INFLUENCE OF SOLUTION pH ON SLAKE DURABILITY AND CHEMICAL WEATHERING OF GRANITE: AN ASSESSMENT USING CIA AND PIA INDICES

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ABSTRACT

The durability of rock materials under environmental conditions is governed by a combination of mechanical disintegration and chemical weathering processes. This study investigates the influence of solution pH on the slake durability behaviour of granite collected from the Bundelkhand region of central India. Repeated wetting-drying cycles were performed following ISRM standards using slaking media with pH values of 3, 5, 7, 9, and 11. The chemical composition of the rock samples and molar proportions of key oxides were computed to evaluate chemical weathering trends. Two widely accepted geochemical indices - Chemical Index of Alteration (CIA) and Plagioclase Index of Alteration (PIA) - were used to quantify the degree of alteration during successive slaking cycles.

The results indicate that CaO exhibits the highest mobility, particularly under acidic conditions, signifying preferential leaching of Ca bearing minerals, while Al_2O_3 remains relatively immobile and becomes residually enriched. CIA values ranging from approximately 72 to 90 indicate moderate to intense weathering, with increasing trends in later cycles reflecting progressive alteration. Consistently high PIA values (> 85) highlight dominant plagioclase weathering and the transformation of feldspar minerals into clay-rich phases. Mildly acidic conditions (pH = 5) were found to promote sustained and systematic chemical weathering, whereas extreme pH environments accelerated reactions but resulted in higher variability.

Keywords: *chemical index of alteration, chemical weathering, pH influence on rock durability, plagioclase weathering, slake durability index.*

INTRODUCTION

Repeated wetting and drying of rocks are considered one of the main processes that can induce micro-fissures in the rock material which may lead to the failure of rock [1]. This process of disintegration of rocks upon wetting and drying is known as climatic slaking [2]. The slake durability index (SDI) is a key parameter used to evaluate the disintegration of the rocks under repeated wetting and drying conditions, particularly in engineering and geological applications . Understanding rock durability is essential for various fields, including geotechnical engineering, construction material selection, and slope stability assessments [3, 4]. However, the rate of disintegration of the rocks under repeated wetting and drying is primarily influenced by their chemical composition and pH of slaking media [5].

Quartz-rich rocks generally exhibit higher mechanical strength and durability, contributing to improved resistance against disintegration during repeated wetting-drying cycles [6, 7]. In the silicate rocks Al_2O_3, CaO, K_2O, and Na_2O play key roles in controlling chemical weathering and represent mobile alkali and alkaline earth elements mainly hosted in feldspars and mica, which are readily leached during weathering through hydrolysis reactions [8, 9]. Their removal leads to weakening of mineral bonds and promotes the formation of secondary clay minerals. In contrast, Al_2O_3 is relatively immobile and becomes progressively enriched as weathering advances, reflecting feldspar breakdown and clay development. This contrasting behaviour forms the basis of widely used chemical weathering indices and strongly influences the mechanical durability of rocks [10].

In this paper, an attempt is made to investigate the coupled effect of chemical weathering and mechanical degradation on the slake durability behaviour of granite under controlled laboratory conditions at different pH conditions. The integration of slake durability testing with geochemical indices provides a comprehensive framework to elucidate the role of pH-dependent chemical processes in controlling rock durability, thereby offering insights relevant to geotechnical engineering and rock performance evaluation under environmental conditions.

EXPERIMENTAL

Materials and methods

For the present investigations, the granite rock samples were collected from the Bundelkhand region of central India. Granite is known for its architectural beauty and is widely used in building construction. It is an igneous rock and has widespread use in construction. It consists of a complex mineralogical composition. To ascertain the chemical composition of the rocks, Shimadzu, XRF EDX-7000 (Energy Dispersive X-ray Fluorescence spectrometer) is used. It works by bombarding a sample with primary X-rays, which causes the atoms in the sample to emit fluorescent rays. The EDX-7000 detects and measures these energies to identify and quantify the elements present in the sample.

To determine the slake durability characteristics of the rock material, representative rock fragments weighing about 40 - 60 g each were collected and oven dried at 105 ± 5°C for 24 h. The initial dry weight of the samples (W_0) was then recorded. The dried specimens were placed in a rotating drum fitted with a mesh screen and partially immersed in a water bath maintained at room temperature. The drum was rotated at a speed of 20 ± 2 rpm for 10 min. After completion of the rotation cycle, the drum was removed, drained, and the retained samples were again oven dried at 105 ± 5°C for 24 h. The dry weight after the first cycle (W_1) was measured. The wetting and drying procedure was repeated successively up to the fifth cycle, and the corresponding dry weights (W_2 to W_5) were recorded after each cycle. The Slake Durability Index (SDI) for each cycle was calculated using the following relationship:

$$SDI_n = \left(\frac{W_n}{W_0}\right) \times 100$$

where W_0 is the initial dry weight of the sample, W_n is the dry weight after the nth cycle, and n represents the cycle number.

All the tests were conducted as per ISRM standards [11]. The slake durability test was performed using aqueous solutions having different pH values, such as 3, 5, 7, 9, and 11 as the slake medium. The distilled water at pH = 7 was used to eliminate the effects of acidity or alkalinity on rock degradation. The choice of distilled water ensured that the disintegration observed was due to the intrinsic properties of the rock itself rather than any external chemical influence, acidic or alkaline, from the testing medium.

To study the effect of chemical indices on weathering, two commonly used indices namely Chemical Index of Alteration (CIA) and Plagioclase Index of Alteration (PIA) are used.

Chemical Index of Alteration (CIA)

The Chemical Index of Alteration (CIA) is a quantitative geochemical parameter that measures the degree of chemical weathering of silicate rocks [12]. It is based on the principle that, during chemical weathering: mobile elements such as Ca, Na, and K are preferentially removed from primary silicate minerals (especially feldspars) by dissolution and leaching. However, Aluminium (Al) is relatively immobile and becomes concentrated in the residual material, often forming secondary clay minerals [13]. Therefore, CIA expresses the extent to which feldspars have been altered into clay minerals, which directly affects the mechanical durability of rocks. Mathematically it is represented in Eq. (1):

$$CIA = \frac{Al_2O_3}{Al_2O_3 + CaO + Na_2O + K_2O} \times 100 \quad (1)$$

Low CIA values, typically in the range of 45 - 55, indicate fresh or slightly weathered rocks with intact feldspar structures and strong intergranular bonding, whereas higher CIA values reflect progressive feldspar dissolution, enrichment of aluminium, and increased development of clay minerals. As chemical alteration advances, porosity and microcracking increase, leading to a gradual reduction in mechanical strength and durability. In laboratory slake durability tests, repeated wetting-drying cycles and variations in solution pH accelerate these chemical processes, resulting in a systematic increase in CIA accompanied by a decrease in slake durability index. Although CIA represents overall silicate weathering and may be less sensitive than more mineral-specific indices, it provides a robust and widely accepted measure of chemical alteration and offers valuable insight into the chemical mechanisms governing rock durability degradation under controlled experimental conditions.

Plagioclase Index of Alteration (PIA)

It is a geochemical parameter widely used to quantify the degree of chemical weathering of plagioclase feldspar, which is one of the most chemically reactive and mechanically significant minerals in many rock types [14]. Plagioclase commonly occurs along grain boundaries and contributes substantially to intergranular bonding; therefore, its alteration has a direct influence on rock strength and durability. This is denoted in Eq. (2):

$$PIA = \frac{Al_2O_3 - K_2O}{Al_2O_3 + CaO + Na_2O - K_2O} \times 100 \qquad (2)$$

During chemical weathering, plagioclase undergoes hydrolysis, resulting in the leaching of mobile cations, particularly Ca^{2+}, while aluminium remains relatively immobile and becomes concentrated in the residual material, leading to the formation of secondary clay minerals. The PIA was developed to specifically isolate the alteration of plagioclase by eliminating the influence of K-feldspar, which weathers more slowly and may not directly control mechanical degradation.

Low PIA values (approximately 50) indicate fresh or slightly weathered plagioclase with strong grain-to-grain bonding and high slake durability, whereas higher PIA values reflect progressive dissolution of plagioclase, development of clay-rich alteration products, increased micro-porosity, and weakening of grain boundaries. As a result, an increase in PIA is closely associated with a reduction in slake durability index during repeated wetting-drying cycles [15]. Compared to other chemical weathering indices, PIA is particularly sensitive to early-stage chemical damage and provides a direct mineralogical link between chemical alteration processes and mechanical degradation of rocks under varying pH conditions.

While calculating the value of CIA and PIA the molar proportions of all chemical components are used. Molar proportions express chemical components in terms of moles rather than weight percent, reflecting the actual number of reacting units [16, 17]. They are obtained by dividing oxide weight percentages by their molecular weights. The formula for calculating molar proportions of an oxide is presented in Eq. (3):

$$\text{Molar proportion of oxide} = \frac{\text{Weight \% of oxide}}{\text{Molecular weight of oxide}} \qquad (3)$$

RESULTS AND DISCUSSION

The slake dur ability test primarily evaluates the mechanical disintegration of rock due to wetting and drying cycles, rather than purely chemical weathering. The chemical composition of intact rock and its molar proportions are indicated in Table 1.

Table 1. Chemical composition of intact rock and its molar proportions.

Analyte	Proportions, wt. %	Molecular weight, g mol^{-1}	Molar proportions
SiO_2	75.339	60.08	1.2540
Al_2O_3	20.594	101.96	0.2020
K_2O	3.058	94.20	0.0325
Fe_2O_3	0.549	159.69	0.0034
CaO	0.321	56.08	0.0057
TiO_2	0.093	79.87	0.0012
MnO	0.012	70.94	0.0002
SrO	0.005	103.62	0.0000

Since granite is a low-porosity rock with minimal susceptibility to water absorption, it does not undergo significant breakdown due to repeated immersion in solutions of varying pH. The lack of microcracks or porous pathways that could facilitate chemical interaction further reinforces its resistance to pH-induced degradation. The chemical composition of the rock samples after each cycle of slake durability test at different pH are summarized in Table 2. For the determination of Slake Durability Index (SDI) and XRF analysis, three representative samples were tested for each case, and the average value obtained was

Table 2. Chemical composition of rock samples after each SDI cycles for different pH.

Analyte	pH = 3	pH = 5	pH = 7	pH = 9	pH = 11
After first SDI cycle					
SiO_2	74.194	75.578	75.726	76.013	75.311
Al_2O_3	21.04	20.196	20.25	19.742	20.096
K_2O	3.248	3.161	3.152	3.086	3.471
Fe_2O_3	0.919	0.467	0.407	0.461	0.528
CaO	0.325	0.353	0.34	0.385	0.452
TiO_2	0.226	0.011	0.085	0.073	0.109
MnO	0.014	0.011	0.009	0.011	0.012
SrO	0.004	0.004	0.003	0.004	0.005
After second SDI cycle					
SiO_2	76.297	76.236	75.452	74.89	77.439
Al_2O_3	19.4	19.328	20.151	20.446	18.09
K_2O	3.379	3.257	3.267	3.629	3.648
Fe_2O_3	0.475	0.614	0.622	0.458	0.393
CaO	0.235	0.392	0.308	0.225	0.265
TiO_2	0.167	0.014	0.163	0.102	0.133
MnO	0.009	0.014	0.012	0.011	0.008
SrO	0.004	0.003	0.005	0.005	0.005
After third SDI cycle					
SiO_2	74.767	75.949	76.214	77.046	76.032
Al_2O_3	20.566	19.625	19.066	18.986	19.724
K_2O	3.565	3.476	2.973	2.934	3.322
Fe_2O_3	0.451	0.556	1.206	0.585	0.519
CaO	0.555	0.231	0.366	0.273	0.258
TiO_2	0.059	0.013	0.109	0.136	0.111
MnO	0.009	0.013	0.018	0.013	0.01
SrO	0.006	0.004	0.003	0.004	0.004
After fourth SDI cycle					
SiO_2	75.05	73.322	74.912	74.063	75.597
Al_2O_3	20.413	21.923	20.739	21.751	19.846
K_2O	2.932	3.684	3.317	3.334	3.553
Fe_2O_3	0.66	0.647	0.474	0.386	0.533
CaO	0.573	0.284	0.454	0.335	0.323
TiO_2	0.116	0.013	0.064	0.099	0.113
MnO	0.016	0.013	0.009	0.008	0.012
SrO	0.005	0.006	0.004	0.005	0.005

Table 2. Chemical composition of rock samples after each SDI cycles for different pH. - *continued.*

Analyte	pH = 3	pH = 5	pH = 7	pH = 9	pH = 11
After fifth SDI cycle					
SiO_2	76.487	72.389	73.996	76.475	76.047
Al_2O_3	19.084	22.614	21.465	19.091	19.446
K_2O	3.24	3.767	3.734	3.495	3.528
Fe_2O_3	0.668	0.57	0.417	0.534	0.517
CaO	0.38	0.408	0.293	0.248	0.274
TiO_2	0.099	0.011	0.059	0.103	0.143
MnO	0.018	0.011	0.011	0.008	0.01
SrO	0.004	0.004	0.004	0.005	0.005

considered for further analysis and interpretation.

However, some of the key observations from the data presented in Table 2, indicates that:

- SiO_2 is relatively resistant to chemical weathering, though it may leach slightly in very alkaline conditions over successive cycles.
- Al_2O_3 is more sensitive to both acidic and alkaline conditions. pH extremes (3 and 11) tend to accelerate leaching or redistribution.
- K_2O leaches out more in alkaline environments, indicating susceptibility to base-induced dissolution.
- Fe_2O_3 is strongly influenced by redox conditions. Its variability could be linked to fluctuating oxidation states at different pH levels.
- CaO is highly soluble and leaches readily under both acidic and mildly alkaline conditions. Greater losses are seen over time.

The molar proportions of influencing chemicals after different cycles of Slake durability index (SDI) at different pH are shown in Table 3. The value for CIA and PIA is graphically represented for different SDI cycle at different pH, in Fig. 1 and Fig. 2, respectively.

The molar proportion and CIA data indicate that repeated SDI cycles under varying pH conditions induce progressive chemical weathering in granite, alongside mechanical disintegration. CaO exhibits the highest mobility, particularly under acidic conditions, reflecting preferential leaching of Ca - bearing minerals, whereas Al_2O_3 remains relatively immobile and becomes residually enriched as weathering advances. Moderate but systematic variations in K_2O suggest progressive feldspar and mica alteration, especially under neutral to alkaline pH. CIA values ranging from 72 to 90 signify moderate to high weathering intensity, with higher values in later cycles indicating enhanced alteration due to exposure of fresh mineral surfaces during slaking. Mildly acidic conditions (pH = 5) promote sustained chemical alteration over successive cycles, while extreme pH environments (pH = 3 and pH = 11) accelerate reactions but produce greater variability. Overall, the results demonstrate that durability loss in granite during SDI testing is controlled by a combined effect of mechanical breakdown and pH-dependent chemical weathering, and that molar proportion analysis and CIA provide robust indicators of weathering progression during slake durability processes.

Overall, the consistently high PIA values (generally > 85) across all pH conditions and SDI cycles indicate advanced chemical weathering of feldspar minerals, particularly the effective removal of mobile alkalis and alkaline earth elements during slaking. The increase in PIA during later SDI cycles, especially at pH = 5 and pH = 9, demonstrates that repeated wetting-drying enhances chemical alteration by exposing fresh mineral surfaces, thereby accelerating feldspar dissolution. Mildly acidic conditions (pH = 5) show the highest PIA values in advanced cycles, suggesting an optimal pH range for sustained plagioclase weathering, whereas extreme acidic (pH = 3) and alkaline (pH = 11) conditions promote rapid but less systematic alteration, resulting in greater index variability. When considered along with CIA trends and changes in molar proportions, such as loss of CaO, slight variation in K_2O, and enrichment of Al_2O_3 and the PIA results clearly show that chemical weathering plays a major role in reducing granite durability during SDI testing. They also indicate that the weathering of feldspar is a key factor controlling slake durability under different pH conditions.

Table 3. Molar proportions of influencing chemicals after different cycles of Slake durability index (SDI) at different pH.

Analyte	pH = 3	pH = 5	pH = 7	pH = 9	pH = 11
After first SDI cycle					
Al_2O_3	0.2064	0.1981	0.1986	0.1936	0.1971
K_2O	0.0345	0.0336	0.0335	0.0328	0.0368
CaO	0.0058	0.0063	0.0061	0.0069	0.0081
After second SDI cycle					
Al_2O_3	0.1903	0.1896	0.1976	0.2005	0.1774
K_2O	0.0359	0.0346	0.0347	0.0385	0.0387
CaO	0.0042	0.0070	0.0055	0.0040	0.0047
After third SDI cycle					
Al_2O_3	0.2017	0.1925	0.1870	0.1862	0.1934
K_2O	0.0378	0.0369	0.0316	0.0311	0.0353
CaO	0.0099	0.0041	0.0065	0.0049	0.0046
After fourth SDI cycle					
Al_2O_3	0.2002	0.2150	0.2034	0.2133	0.1946
K_2O	0.0311	0.0391	0.0352	0.0354	0.0377
CaO	0.0102	0.0051	0.0081	0.0060	0.0058
After fifth SDI cycle					
Al_2O_3	0.1872	0.2218	0.2105	0.1872	0.1907
K_2O	0.0344	0.0400	0.0396	0.0371	0.0375
CaO	0.0068	0.0073	0.0052	0.0044	0.0049

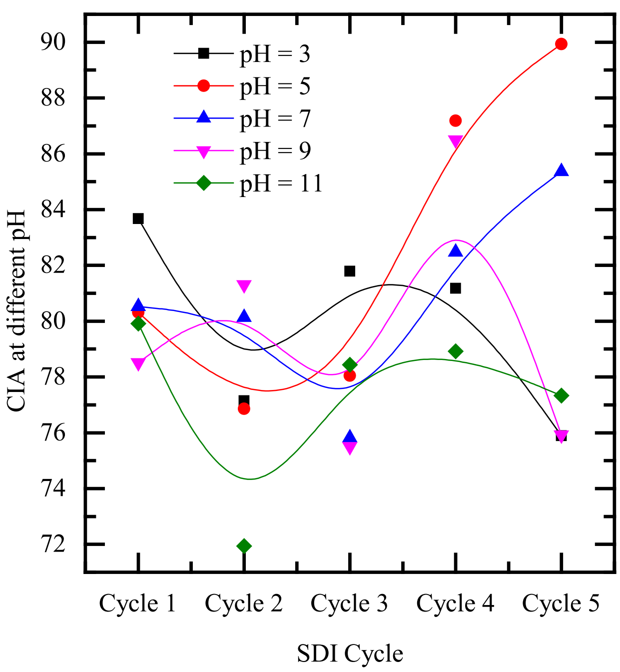

Fig. 1. CIA for different cycles of SDI at different pH.

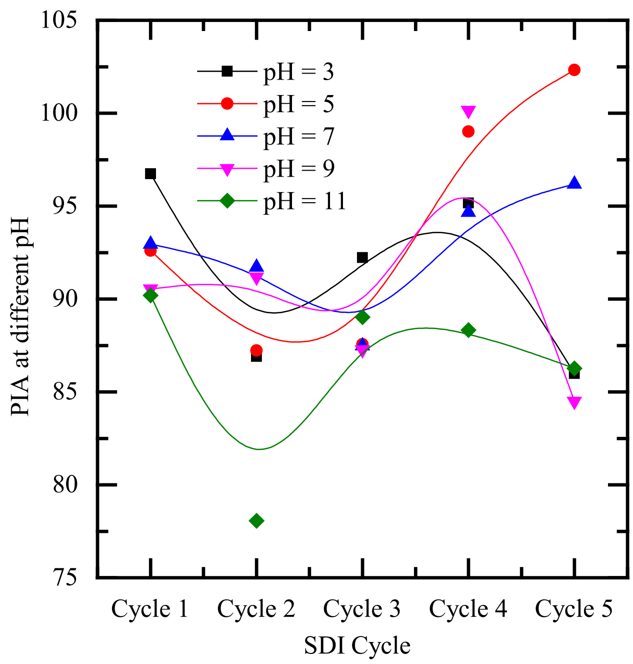

Fig. 2. PIA for different cycles of SDI at different pH.

CONCLUSIONS

The study highlights that the degradation of granite under slake durability testing is governed by the combined influence of mechanical breakdown and progressive chemical weathering. The increasing trends in geochemical indices and oxide mobility clearly demonstrate that chemical alteration, strongly influenced by environmental pH conditions, plays a crucial role in controlling durability loss during repeated wetting - drying cycles. However, some of the main conclusions are listed below:

- Granite degradation is controlled by the combined effects of mechanical disintegration and progressive chemical weathering, with increasing CIA and PIA values indicating intensified alteration over successive cycles.
- CaO exhibits high mobility due to preferential leaching of Ca bearing minerals (e.g., plagioclase), whereas Al_2O_3 remains relatively immobile and shows residual enrichment due to secondary clay mineral formation.
- Weathering of feldspar, particularly plagioclase, dominates the geochemical processes, as reflected by consistently high PIA values (often exceeding CIA).
- Mildly acidic conditions (around pH = 5) promote sustained and systematic chemical weathering, while extreme acidic and alkaline environments lead to rapid but irregular alteration.
- pH dependent chemical weathering significantly influences slake durability, and indices such as CIA and PIA serve as reliable indicators for evaluating alteration and predicting durability loss.

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Authors' contributions

A.K.A: Conceptualized the study, developed the research methodology, and established the overall framework and roadmap of the investigation; N.S.: Generated experimental data and contributed to data analysis and interpretation; R.K.: Conducted laboratory experiments, including sample preparation and XRF analysis, and assisted in manuscript formatting and organization.

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