SCIENCE and ART: A Future for Stone

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Cover image: The front door of the Paisley Technical College building, now University of the West of Scotland. T.G. Abercrombie, architect 1898. Photograph and cover design by T. Howind.
RECOVERING THE ARCHITECTURAL HERITAGE OF THE NUEVA TABARCA ISLAND (SPAIN) BY STUDYING THE DURABILITY OF ORIGINAL AND REPAIR MORTARS

J. Martinez-Martinez1 and A. Arizzi2

Abstract

Nueva Tabarca is a small island located in the Mediterranean Sea, close to the city of Alicante (SE of Spain). Although the island is mainly known for its marine reserve, its fortified village is an exceptional example of Baroque architectural heritage, mainly built with stone and lime mortars. However, in spite of the singularity of its monuments, the majority of walls and buildings of the old town of Tabarca are in an alarming state of conservation. Airborne salt, Aeolian erosion and anthropic activity are the main causes of decay. Although several restoration works were carried out during the 70’s and in the first decade of the present century, all of them have shown to be ineffective, due to the low durability of the repair materials used. To investigate the causes of such an intense decay of both original and repair mortars, a complete characterisation of these materials has been carried out, by means of both field and laboratory studies that included: diagnosis of the conservation state of buildings, mineralogical and textural analyses of mortars, and determination of mortar strength. Our investigations have demonstrated that the decay patterns found in the repaired buildings cannot be related only to the weathering conditions of the island, but also to the choice of inappropriate repair materials. Laboratory results have shown, indeed, that the original mortars are more resistant to decay processes compared to the repair mortars used, mainly because of their lower porosity and higher mechanical strength.

Keywords: lime mortar, Mediterranean climate, durability, salt crystallisation

1. Introduction

This study is focused in the old town of the Nueva Tabarca island (Alicante province, SE of Spain) (Fig. 1). This fortified village represents an exceptional example of homogeneous baroque architectural heritage. The singularity of the monuments was recognized by means of several local and national projects. The initial plans for this fortified city were focused on the construction of a thick wall around part of the island as well as of several buildings with military, religious and civil functions (Canales Martínez and Romero Carrasco, 2014). The reason for this important intervention was to offer a stronger resistance against the Barbary pirates. The construction works began in the middle of 18th century, but they were

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interrupted in 1770 due to economical, political and logistic problems. This resulted in the construction of most parts of the wall, the church, the government building and a complex hydraulic system in order to supply the population with fresh water (Fig. 1).

Fig. 1: Above left: Nueva Tabarca island location; above right: map of the island showing the main lithologies and the location of the fortified village; down: some elements of the architectural heritage of the Nueva Tabarca village (a: San Gabriel door, b: San Pedro and San Pablo church, c: San Miguel door, d: San José tower).

Nowadays, the weathering state of walls and buildings is alarming. The proximity to the sea and salt water, the effect of the aeolian abrasion, and the anthropic damage are the most significant decay causes of the original building materials. Several restoration works were carried out in the local heritage focused mainly on the walls and the church. Two of the
most important works were executed during the 70’s and the first decade of the present century. All the interventions are now being seriously discussed due to their low efficacy and the use of foreign reintegration rocks aesthetically different from the original materials.

One of the weakest aspects of the last restoration work regards the repair mortar chosen. Fig. 2 shows the current situation of a non-restored city wall (a) and a rebuilt section during the 70’s (b). In the original masonry (a) it is possible to appreciate how the original lime-mortar remains well preserved whilst the ashlers are completely eroded. The rebuilt part, instead, presents the opposite behaviour: the rock ashlers show a slight to moderate weathering, whilst the new lime-mortar is strongly deteriorated.

![Fig. 2: examples of two parts of the city walls of Nueva Tabarca: original (a and a’) and rebuilt masonry (b and b’).](image)

With the purpose to understand the reasons for the different durability of both the original and the repair lime mortars, a complete petrographic and petrophysical characterization of these materials has been carried out in the present work.

2. Methodology

Four types of lime-mortars were collected from the original and restored city walls. Firstly, each sample was cut in two pieces and the obtained flat surfaces were scanned for their textural analysis and description. Secondly, one piece was powdered for the chemical and mineralogical analysis, while the other one was cut in a regular shape for the study of its pore system. Owing to the small size of the samples, their mechanical properties were not studied by means of laboratory tests (e.g. uniaxial compression test), but using the Schmidt Hammer in situ.

2.1. Textural and mineralogical characterisation

For the textural study, 48-bits colour images were obtained for each mortar type with a resolution of 600 ppp. An Epson Perfection 2480 PHOTO scan was used. In order to improve the quality of the obtained image, the surfaces of the sample were priory moistened. A semi-quantitative mineralogical analysis was carried out by X-Ray Diffraction using a Phillips PW-1710 powder diffractometer with CuKα radiation and a PHILIPS PW-1404 calibrated with standards from CNRS.

2.2. Pore system characterisation

The connected open porosity (φ₀), defined as the relationship between the volume of voids (ratio of absorbed water to water density) and the volume of the sample and expressed as a percentage, was found using the vacuum water saturation test. Samples were dried at a
temperature of 70°C for 48 hours until constant mass. Dried samples were placed under vacuum at 20 ± 7 mbar for three cycles of 5 hours each (after UNE-EN 1936). The gases trapped in the pores were eliminated during the first cycle. During the second cycle, samples were gently immersed under distilled water, where they were left for 5 hours. Atmospheric pressure was re-established and maintained throughout the last cycle. The pore size distribution of samples was measured by means of Mercury Intrusion Porosimetry (MIP), using an Autopore IV 9500 Micrometics mercury porosimeter. The pore size interval investigated by MIP ranges from 0.002 to 200 μm, which corresponds respectively to highest and lowest head pressures. Finally, the real density ($\rho_r$) of samples was obtained using an AccuPyc 1330 Helium pycnometer.

2.3. Mechanical characterisation
The Schmidt hammer, also named Sclerometer or Rebound Hammer, is a non-destructive test for assessing the uniaxial compressive strength and the Young’s modulus of materials. The used sclerometer is a L-type instrument. This apparatus measures the distance of rebound of a controlled impact on a rock surface. When the Schmidt Hammer is pressed against a surface, its piston is automatically released onto the plunger. The distance travelled by the piston after it rebounds is called the rebound ($R$) value. Harder materials have higher $R$ values. If sclerometer measurements are done in an inclined way, the $R$ values must be normalized with reference to the horizontal direction. A minimum of 15 rebound values were carried out in each tested sample in order to obtain a representative value. Highest and lowest values were discarded (Viles et al., 2011). Uniaxial compressive strength (UCS) and Young’s modulus ($E$) were indirectly determined with the Schmidt hammer test using empirical relations proposed by Yagiz (2009):

$$\text{UCS} = 0.0028 \cdot R^{2.584} \quad \text{(Eq. 1)}$$

$$E = 0.0987 \cdot R^{1.5454} \quad \text{(Eq. 2)}$$

These equations were adopted because they were considered the most suitable for carbonate rocks according to Andriani and Germinario (2014).

3. Results and discussion
Figures 3a and 3b shows the aspect of both original (XVIII century) and new (XX century) lime-mortars used in Nueva Tabarca fortified village. Tab. 1 and Fig. 3c includes the obtained data from the different tests carried out in this work.

A mortar system is characterised by the presence of aggregate grains surrounded by a matrix in continuous mineralogical and textural transformation. Non-hydraulic lime-based mortars, in particular, are characterised by a hardening process (carbonation) that is much slower over time with respect to the hydration reactions that occur in cement mortars and concrete. Initially, the lime-based mortar matrix is mainly composed by portlandite (Ca(OH)$_2$), which slowly reacts with the atmospheric CO$_2$ present in the pores to form calcite (CaCO$_3$) (Moorehead, 1986). In the case of the Tabarca’s mortars, the matrix mineralogy is expected to be mostly calcite, due to the materials age and the chemical aggressiveness of the marine environment where these mortars are placed, which causes the dissolution and removal of the unreacted portlandite. Indeed, portlandite was not detected by XRD (table 1), confirming a completed carbonation process in both types of mortars. From the XRD data we can estimate that both types of mortars present a similar binder-to-
aggregate ratio (approximately 1:1.5 by weight), and that the matrix constitutes around 40% of the sample. However, there are significant differences between the two types of mortars in terms of mineralogy and size of their aggregates. On the one hand, the original lime mortar presents a broad and continuous grading, showing particles with diameters ranging between 1 mm and 4 cm. The clasts nature corresponds to dolostones and gabbros, which were probably collected from the local beach deposits. On the other hand, the aggregate of the repair mortars, mainly proceeding from dolostones, has grains of bigger sizes and with a discontinuous grading (between 5 and 10 mm) (Fig. 3).

Tab. 1: Data obtained from both original (NT-org) and repair lime-mortars (NT-rest) used during the 70’s restauration works. Parameters included in this table: Mineralogical composition (Cc: calcite; Dol: dolomite; Px: pyroxene; Pl: plagioclase); Open porosity (\( \phi_O \)); Real density (\( \rho_r \)), Rebound value after Schmidt Hammer (R) and uniaxial compressive strength (UCS) and Young’s modulus (E) estimated from R value.

<table>
<thead>
<tr>
<th>Mineralogical Composition, %</th>
<th>( \phi_O ) (%)</th>
<th>( \rho_r ) (g/cm(^3))</th>
<th>R (-)</th>
<th>UCS (MPa)</th>
<th>E (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cc</td>
<td>Dol</td>
<td>Q</td>
<td>Px</td>
<td>Pl</td>
<td></td>
</tr>
<tr>
<td>NT-org 39.85</td>
<td>14.58</td>
<td>4.97</td>
<td>18.82</td>
<td>21.87</td>
<td>17.20</td>
</tr>
<tr>
<td>NT-rest 41.85</td>
<td>55.81</td>
<td>2.42</td>
<td>-</td>
<td>-</td>
<td>23.33</td>
</tr>
</tbody>
</table>

Fig. 3: Images a and b: original (a and a’) and repair (b and b’) lime mortars of the walls. Graph c: pore size distribution of both original and restoration mortar (NT-org and NT-rest, respectively).

The pore system of original and repair mortars is also different. The open porosity of the original mortar (around 17%) is lower than that of the repair one (~23%). However, the open porosity in both cases is not too high if we compare them with similar materials (porosity values ranging between 30% and 40% for other lime-based mortars with similar binder-to-aggregate ratio, Arizzi et al., 2013). Pore size distribution is also different (Fig. 3c): the original mortar presents a main size of pores of 0.8 µm and the 60% of the pores are comprised between 0.3 and 10 µm. On the contrary, the pore size distribution of the repair mortar is much more homogeneous (unimodal distribution), being the majority of the pore radii centred between 0.5 and 2 µm. The most frequent pore size in this mortar is slightly higher (1.5 µm). Moreover, the repair mortar presents close rounded pores (in the form of bubbles, Fig. 3) likely to be formed during evaporation of the kneading water.
Finally, the mortar used in the original masonry presents higher mechanical properties (strength and stiffness) than that used during restoration works. This fact can be observed in table 1, where the uniaxial compression strength value (estimated after the R value) is nearly three times higher in the original mortar than in the repair one. This fact is mainly due to the higher porosity and the presence of rounded pores in the latter.

4. Conclusions

The repair mortar collected from the wall of the Nueva Tabarca Island has shown a lower durability compared to the original mortar (XVIII century), as demonstrated by the worse conservation state of the former after only 40 years since the last intervention. This is due to two complementary factors: 1) mortars are exposed to an arid and maritime environment, with the main decay caused by salts (both from the capillary water and the sea spray), aeolian erosion (especially during frequent storms) and sun radiation; 2) the repair mortar shows a worse quality due to its higher porosity (with the majority of pores with size of 1 µm) and its lower mechanical resistance and cohesion, which make it more vulnerable to salt crystallisation and wind erosion. According to this study the repair mortar needs to be replaced with a new one with improved textural and mechanical characteristics. With this purpose, a new repair mortar is being designed for this particular location and environment. As an added value, sustainable materials from the Tabarca Island are being used in the new formulation.

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