MECHANICAL DECAY PROCESSES IN LAPIDEOUS MATERIALS (CARRARA MARBLES) : PRELIMINARY STUDY OF CREEP PHENOMENA

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Abstract
The paper describes some preliminary data relating to a survey of deformation phenomena affecting marble slabs. The data refers to tomb stones in the Florence cemetries and it allow us to draw up a classification of the processes and to direct the analyses towards the modelling of creep phenomena.

1. INTRODUCTION

The subject of this research is mechanical decay and physical degradation processes of lapideous materials, especially of the marble used in important historical and architectural buildings and monuments. The restoration and preservation techniques to be used on buildings and monuments are linked to the development of the knowledge of the relationships existing between physical, mechanical, mineralogc-petrographic and geomechanical characteristics and weathering phenomena, caused both by external agents and intrinsic static stresses. In fact particular mechanical decay processes have been analyzed by Fratini et al.[1], Garzonio et al.[2] and these can be classified and linked to creep phenomena, which occur in conditions where stresses have been applied over a long period of time. The stresses are markedly lower than the breaking ones in rapid conditions but these phenomena can however evolve up to the point where they cause fissures and jointing of varying importance and dimension depending on the materials, their stress history and function. These creep phenomena seem to be particularly widespread in marbles, but they also occur in rocks which have been affected by intense tectonic events (in particular granites). Winkler et Singer [3] and Winkler [4] described these deformations in monuments and buildings. They recognized the importance of plastic deformation phenomena as an effect of the residual stresses in stone -previously studied by Kieslinger [5] and Voight [6]-, and identified the effects in the marble slabs and columns.

In an initial phase of the research programme tests have been and are currently being carried out on slabs of Carrara marble used on the facade of the Collegiata di Sant'Andrea in Empoli (near Florence-Italy), and in some cemetries in Florence area. In particular, the geomechanical features, the extent of the viscous deformations of the marbles and the results of laboratory tests are described, the objective being to obtained a preliminary definition of the creep phenomenology. It is within this context that this material has been analyzed from the point of view of the variations in some physical and mineralogic-petrographic properties linked to the deformations (Garzonio et al. [2]). This analysis highlighted the different geometric distribution of the points of physical-mechanical decay. On the basis of the results of the physical analyses, we find an interesting correlation between the deformations the material has undergone and, above all, the porosity values (mean porosity value is 5,2 % for the concave side of the slab, and 6,1% for the convex one, with an elevated coefficient of variation CV=35%, max value 10,5%, min 3,9%). This property determines and highlights the degradation processes. Figure 1 shows the central vertical axis of the slab of the Collegiata di Empoli. The thin sections also show a considerable difference between the convex and the concave parts. In the former we find intergranular disconnnections (Figure 2), while in the concave part the blasts are closely inteconnetcted.

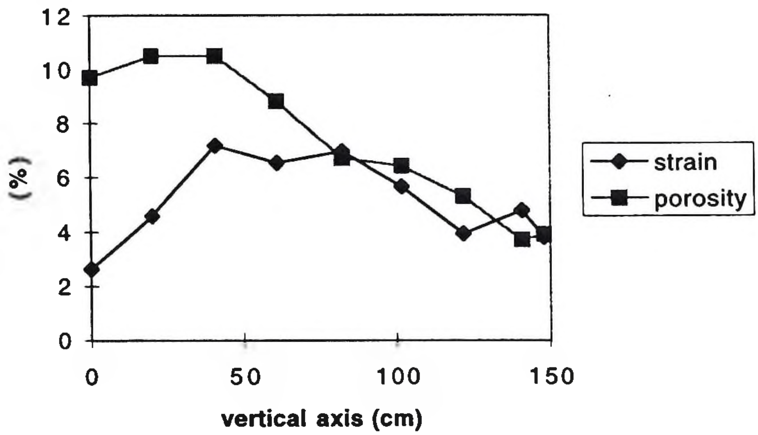

Figure 1 - Pattern of the transverse deformations measured along sections perpendicular to the greater vertical side of the slab, and of the distribution of the porosity values (Collegiata of Empoli slab [1], [2]).

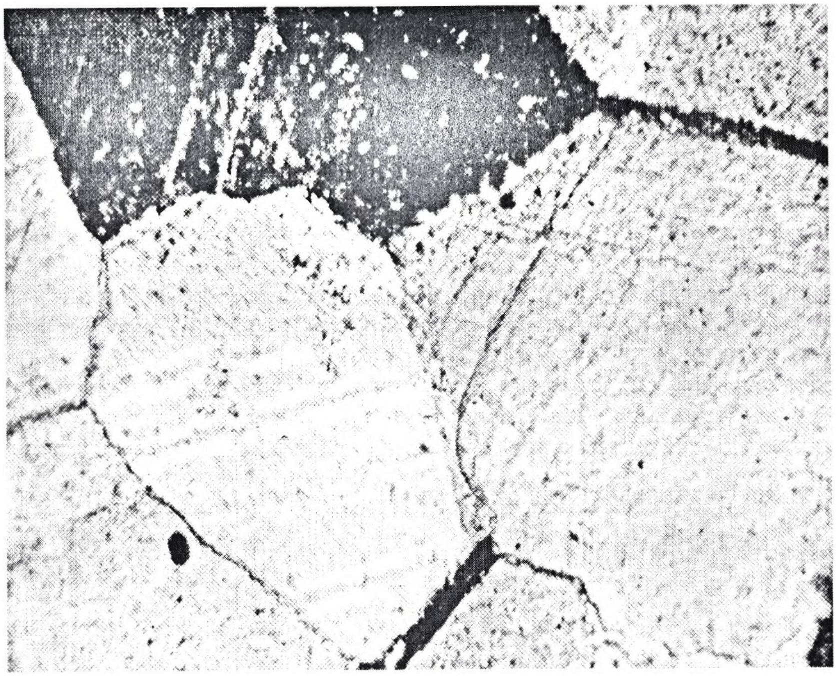

Figure 2 - Petrographic thin section (100x, nicols⊥) of the convex part of the slab. Intergranular disconnection is evident ([1], [2]).

The paper describes some preliminary data relating to a survey of deformation phenomena which confirms the important role, and extremely widespread nature, of the physical and mechanical decay processes affecting marble slabs. The data refers to tomb stones in the Florence area and it allows us to draw up an initial classification of the processes and to make comparisons with some experimental data obtained from the analysis of the above mentioned slab of the facade of the Collegiata di Sant'Andrea in Empoli. Long term bending tests are being carried out using a test apparatus which was specially designed and built so that different tests could be performed at the same time and deformations could be checked continuously.

2. CREEP PHENOMENA

One of the aims of the research is to draw up rheological and numeric simulation models of the situations observed, capable of explaining the dimension, phases and distribution of the deformations measured, relationships with the physical parameters monitored, represented mainly by porosity and density alteration values and by mineralogic and petrographic structures. The research methodology is that of utilizing experimental models based on laboratory tests (in particular bending tests, but also triaxial and uniaxial creep tests), which are capable of reproducing, as far as possible, the state of deformation of the slabs in the various places, in relation to the stress history of the material (geological and geomorphological history of the quarry site, position of the material and relationships with the geometry of the construction etc.), that is if the latter can be reconstructed. In other words it is necessary to define the resodual stresses, the main aim being to draw up time-dependent material degradation models.

An initial classification of the viscous deformation processes, which is only indicative of some cases observed (Garzonio [7]), leads us to place them within the general creep law (Hudson et al. [8]):

$$\sigma = \eta d\varepsilon/dt + \varepsilon E \qquad (1)$$

which can be attributed to simple linear visco-elastic (Kelvin-Voigth) where:

$$\varepsilon(t) = A t^{n} \; (0 < n < 1) \qquad (2)$$

with n= 1 because the bending creep tests are less than 2/3 of the failure stress (34% actually),(Garzonio et al. [2]; Blasi et al. [9]).

Literature on creep phenomena refers mainly to the analysis of the time dependent deformations of rocky masses in relation to engineering problems regarding cuts, escavations and tunnels (Cristescu [10]; Landanyi [11]; Sakuray [12]), or to special problems linked to rock salt behaviour (Ottosen[13]; Fossum [14]; Cristescu [15]) or to gravitational slope phenomena with implications of a geo-tectonic nature (Ter-Stepanian [16]; Radbruch-Hall [17]). That is they refer to the behaviour of large masses, with the characterization of *in situ* phenomena and the development of laboratory experimental tests (Cruden [18]). Indeed it is the latter which can provide useful information for creating, in the future, creep models which are more suitable for the phenomena under examination. Recent models for the time dependent behaviour of rock, in relation to the stability of rock structures, refer to a visco-elasto-plastic constitutive model (Fakhimi et Fairhurst [19]).

Interesting information, useful for perfecting study methodologies, is to be obtained from the case study on the properties of marble presented by Logan et al. [20], where tha various deformation and cracking phases are analyzed, up to the point of the rupture phase. They are correlated with physical parameters and mechanical strength reduction phenomena, the values of which are obtained using standard laboratory tests. These phenomena refer nevertheless to stress fatigue caused by thermal variations and to the relative bowlings. In this respect the cases analyzed in this paper do not seem to be significantly influenced by thermal variations, as the deformed slabs surveyed come from different environmental conditions and are differently exposed. Other experimental research work has been carried by Itô et Sasajima [21], where *in situ* and laboratory tests (the latter included long term creep tests were performed on samples of a similar dimension to the ones used in our studies (Garzonio [7]), however the research was carried out on granite and/or gabbro materials.

3. MATERIALS AND METHODS

Sixty slabs of white marble characterized by clear signs of deformation, from six cemetries in Florence (Soffiano, Trespiano, Santa Maria, San Domenico, The Anglican Cemetry, The Evangelist Cemetry) were examined (Figura 3). These slabs, which are directly exposed and face different directions, form the covers of ground tombs (horizontal slabs) and wall tombs (vertical slabs) respectively. As far as the marble is concerned, it was recognized macroscopically on the basis of the main colour and the absense of veining of a different shade. As regards dating, the year which figures in the inscription on the slabs was taken as the year the slabs were laid. In this way the time interval was set at about 160 years (1830-1990).

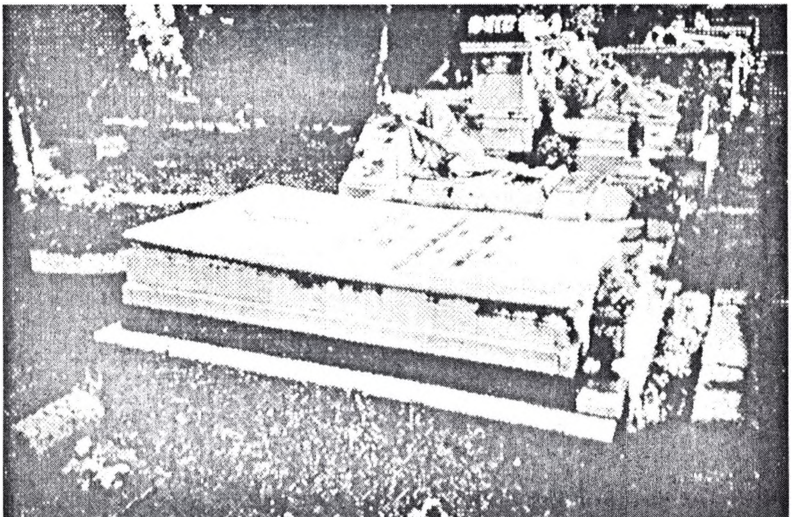

Figure 3 - A typical bent marble slab in a cemetery (Florence, Italy).

Complete photographic documentation was drawn up, surveys were carried out and *in situ* macroscopic observations were carried out for each slab. The aim of the survey and direct observations was to evaluate the following characteristics:

- **main dimensions**: lenght (l); width (w); thickness (t). The measurements, wich were taken manually, were calculated with respect to the plane on which the slab was laid (α). Each value taken into consideration corresponds to the mean value of three measurements carried out, i.e. along the edges and in the centre of the slab, respectively, and they are expressed in cm. The length corresponds to the measurement of the greater side of the slab (Figure 4);

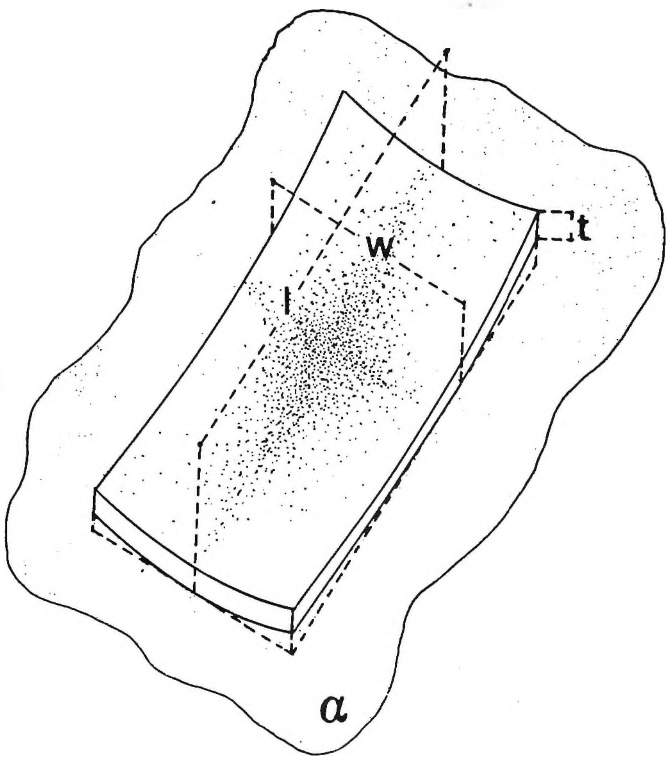

Figure 4- Geometry of slab with respect to the plane on which it is laid (α)

- **deformation**. It must be pointed out that analisis of the deformation, i.e. the variation in the original form from which affects the entire thickness of the material and manifests itself mainly in slab form elements (Normal 1/88 [22]), requires a complex series of measurements which cannot be taken on site. For this reason we have considered the maximum linear strain with respect to the plane on which the slab is laid (s) as the parameter of deformation. This strain was measured along the lower edges of the slabs using a gage. The measurement, expressed in mm, was approximated to the second decimal (Figure 5);

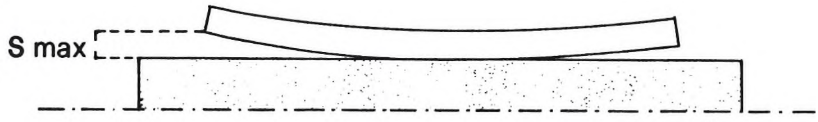

Figure 5 - Maximum linear strain (s) measured along the lower edge of slab.

- **positioning**. The position of the slabs is horizontal (h) and vertical (v). Moreover six slabs were found to have a slanting position. They were inclined at an angle of maximum 10° with respect to the horizontal plane and were therefore included among the horizontal ones. Therefore a total of 44 horizontal slabs and 16 vertical slabs were examined;
- **laying**. The thecniques for fixing the slabs to the masonry support below or behind were divided as follows: stirruping (using metal stirrups), nailing (using nails) and sealing (using mortar);
- **surface alterations**. The main macroscopic alterations found on the exposed surfaces were recognized: chromatic alterations; black patina and incrustations; erosion; cracking; biological patina; presence of vegetation (Normal 1/88 [22]). Macroscopic analysis of the surface alterations has allowed us to verify that the year shown in the epigraph generally corresponds to the date of laying. In fact the older slabs are also affected by greater surface alterations. We can therefore exclude the hypothesis that the material was substituted in recent years.

4. DISCUSSIONS

The parameters relating to the horizontal and vertical slabs are reported in Tables 1 and 2 respectively. In particular, the parameters given refer to the dimensions (l, w, t) (Figure 4) the maximum linear strain (s) (Figure 5) and the date the slafs under examination were laid.
As far as the dimension data are concerned, the marble slabs are characterized by varying lengths, which range from 51 to 237cm. Taking into consideration this parameter, "concentration" intervals were identified. The latter correspond to the maximum number of slabs of similar length. It was therefore possible to identify three groups of horizontal slabs (groups A, B, C) and two groups of vertical slabs (groups D and E). The mean value of these intervals is equal to about 93cm (group D), 98cm (group A), 174cm (group B) and 210cm (groups C and E) respectively. Four horizontal slabs and three vertical slabs were not included in these intervals. They are shown in Tables 1 and 2 and are indicated with progressive numbers in the initial classification.

TABLE 1
Main dimensions, strain and age of horizontal slabs

Gr.	Main dimensions			tot.	Strain	Age
	l (cm)	w (cm)	t (cm)		s (mm)	
A	97.80 ± 8.8	75.50 ± 4.3	3.50 ± 0.8	10	11.56 ± 3.6	1880-1961
B	174.10±11.5	77.30 ± 9.8	4.95 ± 2.5	20	13.48 ± 5.7	1867-1986
C	208.35 ± 4.4	78.98 ± 9.1	4.70 ± 2.1	10	14.19 ± 3.1	1891-1956
40	237.00	78.00	3.10	1	9.15	1846
41	237.00	78.05	3.05	1	8.95	1846
57	125.45	90.45	2.65	1	10.10	1880
60	140.05	85.35	5.05	1	13.05	1920

Gr. =group; tot. =total number of slabs; l=lenght; w=width; t=thickness.

As we can observe in Table 1, given that the width (average value 77.26cm) and thickness (average value 4.38cm) of the horizontal slabs are similar for all groups, the length does not influence the maximum linear strain at all. Furthermore this strain is not influenced by the date when the slabs were laid either.

As far as two groups of vertical slabs are concerned too (groups D and E) (Table 2), even if they are composed of a smaller number of slabs, we can still confirm the observations we made concerning the horizontal slabs.

TABLE 2
Main dimensions, strain and age of vertical slabs

Gr.	Main dimensions			tot.	Strain	Age
	l (cm)	w (cm)	t (cm)		s (mm)	
D	92.50 ± 0.7	60.05 ± 12.7	2.00 ± 0.2	2	17.50 ± 9.1	1833-1851
E	210.00 ± 0.6	64.20 ± 0.4	2.20 ± 0.4	11	16.47 ± 7.9	1908-1924
18	103.05	49.05	1.85	1	23.05	1924
51	77.00	35.05	1.40	1	14.00	1845
53	51.00	37.10	2.05	1	5.95	1851

Gr. =group; tot. =total number of slabs; l=lenght; w=width; t=thickness.

In the case of the vertical slabs, we obtain strains of about 17mm. This is slightly higher in comparison with the strain of the horizontal slabs (about 13mm). These strains can by attributed to the fact that the type of bond. Regarding this point, the vertical slabs measured showed outward bulging even though inverse phenomena were observed on other slabs not considered in this study (Fratini et al.[1]; Garzonio et al.[2]).

We feel that it is important to underline the fact, as we have already mentioned, that in all cases observed, the slabs which were laid in the first decades of the XIX century have a deformation value which is similar to, if not lower than, the one of the slabs which were laid even recently. For example, the maximum linear deformation of a slab dated 1846 is 9.10mm, whereas a slab dated 1986 presents a strain which is almost double that (19.25mm).

5. CONCLUSIONS

The study has hightlighted the extremely widespread character of time dependent deformation phenomena affecting marble slabs. The survey data confirm the important role of these phenomena in decay processes. The analysis of the position and geometric features of sixty bent slabs has not highlighted any correlationship with strains. These preliminary data confirm the main role played by nature, stress history and the directions of the residual stress of the marble slabs.
The data obtained allow us to direct our research work, already underway, towards the study of these phenomena. Quarry materials will be analyzed from the point of view of their compositional, structural characteristics, the aim being the modelling of creep phenomena produced by instruments specially designed by us.

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