IOSR Journal of Applied Geology and Geophysics (IOSR-JAGG)
e-ISSN: 2321–0990, p-ISSN: 2321–0982.Volume 6, Issue 2 Ver. II (Mar. – Apr. 2018), PP 59-76
www.iosrjournals.org

Lk+Petrographic and Physic-Mechanical Characteristics of Quartzite from the Wolframite Mine in Zumba, Northcentral Nigeria: Implication for Their Use as Construction Materials

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Abstract: *Quartzite from the wolframite mine in Zumba, North -Central Nigeria was investigated using petrography and physico-mechanical tests. The aim was to deduce its suitability for use as construction material. Field evidence shows that the quartzite is intrusive to schist and granite and about 138, 300m^3 of quartzite has been excavated from pits in the study area and dumped as waste material. Petrographic examination of thin sections of the quartzite under a petrological microscope reveals two textural varieties. These are the fine to medium and coarse grained varieties and quartz is the most abundant mineral in both varieties. Results of physical tests done on the samples show average porosity of 0.35% with a range of 1 – 0.5% while average water absorption is 0.23% with and range of 0.1 – 0.5%. Average specific gravity of the samples is 2.75 with a range of 2.7 – 2.8 whereas average bulk density is 2.82g/cm^3 with and range of 2.60 – 2.67g/m^3. On the other hand, results of mechanical tests show that compressive, tensile and shear strengths have average values and ranges of 100N/m^2 and 98 – 105N/m^2; 21.1N/m^2 and 10 – 30N/m^2, and 37N/m^2 and 20 – 60N/m^2 respectively. Generally, the physical and mechanical properties when compared to some international standards indicate that it is very good material for construction purposes such as road stabilizers, aggregates, ornamental stones and building blocks. This therefore implies that mine-waste materials can be converted to exploitable resources and industrial products.*

Keywords: *petrographic, quartzite, physical and mechanical properties, construction materials, Zumba*

Date of Submission: 09-04-2018 Date of acceptance: 23-04-2018

I. Introduction

Rocks have been used for construction since ancient times, although the relative importance of this resource has changed with time. Many ancient civilizations developed the used the use of natural stones to a fine art, and dimension stones still occupy vital places in architecture, particularly in the construction of prestigious buildings. The -+5ecd construction industry worldwide has a basic need for rocks and minerals and if man continues to demand for higher standards of housing, road and infrastructural development, then the demands for constructional raw materials will continue to increase (Harrison and Bloodworth, 1994). Industrial mineral and rock raw materials are essential for economic development. Improvement and growth of the manufacturing sector requires a reliable supply of good quality construction materials and a wide range of other industrial raw materials.

Although many less developed countries of the world have significant potential industrial mineral resources, most continue to import these materials to supply their industrial needs. Indigenous resources may not be exploited or are exploited ineffectively because they do not meet industrial specifications, and facilities and expertise to carry out the necessary evaluation and test work are unavailable. Unlike metallic and energy minerals, the suitability of industrial minerals and rocks generally depend on physical behavior, as well as on chemical and mineralogical properties (Muhammed *et al.* (2013). Laboratory evaluation often involves determination of a wide range of inter-related properties. The evaluation must be carried out with knowledge of the requirements of the consuming industries. Evaluation may also include investigation of likely processing required to enable the commodity to meet industrial specifications.

There are two principal sources of materials used for construction. These sources are hard consolidated rocks which must be blasted, crushed and processed aggregates and natural sand and gravel deposits which are unconsolidated deposits and require less or minimal processing. Most of these rocks are potentially suitable for coarse aggregates. However, demanding specifications of aggregate materials used in construction require that high-quality crushed rock aggregates are used. These types of materials are normally derived from indurated and cemented sedimentary rocks and tougher crystalline igneous rocks. This work thus determines the industrial uses of the quartzite waste materials from the tungsten ore mine in Zumba, North central Nigeria, using mineralogical, physical and mechanical properties.

Quartzite is a metamorphic rock which is hard, non-foliated and is made up mostly of the mineral quartz. There are a few large deposits within the basement complex of Nigeria (Abel *et al*. 2014) which can be quarried for constructional purposes. As a popular rock in the construction industry, when split, it splits through the quartz granules rather than around them like its sedimentary protolith, sandstone. The term “quartz” is used often used as a synonym for silica (SiO_2) and is one of the ubiquitous materials in the earth’s crust. According to Indian Bureau of Mines (2015), quartz, quartz crystals, quartzite and silica sand are all coined together in one generic name “silica mineral”. This is because all these commodities are essentially crystalline silicon dioxide (SiO_2) with variations mostly related to their crystalline structure and presence of minor of trace impurities.

II. Regional Geological Setting

Metamorphic and igneous rocks of Precambrian to early Paleozoic age are exposed in about 70 % of the area of Minna sheet. In the southwest, the crystalline rocks are overlain by Upper Cretaceous to Recent sedimentary rocks of the Bida Basin which are made up the remaining 30% of the surface geology of the sheet (Ajibade *et al*., 2008). The crystalline rocks include migmatites, gniesses and quartzites of varying composition and texture; mylonitic rocks (the Zungeru Mylonites); meta-sedimentary and meta-volcanic rocks including kyanite schists, talc actinolite schist, interlayered with gneissic complex; low grade schists which occupy N-S trending belts, and rocks of the Older Granite suite which intruded the metamorphic rocks(Figure 1).

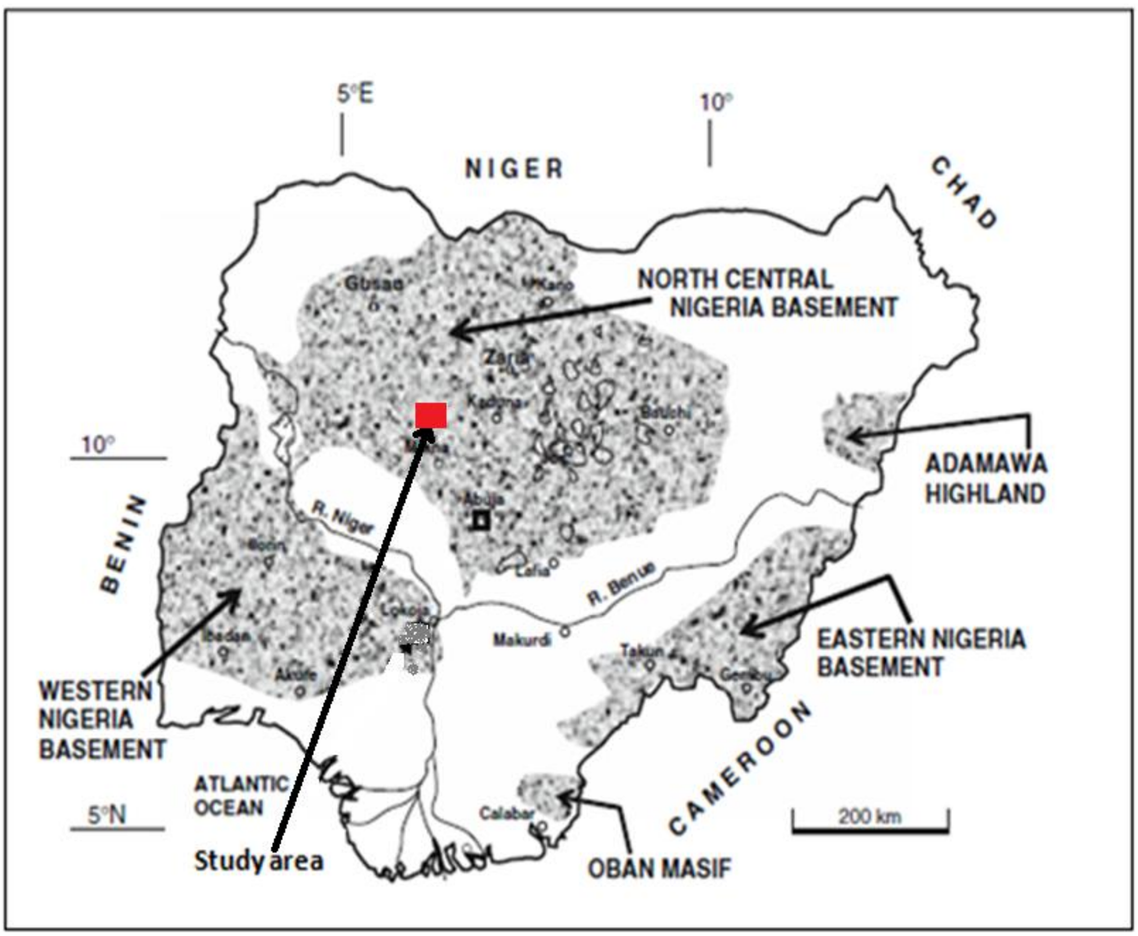

Figure 1: *Geological map of Nigeria showing study area (red square) (modified after Obaje, 2009)*

The Nigerian basement lies within the Pan-African belt of West Africa (Kennedy, 1964) which was affected by a major tectonic event about 600 My. Prior to the availability of isotopic data, the crystalline basement rocks of Nigeria were considered to be of Archaean age and Russ (1957) believed that they are comparable in many respects to the fundamental complexes in Canada, Scotland, Scandinavia and in other parts of Africa. However, the first batch of age determinations, mainly K-Ar and Rb-Sr data on mica and single whole-rocks from the Older Granite Suite, laid in the range 450 My – 550 My (Truswell and Cope, 1963; Jacobson *et al*., 1963). Truswell and Cope (1963) concluded on the basis of the age data that the metamorphic rocks of the Kushiriki region, which they called the "Gwarian Complex", were formed during a single orogenic cycle, the "Gwarian Orogeny" that culminated in the emplacement of the Older Granites. They went further to state that the crystalline rocks of the region (and other parts of Nigeria) could be older than the Cambrian. This conclusion was apparently strengthened by the fact that the metamorphic rocks in the area, which include migmatites, high–grade gneisses and schists, as well as low-grade schists, have parallel structures and apparently grade into each other. This conclusion was criticized by Oyawoye (1964) and Mitchell-Thome (1964) on the basis of the lithological and metamorphic contrasts between the migmatites and adjacent low-grade schist belts. Mitchell-Thome placed the migmatites and the schist belts at Lower and Middle Proterozoic respectively.

The Kusheriki sheet was considered by Jacobson *et al*., 1963 to be a critical area for the understanding of the field relationships within and between the crystalline rocks of the Nigerian basement because the three major rock assemblages (i. e. the migmatite-gneiss complex, the low-grade schists and the Older Granites) are well-exposed in the area. The Minna sheet lies immediately south of the Kusheriki sheet and all the major rock units are continuous, along strike, from the Kusheriki sheet into the Minna sheet. The area covered by the Minna sheet is relatively better exposed, particularly along the River Kaduna, than in many other parts of the Nigerian basement. These exposures have afforded the opportunity to re-examine some of the type localities described by Truswell and Cope (1963), and much of the field evidence on which they based their interpretation of field, structural and age relationships between the different lithological units or groups.

Great advances have been made in the knowledge of the evolution of Precambrian rocks the world over in the last five decades. The acceptance of the theory of plate tectonics in the late 1990s, as well as the availability of large amounts of geochemical and isotopic data has facilitated the interpretation of the origin of many rocks, dating of orogenic episodes, and viewing the geology of any given area in its regional tectonic context. Ajibade *et al*., 2008, attempted to discuss and interpret the geology of the Minna area in the light of modern concepts. They represented a re-interpretation of this classic part of the Nigerian basement and, in particular, provided some evidence for the age relationships between the major rock units in the area. They then considered the evolution of area in its regional tectonic setting in terms of modern geotectonic concepts. Their work also incorporated and discussed some of the recent data and ideas propounded by other workers on the evolution of the Nigerian basement.

III. Materials and Methods

3.1 FIELD METHODS

The field study for this research consisted of systematic mapping and sampling of different lithological units in the study area. The mapping was done on a scale of 1: 25,000 on the topographical map of Minna, Sheet 164. The mapping and sampling were done along transverses and the samples were collected with the objective of sampling all the litho-petrographic units within the study area. These were done with the aid of a global positioning system (GPS), compass clinometers, hammer, markers, measuring tape, sampling bags and a digital camera.

Representative rock samples of each lithological unit were studied and collected from all the available rock exposures along the transverses. In the field each outcrop was observed and described according to its mode of occurrence, macroscopic characteristics, structural elements, presence of any weathered surfaces and field relationship with adjacent rocks; whether they have been intruded by or they have intruded other rocks. Lithological boundaries were carefully identified or inferred using by careful observing changes in rock exposures, nature of soil and topography. Strike and dip values of rock units were measured using a Silva compass clinometers

Specifically, the quartzite rock samples were collected from the mine pits and areas where they have been excavated and dumped as a result of mining of wolframite. A thorough study of the mine pits was carried out so as to determine the total volume of quartzite material that was excavated from the study area as at the time of the field work. To achieve this, the average thickness of overburden of each pit was measured using a measuring tape. In addition, the length, width and depth of each of the pits were also measured. Field photographs and sketches to support observations made in the field were taken and made accordingly.

The samples collected in the field were labeled using a marker and points were plotted on the base map at the exact locations were the samples were observed, described and collected. This was made possible with the aid of a GPS and geographical coordinates of the base map. All the labeled samples were carefully stored using sampling bags.

3.2 LABORATORY METHODS AND PROCEDURES

3.2.1 Thin Section Preparation

Preparation of thin sections free from scratches and bubbles was essential for the examination, identification and textural description and interpretation of the minerals in the rocks using transmitted-light microscope. Five quartzite samples collected in the field were used for thin section preparation.

In the preparation of thin sections, each of the samples was cut into thin slice or section using a diamond saw to a suitable thickness of <0.5 cm and trimmed to removed any sharp irregularities. After the cutting the slice was ground perfectly flat on one side with carborundum powder on a glass plate. The grinding was done first with a coarser powder (which is an abrasive) and continued with the medium and finer powders respectively, until a perfectly smooth surface was obtained. In transferring the slice from one grinding plate to another, the previously used abrasives were washed from the slice and the grinding plate to avoid mixing of the grades of grinding powder on the plates. A glass slide was taken and a small amount of Canada balsam put in its centre. This was then heated gently until sufficient turpentine was driven from off and this caused the balsam to become hard and compact when cool. The rock slice was then placed on the glass slide with the flattened side in contact with the balsam and glass. The rock slice was pressed hard on the glass slide so as to drive off air bubbles between the slice and the slide. When cool, the rock slice was firmly cemented to the glass slide.

The next operation consisted of grinding down the thick chip as in the first process. This was started with the coarse and ended with the finest abrasive until a 0.03mm thickness was achieved. After the final grinding the thin section was carefully washed and all the remaining balsam was scrapped from it. The slice was then covered with fresh balsam and heated again to a slightly less extent than before. When the balsam was harden a very thin sheet of glass called cover-slip was carefully placed over the rock and pressed down so as that no air bubbles were left between the rock slice and the cover-slip as in the first operation. The whole thin section was finally washed with methylated spirit to remove any balsam around it. A specimen label was then inserted into each glass slice and left overnight to harden. The prepared thin sections were used for microscopy study. Preparation of the thin sections was done in the laboratory of Department of Geology, Kogi State University, Anyigba, Nigeria.

3.2.2 Petrographic Study

The thin sections were examined using transmitted light microscope model (Model NP-107B) attached with a digital camera. The observations were done under both plane and crossed polarized lights to reveal the quantitative and qualitative attributes of the minerals in the rocks. Quantitatively, the modal composition of each mineral in each rock sample was determined while the qualitative attributes had to do with observation, identification and description of the optical properties and texture of the minerals in the rocks. In studying the thin sections, attention was paid on optical properties of the minerals like colour, cleavage, relief, habit, pleochroism, interference colours, twinning, alteration and any other optical property that was shown by the minerals. Photomicrographs of the minerals as seen under the microscope under both plane and polarized lights were produced and each mineral was labeled on each photomicrograph. Study of the thin sections was carried out in the laboratory of the Department of Geology, Federal University of Technology, Minna, Nigeria.

3.2.3 PHYSICAL AND MECHANICAL TESTS

Ten quartzite samples were used for the physical and mechanical tests to determine the suitability of the rocks as constructional material. The tests were done according to Indian Standard Laboratory Method (IS 2386 part 4 – 1963). The physical tests done include; porosity, bulk density, specific gravity and water absorption capacity.

Porosity was determined by immersing 1 kg sample of the quartzite in water for 24 hours. This was later removed and dried and the percentage of the increase in weight relative to the original weight of the sample was then calculated to give the porosity in percentage. The porosity of the each sample was determined as the percentage of the ratio of the difference in the soaked and the dry weight to the dry weight according to the equation:

$$Porosity(p) = \frac{Soaked\ weight - dry\ weight}{Dry\ weight} \times 100 \ldots\ldots (1)$$

For bulk density determination, the dried sample was then weighed and immersed in water of known volume. The ratio of the original sample weight and water volume change was measured as the bulk density in g/cm^2.

Specific gravity which is dimensionless and water absorption capacity tests were carried out by drying 2 kg of the sample at 100 to 110^{o} C for 24 hours and later immersed in water for 24 hours. The specific gravity was later calculated from the dry weight of the sample and its apparent loss of weight in water. The water absorption capacity was then calculated from the difference in weight between the dry and the saturated sample as follows:

$$Specific\ Gravity(SG) = \frac{Weight\ in\ air}{Weight\ in\ air\ -\ Weight\ in\ water} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

The density (g/cm^3) of the rock was then calculated from the established specific gravity. Since specific or relative density is the ratio of the density of the substance to the density of the reference material which in this case is water which has a density of 1g/cm^3, then

$$Specific\ Gravity\ or\ rock = \frac{Density\ \ of\ rock}{Density\ \ of\ water} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

Therefore, $Density\ of\ rock = Specific\ gravity\ of\ rock\ \times Density\ of\ water \ldots\ldots\ldots\ldots$ (4)

In the determination of compressive strength of the rock samples, each rock sample obtained from the field was cut into a cube of 5 × 5 × 5 cm using a diamond saw. The sample was later placed in between the two steel loading plates of the compressive testing machine and it was checked to find out whether the sample faces were entirely in contact with the loading plates. In situations where they were any curvatures or if the surfaces were uneven, such defects were corrected by taking out the sample and polishing its faces slightly. During the test the sample was equally enclosed in an outer casing to prevent the crushed pieces of the sample from flying about. The strength values varied with the rate of loading.

The test for determination of tensile strength is known as Brazilian test. The test involved the application of a load in compression along the diameter of the rock cube where the failure stress was obtained. In this test rock samples obtained from the field are cut into thin cubes of about 10 mm thick. Each of the samples (cube) was placed in between the loading plates in the set-up for the test. The strain was measured by fitting a dial gauge in the set-up. The gauge was set to its initial starting value prior to the commencement of the test. A compressive load was on the sample for 5 minutes till failure and the tensile strength was calculated.

Shear strength test for the rock samples was done using the direct shear method. In this method, the sample to be tested was held tightly in position with the grips and sheared under vertical loading. The sample was oriented in any chosen manner to obtain shearing in the preferred direction. The physical and mechanical tests were done in the Civil Engineering Department, Federal University of Technology, Minna, Nigeria.

IV. Results and Discussion

4.1 FIELD OCCURRENCE AND CHARACTERISTICS OF THE ROCKS

Results from field mapping show that the study area consists of two distinct lithological units and the geology is depicted in Figure 2. The first is a metasedimentary unit which is represented by mica schist which is intruded by granite and quartzite veins from which the tungsten ore is mined. The second unit is an igneous unit and is made up of granites. These are rocks of the older granite suite described by Ajibade *et al*., 2008. They occupy about 20 % of the study area and are intrusive to the schists. These granitic rocks are well-exposed than the schists and range in size from small sub-elliptical plutons to elongated batholiths measuring up to 25 – 30 m long. Both rock units have been intruded by large quartzite veins which are host rocks to the tungsten ore that is being mined in the area. Two types of quartzite were observed in the field. These are the ones that have been disintegrated and exposed by erosion and those that occur as intrusions within the country rocks and are host to the tungsten ore. Both types occur on a hillock and have been very resistance to erosion at various degrees. Generally, coarse to fine grained variety was observed although fine flinty type also occurs.

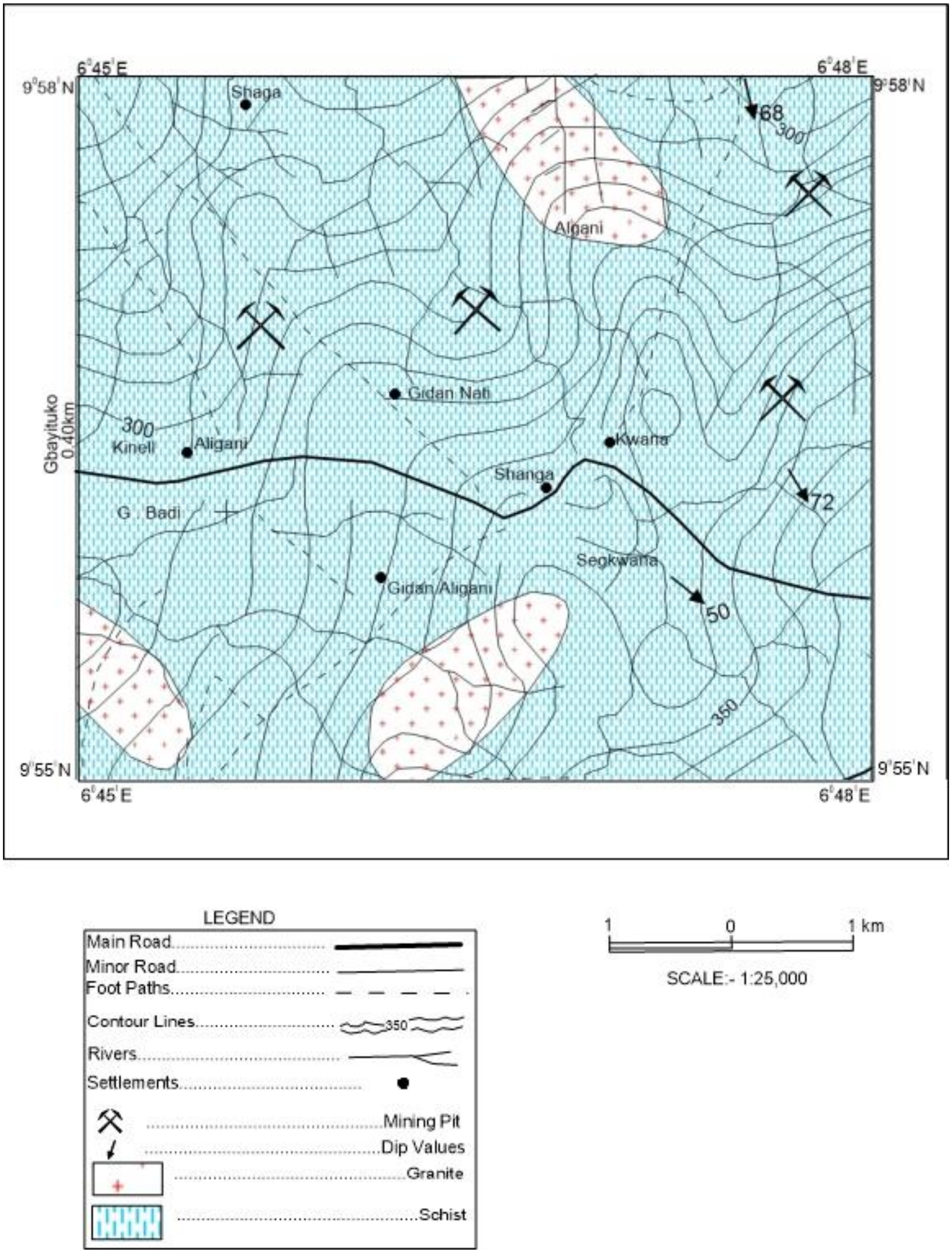

Figure 2: *Geological map of the study area depicting the two distinct lithological units intruded by quartzite from which wolframite is being mined*

The surface variety occurs as unconsolidated materials which range in size from cobbles to pebbles. The cobbles are fine grained with diameter greater than 64 mm while the pebbles are also fine grained with diameter between 16 and 64 mm. They occur as sub-angular to rounded and grey to reddish brown aggregates which show signs of weathering on the surfaces (Figure 3).

Figure 3: *Photograph of quartzite samples with different sizes, shapes and colour exposed on the surface in the study area*

The intrusive variety occurs in the subsurface are covered with overburden of varying thicknesses across the study area (Figure 4a). This variety is well exposed in the mining pits and some of the intrusions have been blasted and crushed to different sizes during the mining process. The thickness of the intrusions in the pits increases from top to bottom of the pits (Figure 4b).

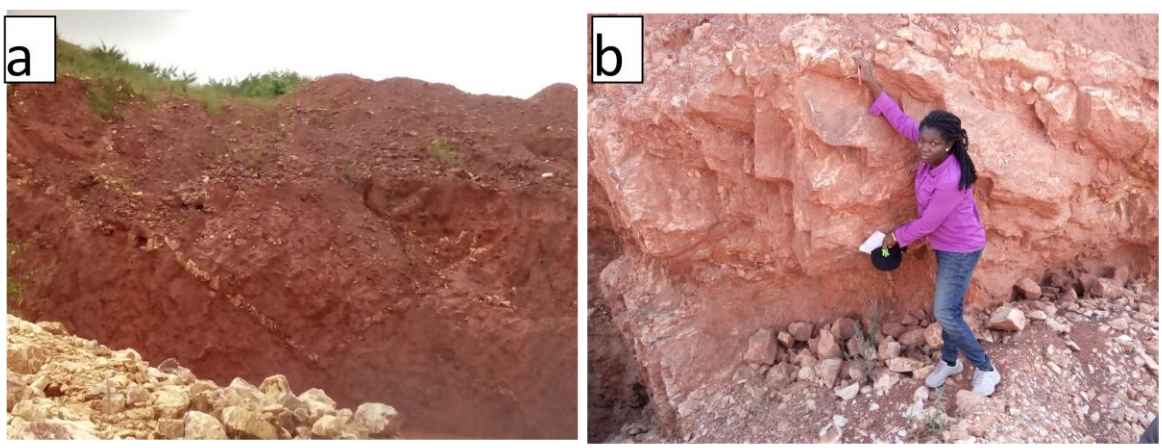

Figure 4: *Field photographs showing (a) the intrusive variety of quartzite covered with overburden of varying thicknesses and (b) variation in the thickness of the quartzite intrusions from top to bottom in one of the pits in the study area*

In some areas in the pits, small tunnels have been created by local miners along the quartzite intrusions (Figure 5a and b). The samples are fine grained and range in diameter from cobbles, pebbles (coarse aggregates) and sand sized particles (fine aggregates). Some of the samples contained disseminations of opaque minerals which are possibly tungsten and other related ores. The schists that the quartzite intrudes have been greatly weathered and form reddish-brown soils while the quartzite is seen as concordant and discordant units within the pits. The red soils may be the result of weathering and oxidation of iron-bearing minerals such biotite and hornblende in the host rocks.

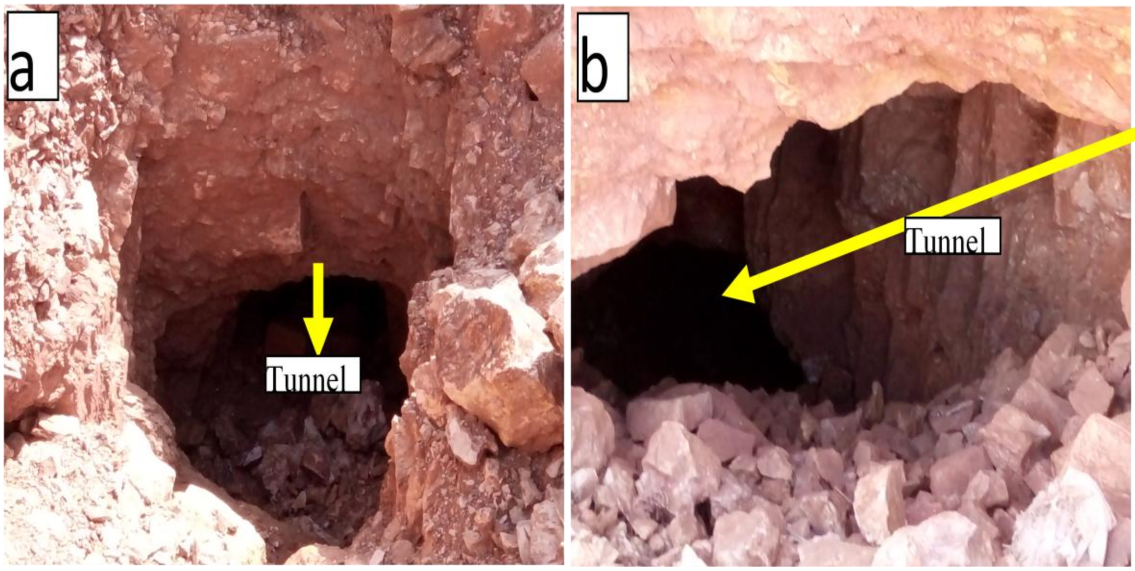

Figure 5: *Tunnels (a and b) created by the local miners along quartzite veins in some areas in the pits of the study area*

Large volume of materials has been removed from the pits and deposits as waste in the vicinity of the mine (Figure 6a and b).

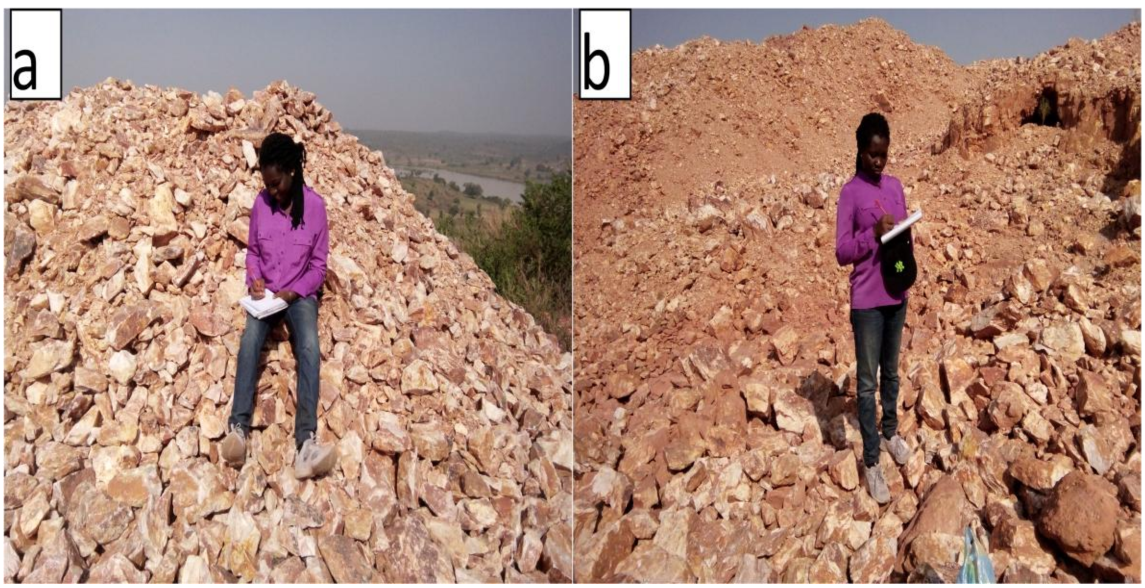

Figure 6: *Large volume of quartzite waste material (a and b) excavated from the pits and deposited at the vicinity of the mine. Such large volume of material could be converted to exploitable resources and some important industrial products*

Such large volume of materials could be used to convert the tungsten-mine waste materials to exploitable resources and industrial products (Arvanitidis *et al.*, 2012 and Platias *et al.*, 2014).

A total of four pits where the quartzite is being excavated are seen in the study area and the total volume of quartzite material removed from the pits is calculated to be 138 300 m^3. This value was used to calculate the mass of the material excavated from the area by multiplying this value by the average density (2.75 g/m^3) of the rock. This

gives a total mass of 380, 325 g/m^3 of wolframite-mine waste material which can be converted to exploitable resources and industrial products.
A summary of the parameters studied and recorded in the pits is presented in table 1.

Table 1: Summary parameters studied and recorded in the pits of the study area

Pit No:	1	2	3	4
Average thickness of overburden:	8 m	8m	8.5m	10 m
Length of quartzite intrusion:	200 m	250 m	100 m	320 m
Average width of quartzite intrusion:	12 m	12 m	5 m	8 m
Average thickness of quartzite intrusion:	20 m	10.5 m	15 m	20 m
Volume of quartzite material:	48000 m^3	31500 m^3	7500 m^3	51200 m^3

It is also estimated that more than this quantity can still be produced below the areas that have been excavated. A hand dug pit in the excavated area measuring about 30m and is expected that more materials could still being brought out from the area (Plate 7).

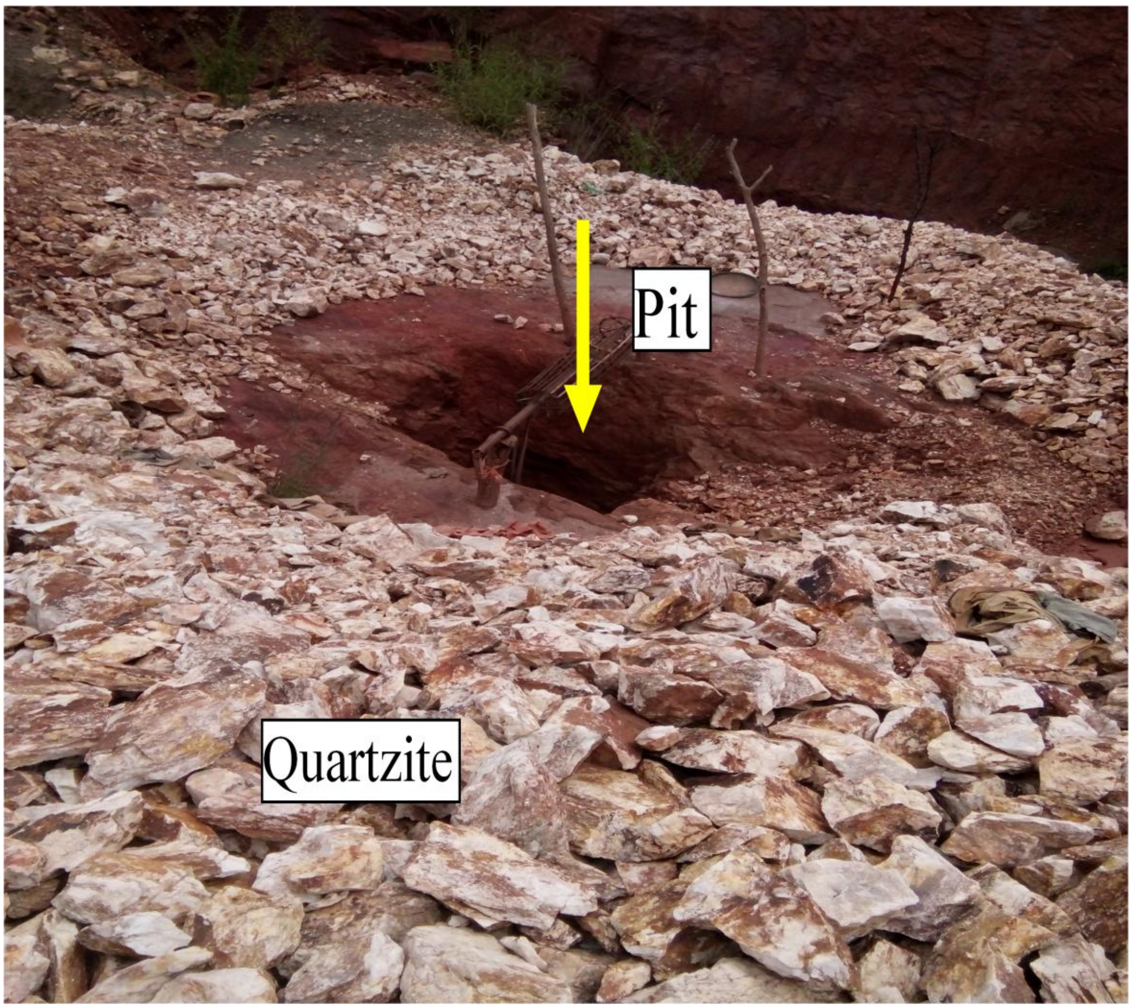

Figure 7: *A hand dug pit in the excavated area measuring about 30m and it is expected that more materials could still being brought out from the area*

4.2 MINERALOGY

Petrographic examination of thin sections of the quartzite samples indicates that the most dominant mineral is quartz. Texturally, two petrographic varieties were observed under the microscope. These are the fine to medium and coarse grained varieties.

The most dominant mineral in the fine grained variety is quartz which is associated with minor amounts of muscovite, biotite, sericite and iron oxides. Wolframite and related ores are accessory minerals. This fine grained variety consists of 85 % quartz, 8 % mica, 5 % sericite and 2 % accessory minerals. Photomicrographs of this variety are shown in figure 8a – d.

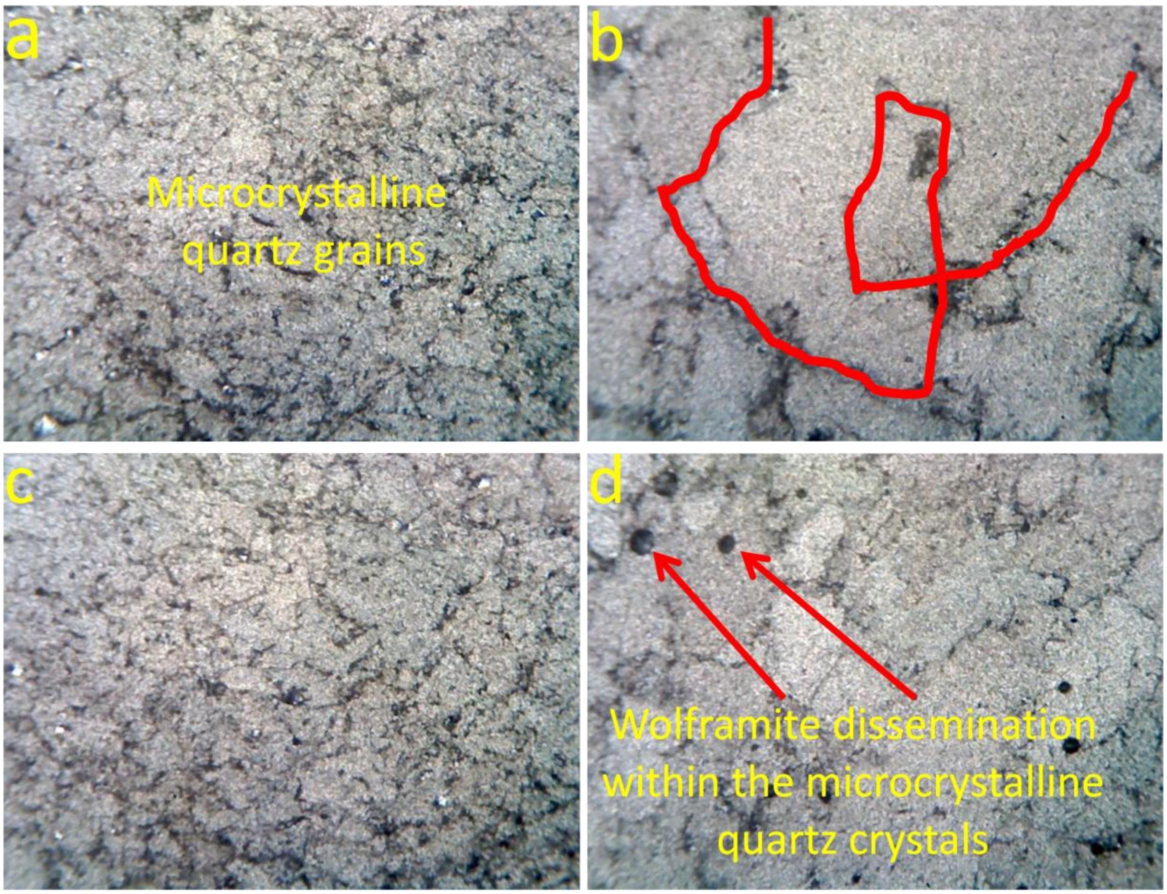

Figure 8: *Photomicrographs of fine grained quartzite with (a) framework of xenoblastic and monocrystalline quartz grains (b) domains of microcrystalline quartz which represent contacts between previous large quartz grains (c)weakly strained and exhibits strong undulatory extinction, stripes of different extinction position and subgrains and (d) wolframite and related ores thoroughly dispersed in the matrix and coat a very few quartz grains*

Quartz occurs as xenoblastic grains with rounded to suture grain boundaries and its grain size varies from 0.03 x 0.03 mm to 1.05 x 1.74 mm (Figure 8a). It consists of framework of grains dominated by monocrystalline quartz with sparse mica and finely disseminated ferruginous minerals along the fractures zones. Disseminated wolframite and related ores are also seen in some areas of the rock. Domains of microcrystalline quartz represent contacts between previous large quartz grains (Figure 8b). Recrystallisation of the grain is evidence in the interlocking nature of the quartz grains. The originally rounded crystals have been deformed to almond shape which is accompanied by extensive recrystallisation and subgraining to form microcrystalline quartz. Quartz is weakly strained and exhibits strong undulatory extinction, stripes of different extinction position and subgrains (Figure 8c).

Muscovite occurs as a colourless, flaky mineral and is associated with biotite. In some areas small flakes of muscovite appear as inclusions within the quartz grains. Very minute grains of recrystallised muscovite are seen discordant to the major foliation plane and, are strained and fractured.

Biotite occurs interlayered with muscovite and also in interstices of quartz. It shows pleochroism from greenish brown to brown and lies parallel to the foliation plane of the rock.

Sericite occurs as matrix and is commonly clouded with dust-like alteration products. It represents the alteration product of weathering of feldspars.

Wolframite and related ores are thoroughly dispersed in the matrix and coat a very few quartz grains in some samples (Figure 8d).

The coarse grained variety consists of two mineralogically distinct types. The first type has the same mineralogical composition as the fine to medium grained variety while the second type is composed of almost 100 % quartz.

The first type of the coarse grained variety is deformed quartzite and consists of quartz with interstitial blasts of mica, sericite and opaque ores along grain boundaries (Figure 9a). The interstitial blasts are arranged in a non- directional heterogranular texture. It shows features of deformation with recrystallisation by grain boundary migration. It is strongly strained with quartz grains displaying strong undulatory extinction, parallel deformation bands and subgrains. The parallel deformation bands show stripes of slightly different extinction position. In some areas, large quartz grains with undulatory extinction and elongated subgrains pass laterally into domains of microcrystalline quartz (Figure 9b). There appear bulging recrystallisation of quartz and irregularity of grain boundaries due to grain boundaries migration and subgrain rotation (Figure 9c). Quartz grain boundaries are serrated, interlobated and straight against mica (Figure 9d). Larger quartz crystals show substantial undulatory extinction and subgraining with the formation of microcrystalline quartz. Quartz-quartz grain contacts vary from straight with triple-junction to slightly concave-convex (Figure 9e). Fine grained matrix in this type of quartzite consists of mica, sericite and microcrystalline quartz (Figure 9f). The coarse grains quartz are angular to sub-rounded are made up of monocrystalline and polycrystalline grains of quartz displaying undulatory extinction and deformation lamellae. These observations are similar to what Isabe *et al*., 2016 reported in the characteristics of aggregates regarding potential reactivity in alkalis

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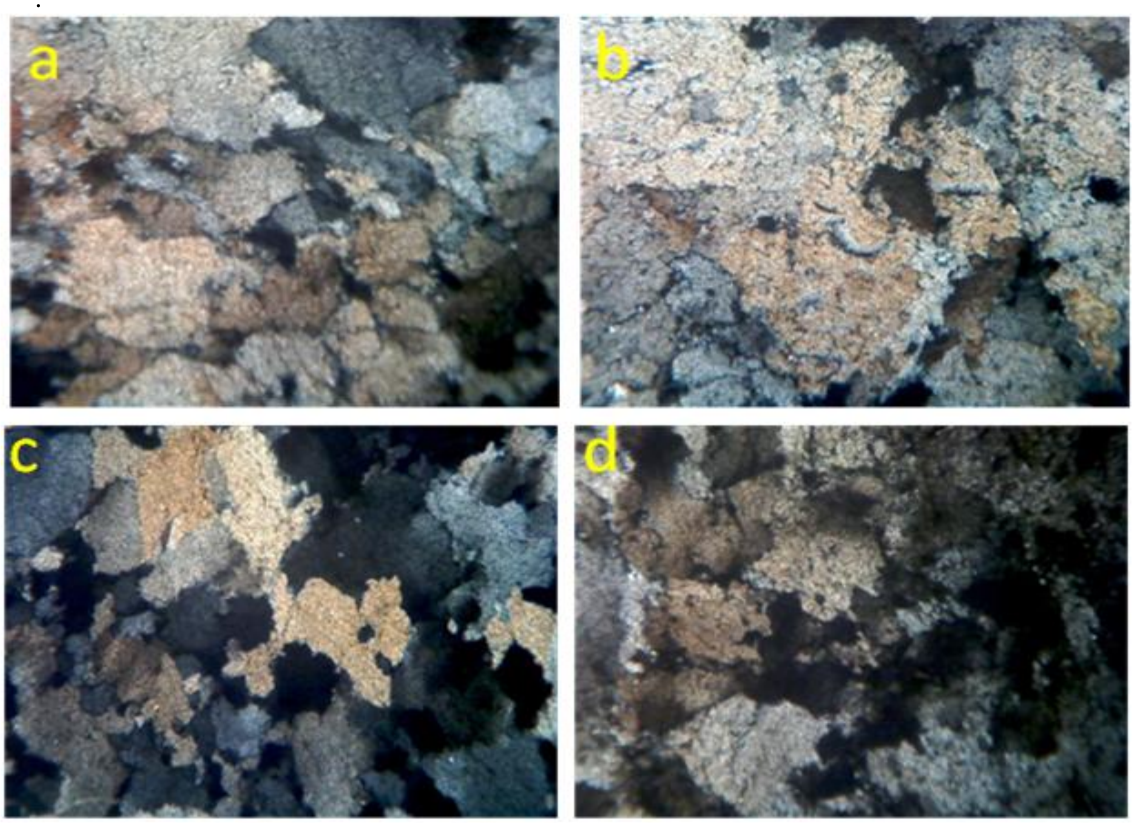


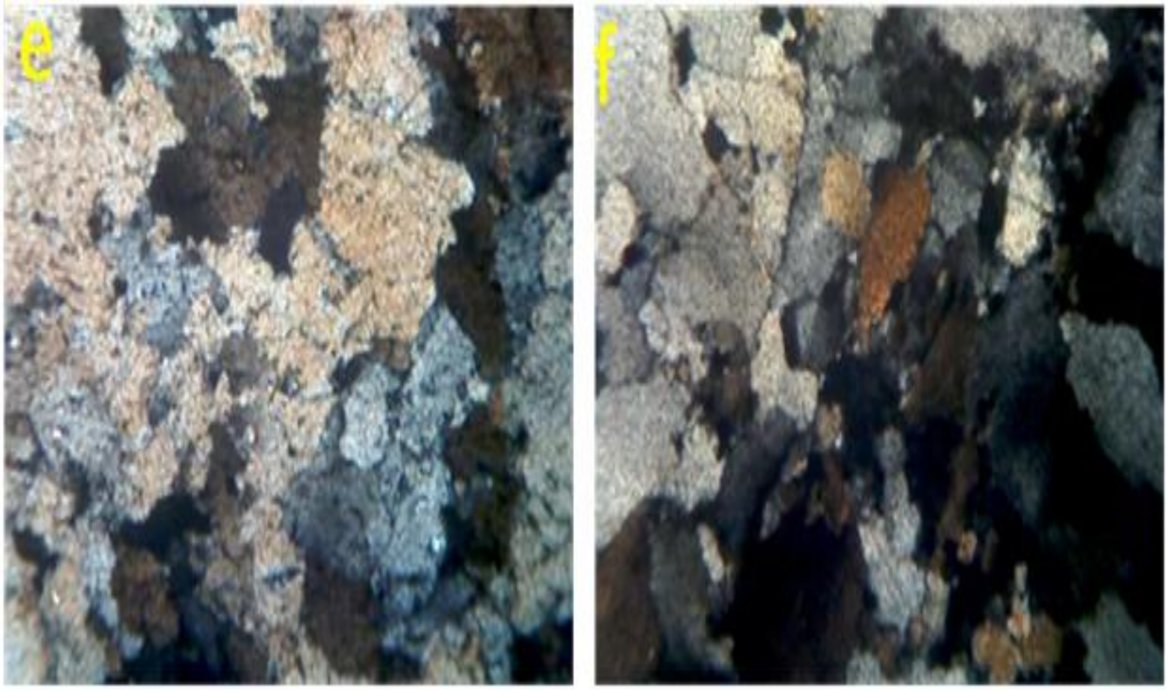
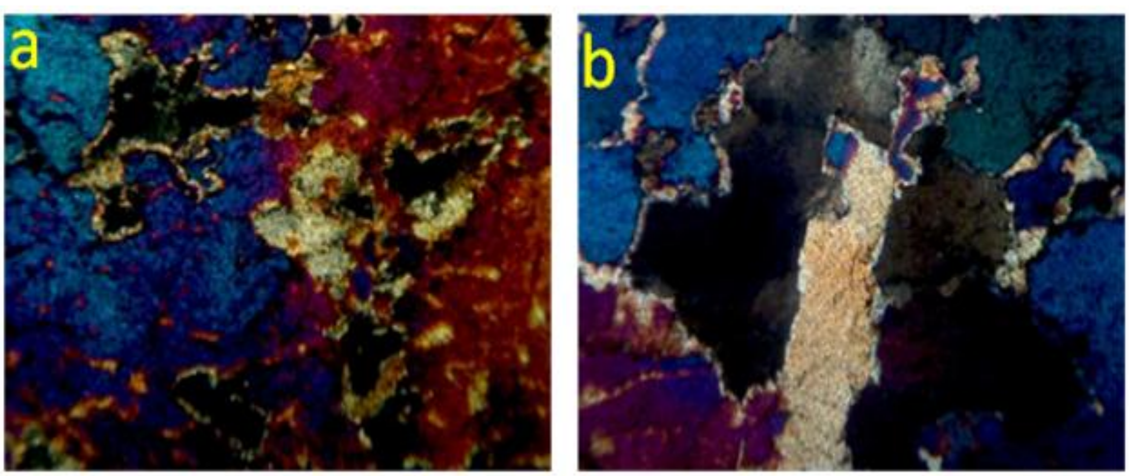


Figure 9: *Photomicrographs of coarse grained quartzite (a) consisting of quartz with interstitial blasts of mica, sericite and opaque ores along grain boundaries (b) large quartz grains with undulatory extinction and elongated subgrains passing laterally into domains of microcrystalline quartz (c) bulging recrystallised quartz displaying irregularity of grain boundaries due to grain boundaries migration and subgrain rotation (d) Serrated quartz grain boundaries interlobated and straight against mica (e) quartz-quartz grain contacts varying from straight with triple-junction to slightly concave-convex and (f) coarse grains quartz with angular to sub-rounded consisting of monocrystalline and polycrystalline grains of quartz displaying undulatory extinction and deformation lamellae*

The second type of the coarse grained variety of quartzite is also deformed but is composed of almost 100 % quartz with minute matrix of mica and iron oxide. It is highly deformed and extensively recrystallised with smaller grains along the boundaries of larger subgrained quartz (Figure 10a). The larger grains of quartz display undulatory extinction, deformation lamellae and lobate to serrated grain edges (Figure 10b). Some crystals have been stretched and this defines the preferred orientation of the rocks (Figure 10c). There is the present of smaller grains along the boundaries of the larger subgrained quartz and a weak alignment of the elongated crystals (Figure 10d). Deformation and recrystallization of the microstructure of the host grains is observed with bulging and boundary migration.



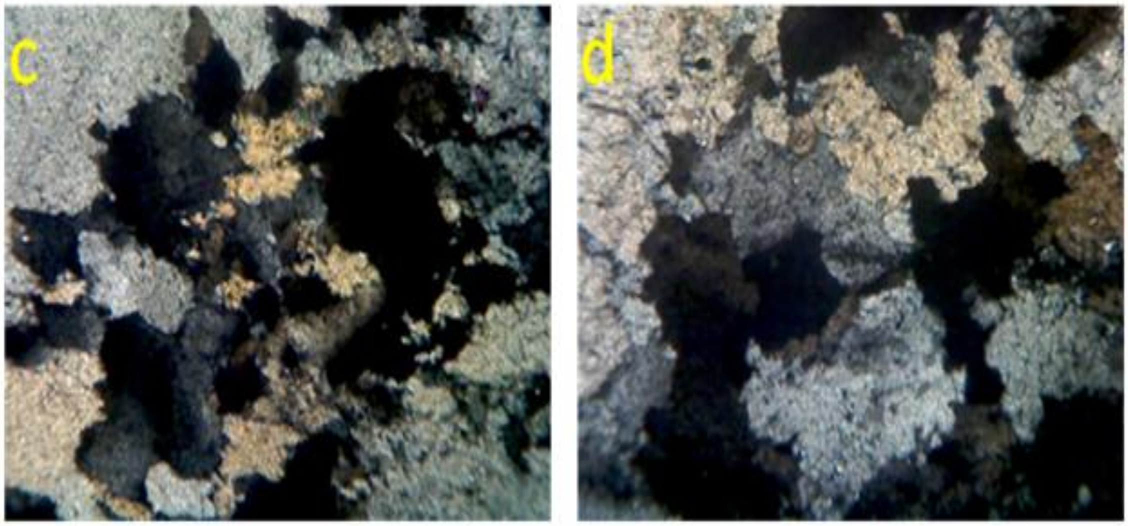


Figure 10: *Photomicrographs of quartzite consisting almost of 100% quartz with (a) extensively recrystallised smaller grains along the boundaries of larger subgrained quartz (b) larger grains of quartz displaying undulatory extinction, deformation lamellae and lobate to serrated grain edges(c) stretched crystals defining preferred orientation of the rocks (d) Deformed and recrystallised microstructures of the host grains observed with bulging and boundary migration.*

Results of petrographical study reveal distinct different in the grain size of the quartzite. It is also clear from this study that there is a difference between the accessory minerals that are more or less irregularly distributed in the rock samples (Cnudde *et al*., 2013). The angular to sub-angular shapes of the initial quartz grains indicate the non-marine origin of the materials.

4.3 PHYSICO-MECHANICAL CHARACTERISTICS OF THE QUARTZITE

Results of the physico-mechanical analyses done on the quartzite samples according to IS 2386 part 4 – 1963 are presented in table 1.

4.3.1 Physical properties

The result of porosity of the quartzite in percentage shows a range of 0.1 – 0.5 and an average value of 0.35. The highest average values were recorded in the coarse grained variety which is represented by sample number 1 (0.4 %), 5 (0.5 %), 6 (0.5 %), 7 (0.4 %) and 9 (0.5%) whereas the medium and fine grained varieties show a medium and lower porosity values respectively. The median grained variety is represented by samples 2(0.3%), and sample 8 (0.3%) respectively while the fine grained variety is represented by samples 3 (0.2%), 4 (0.1%) and 10 (0.2%) respectively (Table 1).

The average value of porosity recorded in this study is similar to that obtained by Abdullah and Singh (2010) in the quartzite of Dehradun, Uttarakhand State, India. They recorded an average porosity value of 0.5% and classified this type of porosity as a very low class and concluded that the rocks with very low porosity class have very high durability index and meet the specification for use as construction materials. Abel *et al*., 2014, however, obtained a very high porosity value of 0.80% (average value) for the quartzite from the Archean-Proterozoic Terrain of Ado-Ekiti, south west Nigeria. The variation in porosity for quartzite in this study and comparable studies may be due to geology. Geology controls porosity in rocks as the size of cracks or fractures in rocks, the size of pores between rock crystals and whether the pores are connected determine their porosity (Ademeso *et al*., 2012 and Oden *et al*., 2013)

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Table 1: Physico-mechanical properties of quartzite of the Study Area

Sample No.	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**Range**	**Average**
Physical property												
Porosity (%)	0.4	0.3	0.2	0.1	0.5	0.5	0.4	0.3	0.5	0.2	0.1 - 0.5	0.35
Bulk density (g/cm³)	2.6	2.62	2.8	2.82	2.6	2.6	2.6	2.63	2.6	2.82	2.6 - 2.82	2.67
Specific gravity	2.8	2.7	2.8	2.8	2.7	2.7	2.7	2.8	2.7	2.8	2.7 - 2.8	2.75
Water absorption (%)	0.3	0.2	0.4	0.2	0.4	0.4	0.3	0.2	0.5	0.1	0.1 - 0.5	0.23
Density (g/cm³)	2.8	2.7	2.8	2.8	2.7	2.7	2.7	2.8	2.7	2.8	2.7 - 2.8	2.75
Mechanical property												
Compressive strength (N/m²)	98	100.5	100	105	98	98	99	102	98	103.4	98 - 105	100.2
Tensile strength (N/m²)	10	28	30	30	10	10	28	25	10	30	10 - 30	21.1
Shear strength (N/m²)	25	20	25	60	20	20	25	60	55	60	20 - 60	37

The results of water absorption analysis for the quartzite show a range of 0.1 to 0.5 % with an average value of 0.23%. The highest values were recorded in the coarse grained samples while the lowest values were recorded in the medium and fine grained samples (Table 1). The coarse grained variety is represented by samples 1, 5, 6, 7 and 9 which have average water absorption values of 0.3, 0.4, 0.4, 0.3 and 0.5% respectively. These values are higher than those of medium and fine grained varieties (Table 1). However, sample 3 which is a fine grained variety has water absorption value of 0.4% which is similar to what is recorded for the coarse grained varieties. According to Abdullah and Singh (2010), this observation and deviation is attributed to geology as explained earlier.

Water absorption value indicates the capacity of a rock to absorb moisture when immersed in water and is directly related to porosity of the same material (Archana and Padma, 2016). Their result on the study of quartzite as aggregate for pavement construction revealed an average water absorption value of 0.17%. To them, this indicates that the porosity of the rock would be very low and therefore, should have very strong strength properties. Such rock materials prove to be of desirable quality. Also, Muhammed *et al*. (2017) also recorded an average water absorption value of 1.87% on the quartzite in Pershawar, Pakinstan. According to British Standard(BS 812) (1992) and Abel *et al*. (2014), standard specification for rock material used for construction, especially aggregates should be less than or equal to 2.5% (≤ 2.5 %). Generally, the value of water absorption of less than 2% is the permissible limit for usage. Moreover, rock materials with absorption less than 1% are more preferred (BS 812, 1992). Based on this, result of water absorption for quartzite for this study shows that they are very good materials for constructional purposes such as road stabilisers, aggregates, ornamental stones and building blocks.

Krynine and Judd (1957) reported that the strength of rock material is a reflection of the amount of water it can absorb. From their findings, they concluded that strong construction materials should have very low water absorption value, usually below 1%. According to American Society for Testing Materials (ASTM) C 127 (2015), water absorption for construction purposes stated above should be < 2.5%. This low water absorption capacity is an indication of the freshness or very low degree of weathering of the constituents minerals in the quartzite of the study area. The hardness of quartzite makes it extremely resistant to water absorption. Similar average value of ≤ 2.5% was recommended by Adom-Asamoah *et al*., 2014 for the hand-quarried partially weathered quartzite in a quarry site located near Juaso in the Ashanti Region, Ghana. Generally, it can be concluded that since porosity of the rocks in this study is very low and water absorption within limits, the quartzite can be considered to be sound and could be used for construction even in consistently water logged areas.

The specific gravity values of quartzite in this study are also presented in table 1. Generally, the specific gravity of the rock ranges narrowly from 2.7 to 2.8 with an average value of 2.75. These values do not depend on the three textural varieties of the rock seen in the field and this may be as result of quartz being the main dominant mineral in the rocks. Lambe and Whiteman (1969) observed that if a rock is dominated by quartz, its specific gravity should range between 2.62 to 2.90. The specific gravity values recorded in the quartzite in this study fall within this range. This is an indication of the dominancy of quartz in the mineral constituents of the quartzite. According to the IS 2386 – 1963, specific gravity of rocks for construction purpose should have a standard specification of not less 2.6. Quartzite samples in this study have average specific gravity of 2.75 (Table 4), hence are of good quality and can be used for construction purposes. Archana and Padma (2016) also recorded the specific gravity of 2.66 to 2.85 in rock materials as aggregate for pavement construction in the quarries of Trivandrum, India. Specific gravity is generally greatest in rocks containing magnesia, iron and heavy minerals and least in rocks rich in alkalis, silica and water. Petrographic studies reveal the presence of some opaque minerals in the samples and these must have also contributed to high specific gravity recorded in the samples. The density of the rock calculated from the product of specific gravity of the rock and density of water gives a tight range of 2.7 – 2.8 g/m^3 with an average 2.75 g/m^3. The British Standard (BS 812, 1992), an average density of 2.74g/m^3 is required specification for a rock material to be used for construction purposes. The quartzite in the study area has an average density value of 2. 75 g/m^3 and can thus be used as construction material.

Similar to the specific gravity values of the quartzite, bulk density values also vary slightly from 2.60g/cm^2 to 2.82g/cm^2 with an average value of 2.67g/cm^2. This average value is classified as very high in accordance with the International Society of Rock Mechanics (ISRM, 1979) and according to Leaman (1973) is good for construction purposes. It is also observed that the percentage of minerals harder than 5 on the Moh's scale of hardness is very high in the rocks. The durability of a constructional material is related to its bulk density such that high bulk density materials tend to have high durability. There is a direct correlation between hardness and density, consequently the very high percentage of hard minerals (quartz) in the rock explains why both the specific gravity and bulk density of the rock is quite high and thus the result is believed to be reliable. As bulk density increases, water absorption decreases in a linear manner (e.g. Archana and Padma (2016) and Gates and West, 2008). Thus there is the existence of a linear inverse relation between bulk density and water absorption of the quartzite in the study area. Rocks with lesser water absorption will thus have lesser porosity. The minerals are more tightly packed with less pore spaces in between and hence increased density (Ademeso *et al.*, 2012, 2014). As bulk density increases, toughness, hardness and crushing strength increases. A rock with a higher bulk density indicates more solid composition and greater strength. Odunyemi and Boluwaji (2014) have reported similar observation with the charnockitic rock of Akure, Southwest Nigeria. Based on these explanations, it can be concluded that the bulk density of the quartzite in the study area meet the specification for use as construction material.

Generally, the physical properties (porosity, specific gravity, water absorption and bulk density) of the quartzite indicate that it is a very good material that can be used for construction purposes such as road stabilisers, aggregates, ornamental stones and building blocks.

4.3.2 Mechanical properties

Results of the mechanical tests of the quartzite are presented in table 1. The compressive strength of the quartzite is probably the most important mechanical property. It ranges from 98 to 105 N/m^2 with an average value of 100.2 N/m^2. The highest value of 100 N/m^2 was recorded in sample 4 whereas the lowest was recorded in samples 1, 5, 6 and 10. Samples 2, 3, 4, 8 and 10 each has compressive strength value $\geq$ 100 N/m^2 while samples 1, 5, 6, 7 and 9 each has a value less than 100 N/m^2. However, there seems to be no great difference in the values recorded for all the samples. Oden *et al*. (2013) reported a range of 34. 2 – 56N/m2 and an average of 48.7 N/m2 for the dolerite of Cross River State and stated that according to Deere and Miller (1966) the material is acceptable for construction stones. Quartzite is made up mostly of quartz and this explains why its compressive strength value is higher than that of dolerite. Quartzite stands out as ridges in the study area reflecting its resistance to weathering. This observation portrays quartzite as the most competent rock and as such the least susceptible to weathering as the dominant mineral quartz controls the strength characteristics of the rock.

The tensile strength values in the rock range from 10 - 30 N/m^2 with an average of 21.1 N/m^2. Samples 2, 3, 4, 7, 8 and 10 each has a value greater than 20 N/m^2 while samples 1, 5, 6 and 9 each has a value of 10 N/m^2. The samples also have shear strength values that range from 20 to 60 N/m^2 with an average of 37 N/m^2. The values are very high in samples 4, 8 and 10 which equally have high values of compressive strength. Wouatong *et al.* (2017) recorded compressive, tensile and shear strengths of 75/m^2, 8.9N/m^2 and 33N/m^2 respectively for marble of the Bidzar Quarry in North Cameroon and concluded that the material is suitable as construction material. According to Scott and Durham, 1984, the strength specification for a material to use for construction purposes is compressive strength > 20 N/m^2, tensile strength > 5 N/m^2 and shear strength > 7 N/m^2. The quartzite in the study area meets these requirements and could thus be used for construction purposes as road stabilisers, aggregates, ornamental stones and building blocks.

Generally, there seems to be a good linear relationship among the physico-mechanical properties which is quite interesting and gives some credence to the results of the analyses.

There is a definite correlation between compressive strength and porosity, compressive strength and density, density and porosity, density and specific gravity, water absorption and porosity, and water absorption and density (Figures 11a - f).

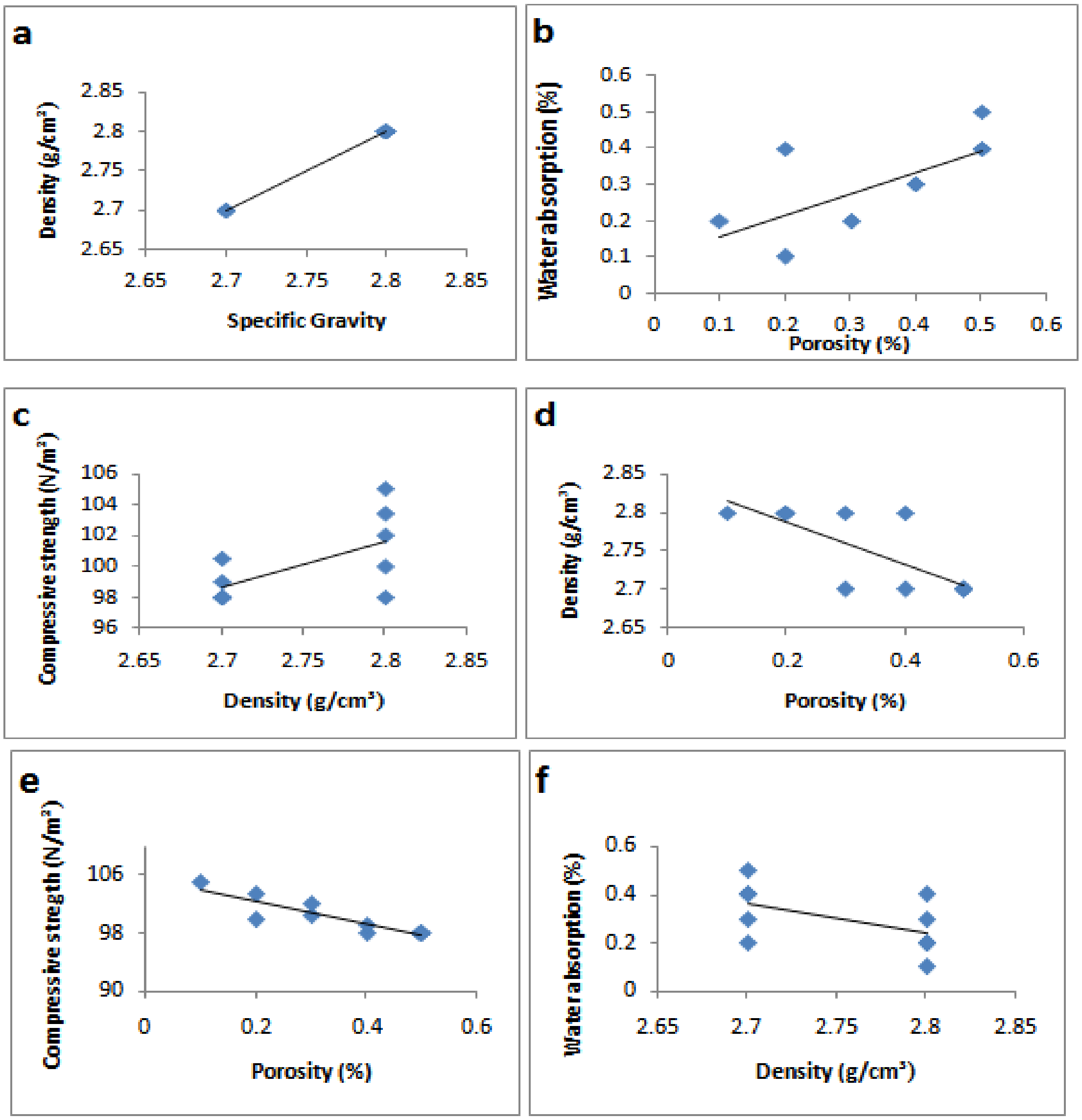

Figure 11: Scatter diagram with regression line correlating (a) density and specific gravity (b) water absorption and porosity (c) compressive strength and density (d) density and Porosity (e) compressive strength and porosity and water absorption and density for the rock in the study area. Note that a, b and c show a positive correlation while d, e and f negative correlation

There is definite positive correlation between density and specific gravity, water absorption and porosity and compressive strength and density (Figure 11a, b and c) while negative correlation exists on the other hand, between density and porosity, water absorption and density as well as compressive strength and porosity (Figures 11d, e and f) in the rock under study. These relationships according to Archana and Padma (2016) and Amad *et al.* (2016) are especially useful in cases where one property could be measure easily while it is difficult to determine the other one. This usually happens in field conditions. These relationships provide a quick and easy method to estimate the parameters which are otherwise difficult to determine.

Density is directly proportional to specific gravity and an increase in the density of a rock will eventually results in an increase in its specific gravity thus resulting in a positive linear correlation as shown in figure 11a. Also, the water absorption of a rock implies its porosity. A low water absorption implies low porosity and hence a better compressive strength. There thus exists a linear direct relation between water absorption and porosity. This means that rocks with such properties have mineral constituents that are tightly packed with less pore spaces (Figure

11b). As density increases compressive strength also increases and thus rock with a higher density will certainly indicate more solid composition and greater compressive strength (Figure 11c).

In an unlike manner, density and compressive strength are inversely proportional to porosity respectively and as they increase porosity decreases (Figure 11d and e). This implies that rocks with high density and compressive strength will have low porosity as such rocks will constitute minerals that are closely packed together with the reduction in pore spaces between the grains. This type of relation also exists between water absorption and density where increase in density results in decrease in water absorption (Figure 11f).

V. Conclusion

After the study of the petrographic and physico-mechanical characteristics of wolframite mine-waste in Zumba in north-central Nigeria, the following conclusions are made:

1. Field evidence reveals that the quartzite that hosts the wolframite that is being mined is intrusive to schist and granite of the study area.
2. Optical examination of the quartzite under the petrological microscope reveals two petrographical varieties which are fine to medium and coarse grained varieties. These two varieties show low degree of weathering and abundance of different types of minerals with quartz making more than 80%.
3. On the basis of the values of comprehensive, tensile and shear strengths, all the studied samples fall in the category of very strong rocks. Correspondingly, the values of their porosity, bulk density, specific gravity, water absorption and density are within the range permissible for their use as construction materials. Also, the presence of deleterious materials such as clay minerals and strained quartz in very small amount further makes the quartzite much more suitable as construction materials.

Acknowledgement

This article is part of the MTech thesis of the first author supervised by Dr. T. A. Ako at Federal University of Technology, Minna, Nigeria and completed within the research framework of Economic Geology on the Precambrian Mineral belt of Nigeria. We gratefully acknowledge Mr. Emmanuel, Okechukwu Princewill of Jalan 18/34, Taman Sri Serdang, 43300 Seri, Kembangan, Selangor, Malaysia, for sponsoring the various analyses in this research. We equally thank the unanimous reviewers whose comments and suggestions improved the quality of this article.

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IOSR Journal of Applied Geology and Geophysics (IOSR-JAGG) is UGC approved Journal with Sl. No. 5021, Journal no. 49115.

S. E. Ali "Lk+Petrographic and Physic-Mechanical Characteristics of Quartzite from the Wolframite Mine in Zumba, Northcentral Nigeria: Implication for Their Use as Construction Materials." IOSR Journal of Applied Geology and Geophysics (IOSR-JAGG) 6.2 (2018): 59-76