Weathering and deterioration evaluation of a Brazilian cultural heritage building

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Abstract: Rio de Janeiro's Municipal Theatre building was built in an eclectic style at the beginning of the 20th century (1905-1909). Its design was inspired in the Paris Opera of Garnier and blocks of gneissic rock were used as masonry on the first floor. It has been considered a Brazilian cultural heritage since 1973.

An evaluation of the deterioration state of those rocks is presented in this article. A visual inspection was carried out and a relationship was found between exfoliation morphologies and rock textures. Macroscopical standardized tests were applied on rock matrix in order to access mineralogical decomposition and physical disintegration of rock fabric. Micro samples were collected for petrography and X-ray diffraction analysis. Considering that it is not possible to sample rocks for mechanical tests, special procedures were applied in this research including acoustic and rebound tests.

Results indicate that rocks are only slightly weathered from a mineralogical point of view, although the rock fabric seems to have undergone some loosening. Rebound tests were useful to map fissures and fractures on rock surfaces.

Résumé: Le Théâtre Municipal a Rio de Janeiro, patrimoine de la culture du Brésil depuis 1973, inspiré par l'Ópera de Paris de Garnier, il a été construit au début du XX eme siècle, em utilisant limosinage de roche gnaissique au première étage. Dans ce travail on présente l'évolution de la dégradation de cettes roches, selon las activités suivantes: inspection visuelle des morphologies d'altération; examens d'avaliation de l'altération de la matrice de la roche pour quantifier la decomposition chimique et dégradation physique; analyse pétrographique et diffraction de rayons X. A cause de l'impossibilité d'obtenir des échantillons pour faire des essays mécaniques, des essays non destructifs et "Schimidt's hammer" ont étes apliqués. Les resultats montrent que les roches sont um peu alterées selon le point de vue minéralogique, malgré la matrice de la roche avoir souffert quelque relachement. Le "Schimidt's hammer" a presenté des resultats utiles pour la cartographie des fractures aux plaques de roches.

Keywords: Weathering, metamorphic rock, in situ tests, environmental urban geotechnics.

INTRODUCTION

Rocks have been fashioned by man since Palaeolithic times and have been used in construction for a long time. The Egyptian pyramids and the Roman temples and baths constitute some of the most famous constructions where rocks were extensively used. These days, building stones can be seen in buildings whose history helps to explain the whole history of humanity. For this reason many of those buildings all over the world are considered as cultural patrimony and must be preserved as heritage for future generations.

The historical worth of ancient buildings and monuments, the economic importance of the tourism industry and the huge presence of highly weatherable sedimentary rocks may be some of the main reasons that probably explain the well-developed preservation policies and activities concerning the rocks in those buildings in Europe. It must be taken into account that weathering can disfigure stone in use and does not necessarily occur in geological time. Depending on the rock type, method of winning and processing and the environment in which it is placed (Smith 1999), the weathering rate can cause rock disruptions and decomposition in engineering time.

There are an enormous assemblage of monuments, buildings and churches that were constructed in different periods of Brazil's history, since Portuguese colonization time to the beginning of Republic era. As a consequence, a great diversity of architectonic styles is observed. Despite a great effort made by the Brazilian Institute for Cultural and Patrimony Conservation (IPHAN) on preservation of this wealth, little attention has been paid to rock weathering in Brazil. Even so some studies recently began to be carried out with an engineering geological approach (Silva, 2005).

The investigation of the weathering of gneissic rock that was used on the first floor of Rio de Janeiro's Municipal Theatre is presented in this paper. Special attention is given to rock weathering morphologies, considered as a rock behaviour sign in response to the processes that internally take place in rock fabric. A data table containing standardized answers to tests performed on rock surfaces is also presented. It was developed to assess and quantify mineral decomposition and matrix desegregation in macroscopic scale. The results of petrography and X-ray diffraction analysis are discussed. Finally, results of non-destructive tests (Schmidt hammer and pulse waves tests) are analysed.

Results indicate that rocks are only slightly weathered from a mineralogical point of view, although rock fabric seems to have undergone some loosening. Rebound tests were useful to map fissures and fractures on rock surfaces.

THE RIO DE JANEIRO'S MUNICIPAL THEATRE

The theatre history

In the period from the end of the 19th century to the beginning of the 20th century, the city of Rio de Janeiro was Brazil's federal capital. As soon as the enslaved work came to an end in the country, a large number of European immigrants and former slaves were attracted to the city, all in search of new work chances. At this time, the city underwent a disordered growth and the population doubled in only 18 years, reaching a number of 522 000 inhabitants in 1890. In the centre of the city co-existed public buildings of the federal administration, inhumane habitations, wagons and animals. This was very inadequate to the federal capital of a country that was growing continuously in importance on the international economic scene. At this point, Brazil had already reached, for instance, the first position among the main worldwide exporters of coffee.

To give a new aspect to the city, the mayor Francisco Pereira Passos accomplished a deep urban reform. Hills were blasted, streets and avenues were sanitized and rivers were channelled. The project and the building of the Municipal Theatre were related to this vigorous transformation of the urban scene. Projected in eclectic style and inspired by the Garnier's Opera, in Paris, the theatre construction started in 1905 and ended in 1909. The first floor was made with gneiss rock blocks and the second with brick masonry. Besides the gneiss, there are also Carrara marble columns that were brought from Italy. It is important to mention that the building has been declared "Brazilian Cultural Patrimony" by IPHAN (National Institute of Historic and Artistic Patrimony) since 1973. Figure 1 shows a view of the front part of the building.

Figure 1. A view of the front side of Municipal Theatre.

The geological context

The gneisses that were used in the construction of the theatre first floor outcrop in the city itself and in its surroundings. The most likely origin for these gneisses is that they are rocks derived from magmatic protolithes. Two kinds of gneiss can be found in the theatre: the first, with a granoblastic texture, is called Leptinite, and the second, with a porphyroblastic texture, is known as 'Augen' gneiss. Both are of Precambrian age and can be considered microcline gneisses, due to this mineral's predominance. Besides microcline, the main mineralogical components of these gneisses are quartz, plagioclase, biotite and garnet. Other minerals occur in a very small quantity. The 'Augen' gneiss is used restrictively in the frontal stairs access to the theatre main entrance, while the Leptinite covers the whole building façade.

The theatre location and the local environmental context

The Municipal Theatre is located beside Rio Branco Avenue, one of the most important downtown avenues in Rio de Janeiro, which has a high amount of vehicle circulation. It is 500 m far from the edge of Guanabara Bay. Figure 2 illustrates its location and the geographic orientation of the building façade.

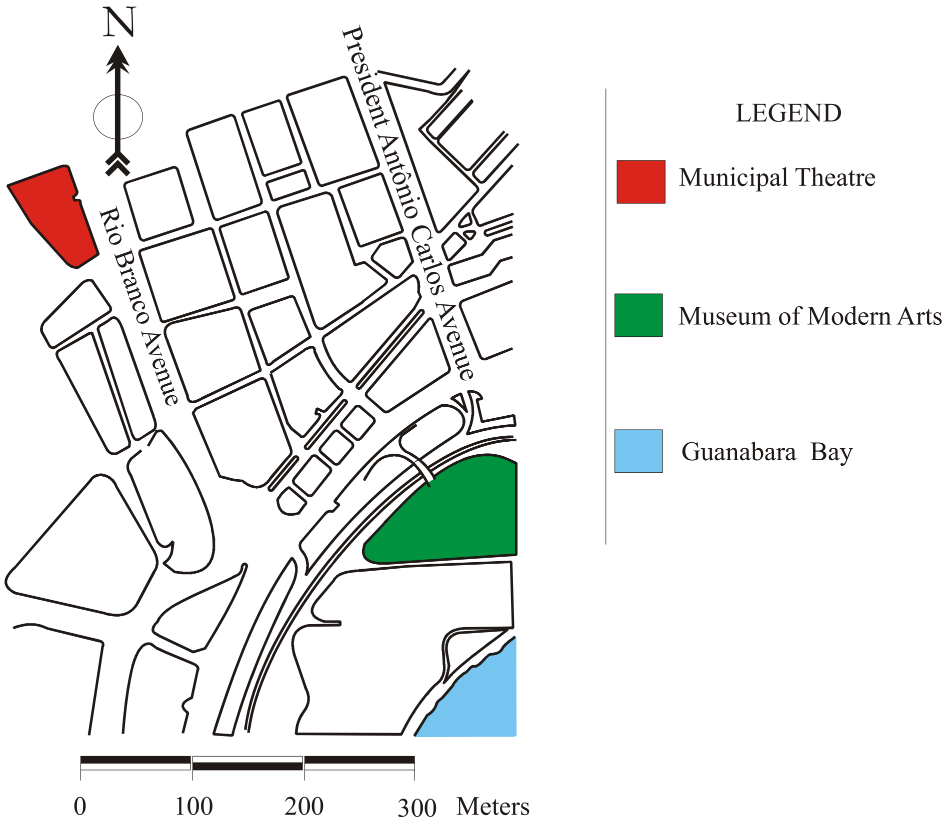

Figure 2. The localization and the geographic orientation of the building façades of Municipal Theatre.

From the environmental point of view, the metropolitan area of Rio de Janeiro is located near the sea and, because of its geographic localization, it presents a great humidity concentration in the atmospheric air. In addition to that, there is not only the ocean wind, but also the high pluviometrical index, caused by the rain concentration, especially from December to April. In Table 1, is presented the data of average temperature for each month of the year, including the period from 1961 to 1990. It is possible to observe that the highest average of temperatures occur in February, and the lowest ones occur in June and July.

Table 1. Data of average temperatures in the period from 1961 to 1990.

Month	Average Maximum Temperature (°C)	Average Minimum Temperature (°C)	Average Thermal Amplitude (°C)
January	29,5	23,0	6,5
February	30,2	23,5	6,7
March	29,5	23,5	6,0
April	28,0	22,0	6,0
May	26,5	20,5	6,0
June	25,2	18,5	6,7
July	25,3	18,5	6,8
August	25,5	19,0	6,5
September	25,0	19,0	6,0
October	26,0	20,0	6,0
November	27,5	21,5	6,0
December	28,5	22,5	6,0

METHODOLOGY

Initially, the weathering morphologies were mapped. This is an important step, since these morphologies are considered an effect of rock alteration and weathering processes. It must be noticed that the data were based on the morphologies described by Urmeneta (1997).

After the visual inspection of the weathering morphologies, some tests were made to identify the chemical decomposition and the physical disaggregation of the rock matrix. A standard result register was developed in an attempt to quantify the rock matrix behaviour. As it can be seen in Table 2, the tests were made considering each mineral present in the rock. They can reach a value that varies from a minimum of 3, for minerals considered not weathered, to a maximum value of 12 for the ones highly weathered.

Table 2. Tests and its answers to access macroscopically the weathering of rocks.

A – Characterization of Chemical Decomposition (for each mineral) (1) not weathered (2) brightness lost or reduced (3) decolourised or colour changed (4) surface clayed or oxidized (5) completely clayed or oxidized
C - Characterization of Physical Desegregation
C,a.- Answer to pocket-knife and to nail scratches (for each mineral) (1) no scratches (2) hardly scratched by pocket-knife (3) easily scratched by pocket-knife (4) scratched by nail
C,b. Easiness to pull out grains from rock matrix (for each mineral) (1) no grains pulled out (2) grains are hardly pulled out by pocket-knife (3) grains are easily pulled out by pocket-knife

After that macroscopic evaluation, micro-samples were collected and analyzed mineralogically based on X-ray diffraction and thin section petrography. In the last one, it was also evaluated the microcracks propagation in the rock matrix. It is worth mentioning that the thin sections were impregnated with a blue pigment to call attention to the void spaces.

In the last phase, geomechanical tests were made. Once it is impossible to obtain samples for this aim, non destructive tests (Schmidt hammer and elastic wave velocities) were made in situ.

RESULTS AND DATA ANALYSIS

Weathering morphology

The weathering morphology is clearly controlled by the texture of the rock. It is noticeable that the formation and propagation of fractures through out the foliation occurs in the places where the gneissic foliation is more developed, producing peeling or exfoliation. Figure 3 shows it very well. It is worth noticing that this fact matches with the observations of Barroso et al. (1993) who, by studying the weathering of these same gneisses obtained from outcrops in the city, verified that the fracture propagation process began parallel to the rock foliation. When the metamorphic rock foliation gives way to a magmatic texture, the weathering morphology is revealed in a granular disaggregation, as it is exposed in Figure 4.

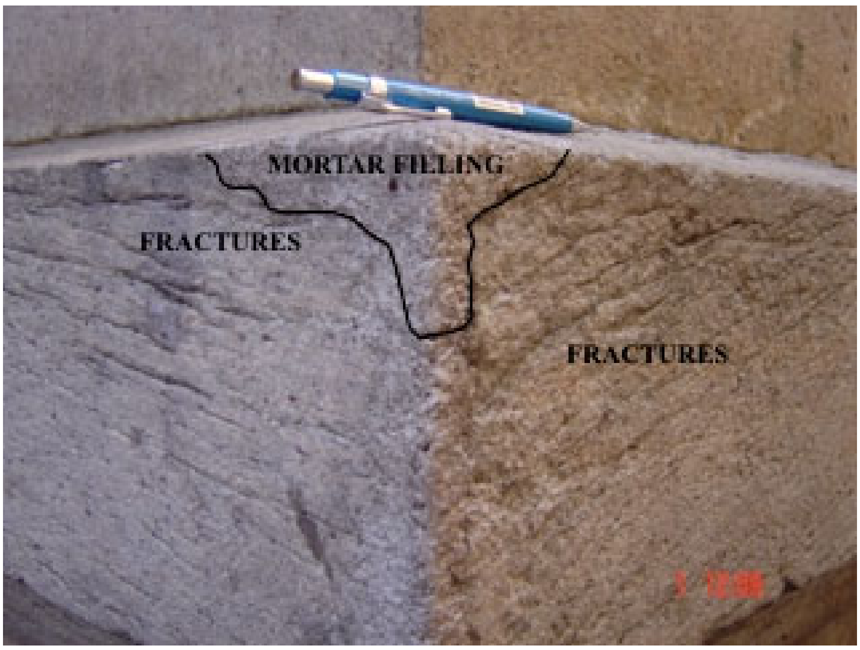

Figure 3. Fractures formed following rock foliation.

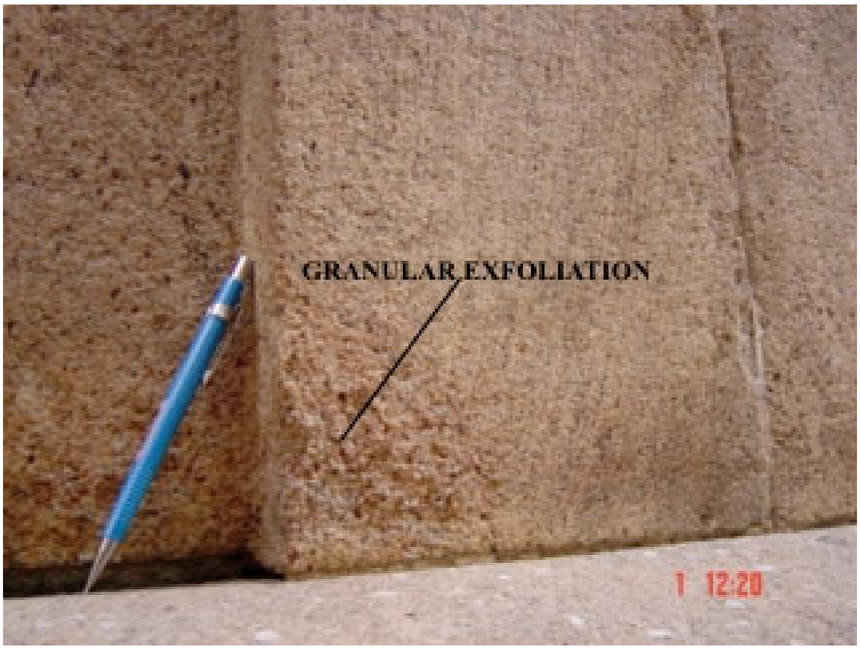

Figure 4. Granular exfoliation developed where foliation is absent.

Rock matrix macroscopic tests

Table 3 is a summary of the results obtained. It must be highlighted that all the data is presented in average values. It is possible to see that, from a mineralogical perspective, the rock seams to be slightly weathered. The higher value of the micas reflects the lower hardness of these minerals, which are easily scratched with a penknife even when not weathered. Quartz, as an inert mineral, presents a value greater than 3, because sometimes some grains could be pulled out from the rock matrix. This does not mean that there is a mineral alteration. In fact, it is merely a physical process. It is interesting to observe that the south-east ocean-facing façade was the one that presented the highest global alteration index, calculated by making the sum of the index of all the minerals.

Table 3. Results of macroscopic tests of matrix.

Minerals	Façade faced to:				Average Weathering Index
	SE	E-NE	SW	N-NW	
Quartz	4,8	3,8	4,0	3,9	4,1
Feldspar	5,5	3,7	5,2	5,0	4,9
Micas	8,2	6,2	6,8	7,2	7,1
Garnet	5,0	5,0	5,0	4,5	4,9
Sum	23,5	18,7	21,0	20,6	21,0

Petrographic diagnosis

Table 4 shows the minerals present in the Leptinite and its percentages. The same table shows the percentage of void spaces, which is given by the microcracks in the thin sections. It is noticeable that this gneiss has a large concentration of quartz and microcline, and a small quantity of mafic minerals. If the percentage of void spaces is greater than 1%, it means that this rock has already suffered a slight physical weathering (Barroso, 1993).

Table 4. Mineral composition and percentage of voids (microcracks) observed in thin sections.

MINERALS (%)	Façade faced to:		
	SE	E-NE	N-NW
Quartz	39,3	40,5	41,6
Microcline	35,2	35,6	33,7
Oligoclase	15,6	14,3	14,4
Biotite	5,5	6,3	6,8
Garnet	2,6	1,7	1,4
Muscovite	0,9	0,5	0,9
Voids (microcracks)	0,9	1,1	1,2

When the mineral alteration characteristics can be verified at a microscopic scale, some interesting behaviour is highlighted. Figure 5 shows a garnet with an enhancement in its internal micro fractures' shape. It is interesting to compare this grain's outline and its internal micro fractures to tenuous outlines of neighbouring grains. This fact might be related to the precipitation of iron oxide. The biotite presents a similar feature in its cleavage, as shown in Figure 6.

The main feature of the plagioclases' alteration is related to the formation of sericites in its surface, especially through the microcracks inside the grain (Figure 7) and also through its twin lamellae (Figure 8).

When it comes to the development of micro fractures (Figure 9), it is evident that they tend to propagate on the grain outlines (intergranular microcracks). This fact probably causes loosening to the rock matrix.

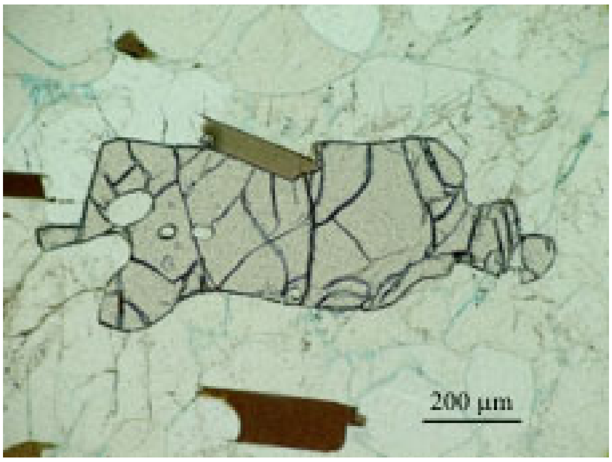

Figure 5. Internal fractures of garnet become evident by iron oxide precipitation.

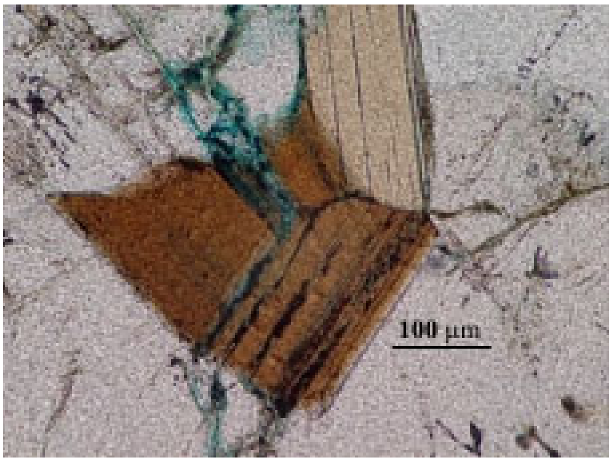

Figure 6. Biotite's cleavage marked by iron oxide.

Figure 7. Sericite formation along microcracks in plagioclase.

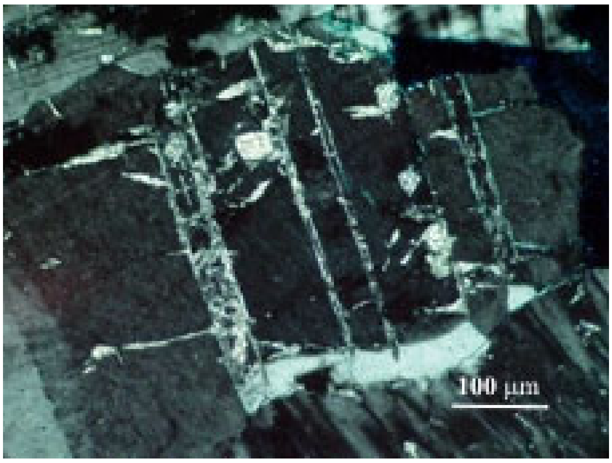

Figure 8. Sericite formation along plagioclase's lamellae.

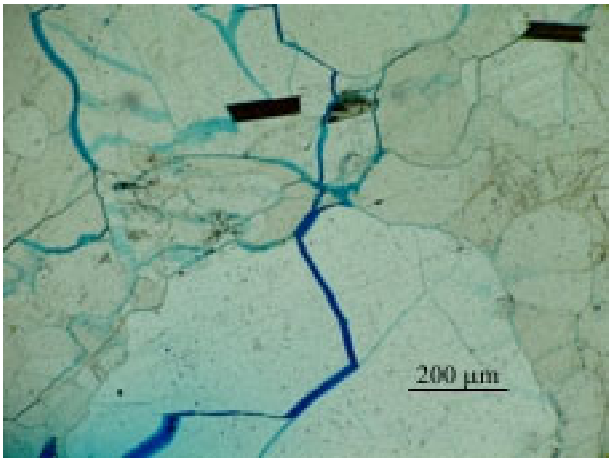

Figure 9. Presence of microcraks (blue lines) on grain outlines.

X-Ray diffraction

The thin sections have been built by using the powder method. Then, the tests were done with the material in its natural state, saturated in a glycol ethylene atmosphere and heated up to 550°C. The only weathering mineral which could be observed was kaolinite traces.

Velocity of elastic waves

The velocity of ultrasonic waves in a solid material depends on the material's density and its elastic properties, as well as Young's modulus and Poisson's ratio. This research was done using the direct transmission method in which the transit time was electronically acquired and the velocity of the compressional waves was calculated by measuring the distance between the transducer and receiver (ISRM, 1981). It's worth mentioning the difficulties in applying this technique due to problems related to coupling conditions and to vibrations caused by the vehicle's traffic in the theatre neighbourhood.

The results of five tests that were done are shown in Table 5. The average velocity of propagation was approximately 4000 m/s, which according to Iliev (1966) classifies these rocks as slightly weathered. Other acoustic data for the same rock in a fresh condition (Barroso 1993) confirm the low weathering state of this rock.

Table 5. Data of compressional wave velocity.

Test Number*	V_p (m/s) †	Average Velocity (m/s)
Test 1	4125	4023
Test 2	4033	
Test 3	3879	
Test 4	4105	
Test 5	3972	

* Tests carried out in different orientations in relation to rock foliation.
† Compressional elastic wave velocity.

Schmidt hammer test

This test comes from the structural engineering area (Bungey 1989). There have been many attempts of using this test to evaluate the rock strength (Cargill & Shakoor 1990, Kolaiti & Papadopoulos 1993, Basu & Aidyn 2004), especially because its results can be trusted and are reproducible (Poole & Farmer 1980, Goktan & Ayday 1993). However, some researchers have shown that there should be some restrictions in the use of this test (Katz et al. 2000, Hack & Huisman 2002). The main restrictions are the following:

- It must be done in well-cemented rocks with elastic behaviour;
- Rocks which separate or break due to impact cannot be appropriately tested;
- It should be done on smooth surfaces;

By doing this test it is possible to get to the rock superficial hardness, the Schmidt hammer index (SHI), which can be empirically related to the unconfined compressive strength. This method consists of exposing the rock surface to a uniform impact using a certain mass with a certain amount of energy, gauging the value of the rebound (SHI). The rebound depends on the value of kinetic energy before the impact as well as how much of this energy is absorbed during the impact, since part of the energy is absorbed due to the mechanical friction of the equipment, while the rest is absorbed during the contact between the percussion bar and the rock. The energy absorbed is related to the rock strength and stiffness (ISRM 1981). The tests were performed on the stairs of the theatre. The hammer was vertically positioned and a 60 mm square-shaped mesh was used, as shown in Figure 10.

Figure 10. Schmidt's hammer test being carried out on stairs of Municipal Theatre.

The Schmidt hammer proved to be very useful to map the rocks' fissures. This was only possible due to the fact that the values near these physical discontinuities became really low if compared with the remaining points of the rock. This investigation was held on the staircases of the Municipal Theatre and the data can be seen in Table 6. In Figure 11 there is a histogram that represents the condition of the external stairs of the Theatre. In order to map the fissures, Schmidt hammer data have been linearly interpolated on the sampling mesh. The shadow diagram presented in Figure 12 exemplifies the use of the technique on one of the steps of the staircase. The dark colours are low values of SHI and represent the presence of fractures or fissures on the rock when its distribution occurs in a stretched form.

Table 6. Schmidt hammer indices (SHI)obtained on rock surfaces of Theatre staircases.

Location	N	SHI_{min}	$SHI_{máx}$	Mean	Standard Deviation.	Variation Coefficient (%)
Right entrance Second Step	120	46	70	60,98	3,59	5,89
Right entrance Fourth Step	129	16	68	59,31	7,25	12,22
Right entrance Sixth Step	129	23	64	56,53	6,10	10,79
Left entrance Second Step	127	19	69	57,76	8,56	14,82
Left entrance Fourth Step	129	24	66	57,95	7,05	12,14
Left entrance Sixth Step	119	34	66	55,80	5,66	10,15

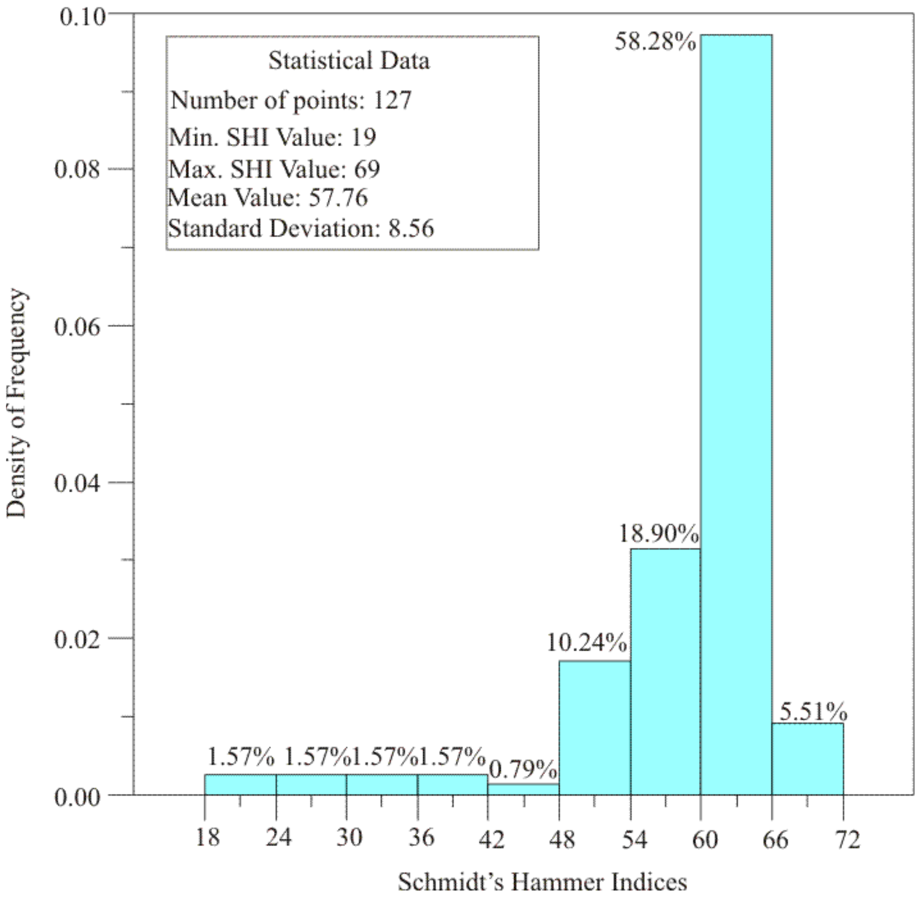

Figure 11. A typical histogram obtained for Schmidt's hammer values.

The unconfined compressive strength of the rock was calculated based on the chart presented by ISRM (1981) for L type hammers used vertically. By applying a 26 KN/m^3 unit weight to this rock and considering the mean value of the histogram in Figure 11 (SHI = 58), a value of unconfined compressive strength of 220±100Mpa is obtained.

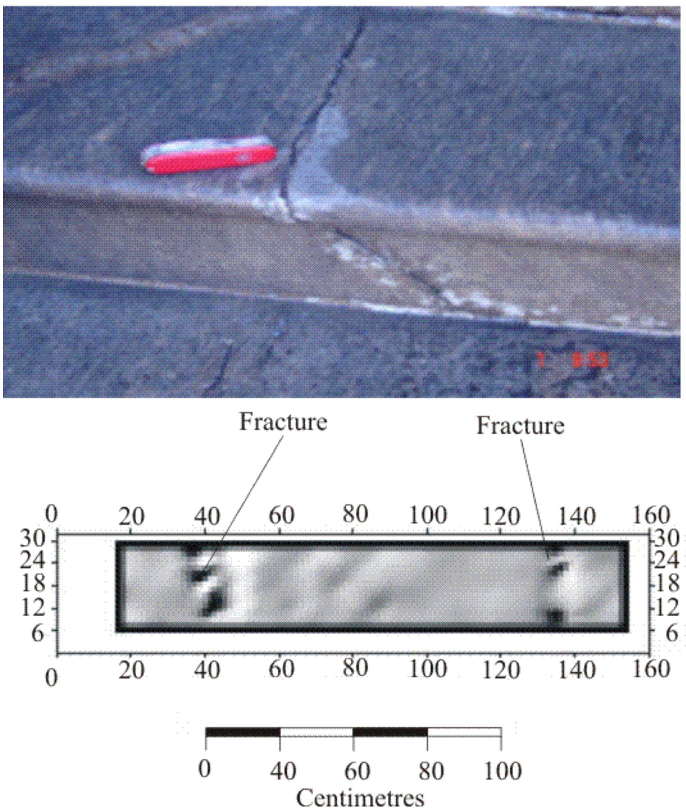

Figure 12. A shadow chart making evident fractures on the stairs.

CONCLUSIONS

The weathering morphology seems to have a close dependence on rock texture. The gneiss, which has been exposed on the façade of the Municipal Theatre of Rio de Janeiro for almost 100 years, is still slightly weathered from a mineralogical point of view, even if it is considered the increasing pollution and the probable appearance of a more aggressive atmosphere. The physical component of the weathering process is represented by intergranular microcracks that imposed a certain loosening to the rock fabric. All data obtained contribute to this conclusion, since the minerals are slightly modified. Although the Schmidt hammer index data have a low accuracy, they indicate high rock resistance, and the propagation velocities of the elastic waves are a little low if compared to other data from this kind of rock.

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