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Investigation on the Limestone Ashlar Masonry in the São Francisco Monastery

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ABSTRACT: The São Francisco church and monastery, in the historical center of the city of Salvador, Bahia, is considered one of the masterpieces of the Colonial Baroque, recognized by all art history specialists. The cloister is showing strong signs of degradation, with alarming signs of possible collapse. Therefore, through this study we intend to identify the origin of the lithic material historically and scientifically, investigating and charting the state of the rock applied in the monastery cloister through non-destructive tests, and comparing, in terms of compactness, with the results of the lab tests of the rock obtained in the resting-place, which should be identified through petrography and historical records. The results of the physical and chemical lab tests made from the resting-place material are also shown. The status of stability of these pillars will be determined through structural analysis, using the finite elements method with the SAP 2000 software.

1 THE *SÃO FRANCISCO* CHURCH AND CONVENT OF SALVADOR

The *São Francisco* church and convent (Fig. 1), in Salvador is, recognizably, one of the most emblematic monuments of the Brazilian Baroque architecture (and Portuguese), praised by every researcher who gets to know it and causing admiration in everyone who visits it.

Figure 1 : Interior of the S. Francisco church.

In this monument we can highlight not only the quality of the architectural spaces, but also the worth of an enormous area covered with Portuguese glazed tiles (around 2500m^2) of exceptional artistic value. It is also abundant in golden carved wood work, produced mainly with some varieties of local cedar (*Cedrella fissilis, Cedrella odorata* and others).

Even though the building has its foundation in the XVII century, the consecration of the current church dates from the early years of XVIII century and, since then, it has served the Franciscan friars, its owners, and the followers of the Catholicism in the City of Salvador, capital of the state of *Bahia,* Brazil. The injuries of the time, the lack of constant cares and, in a way, some mistaken interventions brought many problems to the building; even though countless investments were made by the IPHAN (*Instituto do Patrimônio Histórico e Artístico Nacional*) in its conservation, taking into account it is regarded as a clear representation of our cultural memory and classed in the Book of National Monuments (Fig. 2).

Figure 2 : One of the wings of the cloister

Among the problems that affect the monument two are important at the moment: one of them is the destruction of the vitrification of the images of the glazed tiles through the efflorescence of soluble salts and the other one is the masonry of its cloister, whose degradation is compromising the structural security of the building, particularly in the area which is most covered by glazed tiles (Fig. 3). Regarding the second problem we intend to present some investigations and observations which will probably contribute to the solution or attenuation of the problem.

Figure 3 : Stone decay in the arches.

2 MASONRY MATERIAL

The preliminary knowledge acquired on the lithic material of the masonry of the building obtained thought the studies performed at the NTPR (*Núcleo de Tecnologia da Preservação e da Restauração*) were useful to eliminate some doubts regarding the quarry of origin of the employed material, very important data to obtain the stone in its natural condition and, eventually, extract in the future material to the reintegration of the masonry. These doubts originated from mistaken observations of some art historians who talked about "sandstone" from *Boipeba* Island. So it happens that the petrographic studies that were made of the lithic material of the building's masonry indicated two predominant types: sandstone of calciferous cementation, applied in the largest part of the construction and an argillaceous limestone used in the cloisters. It wasn't much trouble to identify the sandstone's origin, because it was largely used in most monuments of the city and it can be found along the *Baía de Todos os Santos* and in other parts of our coast. On the other hand the sedimentary limestone is much rarer in the region and according to old testimonies; it came mainly from the *Boipeba* Island, even though it also occurred in other islands. This material presents critical degradation problems. It's believed that the mistake of the historians comes from the reference that one of the superiors of the convent made, in the XVIII century, in the *Livro dos Guardiães* (Willeke, 1978), that he had sent for stones from *Boipeba* for the construction of the convent. Well, given that the majority of the masonry was made with sandstone, some studious (often excessively imaginative, and without the scientific investigation back up for their statements) pictured the existence of this sandstone from *Boipeba* that in reality never existed. Searching the literary sources and principally the oral tradition, we found the old limestone deposit, explored since the XVII century in *Boipeba* Island, in a place known as "*Cova da Onça*" (the place is found near a village known as S. Sebastião with the coordinates 13^{o}40'09.3"S e WO 38^{o}57'08.3"W). This material was brought in by boat, in semi-elaborate conditions, though the bay to the old capital of the Portuguese America, to be used in the constructions, due to its workability and prospects of good finishing. The petrographic characteristics found in the stone of the old quarry and in the cloister coincide perfectly.

The density of the lithic material was calculated in 2.4t/m^3, obtained through the Hubbard picnometer. This tells us that this is not a very compact material, if compared to other types of local stones. Our more compact granites, for instance, are about 2.9t/m^3. Consequently, lower mechanical resistance and more porosity is expected, which facilitates the capillarity of the water in a more accelerated degradation process (Fig. 4), as we confirm with subsequent analysis.

Figure 4 : Column base of the cloister with crushing signs

The clay type identification was done by RXD and its percentage in the rock through chemical analysis. The lithic material treated with diluted HCl leaves an insoluble argillaceous residue that submitted to XRD indicates the predominant presence of the argilominerals kaolinite and ilite, this last one with some expansive property (Fig. 5). This represents one more reason for worrying regarding the durability of the masonry exposed to weathering, in a city of great pluviometric precipitation, high temperatures, intense saline spray and an environment very inclined to biodegradation. The carbonatic fraction, dissolved by acid, represents 92.8%, the major part is composed by $CaCO_3$ and the rest by $MgCO_3$ as observed in the petrography and XRD. These petrographic observations pointed out a dolomitic limestone confirmed by Lazzarini (Professor of applied petrography of the School of Architecture of Venice University and director of the L.A.M.A that kindly offered additional observations about Boipeba's rock) who adds in his report: with very reduced crystals but also with well developed hydromorphic crystals (up to 10μm).

Considering its not possible to remove from the monument samples without damaging the original material for mechanical resistance tests, it was extracted from the old quarry unaltered material for the elaboration of samples for tests and analysis, followed by the comparison, though non-destructive methods, with the material applied in the monument.

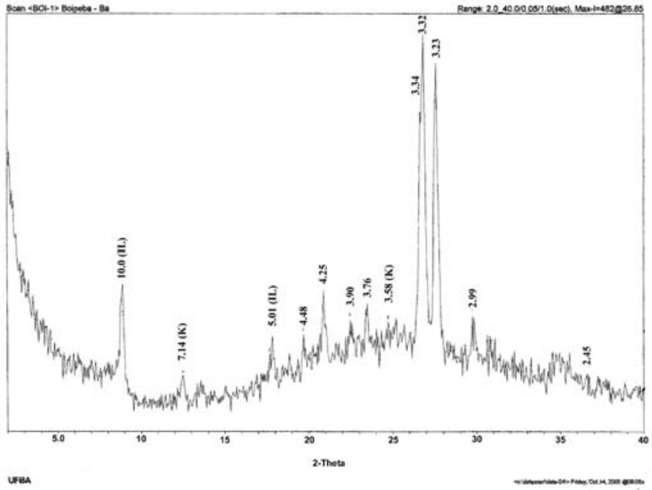


Figure 5 : RXD of the argillaceous residue of limestone.

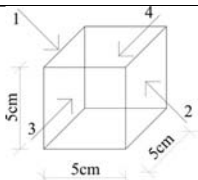
The resistance of the material from the mineral deposit is regular (Table 1), for a sedimentary limestone, but quite inferior to a Portuguese Lioz (cristaline compact limestone with "rudistas", from the Turonian period, coming from Portugal) which according to data from Ayres-Barros (2001) oscillates, depending on the variety, between 90 and 100 MPa and much inferior to most of the granites that were founding the State of *Bahia*.

Table 1 : Axial compression data.

Axial Compression Test (cubic samples of 5x5x5cm)		
	Applied force kN	Ultimate strength MPa
Sample 1	190	76.0
Sample 2	190	76.0
Sample 3	169	67.6
Sample 4	185	74.0
Sample 5	200	80.0

The major dispersion of the result found in sample 3 is justified by the presence of a fossil from the echinoid family practically loose in the interior of the rock. It was observed in cutting the sample that there are some discontinuities (voids) in its interior. On the other hand these samples demonstrated some regularity to the ultra-sound propagation obtained in two different directions (Table 2).

Table 2 : Ultra-sound measures on quarry samples.

Ultra-Sound Tests				
	Opposite Faces			
	Face 1 to 2		Face 3 to 4	
	Time µs	Velocity m/s	Time µs	Velocity m/s
Sample 1	10.7	4.67	10.7	4.67
Sample 2	10.4	4.81	12.1	4.13
Sample 3	10.7	4.67	11.4	4.39
Sample 4	10.4	4.81	11.7	4.27
Sample 5	10.8	4.63	10.7	4.67

The water absorption of the samples, employing vacuum, oscillates between 4 and 5%, and the average of the results points to 4.51%. This allows us to foresee the possibility of the stone material to accept some consolidation by impregnation vacuum.

The rising capillarity tests demonstrate an atypical curve, what could be attributed to the presence of clay minerals in the rock (Fig. 6).

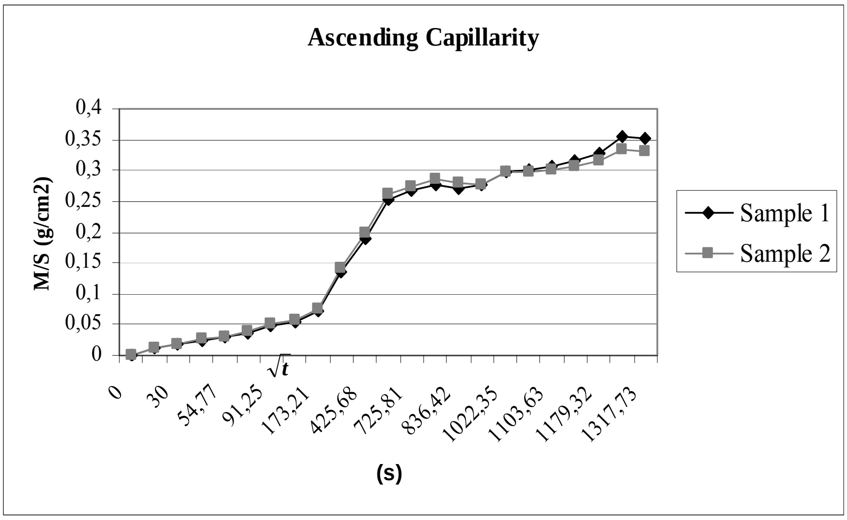


Figure 6 : Capillary rise graphic (two different samples).

3 NON-DISTRUCTIVE TESTS

They were obtained through the measurement of the ultra-sound propagation in the cloister's columns using a *Controls* equipment employing a transmitter/receptor of exponential profile, due to the shape of the surface of the columns. It was observed with a certain concern that where the reintegration of the lacunas were made with Portland cement mortars, in previous "restorations", the ultra-sound signal didn't reach the other side of the column. That might mean that the inadequate cement application is getting loose leaving a void inside. In fact, in some parts, the detachment of the cementitious mortar is observed bringing about some portion of decayed stone (Fig. 4).

Besides that, where the measurement was possible, the propagation velocity of the ultrasound waves in the columns (Table 3) was quite inferior to that found in the unaltered material. This is a sign of loss of compacticity.

Table 3 : Ultra-sound measures on cloister columns.

	Column A		Column B	
Situation	Time µs	Velocity m/s	Time µs	Velocity m/s
Shaft's bottom; ∅ = 0.42m	397	1.06	180	2.30
h = 1.00m; ∅ = 0.41m	192	2.14	224	1.80
h = 1.50m; ∅ = 0.38m	219	1.74	238	1.60

4 STRUCTURAL EVALUATION

The cloister is formed by a central patio surrounded by a gallery composed in the first level by stone arches and by crossvaults, and in the second by wood and ceramic tiles roof supported by stone colonettes. The vaults are made of bricks with lime mortar, supported on the outside by thirty two columns and four stone pillars, with monolithic shaft (except pillars) and on the inside by a stone wall.

To determine the more stressed column, the software SAP 2000 was used to allow the calculation of efforts and deformation through the finite elements method.

The structure was modeled considering the central vault as a shell element of masonry, supported externally by stone arches (frames) that are supported in columns, and internally by stone walls.

For the central vault the calculation elements were the following: 34cm of height with 1.977t/m^3 density; theoretical spam = 3.60m; accidental load = 0.25t/m^2; lateral filling = 71cm high, in stone and mortar, with 2.375t/m^{3}density; permanent built load constituted of 5cm thick mortar with 2.1t/m^3 density and 0.05t/m^2 of hydraulic paving floor.

Besides the crossvault that is supported by arches that are held by the columns with average diameter of 40cm and 2.4t/m^3 density it was also taken into consideration: 0.18t/m roof; 96cm high parapet, in brick masonry; 0.3t/m ornaments; 0.2t colonettes.

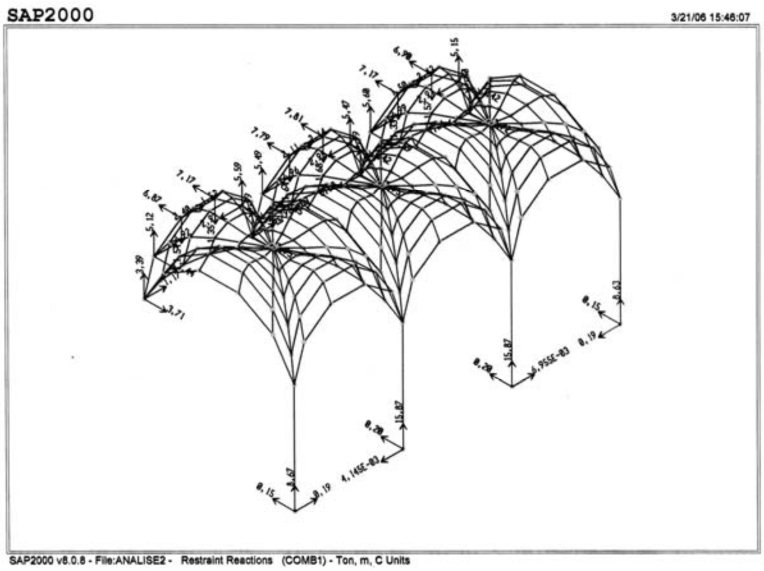


Figure 7 : Stress verification diagram.

As seen in Fig.7, the most loaded column receives 16 tons of vertical weight, which causes a 1.8MPa tension, much lower than 74MPa, resistant tension of the healthy rock.

5 SOME CONCLUSIONS AND SUGGESTIONS

Some results obtained with this investigation are listed below:

(a) – The used stone is actually from *Boipeba* Island, confirmed by petrographic comparison of the quarry's material and of the monument.

(b) – The material is subject to several forms of degradation (as thermic stress, hydrolysis, dissolution, biodegradation, etc.) because it's sedimentary limestone with some porosity and especially for having an argillaceous component.

(c) – There is a real danger of collapse, since signs of crushing were observed at some columns bases. Therefore, it's recommended the use of metal staying, with possibility of adjustments, especially in the neighborhood of most damaged columns. In this situation it's also recommended that vibrations in the neighborhood are avoided.

(d) – A more accurate evaluation can only be performed with the staying of each arch and the removal of all the cementitious mortar that was applied to fill the voids.

From the structural point of view it's noticed that the material would resist well to the existing load, as it has until today, but the degradation of the stone reduces drastically its capacity to stand pressure. Besides that the ultra-sound assay revealed the low compacticity of the altered rock when compared to the healthy rock.

In view of the results obtained with the assays and evaluations it's recommended that the building's masonry is consolidated. It's not only a matter of superficial degradation of the construction, but it also has structural safety implications. And if collapse occurs there will be serious damage to the masonry and the glazed tiles. So the second phase of this work is going to be developed in the investigation on the stone consolidation. To do that it is intended to use vacuum impregnation with cycle-aliphatic epoxy resin that has fluidity and resist well to UV radiation. Initially, stone blocks will be made with 10x10cm dimensions, which will be submitted to a pressure just before its crushing limit. Then they will be treated with the referred epoxy and have their mechanical resistance tested. In local, when the deformations are accentuated, it's possible to substitute the damaged shafts or bases for other ones with the same material extracted from the old quarry that was located.

Because of the nature of the rock it will be necessary protective surface treatment with paraloyds to protect against the weathering and the action of the water that, among other things, can trigger the expansion of the claymineral components of the limestone.

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