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DURABILITY OF SANDSTONES

DURABILIDAD DE ARENISCAS

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RESUMEN

El término durabilidad es usado para describir la calidad natural de una roca. Sin embargo, este término es muy difícil de describir y más aún de medir. En la actualidad, la mayoría de los procedimientos disponibles para evaluar durabilidad han sido desarrollados en calizas y su aplicación en areniscas no está bien establecida. En este trabajo, la durabilidad de algunas areniscas fue determinada mediante los métodos tradicionales para evaluar calizas. Se realizó además, ensayes de durabilidad de Slake y de carga puntual en un intento de encontrar métodos alternativos para cuantificar la durabilidad.

ABSTRACT

The term durability is used to describe the natural quality of a rock, but this term is difficult to define properly and even more to measure. Most of the available procedures to assess durability have been developed for limestones. In this work, the performance of these methods when applied to sandstones was investigated. Slake durability and point load tests were performed in an attempt to find a substitute to the previous methods.

Contribución Nº 997

INTRODUCTION

The selection of the rock to be used as decorative cladding, structural walls and paving depend upon its natural properties and there is no processing or manufacture involved capable to change its quality. Available procedures to assess durability are well defined for limestones (pures). These procedures allowed to define classification systems which give zones of a building exterior in which the rock can be safely used. The more widely used classification are:

- BRE (British Research Establishment): it uses the % of weight loss in the crystallisation test and relates these results directly with durability.

- French: it uses the capillarity data and porosity/water absorption relationship to define durability in terms of the use which can be given to a stone.

- Belgian: it needs to measure the pore size and also capillarity data to give the classes of exposure which can be given to a rock.

In general, the obtainment of each parameter is highly time consuming and in the case of the crystallisation test it needs reference samples. In this study, these parameters will be determined and their values will be compared with the values for limestones. Slake durability and point load tests will be performed in an attempt to find a substitute for the available methods to assess durability.

LITHOLOGY

The rocks chosen to be tested correspond to sandstones coming from different quarries located in the city of Leeds (England). The rocks are from three different geological units: Rough Rock and Rough Rock Flags, both belonging to Millstone Grit Series (upper carboniferous) and Thornhill Rock which belongs to Coal Measures Series (upper carboniferous).

ROUGH ROCK FLAGS

The rock tested is currently used as paving and dressing stone. Macroscopically, the dressing stone is a fine to medium light brown thinly bedded SANDSTONE, with muscovite in the bedding planes. Very thin dark coloured, fine grained, levels of mica and clay are characteristic of this rock. Iron hydroxides are distributed as Liesegang rings. These rings give to the stone a very valuable ornamental figure. The paving stone is similar to the former but the thin argillaceous/micaceous levels are more common. This levels define very weak planes through which the rock can be easily cut. Microscopically, the rock is a fine, well sorted, subrounded to subangular SANDSTONE, constituted mainly by quartz, some of which show undulating extinction. KFd and plagioclase are also present. The cement is siliceous with a small proportion of chlorite and clay minerals (argillaceous cement). Sericite as alteration of feldspars is common. Muscovite, iron hydroxides and biotite are also present. Zircon and sphene are accessory minerals. The packing can be described as tangent (Winkler, 1973). Pores of different sizes are present. The paving stone is very similar, they have the same minerals though the dressing stone has less argillaceous cement. Sericite, biotite and iron hydroxides are also more abundant. The packing in this case is floating (Winkler, 1973).

ROUGH ROCK

Rocks of this unit were widely used in the past. Currently, it is not being quarried so samples were taken from two old quarries;

both samples being fairly similar. Macroscopically, the stone is a light grey, coarse grained, subrounded SANDSTONE with quartz as a main mineral; pink KFd which in parts is altered to sericite, is common. The rock shows an incipient cross-bedded structure. Microscopically, it correspond to a subrounded SANDSTONE, constituted mainly by quartz, some of which have undulating extinction. Microcline, KFd and plagioclase, partially altered to sericite, are also present. Biotite, muscovite and iron oxides are syngenetic minerals. Zircon and epidote are present as accessories. The cement is constituted mainly by quartz, silica, clay minerals and sericite. Microsparritic calcite is also present in small quantities. In one sample, fractured and lightly altered garnet in small quantities. In one sample, fractured and lightly altered garnet appear. The package is tangent to long (Winkler, 1973). Pores of different sizes are also common.

THORNHILL ROCK

Two samples were taken from an "in production" quarry. At this place, light brown sandstone is quarried together with the rock here described.

Macroscopically, the samples can be described as a grey-greenish, fine grained SANDSTONE with small tabular fragment of organic rests (coal) which are oriented parallel to bedding planes. Some samples show iron hydroxides distributed as Liesegang rings. Microscopically, they correspond to a well sorted, fine grained, subrounded to subangular SANDSTONE, the main constituent being quartz, some of which show undulating extinction. KFd, microline and plagioclase are also present in less quantities as detritic minerals. Iron hydroxides and muscovite are randomly distributed in the samples. The cement is not very abundant and it is constituted mainly by silica and in less proportion sericite, chlorite and biotite. Sericite came from the alteration of feldspars. Epidote and zircon are present as accessory minerals. The packing is tangent to floating. Although macroscopically both samples seem to be the same, through the microscope one of the samples shows sparry calcite as part of its cement together with silica and chlorite.

DURABILITY

Rocks are generally considered a very good material for construction.

However, the decay of a number of monuments and the behaviour of some rocks in polluted environments raises questions about the quality of the stones. The results of studies, performed in limestones (Winkler, 1973; Leary, 1981; Homeyborne, 1982; BRE, 1983; Sedman and Barlow, in prep.), demonstrated that the internal structure rather than the chemical composition is the indicator of durability of this rock. A stone with a high proportion of very small pores is less durable than a stone having larger pores. Consequently, the assessment of the durability of limestones can be derived from parameters which are related with the pore characteristics of the rock (indirect assessment) or from tests capable to simulate the conditions at which the stone will be exposed (direct assessment). Although the performance of limestone is well established, sandstones have not been very well described in terms of durability. Available literature shows that for this rock the relevant indicator of durability is the cement rather than the internal structure. In this study, the behaviour of some sandstones when subjected to the test procedures recommended for limestones and to point load and slake durability tests will be investigated. In the following paragraphs, test procedures and parameters used for limestones are described.

SPECIFIC PROCEDURES FOR LIMESTONES

i) Indirect assessment of durability

The indirect assessment is based in the following properties:

- The pore characteristics, which refers mainly to the volume of pores in the rock (porosity) and the size distribution of them (porosimetry). In this study, these properties were measured by using the mercury intrusion method (Autopore 9200 machine). Porosity is expressed as a percentage of the total volume of the rock.

- Saturation Coefficient (S) which is the proportion of the pore spaces that become filled with water after an specimen is soaked in water. Values can range from about 0.4 to 0.95. A high value indicates a stone with a high proportion of fine pores. S is expressed as:

$$S = \frac{\text{Absorption}}{\text{Total porosity}}$$

Absorption is measured by the method which is suggested in Honeyborne (1982) described in Rebolledo (1990).

- Capillarity: it refers to the facility of the water to rise through the pores of a rock. The Capillarity Coefficient is calculated from capillarity test by using the expression:

$$C = \frac{100\,M}{S\,\sqrt{t}}$$

where M= mass of water absorved from the beginning of the test (gr).

S= section area of the lower face of the test piece (cm)

t= total time in min since the beginning of the capillarity rise

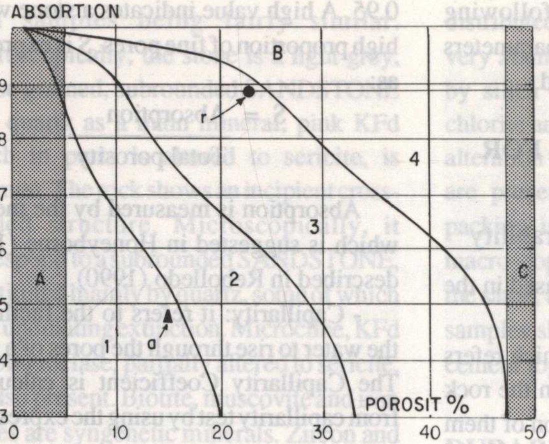
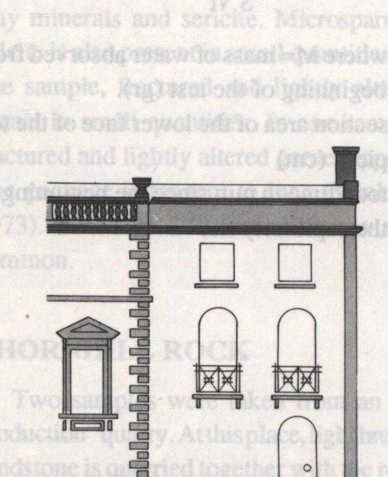
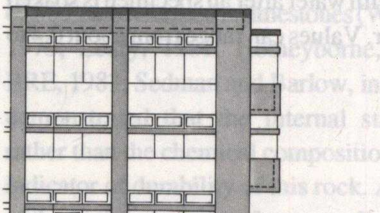
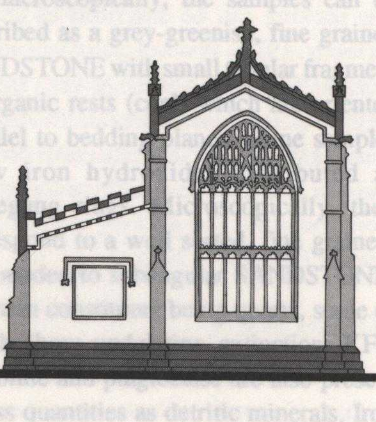


Fig. 1 Indirect assessmento of frost susceptibility. Graph of zones.- (AFTER BRE, Digest 269, 1983).

Fig. 1 Estimación indirecta de susceptibilidad al congelamiento. Gráfico de zonas.







■ Zone 1 Paving, steps

▩ Zone 2 Copings*, chimneys, cornices*, open parapets, finials, plinths*

▨ Zone 3 Strings, plinths*, quoins, tracery hood moulds, solid parapets (excluding coping stones*), cornices*, mullions

☐ Zone 4 Plain walling

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*A stone normally suitable for Zone 3 could be used for copings and cornices in Zone 2 if it is protected by lead. Similary, a plinth in Zone 2 could be considered as Zone 3 if there is protection against rising damp.

Table 1
French zones

Zone	Characteristics of stone	Position where it can be used
1	Zone 1 of Porosity/Saturation graph; Capillarity < 2	Exterior paving, dock linings bridge piers
2	Zone 1 or 2 of Porosity/ Saturation Coefficient; Capillarity < 5	Base courses, balconies
3	Zone 1, 2 or 3 of Porosity/Saturation graph	Cornices, string courses, sills, splash courses Capillarity < 15
4	Porosity < 47%	Elevation under projections

These parameters are used by the available stone selection procedures to give an approach to the durability of a rock or to exterior zones in which a stone can be safely used:

The French procedure uses the *Capillarity Coefficient* and the *Porosity Saturation Coefficient ratio* (Fig. 1) to define zones of a building where a stone can be used (Table 1).

The Belgians use a system which is similar to the French's one but with emphasis on frost resistance and on the observation of the rock behaviour in buildings before deciding on the durability of a limestone. The system uses capillarity data to define two different capillarity coefficients G and GC (calculated from % Saturation vs $\sqrt{t}$ graphs). G is a measure of frost resistance and GC defines classes of exposures (Table 2).

For porous stones, G is defined as:

$$G = St + 178\alpha_2 - 81$$

and

$$GC = 14.53 - 0.31\alpha_1 + 0.203\,St$$

Where St is the water content at the point of inflection of the two stage line in graph % Saturation vs $\sqrt{t}$ and α_1 is the slope of the first stage line in the same graph.

For low porosity stones, G and GC are defined as:

$G = St + 178\,\alpha_2 - 81$, calculated at $\sqrt{t} = 100$ and,

$$GC = -6.35 + 21.47\,\alpha_1$$

G should be less than zero for stones which are resistant to frost.

Table 2
Classes of exposures. Belgian system.

GC < -2.5	class D - stone survives 4 winters in a tray of sand or at least 2 winters at Bertrix;
GC > -2.5 to 0.95	class C - stone survives 4 winters as a paving stone;
GC > -0.95 to 0	class B - stone survives free standing for 4 winters;
GC > 0 to 4.5	class A - stone survives in a vertical wall for 4 winters;
GC > 4.5	class O - stone does not survive in a vertical wall.

The Belgian system uses also the d10 value as measure of frost resistance. d10 is the pore diameter corresponding to the 10% of the pore spaces. A stone with d10 greater than 2.5 microns and a saturation coefficient less than 0.8 is considered to be frost resistant.

The proportion of total pore space that is accounted for by pores with an effective diameter less than 5 microns is the Microporosity, which has been found to be a useful indicator of the durability. Stones with a low microporosity -less than 30%- are durable; stones with a high microporosity -greater than 90%- are not durable. Between 50 and 80% region, microporosity is an unreliable guide to durability (Leary, 1981).

ii) Direct assessment of durability

The main cause of limestone decay in U.K. is the crystallisation of salts within the pores of the stone. Crystallisation test simulates very well this condition and therefore, it is the best single test for assessing the general weathering resistance of a limestone. In this test, the samples are subjected to cycles of immersion in a sodium sulphate solution following by drying in an oven. The results are in % of weight loss during the test. Table 3 suggests those zones of a building where the stone can be safely used (depending on the environment).

Specific procedures for Sandstones

i) Sulphuric acid immersion test

This is the first stage in testing sandstones for durability. It simulates the behaviour of the rock when placed in highly polluted environments.

ii) Crystallisation test

As was mentioned before, in this rock the cement is the decisive indicator of durability. The durability of the cement is related with its chemical composition; siliceous cement is durable, whilst ferrouginous and argillaceous are not very resistant. The environment is a relevant factor for the resistance of the cement: coastal areas, low temperature zones and high pollution environments being the places where the durability should be assessed. In these areas, the cement is attacked by salt

Table 3

Effec of change of environment on suitability of limestones for various building zones*. (After Honeyborne, 1982).

Lime stone type	Loss in crystallization test (%)	Suitability zones for various limestones in a range of climatic conditions							
		Inland				Exposed coastal			
		Low pollution		High pollution		Low pollution		High pollution	
		No Fros	Frost	No Fros	Frost	No Fros	Frost	No Fros	Frost
A	1	1-4	1-4	1-4	1-4	1-4	1-4	1-4	1-4
B	1 to 5	2-4	2-4	2-4	2-4	2-4	2-4	2'-4	2'-4
C	5 to 15	2-4	2-4	3-4	3-4	3'-5	4	—	—
D	15 to 35	3-4	4	3-4	4	—	—	—	—
E	35	4	4	4'	—	—	—	—	—
F	Shatters early in test	4	4	—	—	—	—	—	—

Note: 1-4 are zones referred to those in French Standard for limestones
'Probably limited to 50 years' life

and/or acid solutions and in the case of low temperature areas the decay is due to crystallisation of water in the pores of the stone. The crystallisation test simulates the effect of crystallisation attack, i.e. it reproduces some of the more demanding environments.

iii) The Index of Durability

It is another useful indicator of durability. It corresponds to a dry to wet strength ratio based on uniaxial compressive strength. Winkler (1986) suggests that this ratio is a valid index of durability. Colback and Wiid (1965 in Winkler, 1986) plot UCS against increasing moisture content; the decreasing strength with increasing water content is credited by the authors to decreasing surface free-energy of quartz by the presence of any given liquid. Winkler (1986) has observed a considerable increase in strength of fine grained rocks when water sorbed under vacuum as compared with sorption under atmospheric pressure. In general, sandstones with a mean grain size less than 0.2 mm tend to increase the strength when water-sorbed under vacuum, thus interfering with the true dry to wet strength ratio. In this work, the point load test was chosen as a useful mean to obtain a measure of strenth. This test is easy to carry out and does not require sample preparation, its results will be related with the crystallisation test results to obtain a measure of durability.

iv) Slake Durability Test

This is a standard test, common for all rock types, which intends to evaluate the resistance offered by a rock to weathering and disintegration when subjected to short term cycles of drying and wetting. The *Slake Durability Index* (Id2) obtained from this test has been proposed by Franklin and Chandra (in Ebrahimi, 1985) for use in rock classification (Table 4).

Table 4
Durability Classification from Slake Durability Index

Slake Durability Index (Id2)	Durability
0 - 25	Very low
25 - 50	Low
50 - 75	Medium
75 - 90	High
90 - 95	Very high
95 - 100	Extremely high

Test Results

Sulphuric acid immersion test

The sandstones which have no calcite as sparritic cement are not affected by the acid as they keep the same initial strength. However, the sample with calcite show opened fractures due to the disolution of calcite by sulphuric acid.

Crystallisation test

In general, the samples performed quite well in terms of weight loss, although the samples of paving were divided by the fine grained levels, and the samples with calcite show opened fractures due the disolution of this mineral. The results are shown in Table 5.

Capillarity test

This test was performed on cubes of 7 cm edge and also on small cylinders (2.5 cm diameter, 2.5 cm length). The capillarity rise observed shows three different slopes, the first one corresponding to initial gain in water (direct contact between the sample and the water level), the second one corresponding to capillarity rise using the big pores and the third one is capillarity rise by the infill of micropores. The value of 1 and 2 being the slopes of the second and third part of the curve respectively. The capillarity test was used to calculate Capillarity Coefficient (for French procedures) and G and GC for Belgian classification (Table 5).

Point load test

The values of Is(50) obtained from testing saturated and oven dry samples is presented in Table 5. An immediate result is the high decrease in strength in samples water soaked (saturated at atmospheric pressure). The decrease in strength for most of them is about 30%. The relationship between Dry to wet strength is shown in Fig. 2

The summary of test results are shown in Table 5.

Fig.2 Is(50) saturated vs Is(50) dry.

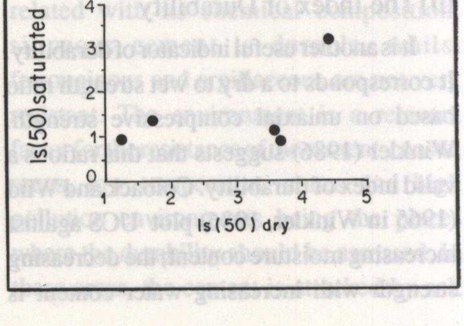


Table 5
Summary of test results

Sample	% loss crysta. test	Poro sity	Micro poro sity	d10	Slake Index (Id2)	Water Absorp	Satur. Coeff.	St
CA	1.5	13.96	99.62	3.23	98.83	0.108	0.77	84
CB	15.2	15.20	100	3.11	98.41	0.112	0.74	88.5
W	12.27	12.53	81.86	8.18	97.23	0.12	0.96	74.5
B1	24.31	13.90	100	2.59	99.21	0.095	0.69	81.5
B1	5.0	13.90	100	2.59	99.21	0.095	0.69	81.5
M	9.3	9.74	25.71	40.00	98.48	0.127	1.30	68.7
M	1.5	11.27	47.14	48.81	98.43	0.098	0.87	78.3
MA	1.16	14.39	43.57	42.27	98.72	0.111	0.77	72.5

Sample	α1	α2	Capill. Coeff.	Is(50) dry	Is(50) satur.	Dry/wet strength	G	GC
CA	5.00	067	1.51	3.57	1.13	3.17	122.3	0.97
CB	6.17	0.50	1.92	3.57	1.13	3.17	96.5	1.52
W	10.87	0.67	3.31	3.65	0.88	4.15	117.8	2.78
B1	5.51	0.10	1.50	4.39	3.18	1.38	18.3	0.31
B1	5.51	0.10	1.50	4.39	3.18	1.38	18.3	0.31
M	11.08	0.43	3.17	1.27	0.94	1.35	64.2	4.02
M	28.41	0.78	1.88	1.71	1.36	1.25	136.2	7.44
MA	8.19	0.28	1.88	1.71	1.36	1.25	41.3	2.35

Rough Rock Sandstones (M, MA)
Rough Rock Flags Sandstones (B, W)
Thornhill Sandstones (CA, CB)

Table 6
Classification of the tested rocks using different systems

Sample	BRE		French System	Belgian exposures (class)	From direct obser. type (BRE)
	Type	No frost zones	Zones		
M	C	2-4	2	-	A
MA	B	2-4	1	-	A
B	D	3-4	1	A	B
W	C	2-4	2	D	B
CA	B	2-4	1	A	B
CB	D	3-4	1	A	C

The comparison between the actual quality of the tested sandstones, assessed by direct observations of the behaviour of them in old buildings, and the durability obtained from the available classifications for limestones are presented in Table 6. From this table it is possible to conclude that the method of classification which is more concordant with the actual behaviour of sandstones is the BRE classification system, which is based in the crystallisation test. However, this method is a bit conservative.

Indirect assessment of durability

One of the aims of this work is to investigate if one or more parameters are well and directly related with the % loss of weight in the crystallisation test (direct measure of durability) to find a substitute of this time consuming method. To achieve this goal, an statistical analysis of the test results was performed in two stages. First, the analysis of the correlation matrix of the observations obtained in different samples in different tests, provides a good picture of the linear relationship between pairs of different test results, i.e. to what extent one test can be well explained by another. In particular, it indicates which test can most probably be a substitute of the crystallisation test. The matrix shows a clear (but not very high) correlation between crystallisation test result and: slake durability, French capillariry coefficient C and water absorption, in that decreasing order (Table 7).

Table 7
Correlation coefficient of different parameters with the % of weight loss in crystallisation test

Parameter	Correlacion Coeff. with % loss in cryst. test
Slake durability	-0.695
C: French Cap. Coeff.	0.684
Water absorption	0.630

An interesting result is the good correlation between Crystallisation test and Slake durability. The slake test is easily performed and the observations are obtained quickly which is a desired characteristic. It would be interesting to measure the third or four Slake durability index (i. e. three or four cycles test) and compared them with the crystallisation test results.

Secondly, it is likely that a group of parameter is able to explain better the results of the crystallisation test than any one parameter alone. To that end, the values of the crystallisation test were linearly regressed against all the other parameters and groups of parameters derived from different tests (multivariated regression). Regressions were performed for linear and quadratic expressions attemping to search for a better fit. However, the results do not provide further information from that of the correlation matrix.

Graphs showing the relationship between the parameters above mentioned are presented in Fig. 3 to 9. From these graphs, as well as from the statistical analysis, it is possible to verify that for the tested rocks, there is no an appropriate indicator of durability as a substitute of the crystallisation test. However, the analysis also indicates that, within the limitation of the empirical work, the slake durability, Capillarity coefficient and water absorption are good candidates to provide an approximate estimation of the durability for the tested rocks. Perhaps, an important conclusion is that the statistical analysis seems to be a useful method in searching for substitute tests.

Fig.3 % weight loss in crystallisation test vs saturation coefficient.

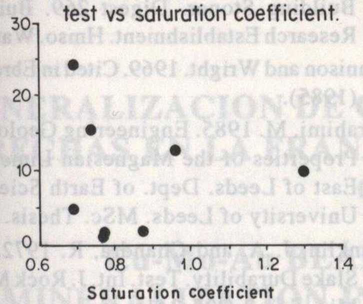


Fig.4 % weight loss in crystallisation test vs dry/saturation strength.

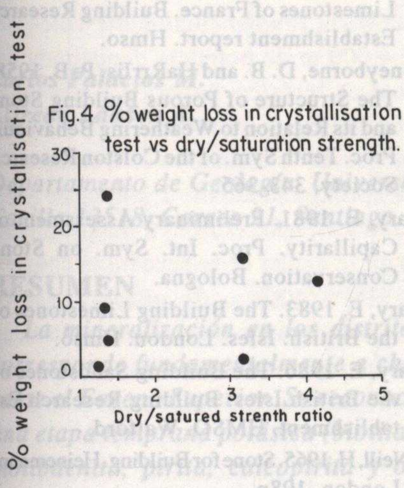


Fig.5 % weight loss in crytallisation test vs durability index Id_2.

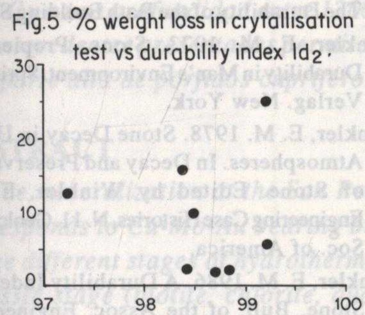


Fig.6 % weight loss in crystallisation test vs water absorption.

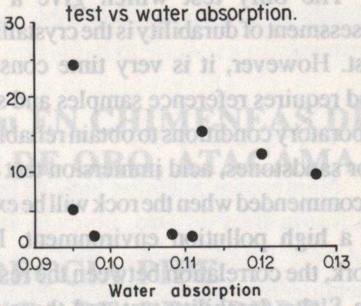


Fig.7 % weight loss in crystallisation test vs french capillarity coefficient : C

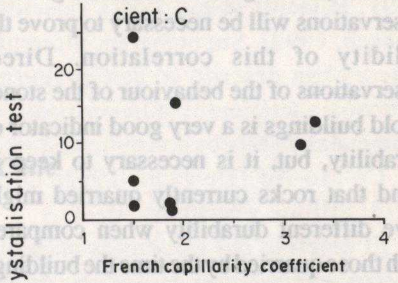


Fig.8 % weight loss in crystallisation test vs Is(50) dry.

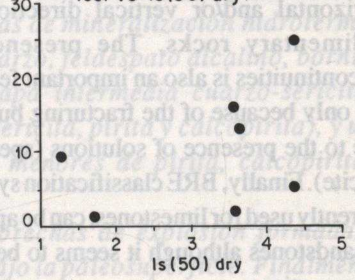
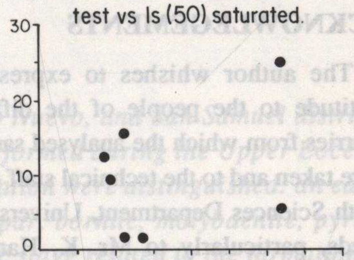


Fig.9 % weight loss in crystallisation test vs Is (50) saturated.



CONCLUSIONS

The only test which give a direct assessment of durability is the crystallisation test. However, it is very time consuming and requires reference samples and special laboratory conditions to obtain reliable data. For sandstones, acid immersion test is also recommended when the rock will be exposed to a high pollution environment. In this work, the correlation between the results of the Slake durability test and those of the Crystallisation test is highly encouraging. Further investigations involving more observations will be necessary to prove the validity of this correlation. Direct observations of the behaviour of the stones in old buildings is a very good indicator of durability, but, it is necessary to keep in mind that rocks currently quarried might have different durability when compared with those quarried by the time the buildings were built. This difference is caused by the natural variability in the properties, both in horizontal and/or vertical direction, of sedimentary rocks. The presence of discontinuities is also an important feature, not only because of the fracturing but also due to the presence of solutions (specially calcite). Finally, BRE classification system, currently used for limestones, can be applied to sandstones although it seems to be a bit conservative.

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