Chemical and mineralogical weathering indices as applied to a granite saprolite in South Africa

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Abstract: The changes in the microfabric of a deep, chemically weathered granite saprolite at Injaka Dam site, South Africa, are conceptually reflected in the geochemical and mineralogical trends or signatures of the material. Thus, the degree of weathering (and its implied changes to the physical and engineering behaviour of the weathered material) can be scaled quantitatively according to the geochemical and mineralogical changes. This can be achieved by the use of chemical and mineralogical weathering indices. Over thirty such weathering indices have been proposed in the past. Whilst many were not originally designed specifically for engineering geological purposes, some have subsequently become popular in the past ten years due to their successful application, particularly on the weathering of basalts and granites. The role of chemical and mineralogical weathering indices is essentially to quantify the degree of depletion of mobile components relative to immobile components during weathering. These indices can then be applied to standard weathering grades of material set up by specific weathering classifications systems, which in turn are correlated with engineering behaviour. This paper describes the application of various chemical and mineralogical weathering indices to a deeply weathered granite saprolite in South Africa and to attempt to relate these indices to the density of the material which in turn has bearing on its engineering performance.

Résumé : Les changements dans la structure d'un granite saprolite profond, altéré chimiquement sur le site du barrage à Injaka, Afrique du Sud, rejaillissent conceptuellement dans les tendances géochimiques et minéralogiques ou dans les signes du matériau. Par conséquent, le degré d'altération (et ses changements impliqués dans le comportement physique et mécanique du matériau altéré) peut être mesuré quantitativement selon les changements géochimique et minéralogique. Ceci peut être réalisé en se servant des indices d'altération chimiques et minéralogiques. Plus de trente de ces indices d'altération ont été proposés dans le passé. Alors que bon nombre d'entre eux n'étaient pas spécialement destinés à l'origine à des besoins d'ingénierie géologique, quelques-uns sont devenus par la suite populaires au cours des dix années passées grâce à leur utilisation qui s'est révélée être une réussite, en particulier sur l'altération des basaltes et des granites. Le rôle des indices d'altération chimique et minéralogique est essentiel pour quantifier le degré d'appauvrissement des composants mobiles par rapport aux composants immobiles au cours de l'altération. Ces indices peuvent être appliqués aux standards des catégories de matériaux altérés établis par des systèmes spécifiques de classifications d'altérations, qui à leur tour correspondent au comportement mécanique. Cet article décrit l'application de divers indices d'altération chimique et minéralogique d'un granite saprolite profondément altéré en Afrique du Sud et tente de faire la relation de ces indices envers la densité du matériau qui à son tour se répercute sur sa performance de construction.

Keywords: geochemistry, weathering, engineering properties, igneous rock, soil description.

INTRODUCTION

As part of a detailed engineering geological investigation of granite saprolite at Injaka Dam in the north eastern region of South Africa, a chemical and mineralogical weathering index study has been applied to this material in an attempt to correlate the weathering characteristics (as defined by these indices) with the density (and hence engineering behaviour) of the saprolite. According to Aydin and Duzgoren-Aydin (2002), over 30 such chemical weathering indices have been proposed. Many were not originally designed for engineering geological purposes but have subsequently become popular in the last ten years due to their successful application, particularly to the weathering of basalts and granites as shown by Tugrul and Gurpinar (1997), Arel and Tugrul (2001), Gupta and Rao (2001), Ng *et al.* (2001) and Kim and Park (2003).

GEOLOGICAL AND GEOMORPHOLOGICAL SETTING OF THE SITE

Injaka Dam site is located in northeastern South Africa (Figure 1) and is underlain by medium-grained quartz-microcline-plagioclase-biotite migmatite and granite belonging to the 3 075 Ma Nelspruit Suite (SACS, 1980). According to the description of the geomorphic evolution of southern Africa by Partridge and Maud (1987), the site is located below the former position of the African erosion surface. This extensive geomorphic surface is representative of enduring, multiple weathering and erosion cycles that started in the Cretaceous and terminated in the Miocene, lasting some 140 million years and that was initiated by a series of continental uplifts. The extreme intensity of the weathering during this period has resulted in the formation of saprolitic soils up to 35 m thick in places typified by extensive kaolinisation of the weathered profile. The current sub-tropical climate of the area has also contributed to the enhanced chemical weathering, although the full extent of this effect has not been quantified. A typical sequence of the weathering profile encountered at the dam site is shown in Figure 2.

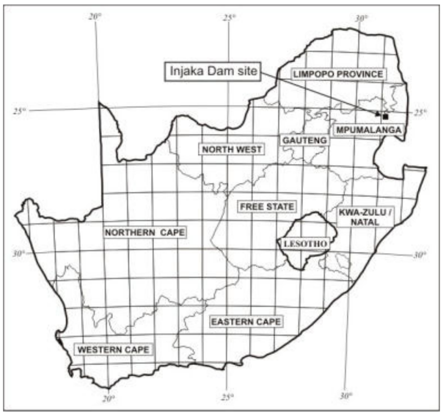

Figure 1. Locality of Injaka Dam site in South Africa.

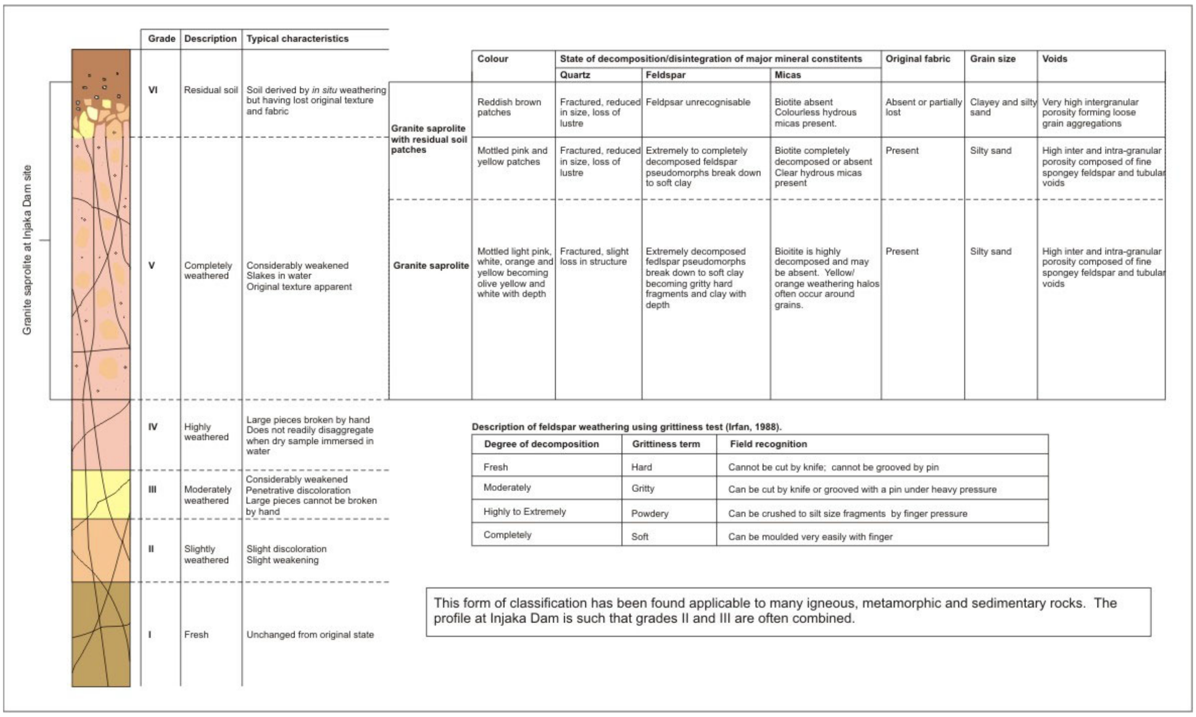

Figure 2. Typical weathering profile at Injaka Dam site (modified after Anon, 1995 and Irfan, 1988).

DESCRIPTION OF WEATHERED GRANITE AT INJAKA DAM SITE

The samples retrieved for this study included granite saprolite with residual soil patches, granite saprolite and highly weathered granite. The granite saprolite with residual soil patches occurs at the top of the profile and is distinguished from the saprolite proper in that it has some loss of relict fabric due to a more advanced weathering state. The horizon varies in thickness from 1.0 to 2.0 m with a gradational contact with the underlying granite saprolite. This material characteristically features irregular shaped, highly oxidised, reddish brown patches of loose, silt and clay aggregations often having a high porosity. These patches occur irregularly throughout the horizon decreasing in abundance with depth and coalescing towards the surface to grade into the overlying reddish brown colluvial horizon. In some instances these patches coincide with root traces. The remainder of the material comprises a mottling of light pink, pale yellow and white, equigranular, firm, highly voided with void sizes ranging from 177 to 1500 μm clayey and silty sand retaining the original fabric of the parent material. The macro-voids exhibit spherical openings and are vermiform whilst the micro-voids can be observed as fine sponge-like accumulations within feldspar pseudomorphs and kaolinite aggregations. The quartz grains are often fractured, reduced in size and have a loss of lustre. The plagioclase feldspar grains are extremely decomposed, breaking down to soft clay whilst the microcline feldspar grains break down to clay, and occasional gritty fragments when scraped with a knife. Within the reddish brown patches, the feldspars are not recognisable. Biotite is completely absent with clear hydrous micas present.

The granite saprolite exhibits a variety of colours and grain sizes which can change over very short distances (0.2 m). This heterogeneity is a product of the heterogenous parent material fabric and local differences within the weathering microclimate. The granite saprolite varies from orange with fine yellow and light pink mottles in the upper profile to yellowish white with irregular dark olive patches towards the base of the profile. The material is equigranular except where localised quartz pegmatite veins occur and is firm in consistency. Typical of this material is the presence of numerous tubular macro-voids (250 to 1000 µm in diameter). These voids tend to preferentially form within feldspar-rich and coarser-grained zones. Micro-voids often manifest themselves as a sponge-like texture within feldspar pseudomorphs. The quartz grains are often fractured with a slight loss in lustre. Plagioclase feldspar grains are extremely decomposed forming pseudomorphs which break down to soft clay, whilst the less weathered microcline feldspar is moderately to highly decomposed and breaks down to clay and gritty fragments. Biotite may be absent in the upper reaches, but is highly decomposed lower down, often exhibiting halos of orange staining. The original fabric of the parent material is completely intact. The contact of the saprolite with the underlying weathered bedrock is abrupt with no formation of corestones. It is not unusual for the saprolite to either directly overlie moderately or highly weathered granite, indicating that not all weathering grades are necessarily included in the weathering profile.

The highly weathered bedrock comprises light yellow or olive yellow with white and dark green mottles, close to medium jointed, equigranular (except where quartz pegmatite veins occur) granite. No voids are present within the material. Quartz grains are intact without any grain size reduction although they may show signs of fracturing. The plagioclase and microcline feldspars are highly to moderately decomposed breaking down to clay and gritty fragments. Dark green biotite grains are present, ranging from moderately to highly weathered with orange stain halos surrounding the grains.

The fresh and slightly weathered granite bedrock is light grey to light greenish grey, medium to coarse-grained with a poorly developed gneissic texture in places. The granite is often characterised by a heterogenic appearance, often caused by pegmatitic zones and darker coloured bands associated with a higher percentage of biotite or amphiboles. The granite is close to medium jointed and equigranular (except where pegmatite veins occur). In places adjacent to the diabase dykes the granite has been influenced to some extent such that recrystallisation and assimilation has taken place forming granite migmatite. Fracturing also tends to be more intense at these localities. The fresh granite shows no discolouration. Quartz and feldspar grains are hard and intact and dark green biotite grains can be observed.

MINERALOGICAL AND GEOCHEMICAL ANALYSIS OF WEATHERED GRANITE AT INJAKA DAM SITE

Tables 1 and 2 provide a summary of the mineralogical and geochemical analyses undertaken on the weathered granite at Injaka Dam site for the purposes of this investigation. A Siemens D5000 X-ray system was used for the semi-quantitative XRD analysis and mineral phase concentrations were determined as semi-quantitative estimates using relative peak height/area proportions according to Brime (1985). Detection limits range from 0.5% to approximately 5% depending upon the sample composition and origin. For the geochemical analyses, a Philips PW1480 wavelength sequential X-ray spectrometer containing Rh/Sc side window tube was used.

The most striking feature of the mineralogical analysis is the very high degree of variability within the weathered profile. However, certain systematic relationships can be observed with the most significant being the increase in kaolinite and corresponding decrease in plagioclase towards the surface. A general decrease in microcline with increasing weathering occurs, although this is only noticeable above 5 m depth. The variation of quartz can be considered to be dictated by its variation within the parent material. Although the mica content appears neither to increase nor decrease it must be realised that the XRD mica analysis includes primary and secondary forms of mica and consequently, the alteration of biotite is off-set by the formation of illite.

CHEMICAL WEATHERING INDICES

Introduction

The role of chemical weathering indices is essentially to quantify the degree of depletion of mobile components relative to immobile components during weathering (Harnois, 1988). These indices can then be applied to standard weathering grades of material set up by specific weathering classifications systems which in turn may be correlated with engineering behaviour. For the successful application of chemical weathering indices four important factors should be noted:

- Only those elements which have consistent geochemical behaviour during weathering should be used. There is some discrepancy in the literature with regard to the consistency of certain elements, particularly Al and Ti (Gardner, 1980), but generally Ca, Na, Mg, K, Si and Fe are considered useful in assessing weathering trends. This study has included results using Al and Ti.
- The indices should be independent of the degree of oxidation of the weathered material.
- Only those chemical elements commonly reported in analyses should be utilised. This means that such indices can be calculated and routinely applied from standard analyses.

- Chemical indices should be relatively easy to use and simple to apply.

Duzgoren-Aydin et al. (2002) have also shown that the behaviour of different chemical elements is complex due to the redistribution and type of the weathered products and they concluded that chemical weathering indices should be selected according to site specific behaviour.

Table 1. Summary of mineralogical analysis of weathered granite at Injaka Dam site.

Sample	Depth (m)	Microcline	Plagioclase	Quartz	Kaolinite	Mica	Smectite	Interstratified Illite and Smectite	Hematite	Calcite	Chlorite
RF 12*	1,0	3	2	49	33	5	4	0	5	0	0
RF 17*	2,2	5	0	20	53	16	3	0	3	0	0
LF 1*	0,9	5	0	43	32	17	2	0	0	0	0
LF 7*	1,1	11	0	48	30	12	0	0	0	0	0
LF 18*	1,1	0	0	36	31	33	0	0	0	0	0
RF 10	3,5	8	10	61	14	7	0	0	0	0	0
RF 9	4,5	9	14	39	30	8	0	0	0	0	0
RF 8	5,7	2	3	41	46	9	0	0	0	0	0
RF 7	6,6	3	17	44	29	6	0	0	0	0	0
RF 6	2,5	6	0	33	48	14	0	0	0	0	0
RF 5	4,8	14	0	43	25	18	0	0	0	0	0
RF 4	6,9	0	4	30	46	20	0	0	0	0	0
RF 3	9,2	22	17	29	16	16	0	0	0	0	0
RF 18	3,8	7	0	17	69	9	3	0	0	0	0
RF 19	5,2	5	22	51	12	6	2	0	0	0	0
RF 20	6,1	3	17	41	17	22	0	0	0	0	0
RF 21	6,2	5	34	34	14	8	5	0	0	0	0
LF 2	2,4	8	0	38	45	6	0	3	0	0	0
LF 3	3,8	12	0	38	39	7	0	3	0	0	0
LF 4	4,5	13	0	36	39	12	0	0	0	0	0
LF 5	5,2	10	3	45	27	11	4	0	0	0	0
LF 6	5,5	6	0	38	40	11	0	6	0	0	0
LF 8	2,8	8	0	33	40	19	0	0	0	0	0
LF 9	4,0	21	7	30	34	8	0	0	0	0	0
LF 10	5,5	3	0	42	42	13	0	0	0	0	0
LF 11	6,5	15	0	25	50	10	0	0	0	0	0
LF 12	7,3	5	2	51	34	4	0	4	0	0	0
LF 13	7,7	13	17	30	27	8	0	5	0	0	0
LF 19	2,3	0	0	65	20	12	4	0	0	0	0
LF 20	3,2	5	0	41	39	12	3	0	0	0	0
LF 21	4,0	14	0	21	52	10	3	0	0	0	0
LF 22	5,1	12	0	29	51	5	3	0	0	0	0
LF 24	5,7	6	0	51	36	7	0	0	0	0	0
LF 25	6,2	4	0	57	31	8	0	0	0	0	0
LF 26	7,2	12	25	38	20	5	0	0	0	0	0
LF 27	7,8	7	21	39	17	15	0	0	0	0	0
RF 2#	8,2	13	17	51	3	9	3	0	0	3	0
RF 1#	9,6	17	12	48	13	8	0	0	0	2	0
RF 13#	10,6	11	33	46	4	6	0	0	0	0	0
RF 14#	11,8	17	22	54	0	5	0	0	0	2	0
RF 15#	10,9	9	27	22	10	10	21	0	0	0	0
RF 16#	11,8	18	23	50	0	5	2	0	0	2	0
RF 22#	7,7	9	23	54	0	6	8	0	0	0	0
RF 23#	9,1	13	10	75	0	2	0	0	0	0	0
RF 24#	9,8	6	20	68	0	2	4	0	0	0	0
RF 25#	10,2	7	25	50	0	14	4	0	0	0	0
LF 28#	8,8	13	23	54	2	8	0	0	0	0	0

* Granite saprolite with residual soil patches
\# Highly weathered granite

Appropriate Selection and Application of Chemical Weathering Indices

Several chemical weathering indices have been proposed and refined since the inception of Reiche's (1943), Weathering Potential Index (WPI). These indices range from a ratio of many variables to simple binomial ratios. The common elemental oxides repeatedly used in many of the indices include K_2O, Na_2O, CaO, MgO, Al_2O_3, SiO_2, Fe_2O_3, FeO, TiO_2 and H_2O^+. These have been selected because of their respective mobility or resistance to leaching. Na, Ca, Mg and Si can be considered to be leached during the weathering of granite, although the behaviour of silica is often irregular and the total proportion lost is ordinarily very small (Parker, 1970). Al and Ti can be considered to remain essentially within the weathering system (although some loss does occur with increased weathering), whilst Fe and K exhibit more complicated behaviour dependent upon the redox conditions and chemistry of ambient fluids, respectively. H_2O^+ can be defined as the amount of water within the internal structure of minerals (hydroxyl water) and it increases with increasing weathering (increasing clay formation).

The selected chemical indices shown in Table 3 have been applied to the weathered granite at Injaka Dam site to assess its degree of weathering and to attempt to relate these indices to the density of the material which in turn has bearing on its engineering performance. All of these indices were derived using molecular weight percentages. It can be seen from Table 3 that a decrease in WPI reflects a loss in the mobile cations from the weathering system, and similarly a decreasing Product Index (PI) suggests a decreasing silica content which occurs with the onset of weathering.

Table 2. Major element analyses (weight %) from XRF determinations for weathered granite at Injaka Dam site.

Sample		SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO**	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Cr_2O_3	H_2O^+	CO_2	S	Total	H_2O^-
RF 12*	1,0	56,82	0,58	22,20	6,94	0,10	0,04	0,31	0,09	0,04	1,87	0,04	0,04	9,45	1,42	0,001	99,78	1,08
RF 17*	2,2	63,83	0,49	20,82	3,37	0,19	0,03	0,36	0,09	0,07	2,67	0,04	0,02	7,14	0,24	0,001	99,29	0,96
LF 1*	0,9	69,99	0,24	17,45	2,22	0,40	0,02	0,24	0,09	0,04	3,17	0,02	0,04	5,62	0,41	0,001	99,88	0,09
LF 7*	1,1	69,63	0,12	18,64	1,22	0,15	0,02	0,14	0,09	0,05	3,48	0,02	0,04	5,79	0,35	0,001	99,67	0,44
LF 18*	1,1	66,53	0,44	19,71	2,39	0,40	0,02	0,59	0,10	0	2,93	0,03	0,01	5,90	0,14	0,001	99,19	0,43
RF 10	3,5	69,50	0,26	17,72	2,03	0,19	0,03	0,35	0,16	1,46	3,35	0,02	0,02	4,18	0,10	0,001	99,38	0,05
RF 9	4,9	68,55	0,25	18,09	1,95	0,14	0,03	0,40	0,15	1,77	3,07	0,02	0,02	4,35	0,08	0,001	98,84	0,43
RF 8	5,7	64,45	0,61	18,09	5,27	0,19	0,05	0,74	0,36	0,64	2,50	0,04	0,03	6,68	0,17	0,001	99,8	0,05
RF 7	6,6	69,18	0,30	16,10	2,35	0,10	0,04	0,60	0,56	4,56	2,87	0,04	0,02	1,87	0,05	0,001	98,49	0,56
RF 6	2,5	63,96	0,35	20,92	3,08	0,15	0,02	0,33	0,08	0	2,03	0,03	0,02	8,17	0,65	0,001	99,8	1,07
RF 5	4,8	73,70	0,07	15,49	0,76	0,20	0,02	0,27	0,12	0,04	5,57	0	0	3,50	0,05	0,001	99,76	0,30
RF 4	6,9	68,51	0,30	18,75	2,25	0,10	0,04	0,38	0,12	0,60	2,98	0,03	0	5,82	0,06	0,001	99,92	0,62
RF 3	9,2	73,36	0,18	15,08	1,07	0,20	0,03	0,27	0,22	2,70	4,75	0,02	0	1,85	0,05	0,001	99,73	0,22
RF 18	3,8	66,35	0,47	19,23	2,88	0,19	0,03	0,47	0,18	0,61	3,02	0,02	0,02	5,88	0,08	0,001	99,42	0,76
RF 19	5,2	72,04	0,17	16,02	1,32	0,10	0,02	0,26	0,22	3,02	3,54	0,02	0,02	2,34	0,05	0,001	98,97	0,29
LF 2	2,4	64,43	0,48	20,08	4,03	0,20	0,02	0,21	0,24	0,05	2,53	0,07	0,04	7,28	0,24	0,001	99,84	0,67
LF 3	3,8	67,87	0,27	18,89	2,19	0,10	0,02	0,15	0,10	0,06	4,17	0,04	0,04	5,81	0,13	0,001	99,75	0,51
LF 4	4,5	68,29	0,37	17,71	2,64	0,30	0,04	0,38	0,10	0,16	4,99	0,06	0,04	4,74	0,05	0,001	99,74	0,07
LF 5	5,2	68,96	0,39	17,17	2,70	0,20	0,04	0,44	0,14	0,72	4,63	0,06	0,04	4,28	0,05	0,001	99,77	0,48
LF 6	5,5	64,01	0,73	18,80	5,60	0,20	0,07	0,84	0,11	0,18	2,21	0,11	0,04	6,99	0,05	0,001	99,84	0,97
LF 8	2,8	68,96	0,21	18,67	1,75	0,30	0,02	0,32	0,11	0,04	3,91	0,02	0,04	5,33	0,13	0,001	99,75	0,31
LF 9	4,0	69,26	0,24	17,72	1,45	0,10	0,02	0,13	0,13	0,10	6,64	0,03	0,04	3,85	0,09	0,001	99,70	0,07
LF 10	5,5	63,61	0,73	19,81	5,23	0,20	0,04	0,48	0,08	0,04	2,14	0,08	0,04	7,30	0,06	0,001	99,77	0,19
LF 11	6,5	68,67	0,37	17,46	2,97	0,29	0,05	0,39	0,10	0,28	4,47	0,06	0,04	4,71	0,05	0,001	99,77	0,48
LF 12	7,3	64,52	0,89	17,49	6,42	1,11	0,07	0,69	0,20	0,28	1,34	0,12	0,04	6,58	0,05	0,001	99,75	0,42
LF 13	7,7	67,23	0,44	16,77	3,10	0,28	0,06	0,69	0,24	2,47	3,72	0,06	0,04	3,29	0,07	0,001	98,42	0,28
LF 19	2,3	69,65	0,19	18,64	1,20	0,30	0,01	0,36	0,10	0	2,44	0,01	0	6,10	0,12	0,001	99,13	0,28
LF 20	3,2	67,93	0,31	18,96	2,45	0,20	0,02	0,27	0,09	0	2,76	0,03	0	6,55	0,07	0,001	99,64	0,42
LF 21	4,0	67,27	0,34	18,65	2,49	0,15	0,01	0,18	0,10	0	4,03	0,04	0	5,85	0,05	0,001	99,12	0,47
LF 22	5,1	68,82	0,23	17,68	1,64	0,10	0,02	0,14	0,09	0	4,61	0,02	0	5,17	0,06	0,001	99,60	0,36
LF 24	5,7	69,26	0,21	17,75	1,67	0,20	0,02	0,23	0,10	0,01	4,07	0,02	0	5,60	0,09	0,001	99,25	0,40
LF 25	6,2	68,66	0,42	15,63	5,92	0,10	0,03	0,48	0,16	0,19	2,27	0,10	0,03	5,80	0,16	0,001	99,95	0,79
LF 26	7,2	74,16	0,13	15,53	0,98	0,10	0,03	0,26	0,16	1,25	4,40	0,02	0,01	2,15	0,05	0,001	99,18	0,16
LF 27	7,8	70,98	0,25	16,31	1,02	0,2	0,03	0,42	0,22	2,45	4,41	0,03	0,01	2,20	0,05	0,001	98,54	0,27
RF 2#	8,2	78,23	0,08	12,21			0,1	0,02	0,19	2,83	4,4	0,02	0,01				99,67	
RF 1#	9,6	72,42	0,16	16,22			0,03	0,06	0,09	1,33	4,55	0,02	0,01				99,95	
RF 13#	10,6	74,42	0,10	14,45	0,90	0,1	0,02	0,19	0,34	3,58	4,13	0,02	0,02	0,86	0,05	0,001	99,05	0,05
RF 14#	11,8	74,83	0,17	13,37	1,44		0,03	0,40	0,31	2,97	4,73	0,01					99,42	0,28
RF 15#	10,9	71,8	0,22	15,41	1,81	0,19	0,05	0,64	0,62	4,51	2,33	0,03	0,02	1,45	0,05	0,001	99,08	0,05
RF 16#	11,8	77,23	0,1	11,92	0,72		0,1	0,27	0,37	3,2	4,61	0,02	0,01				99,32	0,11
RF 22#	7,7	75,99	0,10	13,11			0,02	0,18	0,51	3,87	3,80	0,02	0,02				99,11	0,24
RF 23#	9,1	74,65	0,10	14,16			0,02	0,15	0,90	4,33	3,88	0,04	0,02				99,50	0,18
RF 24#	9,8	74,69	0,10	14,07			0,02	0,2	0,61	3,96	3,99	0,02	0,02				99,29	0,29
RF 25#	10,2	71,86	0,22	15,38			0,03	0,45	0,37	4,24	4,33	0,03	0,02				99,59	0,44

* Granite saprolite with residual soil patches
** determined through analysis
# Highly weathered granite
H_2O^+ expressed as weight percentage

The Silica-Alumina Ratio formulated by Ruxton (1968) provides a measure of the total element loss (he assumed silica loss to equate to total element loss) as a ratio of the alumina content. He considered the ratio of SiO_2 to Al_2O_3 to indicate the degree of weathering and found this to be applicable to free draining, acidic weathering environments in humid climates on acidic rocks.

The Parker Index (Wp) derived by Parker (1970) is based upon the proportions of the major alkaline metals and their bond strength with oxygen used as a weighting factor. Gupta and Rao (2001) considered this index to be applicable to acid, intermediate and basic rocks where hydrolysis is the main process of silicate weathering.

The Vogt Ratio (VR) derived by Vogt (1927) and advocated by Roaldset (1972), attempted (incorrectly) to determine the ratio of immobile to mobile cations, but assumed that potassium remained stable within the weathering system.

Vogel (1975) modified Reiche's WPI in his assessment of the weathering of acid metavolcanics whereby the H_2O^+ and oxidation state of iron were omitted from the original WPI equation to form the Modified Weathering Potential Index (MWPI).

Nesbitt and Young (1982), understanding that feldspars are the most abundant reactive minerals in the earth's upper crust, realised that calcium, sodium and potassium are generally removed from the feldspars during weathering by aggressive soil solutions. They proposed that during weathering the proportion of alumina to alkalis would typically increase in the weathered product and that a good measure of the degree of weathering could be obtained by the Chemical Index of Alteration (CIA).

Table 3. Summary of chemical weathering indices used to measure weathering changes for weathered granite at Injaka Dam site.

Chemical Weathering Index	Formula	Reference	Weathering grade applied in past studies
Weathering potential index (WPI)	$WPI = \frac{(CaO + Na_2O + MgO + K_2O - H_20^+)*100}{(SiO_2 + Al_2O_3 + Fe_2O_3 + FeO + TiO_2 + CaO + MgO + Na_2O + K_2O)}$	Reiche (1943)	I-VI?
Product index (PI)	$PI = \frac{(SiO_2 *100)}{(SiO_2 + TiO_2 + Fe_2O_3 + FeO + Al_2O_3)}$	Reiche (1943)	I-VI?
Silica-Alumina Ratio	$Silica - Alumina\ Ratio = \frac{SiO_2}{Al_2O_3}$	Ruxton (1968)	I-VI?
Parker Index (W_p)	$Wp = \left(\frac{2Na_2O}{0,35} + \frac{MgO}{0,9} + \frac{2K_2O}{0,25} + \frac{CaO}{0,7}\right)*100$	Parker (1970)	I-VI
Vogt Ratio (VR)	$VR = \frac{Al_2O_3 + K_2O}{MgO + CaO + Na_2O}$	Vogt (1927) and Roaldset (1972)	I-VI
Modified Weathering Potential Index* (MWPI)	$MWPI = \frac{(Na_2O + K_2O + Cao + MgO)*100}{(Na_2O + K_2O + CaO + MgO + SiO_2 + Al_2O_3 + Fe_2O_3)}$	Vogel (1975)	I-III?
Chemical Index of Alteration (CIA)	$CIA = \frac{Al_2O_3 *100}{Al_2O_3 + CaO + Na_2O + K_2O}*100$	Nesbitt and Young (1982)	I-VI?
Chemical Index of Weathering (CIW)	$CIA = \frac{Al_2O_3 + K_2O}{Al_2O_3 + CaO + Na_2O}*100$	Harnois (1988)	I-VI
Ignition (H_2O^+) loss	H_2O^+	Sueoka et al. (1985), Jayawardena (1993)	I-VI
Si-Ti Index	$\frac{\frac{SiO_2}{TiO_2}}{\frac{SiO_2}{TiO_2} + \frac{SiO_2}{Al_2O_3} + \frac{Al_2O_3}{TiO_2}}$	Jayawardena and Izawa (1994)	I-VI
Mobiles Index	$I_{mob} = \frac{(K_2O + Na_2O + CaO)_{fresh\ rock} - (K_2O + Na_2O + CaO)_{weathered\ rock}}{(K_2O + Na_2O + CaO)_{fresh\ rock}}$	Irfan (1996)	I-V

Harnois (1988) suggested that potassium cations, whilst been leached during weathering can in fact be adsorbed on other clays in the weathered profile through ion exchange, and may consequently disrupt geochemical trends of K^+. He therefore proposed the Chemical Index of Weathering (CIW), devoid of K_2O, as an improved measure of degree of weathering to that of the WPI, Wp VR, MWPI and CIA.

The Ignition Loss Index or H_2O^+ as proposed by Sueoka *et al.* (1985) and used by Jayawardena (1993) represents the amount of crystalline water within the weathered material. An increasing H_2O^+ content is caused by hydration and clay formation during weathering.

Jayawardena and Izawa (1994) determined through their analyses of metamorphic rocks in Sri Lanka that possible relationships exist between Al_2O_3, SiO_2 and TiO_2 and proposed the silica-titania index for chemical weathering.

Irfan (1996) in his comprehensive review of weathered granite in Hong Kong proposed the Mobiles Index (I_{mob}) which compared the different behaviour of "mobile" and "immobile" elements during weathering using the fresh rock as a comparative component for the index derivative.

The applicability of the various weathering indices to different material types and weathering conditions has long been a source of debate. Parker (1970) stated that the Silica-Alumina Ratio was restricted as to its use because the amount of sesquioxides must remain approximately constant during weathering and there must preferably be no formation of smectites or vermiculites as initial weathering products. Harnois (1988), maintained that the use of K_2O as a mobile component in the CIA, WPI and MWPI limits their application to soils in which potassium has been leached, as potassium, through its high exchange capacity can be adsorbed onto other clays in the weathering profile, thus masking its mobility. The Vogt Ratio uses K_2O as an immobile component which contradicts the evidence that potassium is commonly leached. The common point made by all of these authors is that for chemical weathering indices to be effective, an understanding of the geochemical composition and nature of geochemical processes and trends of the particular material of interest is required for the successful application of any weathering index.

Results from Injaka Dam site

Table 4 provides a summary of the above-mentioned chemical weathering index values obtained for samples from Injaka Dam site at various depths within the weathering profile. From this table it can be seen that a relationship exists between the weathering indices, density and grade of weathering. Density has been chosen as the comparative physical property because Haskins *et al.* (1998) and Haskins and Van Zyl (2002) have shown through petrographic and SEM studies that weathering effects manifest themselves most significantly through a change in the material porosity, and consequently density. In general, the values of WPI, PI, Si-Al, Wp and MWPI decrease as the weathering grade or density increases. This is in accordance with findings from Jayawardena and Izawa (1994) and Gupta and Rao (2001). Decreasing values of WPI, MWPI and Wp indicate decreasing mobile cations and increasing hydroxyl water with increasing weathering. Decreasing PI, Si-Al and Si-Ti values are indicative of a decreasing silica content. It can be seen that there is a sharp decrease in these particular weathering indices from the highly weathered granite to granite saprolite state and this confirms the field observations of the abrupt change between the weathered rock and saprolite. Alternatively, CIA, CIW, H_2O^+ and I_{mob} show a continuous increase with increasing degree of weathering. This can be attributed to the loss of mobile cations and alteration of the crystal structure - hence the increase in hydroxyl water.

Table 4. Summary of chemical weathering index analysis for weathered granite at Injaka Dam site.

SAMPLE	DEPTH (m)	DENSITY ($kg.m^{-3}$)	WPI	PI	Si-Al	W_p	VR	MWPI	CIA	CIW	H_2O^+	I_{mob}	Si-Ti
LF 1*	0,9	1478	-19,31	85,75	6,81	28,18	24,97	3,01	82,66	98,70	5,62	0,68	79,17
RF 12*	1	1511	-39,77	77,80	4,34	17,33	23,91	2,41	90,78	98,98	9,45	0,80	70,58
LF 7*	1,1	1444	-19,98	85,66	6,34	30,63	37,35	3,08	82,29	98,70	5,79	0,65	78,48
LF 18*	1,1	1535	-20,40	83,46	5,73	26,76	13,67	3,49	85,46	99,09	5,9	0,71	75,84
RF 17*	2,2	1389	-26,69	81,94	5,20	24,54	19,94	3,01	86,79	98,68	7,14	0,72	74,09
LF 19	2,3	1307	-21,71	85,48	6,34	21,97	19,49	2,64	86,85	99,03	6,1	0,75	78,26
LF 2	2,4	1400	-27,40	82,28	5,44	23,14	21,74	2,79	86,04	97,48	7,28	0,71	74,87
RF 6	2,5	1458	-31,87	82,17	5,19	18,35	23,59	2,36	89,93	99,31	8,17	0,79	74,42
LF 8	2,8	1434	-17,43	85,10	6,27	34,74	21,30	3,73	80,59	98,60	5,33	0,61	78,00
LF 20	3,2	1305	-23,71	84,46	6,08	24,41	25,93	2,75	85,75	99,14	6,55	0,72	77,19
RF 10	3,5	1330	-11,38	85,74	6,66	43,28	5,97	5,00	73,72	86,81	4,18	0,45	78,76
LF 3	3,8	1416	-19,66	84,72	6,10	36,64	35,47	3,68	79,76	98,54	5,81	0,58	77,36
RF 18	3,8	1383	-19,61	83,69	5,85	33,02	8,93	4,15	80,70	93,53	5,88	0,60	76,09
LF 9	4,0	1429	-9,61	86,02	6,63	58,00	34,14	5,49	70,02	97,79	3,85	0,33	78,78
LF 21	4,0	1386	-20,09	84,53	6,12	34,98	36,13	3,59	80,41	99,03	5,85	0,60	77,19
LF 4	4,5	1523	-14,02	85,10	6,54	45,15	16,44	4,79	75,18	97,55	4,74	0,49	78,11
RF 5	4,8	1763	-8,65	88,44	8,07	48,72	22,26	4,73	71,05	98,20	3,5	0,45	82,33
RF 9	4,9	1375	-11,92	85,42	6,43	43,87	5,10	5,25	73,55	85,04	4,35	0,43	78,26
LF 22	5,1	1409	-16,81	85,90	6,60		43,79	3,91	77,43	99,08	5,17	0,55	78,75
LF 5	5,2	1610	-11,56	85,61	6,81	47,53	8,69	5,27	72,69	92,27	4,28	0,43	78,63
RF 19	5,2	1696	-2,28	87,65	7,63	59,17	3,30	6,62	63,53	74,91	2,34	0,19	81,10
LF 10	5,5	1431	-27,65	81,58	5,45		15,53	2,77	88,68	98,94	7,3	0,79	74,17
LF 6	5,5	1433	-25,20	82,16	5,78	23,02	8,09	3,69	86,68	97,43	6,99	0,75	75,04
RF 8	5,7	1482	-22,84	82,93	6,05	30,09	5,81	4,58	80,39	91,38	6,68	0,61	76,08
LF 24	5,7	1398	-18,68	85,85	6,62	35,54	28,41	3,66	79,41	98,90	5,6	0,60	78,86
RF 20	6,1	1479	5,98	87,76	7,31	46,45	2,96	5,99	68,30	75,73		0,32	80,18
LF 25	6,2	1533	-20,29	85,29	7,45	22,76	9,95	3,05	83,63	96,28	5,8	0,73	79,71
RF 21	6,2	1663	6,12	88,52	7,89	45,04	2,43	6,14	66,08	71,81		0,30	80,22
LF 11	6,5	1362	-14,11	85,20	6,67	41,87	13,69	4,54	76,11	96,45	4,71	0,52	78,40
RF 7	6,6	1855	1,71	86,62	7,29	69,48	1,91	8,87	58,07	65,40	1,87	-0,02	79,91
RF 4	6,9	1457	-19,37	84,88	6,20	32,19	10,15	3,80	80,89	93,96	5,82	0,61	77,54
LF 26	7,2	1522	-2,94	88,43	8,10	50,01	6,76	5,19	68,60	86,87	2,15	0,38	82,12
LF 12	7,3	1226	-24,13	81,84	6,26	16,37	7,37	2,98	88,49	95,50	6,58	0,80	75,64
LF 13	7,7	1625	-5,81	85,27	6,80	56,87	3,33	7,18	66,30	78,85	3,29	0,25	78,39
RF 22#	7,7	2350	7,70	90,69	9,84	69,74	2,22	7,71	53,48	64,26		0,00	84,73
LF 27	7,8	1797	-1,48	87,27	7,38	61,75	3,84	6,95	63,93	78,64	2,20	0,19	80,31
RF 2#	8,2	1779	6,34	91,51	10,87	63,99	3,36	6,34	55,57	70,95		0,14	86,01
RF 23#	9,1	2210	8,64	89,86	8,95	75,57	2,01	8,65	52,22	61,79		-0,14	83,56
RF 3	9,2	1683	0,12	88,44	8,25	66,53	3,66	7,07	60,17	75,70	1,85	0,12	82,14
RF 1#	9,6	1823	5,06	88,21	7,58	51,29	8,45	5,07	69,03	87,34		0,36	81,05
RF 24#	9,8	2250	8,11	89,93	9,01	72,49	2,26	8,12	54,09	64,86		-0,04	83,65
RF 25#	10,2	2437	8,92	88,62	7,93	78,03	2,28	8,93	55,50	66,80		-0,08	81,41
RF 13#	10,6	2010	4,30	89,20	8,74	69,46	2,71	7,50	56,83	69,00	0,86	0,04	83,26
RF 15#	10,9	2417	2,95	87,68	7,91	64,70	1,76	8,40	58,20	64,33	1,45	0,03	81,377
RF 14#	11,8	2159	7,57	89,75	9,50	69,44	2,86	7,58	55,85	71,05		0,07	83,34
RF 16#	11,8	2480	7,48	91,29	10,99	70,33	2,56	7,49	52,18	66,76		0,04	86,00

* Granite saprolite with residual soil patches
\# Highly weathered granite

The relationship between dry density and the various weathering index values for the granite saprolite is shown in Figure 3. Good correlations can be observed for all of the indices with the exception of the Vogt Ratio. The poor correlation shown by VR is due to the incorrect use of K_2O as an immobile component for the determination of VR. Haskins *et al.* (1998) have shown that potassium is extensively leached from the weathering system at Injaka Dam.

Although an acceptable correlation was obtained using the Si-Al index value, it should also be noted that it is subject to a number of restrictions as to its reliability (Parker, 1970). The sesquioxides content must remain approximately constant during weathering, and there must preferably be no formation of smectite or vermiculite as initial weathering products. Mineralogical analyses have shown that some local smectite formation may occur in the early stages of weathering of the granite at Injaka Dam site where free-draining conditions do not occur and this should be borne in mind when assessing this index under such weathering conditions.

The mobiles index (I_{mob}) was developed by Irfan (1996) to measure the relative removal of the mobile cations from the rock with weathering. Consequently, it serves as an index for the degree of decomposition of feldspars, particularly under highly leached conditions such as those encountered within the granite saprolite at Injaka Dam site. A plot of I_{mob} against the amount of unaltered feldspar content is given in Figure 4 and shows a near linear relationship confirming this. Irfan (1996) also demonstrated a similar relationship with his study on weathered Hong Kong granites.

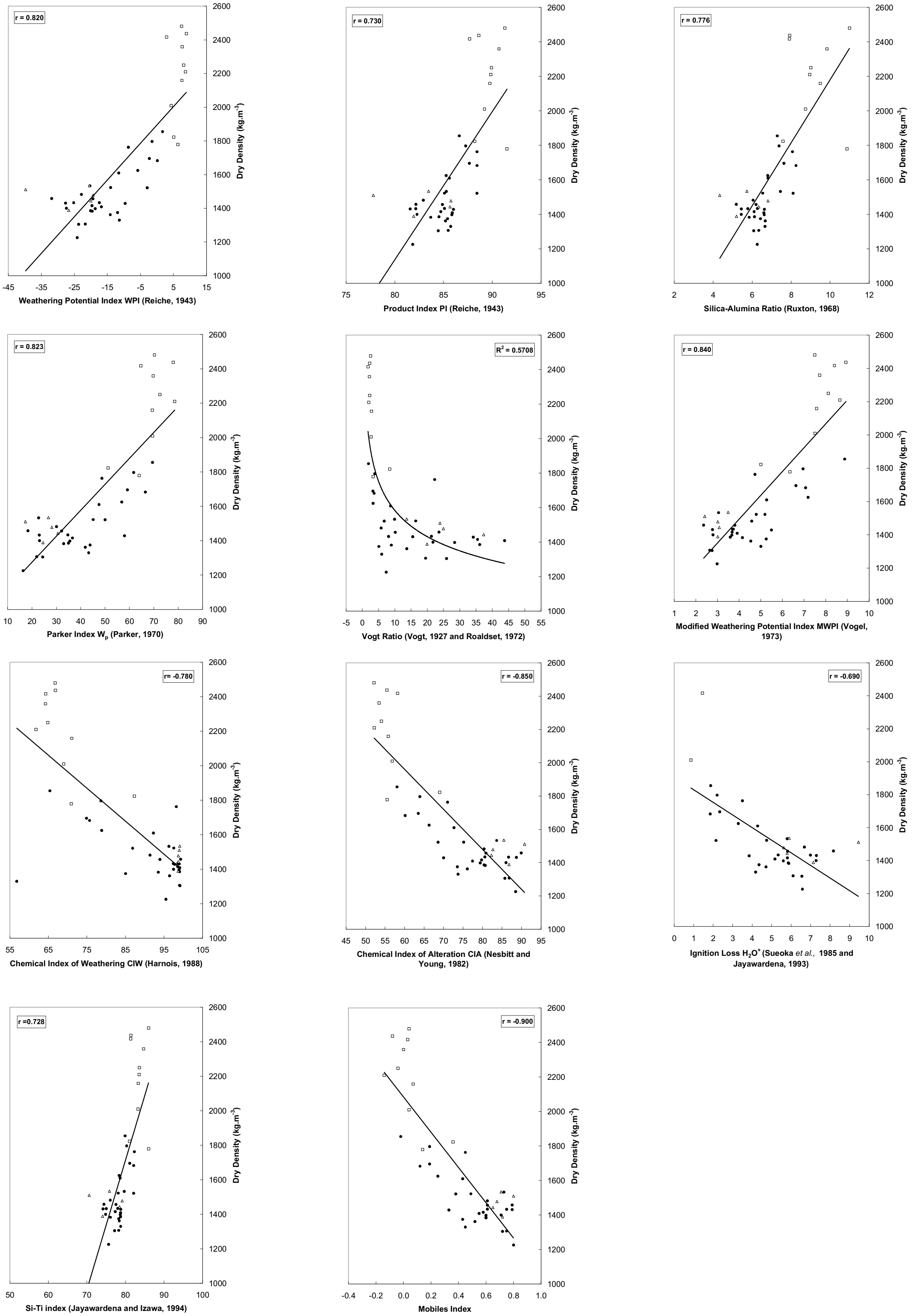

Figure 3. Relationship of chemical weathering indices and dry density for granite saprolite with residual soil patches (△), granite saprolite (●) and highly weathered granite (□).

A summary of the weathering index values with respect to the weathering grade of the granite is presented in Table 5 which is effectively a compilation of Table 4. This Table shows that these indices can be tentatively used to rationally classify the weathered granite according to its degree of weathering (and density). Jayawardena and Izawa (1994) were similarly able to demonstrate this in their study of weathered granite gneiss from Sri Lanka.

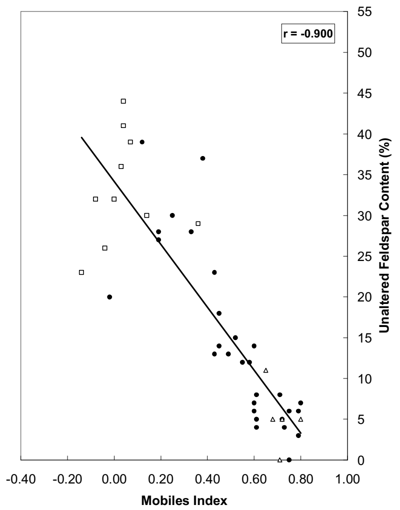

Figure 4. Plot of unaltered feldspar content and I_{mob} for granite saprolite with residual soil patches (△), granite saprolite (●) and highly weathered granite (☐).

Table 5. Typical mean values of chemical weathering indices for different weathering grades of granite.

Weathering index	Mean of weathering index		
	Highly weathered granite (n = 10)	Granite saprolite (n = 31)	Granite saprolite with residual soil patches (n = 5)
WPI	6,71	-15,46	-25,23
PI	89,67	85,11	82,92
Si-Al	9,13	6,59	5,68
W_p	68,80	39,98	25,49
VR	3,05	15,54	23,97
MWPI	7,57	4,52	3,00
CIA	56,30	76,85	85,60
CIW	68,71	91,06	98,83
H_20^+	1,16	4,97	6,78
Si-Ti	83,44	78,20	75,63
I_{mob}	0,04	0,52	0,71

Table 6 details the Pearson correlation co-efficient values (r) for the various weathering indices and shows that all indices excluding the Vogt ratio show good correlation against one another. Kim and Park (2003) showed similar results in their study of weathered granites around Seoul, South Korea.

Table 6. Pearson correlation coefficient (r) for various weathering indices.

	PI	SI-Al	Wp	VR	MWPI	CIA	CIW	H2O+	IMOB	Si-Ti
WPI	0.931	0.890	0.959	-0.613	0.923	-0.973	-0.838	-0.998	-0.955	0.916
PI		0.942	0.857	-0.433	0.768	-0.893	-0.707	-0.902	-0.841	0.990
Si-Ti			0.811	-0.536	0.753	-0.883	-0.736	-0.914	-0.815	0.965
Wp				-0.588	0.967	-0.987	-0.841	-0.946	-0.990	0.837
VR					-0.675	0.606	0.738	0.477	0.606	-0.449
MWPI						-0.962	-0.891	-0.905	-0.983	0.757
CIA							0.876	0.966	0.989	-0.887
CIW								0.743	0.888	-0.708
H2O+									0.940	-0.899
IMOB										-0.828

Chemical weathering indices are only useful in engineering characterisation of material if they can be related to some measurable physical or mechanical properties. It can be concluded that the application of a number of chemical weathering indices to the granite saprolite at Injaka Dam site has proven that these indices can be successfully used to assess the degree of weathering of this material and can in fact provide an indication of their engineering behaviour based upon dry density relationships.

MINERALOGICAL WEATHERING INDICES

Introduction

In a similar manner to chemical weathering indices, mineralogical indices, using suitable ratios of specific minerals can be applied to assess the weathering of rocks. As feldspars undergo significant changes during weathering, and quartz is relatively resistant, these two minerals can be used to assess weathering trends. When microfracturing and decomposition have reduced granite to an engineering soil it consists of an interlocking granular aggregate in which a certain proportion of the grains has decomposed (Baynes and Dearman, 1978b). Lumb (1962) proposed a quantitative mineralogical measure of this degree of decomposition that he called *Xd*. This can be defined as follows:

$$Xd = \frac{(Nq - Nq_0)}{1 - Nq_0}$$

$$Nq = \frac{(Weight\ Quartz)}{(Weight\ Quartz + Weight\ Feldspar)}\ SOIL$$

$$Nq_0 = \frac{(Weight\ Quartz)}{(Weight\ Quartz + Weight\ Feldspar)}\ ORIGINAL\ ROCK$$

If *Xd* =1, then weathering and leaching has reduced the feldspar content to zero, and the soil can be considered to be in a state of advanced weathering. Baynes and Dearman (1978b), provided a visual impression of variations for *Xd* (Figure 5) using a grid of blocks representing unweathered and weathered remnant granite minerals. This shows that when *Xd* is less than 0.5 the microfabric consists of an interlocking granular aggregate enclosing isolated decomposed minerals (granular-framework). As *Xd* approaches 0.5 so the microfabric develops into a framework of original granitic minerals containing decomposition products. When *Xd* is greater than 0.5 the microfabric is dominated by the decomposition products which enclose remnant original granite minerals (clay-matrix microfabric).

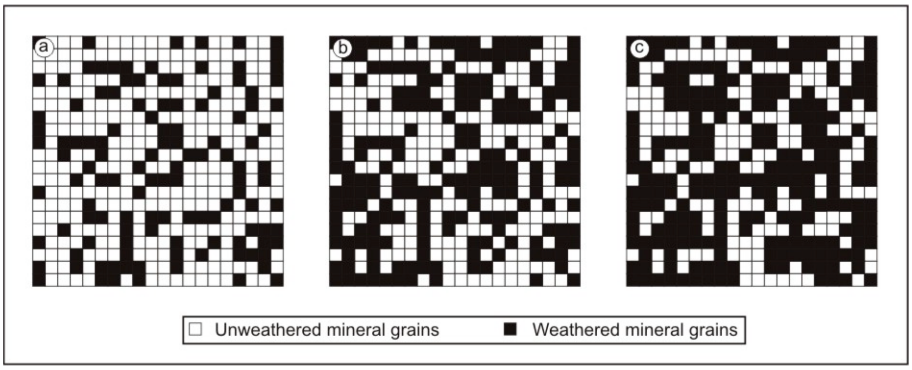

Figure 5. Model to illustrate the microfabric consequences of differing degrees of decomposition, (Baynes and Dearman, 1978a). White squares are representative of unweathered mineral grains whilst black squares are representative of weathered mineral grains. Assuming all decomposed mineral grains are feldspar then (a) represents 30% weathered mineral grains where *Xd* = 0.2; (b) represents 50% weathered mineral grains where *Xd* = 0.5 and (c) represents 60% weathered mineral grains where *Xd* = 0.8.

Nq has traditionally been determined by physically separating the quartz and feldspar grains from a disaggregated specimen of weathered granite. This was accomplished by Lumb (1962) using a binocular microscope. Due to the difficulty in manipulating the very fine grains only the fraction retained on the BS 100 sieve was examined by Lumb. As this method was considered to be time consuming, cumbersome and possibly inaccurate due to exclusion of material finer than that retained on BS 100, it was decided to use the same weight ratio equation but with semi-quantitative mineralogical results derived from the XRD analyses to produce Xd_{XRD}:

$$Xd_{XRD} = \frac{(Nq - Nq_0)}{1 - Nq_0}$$

$$Nq_{XRD} = \frac{(\%\ Quartz)}{(\%\ Quartz + \%\ Feldspar)}\ SOIL$$

$$Nq_{0\ XRD} = \frac{(\%\ Quartz)}{(\%\ Quartz + \%\ Feldspar)}\ ORIGINAL\ ROCK$$

Although the average value of Nq_0 for granite at Injaka Dam site is 0.648 (calculated from XRD analyses), this value was normalised to 0.333 such that the results from Lumb (1962) could be made comparable with results from this investigation.

Results from Injaka Dam Site

Table 7 provides a summary of the results obtained for the samples from Injaka Dam site at various depths. The granite saprolite with residual soil patches shows advanced weathering with values of Xd_{XRD} ranging from 0.70 to 1.00. The granite saprolite shows a much higher variability with *Xd* values ranging from 0.14 to 1.00. It follows then, that the granite saprolite exhibits a broad range of weathering intensities with the high average Xd_{XRD} value suggesting that the majority of the samples are in a state of intense weathering. *Xd* values for the highly weathered granite bedrock are significantly lower, ranging from 0.07 to 0.65 and are indicative of a significantly lower weathering intensity.

Mineralogical indices are also only useful if they can be applied to assessing the engineering behaviour of a material. The void ratio (and density) of a soil is an important component of the soil fabric exerting significant influence on the engineering behaviour of the material. For saprolitic soils it can be expected that the void ratio increases away from the fresh rock, although local variations of this trend will occur. The relationship between void ratio and weathering can be expressed using Xd_{XRD} and is shown in Figure 6.

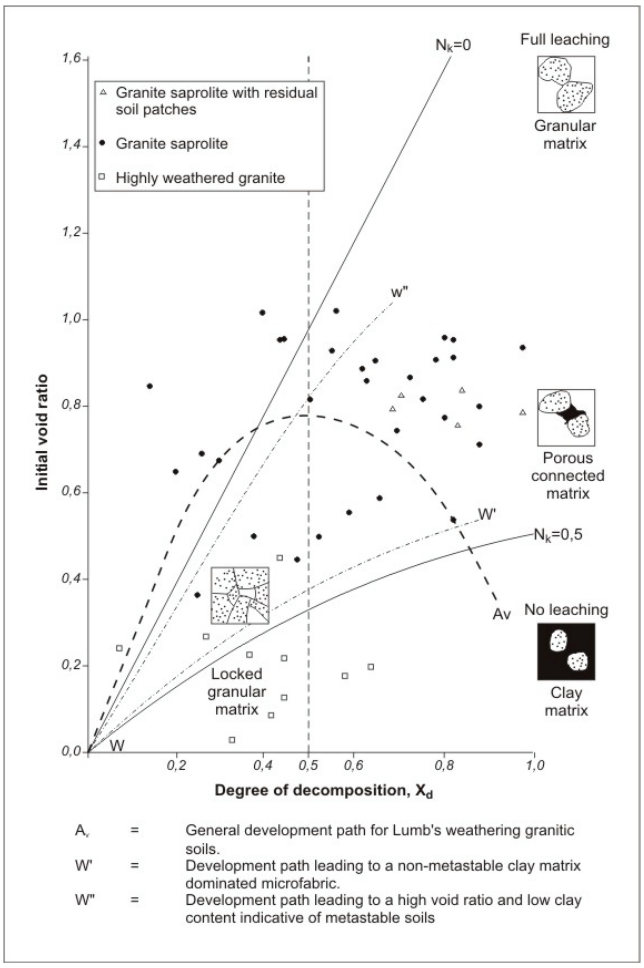

Figure 6. Relationship of Xd_{XRD} with initial voids ratio for granite saprolite with residual soil patches (△), granite saprolite (●) and highly weathered granite (□).

There is a considerable scatter of points as is to be expected from the crudeness of the measure of Xd_{XRD} and the variations in original rock composition. Lumb (1962) constructed two simplified boundary conditions for the relationship of *Xd* and void ratio, expressing "full leaching" conditions and "no leaching" conditions, respectively. The "no leaching" boundary can be defined as no leaching apart from the loss of colloids removed during feldspar alteration. Alternatively, the "full leaching" boundary is defined as the complete loss of colloids with no loss of quartz. Neither of these two conditions is entirely correct and both simplify actual conditions. However, the "no leaching" boundary condition represents the early stages of weathering, whilst the "full leaching" condition can be applied to advanced stages of weathering. These boundary conditions can be defined according to the void ratio as follows:

"No leaching" condition:

N_k = weight of kaolinite produced from unit weight of feldspar = 0.5.

N_{q0} = 0.333

$$e_0 = \frac{(1 - N_k)}{\left(N_k + \dfrac{N_{q0}}{Xd(1 - N_{q0})}\right)}$$

"Full leaching" condition:

$$e_0 = \frac{1 - N_{q0}}{N_{q0}} Xd$$

Table 7. Mineralogical weathering indices for weathered granite at Injaka Dam site.

Sample	Depth (m)	Dry density (kg.m^{-3})	Nq_{XRD}	$Nq_{o\ XRD}$	Xd_{XRD}	Kaolinite	Plagioclase	Microcline
LF 1*	0,9	1478	0,90	0,33	0,85	32	0	5
RF 12*	1	1511	0,91	0,33	0,86	33	2	3
LF 7*	1,1	1444	0,81	0,33	0,72	30	0	11
LF 18*	1,1	1535	1,00	0,33	1,00	31	0	0
RF 17*	2,2	1389	0,80	0,33	0,70	53	0	5
LF 19	2,3	1307	1,00	0,33	1,00	20	0	0
LF 2	2,4	1400	0,83	0,33	0,74	45	0	8
RF 6	2,5	1458	0,846	0,33	0,77	48	0	6
LF 8	2,8	1434	0,81	0,33	0,71	40	0	8
LF 20	3,2	1305	0,89	0,33	0,84	39	0	5
RF 10	3,5	1330	0,77	0,33	0,66	14	10	8
LF 3	3,8	1416	0,76	0,33	0,64	39	0	12
RF 18	3,8	1383	0,71	0,33	0,57	69	0	7
LF 9	4,0	1429	0,52	0,33	0,30	34	7	21
LF 21	4,0	1386	0,60	0,33	0,40	52	0	14
LF 4	4,5	1523	0,74	0,33	0,60	39	0	13
RF 5	4,8	1763	0,754	0,33	0,63	25	0	14
RF 9	4,9	1375	0,63	0,33	0,45	30	14	9
LF 22	5,1	1409	0,71	0,33	0,56	51	0	12
LF 5	5,2	1610	0,78	0,33	0,67	27	3	10
RF 19	5,2	1696	0,65	0,33	0,48	12	22	5
LF 10	5,5	1431	0,93	0,33	0,90	42	0	3
LF 6	5,5	1433	0,86	0,33	0,80	40	0	6
RF 8	5,7	1482	0,89	0,33	0,84	31	3	2
LF 24	5,7	1398	0,90	0,33	0,84	36	0	6
RF 20	6,1	1479	0,67	0,33	0,51	17	17	3
LF 25	6,2	1533	0,93	0,33	0,90	31	0	4
RF 21	6,2	1663	0,47	0,33	0,20	14	34	5
LF 11	6,5	1362	0,63	0,33	0,44	50	0	15
RF 7	6,6	1855	0,69	0,33	0,53	7	17	3
RF 4	6,9	1457	0,882	0,33	0,82	46	4	0
LF 26	7,2	1522	0,51	0,33	0,26	20	25	12
LF 12	7,3	1226	0,88	0,33	0,82	34	2	5
LF 13	7,7	1625	0,50	0,33	0,25	27	17	13
RF 22#	7,7	2350	0,63	0,33	0,45	0	23	9
LF 27	7,8	1797	0,58	0,33	0,38	17	21	7
RF 2#	8,2	1779	0,63	0,33	0,45	3	17	13
RF 23#	9,1	2210	0,77	0,33	0,65	0	10	13
RF 3	9,2	1683	0,426	0,33	0,14	16	17	22
RF 1#	9,6	1823	0,62	0,33	0,44	13	12	17
RF 24#	9,8	2250	0,72	0,33	0,59	0	20	6
RF 25#	10,2	2437	0,61	0,33	0,42	0	25	7
RF 13#	10,6	2010	0,51	0,33	0,27	4	33	11
RF 15#	10,9	2417	0,379	0,33	0,07	10	27	9
RF 14#	11,8	2159	0,58	0,33	0,37	0	22	17
RF 16#	11,8	2480	0,549	0,33	0,33	0	23	18

* Granite saprolite with residual soil patches
\# Highly weathered granite

Baynes and Dearman (1978a) have shown that when $Xd < 0.5$ a granular microfabric is present with interlocking grains and minimal leaching conditions. When $Xd > 0.5$ they showed that a variety of microfabrics can occur including poorly leached, but highly decomposed microfabric ("no leaching, clay matrix"); porous interconnected granular and clay microfabric ("porous connected matrix") and full leaching conditions resulting in a granular matrix with minimal clay ("full leaching - granular matrix"). The plot of Lumb's average trend for weathered granites in Hong Kong (line A_v) shows an increase in porosity up to $Xd = 0.5$ after which collapse of the microfabric occurs producing a poorly leached, more dense microfabric (which approaches that of a residual soil proper).

The results from this study show a much different relationship with increasing *Xd* suggesting increasing porosity and very little densification of the material at high *Xd* values. This is in agreement with the field observations which show only a poorly developed, thin veneer of material exhibiting a true residual soil structure. The difference between these observations and Lumb's results can probably be related to the much higher rainfall encountered in Hong Kong and consequently more advanced weathering of Lumb's materials. The trend shown by the weathered granites at Injaka Dam shows that the microfabric comprises a predominantly porous connected matrix. This has been substantiated by SEM observations made by Haskins *et al.*, (1998).

CONCLUSIONS

This study has shown how the application of chemical and mineralogical weathering indices to a granite saprolite can be used to classify the material according to its degree of weathering and quantify the weathering effects such that they may be scaled to the density (and hence engineering behaviour) of the material. Of the eleven chemical weathering indices applied to the granite saprolite, all indices with the exception of the Vogt Ratio provided good correlations with the density of the material. The poor correlation shown by the Vogt Ratio is due to the incorrect use of K_2O as an immobile component. The microfabric weathering effects of the weathered granite could also be quantified using the relationship of the mineralogical index, Xd_{XRD} with void ratio. This index is a modification of the degree of decomposition index (Xd) used by Lumb (1962).

Acknowledgements: The Author wishes to acknowledge the Council for Geoscience and Department of Water Affairs and Forestry for sponsoring this research.

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