium with pyroxene and b) as alteration product of pyroxene and amphibole.

5. Geotechnical Properties

The different geotechnical characteristics of studied samples investigated in current approach include unconfined compressive strength, water absorption, specific gravity (surface saturated, dry and apparent), Porosity, Los Angeles Abrasion, Soundness, ASR and FnE Index. The result of each test is presented in Table 2 and comparison has been made with standard values from the literature (Table 2). Chemical method has been used for determination of ASR (ASTM, 2007) and the results are plotted in relevant graph. The FnE index of the specimen is measured on separate crushed material of same rocks and the results are presented in Table 3.

5.1. Assessment of suitability as aggregate material

The average unconfined compressive strength (UCS) value of the studied rock is 94.37 MPa having maximum UCS value of sample # T4-8 (125.79 MPa) and a minimum value of the sample # T4-3 (60.24) MPa. The strength of the mafic rock of the TAC falls in moderately strong to strong category of the strength grading (Table 2). According to Duggal (2008), rocks aggregate having LAAV value < 30 % are suitable for wearing coat/run of roads. Similarly, LAAV values of < 50% are suitable for concrete design. According to Jabatan Kerja Raya (JKR) Specification (2005), the maximum limits for LAAV of aggregate material is 50% for concrete and 40% for bituminous road surfacing. The average LAAV of studied mafic rocks from TAC is 13.41 %. The low value leads to the interpretation that studied rock materials are appropriate to be used as coarse aggregates and other geotechnical applications as high strength concrete and road construction.

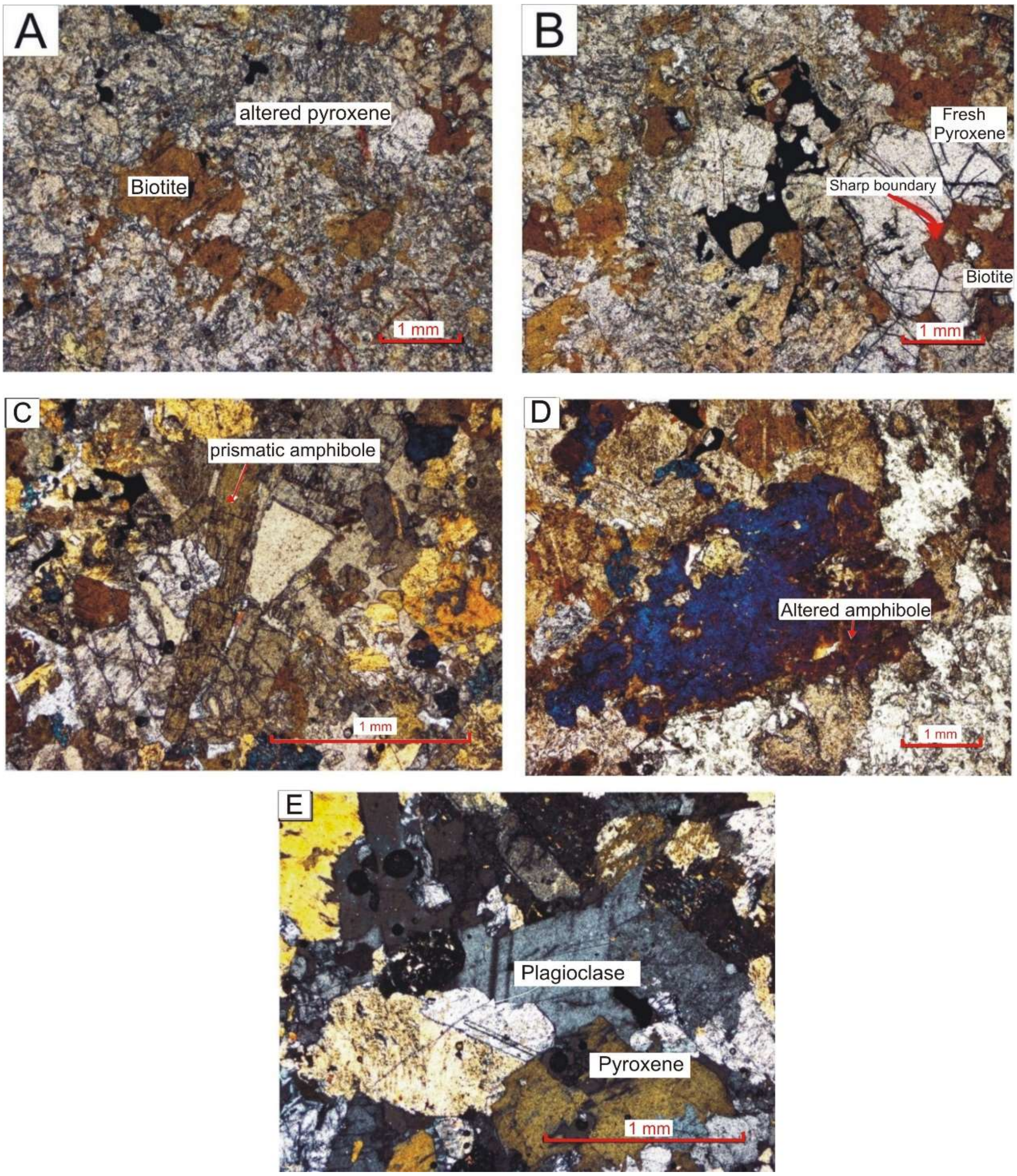

Fig. 5. Photomicrographs: A) altered clinopyroxene alteration along with biotite growth (PPL), B) pyroxene have sharp contact with fresh biotite grains(PPL), C) prismatic amphibole with associated pyroxenes (XPL), D) amphibole alteration (XPL), E) plagioclase having sharp boundary contact with pyroxene (XPL)

The specific gravity and water absorption control the strength and quality of the aggregate (ISRM, 1981). The presence of the voids reduces strength and specific gravity of the material. The average value of water absorption of studied samples is 0.091 %, which is recommended to be used both as a crushed aggregate with cement and as dimension stone. Due to very low water content, it is also recommended as a significant raw material that does not require any further laboratory treatment (adding admixture/ additive or use by adding another aggregate with it) to maintain the water-cement ratio, aggregate proportioning and slump of the concrete (Blyth and de Freitas, 1974; Muhit et al., 2013; Egesi and Tse et al., 2012). The average specific gravity of studied samples is 3.26 and hence declared as the suitable aggregate material and safely used for any small- and large-scale civil construction (Blyth and de Freitas, 1974).

Table 2. Average results of geotechnical properties of the studied rock specimens

Sample	T4-1	T4-2	T4-3	T4-4	T4-5	T4-6	T4-7	T4-8
UCS (MPa)	118.96	99.52	60.24	88.0	98.41	73.73	90.34	125.79
Specific Gravity (Dry)	3.28	3.24	3.29	3.29	3.29	3.15	3.26	3.29
Specific Gravity (surface saturated)	3.2811	3.242	3.157	3.261	3.298	3.299	3.298	3.297
Specific Gravity (Apparent)	3.2867	3.492	3.1655	3.2687	3.305	3.307	3.305	3.3023
L.A Abrasion Values (%)	10.2	13.4	16.2	14.6	14.2	15.03	14.4	9.3
Water Absorption (%)	0.07	0.09	0.11	0.11	0.09	0.11	0.09	0.06
Weight loss in Soundness test (%)	0.56	0.63	0.92	0.86	0.63	0.9	0.73	0.49
Porosity (%)	0.19	0.2	0.36	0.25	0.21	0.26	0.23	0.18

Table 3. Results of Flakiness and Elongation Index tests on crushed samples

Crush sample	Flakiness index	Elongation index	Flakiness and Elongation index
A-F1	9.4	3	12.4
A-F2	7.3	2.9	10.2
A-F3	7.2	3.8	11.0
B-F1	6.3	2.8	9.1
B-F2	6.7	2	8.7
B-F3	5.7	3.7	9.4
B-F4	6.4	3.7	10.1
B-F5	6.3	4	10.3
B-F6	6.5	4.3	10.8
B-F7	6.2	4	10.2
C-F1	4.9	1.1	6.0
C-F2	5.2	0.8	6.0
C-F3	6.6	0.8	7.4
C-F4	5.2	1	6.2
C-F5	5.2	1	6.2
C-F6	5	1.1	6.1
C-F7	5.5	1	6.5

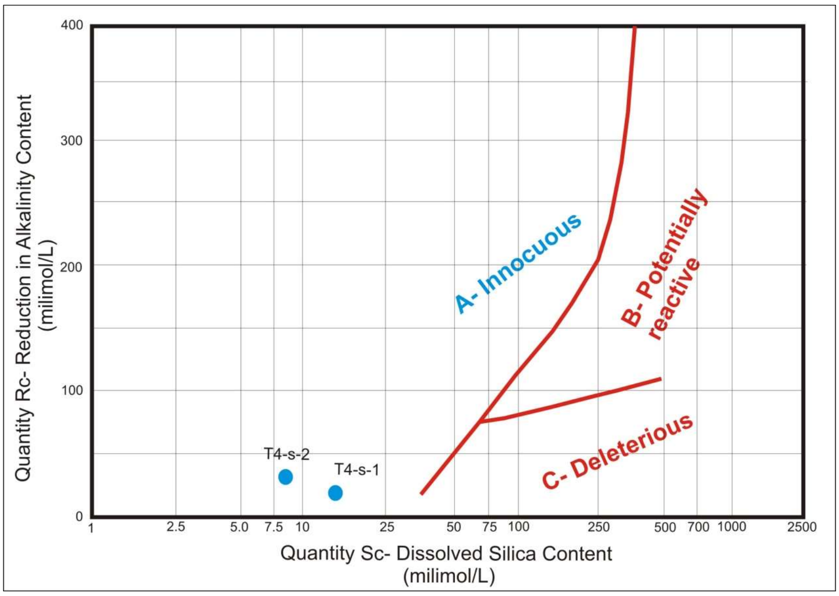

Fig. 6. Results of geochemically investigated ASR potential of studied specimens plotted on relevant diagram after Tiecher et al. (2017)

The chemical durability of aggregates depends upon the soundness of the aggregate in chemically reactive environment. The weight loss of aggregate after soundness test should not exceed the limit of 12% (ASTM C88-05) or 6 to 16 % (AASHTO T-104) for using sodium sulfate solution. The average value of soundness test of studied sample is 0.715 % which falls into the category of suitable material for aggregate use as per standard specifications (Irfan, 1996).

The increase in FnE index of the coarse aggregate creates a problem during compaction procedures. The average FnE index for studied aggregates group size # 3A, 5A and 7A is 11.2 %, 9.8% and 6.1 % respectively, whereby the maximum allowable limit for flakiness and elongation index is 15%. The results of ASR test result show low values of reduction in Alkalinity Content and Dissolved Silica Content for the studied rocks (Fig. 6). The material is inferred as innocuous and has no deleterious or potentially deleterious degree of alkalinity (Fig. 6) present and can be safely used without any further treatment.

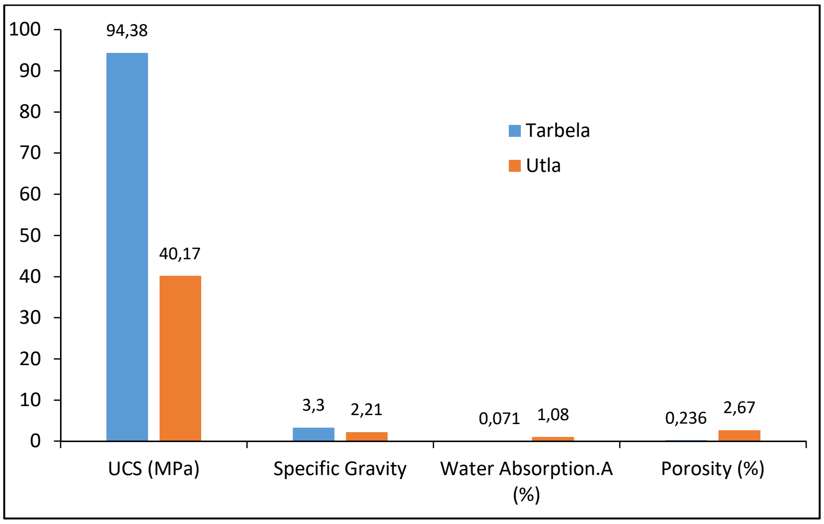

Fig. 7. The comparison of geotechnical properties between Utla granites (Sajid and Arif 2015) and mafic rocks of the TAC (this study)

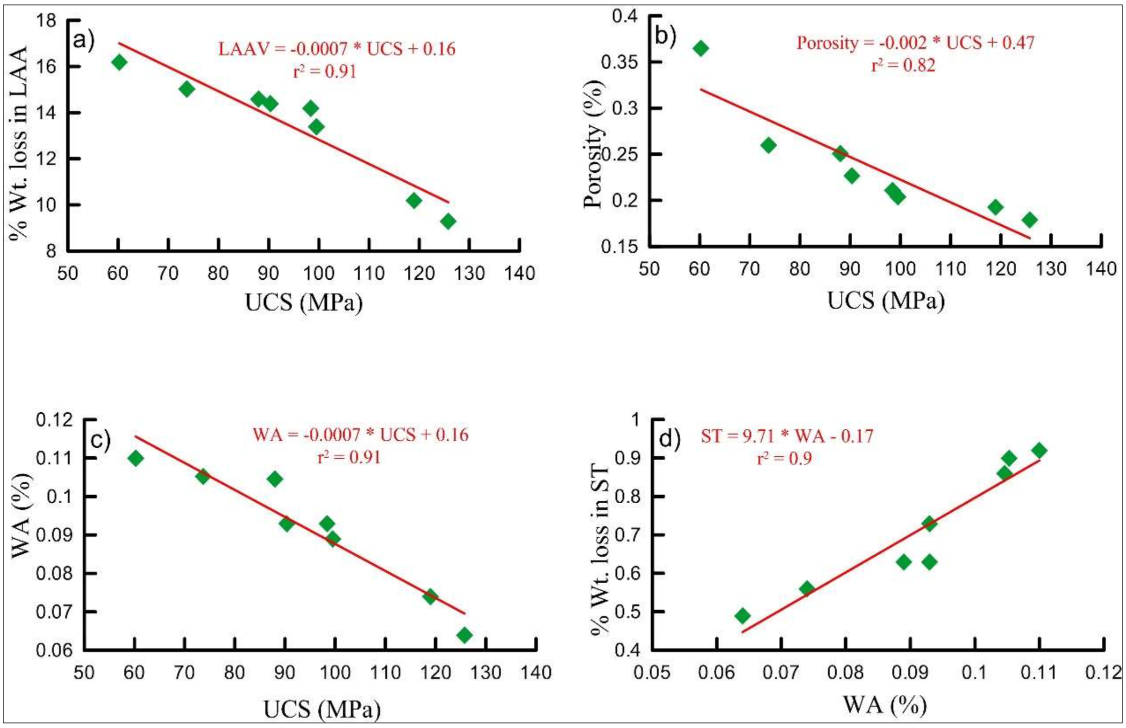

Fig. 8. Correlation plots between different geotechnical properties a) UCS and weight loss during LA abrasion, b) UCS and porosity, c) UCS and water absorption and water absorption and weight loss during soundness test. Results of regression analysis is also shown with each plot

5.2. Comparison of studied samples with Utla Granite

The physical and mechanical properties of the Utla Granites, exposed nearby mafic rock of the Tarbela alkaline igneous complex were investigated in detail by Sajid and Arif (2015). The average values of each test of the Utla Granites and studied samples from Tarbela Region are summarized in Table 2 and graphically presented in Fig. 7. The studied mafic rocks are dominantly composed of relatively softer minerals than acidic rocks (e.g. granites). Rock composed of softer minerals generally exhibit lower strength than rock containing harder minerals (Lindqvist et al., 2007). Opposite results are observed in the comparison between studied samples and Utla Granites. It can be explained as the hardness of individual minerals is usually shaded by the textural relations (granular and crystalline) of different minerals in a rock (Rigopoulos et al., 2014; Sajid et al., 2016). Hence the latter relation elaborating the minerals textural relation with geotechnical properties has been supported by the current investigation.

5.3. Correlation among the geotechnical properties

The pioneering work of most of researchers (e.g. Gunsallus and Kulhawy, 1984; Shakoor and Bonelli, 1991; Irfan, 1996; Tugrul and Zarif, 1999; Fell et al., 2005; Yilmaz, et al. 2011; Sajid et al., 2016) elaborate the correlation of different geotechnical properties and petrographic parameters of rock.

The mechanical performance of rock aggregate is significantly affected by their textural and mineralogical characteristics (Sajid and Arif, 2015; Sousa, 2013). Regression analysis have been applied to the geotechnical data set to investigate any potential relationship between different properties. The average results are presented in Table 2 and have been consequently used for statistical analysis.

The strong negative relationship (R^2 = 0.89) between UCS and weight loss percentage during Los Angeles abrasion test is observed (Fig. 8a). The results are in accordance with the Duggal (2008) where it has been observed that the percentage of the Los Angeles abrasion values increases with the decreasing UCS values

As expected, the UCS values established a negative correlation with respective water absorption (R^2 = 0.91) and porosity (R^2 = 0.81) values of the studied samples (Fig. 8b and 8c). Increase in the amount water absorption will decrease the strength of the rock materials (de Freitas, 2009; Sajid and Arif, 2015). This correlation also shows the positive relation between water absorption and porosity values. The term porosity in igneous rocks is referred to voids in the form of fractures and small veins its crystalline fabric, hence, it can be explained as the most of water lost during the testing procedures is entrapped in these fractures.

The % age of weight loss values during the soundness testing procedure establish a strong positive correlation (R^2 = 0.9) with water absorption values of the studied samples (Fig. 8d). Increases in the value of water absorption will lead to increase in the % age of weight loss during soundness of a rock aggregate (Mallo et al., 2012). This relationship elaborates enhancement of weathering degree with an increase in the amount of water, thus relatively poor performance during their exposure to chemical variable conditions.

6. Conclusions

Based on the detailed investigation, the following conclusions could be drawn regarding the mafic rocks of Tarbela alkaline complex:

- The mafic rocks of the TAC mostly contain pyroxene, amphibole and plagioclase as essential minerals while biotite, chlorite, olivine and opaque phases occur in accessory amounts.
- The rocks are geotechnically in the range from moderately strong to strong and are recommended to be used as raw construction material.
- The bearing capacity and strength of these rocks are enough to be used as the foundation rock for the construction of heavy structures.
- The rocks are non-deleterious and have no Alkali-Silica Reactivity potential. Therefore, these rocks can be safely used as an aggregate with Ordinary Portland Cement (OPC).
- The Los Angeles abrasion and soundness values recommend the studied rocks as strong enough to resist weathering and can be safely used in concrete without any further treatment.
- All the geotechnical results show that the studied rocks are recommended for use as primary raw material for small- or large-scale engineering projects e.g. Tarbela 5th Extension Hydro Power Project.
- The comparisons of the geotechnical properties elaborate more durability and strength of studied mafic rocks than adjacently exposed granites from Utla Region.
- The UCS exhibit strongly negative linear relationship, with weight loss during Los Angeles Abrasion, Porosity and water absorption. Water absorption yields positive relation with weight loss during the soundness tests. The latter relationship shows increase in the degree of weathering with the greater amount of water present/ absorbed by the rock material which could in turn creates less durability during their exposure to chemically variable conditions.

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