Durability of some pelitic rocks as construction aggregates in South-Eastern Nigeria: effects of petrogenesis and density

Ugwoke, Tochukwu A.S.
Department of Geology, Michael Okpara University of Agriculture, Umudike, Nigeria
E-mail: tcugwoke@yahoo.com; Phone: +2348035138381
Okogbue, Celestine O.
Department of Geology, University of Nigeria, Nsukka, Nigeria

Abstract

Ten rock samples collected from five quarry units were studied megascopically and by use of X-RD to determine their petrography. The samples were subjected to short soaking/partial drying and long soaking/complete drying degradability tests to simulate their resistance to intra-seasonal and inter-seasonal weathering common in south-eastern Nigeria. The samples were further subjected to density tests to determine the variations of densities among the rocks. Petrographic studies revealed that the rock samples are of varying petrogenesis namely: hydrothermally altered pelites, volcanic bomb, pelitic hornfels, pelitic argillites and pyroclastics. Results of the degradability tests revealed that all the pelitic argillites showed significant deterioration (≥1%) in both degradability versions while the hydrothermally altered pelites, containing sizeable amount of soluble minerals, showed significant deterioration (≥1%) in version B test. The density tests results reveal that the difference between matrix and bulk density is low (0.01gcm^{-3}) for pyroclastic and volcanic bomb; moderate (0.04-0.07gcm^{-3}) for pelitic hornfels and hydrothermally altered pelites and high (0.09-0.12gcm^{-3}) for pelitic argillites. This work showed that durability of rocks is not only controlled by mineralogy and texture but also by petrogenesis of rock.

Keywords: Petrogenesis, Degradability test, Matrix density, Bulk density, Significant deterioration

1. Introduction:

Durability is the resistance of rock to weathering (deterioration) caused by agents like water, fluctuating temperature, organism or chemical substance. Works by Cobanoglu et al (2003) and Benavente (2011) revealed that rock wetting (water absorptivity of rock), which also enhances the effect of other weathering agents like chemical substance, is mostly controlled by the effective porosity, density and mineralogy of the rock. The effective porosity of the rock is actually controlled by the rock texture (grain sizes and type of grain cementation). For example, Koch et al (2008) and Garci-del-Cura et al (2011) discovered that loosely compacted calcite sparitic coarse-grained rocks have higher effective porosity and water absorptivity and thus are more prone to deterioration than highly compacted micritic fine-grained rocks. According to Tarhan (1989) and Siegesmund and Durrest (2011), rock density is of two types namely bulk density and matrix density and is controlled by rock porosity and mineralogy respectively. According to the authors, rocks of high porosity have low bulk density while rocks composed mainly of dense minerals will have high matrix density and vice versa. Works by Strohmeyer (2003) and Hoffmann and Siegesmund (2007) further revealed that matrix density is always higher than bulk density and the difference between them (matrix and bulk density) is generally least for igneous rocks and highest for sedimentary rocks, which are both related to the petrogenesis (origin) of the rock in question.

On aspects of mineralogy, Hudec (1980) and Christaras (1991) discovered that the abundance of water-absorbent/soluble minerals like clay-minerals and zeolites in a rock exposed to repeated wetting and drying, reduces the durability of the rock. This is firstly due to dissolution of such minerals by moisture and secondly due to high isothermal expansion and contraction of the minerals upon wetting and drying respectively. In other words, rocks rich in water-absorbent/soluble minerals are not suitable for making structures like embankment and facades that are exposed to wetting and drying in regions (like south-eastern Nigeria) characterized by wet and dry seasons. Works by Buck and Mather (1984) and Cbatterji (1989) revealed that rocks like chert, quartzite and dolomitic limestone that are rich in siliceous or calcareous minerals are not suitable for making concrete structures in regions characterized by rainfall because, in the presence of moisture, the hardened concrete deteriorate (in form of popout, spalling or cracking) due to alkali-aggregate reactivity between the minerals and Portland cement. Also, Fitzner and Kalde (1991) had shown that variation in hygroscopic property of rock-forming minerals and pH of the pore water influence the rate/degree of rock weathering. Rocks rich in calcareous or alkali minerals (like nepheline, orthoclase and dolomite) will weather faster if the pore water is of low pH (acidic) than when it (pore water) is of high pH (alkaline) or neutral. In other words, the durability of rocks is controlled by both the rock properties and the environment where the rock exists.

As a result, tests used for assessing rock weatherability (durability potential) are each formulated to simulate the deterioration effect of a particular environment (climatic condition) on the rock(s) in question (Hudec 1998). For example, slake durability test (wetting-drying cycles) is used to assess the resistance offered by rock when subjected to two cycles of abrasive wetting and drying; sodium sulphate soundness test determines the resistance of building stone to the forces associated with the crystallization of soluble salts while freeze-thaw cycles test determines the resistance of rock to repeated freezing and thawing (ASTM D4644-87 1998; ASTM D5312/D531M-12 2013; ASTM C88-13 2013). While the slake durability test is relevant to regions that experience rainfall and high temperature, the soundness test is relevant only in areas that have high concentration of soluble salt (like environments that are saline in nature) and the freeze-thaw test relevant in temperate regions that experience freezing temperature. In other words, test that can be used to assess the durability of some rocks in one area may not be relevant in assessing the same or different rocks in another area. Hence, the durability of rocks as construction aggregates has been based mostly on the physical and mechanical properties of the rock and environmental factors with little or no consideration of other factors such as the origin (petrogenesis) and densities of the rock.

This work assesses the influence of petrogenesis and densities (matrix and bulk) on the durability of some pelitic rocks as construction aggregates especially in south-eastern Nigeria. The results can be useful in determining the extent to which petrogenesis, mineralogy and density individually or collectively contribute to the deterioration of rock aggregates used so as to aid in the design consideration of constructions in south-eastern Nigeria and similar climatic regions of the world.

2. Regional Geology and Climate of South-Eastern Nigeria:

The study area, Abakaliki metropolis, is underlain by the oldest stratigraphic unit (Asu-River Group) of Benue Trough, which evolved as third failed arm of a triple rift system in the Neocomian/early Gallic Epoch (Grant 1971; Burke et al 1971). According to Olade (1975), the rift formed due to violent mantle plume upwelling that resulted to stretching, uplift, faulting and subsidence of the major crustal blocks in Aptian/early Albian Stage. Murat (1972) and Ojoh (1990) reconstructed that the subsidence was spasmodic and that the upwelling reactivated in early-middle Turonian Stage after the basin had received its first phase of sediments, the Albian Asu-River Group, from bordering Basement complex. According to Nwachukwu (1972) and Ofoegbu (1983), the Benue Trough experienced another tectonic event in the Santonian Stage, which resulted to fracturing, uplifting and folding of the Lower (southern) part. These three tectonic upheavals were all characterized by volcanic eruptions/intrusions. Obiora and Umeji (2004) and Obiora and Charan (2010) reported that these volcanic ejecta intruded the low-grade regionally metamorphosed Asu-River Group at different places (including Abakaliki) giving raise to igneous and contact metamorphosed rocks.

According to Koppen's climatic classification system (Kottek et al 2006; Peel et al 2007), south-eastern Nigeria is located in tropical savanna climatic region, which is characterized by dry and wet seasons. The wet season occurs from April to October with monthly average precipitation (rain and dew) and atmospheric temperature varying from 90mm to 250mm and $24^{o}C$ to $32^{o}C$ respectively while the dry season occurs from November to March with monthly average precipitation (mostly dew) and atmospheric temperature varying from 15mm to 50mm and $22^{o}C$ to $32^{o}C$ respectively. Most often, a short dry season that lasts for about two weeks, characterized by no rainfall and the same atmospheric temperature as the long dry season, occurs in August or September. In other words, the region is characterized by a long and short wet season and a long and a short dry season. During the wet seasons, rocks (especially those of high effective porosity) experience saturation due to high precipitation (rain/dew) and are partially dried during the fluctuating temperature caused by irregular sunshine intensity while during dry season, they (rocks) are completely dried due to prolonged high temperature and very low precipitation. Generally, the repeated rock saturation and partial drying process common during the wet seasons has its effects on rocks particularly the excavated/quarried ones. This is so due to the increased surface area of the excavated/quarried rocks relative to their in-situ counterparts.

3. Study Methodology

3.1 Field Studies and Observations

Five rock quarry units, each located at Onyikwa, Umuoghara, Agu-Akpu, Ezzamgbo and Enyigba (Fig. 1) were studied to assess the rock types occurring at the units. The study revealed that in field view, three rock types (coded as O1, O2, O3) occur at Onyikwa, two types (U1, U2) occur at Umuoghara, two types (A1,A2) occur at Agu-Akpu, one type (Z1) occurs at Ezzamgbo and two types (E1, E2) occur at Enyigba. Portions of Onyikwa unit contain hyperbyssal features while Umuoghara unit contains grown mineral crystals suspected to be of hydrothermal origin. It was observed at Agu-Akpu unit that A2 occurs at the western part while A1 occurs at the eastern part. Only A2 and Z1 are stratified.

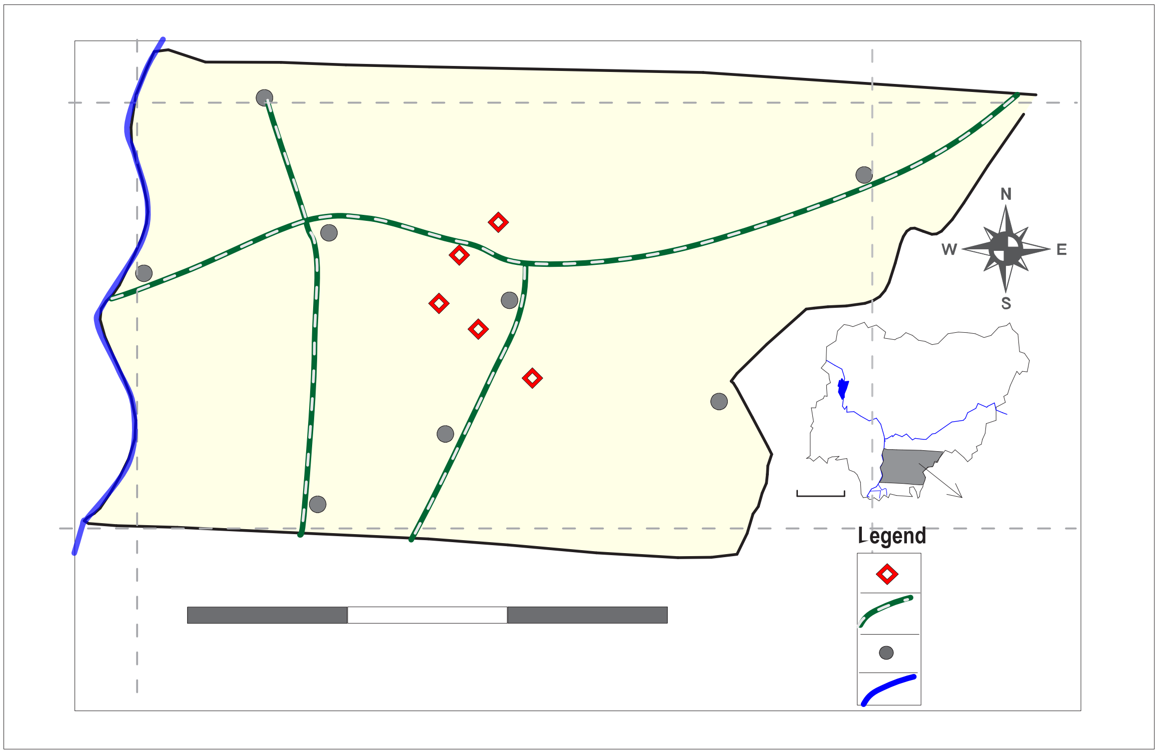

Figure 1 Map of South-eastern Nigeria showing location of the Rock Quarry Units

As the rocks were quarried for various civil engineering constructions like road embankment and pavement structures, the civil engineering structures constructed using them were also observed to evaluate their (rocks) performance. The observed civil engineering structures revealed that the quarried rocks, which were durable in appearance during and immediately after quarrying (see Fig. 2), start deteriorating/cracking after about 4 months of their use in constructing civil engineering structures like road embankment and pavement (Fig. 3a and 3b). Figure 3c shows the base of a road constructed using the rocks. These observed construction flaws instigated the authors to undertake the present study.

3.2 Sampling and Analyses

A total of ten rock samples, corresponding to the rock types (O1, O2, O3, U1, U2, Z1, A1, A2, E1 and E2), collected from the units and coded earlier were each divided into four portions. The first portion was studied megascopically to determine their texture; the second was subjected to x-ray diffraction (X-RD) test to determine their dominant and water-absorbent/soluble mineralogy (mostly clay minerals and zeolites); the third portion was subjected to degradability tests to simulate the effect of repeated wetting and drying on the rocks as common in south-eastern Nigeria and the fourth portion was subjected to density tests (matrix and bulk densities) to determine variation of densities among the samples.

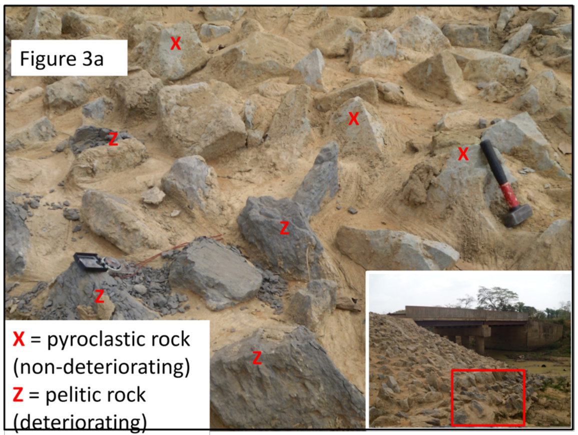

Figure 2 The durable appearance of the pelitic rock quarried at Umuoghara
Figure 3a Comparing the durability of the pelitic rock and pyroclastic rock in service
Figure 3b Cracking of concrete pavement constructed at Ogbaga using some of the pelitic rock (notice that the rock aggregates cracks alongside with the hardened mortar)
Figure 3c Some of the pelitic rocks used as base/sub-base along Ogbubara road

About 3g dry rock sample, that was megascopically homogeneous, was pulverized and subjected to X-RD test using Schimadzu X-Ray diffractometer (XRD-6000) for a scan range of 0 and 70 2θ to generate the diffractogram. Peaks of the diffractogram denote minerals present in the analyzed sample which were identified and labeled by matching the peaks with the software mineral cards installed in the diffractometer. The peak matching was done to identify the dominant minerals, including clay minerals and zeolites, contained in the rock. Relative abundances of the identified minerals were calculated from heights and population of the peaks.

Two batches of dry lump rock test samples, each weighing between 120g and 180g, were washed with water and finger pressure to remove loose/dust particles adhering to their surfaces, oven-dried at 105^{o}C for 24 hours to ensure complete drying and cooled to ambient temperature. The weight range 120g to 180g, which is triple the slake durability sample weight range of 40g to 60g (ASTM D4644-87 1998), was used in order to observe a bigger picture of the samples deterioration as the use of the 40g to 60g weight range in trial tests resulted to near total breakdown of some samples and hence difficulty in assessing their actual degree of deterioration.

One batch of the test samples was subjected to short soaking and partial drying (version A) degradability test to simulate the wetting and partial drying that occurs during wet season and the other batch subjected to long soaking and complete drying (version B) degradability test to simulate the wetting and drying that occur over a complete cycle of wet and dry seasons in south-eastern Nigeria. In version A test, the test sample was weighed (W_{dry1st}), placed inside a non-corrodible can and filled with potable water of natural climatic temperature (23^oC to 26^oC) determined with a mercury glass-tube thermometer inserted in the water. The set-up was left for 2 days (48 hours) according to the ASTM-C97 (1990) rock saturation duration. The water was carefully decanted and the sample washed with fresh water and finger pressure. Particle(s) that got detached during the washing and/or soaking was/were carefully picked, oven-dried at 105^oC for 24 hours to achieve complete drying, cooled to ambient temperature and thereafter weighed (W_p). The intact rock samples were surface-dried with water-absorbent cloth to dry water adhering to the surfaces and subsequently air-dried for 24 hours at room temperature (23^oC to 28^oC) to achieve partial drying. Trial tests had shown that samples achieved only partial drying when left for 24 hours under room temperature. This process was repeated for 14 cycles simulating a 14 periodic complete wetting and partial drying of the rocks, a conservative period compared to the four months period observed as beginning of deterioration of the rocks in service. At the end of each cycle, the partially dried intact rock was used as the next subsequent test sample (W_{dry}) and cumulative percentage of mass lost (ShM_{lost}) at the end of the 14^{th} cycle was calculated using Equation 1.

$$ShM_{Lost} = \left[\frac{(\sum_{i=1}^{n=14} W_p)}{W_{dry\ 1st}}\right] X\ 100\% \qquad 1$$

where W_{dry1st} = Dry weight of intact rock at the beginning of the test
W_p = Dry weight of the detached particles
$\sum_{i=1}^{n=14} W_p$ = sum of W_p

In version B test, the test sample was soaked in water for 6 days (144 hours) and the intact rock oven-dried at 105^oC for 24 hours to achieve complete drying thus simulating complete wetting of rocks that occurs during wet seasons and complete drying that occurs during dry season. The test sample was soaked for 6 days as trial tests had shown that 2-days soaking (ASTM-C97 1990) and oven-drying at 105^oC produced the same deterioration as in version A test. The detached particle(s) determination followed the same procedure as in version A but the process was repeated for 6 cycles, each cycle simulating a wet and dry season. In other words, the 6 cycles represent three years, each made up of 2 wet seasons and 2 dry seasons as earlier explained to occur in southeastern Nigeria. At the end of the test, the cumulative percentage of mass lost (LgM_{lost}) was also calculated using Equation 1, except in this case, n=6, representing 6 cycles.

The fourth portion of the test rock samples was, as earlier said, subjected to matrix and bulk density tests following the weighing and water immersion methods described by Balco and Stone (2003). Three tests were done using three test samples for each of matrix and bulk density tests and each of the averages calculated as the matrix and bulk density of the sample.

4. Results and Discussion:

Examples of the labeled X-RD mineral diffractograms are shown in Figure 4 while the megascopic descriptions and mineralogy (water-absorbent/soluble minerals and other dominant minerals) of the analyzed samples are shown in Table 1. The relative cumulative abundance of the water-absorbent/soluble minerals is plotted as bar charts shown in Figure 5 and the cumulative percentage of rock mass lost (ShM_{lost} and LgM_{lost}) in the degradability tests is shown in Figure 6. 1% was used as the significant deterioration (s-line in Fig 6) in order to be as conservative as possible.

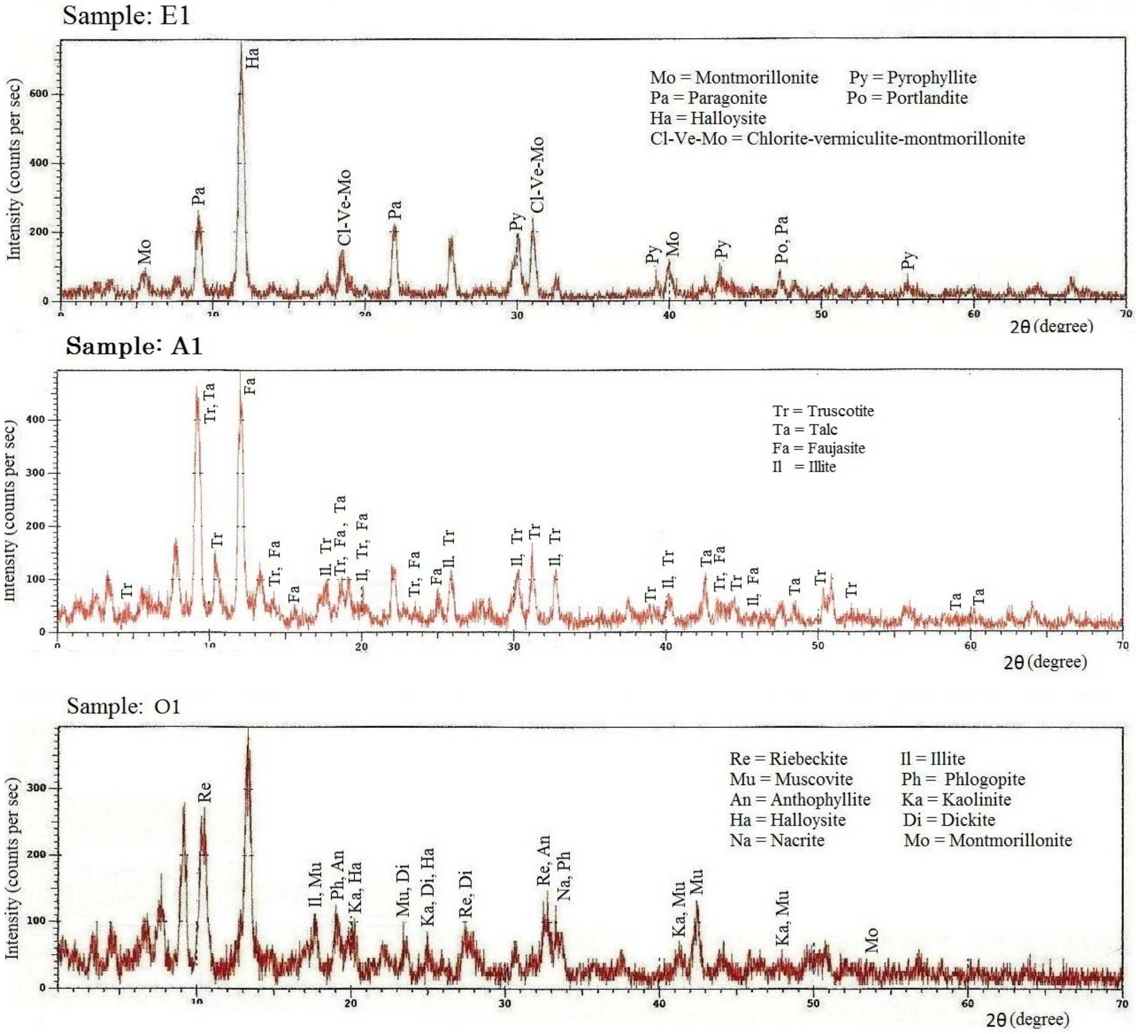

Figure 4 Examples of the labeled diffractogram

Table 1 Macroscopic description and mineralogy of the analyzed rock samples

s/n	Location	Sample	Macroscopic description	*Dominant mineralogy of the analyzed rock samples	
				Water-absorbent/soluble minerals	Other dominant minerals
1	Enyigba	E1	Dark grey in colour, clayey in grain size, smooth surfaced, micaceous and massive.	Halloysite(cl, 22.44), Chlorite-vermiculite-montmorillonite(xc,14.20) Montmorillonite(cl, 11.92), Portlandite(br, 8.24).	Paragonite(mc, 22.72), *P*yrophyllite(ta, 20.45),
2	Enyigba	E2	Dark grey in colour, clayey in grain size, smooth surfaced, micaceous and massive.	Illite(cl, 12.68), Mordenite(ze, 8.85), Corrensite(xc, 4.32).	Antigorite(sp, 28.22), Tremolite(am, 13.36), Lizardite(sp, 13.18), Osumillite(mi, 9.84), Hopeite(ph, 9.51),
3	Umuoghara	U1	Grey coloured and micaceous, coarse-grained, rough surfaced.	Faujasite(ze, 19.21), Illite(cl, 10.40), Montmorillonite(cl, 5.99), chlorite-vermiculit-montmorillonite(xc, 5.01),Beidellite(cl,1.71).	Truscottite(tr, 20.56), Paragonite(mc, 19.09), Sepiolite(se, 17.99),
4	Umuoghara	U2	Grey coloured and Sub-spherical in shape.	Illite(cl, 9.12).	Lizardite(sp, 30.43), Chrysotile(sp, 21.49), Ferropargasite(am, 20.88), Muscovite(mc, 18.05),
5	Agu-Akpu	A1	Similar to U1 but not micaceous.	Faujasite(ze, 32.93), Illite(cl, 11.97).	Truscottite(tr, 44.39), Talc(ta, 18.47),
6	Agu-Akpu	A2	Grey/ash coloured. Fine-grained. Less brittle than other samples.	Mordenite(ze, 6.48), Kaolinite(cl, 6.29), Illite(cl, 5.05), Nacrite(cl, 5.00), Dickite(cl, 1.56) Periclase(ox, 1.12).	Parahopeite(ox, 20.94), Muscovite(mc, 18.38), Tremolite(am, 14.74), Riebeckite(am, 10.31), Osumillite(mi, 10.07),
7	Onyikwa	O1	Porphyroblastic texture, phenocrysts are light-green while matrix is grey portions.	Kaolinite(cl, 12.41), Dickite(cl, 8.73), Illite(cl, 8.08), Halloysite(cl, 6.76), Nacrite(cl, 5.37), Montmorillonite(cl, 0.64).	Muscovite (mc, 19.84), Riebeckite(am, 16.08), Phlogopite(mc, 10.86), Anthophyllite(am, 11.17),
8	Onyikwa	O2	Pyroclastic texture of milky-coloured coarse particles mixed with grey fine-grained matrix.	Montmorillonite(cl, 10.08), Illite(cl, 7.32), Kaolinite(cl, 7.23), Dickite(cl, 5.80), Nacrite(cl, 3.18), Halloysite(cl, 1.99), Vermiculite(cl, 0.99).	Grunerite(am, 24.21), Osumillite(mi, 11.98), Tremolite(am, 9.42), Ferropargasite(am, 9.18), Edenite(am, 8.56),
9	Onyikwa	O3	Ash-coloured and massive. Finer in grain size than O1 and O2.	Dickite(cl, 9.34), Nacrite(cl, 6.71), Montmorillonite(cl, 6.44), Kaolinite(cl, 4.53) Illite(cl, 0.98).	Osumilite(mi, 17.65), Muscovite(mc, 17.43), Tremolite(am, 14.64), Ferropargasite(am, 11.19), Phlogopite(mc, 11.03),
10	Ezzamgbo	Z1	Grey/ash coloured, silty in grain sized. Similar to A2 in brittleness.	Mordenite(ze, 5.81), Illite(cl, 5.72), Dickite(cl, 2.20), Kaolinite(cl, 1.40), Montmorillonite(cl, 0.59), Halloysite(cl, 0.39).	Anthophyllite(am, 24.67), Tremolite(am, 20.36), Sepiolite(se, 16.84), Antigorite(sp, 12.13), Grunerite(am, 9.83),

Note: * mineral group and calculated relative abundance is included in parenthesis: mc=mica, ta=talc, cl=clay, xc=mixed-clay, br=brucite, sp=serpentine, am=amphibole, mi=milarite, ph=phosphate, tr=truscottite, ze=zeolite, se=sepiolite, ox=oxide.

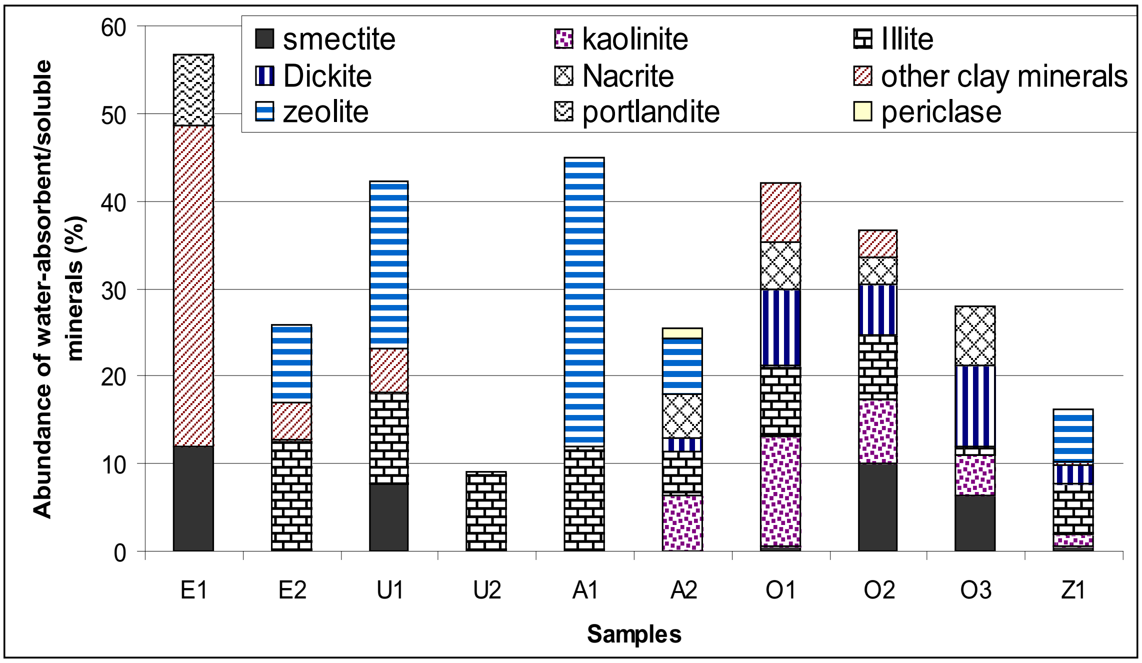

Figure 5 Relative abundance of the water-absorbent/soluble minerals contained in the samples

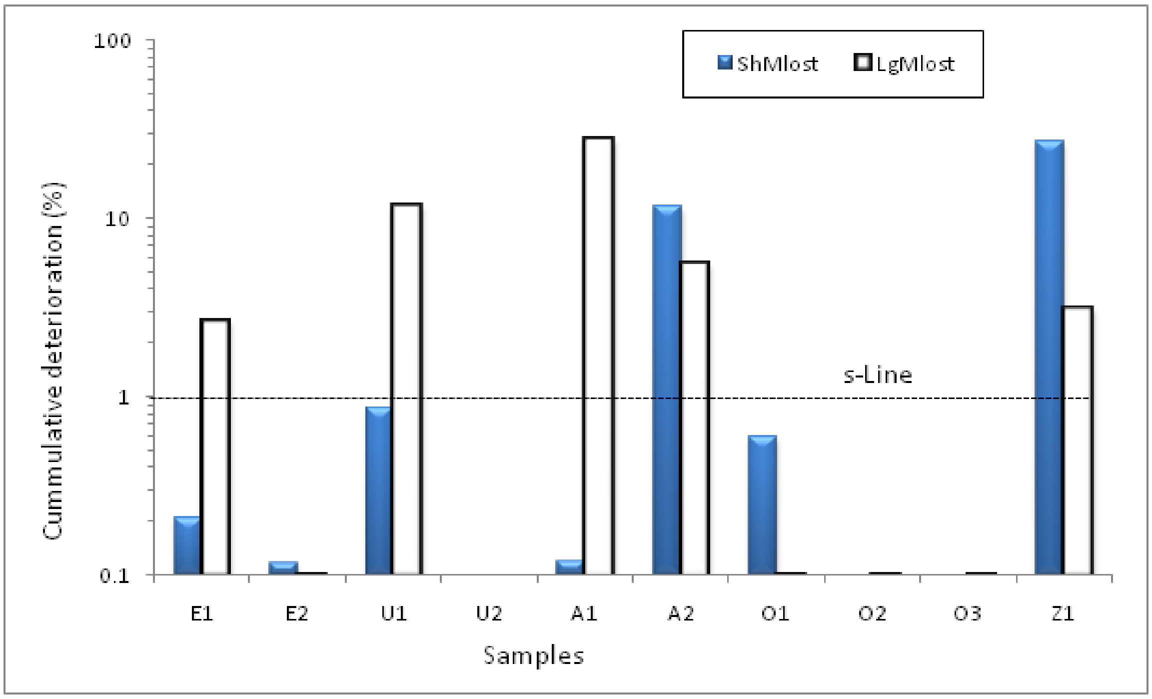

Figure 6 Cumulative percentage of mass lost in the degradability tests (s-line = significant deterioration level)

From Table 1, the megascopic studies reveal that except U2 and O2, the other eight samples have pelitic appearance (texture) giving the impression that they are of pelitic protholits. Figure 6 reveals that, for short soaking and partial drying degradability test that had 14 cycles, two samples, notably, A2 and Z1 showed significant (≥1%; s-line) deterioration. For long soaking and complete drying degradability test that had 6 cycles, the two samples again showed significant (≥1%, s-line) deterioration alongside three other samples – E1, U1 and A1. This clearly shows that long soaking and complete drying degradability test has more deteriorating effect (as per cycle) than short soaking and partial drying degradability test. The significant deterioration shown by samples Z1 and A2 in both short soaking/partial drying test and long soaking/complete drying test shows that they (Z1, A2) are generally more susceptible to deterioration than the other rocks. Only sample U2 showed zero deterioration in both short soaking/partial drying test and long soaking/complete drying test implying that it (U2) is degradably stable. It implies that samples Z1 and A2 are perhaps, different rock types or origin (petrogenesis) from other rocks and also different from sample U2.

Comparing Figure 6 with Figure 5, it can be seen that samples E1, U1 and A1 that showed significant deterioration only in long soaking and complete drying degradability test contain sizeable (≥35% of the identified minerals) amount of water-absorbent/soluble mineral(s). The lower deterioration shown by E1 relative to U1 and A1 in long soaking/complete drying test is attributed to its fine grain size (see Table 1). Samples A2 and Z1 that showed significant deterioration in both versions of degradability test contain lower (< 35 >10% of the identified minerals) amount of water-absorbent/soluble mineral(s) and only sample U2 that showed zero deterioration in both versions of degradability test contain negligible (<10% of the identified minerals) amount of water-absorbent/soluble mineral(s). Interestingly, samples O1 and O2 that also contain sizeable (≥35%) amount of water-absorbent/soluble minerals did not show significant deterioration in either versions of the degradability test. These findings suggest three things. The first is that some rocks deteriorate because they contain sizeable amount of water-absorbent/soluble minerals (rocks E1, U1 and A1) and some do not deteriorate because they contain negligible amount of water-absorbent/soluble minerals (rock U2). The second is that some rocks do not deteriorate even though they contain sizeable amount of water-absorbent/soluble minerals. Examples here are rocks O1 and O2. The third is that mineralogy controls deterioration of rocks in long soaking/complete drying test more than it does in short soaking/partial drying test. Examples here are illustrated by rocks E1, U1 and A1 versus rocks A2 and Z1. All these findings show that the analyzed rocks are of varying types or petrogenesis.

The deterioration history curves of the samples that showed significant (≥ 1%) deterioration in Figures 7a and 7b. Figures 7a and 7b reveal that, for both versions of the degradability test, none of the samples started deteriorating in the first cycle. This shows that deterioration of the rocks was caused by repeated wetting (soaking) and drying and not by ordinary (not repeated) wetting or drying. The samples that showed highest initial deterioration are not the samples that showed the highest cumulative deterioration. In long soaking/complete drying (Fig. 7a), Z1 showed the highest initial deterioration while A1 showed the highest cumulative deterioration. Similarly, in short soaking/partial drying (Fig. 7b), A2 showed the highest initial deterioration while Z1 showed the highest cumulative deterioration. This indicates that rocks that first show evidence of deterioration (weathering) due to repeated wetting and drying are not necessarily the most susceptible to weathering. This also suggests that the analyzed rocks are of varying petrologic origin (petrogenesis).

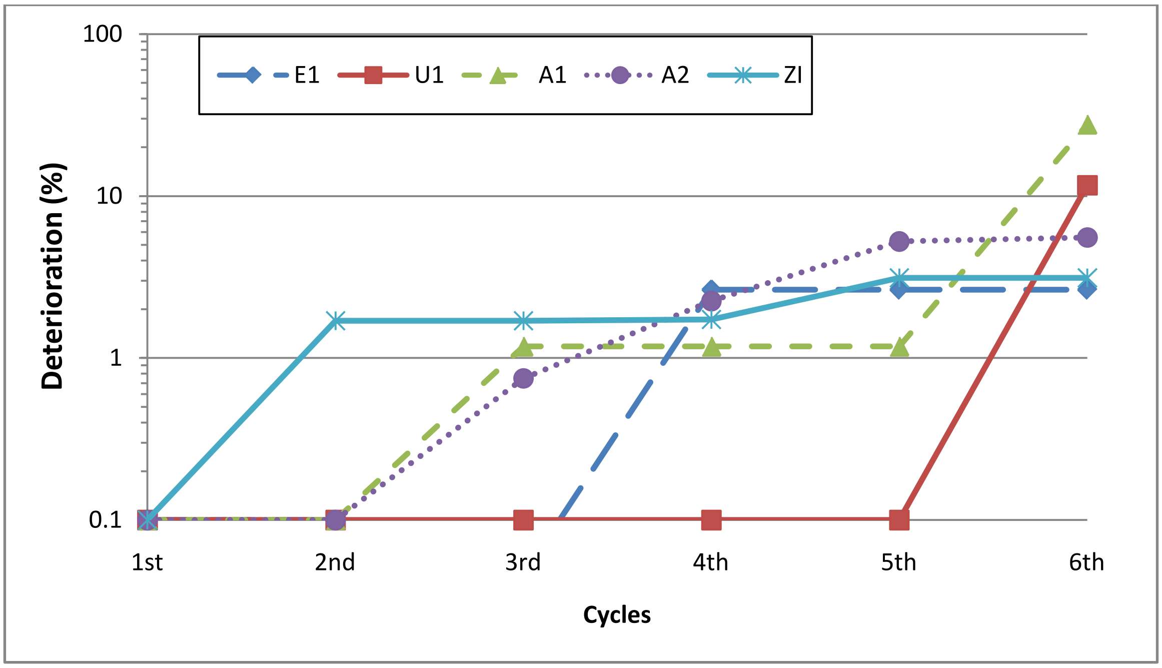

Figure 7a Deterioration history curves of samples that showed significant deterioration in long soaking and complete drying test

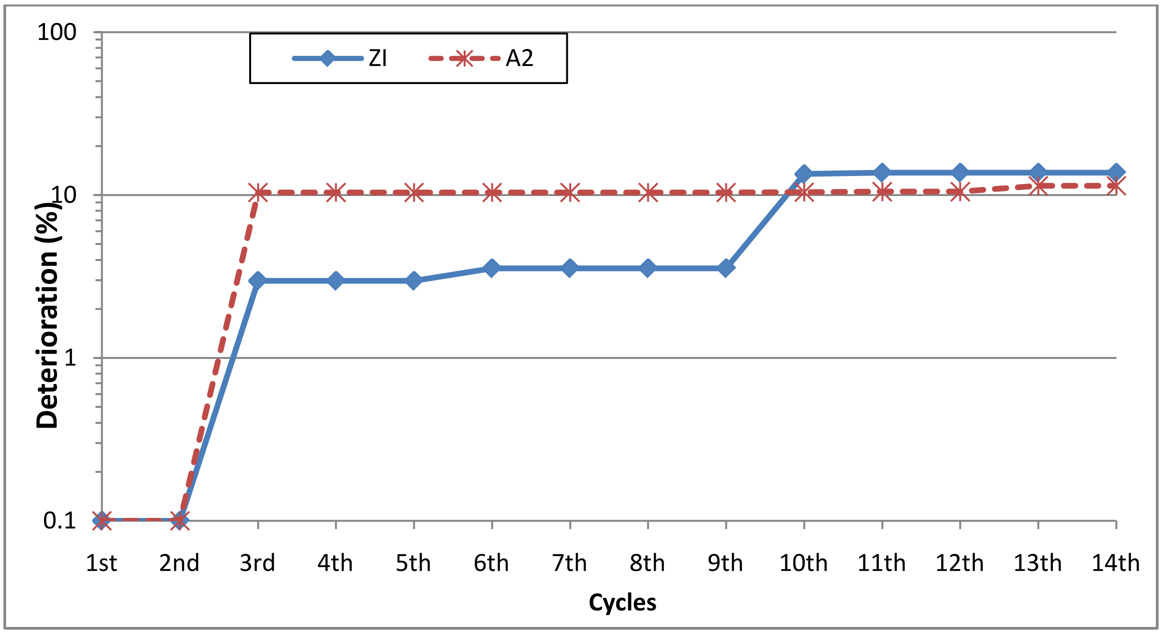

Figure 7b Deterioration history curves of samples that showed significant deterioration in short soaking and partial drying test

The rock densities (ρ_{mat} and ρ_{bulk}) and the difference between matrix and bulk density ($\rho_{mat-bulk}$) of the samples are shown in Figures 8a and 8b respectively.

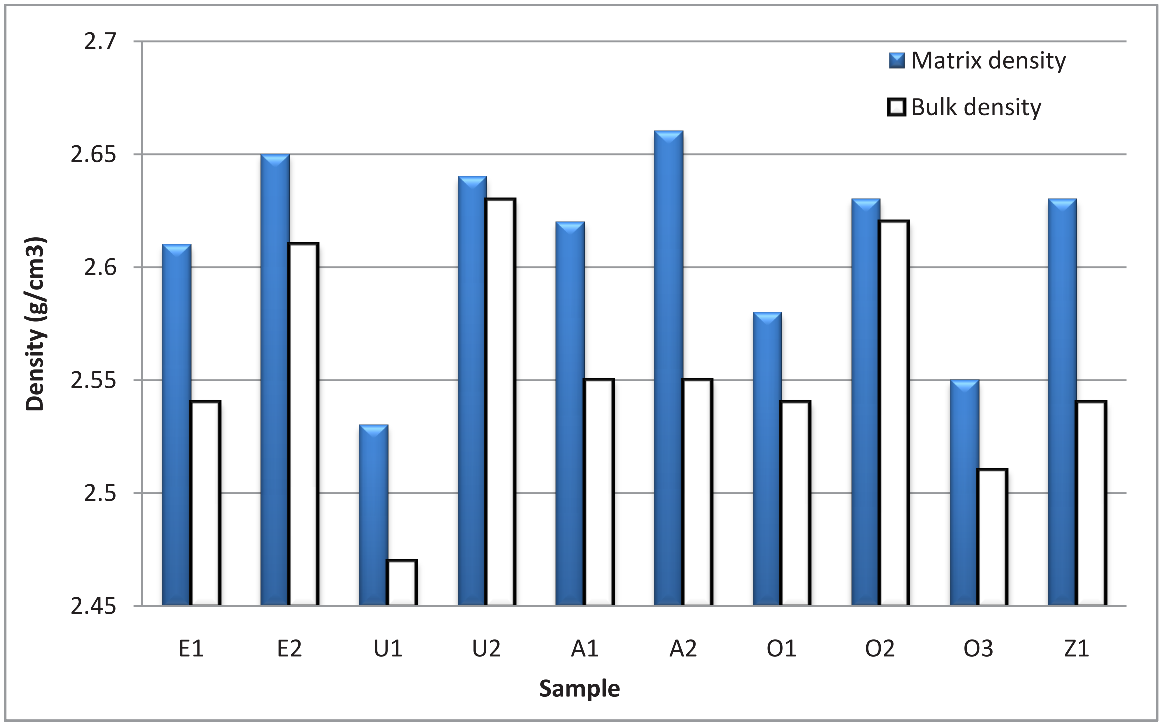

Figure 8a Matrix and bulk densities of the analyzed samples

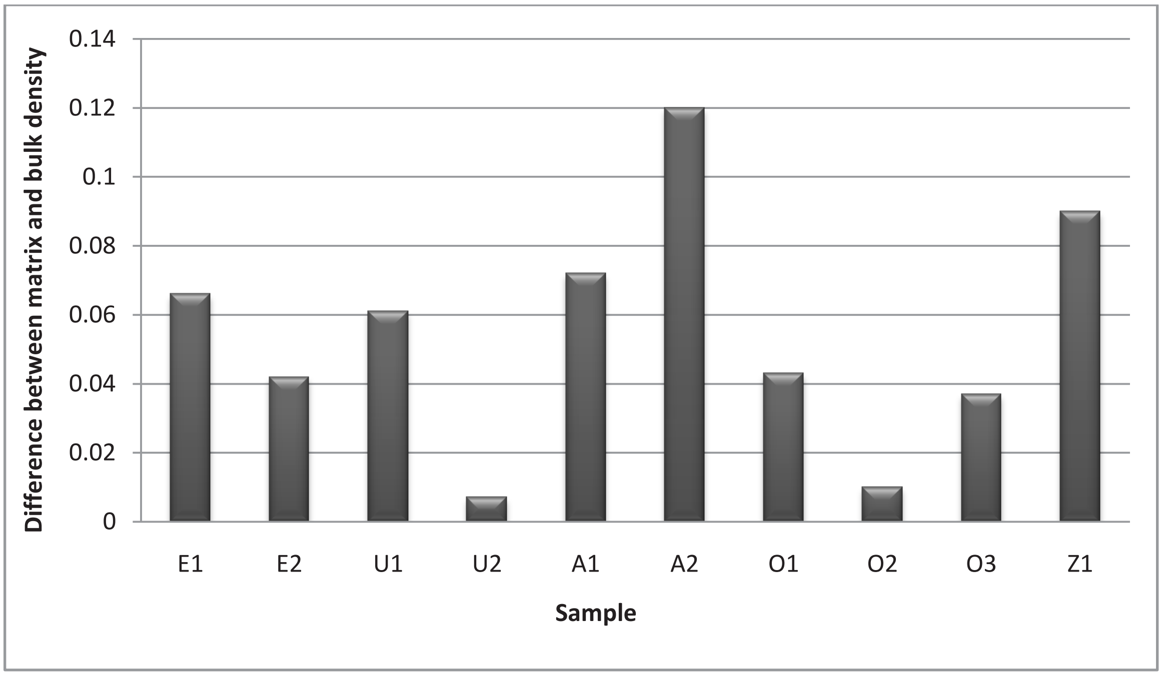

Figure 8b Difference between matrix and bulk density of the rock samples

Figure 8a reveals that for each of the analyzed samples, matrix density is more than bulk density which agrees with the findings of Strohmeyer (2003) and Hoffmann and Siegesmund (2007). The difference between matrix density and bulk density ($\rho_{\text{mat-bulk}}$) shown in Figure 8b varies among the samples; it ($\rho_{\text{mat-bulk}}$) is least in the cases of U2 and O2 and highest in those of A2 and Z1. Following work by Hoffmann and Siegesmund (2007), as stated earlier, these variations in matrix and bulk densities suggest that the analyzed rocks are not of the same petrologic type.

4.1 Petrogenesis of the Rocks

The absence of biotite and orthoclase; predominance of amphiboles and serpentine in the studied and analyzed rocks (see Table 1) indicate that the rocks are not sedimentary but are either igneous or metamorphic rocks (Winkler 1979; Tucker 1991; Nichols 2009). This is in agreement with the work by Obiora and Umeji (2004) that rocks of the Asu-River Group (rocks of the study area) are composed of low-grade regionally metamorphosed shales, pyroclastic (igneous) and contact metamorphosed rocks. A closer look at Table 1 reveals that the analyzed rocks can be grouped into two. Rock samples E1, E2, U1, U2, and A1 are composed of mineral species from diverse mineral groups while rock samples A2, O1, O2, O3 and Z1 are composed of mineral species from fewer mineral groups (relative to the number of minerals each rock contains), which are mostly amphiboles and micas. For example, each of samples E2 and O1 contains six minerals from five groups while each of samples O1 and O2 contains eight minerals from four groups. It is opined that the different petrogenesis (origin) of these two rock groups contributed to their diversity in mineralogy.

Following works by Mason (1970) and Gillen (1982), rocks of the second group (A2, O1, O2, O3, and Z1) can be said to have originated either from low-grade regional metamorphism or contact metamorphism. O2 has pyroclastic texture (see Table 1), which according to Ekwueme (1993) resulted from the mixing of pyroclastic ejecta and the host shale, implying that it (O2) originated from volcanic eruption. This mixing explains why the pyroclastic O2 has the mineralogy of the second group. Rocks O1 and O3 co-occur with O2 and hyperbyssals were also mapped in the Onyikwa outcrop from where the three rocks (O1, O2 and O3) were collected. This implies that O1 and O3 actually originated from contact metamorphism of the host shale with the volcanic ejecta that gave rise to O2. On the other hand, the low brittleness and stratified field occurrence of Z1 and A2 indicate that they formed from low-grade regional metamorphism of pelites.

Since it has been indicated that the two rock groups are not of the same petrogenesis, it implies that the first rock group (E1, E2, U1, U2 and A1) originated neither from regional metamorphism nor contact metamorphism. They originated either from igneous/volcanic activities or hydrothermal process. The grown mineral crystals observed at Umuoghara unit (U1 outcrop); the close similarity of A1 to U1 in macroscopic view and occurrence of lizardite, truscottite and faujasite in one or more of E2, U1 and A1 indicate that these rocks (E2, U1, A1) are of hydrothermal petrogenetic origin. And since E1 and E2 occur at the same outcrop and are quite similar macroscopically, E1 is equally of hydrothermal petrogenesis. The shape, field occurrence and predominance of serpentines in U2 clearly reveal that it is volcanic bomb. Therefore, E1, E2, U1 and A1 formed through hydrothermal alteration of pelitic rocks while U2 formed from volcanic activity. Table 2 summarizes the petrogenesis of the studied rocks.

Table 2 Petrogenesis of the studied rocks

Petrogenesis	Rock	Location	Rock Type
Hydrothermal alteration of pelites	E1	Enyigba	Hydrothermally altered pelitic rock
	E2	Enyigba	Hydrothermally altered pelitic rock
	U1	Umuoghara	Hydrothermally altered pelitic rock
	A1	Agu-Akpu	Hydrothermally altered pelitic rock
Low-grade regional metamorphism	Z1	Ezzamgbo	Pelitic argillite
	A2	Agu-Akpu	Pelitic argillite
Contact metamorphism	O1	Onyikwa	Porphyroblastic Pelitic hornfel
	O3	Onyikwa	Fine Pelitic hornfel
Volcanic/igneous activity	O2	Onyikwa	Pyroclastic rock
	U2	Umuoghara	Volcanic bomb

4.2 Relationship among Petrogenesis, Density and Durability of the Rocks:

Sequel to earlier discussion and from Table 2, Figures 6 and 8b, the rocks that formed through igneous activities (O2, U2) have the least difference between their matrix and bulk density ($\rho_{mat-bulk}$) and are least susceptible to deterioration while those that formed through low-grade regional metamorphism (A2, Z1) have the highest $\rho_{mat-bulk}$ and are most susceptible to deterioration. It implies that, generally, rocks of low $\rho_{mat-bulk}$ are more durable than those of high $\rho_{mat-bulk}$ and vice versa. Considering that rocks that formed through low-grade regional metamorphism can be loosely taken as sedimentary rocks; those that formed through igneous activity taken as igneous rocks and those that formed through hydrothermal alteration and contact metamorphism taken as metamorphic rocks, it can be said that $\rho_{mat-bulk}$ of igneous rocks are low relative to those of sedimentary and metamorphic that are high and moderate respectively. This is also in agreement with works by Hoffmann and Siegesmund (2007) and implies that $\rho_{mat-bulk}$ can serve as petrologic classification index.

The petrogenetic classification of the studied rocks explains why the pelitic argillites (A2, Z1), which are fine-grained and contain low (<35%) water-absorbent/soluble minerals, are the most susceptible to deterioration while the volcanic bomb (U2) and pyroclastic (O2) are the least susceptible to deterioration. It indicates that petrogenesis is a strong factor controlling deterioration of rocks. Also, only the pelitic argillites (A2, Z1) showed significant deterioration in short soaking/partial drying test while the coarse-grained hydrothermally altered pelites (U1, A1), containing sizeable (≥35%) amount of water-absorbent/soluble minerals, showed higher significant deterioration in long soaking/complete drying test than other samples. It implies that deterioration of rocks due to short soaking/partial drying is controlled more by petrogenesis than mineralogy and texture while deterioration of rocks due to long soaking/complete drying is controlled more by mineralogy and texture than petrogenesis. This also explains why samples E1 and E2, which are both fine-grained hydrothermally altered pelites behave differently. Whereas sample E1 that contains sizeable water-absorbent/soluble mineral showed significant deterioration in long soaking and complete drying, E2 that does not contain sizeable water-absorbent/soluble minerals did not (see Figs. 5 and 6 for clarity). Conversely, the non-significant deterioration shown by the pyroclastic rock (O2) and porphyroblastic hornfel (O1), that contain sizeable amount of water-absorbent/soluble minerals, in either versions of the degradability test implies that deterioration of the rocks (O2, O1) is controlled more by petrogenesis than mineralogy and texture.

The above discussion reveals that the deteriorating embankments and cracked pavements shown in Figures 3a and 3b were constructed with either hydrothermally altered pelites (U1, A1, E1, E2) or pelitic argillites (A2, Z1). As base/sub-base of roads/highway, these rocks may also not serve satisfactorily well because of possible potholes or other failure points that usually expose the base of the road (such as the case shown in Figure 3c). Such exposures will certainly lead to fast deterioration of the base/sub-base material and eventual failure of the road. It can be summarized therefore, that amongst the rocks studied, only the pelitic hornfels, pyroclastics and volcanic bombs are durable enough to be used in constructing civil engineering structures like embankment, armourstone and facades that are exposed to repeated wetting and drying common in south-eastern Nigeria. Petrogenesis, therefore, plays an important role on the durability of the analyzed pelitic rocks.

5. Conclusions:

The following conclusions are drawn from the present work:

1. Rocks that have low difference between their matrix and bulk density are more durable than those that have high difference between their matrix and bulk density.
2. Durability of rocks, which can be assessed using degradability test, is controlled by mineralogy, petrogenesis and texture of the rocks.
3. Deterioration of rock due to long soaking and complete drying degradability test is controlled more by mineralogy and texture than petrogenesis while deterioration of rock due to short soaking and partial drying degradability test is controlled more by petrogenesis than mineralogy and texture of the rock.
4. Among the pelitic rocks studied, only the pyroclastics, volcanic bombs and pelitic hornfels are durable enough to serve as aggregate for constructing civil engineering structures exposed to wetting and drying common in south-eastern Nigeria.

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