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Study of Mortars for Repair by Anastylosis of Ruins of Our Lady of Nazareth Church (Almagre Ruins), Cabedelo, Paraíba, Brazil

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ABSTRACT: This paper seeks to present a study performed on historical mortars in order to propose mortar characteristics for restoration by anastylosis of part of the Almagre ruins. The study consisted of chemical and physical analyses of historical mortars and characterization trials of mortars proposed for carrying out the work. The mortars are composed of hydraulic lime, prepared by mixing lime and pozzolanic metakaolin, and granulometric composition of two types of sand.

1 INTRODUCTION

The State of Paraíba, located in the Northeast Region of Brazil (Fig. 1), boasts exquisite and unique baroque stonemasonry in limestone on several of its monuments, including the Church of Our Lady of Nazaré, located at Praia do Poço, Cabedelo County, built in the 18th century from limestone blocks 600x300x300 mm, with beautiful sculpted ornamentation, and lime-based mortars with mineral and organic additions. The monument, today called the Almagre Ruins, lies on privately-owned land and remained in a state of abandonment for many decades. The ruin has some fallen walls, deterioration caused by climatic action and slash and burn farming practices in the nearby surroundings, with dissolution of some sections of the stone.

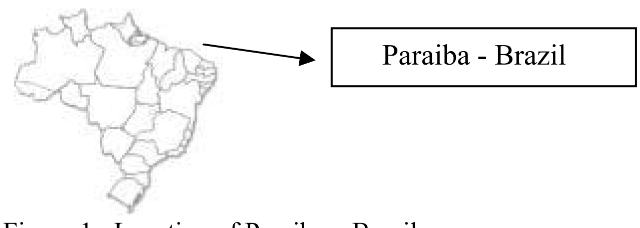

Figure 1 : Location of Paraiba – Brazil

The restoration project, the first phase of which was performed in 2005 by the National Institute for Historic and Artistic Heritage Buildings –IPHAN (a sub-division of the Ministry of Culture) involved structural stabilization of the stonemasonry in disarray and fragments of the base, anastylosis of fallen structural elements, which, in this phase, were re-erected up to the height of 2.0 m. The work was guided by the Restoration Charter of 1972, according to which interventions must be visible and differentiated form the original construction, showing esthetic and visual harmony therewith, respecting and showing similar physical characteristics to the original work, as well as reversibility (ICOMOS 2001). These principles, together with requirements determined by the structural design, 8.0MPa compressive strength, constituted the guidelines for this work, which sought to contribute to this phase of the project and to later phases, by characterizing the mortars used in the original construction and suggesting new mortars for the work of repair by anastylosis, the archeological reassembly of ruined monuments from fallen or decayed fragments (incorporating new materials when necessary).

2 CHARACTERIZATION OF ORIGINAL MORTARS

Based on macroscopic analysis of mortars used in construction of the Almagre Church, it was found that they were coarse in texture, with the presence of crushed seashells and sand. There are two different colorations, stratified and clearly marked: one reddish mortar used up to 1.7 m on average, and a yellow mortar, used from that height up to the top of the masonry. These mortars were used for two main purposes: that of joint mortar and as plaster to cover masonry, comprising not only limestone but also ferruginous sandstone blocks, to a lesser extent.

For performance of tests, mortar samples were taken from seven different points in the ruin. All samples had an unaltered core and surface alterations due to the presence of fungi and moss. For removal thereof, sample surfaces were scrubbed prior to testing. Samples were extracted manually (plasters) and using a chisel (joint mortars), with the exception of those taken from fallen pieces. Plaster mortars are in a fragile state of adhesion to walls, and may be removed without difficulty. Joint mortars show cohesion, with some difficulty in extraction, crumbling and grinding. The thickness of plaster applied by the builders, amongst the samples taken, varied from 7 to 18 mm, although it should be noted that of the samples taken, the red mortar were thicker than the yellow samples. The layer of joint mortar varied in thickness, in the samples taken, from 230 to 500 mm, permeated by fragments of gap-filling stone. Table 1 shows the data from samples removed from the ruins.

Table 1 : Data on samples taken

Sample	Color	Type	Location	Height
1	Red	Joint mortar	Internal wall of left side aisle	1.30m
2	Red	Joint mortar	Base of main altar	0.30m
3	Yellow	Plaster	Internal wall of left side aisle	2.00m
4	Yellow	Joint mortar	Fallen left wall	4.00m
5	Yellow	Joint mortar	Tower foundations, left side	-2.00m

2.1 Analyses of Historical Mortars

For characterization of mortars, several tests for determining composition were used, including X-ray fluorescence and X-ray Diffraction and granulometric distribution by sieving. Fig. 2 shows the curve of granulometric distribution of mortars. This graph shows that curves have similar granulometric distribution, with a continuous profile. For X-ray fluorescence analysis, the mortar samples were finely ground, part being sent for drying and heating to determine ignition loss. Another portion was weighed and pressed, and the resulting tiles were sent for qualitative sweeping in a Rigaku ray fluorescence spectrometer, model FIX 3000, with Rh tube. Table 2 shows the results presented in percentages, including the portion tested for ignition loss.

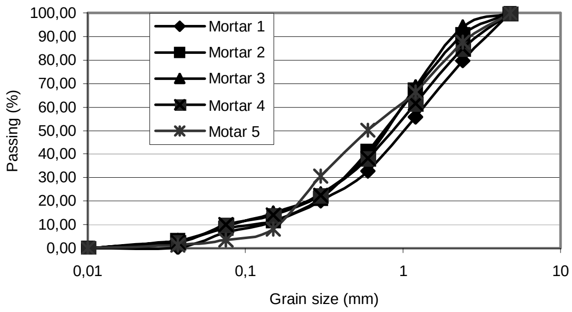

Figure 2 : Granulometric distribution curves of historical mortars

Table 2 : Results of XR Fluorescence of Samples

Components	Mortar 1	Mortar 2	Mortar 3	Mortar 4	Mortar 5
CaO	36.99	44.10	54.77	55.21	56.34
SiO_2	5.08	13.31	7.82	10.42	2.30
Al_2O_3	1.64	5.77	2.34	3.80	0.50
Fe_2O_3	2.91	6.15	1.46	2.52	0.83
SrO	0.98	1.05	1.15	1.29	1.26
Na_2O	0.82	0.02	---	---	---
K_2O	0.47	0.37	0.44	0.80	0.07
P_2O_5	0.35	0.54	0.37	0.48	0.31
SO_3	0.27	0.35	0.42	0.48	0.26
TiO_2	0.55	1.13	0.24	0.42	0.13
Cl	14.73	0.06	0.04	0.04	0.03
Cr_2O_3	0.04	0.05	0.03	0.03	---
ZrO_2	---	0.24	---	---	---
MnO	---	0.03	0.02	0.02	0.01
NiO	0.01	---	0.01	0.01	0.01
Rb_2O	---	---	tr	0.01	---
Br	0.01	---	---	tr	---
Ignition loss (1000^oC)	35.11	26.87	30.84	24.48	37.95
Total	99.96	100.04	99.95	100.00	100.01

From analysis of the data in Table 2, it was noted that in all the mortars, the percentage value of ignition loss is high, which indicates the presence of organic components and free water (Frazini et al. 2000). This organic material may come from contamination by fungi and moss during the years of abandon of the ruins, from the use of organic binder, such as fish or whale oil, and free water from the humidity of the environment itself and excess water used during mixing of mortars. From the concentration of Al_2O_3; Fe_2O_3; SiO_2 and CaO, obtained in this chemical analysis, it is possible to calculate the hidraulicity index , using Eq. (1), and the cementation index, from Eq. (2) (Elsen et al. 2004). The values obtained are in Table 3.

$$\text{Hidraulicity index} = (\%Al_2O_3 + \%Fe_2O_3 + \%SiO_2) / (\%CaO + \%MgO) \quad (1)$$

$$\text{Cementation} = (1.1\%Al_2O_3 + 0.7\%Fe_2O_3 + 2.8\%SiO_2) / (\%CaO + 1.4\%MgO) \quad (2)$$

Table 3 : Results of mortar water-content test

Indicators	Mor. 1	Mor. 2	Mor. 3	Mor. 4	Mor. 5
Hidraulicity index	0.26	0.57	0.22	0.31	0.03
Cementation	0.48	1.08	0.46	0.64	0.14

Although chemical analysis failed to detect concentration of MgO, the calculations were performed based only on CaO. The Hidraulicity index is an indicator of the quantity of material that may hydrate over time, and the degree of cementation indicates how much the material hydrated during a given time (Maravelaki 2005). Consequently, both indicate the degree of resistance of these mortars. The comparison in this study of these indicators is between the mortars studied herein. Thus, from analysis of data in Table 3, it may be seen that the mortar with the highest indicators is number 2, which has a higher concentration of Al_2O_3, Fe_2O_3 and SiO_2, as these are composed of hydrated elements of water-based binders. Mortar number 4 would be the second most resistant, and mortars numbers 1 and 3 form a group of intermediate indicators. Mortar number 5 shows the lowest indicators, and is therefore the least resistant. The hidraulicity index may also be an indicator that the binder used was limed at a low temperature, as when it is compares with Portland Cement, these amounts are lower or near, e.g. Hidraulicity index of PC II F 32 is around 0.4 and that of an Ordinary Portland Cement (OPC) is around 0.45. At the time, it was not possible to find a technical explanation for the fact that mortar number 2 shows high hidraulicity index, like that of a modern-day Portland cement. It is safe to assume that in the mid 20th century, there may have been some intervention using Portland cement, without additions, common enough fifty years ago. Based on these values, it is possible to draw a relationship with the site of exposure of the mortar and the required strength, probably because it supported decorative adornments that required strong mortar. Mortar 4, being the second-strongest, was used for laying the stone blocks, requiring strong mortar. Mortars 1 and 3 are similar and are found in the same structural element, internal aisle walls; that require low strength to perform their function. Finally, mortar 5, with the lowest indicators, at the tower foundations, must have been used only for colmatation of soil. XR Diffraction results for all mortars are similar, so only mortars 1 and 3 were chosen, as shown in Figs. 3 and 4.

According to analysis of XRD graphs in all mortars, the presence of calcite ($CaCO_3$) and quartz (SiO_2) is predominant and indicates a binder homogeneity, confirming the widespread use of lime and sand (Bianchini et al. 2004, Bruno et al. 2004).The high intensity peaks of carbonate must be due to carbonatation over time of the binder used and use of sand from near the sea. In this study, magnesite ($MgCO_3$) was not detected, which corroborates with the XR fluorescence test, which also failed to detect that compound in the mortars.

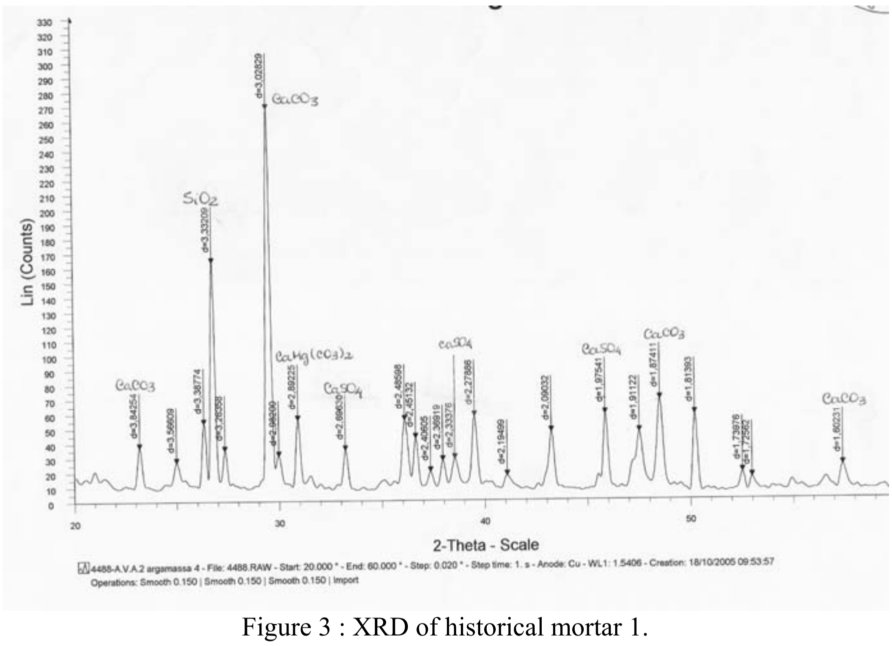

Figure 3 : XRD of historical mortar 1.

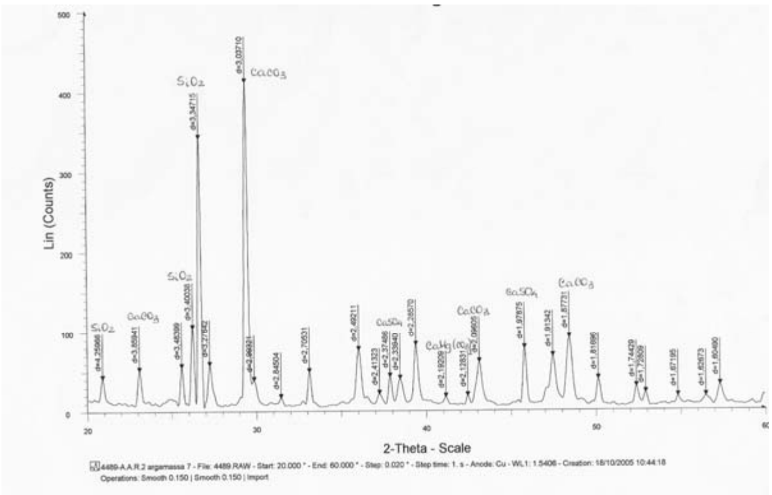

Figure 4 : XRD of historical mortar 3

3 MATERIAL AND SPECIFICATION OF MORTAR FOR ANASTYLOSIS

From data analysis for original mortars, it was decided that the new mortar for the job of anastylosis should not be based on Portland Cement, as damage was found, in several studies, to have been caused by incompatibility of materials, such as chemical reactions of alkalis in cement with the mineral components of stones used in construction, and lixiviation and salt efflorescence, causing total decomposition of materials (Maravelaki et al. 2005, ICOMOS 2001). It also happens that there is a difference in the physical behavior of Portland Cement materials in terms of mechanical strength, porosity and permeability, which also cause problems that may become serious in terms of stability of buildings, as they may cause crushing due to their different behavior in the face of external action, caused by different modulus of elasticity of original and cement-based materials (Moropoulou et al. 2005). Furthermore, mortars with Portland Cement compromise the waterproofing system of walls, as these are in harmony with the environment and perform humidity exchange with the outside (Moropoulou et al. 2004).

Thus, specification of mortar for anastylosis is based on hydrated lime, as this type, when carefully measured, shows ideal performance traits, in terms of reversibility, workability, mechanical strength and compatibility with ancient materials, provided the specific nature of the work is respected. On the other hand, arguments against the use of hydrated lime mortars include low mechanical strength, delay in execution, as the ideal scenario is maturation of the lime prior to use and its hardening is slow, as well as the strong local habit of using cement mortars for all kinds of task.

To improve the performance of hydrated lime mortar, the possibility of adding a pozzolanic material was studied, in order to form a hydrated lime and accelerate the hardening of restoration mortars (Moropoulou et al. 2005). The hydrated lime was of the CH II type and the pozzolanic material used was a red metakaolin, both sold locally. Tables 4 and 5 show data relating to the chemical composition of these materials. The specific mass of metakaolin is 2560 kg/m^3 and its bulk density is 1645 kg/m^3.

The sands used were of a natural origin. According to the graph in Fig. 5, these sands are not highly continuous when compared with sand used in original mortars. It was found that sand 1 is slightly finer than sand 2, which enables analysis of granulometric composition to obtain a more continuous sand (Degryse et al. 2002). The bulk density of sand 1 is 1398 kg/m^3 and that of sand 2 is 1405kg/m^3, and as they are both from the same origin, they have identical specific mass of 2650kg/m^3.

Table 4 : XR Fluorescence results for Red Metakaolin

Components	Weight %	Components	Weight %
SiO_2	46.87	Cr_2O_3	0.09
Al_2O_3	31.90	MgO	0.08
Fe_2O_3T	11.74	PbO	0.06
TiO_2	1.85	Ga_2O_3	0.03
CaO	1.79	NiO	0.02
P_2O_5	1.58	ZnO	0.01
K_2O	0.57	Rb_2O	0.01
SO_3	0.37	Y_2O_3	0.01
BaO	0.38	ThO_2	0.01
SrO	0.23	U_3O_8	tr
ZrO_2	0.15	PF	2.15
Cl	0.12	Total	100.02

Table 5 : Characterization of hydrated lime used

Physical Characteristics	
Grain size N. 30 (0.60mm)	8.0%
Grain size N. 200 (0.075mm)	18.2%
Bulk Density (kg/m^3)	$595kg/m^3$
Density (kg/m^3)	$2305kg/m^3$
Chemical Chraracteristics	
Total non-volatile oxides at base	87.2%
Sulfuric Anhydrite	0.1%
Magnesium in MgO	4.6%
Calcium in CaO	64.2%
Insoluble in HCl	5.5%
Ignition Loss (1000°C)	21.1%

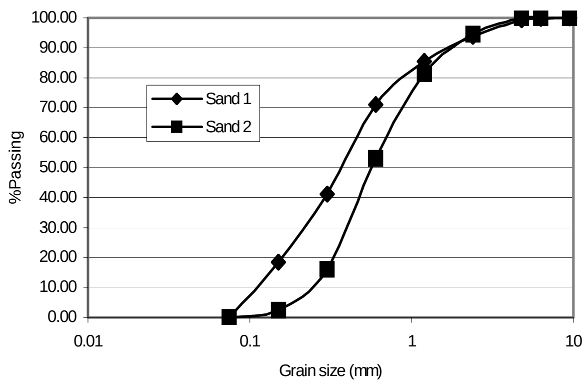

Figure 5 : Graph of granulometric distribution of sands 1 and 2

4 STUDY OF RESTORATION MORTAR

The choice of mortar to be used was based on the following criteria: compatibility with original mortar still present in parts of the ruins, such compatibility being both mechanical and esthetic (Maravelaki et al. 2005), that is, withstanding the strain on stonemasonry and being consistent with original in terms of color; having, in the fresh state, a consistency which enables the builders to mount the stonemasonry manually, and retention of water from mixing; in the hardened state, having mechanical compressive strength so that, after seven days, at least, it can withstand strain on the wall under construction, and plaster to cover the stonemasonry, hardening over time without losing compatibility with the base (ICOMOS 2001). Mortar tests were performed in the Materials and Structures Lab at UFPE. According to the specifications discussed in item 3, restoration mortars are based on hydrated lime and metakaolin as a pozzolanic material, and natural sand. Based on pilot studies, three traits of mortar were chosen: 1:1, 1:2 e 1:3 (binder: sand), the binder fraction being formed by mixing hydrated lime and pozzolan in equal proportions, that is, 1:1. For the fraction of sand, binary mixtures were studied, seeking greater capacity and continuity in granulometric distribution. Thus, the composition of 30% sand 1 and 70% sand 2 was determined. With the mortars, the following tests were performed: bulk density in anhydrous state; consistency and compressive strength.

Bulk densities of mortars in anhydrous state increased as proportion of sand increased, due to higher specific mass of sand, in relation to the hydrated lime of metakaolin, see Table 6.

Table 6 : Bulk Density of mortars studied in anhydrous state

Mortars	Bulk density (kg/m^3)
1:1	1123.22
1:2	1346.75
1:3	1408.27

In the flow-table test, it was found that mortars of the 1:2 and 1:3 type consume the lowest amount of water for 250mm consistency and 1:3 mortar requires more water. This occurs due to the high quantity of fine sand in its composition, see Fig. 6.

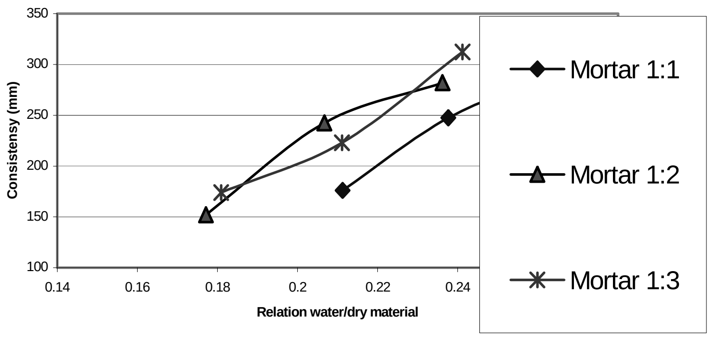

Figura 6 : Graph of mortar consistency

Test show that 1:1 mortar has greatest compressive strength after 7 days, 5.0MPa and the others show lower values. This is a result of the higher amount of hydrated lime in the composition and granulometric distribution of sand having good continuity. 1:1 type mortar is recommended for anastylosis, as it has a consistency of 250 mm, which facilitates manual work of mounting stonemasonry, and after seven days, it reaches 50% of the compressive strength necessary to withstand the weight inherent to the stonemasonry, which was stipulated as 8.0MPa. 1:2 type mortar, with 2.0 MPa, shall be used for plastering walls near the floor, up to a height of 1.0 m, as this is the portion that suffers most from the environment, and above that height, 1:3 type mortar, with 0.5 MPa shall be used, where wear is less considerable, see Table 7.

Table 7 : Compressive strength after 7 days (MPa)

Mortar	fc (MPa)
1:1	5.2
1:2	2.0
1:3	0.5

5 CONCLUSIONS

The mortars studies, with hydrated lime, metakaolin and sand, for the task of restoration by anastylosis reached the necessary requirements, for the following reasons: (a) granulometric composition formed by natural sands, wherein continuous granulometric distribution was found, contributing to consistency and compressive strength of mortars.

Mixture of hydrated lime binder, with addition of metakaolin, as the fine material content contributed to consistency of mortars, and offered satisfactory compressive strength after seven days.

Coloration obtained from this mixture is in keeping with original pieces.

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