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Quality and durability of some marble deposits in the southern schist belt (Nigeria) as construction stones

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Abstract The quality and durability of some marble deposits from Nigeria as construction stones were evaluated. Results indicate that the whitish-pinkish-greyish marbles were pure to relatively pure (generally ≥85 wt% calcite) and possess geotechnical properties that appeared to be controlled largely by mineralogy and texture. While the coarse-grained variety indicated good performance as a result of favourable geotechnical properties such as relatively high values of bulk density, specific gravity, strength, and low water absorption, the fine- and medium-grained varieties would likely perform marginally due to comparatively poor geotechnical properties they possess. Caution is, however, required particularly for outdoor purposes, as weak constituents (chlorite and graphite) were present in some samples and appreciable material loss was recorded in all during laboratory experimentation. This could denote, generally, that the quality of marble stones may be progressively lowered by repeated changes of temperature and other climatic conditions, as is the case in a tropical region like Nigeria.

Keywords Construction stone · Durability · Geotechnical analysis · Marble deposit · Schist belt · Nigeria

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Introduction

The level of development of a country is easily assessed, in recent times, by the architectural designs, and quality of finished buildings, public and residential. The demand for both natural and synthetic stones and aggregates, especially for construction of buildings and other purposes, has generally been on the increase the world over (Freedonia 2009). Construction stones, also referred to as building (Boynton 1979) or cut stones, serve several purposes such as monuments, gravestones, sculptures, and tiles for walls and floors in offices, homes, industries and corporate institutions, where aesthetic and luxurious styles are uniquely valued. They could also serve as pulpits and alters in churches, cathedrals and other worship houses. Carbonate rocks, especially limestone and marble, are commonly used as construction stones in most parts of the world (Waltham 1994). Marble is, however, preferable, due to some favourable geotechnical properties, such as high strength and low porosity, it possesses (Alabi et al. 2013).

In Nigeria today, despite the high demand and abundance of limestone and marble (McCurry 1976; Folami and Ojo 1991; Emofurieta and Ekuajemi 1995; Fatoye and Gideon 2013) in most parts of the country (Fig. 1), local supplies of construction stones are still very inadequate. The main reasons for this situation include limited number of investors and operators, and unavailability or scarcity of data on the quality and durability of those carbonate rocks that have good potential as construction stones. Obaje (2009) reported that only three marble deposits (Jakura, Kwakuti and Igbetti) are exploited for local construction stone production in Nigeria. Most other deposits are mainly for production of lime for cement industries and other purposes. The general under utilization of marbles in the construction industry in Nigeria is also due to the fact that

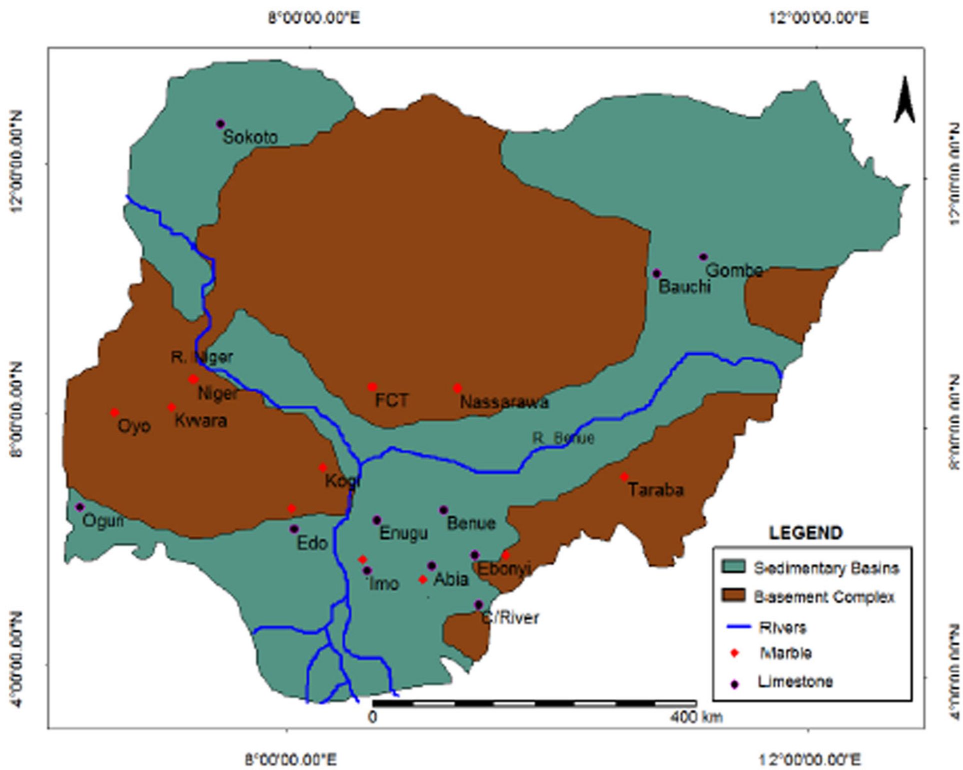

Fig. 1 Generalized geological map of Nigeria showing states with limestone and marble occurrences (after Fatoye and Gideon 2013)

granitic rocks and other types of igneous rocks, which have greater strength, quality and durability, abound.

In this study, samples from five different marble deposits, all within the area underlain by the schist belt in the Ukpilla area of Edo State (Nigeria), were subjected to standard laboratory analyses. The aim was to evaluate the potentials of the deposits as sources of construction stones. The evaluation will not only assist in highlighting the performance of deposits in some construction and building projects but will also form part of the data base that could guide current and future investors and operators interested in the business of construction stone production in Nigeria.

Review of the geotechnical properties of marbles

The usability of marbles for most construction and building purposes is largely dependent on their mineralogy and geotechnical properties. While the mineralogical characterization deals with the evaluation of mineral composition and texture of the samples, geotechnical property assessment is primarily concerned with strength and durability. Fatoye and Gideon (2013) noted that strength of marble is the measurement of its capacity to resist stresses and this depends on the presence of defects, hardness of grains, state of aggregation and degree of cohesion and interlocking of grains, among other factors.

Fatoye and Gideon (2013) noted that as aggregates, the average crushing strength of Nigerian limestone and marble varies between 55 and 186 MPa, while their average specific gravity ranges from 2.70 to 2.86. Krynine and Judd (1957) had earlier pointed out that high values of specific gravity ($\geq$2.70) are indications of stability and durability of rock materials in construction projects. Bangar (2005) defines durability of a stone as its capacity to retain its original size, strength and appearance throughout a long period.

A major concern to most users of marble in construction is the issue of its dissolubility under the influence of unfavourable climatic conditions (Sowers and Sowers 1970). Fatoye and Gideon (2013) remarked that the surface of marble crumbles readily when exposed to a moist, acid atmosphere, but marble is durable in a dry atmosphere and when protected from rain. The extent to which a rock is dissolved by an acid is a function of both mineralogy and porosity of such rock (Waltham 1994). Direct determination of porosity of rocks, especially crystalline rocks like marble, is somewhat difficult. Parasnis (1962) has, however, found out that the in situ density of subsurface rocks lies between their dry and wet densities. Hence, high density contrast of dry to wet for a rock could be a signature of high porosity. Marble has a very low porosity which ranges from 0.0002 to 0.5 % (Alabi et al. 2013). Sodium and magnesium sulphate soundness test results, however, give better understanding of the durability of construction rocks over time (Aghamelu and Okogbue 2013). Bates (1969) observed that the susceptibility to polish and resistance to weathering of marbles are mainly controlled by mineralogy and structure/texture.

Description of the study area

Location and accessibility

The marble deposits studied in this work are located within the Igarra, Ikpeshi and Ukpilla (also known as Okpella) areas, all within latitudes 7°00N and 7°30N, and longitudes 6°00E and 6°30N, of Edo State (Fig. 1). Edo is one of the states that falls within the south geographical zone of Nigeria. It has its capital at Benin City, an ancient city of the Edo people, and also the historical headquarters of the *Bini* Kingdom. The deposit areas are accessible through the Benin-Lokoja-Abuja federal highway, as well as through the Auchi-Ikpesi-Igarra highway. There is a local airport in Benin City and a good network of intra- and interstate highways that connect the capital city to the rest of the cities in the country. Southwards of Benin City, a major international seaport exists in the city of Warri, the commercial centre of a neighbouring, crude oil-rich, Delta State.

Climate and physiography

Two main climatic seasons exist in the Edo area of Nigeria, the dry and the rainy seasons. The dry season begins in October and ends in February–March. The rainy season, which may also be referred to as the 'wet season', begins in March and ends in October. While the dry season is characterized by high atmospheric temperature, general dryness and low relative humidity, the rainy season is characterized by low atmospheric temperature, high volume of rainfall, as well as high relative humidity. The two seasons are dependent on the prevailing winds blowing over the country at different times of the year; the dry harmattan wind from the Sahara and the marine wind from the Atlantic Ocean. While the harmattan wind causes the dry season, the marine wind brings about rainfall.

Temperature in the dry season ranges from about 20 °C to approximately 40 °C and during the rainy season from about 16 °C to about 30 °C. The average annual rainfall stands at about 4000 mm. The climatic and vegetation characteristics of the area are typical of that of a tropical region, but locally range from rain forest in the north of the area to swamp forest in the southern part (Inyang 1979). The climatic conditions as experienced in the tropics are commonly associated with chemical weathering or material deterioration over time (Aghamelu and Okogbue 2013). Obasi (2012) describes the landform as comprising undulating low-land separated by hillrocks which represent granites, especially in the northeast and southeast of Igarra.

Geology and occurrence of marble deposits in Nigeria

The geology of Nigeria is made up of three major geological components (Obaje 2009), namely, the Precambrian basement complex, the Jurassic younger granites, and the cretaceous to recent sedimentary basins. A generalized distribution of these geological components is presented in Fig. 1; note that the younger granites have been incorporated into the basement complex in the figure for simplicity. Obaje (2009) and Woakes et al. (1987), among other researchers, gave detailed geological maps of Nigeria. The basement complex is made up of the migmatite–gneiss complex, the schist belts, the older granites and the undeformed acid and basic dykes. Oyawoye (1964), Burke and Dewey (1972), Abaa (1983), Gandu et al. (1986), Rahaman (1976, 1988) and Dada (2006) are some of the authors that present detailed accounts on the origin, petrology, structural and descriptive features of the basement complex.

The marble deposits, which were re-crystallized from the Precambrian limestone and other fine-grained clastics and sedimentary carbonate rocks (Emofurieta and Ekuajemi 1995, Grant 1970; Gandu et al. 1986), are confined within the southern schist belts of the western half of Nigeria; west of longitude 8°E. The origin of the deposits is likely to be dynamotherrnal, according to Bates (1969), who pointed out that marble occurrence with schist and gneisses is an evidence of a dynamotherrnal history. Other rock types within the schist belt include phyllites, pelites, quartzites, amphibolites and banded iron formation (Emofurieta and Ekuajemi 1995). Alabi et al. (2013) noted that in addition to calcite and dolomite, marbles may contain various percentages of other minerals of non-silicates such as graphite, hematite, limonite and pyrite. The common silicates in marbles are mica, chlorite, tremolite, wollastonite, diopside and hornblende. According to Fatoye and Gideon (2013), the marble deposits in the schist belt are predominantly white and greyish when relatively pure. This study observed the occurrence of pinkish variety during the field work, and attributes it to hematite and other impurities.

Notable occurrences of marble in Nigeria (see Fig. 1) are the Igbeti, Elebu, and Kwakuti marble on the western part and the Uba, Ukpilla and Jakura marbles on the eastern part of the schist belts. Occurrences have also been reported from the Igarra, Ikpeshi, Ubo, Ososo, and Atte in Edo State (present study area), Idoani in Ondo State as well as Osara in Kogi State (Folami and Ojo 1991). Others include Isale-Osin, Okelute, Oro (Kwara State), Takalafia in the Fderal Capital Territory (Abuja), Toto-Muro Hill (Nasarawa State), Kankata (Kaduna State), and Itobe (Kogi State). Fatoye and Gideon (2013) estimated the marble in the schist belt to be about 150 million metric tonnes, and also pointed out that many other deposits are yet to be discovered.

Materials and methods

Sampling

A total of 15 fresh crystalline, representative, bulk samples were collected from different marble deposit quarries within the Igarra, Ososo, Ukpilla and Ikpesi areas of Edo State, Nigeria. Figure 2 shows the sample location distribution, while Table 1 presents the field characteristics and global positioning system (GPS) device readings of the marble samples. The samples are herein numbered 1–15. Most of the quarries, especially those within the Ukpilla area, are owned by the Edo Cement Company, Ukpilla, while those located elsewhere, like GeoWorks Limited, are owned by private investors and operators.

The hand specimens were generally granoblastic in texture, but could be grouped in fine-grained (<0.006 mm), medium-grained (0.006–2 mm) and coarse-grained (>2 mm) categories judging from the predominant crystal sizes. Colour of the samples ranges from whitish to greyish to pinkish-white. However, there were no observed distinct alternating layers or beds of different colours, textures or compositions in the deposits, with respect to each sample location. In other words, the deposits were uniform in structural and physical attributes per location.

Laboratory testing

The various laboratory tests and testing procedures adopted in this research are summarized in Table 2. Porosity (apparent) was obtained by an indirect method of density determination Parasnis (1962). This is done by immersing a dry sample of known mass in water for 48 h. The percentage increase in mass relative to the original mass of the sample was then determined, and the apparent porosity recorded as the difference between the wet and dry densities. Rock specimens for the compressive strength tests were cut and trimmed into circular cylinders having diameter of 80 mm and height of 160 mm approximately. Sodium sulphate soundness test was on aggregates passing through a 9.52-mm sieve and retained in a 4.76-mm sieve. In order to ensure accuracy of data and in accordance with testing guideline, the recorded value for each parameter is an average of two or more tests carried out on portions of a specimen. All the tests were carried out at the Material Laboratory of the Ministry of Works and Housing, Abakaliki, Nigeria.

Results and discussion

Petrography

The results of the petrographic (modal) analyses are summarized in Table 3. The table shows that the marble deposits are pure to relatively pure. They consist predominantly of calcite (ranging between 85 and 99 %) and dolomite (ranging between 1 and 10 %), and are mostly white in colour. Alabi et al. (2013) noted that absolutely pure marble (100 % calcite) is brilliant white. The thin section analysis supported the observed granoblastic texture of the hand specimens. It also buttressed the fact that the samples could be grouped in fine-, medium- and coarse-grained categories owing to disparity in the predominant crystal sizes from one location to another. Calcite and dolomite have good to fairly good physical properties, which include reasonable hardness (average of 3 and 3.5–4, respectively, on Moh's hardness scale) and good stability as constituents of construction rocks or aggregates.

Other minerals present, although in small to insignificant amounts in the marble samples, as shown in Table 3, include quartz, muscovite, chlorite, tremolite, wollastonite, graphite and hematite. The occurrence of these set of minerals would have some implications in the usability and durability of marbles as construction stones. For instance, occurrence of quartz in rocks could increase the strength, durability and polishing resistance of such rocks (Jaeger and Cook 1969). This may, however, not be applicable here, taking into account of the very low quartz content of the studied marbles. Muscovite usually introduces minute defects in rocks, thus could cause deterioration over time. Chlorite and graphite are considered weak materials in rocks. Their presence, even in small quantity, would ultimately bring about deterioration in rocks (Krynine and Judd 1957), and also introduce colouration in marbles; green and grey (for example, samples 4 and 7), respectively. Hematite is usually a common cause of pinkish marbles, and would likely be responsible for pink colouration of samples 2, 6, 11 and 15.

The fact that the marble deposits showed uniform texture (that is, no alternating layers or beds of different textures or composition), with respect to locations, suggests that their susceptibility to polish and resistance to weathering would be uniform. Bates (1969) observed that the occurrence of alternating beds or masses of calcite and dolomite in marbles are undesirable because the two minerals frequently differ in colour, texture, and susceptibility to polish and resistance to weathering.

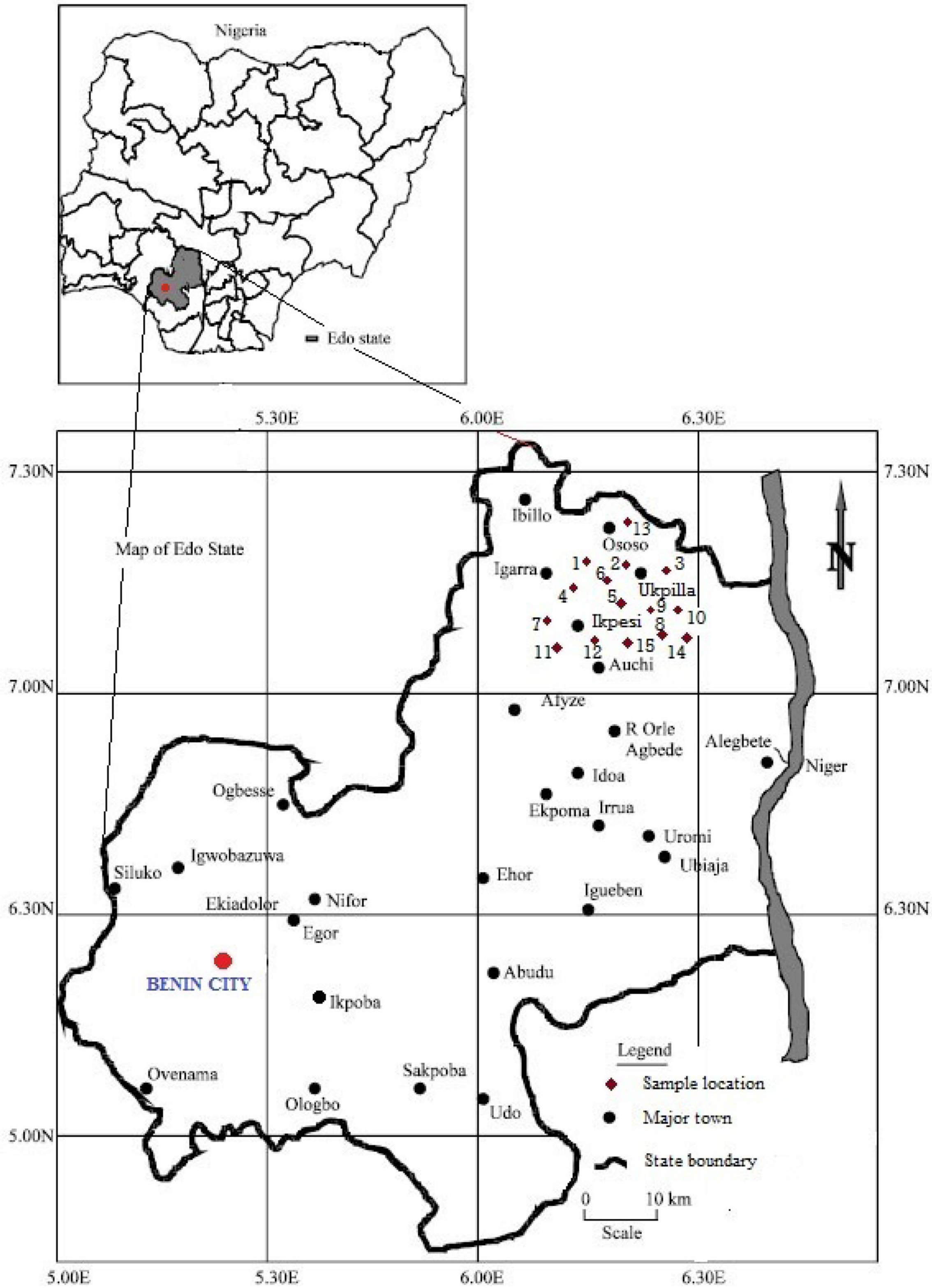

Fig. 2 Map of Edo State (Nigeria) showing sample locations

Table 1 Locations and field characteristics of samples of marble used in this study

Geological unit	Sample no.	Quarry location	Texture	Colour	GPS reading	
					Northing	Easting
Precambrian schist belt	1	Ososo	Coarse-grained	White	7.17N	6.15E
	2	Ososo	Medium-grained	Pinkish	7.16N	6.22E
	3	Ukpilla	Coarse-grained	Greyish-white	7.15N	6.26E
	4	Igarra	Fine-grained	Grey	7.13N	6.13E
	5	Ikpeshi	Fine-grained	White	7.12N	6.20E
	6	Ososo	Coarse-grained	Pinkish-white	7.14N	6.18E
	7	Igarra	Fine-grained	Grey	7.10N	6.09E
	8	Ikpeshi	Coarse-grained	White	7.07N	6.25E
	9	Ukpilla	Coarse-grained	Pinkish-white	7.11N	6.23E
	10	Ukpilla	Coarse-grained	White	7.11N	6.28E
	11	Ikpeshi	Fine-grained	Pinkish-white	7.06N	6.10E
	12	Ikpeshi	Coarse-grained	White	7.09N	6.17E
	13	Ososo	Medium-grained	White	7.23N	6.21E
	14	Ikpeshi	Fine-grained	White	7.06N	6.29E
	15	Ikpeshi	Fine-grained	Pinkish-white	7.08N	6.23E

Table 2 Testing procedures adopted in this study

Parameter	Nature of sample	Unit	Test standard
Modal analysis	Thin section	–	Point counting (Chayes 1956)
Geochemical analysis	Powder	wt%	Semi-automatic x-ray fluorescence
Porosity	Crushed	%	Indirect method (Parasnis 1962)
Water absorption	Crushed	%	ASTM[a] C127 (1988)
Bulk density	Crushed	kN/m^3	ASTM[a] C29/C29M (1990a)
Specific gravity	Crushed	–	ASTM[a] C127 (1988)
Schmidt hammer rebound	Lump	%	ISRM[b] (1978, 1981a)
Uniaxial compressive strength	Cylindrical	MPa	ISRM[b] (1972)
Sodium sulphate soundness	Crushed	%	ASTM[a] C88 (1990b)

[a] American Society for Testing and Materials

[b] International Society for Rock Mechanics

Table 3 Results of modal (petrography) analysis for the studied marble deposits

Mineral (wt%)	Sample no.															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Mean
Calcite	87	90	95	85	94	87	90	98	96	99	89	93	92	97	89	92
Dolomite	10	2	1	3	2	6	7	–	2	–	3	4	3	–	2	3
Quartz	2	1	2	–	–	2	–	1	–	1	3	–	2	3	2	2
Muscovite	–	–	–	2	2	2	–	1	1	–	–	2	1	–	–	2
Chlorite	–	–	1	1	–	–	–	–	–	–	–	–	1	–	–	–
Tremolite	–	–	1	3	–	1	–	–	1	–	–	–	–	–	1	1
Wollastonite	–	–	–	2	2	–	–	–	–	–	1	1	1	–	3	–
Graphite	1	–	–	4	–	–	3	–	–	–	–	–	–	–	–	–
Hematite	–	7	–	–	–	3	–	–	–	–	4	–	–	–	3	–

Major oxides

The results of the geochemical analysis on major oxides of the marble samples are summarized in Table 4. The results affirm the predominance of carbonate minerals in the marble deposits. It is interesting to note that white variety recorded CaO (≥51.30 wt%) at amounts relatively higher than amounts recorded in the greyish (≤47.70 wt%) and pinkish (≤46.33 wt%) varieties. MgO and Fe_2O_3 are shown, in Table 4, to be appreciable only in those samples that contained significant amounts of dolomite and hematite, respectively. SiO_2 is generally low in all the tested marble samples, reflecting a general low content of silicates.

Sowers and Sowers (1970) attribute specific gravity values in rock to elemental contents, especially Fe and Mg. In view of this, only samples 2, 3, 4, 6, 7, 11, 13 and 15 with appreciable MgO and Fe_2O_3 are likely to have high specific gravity values. Presence of secondary carbonates and volatiles in the marble samples can be inferred from the appreciable values of loss on ignition (LOI; 31.17–44.79 wt%) recorded. LOI, according to Sayat and Gonconglu (2009), is an indication of some degree of alteration and of the presence of secondary volatile and carbonate phases. Petrographical analysis on the marble samples in this study had revealed presence of tremolite, muscovite and chlorite which have volatile (hydroxide, OH) components.

Porosity

The results of the indirect apparent porosity tests on the marble samples are summarized in Table 5. All the tested samples have their apparent porosity values fall below 0.50 %, and are likely to have resulted from cracks rather than from pores. Theoretically, apparent porosity in most porous (sedimentary or weathered) rocks is the total amount of interconnected pores or pores available for water absorption. Alabi et al. (2013) had earlier noted that marbles due to their tight interlocking crystalline fabric have very low porosity that ranges from 0.0002 to 0.5 %. It can be seen in Table 5 that no established trend is possible with respect to the porosity values of the tested marble deposits, despite slight variations in mineralogy and textures of the tested samples. This may buttress the fact that re-crystallization that occurred during the metamorphism of the carbonate rocks brought about a general and remarkable decrease in the porosity of the transformed rocks.

However, it is interesting to note that marble samples (samples 3, 4 and 13) that contained chlorite recorded porosity values (≥0.22 %) that are significantly higher than the rest (≤0.13 %). Chlorite is considered an impurity in marble, and may have introduced interstitial defects in the samples in question. Chlorite is a magnesium compound, and it occurs in samples 3 and 4 alongside other magnesium compounds like dolomite and tremolite. Among the tested marble samples, the purest (sample 10), with 99 % calcite, recorded the lowest porosity value of 0.01 %.

Dearman (1981) deduced from his studies that microporosity is a better indicator of carbonate rocks resistance to weathering than strength. Since porosity generally controls flow, it may well be right to assume that samples 3, 4 and 13 are most prone to dissolubility and acid attacks, thus reduces the strength and suitability of these samples as construction stones, especially when used outdoors. From the same point of view, samples 5, 6, 9 and 15 with the lowest porosity values should comparatively be the least in terms of susceptibility to dissolution and acid attacks, particularly when all the samples are exposed to the same climatic conditions.

Water absorption

The results of the water absorption analysis are presented in Table 5. Water absorption has been noted as an excellent

Table 4 Results of major oxides (wt%) analysis for the studied marble deposits

Oxide (wt%)	Sample no.														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Mean
SiO_2	0.42	0.29	3.51	2.03	2.32	2.20	2.53	3.41	3.24	2.45	2.36	4.31	4.40	2.20	3.42	2.61
$Fe_2O_3^a$	–	7.16	2.46	1.34	–	2.92	2.87	–	–	–	6.82	–	2.01	–	5.46	2.06
MgO	5.86	1.43	3.83	3.98	1.84	5.10	4.85	4.16	3.10	1.03	3.10	2.89	3.12	1.25	1.83	3.16
CaO	51.30	46.33	55.21	48.20	56.02	49.08	47.70	54.07	57.23	55.49	54.62	55.81	54.53	52.42	58.15	53.08
Al_2O_3	–	–	0.44	0.38	0.47	0.42	–	0.16	0.32	–	0.45	0.51	0.49	–	0.35	0.27
K_2O	–	–	–	0.23	2.61	4.05	–	3.42	4.94	–	–	4.63	3.24	–	–	1.54
LOI[b]	4 2.42	44.79	34.55	43.84	36.74	35.23	40.05	34.78	31.17	41.03	32.65	31.85	32.07	44.13	31.44	37.12

– Below detection

[a] Total Fe

[b] Loss on ignition

Table 5 Results of index property tests on the studied marble deposits

Sample no.	Parameter			
	Apparent porosity (%)	Water absorption (%)	Bulk density (Mg/m^3)	Specific gravity[a]
1	0.03	0.64	2.38	2.68
2	0.02	0.33	2.62	2.70
3	0.22	0.68	2.63	2.74
4	0.35	0.73	2.67	2.85
5	0.05	0.40	2.58	2.69
6	0.02	0.43	2.56	2.73
7	0.05	0.70	2.52	2.87
8	0.09	0.41	2.46	2.73
9	0.02	0.42	2.47	2.71
10	0.01	0.21	2.54	2.72
11	0.13	0.63	2.71	2.70
12	0.03	0.61	2.75	2.78
13	0.45	0.85	2.62	2.74
14	0.03	0.65	2.51	2.73
15	0.02	0.43	2.35	2.76

[a] Measured as apparent specific gravity

indicator of strength of rocks (1957). Jaeger and Cook (1969) listed texture and presence of weak materials among the factors that control porosity in rocks. No definite similarity in data trends appear to exist between the water absorption and texture of the marble samples. It may, therefore, be incorrect to predict, unlike in other rock types such as granite and gabbro, that coarseness, especially for the studied marble deposits, would introduce appreciable minute (crystal to crystal) contacts and cleavages through which water inflow is initiated. On a general note, however, the smaller the grain or particle size the greater the surface area exposure for chemical weathering (Bangar 2005).

A statistical data correlation of water absorption and apparent porosity of the studied marble samples is presented in Fig. 3. As can be seen in the figure, a reasonable positive correlation exists between the two parameters (that is, water absorption and apparent porosity). To buttress this correlation trend further, sample 10 with the lowest apparent porosity also recorded the lowest water absorption, while the highest water absorption was recorded in sample 13 with the lowest porosity. The porosity and water absorption results could suggest that deterioration is to be expected, especially in sample 13, as inflow of water (particularly, acidic water) into the material through the available pores would result in development of secondary porosity in the marble, and as well, cause further decomposition of the weak constituents like chlorite.

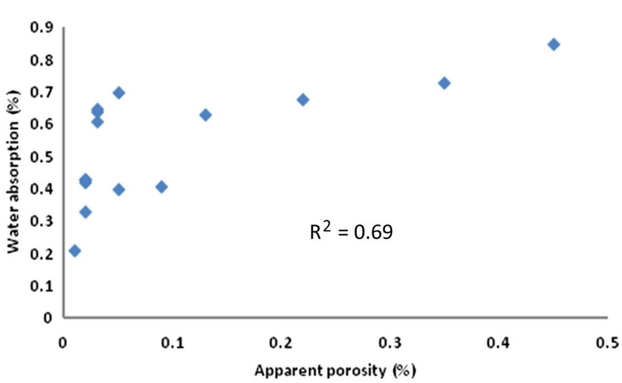

Fig. 3 Plot of water absorption against apparent porosity

Bulk density and specific gravity

The results of bulk density (BD) tests are presented in Table 5. BD reflects the total density of material (including the void contents). The lowest bulk density value (2.35 Mg/m^3) was for sample 15, while the highest value (2.75 Mg/m^3) was for sample 12. Krynine and Judd (1957) had identified high amount of voids, high moisture content and presence of weak or low-density minerals (especially feldspars and clay minerals) as some of the factors that could result in low BD values in rocks. Thus, presence of voids and appreciable moisture are likely to be the cause of low bulk density in sample 15. According to Sowers and Sowers (1970), voids in crystalline rocks could result from grain sizes/textural arrangement, structural features or defects and degree of weathering. This would suggest caution during the excavation, transportation and handling of the marble deposits as these activities could easily result in rock mass distortion or structural defects, thus lowering their quality as construction stones.

As shown in Table 5, the specific gravity (SG) of the marble samples is between 2.63 and 2.79. This could be a confirmation of the predominance of calcite in the marble deposits. The average SG of calcite is 2.71 and that of dolomite is 2.84. Jaeger and Cook (1969) had reported that SG is a reflection of the amount of heavy elements (especially Fe and Mg) present in a rock. Okogbue and Aghamelu (2013) got a perfect correlation when they plotted the sum of Fe and Mg in the Abakaliki pyroclastics against the SG of rocks. Eze (1997) also noted high specific gravity on charnockites from Nigeria and attributed that to the relatively high contents of iron-rich minerals. A comparison of data in Tables 4 and 5 indicates that samples 4 and 7, with the highest amounts of Fe plus Mg, also recorded the highest amount of SG, 2.85 and 2.87, respectively. This buttresses a relationship between heavy elements and specific gravity. Although SG does not serve as a direct means of determining potentially durable rocks, most authors, for example Krynine and Judd (1957) and Reidenouer (1970), suppose that SG of about 2.65 and above usually denotes stability and durability of rocks for most construction purposes.

Schmidt hammer rebound

The results of the Schmidt hammer rebound tests on the marble samples are presented in Table 6. Earlier researchers, Roberts (1977) and Franklin and Dusseault (1989), showed that the rebound number (*R*) depends upon the rock's elastic properties. It has also been suggested that the degree of surface irregularity, impact on surface, moisture content, inhomogeneities in the rock fabric, size and orientation of the test surface and degree of weathering of the test surface could influence *R* values of rocks (Krynine and Judd 1957; Eze 1997; Waltham 1994). Despite the influence of these factors on *R*, Roberts (1977) and Franklin and Dusseault (1989) observed that hard rocks, including igneous rocks, would generally record a high *R* that may be up to 60 %. The studied marble samples may likely not be among those rocks for which moisture content influences their *R*. Figure 4 reveals that there is no correlation between *R* and water absorption.

The tested marble samples all have an *R* above 63, despite their textural variation. The high *R* (higher than an average igneous rock) recorded in all the samples, fine-, medium- and coarse-grained samples alike, could be attributable to high degree of crystallinity, achieved during metamorphism of the carbonate rocks. It may also be due to the predominance of a fairly hard and physical stable mineral, calcite. Higher values of *R* in the marble samples may translate to low suitability as construction stones, as *R* commonly infers hardness of rocks; excessive hardness would likely mean high resistance to polishing.

Table 6 Results of strength and soundness (25 cycles) tests on the samples of the studied marble deposits

Sample no.	Parameter		
	Schmidt hammer (%)	UCS (MPa)	Na_2SO_4 soundness rebound number (%)
1	63	238	6
2	66	105	8
3	64	210	6
4	74	157	9
5	73	182	9
6	68	201	6
7	75	196	8
8	71	218	6
9	67	106	7
10	72	220	3
11	69	101	8
12	70	212	6
13	68	107	6
14	73	103	4
15	69	104	7

UCS unconfined compressive strength

Unconfined compressive strength

As shown in Table 6, the unconfined compressive strength (UCS) values of the tested samples range from 101 to 238 MPa. Eze (1997) had noted that a sound rock (devoid of fissures and defects) should have UCS close to or above 200 MPa for it to be considered a good source for most civil engineering works. The International Society for Rock Mechanics (ISRM 1981a) has rated intact marble, alongside limestone, sandstone and schist, as 'strong' on the basis of field estimates and UCS that ranged from 50 to 100 MPa.

All the tested marble samples, including those with UCS below 200 MPa, are likely to be favourable as construction stones. This stems from the fact that the recorded UCS values are well above 50 MPa, given as the lower limit for a good construction stone by Waltham (1994). They would equally serve well as cladding stone having recorded their UCS above 100 MPa (Waltham 1994). Carthage marble from Tunisia, with UCS of 52 MPa (Bredthauer 1957), and Wombeyan marble, from the UK with UCS 68 MPa (Jaeger 1960), had both served as construction stones. However, judging from Eze's (1973) point of view, samples 1, 3, 6, 8, 10 and 12 (with UCS above 200 MPa and rated as 'very high strength' rocks in Table 7) would likely perform better than the rest of the samples. This is especially where, as construction stones, they would be exposed to compressive stresses.

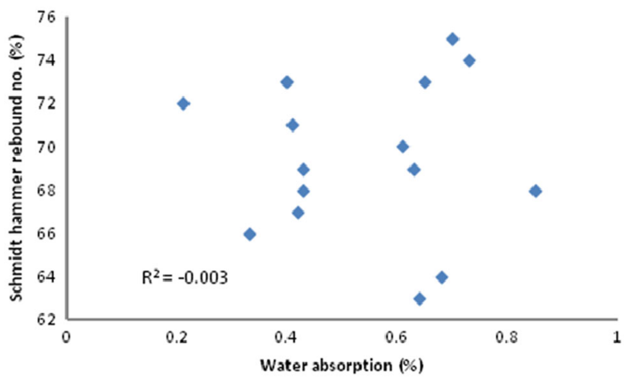

Fig. 4 Plot of Schmidt hammer rebound against water absorption

There is a general view that fine-grained rocks are usually stronger than the coarse-grained, especially for fresh igneous rock samples. With respect to the studied marble samples, a situation that is different from this general view was observed. All the samples with UCS above 200 MPa are coarse-grained, while those with UCS below 200 MPa are fine-grained. One of the possible explanations to this seemingly unique situation is that there were some differences in the intensity of tectonisation on the pre-existing carbonate rocks in the area. Thus, the most tectonically affected carbonate rocks formed marbles with coarser grains and higher strength. It is also possible that calcite may have special properties in which its coarse-grained particle impacts higher strength in fresh marble samples than its fine-grained particle.

There is no correlation between UCS and water absorption of the tested samples (see Fig. 5), thus supporting the fact that the marbles could have some unique engineering properties. Figure 6 shows that the correlation coefficient (R^2) of UCS against Schmidt hammer rebound number is very negligible. Thus, no meaningful statistical relationship exists between these two strength related parameters. Their testing procedures differ significantly and this might be responsible for the observed non-correlation of data.

Sodium sulphate soundness

The results of sodium sulphate soundness tests indicate that the studied samples have sodium soundness values that range between 4 and 9 %. Soundness testing is aimed at simulating extreme weathering conditions that rocks, such as carbonate rocks (1981), are likely to encounter under severe climatic setting, while the soundness value generally indicates the mass that would be lost in such severe climatic setting. Soundness testing assisted in indentify non-durable rocks (Aghamelu and Okogbue 2013). The American Society for Testing and Materials (ASTM C 88 1990b) points out that the soundness value is a measure of percentage of unsound constituents of an aggregate. A durability class scheme, for some Australian sandstones, developed by Spry (1989) is given in Table 8. In his work, he rated sandstone aggregates with soundness values between 0 and 1 % as most durable (Class A) and those with soundness values between 10 and 100 % as least durable (Class D). In between A and D, are classes B and C, that translate to durable and less durable, respectively.

Following Spry's (1989) durability rating, the marble deposits fall within classes B and C. This could mean that only two samples (8 and 10), which are among the purest samples and rated as B, would survive chemical attacks over a long period of time; significant mass loss started after 10 cycles (see Fig. 7). On the other hand, the durability of the rest of the 13 samples, that rated as C, would depend on the usage and exposure of the samples. Worth noting is the fact the fine-grained variety recorded soundness values that are higher than those recorded in the coarse- and medium-grained varieties. Probable explanation for this is that the smaller the particle sizes had brought out greater surface area exposure for chemical weathering (Bangar 2005), thus, more mass loss and deterioration when subjected to alternate drying and wetting condition as occurs in the tropics. Minty (1965) reported that the percentage breakdown of rocks during the sodium sulphate soundness test is inversely proportional to particle size.

Table 7 Strength classification of rock based on unconfined compressive strength (UCS)

Description	UCS[a] (MPa)	Studied marble deposits[b]	Remarks
Very low	<6	–	No sample
Low	6–20	–	No sample
Moderate	20–60	–	No sample
High	60–200	2, 4, 5, 7, 9, 11, 13, 14 and 15	9 Samples
Very high	>200	1, 3, 6, 8, 10 and 12	6 Sample

[a] Data from ISRM (1981b)

[b] This study

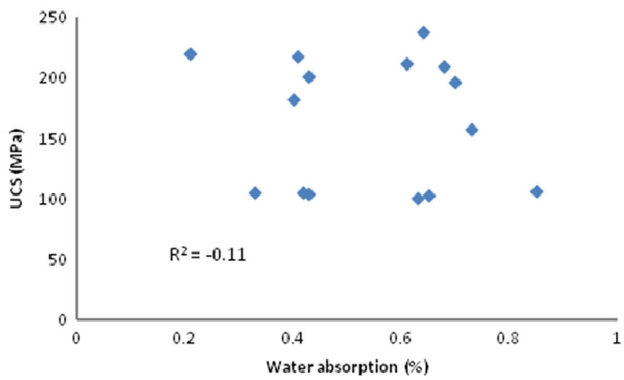

Fig. 5 Plot of unconfined compressive strength (UCS) against water absorption

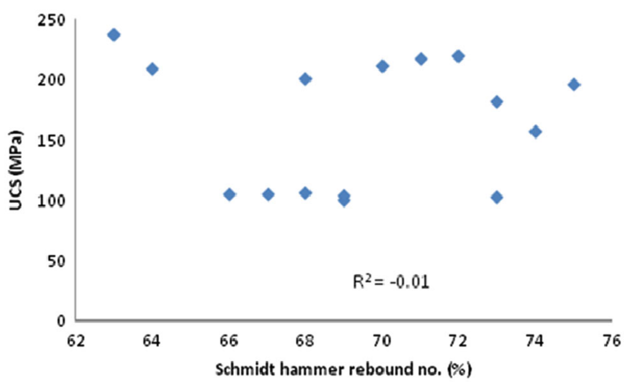

Fig. 6 Plot of unconfined compressive strength (UCS) against Schmidt hammer rebound number

Quality and durability of the marble deposits as construction stones

For indoor uses

The indoor uses of marbles include sculptures, tiles for walls and floors, as well as for pulpits and alters. For most of these purposes, bright and uniform colouration, adequate polishing quality and strength are required. Study suggests that the marble deposits fairly well meet these criteria, and are likely to perform well as indoor construction stones. Contact with acids should, however, be minimal as study indicates that they could deteriorate after long exposure to acidic environments. A coarse variety should be the primary target owing to their possessing better hardness and strength than the fine- and medium-grained varieties. Presence of defects could negatively affect the mass properties of these marble deposits, hence, caution must be applied in all stages of excavation and processing of the deposits.

For outdoors uses

Outdoors, marbles can serve as monuments, gravestones, sculptures, and platform for inscriptions. The two major factors that influence the utilization of marbles outdoors are rock mass defects and dissolubility. Both factors are dependent on the presence or absence of micro or macro-structures and mineralogy. Study indicates that the marble deposits sufficiently lacked macro and micro-structures owing to a high degree of re-crystallization. The lack of macro- and micro-structures is further buttressed by low porosity and water absorption recorded in the samples. The results of sodium sulphate soundness tests, however, reveal that the marble deposits are prone to deterioration after a long period of exposure; although the coarse-grained variety show better durability signs than fine- and medium-grained varieties. Carbonate rocks are generally soluble in the presence of strong acids, hence, coating technology may be applied to enhance the performance and durability of the marble deposits outdoors, especially those that have occurrences of weak materials like chlorite and graphite.

Conclusions

Qualitative and durability analyses on some samples of marble from Nigeria revealed that the pure to relatively pure marble deposits, especially the coarse-grained variety, would likely serve well for most construction stone purposes. The reason for this good rating was mainly due to the fact that the tested coarse-grained samples, on average, possessed favourable physical and geotechnical properties such as relatively high values of bulk density, specific gravity, Schmidt hammer rebound number and unconfined compressive strength, as well as showed low porosity and water absorption.

Table 8 Durability classification of rock aggregates based on sodium sulphate soundness (adapted from Spry 1989)

Material class	Mass loss (%)	Durability rating	Marble sample	Remarks
A	0–1	Most durable	–	No sample
B	1–5	Durable	8 and 10	2 Samples
C	5–10	Less durable	1, 2, 3, 4, 5, 6, 7, 9, 11, 12, 13, 14 and 15	13 Samples
D	10–100	Least durable	–	No samples

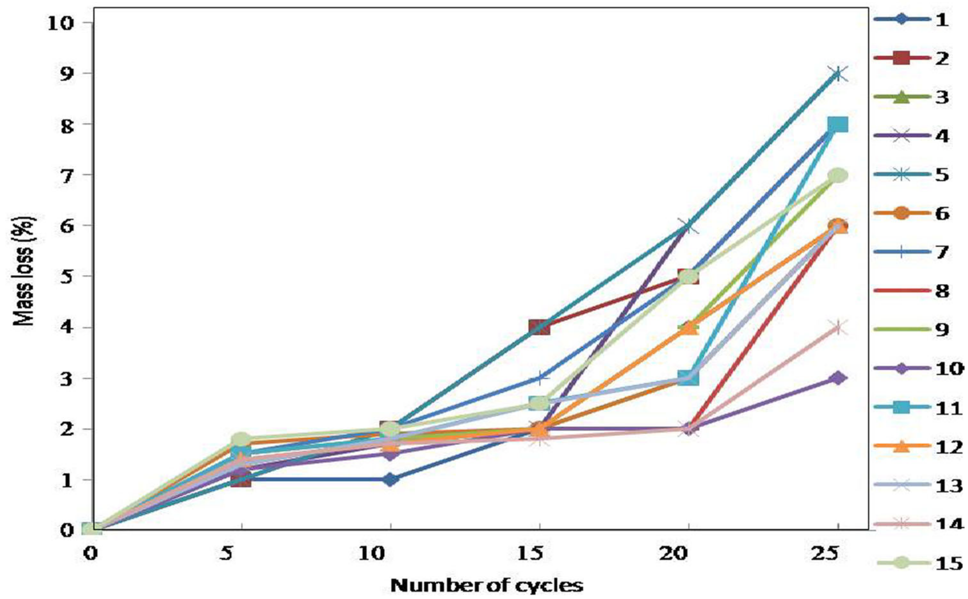

Fig. 7 Plot of soundness value (percent mass loss) against number of cycles (1–15 are sample numbers)

Probable explanation for this situation could be that the predominance of reasonably hard and stable minerals (calcite and dolomite), original sedimentological characters inherent in the carbonate rocks and a very high degree of re-crystallization that is associated with regional metamorphism, have most impact on the coarse-grained variety than the rest. As for the fine- and medium-grained varieties, their physical and geotechnical behaviours are somewhat inappropriate, hence, they would likely perform in a lesser manner than the coarse-grained samples.

The use of the marble deposits, especially for outdoor construction purposes, would require caution. Weak constituents (chlorite and graphite) and appreciable percent loss in material size were recorded in all the samples during the Na_2SO_4 soundness testing. These could point to deterioration in service or progressive durability lowering over time, especially when the marbles are exposed to acidic environments, as is the case in most industrialized cities in Nigeria, or repeated changes in temperature. Coating technology would help to enhance the effectiveness, service, and durability of the studied Nigerian marble deposits.

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References

Abaa SI (1983) The structure and petrography of alkaline rocks of the Mada Younger Granite Complex, Nigeria. J Afr Earth Sci 3:107–113

Aghamelu OP, Okogbue CO (2013) Some geological considerations and durability analysis on the use of crushed pyroclastics from Abakaliki (southeastern Nigeria) as concrete aggregate. Geotech Geol Eng 31:699–711. doi:10.1007/s10706-013-9619-5

Alabi AB, Olatunji S, Babalola AO, Nwankwo LI, Johnson LM, Odutayo JO (2013) Structural and qualitative analysis of solid minerals (marble) in selected locations in Nigeria. Niger J Phys 24:68–76

American Society for Testing and Materials (ASTM) (1988) Test for specific gravity and absorption of coarse aggregate. ASTM Designation C-127, American Society for Testing and Materials, Philadelphia

American Society for Testing and Materials (ASTM) (1990a) Test method for bulk density (unit weight) and voids in aggregate. ASTM Designation C29/C29M, American Society for Testing and Materials, Philadelphia

American Society for Testing and Materials (ASTM) (1990b) Test for soundness of aggregate by use of sodium or magnesium sulphate. ASTM Designation C-88, American Society for Testing and Materials, Philadelphia

Bangar KM (2005) Principles of engineering geology. Standard Publishers, Delhi

Bates RL (1969) Geology of the industrial rocks and minerals. Dover Publications, New York

Boynton RS (1979) Chemistry and technology of lime and limestone. Wiley, New York

Bredthauer RO (1957) Strength characteristics of rock samples under hydrostatic pressure. Trans Am Soc Mech Eng 79:695–708

Burke KC, Dewey JF (1972) Orogeny in Africa. In: Dessauvagie TFJ, Whiteman AJ (eds) African geology. Ibadan University Press, Ibadan

Chayes F (1956) Petrographic modal analysis: an elementary statistical appraisal. Wiley, New York

Dada SS (2006) Proterozoic evolution of Nigeria. In: Oshi O (ed) The basement complex of Nigeria and its mineral resources (a tribute to Prof MAO Rahaman). Akin Jinad & Co., Ibadan, pp 29–44

Dearman WR (1981) Geological problems of constructing on on soluble rocks. Bull Int Assoc Eng Geol 24:3–17

Emofurieta WO, Ekuajemi VO (1995) Lime products and economic aspects of Igbeti, Ososo and Jakura marble deposits in southwest Nigeria. J Miner Geol 31:89–97

Eze EO (1997) Geotechnical assessment of some charnockites from Nigeria as construction materials. Quart J Eng Geol 30:231–236
Fatoye FB, Gideon YB (2013) Geology and occurrences of limestone and marble in Nigeria. J Nat Sci. Res 3:60–65
Folami SL, Ojo JS (1991) Gravity and magnetic investigations over marble deposit in the Igarra area. Bendel State. J. Miner Geol 27:49–54
Franklin JA, Dusseault MB (1989) Rock engineering. McGraw-Hill, New York
Freedonia (2009) World construction aggregates: industry study with forecasts for 2013 and 2018. The Freedonia Group Inc, Cleveland, p 322 **(Study No 2564)**
Gandu AH, Ojo SB, Ajakaiye DE (1986) A gravity study of the Precambrian rocks in the Malumfashi area of Kaduna State, Nigeria. Tectonophys 126:181–194
Grant NK (1970) Geochronology of Precambrian basement rocks from Ibadan, south-western Nigeria. Earth Planet Sci Lett 10:19–38
International Society for Rock Mechanics (ISRM) (1972) Suggested methods for determining the compressive strength and compressibility of rocks. Int J Rock Mech Miner Sci Geomech Abstr 16:135–140
International Society for Rock Mechanics (ISRM) (1978) Suggested methods for determining the hardness and abrasiveness of rocks. Int J Rock Mech Miner Sci Geomech Abstr 15:89–98
International Society for Rock Mechanics (ISRM) (1981a) Suggested methods for rock characterisation, testing and monitoring. In: Brown ET (ed) rock characterisation, testing and monitoring. Pergamon Press, Oxford, p 211
International Society for Rock Mechanics (ISRM) (1981b) Basic geotechnical description of rocks masses. Commission for Standardisation of Laboratory and Field Tests. Int J Rock Mech Miner Sci Geomech Abstr 22(2):51–60
Inyang PEB (1979) Climatic regions. In: Ofomata GCE (ed) Nigeria in maps: eastern state. Ethiope Publishing House, Benin, pp 27–29
Jaeger JC (1960) Rock failures at low confining pressures. Engineering 189:283–284
Jaeger JC, Cook NGW (1969) Fundamentals of rock mechanics, Science Paper Back edn. Chapman and Hall, London
Krynine DP, Judd WR (1957) Principles of engineering geology and geotechnics. McGraw-Hill, New York
McCurry P (1976) The geology of the Precambrian to lower Paleozoic rocks of northern Nigeria. In: Kogbe CA (ed) The geology of Nigeria. Elizabeth Publishing Co., Lagos, pp 15–39
Minty EJ (1965) Preliminary report on an investigation into the influence of several factors on the sodium sulphate soundness test for aggregates. Aust Road Res 24:49–52
Obaje NG (2009) Geology and mineral resources of Nigeria: lecture notes in earth sciences, vol 120. Springer, Berlin
Obasi RA (2012) Geochemistry and appraisal of the economic potentials of calc-gneiss and marble from Igarra, Edo State, southwestern Nigeria. ARPN J Sci Tech 2:1018–1021
Okogbue CO, Aghamelu OP (2013) Performance of pyroclastic rocks from Abakaliki metropolis (southeastern Nigeria) in road construction projects. Bull Eng Geol Environ 72:433–446. doi:10.1007/s10064-013-0489-0
Oyawoye MO (1964) Geology of the Nigerian basement complex. J Miner Geol 1:87–102
Parasnis DS (1962) Principle of applied geophysics. Chapman and Hall, London
Rahaman MA (1976) Review of the basement geology of southwestern Nigeria. In: Kogbe CA (ed) Geology of Nigeria, 2nd edn. Elizabethan Publishers, Lagos
Rahaman MA (1988) Review of the basement geology of southwestern Nigeria. In: Kogbe CA (ed) Geology of Nigeria. Rockview Publishers, Jos, pp 39–56
Reidenouer DR (1970) Shale suitability: phase II, Pennsylvania Department of Transportation, Bureau of Materials, Testing and Research. Interim Report, No. 1
Roberts A (1977) Geotechnology: an introduction text for students and engineers. Pergamon Press, Oxford
Sayat K, Gonconglu MC (2009) Geochemistry of mafic rocks of the Karakaya Complex, Turkey; evidence for plume-involvement in the Palaeotethyan extensional regime during the middle and late Triassic. Int J Earth Sci 98:367–385
Sowers GB, Sowers GF (1970) Introductory soil mechanics and foundations. Macmillan, New York
Spry AH (1989) Stone testing-general. In: Gere AS, Perry JC, Spry AH, West AG (eds) Stone in modern buildings: the state of the art. Seminar notes, Sydney
Waltham T (1994) Foundations of engineering geology, 2nd edn. Spon Press, London
Woakes M, Rahaman MA, Ajibade AC (1987) Some metallogenetic features of the Nigerian basement. J Afr Earth Sci 6:54–64