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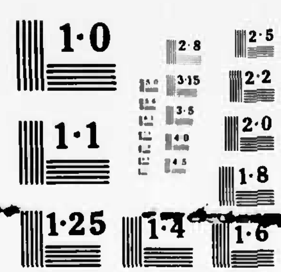

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MICROCOPY RESOLUTION TEST CHART

ACCELERATED WEATHERING OF ROCKS

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Comparative study between rates of experimental laboratory weathering of rocks and their natural environmental weathering decay

Final Technical Report

by

L. AIRES-BARROS

INSTITUTO SUPERIOR TECNICO
LISBON-PORTUGAL

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Project concerns correlation between weathering indices obtained from samples of one type of sedimentary rock (graywacke) and those obtained after laboratory agency tests of the same rocks. Study is made of the process of natural alteration in three stages. In laboratory thermal fatigue tests, the alteration by ageing is studied to obtain weatherability indices. Then, the two processes are compared, to compare laboratory and natural weathering correlation.

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COMPARATIVE STUDY BETWEEN RATES OF EXPERIMENTAL LABORATORY WEATHERING OF ROCKS AND THEIR NATURAL ENVIRONMENTAL WEATHERING DECAY

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Abstract

The aim of this work is to find a possible correlaction between the weathering indexes obtained from samples of one type of sedimentary rocks — a graywacke — in several degrees of alteration and those obtained after laboratorial ageing tests of the same rocks.

In a first part we study the process of natural alteration taking samples of three different alteration stages. These samples were colected in a vertical bore hole and the natural weathering process was followed through geochemical and petrological observations. Geochemical calculations were made, in order to obtain the amount of gain and loss of chemical elements. The quantification of the weathering through the application of weathering indexes and finally an attempt of application of an alterability index to these rocks were made.

Samples of the same rocks were submited to laboratory thermal fatigue tests (AIRES-BARROS et allia, 1975), in order to follow the alteration by laboratorial ageing and to obtain weatherability indexes. Besides physical values of supersound velocity, porosity, permeability and swelling of those rocks were determined. The presentation of the corresponding results forms the second part of this report.

In a third part the values obtained in the two precedent parts are compared in order to test the laboratorial work and to find the correlation between the "one laboratory year test" and the natural weathering.

Study of the degree of alteration of graywacke

samples from a vertical bore hole

The studied graywacke is a clastic, fine grained rock, rich in quartz and muscovite flakes, with some plagioclase and secondary calcite. All the clastic minerals are embeded in a phyilitic groundmass with graphitose films, which emphasizes the lineation of the rock.

These rocks occur in the province of Algarve (south Portugal). They belong to a large and thick geological formation of marine facies of the Carboniferous system (Dinantian). The samples studied are from one of the bore holes made for the study of dam foundation bedrock in Odeleite river.

One of the samples represents the sound rock (SR). It was collected at 28.38m depth and does not denote any phenomena of alteration. The sample of medium altered rock (MAR) was collected at 19.68m depth. It shows generalized ferruginization and secondary quartz (silicification). That iron enrichment is responsible for a light brown colour of the rock (SR is gray).

The sample of the very altered rock (VAR) was collected at 1.93m depth. This brown rock is not so coherent as the other two types. Microscope study shows a rock with generalized ferruginization. In fact the phyllitic groundmass is isotrope due to the iron enrichment (generalized ferruginization).

In TABLE I the main physical properties of the described samples are shown. TABLE II presents the chemical analyses and the isovolumetric calculation according MILLOT & BONIFAS (1955) of these graywackes which shows the gain and loss of oxides both absolute and relative values. These values describe the chemical transformations which from SR gives MAR, and from MAR atteins VAR.

The addition or subtraction of ions and water can be visualised comparing the chemical composition of the parent material (sound rock - SR) with the products resulting from the action of the surface weathering. In fact during the process of surface weathering certain ions may be removed from the sound rock (taken as reactant parent rock), some other may be added from the outside (from circulating waters) forming new products, and others may be rearranged giving new associations.

In order to compute the gain and loss of ions Barth's rock cell (BARTH, 1948) was used. With its help each rock-type could be described by the following formula:

$$SR — Si_{55.89}\ Al_{13.30}\ (Fe^{3+}_{1.12}\ Fe^{2+}_{1.52})\ Mg_{3.30}\ Ca_{1.73}\ Na_{3.96}\ K_{1.72}\ Ti_{0.36}\ Mn_{0.05}\ H_{30.54}\ O_{160}$$

$$MAR — Si_{54.00}\ Al_{15.53}\ (Fe^{3+}_{2.56}\ Fe^{2+}_{1.12})\ Mg_{2.96}\ Ca_{0.26}\ Na_{3.26}\ K_{2.46}\ Ti_{0.72}\ P_{0.31}\ Mn_{0.00}\ H_{30.96}\ O_{160}$$

Thus we can write:

$$SR + (Al_{2.23}+Fe^{3+}_{1.44}+K_{0.44}+Ti_{0.36}+P_{0.01}+0.21\,H_2O) - (Fe^{2+}_{0.40}+Mg_{0.34}+Ca_{1.47}+Na_{0.70}+Mn_{0.05}+Si_{1.89}) = MAR$$

and

$$MAR + (4.03SiO_2+Fe^{3+}_{1.32}+Na_{0.82}+Mn_{0.10}) - (Al_{1.44}+Fe^{2+}_{0.56}+Mg_{1.33}+Ca_{0.26}+K_{0.82}+Ti_{0.31}+P_{0.21}+H^{+}_{9.42}) = VAR$$

These equations and that table of gain and loss (TABLE II), show that the weathering process of this silicate rock is hydrolysis. Substances added in significante quantities are H_2O and Fe_2O_3. Alkali metals and alkaline earth metallic ions suffer a severe loss being removed by solution. The oxidizing medium is responsible for the transformation $Fe^{2+} \rightarrow Fe^{3+}$. The circulating waters are leaching the high levels of the rock, removing alkali and alkali earth metallic ions and deposing ferric oxides, which causes generalized ferruginization of the outer parts of the rocks.

Besides the quantifications of the weathering through equations such as those presented, we also tryed to quantify the degree of chemical weathering of these rocks reworking the figures of TABLE I. We can establish the following picture (TABLE III) taking the values of SR for all the physical properties refered as equal to 1.

Regarding the quantification of weathering we can try to use some weathering indexes refered in the literature. So, PARKER (1970, p. 501) establishes a weathering index for silicate rocks based on the proportions of alkali and alkaline earth metals in the different levels of the weathered rock. These index considers also the bond strengths of these elements (alkali and alkaline earth metals) with oxygen. Thus the Parker's index measures both the degree to which a rock has already been weathered with respect to the parent rock, and also its susceptibility to further weathering. According to PARKER (op. cit. p. 502) this index is defined by the following expression

$$\left(\frac{(Na)_a}{(Na\text{-}O)_b} + \frac{(Mg)_a}{(Mg\text{-}O)_b} + \frac{(K)_a}{(K\text{-}O)_b} + \frac{(Ca)_a}{(Ca\text{-}O)_b}\right) \times 100$$

where $(X)_a$ indicates the atomic proportion of the element X, defined as atomic percentage divided by atomic weight, and $(X\text{-}O)_b$ is the bond strength of the element X with oxygen. Using Nicholl's values the PARKER index expression becomes:

$$\left(\frac{(Na)_a}{0.35} + \frac{(Mg)_a}{0.90} + \frac{(K)_a}{0.25} + \frac{(Ca)_a}{0.70}\right) \times 100$$

Regarding the three stages of our graywacke this index takes the values reported in TABLE IV. We can conclude that the values of this index show a continual decrease with increased heigh in the bore hole. Otherwise, the sound rock, with a high index value is more susceptible to weathering than the medium altered rock. The lowest index value refers to the most altered rock-type.

More recently MIURA (1975) has presented an index to measure the degree of absolute chemical freshness (DACHEF). This index has the following expression:

$$DACHEF = \frac{\left(\frac{FeO+MnO+MgO+CaO+Na_2O+K_2O}{Al_2O_3+Fe_2O_3+H_2O}\right)_{\text{altered rock}}}{\left(\frac{FeO+MnO+MgO+CaO+Na_2O+K_2O}{Al_2O_3+Fe_2O_3+H_2O}\right)_{\text{sound rock}}}$$

The values of DACHEF are also presented in TABLE IV.

Parker's index is an weatherability index, so it measures not only the degree of weathering but also the potential weatherability. DACHEF, on the contrary, is only a measure of the chemical weathering, it is a picture of the static degree of alteration of a rock.

Using the values of TABLE IV we obtained Fig. 1, where we try to emphasize that an weathering action that weakens the rock to one half of its initial strenght, is enough to reduce the potential behaviour to weathering (potential weatherability) to 0.35. So the weatherability decreases more quickly than the weathering. In fact the measurement of chemical leaching (v.g. DACHEF) has a strong impact on the behaviour of the rock against the weathering agents (weatherability), as is emphasized by Parker's index.

Elsewhere we have defined an alterability index (AIRES-BARROS, et allia, 1975) by the following formula

$$K = K_{min} + g_j K_{min} = (1+g_j) K_{min}$$

being

K = an alterability index

K_{min} = a factor regarding mineralogical influence

g_j = a factor regarding textural, permeability and porosity influence

In the case we can studying, we can consider $K_{min} = \delta$ (density of rock in the three different stages of alteration). Regarding g_j we can take it as the chemical loss expressed by the amount of oxides leached (values from TABLE II). Considering the loss of the main chemical mobile constituents, as FeO, CaO and MgO (TABLE II), we may draw the TABLE V. From these values and from those of the densities of the three types of graywackes we can draw the TABLE VI.

In order to establish the relative behaviour of the three rock-types studied we can calculate this alterability index as:

$$K_{SR} = 1$$

$$K_{MAR} = \frac{2.85}{3.08} + 2.45 \times \frac{2.85}{3.08} = 3.17$$

$$K_{VAR} = \frac{2.70}{3.08} + 4.61 \times \frac{2.70}{3.08} = 4.88$$

Transforming these values in potential values, we will obtain:

$$K_{(SR)_{Pot}} = 1$$

$$K_{(MAR)_{Pot}} = \frac{1}{3.17} \simeq 0.3$$

$$K_{(VAR)_{Pot}} = \frac{1}{4.88} \simeq 0.2$$

In Fig. 1 we compare also the values of the weatherability index according to Parker and those obtained from our index (AIRES-BARROS et allia, 1975).

Laboratory study by thermal fatigue tests

We submited specimens of the three graywacke-types in study to thermal fatigue tests, which have been previously described (AIRES-BARROS et allia, 1975).

The thermal fatigue tests have the following steps of experimental work:

i) Dry tests on polished specimens with alternating heating and cooling actions;

ii) Wet tests in destilled water, with alternating heating and wet cooling actions;

The duration of the test for one apparatus cycle was 15 minutes. An apparatus cycle includes a period of high temperature (10 minutes at 70°C) and a period of pause at room temperature (5 minutes), either in a dry medium (air) or in immersion in destilled water.

All the specimens were studied by microscope observations in order to determine their reflectance and its variation along the assays. Other variations (mainly qualitative) were also followed in this microscopic study. A correlation between reflectance and Vickers microhardness of polished surfaces of rock specimens submitted to thermal fatigue tests was already attempted successfully (AIRES-BARROS, 1977).

In TABLES VII and VIII we present the values obtained from thermal fatigue experiments regarding weight loss and chemical leaching. From these data we can derive the values of TABLE IX in which the values of the weatherability index (K) are presented. In this case $K_{min}=\Delta p$ (weight loss) and g_j = total chemical leaching.

In TABLE X we present the microhardness determinations and the reflectance measurements obtained before the tests, during them and after them.

With the values of TABLES IX and X we can conclude that:

i) the alterability index K is a consistent measurement of the state of weathering of the rocks;

ii) reflectivity and Vickers microhardness give very good information about rock alterability and they are quick techniques for measuring the degree of alteration.

Comparative study and conclusions

The problem of comparision of the weathering degree of samples taken from the Nature with those submited to artificial laboratory ageing is difficult but we will try to resolve it.

The values of TABLE XI enable us to make some comments:

i) If we consider SR as 100% of potential weatherability and the increasing values of laboratory K as a true degree of weathering, the weatherability (the capacity to weathering in percentage) is shown in that table.

ii) The same reasoning is applicable to samples not tested in the laboratory. So we can state that MAR has 31.5% of capacity to weathering and that VAR is at 20% of its total desagregation.

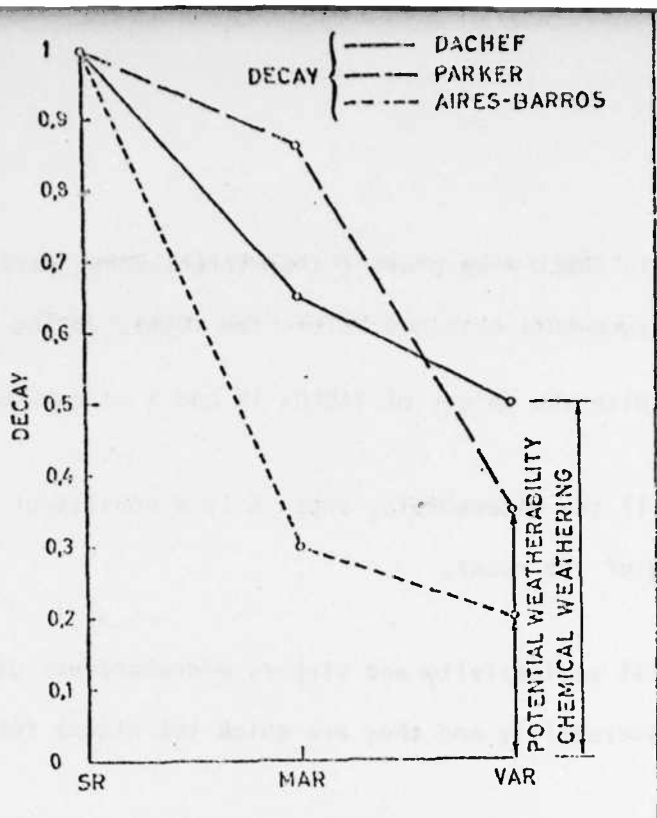

Fig. 1 - Evolution of rock decay according DACHEF, Parker and Aires-Barros indexes

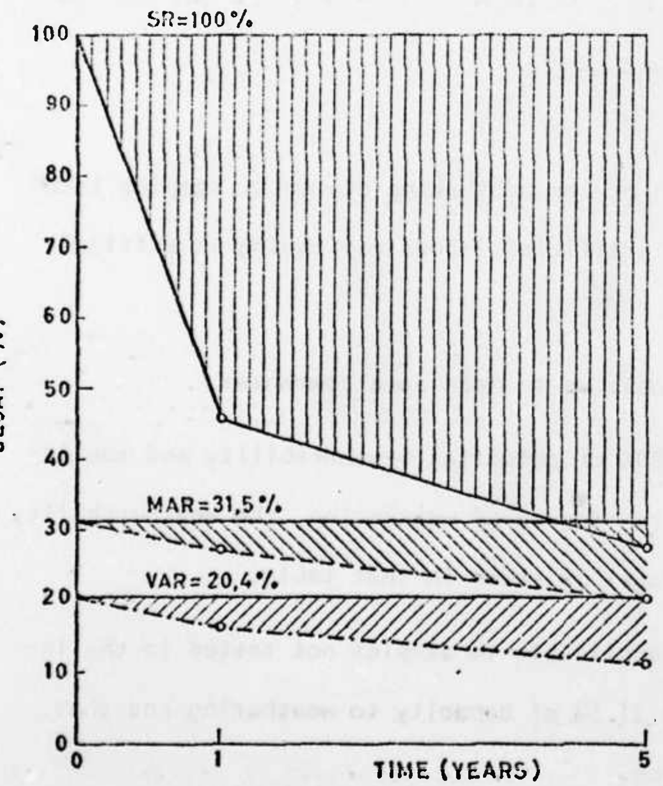

Fig. 2

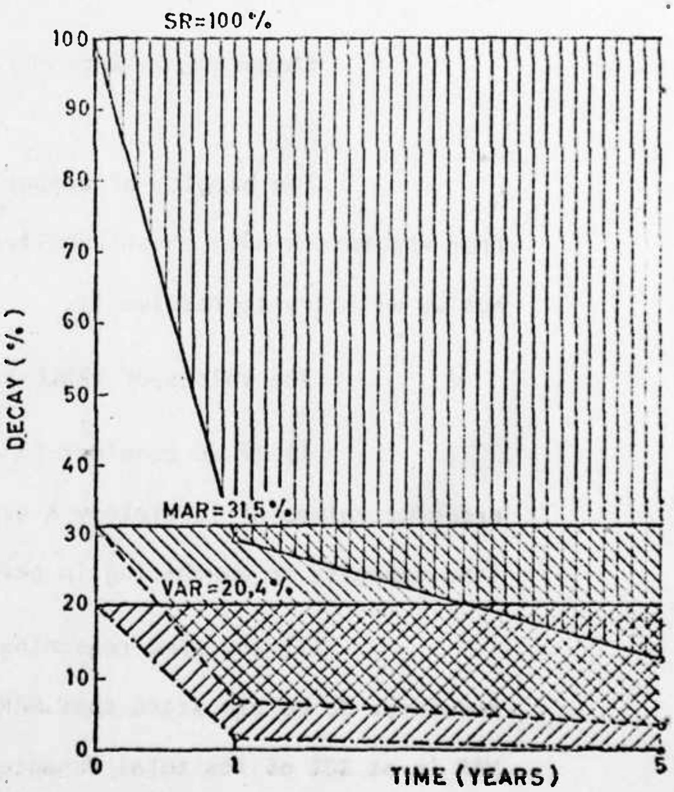

Fig. 3

- Evolution of the behaviour of the three rock-types studied against ageing by thermal fatigue tests in dry (Fig. 2) and wet (Fig. 3) conditions

iii) The comparision of the values obtained in laboratory tests with those of the samples not submited to these assays enables us to conclude that

$$K_{(SR)_{1\ \text{year wet lab.}}} \simeq K_{(MAR)_{\text{Nature}}}$$

and that

$$K_{(MAR)_{5\ \text{years dry lab.}}} \simeq K_{(VAR)_{\text{Nature}}}$$

So we can try to compare laboratory K values with those obtained from the geochemical study of natural alteration phenomena.

iv) We can list the rocks studied (tested and not tested at the laboratory) as follows:

$$\%\quad \underbrace{K_{SR)_0}}_{100} \rightarrow \underbrace{K_{SR)_{1y.\ dry}}}_{45.4} \rightarrow \underbrace{K_{MAR)_{nat.}}}_{31.5} \rightarrow \underbrace{K_{SR)_{1y.\ wet}}}_{29.4} \rightarrow \underbrace{K_{SR)_{5y.\ dry}} \simeq K_{MAR)_{1y.\ dry}}}_{27.5} \text{—}$$

$$\%\quad \rightarrow \underbrace{K_{VAR)_{nat}}}_{20.4} \rightarrow \underbrace{K_{MAR)_{5y.\ dry}}}_{20.3} \rightarrow \underbrace{K_{VAR)_{1y.\ dry}}}_{16.9} \rightarrow \underbrace{K_{SR)_{5y.\ wet}}}_{12.0} \rightarrow \underbrace{K_{VAR)_{5y.\ dry}}}_{11.2} \rightarrow \underbrace{K_{MAR)}}_{6.4}$$

$$\%\quad \underbrace{K_{MAR)_{5y.\ wet}}}_{3.1} \rightarrow \underbrace{K_{MAR)_{1y.\ wet}}}_{1.7} \rightarrow \underbrace{K_{VAR)_{5y.\ wet}}}_{0.86}$$

In Figs. 2 and 3 we show a picture of the evolution of the behaviour of the three rock-types against ageing by thermal fatigue tests in dry and wet conditions. We can see clearly that in dry conditions after 5 years of laboratory tests we attain the MAR level of alteration. Regarding MAR rock-type, after 5 years of dry laboratory tests it attains the VAR level of alteration.

So we can establish a correlation between the time of laboratory thermal fatigue tests (and its effects on the rocks tested) and the degree of alteration of rocks not submited to any laboratorial assay.

If we consider the K values from the wet thermal fatigue tests we can conclude about the very quick decay of the rocks submited to this type of laboratory assays. In fact SR rock after 1 laboratorial year reaches MAR level of alteration (in dry conditions 5 laboratory years are necessary). This SR rock--type after 5 laboratory wet years is below VAR level of alteration (Fig. 3).

MAR — and VAR-rock-types undergo severe ageing and decay by wet tests. VAR rock-type after 5 laboratory wet test is almost a "dead rock" and its potential weathering is ≈0. Even MAR rock-type weatherability after that wet test attains 5%.

We have presented an attempt of correlation between laboratorial ageing of rocks and natural weathering. The main aim of our research was to obtain (if possible) the link between our laboratory values and the true alteration of rocks. If we take this link we can extrapolate with some consistance our values to the reality of geotechnical behaviour of rocks.

The next step is to obtain, for instance, rocks used in the foundation of a large dam (or from the foundation of a bridge, etc.) and to compare their evolution (geochemical and geomechanical) with their behaviour against laboratory ageing assays.

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TABLE I

ROCK-TYPE	PROPERTY						
	Supersound velocity (ms^{-1})	Porosity (%)	Permeability (mdy)	Swelling test $\frac{\Delta Z}{Z}$	density	Reflectivity (%)	Micro-hardness (Hv)
Sound rock (SR)	5330.17	1.06	-	0.113	3.08	2.76	429
Medium altered rock (MAR)	5184.95	3.53	0.02	0.218	2.85	1.29	183
Very altered rock (VAR)	2392.05	20.21	0.11	0.453	2.70	0.40	not determinable

TABLE II

	CHEMICAL ANALYSES			CHEMICAL GAIN AND LOSS			
	SOUND ROCK (SR) %	MEDIUM ALTERED ROCK (MAR) %	VERY ALTERED ROCK (VAR) %	ABSOLUTE VALUES SR→MAR %	ABSOLUTE VALUES MAR→VAR %	RELATIVE VALUES SR→MAR %	RELATIVE VALUES MAR→VAR %
SiO_2	66.06	63.44	68.22	-22.87	+ 1.47	-11.14	+ 0.81
Al_2O_3	13.40	15.52	14.11	+ 2.99	- 6.62	+ 7.18	-14.82
Fe_2O_3	1.74	3.92	6.14	+ 5.87	+ 5.26	+108.30	+46.59
FeO	2.14	1.57	0.78	- 2.12	- 2.42	-31.88	-53.42
CaO	1.93	0.31	0.00	- 5.13	- 0.88	-85.36	-100.00
MgO	2.60	2.32	1.28	- 1.40	- 3.21	-17.35	-48.13
Na_2O	2.42	1.99	2.51	- 1.79	+ 1.05	-23.80	+18.32
K_2O	1.58	2.28	1.48	- 1.66	- 2.56	+33.88	-39.02
TiO_2	0.88	1.13	0.66	+ 0.51	- 1.47	+18.61	-45.23
P_2O_5	0.47	0.37	0.11	- 0.40	- 0.75	-27.59	-71.43
MnO	0.09	0.03	0.16	- 0.19	+ 0.34	-67.86	+377.78
H_2O^-	0.34	0.71	0.87	+ 1.00	+ 0.30	+95.24	+14.63
H_2O^+	5.42	5.46	3.79	- 1.15	- 5.49	- 6.82	-34.97
Σ	99.07	99.05	100.11	-	-	-	-

TABLE III

ROCK-TYPE	Superscund velocity	Porosity	Swelling	density	Reflectivity	Microhardness
SR	1	1	1	1	1	1
MAR	0.97	0.28	0.52	0.92	0.46	0.42
VAR	0.44	0.05	0.25	0.87	0.14	-

TABLE IV

ROCK-TYPE		PARKER'S index	DACHEF index
Depth (m)	State of alteration		
28.38	Sound rock (SR)	31.35 <> 1	1
19.68	Medium altered rock (MAR)	27.19 <> 0.86	0.65
1.93	Very altered rock (VAR)	11.09 <> 0.35	0.50

TABLE V

Rock-type	SR	MAR	VAR	SR-MAR	SR-VAR
FeO	2.14	1.57	0.78	0.57	1.36
MgO	2.60	2.32	1.28	0.28	1.32
CaO	1.93	0.31	0.00	1.60	1.93

TABLE VI

Rock-type	K_{min}	g_j	K
SR	3.08	0	3.08
MAR	2.85	2.45	9.83
VAR	2.70	4.61	15.15

TABLE VII

WEIGHT LOSS

Rock-type	type of test	Prior to testing P_o	1 year lab. test P_1	5 years lab. test P_5	$\Delta P_i = \frac{P_o - P_i}{P_o} \times 100$	
					$\Delta P_1 \times 10^2$	$\Delta P_5 \times 10^2$
Sound rock SR	Dry	35.4048	35.4006	35.3956	2.20	3.64
	Wet	36.2702	36.2579	36.2565	3.39	3.78
Medium altered rock MAR	Dry	34.6851	34.6725	34.6679	3.63	4.96
	Wet	32.4155	32.3945	32.3838	6.48	9.78
Very altered rock VAR	Dry	28.1332	28.1166	28.1082	5.90	8.89
	Wet	30.8480	30.8275	30.8176	6.65	9.85

TABLE VIII

CHEMICAL LEACHING

Rock-type	"Laboratory years"	MgO ($\% \times 10^3$)	CaO ($\% \times 10^3$)
Sound rock SR	one year	-	-
	five years	1.1	0.1
Medium altered rock MAR	one year	1.4	-
	five years	1.6	0.6
Very altered rock VAR	one year	4.0	4.8
	five years	5.6	6.2

TABLE IX

Rock-type	Dry tests $K \times 10^2$	Wet tests $K \times 10^2$
Sound rock SR	3.64	8.31
Medium altered rock MAR	4.96	31.58
Very altered rock VAR	8.89	116.20

TABLE X

		Sound rock SR		Medium altered rock MAR		Very altered rock VAR	
		dry test	wet test	dry test	wet test	dry test	wet test
Reflectivity R (%)	Prior to testing	2.76 (100%)		1.29 (100%)		0.40 (100%)	
	One lab. year	2.21 (80.1%)	1.25 (45.3%)	0.80 (62.0%)	0.76 (58.9%)	0.36 (90.0%)	0.31 (75.6%)
	Five lab. years	1.57 (56.9%)	1.02 (37.0%)	0.72 (55.8%)	0.70 (54.3%)	0.32 (80.0%)	0.22 (55.0%)
Vickers microhardness Hv ($9.8\times10^6 N/m^2$)	Prior to testing	429 (100%)		183 (100%)		no possibility of determination	
	One lab. year	275 (64.1%)	211 (49.2%)	176 (96.2%)	165 (90.1%)		
	Five lab. years	263 (61.3%)	165 (38.5%)	119 (65.0%)	114 (62.3%)		

TABLE XI

		K values Laboratory tests				K values Samples notsubmited to laboratorial tests	
		Dry		Wet			
SR	prior to testing	0	100%	0	100	3.08	100%
	one year lab.	0.20	45.4	3.39	-29.4		
	five years lab.	3.65	27.5	8.31	12.0		
MAR	SR (prior to testing)	0		0		9.83	31.5
	one year lab.	3.63	27.5	15.55	6.4		
	five years lab.	4.96	20.3	31.58	3.1		
VAR	SR (prior to testing)	0		0		15.15	20.4
	one lab. year	5.90	16.9	58.5	1.7		
	five lab. years	8.89	11.2	116.2	0.86		

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