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Effect of Salty Solutions on the Slake Durability of Some Granitic Rocks

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Abstract
The degradability of rocks is one of the notable factors in any engineering structure or construction relevant to the environment, mining, civil or geological works. Rocks or rock aggregates are vulnerability to salt weathering or crystallization when exposed to different conditions. Salt weathering can come from different sources such as seawater or groundwater, air pollutants, or mortars. This study assesses the effect of wetting - drying cycles and salty solutions on slake durability of some granitic rocks (fine-grained granite and porphyritic granite). Slake durability test using two salty solutions of different concentrations was conducted according to the standard ASTM procedure in the aqueous solutions (slaking fluids) with dissolved electrolytes of Na_2SO_4 and $CaCl_2$. The slake durability of the rocks was evaluated up to eight cycles in the salty solutions with different concentration of 25, 50, and 75% by weight. Results show the granitic rocks are not significantly different from each other petrologically in terms of observed mineral components. The average water content, porosity, and water absorption of the porphyritic granite is higher compared to those of fine-grained granite. Percentage mass loss of the rocks increased with the number of slaking cycles and the rate of mass loss is higher at the initial cycles than the final cycles of the slake durability test. The mass loss was higher in porphyritic granite samples both in Na_2SO_4 and $CaCl_2$ aqueous solutions. The slake durability index of the rocks range from very high to extremely high under the influence of salty solutions. Increase in number of slaking cycles and concentration of the solutions decreased the slake durability indices of the rocks. The porphyritic granite samples have lower slake durability index in all the slaking cycles and both in Na_2SO_4 and $CaCl_2$ solutions. The slake durability index of the fine-grained granite in Na_2SO_4 is lower than in $CaCl_2$ in all the slaking cycles except in few cases. In contrast, the slake durability index of the porphyritic granite in $CaCl_2$ at 50% and 75% concentration was lower than in Na_2SO_4 solution. It is concluded that the porphyritic granite with low strength, high water absorption capacity and porosity is more liable to degradation in salty solution compared with fine-grained granite.

Keywords: *Granite, Salty Solution, Slake Durability, Slaking Fluid, Weathering*

Introduction

Weathering and hydrothermal alteration are geological processes that can alter or change the original features/properties of rocks. During weathering process, rocks are subjected to chemical, mineralogical and physical changes. Rock-forming minerals (e.g., alkali feldspar, biotite, and plagioclase feldspar) are altered into secondary minerals and clays. Consequently, rocks become more permeable and porous, suffer reduction in strength, develop more microfractures and lose their original appearance (Ceryan et al. 2008; Momeni et al. 2015b). These deteriorations and the consequent changes can impact the performance and durability of rocks when used as building stones and in other engineering construction activities in the course of time (Blows et al. 2003). Hence the knowledge of durability of rocks under different environmental conditions is important in civil, mining, and geotechnical applications to ensure reliability of structure(s) constructed on or with the rocks also in addition to ensuring sustainability and safety.

From a geological point of view, the nature of rock deterioration is influenced by intrinsic factors such as mineralogical, chemical or structural characteristic and extrinsic factors such as environmental conditions and weathering agents (White and Blum 1995; Zorlu 2008).Weathering is most significant in areas where rocks are exposed extensively to different weathering episodes such as alternating heating and cooling, wetting and drying, and freezing and thawing (Momeni et al. 2015a). Previous studies have shown that periodic rock–water interactions accelerate rock material weathering, and this can significantly affect its durability as well as its mechanical and physical properties (Ghobadi and Mousavi 2014; Özşen et al. 2017). Salt crystallization and acid rainfall are important environmental weathering processes or factors with a destructive effect on rocks as well as engineering constructions and monuments (Bell 2007; Pinho et al. 2017).

Over the past few years, field and laboratory studies have revealed that salt weathering (through salt crystallization) plays a key role in water–rock interactions (Bell 2007). Hence, it is regarded as one of the most serious degradation mechanisms that rocks undergo at and near the Earth's surface (Benavente et al. 2001). Salt weathering has also been recorded in different geo-environments (Cultrone and Sebastián

2008). Previous authors found out that crystallization pressure of salt crystals growing in confined pores happened to be the main cause of damage to the rocks. Ruiz-Agudo et al. (2007), however, observed that properties of saline solution and viscosity are critical in salt weathering. Ghobadi and Mousavi (2014) also found out that durability of rocks also differs in different salty solutions. Consequently, understanding the effect of different saline or salty solutions on the durability or disintegration of rocks and building stones has now become imperative.

Slake durability test is commonly used to evaluate the rock degradation, and the durability and water sensitivity of rocks with respect to engineering applicability requirements (ASTM D4644_08 2008). Slake durability, according to Gupta and Ahmed (2007), represents "the degradability of rocks due to the process of physical and chemical breakdown as in exfoliation, oxidation, solution, hydration, and abrasion". Recently, series of experimental investigations have been conducted to understand the influence of wetting-drying cycles and salty solutions of different concentrationon durability of different types of rocks such as travertine, tuff, pyroclastic, and sandstone (Dhakal et al. 2002; Ghobadi and Mousavi 2014). There are, however, few studies in literature on the effect of wetting-drying cycles and salty solutions to simulate the influence of diverse geo-environmental conditions on durability of granitic rocks.

Precambrian Basement Complex rocks are common in Ado-Ekiti, Southwestern, Nigeria. The different rocks which make up the Complex vary in their mineralogy, petrographic and textural characteristics. An increasing use of the granitic suite of the Precambrian Basement Complex rocks as construction materials point to their importance as construction material. These rocks are used for construction purposes such as foundations, building stones, facade stones, rock aggregates and filling with little or no information related their degradation mechanism and weathering potential in salty or saline environment. This study therefore examines the influence of wetting - drying cycles and salty solutions of different concentrations on the degradability and durability of porphyritic and fine-grained granites from Ado-Ekiti SW, Nigeria.

Study Area

Ado-Ekiti is located in a tropical climatic zone with well-defined dry and rainy seasons. High temperature and availability of moisture in the location promotes chemical weathering. The rocks of Pre-Cambrian basement complex underlie Ado-Ekiti, southwestern, Nigeria (Elueze 2000; Talabi 2013). The Basement Complex terrain of southwestern Nigeria is dominated by three petrological groups which include a complex of migmatite-gneiss lithofacies, an assemblage of schistose rocks in defined N-S belts, and the Pan-African granites. According to Odeyemi et al. (1999), southwestern Nigeria is underlain by rocks of Precambrian age dominated by migmatite-gneiss, Neoproterozoic metasedimentary units and granites. Geological mapping revealed that the main lithological units in Ado-Ekiti include migmatite gneiss, granite gneiss, quartzite, older granite and charnockites (Fig. 1). Migmatite gneiss outcrops occur as highly denuded hills of fine-grained textures consisting of closely spaced alternating bands of melanocratic and leucocratic minerals. Structures such as joints and folds as well as late intrusive veins of felsic-mafic compositionare found on the rock unit. Quartzites occur as ridges and their outcrops are massive and non-foliated. The major mineral constituent of the rock is quartz with feldspar occurring in minor quantity. The granites are made up of felsic (quartz, orthoclase, plagioclasefeldspar and muscovite) and mafic (biotite and hornblende) minerals. They are uniquely distinguishable becauseof their visible minerals, lack of foliation, fine-mediumgrained and sometimes porphyritic texture with compactinterlocking crystals that developed during the crystallization of magma. The charnockites occur as massive dark-grey medium-coarse grained. The charnockites are found along the edges of thegranites.

Material and Methods

Rock samples were taken from outcrops of two different varieties of granite: fine-grained and porphyritic granite. Rock blocks (40*40*60 mm) taken were inspected to ensure they were fresh, not altered or weathered and free of macroscopic defects such as fractures.

The mineralogical and physical properties of each of the rock samples were determined using appropriate ISRM standard testing procedures. The mineralogical properties of the granitic rocks were observed by preparing thin sections. The prepared thin sections were studied under a polarizing microscope and the images analyzed. The modal composition was obtained by point counting method. The petrographic analysis was done in accordance with the standard specified by ISRM (1978). The physical properties of the granitic rocks such as density, water content, water absorption capacity,

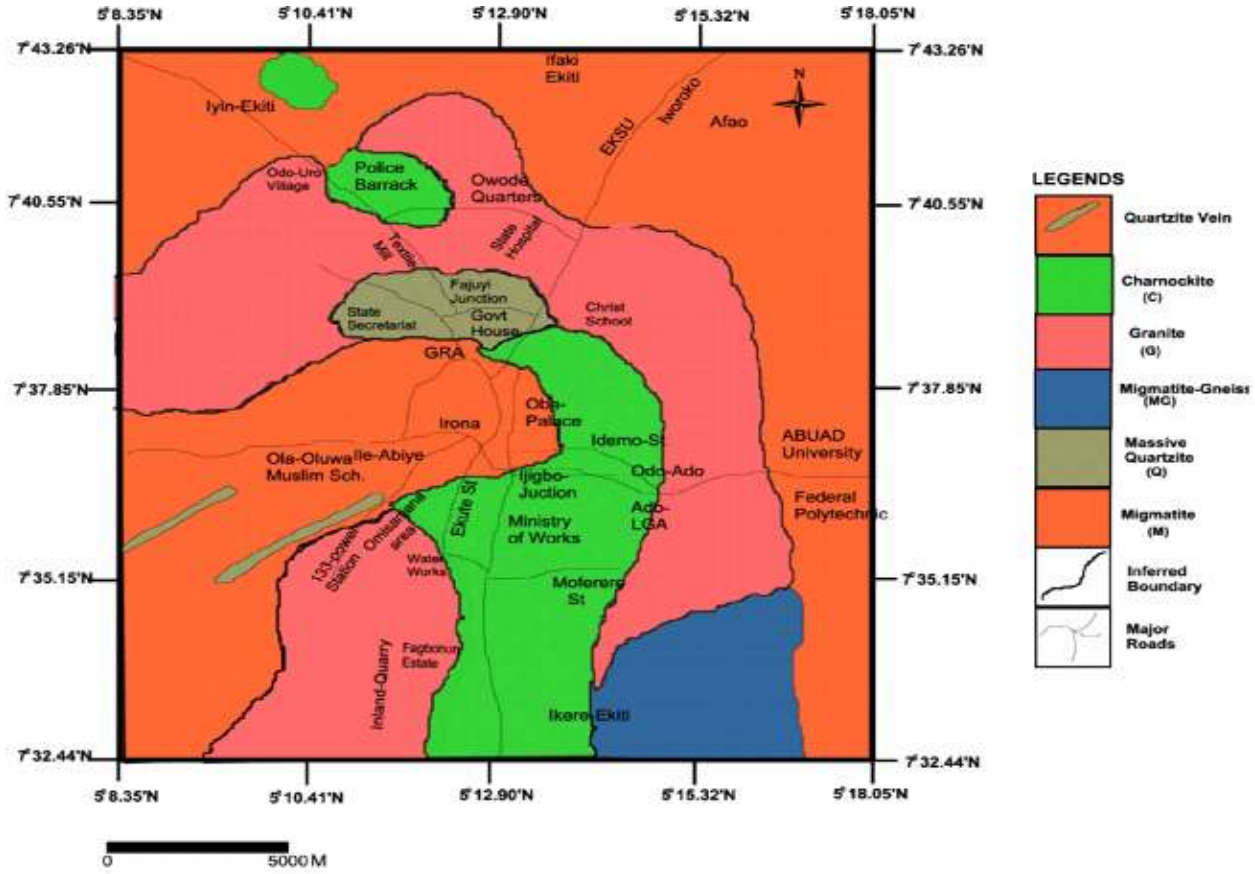


Fig. 1: Geological Map of Ado-Ekiti (Ajayi et al. 2019)

porosity, and Schmidt Rebound Hammer (SRH) test were determined using the ISRM (2007) suggested methods.The point load test (PLT) was carried out according to the procedure recommended by the ISRM (1985). The PLT test was carried out at least three times and the average values recorded.

Slake durability test serve as one of the methods to examine the susceptibility to weathering or durability of rocks in different geo-environmental conditions or chemical environment. According to the procedure suggested by Franklin and Chandra (1972), the durability of a rock is usually assessed using the 2ndslake durability index. However,Ghobadi and Momeni (2011) argued that two cycles slake durability test may not be adequate to indicate the durability of a rock. Based on this assertion, the slake durability test in this research was performed in eight cycles. This is based on the work of Momeni et al. (2017) which states that for evaluating the long term durability of granitic rocks, at least eight slake durability cycles should be considered. The granitic rocks were evaluated for slake durability using different saline solutions (Na_2SO_4 and $CaCl_2$solutions) as slaking fluid. Six different Na_2SO_4 and $CaCl_2$solutions (3 each) were prepared with concentration values of 25, 50, and 75 % by weight. Based on ASTM (2008) standard, ten representative rock pieces of the granitic rocks, each weighing about 40 – 60g were prepared and their edges were made blunt using a hammer (Figure 2). The rock pieces were air-dried and placed in the drum of slake durability test apparatus. The drum was submerged or immersed in the slaking fluid at 20° C and rotated at a standard rate (i.e., 20 rev/min) for ten minutes. The rock fragments retained in the drum were oven-driedat 110° C for twenty-four hours, and subsequent cooled and mass determined. This process was repeated eight times (8 cycles). SDI is defined "as percentage ratio of final and initial dry mass of rocks" in the drum.

Results and Discussion

Petrographic Characteristics

Thin sections prepared from the rock samples and observed on a polarizing microscope indicate that the petrographic characteristics of the rocks reflect the mineralogical features and textural variations observed

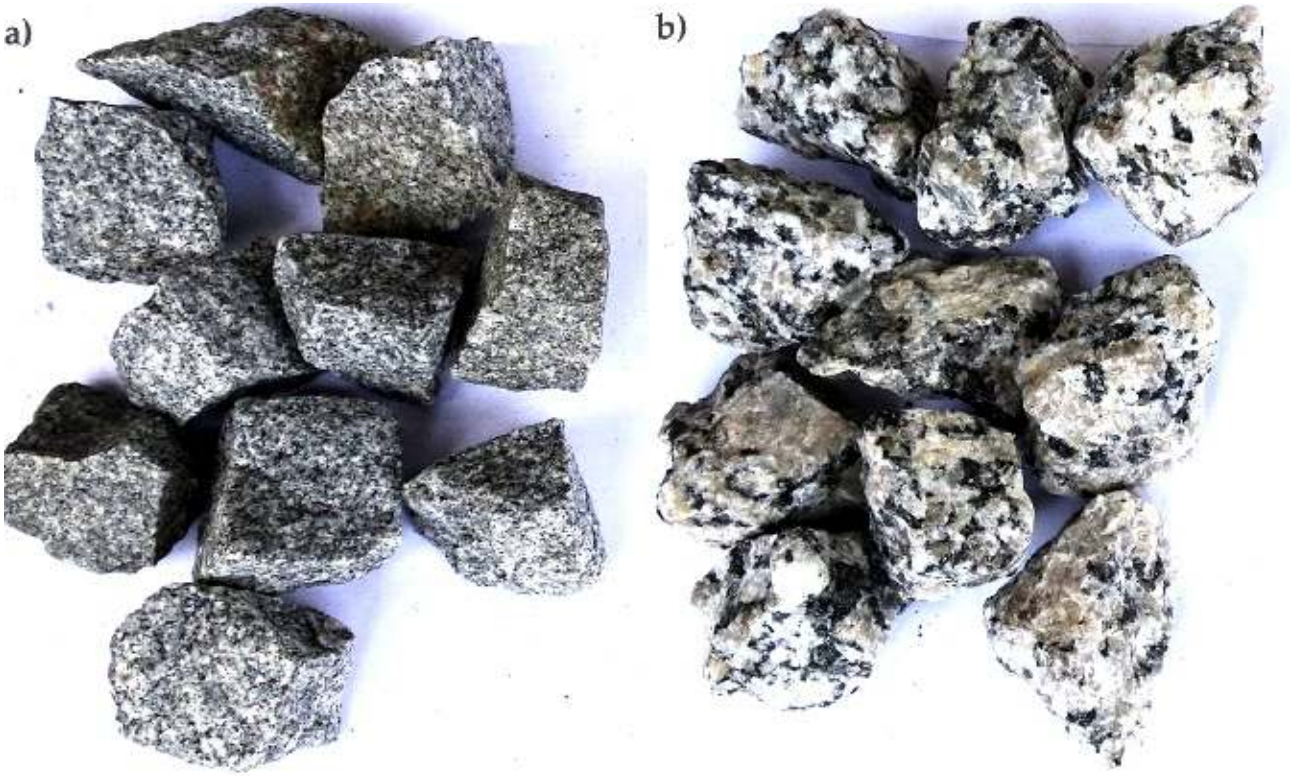


Fig. 2: Tested rock lumps. a) Fine-grained granite b) Porphyritic granite

in hand specimen and on outcrops. The porphyritic granite consists of quartz (12- 18%), and feldspars (microcline, 16-23%; orthoclase, 18-21%; plagioclase, 20-26%) as the major mineral aggregates. Hornblende (6-9%), biotite (8-12%), and muscovite (1-2%) occurs as the minor mineral aggregates. Quartz crystals have well defined edges and irregular. They vary in sizes and are isolated. Grains of quartz and hornblende form the supporting minerals in an interlocking crystal structure (Figure 3). Biotite occurs in form of large brown acicular crystals with high aspect ratios. They occur in clusters while they are separated from each other in some places. However, all the minerals show random distribution (Figure 3a, b). The color of microcline ranges from grey to light brown and has acharacteristic cross-hatched twinning (Figure 3b). Plagioclase shows recognizable Carlsbad twinning with well-defined edges and appears subhedral. Orthoclase crystals appear bulky and make contact with quartz and plagioclase. It has sutured edges and the crystals are striated.

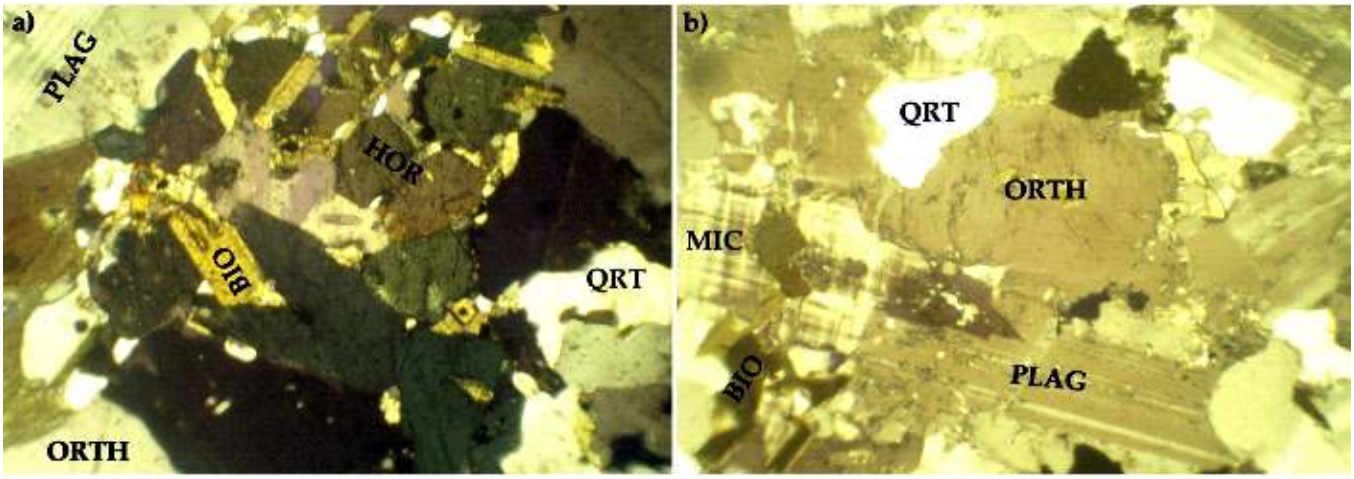


Fig. 3: Photomicrograph of porphyritic granite in transmitted light. **QTZ,** Quartz; **PLAG,** Plagioclase Feldspar; **ORTH,** Orthoclase Feldspar; **MIC,** Microcline; **BIO,** Biotite

The fine-grained granite is made up of quartz (40-46%), microcline (6-7%), hornblende (32-35%) and biotite (10-15%). Biotite grains have low relief, randomly arrangedand haphazard in orientation. They are dark to brown in color and located in interstices of other minerals (Figure 4a and b). The biotite crystals are in the form of acicular grains. Microcline appears as large, bulky grains with pronounced grid twins (Figure 4a). Quartz is made up of fine, clear, and angular crystalswith sharp contacts. Hornblende is few, scattered and dark to straw green in color (Figure 4a and b).

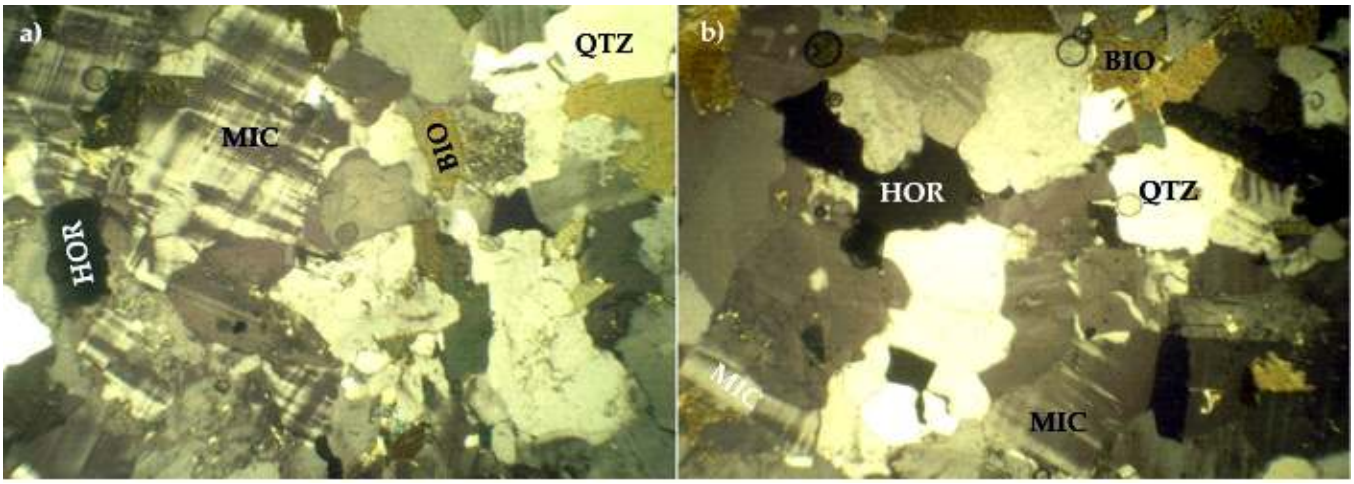


Fig. 4: Photomicrograph of fine-grained granite in transmitted light. QTZ, Quartz; PLAG, Plagioclase Feldspar; ORTH, Orthoclase Feldspar; MIC, Microcline; BIO, Biotite

Physical and Index Properties

Mineral component and texture are factors that influence the physical and mechanical properties of rocks. Table 1. presents the physical and index properties of the granitic rocks. The average water content, water absorption capacity and porosity of the porphyritic granite is higher compared to those of fine-grained granite. The low water absorption capacity of the two granitic rocks may be due to low degree of weathering of the ferromagnesian and feldspathic minerals in the rocks.

The average values of porosity obtained for the fine-grained and porphyritic granites, respectively, are 0.34 and 0.52%. These values are classified as very low according to the International Association for Engineering Geology and the Environment (IAEG 1979). The very low porosity of the tested granitic rocks may be due to their tight interlocking crystalline texture.

The average dry density of the fine-grained granite (2.51 g/cm^3) is lower compared to the average dry density of theporphyritic granite (2.61 g/cm^3). The absence of voids and low moisture contents may be responsible for the high dry density of the tested granitic rock samples. Among the index tests, the point load and SRH tests are

Table 1: Physical and Index Properties of the Granitic Rocks

Rock Type	W (%)	WAC (%)	η	ρ (g/cm^3)	PLS (MPa)	SRH
PG	0.31	0.98	0.56	2.60	7.84	56
	0.27	0.64	0.55	2.60	9.81	54
	0.34	0.51	0.53	2.63	8.83	52
	0.44	0.55	0.52	2.64	8.83	52
	0.50	0.89	0.45	2.60	9.81	50
Ave.	0.37	0.71	0.52	2.61	9.02	52.8
FGG	0.08	0.45	2.38	2.65	15.92	52
	0.10	0.53	0.36	2.53	14.71	52
	0.06	0.39	0.67	2.62	16.67	50
	0.09	0.64	0.089	2.44	15.79	50
	0.06	0.46	0.2	2.65	15.69	48
Ave.	0.078	0.49	0.34	2.57	14.76	50.4

FGG, Fine-grained granite; PG, Porphyritic granite. The values presented in the table are the average of seven granitic rock specimens. In determining the Schmidt Rebound Hammer value the ten least values were discarded and the average of the highest ten values was calculated.

inexpensive methods for rock strength estimation. The Point Load Strength (PLS) and SRH value of fine-grained granite are higher compared to those of porphyritic granite. This indicates that fine grained granite is better in terms of strength than the porphyritic granite. Afolagboye (2021) pointed out that a strong linear relationship exists between the unconfined compressive and point load strength of the Precambrian

Basement Complex rocks. The variations in properties of the two granitic rocks may be due to the variation in texture and degree of interlocking or compactness of the rocks.

Slake Durability Index

Fig. 5 shows the effects of the wetting-drying cycles on variation in mass loss of the granitic samples during the slake durability test. Figure 5a and 5b is showing the mass loss in fine-grained and porphyritic granite, respectively. Not much difference exists in the shape of the rock aggregates after the eighth cycle of the slake durability test. While the percentage mass loss increased with the number of slaking cycles, the rate of mass loss decreased as the number of slaking cycles increases in both salty solutions. In addition, compared with the final cycles, the rate of mass loss is higher at the initial cycles of the slake durability test. It was also observed that the mass loss was maximum in porphyritic granite samples both in Na_2SO_4 and $CaCl_2$ aqueous solutions.

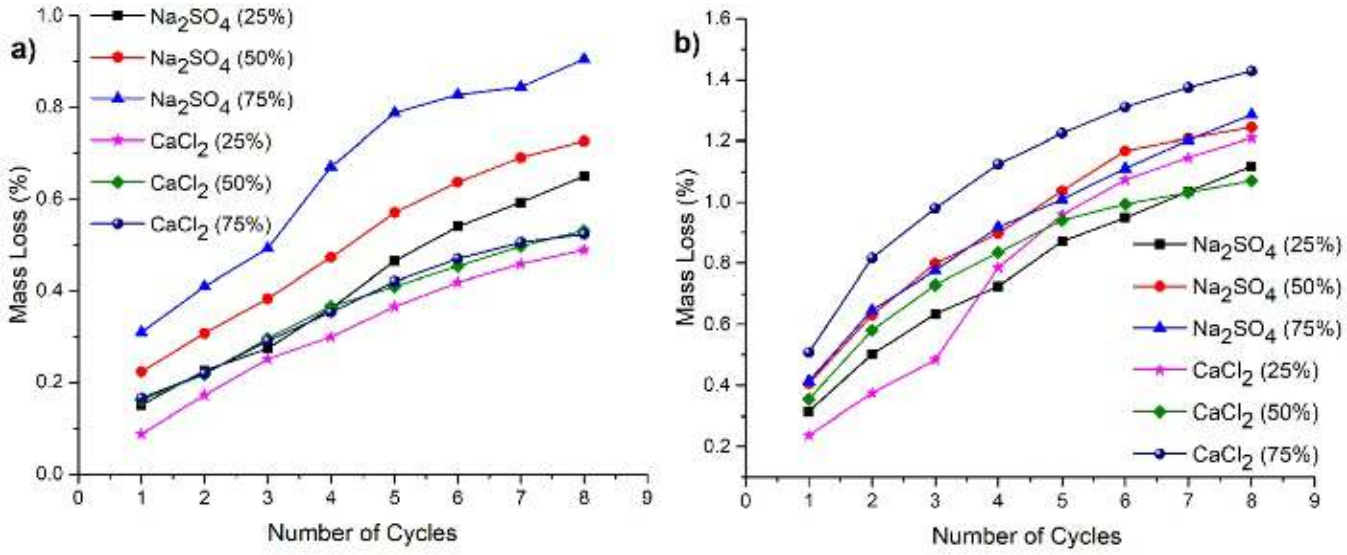


Fig. 5: Plots of mass loss (%) in Na2SO4 and CaCl2 solutions against number of slaking cycles during the 8-cycle slake durability test. a) Fine-grained granite b) Porphyritic granite

The increase in mass loss with increase in number of cycles shows the influence of the number of slaking cycles, rock texture, variation in the rock properties, along with the type and concentration of salt on the durability of the granitic rock samples. In fine-grained granite, however, the rock experienced greater mass loss in Na_2SO_4 solution (in all concentration and slaking cycles) than in $CaCl_2$ solution. This is contrary to what was observed in porphyritic granite where the mass loss in Na_2SO_4 and $CaCl_2$ solutions was indistinct in nature. This is possibly due to the texture and high porosity of porphyritic granite compared to fine-grained

The slake durability index of the granitic rocks in different salty solutions is shown in The slake durability indices of the fine-grained and porphyritic granites decreased as number of slaking cycles increases in both salty aqueous solutions. The porphyritic granite samples compared with fine-grained granite have lower slake durability index in all the slaking cycles and both in Na2SO4 and CaCl2 solutions. This may be because of the difference in texture and properties such as porosity and water absorption capacity. Porphyritic granite samples may be quite susceptible to the salty aqueous solution because of their lower strength, higher water absorption capacity and higher porosity. It is assumed that the porphyritic granite with high porosity and absorption capacity will absorb large amount of salt solution and as a result more salt crystallizes within the pore spaces. This will eventually produce stronger stresses in the rock fabrics. The rock, due to its lower strength, will offer little resistance to the stress induced by the salt recrystallization.

Table 2. Figures 6 and 7, respectively, show the slake durability index against the number of slaking cycles in Na_2SO_4 and $CaCl_2$ solutions for the granitic rock samples. The slake durability indices of the fine-grained and porphyritic granites decreased as number of slaking cycles increases in both salty aqueous solutions. The

porphyritic granite samples compared with fine-grained granite have lower slake durability index in all the slaking cycles and both in Na_2SO_4 and $CaCl_2$ solutions. This may be because of the difference in texture and properties such as porosity and water absorption capacity. Porphyritic granite samples may be quite susceptible to the salty aqueous solution because of their lower strength, higher water absorption capacity and higher porosity. It is assumed that the porphyritic granite with high porosity and absorption capacity will absorb large amount of salt solution and as a result more salt crystallizes within the pore spaces. This will eventually produce stronger stresses in the rock fabrics. The rock, due to its lower strength, will offer little resistance to the stress induced by the salt recrystallization.

Table 2: Slake Durability Indices of the Granitic rocks

Rock Type	No. of Cycles	Na_2SO_4			$CaCl_2$		
		25%	50%	75%	25%	50%	75%
FGG	1	99.28	98.92	98.61	99.59	99.28	99.19
	2	98.92	98.50	98.15	99.20	99.02	98.92
	3	98.69	98.13	97.78	98.83	98.67	98.57
	4	98.27	97.70	96.98	98.61	98.36	98.26
	5	97.78	97.22	96.45	98.30	98.16	97.93
	6	97.42	96.90	96.27	98.06	97.97	97.69
	7	97.17	96.64	96.19	97.87	97.77	97.52
	8	96.89	96.46	95.92	97.73	97.61	97.43
PG	1	98.62	98.29	98.14	98.96	98.11	97.82
	2	97.80	97.34	97.09	98.36	96.90	96.50
	3	97.22	96.64	96.51	97.88	96.11	95.80
	4	96.82	96.22	95.87	96.56	95.55	95.18
	5	96.19	95.63	95.46	95.80	94.99	94.75
	6	95.85	95.08	95.01	95.30	94.70	94.38
	7	95.47	94.91	94.59	94.98	94.50	94.11
	8	95.11	94.76	94.22	94.70	94.30	93.87

FGG, Fine-grained granite; **PG,** Porphyritic granite

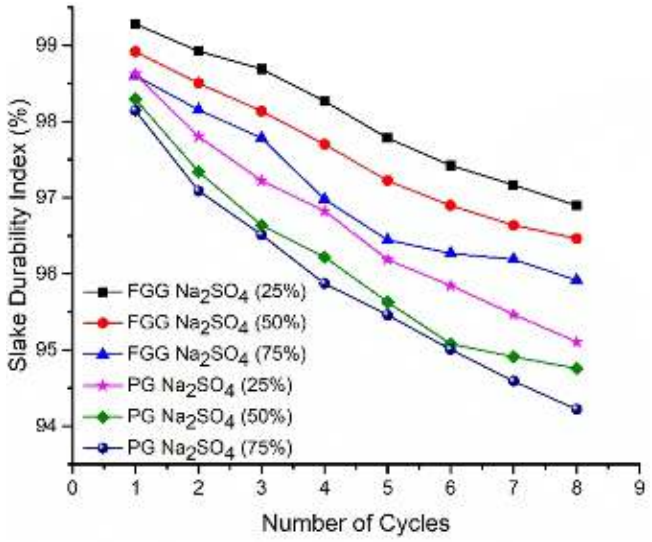


Fig. 6: Slake durability index of granitic rocks tested in Na_2SO_4 solution of different concentration

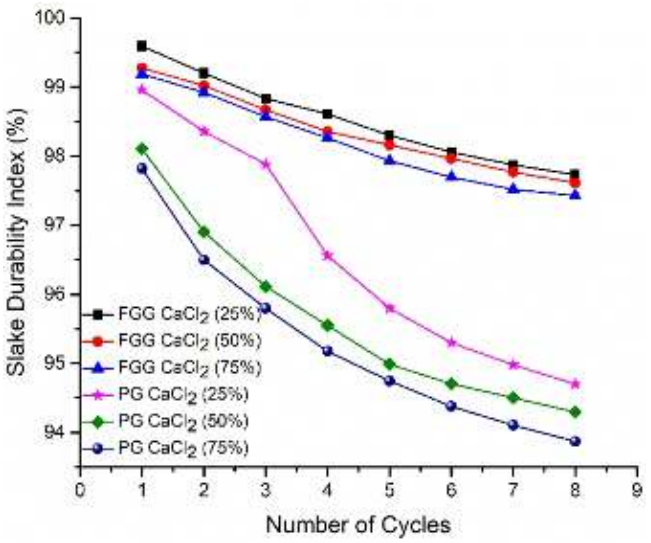


Fig. 7: Slake durability index of granitic rocks tested in $CaCl_2$ solution of different concentration

In both salty solutions, the slake durability index decreased as the concentration of the solutions increases (Figs. 6 and 7). This, according to Coussy (2006), is because increase in salt concentration in the solution can increase the pressure exerted on the pore wall by the salt crystals, which will eventually lead to more damage. The fine-grained and porphyritic granites have the least slake durability when the concentration of the salty solutions was 75% at all the slaking cycles. This may be as a result of attack by dissolved electrolytes in the salt solutions. The influence of salt concentration on the slake durability index is distinct as the concentration increases from 25% to 75% in all the slaking cycles. This is contrary to the results obtained when hornfels, granite and carbonate rocks are evaluated in acidic and alkaline solutions of different pH(Ghobadi and Momeni 2011; Ghobadi and Mousavi 2014; Yagiz 2018). The influence of pH on the slake durability index of the rocks is indistinct as the pH increases from 4 to 12 in some of the slaking cycles.

Comparing the slake durability index of the granitic rocks in the two salty solutions, it was observed that the granitic rocks behaved differently in the salty solutions. The slake durability index of the fine-grained granite in Na_2SO_4 is lower than in $CaCl_2$ in all the slaking cycles except in few slaking cycles (1,2,3 and 4) when the concentration of Na_2SO_4 was 25 % (Fig. **8**a). On the other hand, the slake durability index of the porphyritic granite in $CaCl_2$ at 50% and 75% concentration was lower than in Na_2SO_4 in all the slaking cycles (Figure 8b). However, the slake durability index of the porphyritic granite in $CaCl_2$ at 25% concentration (slaking cycles 1, 2 and 3) was higher than in Na_2SO_4.

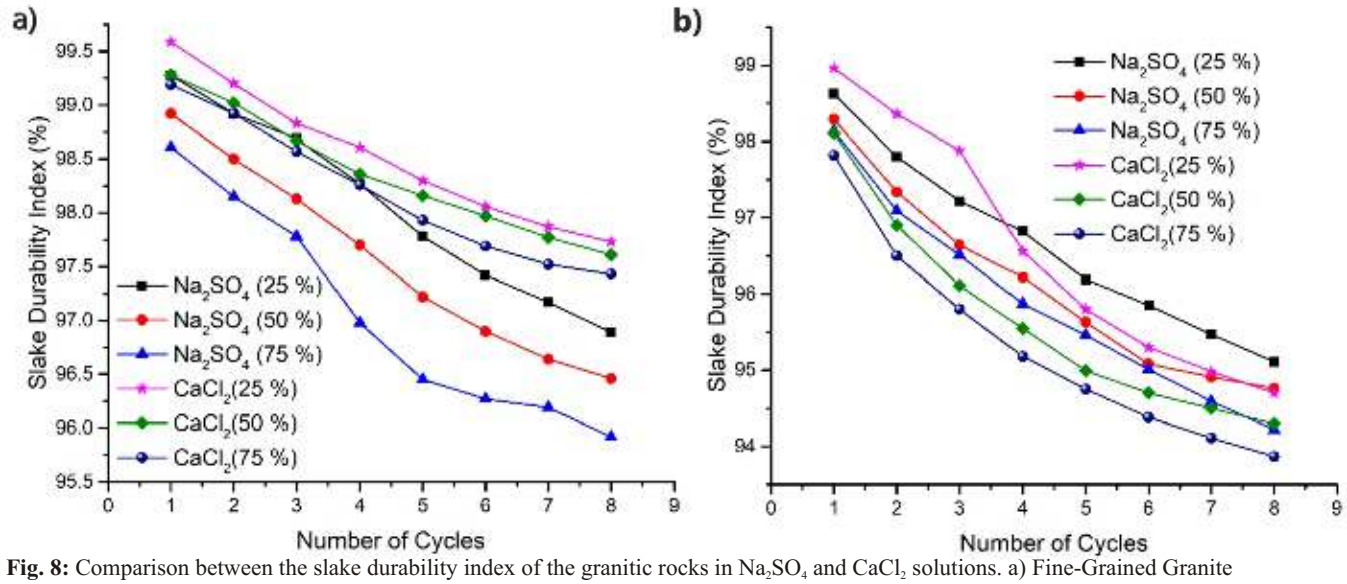


Fig. 8: Comparison between the slake durability index of the granitic rocks in Na_2SO_4 and $CaCl_2$ solutions. a) Fine-Grained Granite b) Porphyritic Granite

According to Ghobadi and Mousavi (2014), the difference in damage or behavior between the salty solution is due to the kinetics of crystallization and the presence of hydrated and anhydrous crystals. The varied texture and porosity of the porphyritic granite might explain why the slake durability index of the porphyritic granite in $CaCl_2$ was lower than in Na_2SO_4 This creates a situation where the durability index is influenced more by rock material properties rather than the type of the slaking fluid.

The durability classification of Franklin and Chandra (1972) when compared with the slake durability index results of thefine-grained and porphyritic granites show that rocks have very high to extremely high durability.The durability range of the granitic rocks based on the concentration of slaking fluid at the 2^{nd}, 4^{th}, 6^{th} and 8^{th} cycles of slaking is presented in Table 3. At all the concentration of the salty solutions, the durability index of fine-grained granite is extremely high. On the other hand, the durability of the porphyritic granite is very high at higher concentration of the slaking fluids and slaking cycles.

Conclusions

Slake durability test up to eight cycles was carried out on fine-grained and porphyritic granites in different salty

Table 3: Durability index of the granitic rocks based on concentration of slaking fluid at the different cycles of slaking

Rock Type	# Cycle	Na_2SO_4			$CaCl_2$		
		25%	50%	75%	25%	50%	75 %
FGG	2	1	1	1	1	1	1
	4	1	1	1	1	1	1
	6	1	1	1	1	1	1
	8	1	1	1	1	1	1
PG	2	1	1	1	1	1	1
	4	1	1	1	1	1	1
	6	1	1	1	1	2	2
	8	1	2	2	2	2	2

1, 95-100 (extremely high); **2, 90-95** (very high); **FGG,** Fine-grained granite; **PG,** Porphyritic granite

solutions of various concentration to study the effects of concentration of salty solutions (slaking fluid) and different solutions on the durability of the granitic rocks. The granitic rocks are not significantly different from each other petrologically in terms of observed mineral components but differ in term of texture. The average water content, porosity, and water absorption of the porphyritic granite is higher compared to those of fine-grained granite. The point load strength and Schmidt rebound hammer value of porphyritic granite are lower compared to those of fine-grained granite. The percentage mass loss increases with the number of slaking cycles. Compared with the final cycles, the rate of mass loss is higher at the initial cycles of the slake durability test. The mass loss was maximum in porphyritic granite samples both in Na_2SO_4 and $CaCl_2$ aqueous solutions. The slake durability index of the granitic rocks range from very high to extremely high in the different salty solutions and concentration. The slake durability indices of the fine-grained and porphyritic granites decreased as the number of slaking cycles and concentration of the solutions increases in both salty solutions. The porphyritic granite samples compared with fine-grained granite have lower slake durability index in all the slaking cycles and both in Na_2SO_4 and $CaCl_2$ solutions. Comparing the slake durability index of the granitic rocks in the two salty solutions, it was observed that the granitic rocks behaved differently in the salty solutions. The granitic rock with coarse texture, high porosity and low strength is relatively more susceptible to degradation in salty solutions. Hence, fine-grained granite is less susceptible to degradation in comparison with porphyritic granite.

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