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

ÉTUDE COMPARATIVE DES DÉGRES D'ALTÉRATION EXPERIMENTALE DES ROCHES AU LABORATOIRE ET DE LEUR DÉGRADATION NATURELLE

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Summary:

The aim of this work is to find a possible correlation between the weathering indices obtained from samples of one type of sedimentary rock, a greywacke, altered to various degrees and those obtained after laboratory aging tests on the same rocks.

In a first part the process of natural alteration is studied taking samples of three different alteration stages. These samples were collected in a vertical borehole and the natural weathering process was followed by 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 indices and finally an attempt was made to apply an alterability index to these rocks.

Samples of the same rocks were submitted to laboratory thermal fatigue tests (Aires-Barros et al. 1975), in order to follow the alteration by laboratory aging and to obtain weatherability indices. Physical values of sonic velocity, porosity, permeability and swelling were also determined. The presentation of the corresponding results forms the second part of this paper.

In the third part, the values obtained in the two preceding parts are compared in order to test the laboratory work and to determine the correlation between the "one laboratory year test" and natural weathering.

Résumé:

Cette étude a pour but de trouver une relation possible entre les indices d'altération obtenus sur des échantillons d'un type de roche sédimentaire, une grauwacke, plus ou moins altérés, et ceux que l'on obtient sur les mêmes roches après des essais de vieillissement artificiel.

Dans la première partie, nous étudions le processus d'altération naturelle, en prenant des échantillons de trois phases d'altération différentes. Ces échantillons ont été prélevés dans un forage vertical et le processus d'altération naturelle fut étudié au double point de vue, géochimique et pétrologique. Les calculs géochimiques furent faits pour mettre en évidence les variations quantitatives des divers éléments. La quantification de l'altération par application d'index d'altération conduit finalement à un essai d'application d'un "index d'altérabilité" à ces roches.

Des échantillons des mêmes roches furent soumis, au laboratoire, à des tests de fatigue thermique (Aires-Barros et al. 1975), pour permettre d'observer les changements d'altération qui accompagnent un vieillissement artificiel. Diverses propriétés physiques de ces roches furent aussi déterminées: vitesse des ultra-sons, porosité, perméabilité, gonflement. La présentation des résultats correspondants constitue la deuxième partie de cette étude.

Dans une troisième partie, les données obtenues dans les deux premières parties sont comparées pour étalonner le travail de laboratoire et pour trouver la corrélation entre le test d'un an au laboratoire et l'altération naturelle.

Study of the degree of alteration of greywacke samples from a vertical bore hole

The greywacke studied is a clastic, fine-grained rock, rich in quartz and muscovite flakes, with some plagioclase and secondary calcite. All the clastic minerals are embedded in a phyllitic groundmass with graphitic 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 boreholes made for the study of dam foundation bedrock on the Odeleite river.

One of the samples represents sound rock (SR). It was collected at 23.38 m depth and does not show any alteration. The sample of medium altered rock (MAR) was collected at 19.68 m depth. It shows generalized ferruginization and secondary quartz (silicification). 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 1.93 m depth. This brown rock is not as coherent as the other two types. Microscopic study shows a rock with generalized ferruginization. In fact the phyllitic groundmass is isotropic due to iron enrichment (generalized ferruginization).

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

The addition or subtraction of ions and water can be visualised by comparing the chemical composition of the parent material (sound rock —SR) with the products resulting from the action of 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 others 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:

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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 I

	CHEMICAL ANALYSES			CHEMICAL GAIN AND LOSS			
				ABSOLUTE VALUES		RELATIVE VALUES	
	SOUND ROCK (SR) %	MEDIUM ALTERED ROCK (MAR) %	VERY ALTERED ROCK (VAR) %	SR→MAR %	MAR→VAR %	SR→MAR %	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 II

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 the table of gains and losses (Table II), show that the weathering process of this silicate rock is by hydrolysis. Substances added in significant quantities are H_2O and Fe_2O_3. Alkali metals and alkaline earth metallic ions suffer a severe loss, being removed by solution. An oxidizing medium is responsible for the transformation $Fe^{2+} \rightarrow Fe^{3+}$. Circulating waters leach the high levels of the rock, removing alkali and alkali-earth metallic ions and depositing ferric oxides, which causes generalized ferruginization of the outer parts of the rocks.

Besides the quantification of weathering by the equations such as those presented, the degree of chemical weathering of these rocks was also quantified reworking the figures of Table I. The following picture (Table III) can be established taking the values of SR for all the physical properties referred as equal to 1.

Regarding the quantification of weathering, some weathering indices referred to in the literature may be used. PARKER (1970, p. 501) established a weathering index for silicate rocks based on the proportions of alkali and alkaline earth metals in the different levels of the weathered rock. This index considers also the bound strengths of these elements (alkali and alkaline earth metals) with oxygen. Thus 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.

ROCK-TYPE	Supersound 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 III

$$\left(\frac{(Na)_a}{(Na\text{-}0)_b} + \frac{(Mg)_a}{(Mg\text{-}0)_b} + \frac{(K)_a}{(K\text{-}0)_b} + \frac{(Ca)_a}{(Ca\text{-}0)_b} \right) \times 100$$

where $(X)_a$ indicates the atomic proportion of the element X, defined as the atomic percentage divided by the 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 the greywacke, this index takes the values given in Table IV. It can be concluded that the values of this index show a continual decrease with increased height in the borehole. 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 alterd rock type.

ROCK-TYPE Depth (m)	ROCK-TYPE State of alteration	PARKER'S index	DACHEF index
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 IV

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

$$DACHEF = \frac{\left(\dfrac{FeO+MnO+MgO+CaO+Na_2K_2O}{Al_2O_3+Fe_2O_3+H_2O}\right)_{\text{altered rock}}}{\left(\dfrac{FeO+MnO+MgO+CaO+Na_2O+K_2O}{Al_2O_3+Fe_2O_3+H_2O}\right)_{\text{sound rock}}}$$

The values of DACHEF are also presented in Table IV.

Parker's index is a 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, a weathering action that weakens the rock to one half of its initial strength is enough to reduce the potential behaviour on weathering (potential weatherability) to 0.35 (Fig. 1). Thus the weatherability decreases more rapidly 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 al. 1975) by the following formula

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

where

K = an alterability index

K_{min} = a factor regarding mineralogical influence

g_j = a factor regarding textural, permeability and porosity influence

In the present case, consider $K_{min} = \delta$ (density of rock in the three different of alteration). Regarding g_j it is the chemical loss expressed by the amount of oxides leached (values from Table II). Table V may be drawn up considering the loss of the main chemical mobile constituents, such as Fe0, Ca0 and Mg0 (Table II). From these values and from those of the densities of the three types of greywackes, Table VI can be derived.

In order to establish the relative behaviour of the three rock types studied the alterability index can be calculated as:

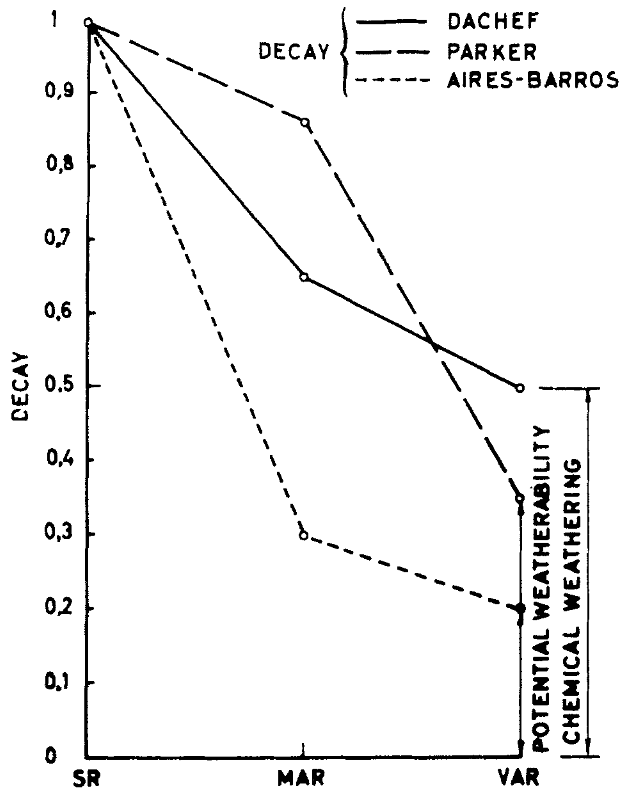

Fig. 1: Evolution of rock decay according to the DACHEF, Parker and Aires-Barros indices

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 V

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 VI

$$K_{SR} = 1$$

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

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

Transforming these values into potential values:

$$K_{(SR)POT} = 1$$

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

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

In Fig. 1 the values of the weatherability index according to Parker are compared with those obtained from the present index (AIRES-BARROS et al. 1975).

Laboratory study by thermal fatigue tests

Specimens of the three greywacke-types under study were subjected to thermal fatigue tests, which have been previously described (AIRES-BARROS et al. 1975).

The thermal fatigue tests have the following experimental stages:

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

ii) Wet tests in distilled water, with alternating heating and wet cooling action;

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 with immersion in distilled water.

All the specimens were studied microscopically in order to determine their reflectance and its variation with the tests. Other variations (mainly qualitative) were also followed in this microscopic study. A correlation between reflectance and Vickers microhardness of polished surface of rock specimens submitted to thermal fatigue tests has already been attempted successfully (AIRES-BARROS 1977).

In Tables VII and VIII the values obtained from thermal fatigue experiments regarding weight loss and chemical leaching are presented. 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 microhardness determinations and reflectance measurements obtained before, during and after the tests.

With the values of Tables IX and X it can be concluded that:

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

ii) reflectivity and Vickers microhardness give a very good indication of rock alterability and are rapid techniques for measuring the degree of alteration.

Comparative study and conclusions

The problem of comparison of the weathering degree of natural samples with those submitted to artificial laboratory aging is difficult, but an attempt will be made to resolve it.

The values of Table XI permit some comments:

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

ii) The same reasoning is applicable to samples not tested in the laboratory. Thus, MAR has 31.5 % of capacity to weathering and VAR is at 20 % of its total disaggregation.

iii) The comparison of the values obtained in laboratory tests with those of the samples not submitted to these leads to the conclusion that

$$K_{(SR)1\ year\ wet\ lab} = K_{(MAR)Nature}$$

and that

$$K_{(MAR)5\ years\ dry\ lab.} = K_{(VAR)Nature}$$

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 in the laboratory) as follows:

$$\% \quad \underbrace{K_{SR)0}}_{100} \rightarrow \underbrace{K_{SR)1y \cdot dry}}_{45.4} \rightarrow \underbrace{K_{MAR)nat.}}_{31.5} \rightarrow \underbrace{K_{SR)1y \cdot wet}}_{29.4}$$

$$\% \quad \underbrace{\rightarrow K_{SR)5y \cdot dry} \cong K_{MAR)1y \cdot dry}}_{27.5} - \underbrace{\rightarrow K_{VAR)nat.}}_{20.4}$$

$$\% \quad \underbrace{\rightarrow K_{MAR)5y \cdot dry}}_{20.3} \underbrace{\rightarrow K_{VAR)1y \cdot dry}}_{16.9} \underbrace{\rightarrow K_{SR)5y \cdot wet}}_{12.0}$$

$$\% \quad \underbrace{\rightarrow K_{VAR)5y \cdot dry}}_{11.2} \underbrace{\rightarrow K_{MAR)1y \cdot wet}}_{6.4} - \underbrace{K_{MAR)5y \cdot wet}}_{3.1}$$

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

In Figs. 2 and 3 a picture of the evolution of the behaviour of the three rock-types is shown against aging by thermal fatigue tests in dry and wet conditions. After 5 years of laboratory tests in dry conditions it can clearly be seen that the MAR level of alteration is attained. Regarding the MAR rock-type, after 5 years of dry laboratory tests it attains the VAR level of alteration.

So a correlation can be established between the time of laboratory thermal fatigue tests (and their effects on the rocks tested) and the degree of alteration of rocks not submitted to any laboratory to any laboratory test.

If the K avlues from the wet thermal fatigue tests are considered conclusions can be drawn about the very quick decay of the rocks submitted to this type of laboratory assays. In fact, after 1 laboratory year SR rock reaches the MAR level of alteration (in dry conditions 5 laboratory years are necessary). After 5 laboratory wet years this SR rock-type below VAR level of alteration (Fig. 3).

MAR- and VAR-rock types undergo severe aging and decay by wet tests. VAR rock-type after 5 years of laboratory wet testing is almost a "dead rock" and its potential weathering is$\simeq$0. After such a wet test, even MAR rock-type weatherability attains 5 %.

Rock-type	type of test	Prior to testing P_o	1 year lab. test P_1	5 years lab. test P_5	$\Delta P_i = \frac{P_o - P_i}{P_o} \times 100$	
					$\Delta P_1 x 10^2$	$\Delta P_5 x 10^2$
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 VII: Weight Loss

Rock-type	"Laboratory years"	MgO (%x10^3)	CaO (%x10^3)
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 VIII: Chemical Leaching

Rock-type	Dry tests Kx10^2	Wet tests Kx10^2
Sound rock SR	3.64	8.31
Medium altered rock MAR	4.96	31.58
Very altered rock VAR	8.89	116.20

Table IX

		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 (9.8x10^6N/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 X

		K values Laboratory tests				K values Samples not submited 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		

Table XI

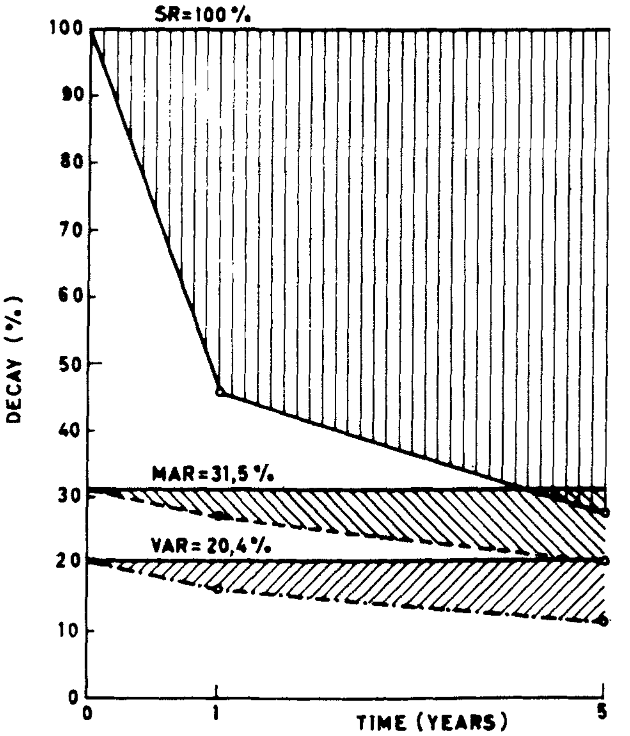

Fig. 2 and Fig. 3: Evolution of the behaviour of the three rock-types studied against aging by thermal fatigue tests in dry (Fig. 2) and wet (Fig. 3) conditions

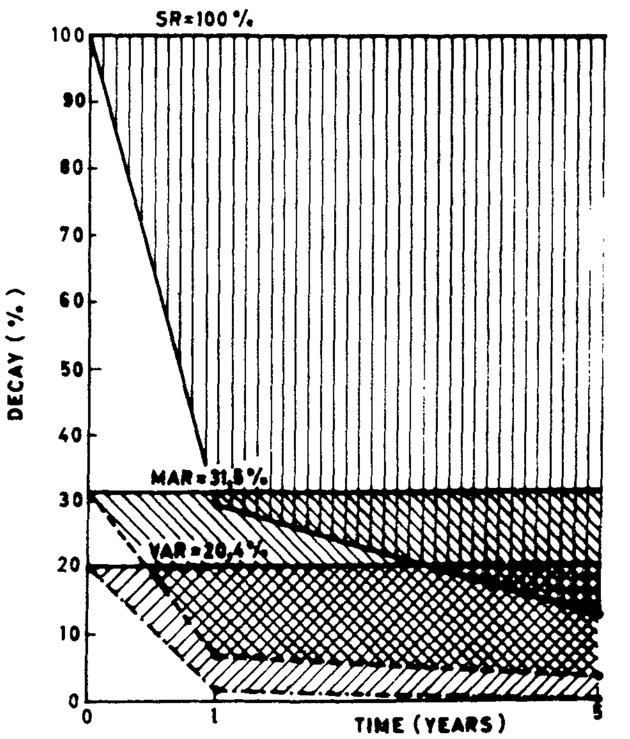

Fig. 3: Caption see Fig. 2

An attempt has been presented at a correlation between laboratory aging of rocks and natural weathering. The main aim of the research was to obtain a link between laboratory values and the true alteration of rocks.

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