Rehabilitation of a Cruzeiro in Portugal

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Abstract

Interventions in historic buildings and structures may vary with the degree of decay they present. Due to the fact that Cruzeiro de Sangalhos had suffered considerable damage and varied interventions during the ages, the method adopted for the developed action was of respect for the remaining original elements and of ensuring compatibility of added structures and their differentiation from the original monument. The rehabilitation process is described, mainly in what concerns the formulation of mortars and their application. New mortars had to be used in column joints and in the dome, which needed total rebuilding. For this purpose pre-existant mortars were studied, several formulations were tested for their main mechanical, physical and chemical characteristics and the structural analysis of the dome with the chosen mortar was executed using finite element software. Cruzeiro de Sangalhos was then rebuilt using specified mortars and the works were supervised.

1. Introduction

Throughout Portugal, ‘cruzeiros’ were built to fulfil the function of prayer sites or linked to prayer paths, in accordance with the religious culture of the country. These structures present themselves in various forms and especially in the centre of the country a few were built with a dome over the omnipresent cross; that is the case of Cruzeiro de Sangalhos.

Situated in the centre of the village of Sangalhos, this ‘cruzeiro’ is composed of a central column and a surmounting structure of limestone columns, forming a quadrangular shape. Over the columns a small dome was built, possibly with mortar and supported on supporting stone beams bearing angel faces on each internal corner; on top of this dome stands a smaller cross. The original building was erected during the 17th
century and the first known intervention took place during 19th, 20th century when the actual cross was added. A new dome was probably built during this intervention. During the 20th century, the whole construction was moved to its actual standing place, but suffered severe damage recently, in 2001, due to a car accident [1] as shown in Figure 1.

Figure 1 – State of the monument prior to intervention

2. Study of replacement mortars

All retrievable original elements were cleaned and replaced; this was the case of most external columns, the central cross and the supporting stone beams. The dome, however, due to the extent of damage it suffered, had to be totally rebuilt.

2.1. Dome reconstruction

The cracks that were inflicted on the dome by the accident which led to its collapse, made it possible to verify that it was made of a cement-based mortar, therefore, probably a 20th century intervention with no particular care for the maintenance of the monument’s originality. In comparison with ancient photographs, it may be ascertained that the original form itself was not maintained. Therefore, a choice was made to reproduce the original dome in what concerns shape and to use a new mortar, taking into account the exposure of such a structure to atmospheric conditions and structural performance.

2.1.1. Mortar formulation

As there is no available source of information concerning the mortar used for the making of the original dome and the rehabilitation procedure predicted the
differentiation of added parts, various mortar compositions were studied. Mechanical resistance, carbonation speed and capillary absorption, the main characteristics that guide the performance of mortars were the executed tests.

2.1.1.1 Tested mortar formulations Based on dry hydrated aerial lime, hydraulic lime, brick dust and natural Cape Verde pozzolans, five different mortar compositions (table 1) were tested [3]; for this purpose, two different sands were used: a fine, previously washed, dune sand (S1) and a coarser and yellowish sand (S2), both of common use in the region. Their granulometric curves are shown below (Graph 1 & Graph 2).

Table 1 – Mortar composition

<table>
<thead>
<tr>
<th>Mortar</th>
<th>Lime</th>
<th>Hydraulic Lime</th>
<th>Brick dust</th>
<th>Pozzolans</th>
<th>Sand S1</th>
<th>Sand S2</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>-</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>3</td>
</tr>
<tr>
<td>M2</td>
<td>1</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>6</td>
</tr>
<tr>
<td>M3</td>
<td>-</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>3</td>
</tr>
<tr>
<td>M4</td>
<td>1</td>
<td>1</td>
<td>-</td>
<td>0,5</td>
<td>-</td>
<td>6</td>
</tr>
<tr>
<td>M5</td>
<td>1</td>
<td>1</td>
<td>0,5</td>
<td>-</td>
<td>-</td>
<td>6</td>
</tr>
</tbody>
</table>

On a first stage, M5, containing brick dust, was eliminated due to its colouring, which was of a soft pink, aesthetically not compatible with the rest of the monument.

Graph1 – Granulometric analysis – S1
2.1.1.2 Carbonation speed  The evaluation of carbonation speed was effectuated using a phenolphthalein solution and was based on the procedure specified by ARC [2]. The results are shown in Table 2, as the percentage of carbonated area on a mortar specimen.

<table>
<thead>
<tr>
<th>Mortar</th>
<th>Carbonation speed (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>93</td>
</tr>
<tr>
<td>M2</td>
<td>36</td>
</tr>
<tr>
<td>M3</td>
<td>87</td>
</tr>
<tr>
<td>M4</td>
<td>100 (complete)</td>
</tr>
<tr>
<td>M5</td>
<td>100 (complete)</td>
</tr>
</tbody>
</table>

2.1.2.3 Flexural and compressive strength  The remaining mortars were tested for mechanical strength, using flexural and compressive strength testing procedures following EN 1015-11. The obtained results were as follows (Graph 3 & Graph 4). Due to the poor results obtained in this test, mortars M1, M2 and M3 were eliminated.
2.1.1.3. Water absorption by capillary action This test was performed using the procedure specified in Cahier 2669-4 CSTB. The results revealed an intermediate value of the water absorption coefficient for all mortars, compatible with the mortar's specific use.

2.1.2. Structural analysis
After the mortar composition was known, M4 having been chosen, it was necessary to analyse the stresses that will take place at the dome. Three major issues had to be solved in order to accomplish a satisfactory design of the dome. The first one is related with the nature of the material used in the restoration that has a low tensile strength (characteristic value of 450 kPa) and the second is related with the need to ensure that
the thickness allows good hardening conditions and simultaneously guarantees that the tensile strengths at the dome were below the tensile strength of the mortar. The third question is related with the uncertainties in the behaviour of the mortar in such severe structural conditions, since this type of material is not commonly used in these situations.

The structural behaviour of the dome was analysed with the finite element software SAP2000. The analysis was carried out with shell elements. The finite element mesh is illustrated in Figure 2. The base of the dome is a 2,2m square and the total height is 0,8m. The thickness was determined by a trial and error procedure where various solutions were tested. At the final stage a constant thickness of 9 cm was adopted.

The boundary conditions at the bottom of the dome were of crucial importance for the overall structural behaviour. In fact, if the bond between the dome and its foundation was sufficient to block the horizontal displacements an arch behaviour could be achieved. Otherwise if the bond was not enough there will be horizontal displacements at the base of the dome and a slab-like behaviour could be observed. Since the mortar dome was cast directly over the stone without anything that could prevent the horizontal displacement at the base except the bond between stone and mortar it was decided to carry out two types of analysis that could be used as envelopes for the real behaviour: in analysis A the horizontal displacements of the dome were blocked and in analysis B the horizontal displacement were left free. The loads considered are the self-weight and a stone cross, placed at the top of the dome weighing about 0,3 KN.
The displacements of the two analysis are presented in Figure 3 with a magnification of 3000 times. The maximum vertical displacement of the dome in analysis B was twice that of analysis A. In any case this displacement was below 0,1mm.

Figure 3 - Displacements in finite element analysis (left: analysis A; right: analysis B)

In what follows only the results of analysis B are displayed since this case is more severe for the dome than case A. Although the design was based on the assumption that the horizontal displacements of the base were possible, it is advantageous that an arch-type behaviour could be achieved. The stress output can be found in Figures 4 to 7. The stresses were calculated averaged at the nodes of the finite elements and tension is indicated as positive. The critical zones are clearly the corners at the base of the dome and the bottom face underneath the cross.

Figure 4 - Horizontal stresses at top face
Figure 5 - Horizontal stresses at bottom face

Figure 6 - Vertical stresses at top face

Figure 7 - Vertical stresses at bottom face
For the determination of the tensile strength a safety coefficient of 1.5 was adopted which leads to a design value of 300 kPa. The safety coefficient used was fixed by analogy with concrete since there are no explicit rules for use in mortar. It can be observed that with the exceptions of the corners (tensile stress of 375 MPa), the stresses were kept below the design tensile strength assumed for the design. Furthermore, this situation is for the most unfavourable case where the horizontal displacements were allowed. In fact, if the displacements were prevented a tensile stress of 72 kPa is observed. This difference is enough to guarantee that even if only a small part of the displacements were prevented a huge drop in the tensile stresses occurs.

To improve the structural performance of the dome, a galvanized steel mesh with 4.5 mm bars spaced 10 cm was added at both faces 2 cm below surface. This mesh was not considered in the structural analysis and was placed as an additional security device. Its main function is to increase the stiffness of the dome reducing the horizontal displacements of the base thus attaining an arch-like behaviour.

2.2. Formulation of joint mortar

As mortars from joints between columns and remaining structure were still available on site, it was decided to study their composition and formulate a new mortar with a similar composition.

2.2.1. Chemical analysis

Using the testing procedure described in ARC [1], the mortar was divided into three fractions with the aid of a chloridric acid solution – insoluble fraction (siliceous sand), argilaceous fraction and filtrate (binder). Using this method, the volumetric ratio between clay, sand (or argilaceous sand, most probably, due to local characteristics) and binder was determined. In order to evaluate the chemical composition of the mortar, a qualitative analysis was performed on both the soluble fraction and the filtrate. Results indicate that the mortar in study was lime based, containing argilaceous compounds, probably provenient from the type of sand used locally, of yellowish colour. The granulometric curve of the insoluble fraction was determined as shown in Graph 5.

2.2.2. Mortar formulation

A similar composition as that of the original mortar was used for joint mortars, taking into account the materials and proportions determined. Therefore, dry hydrated lime was the chosen binder and local sand with analogous characteristics was the employed aggregate.

3. Intervention

Due to the fact that the dome mortar needed to be applied on a rather big extension and with a significant width, several specifications were applied in order to improve its performance. The use of a fibre mesh was applied on both sides of the dome, 0.5 cm from the surface and water was sprinkled on the outer surface twice a day. However, the
dome execution was particularly delicate due to excessive temperature (MPa); in order to minimize cracking it was specified that water sprinkling should take place more often, specially in the hottest times of day and a light coloured TOLDO was placed over it in order to avoid excess heat. Concerning the joint mortars, it was specified that the adjacent stone must be brushed and cleaned in order to provide a rough and particle free surface that would favour a good adhesion (Figure 8).

![Figure 8 - Joint mortar](image)

References

[1] www.monumentos.pt