Materials and reconstruction techniques at the Aqueduct of Carthage since the Roman period

M. O. Figueiredo, J. P. Veiga and T. P. Silva

Crystallography and Mineralogy Centre, IUCT, Lisbon, & CENIMAT, New University of Lisbon, FCT-Materials Sc. Dept., Caparica, Portugal

ABSTRACT: Structural features and materials plus construction and reconstruction techniques used at the Aqueduct of Carthage are reviewed. A minerochemical study of mortars from the water conduits, pillars and arches was undertaken. Differentiating features between mortar types - early Roman, Byzantine, medieval (Hafsid) and modern - are outlined on the basis of an easy test based on loss-on-ignition to estimate calcite-to-quartz ratios in the masonry. Reconstruction works within the Roman period are briefly discussed considering jointly materials and techniques, and guidelines for identifying interventions conducted in the past are advanced. Geotechnical constraints and environmental aspects – particularly anthropogenic actions – are also commented in relation to observed structural failures. Intervention strategies and techniques are commented, focusing on materials conformability under the perspective of a durable restoration of this unique Mediterranean cultural heritage.

1 INTRODUCTION

The Romans have left remarkable hydraulic engineering works, nowadays included in the common cultural patrimony of the Mediterranean basin. Amongst the most important pieces of such architectural heritage is the Aqueduct of Carthage, also quoted as Aqueduct of Hadrian, the Roman emperor that decided about its construction to assure water supply to the great capital of Africa Proconsularis (actual Tunisia).

Being a jewel of structural (engineering) and architectural archaeology, this aqueduct is an emblematic historical construction that received lately great attention in view of urgent intervention and restoration works necessary to strengthen the still-standing pillars, arches and water conduits.

The present work summarizes the results attained so far within an international study focused on characterizing degradation phenomena in ancient and traditional building materials used for constructing historical monuments in the Mediterranean area, developed with the financial support of the European Union (DG XII-CEOR) through Concerted Action IC18-CT-0384 within Prospective Study nr.1 concerning the case-study of Carthage Aqueduct.

2 THE AQUEDUCT OF CARTHAGE: A BRIEF HISTORICAL OVERVIEW

Old of eighteen centuries, the complex of Hadrian’s Aqueduct comprises three recognized water captions – Zaghouan at an altitude of 289 m, Ain Djougar at 360 m and Ain Djour (Ferchiou, 1999) – and water conduits - aerial, 17 km in the plane of river Miliane (fig. 1) and subterranean - along a total of 90.4 km from Zaghouan to Antonin public baths in Carthage, plus 42 km of secondary extensions linking to other sources. The inclusion in this complex of the cisterns for collecting water at La Malga (24 tanks 816 m long and 8 m large) and Borj-Djedid (altitude
24 m) is still object of discussion (Rakob, 1970). An water flow of 370 l per sec was estimated for the early period of functioning (Hassine & Karoui, 1999). A detailed description of the aqueduct development may be found in Rakob (1979).

The exact period of construction is not historically established but was for sure latter than 128 A.C. – the year Hadrian traveled to the colony after five years of dryness – being also known that it was already concluded in 162 when Antonin thermae were finished (Ferchiou, 1999).

The first historically reported restoration took place under Septimius Severus in the year 203. All data indicate that the aqueduct was thereafter kept in service until the invasion of the Vandals that conquered Carthage in 439 and destroyed the water conduits at various places.

Reconstruction of the aqueduct follows the Byzantine recover of Carthage in 534. Again destroyed when Hassen Ibn Noâmen during the siege of Carthage in 698 followed by the expulsion of Byzantines, the aqueduct was partially but not significantly repaired under the Fatimids in the X century and also in the XIII century (between 1249 and 1277) under the Hafsid caliph Abu Abdallah El Moustansir who determined an extensive rehabilitation: the branch of Djougar was reset in service and two new derivations were constructed. Two centuries later further reconstruction works were carried out under caliph Abou Amr-Otman (Khosrof, 1999).

The Spanish occupation of Tunisia in the XVII century culminated with the destruction of all means of water supply, including the remaining of the old Roman aqueduct, largely documented in a series of tapestries now exposed in a museum at Seville and illustrating the conquer of Tunis by emperor Charles V. However, this iconography is merely artistic once it figures out the Aqueduct of Carthage in a way much closer to the Roman aqueduct of Segovia in Spain rather than to what can actually be seen in Tunisia with pillars of uniform cross section.

Further rehabilitation works were conducted by a French engineer between 1859 and 1862, including the construction of a new bridge over the river Miliane, incorporating lithologic materials recovered from ruins of the Aqueduct in the valley.

![Figure 1: Partial reproduction of the geodesic chart (sheet nr. XXVIII, B 3 – C 36) figuring the Aqueduct development (double broken line) divided into sectors labeled A to E.](image-url)
Despite the recognized seismic activity in the region crossed by this splendid hydraulic engineering work, there are no historical records of seismic events between the third and the fifth century of our era that might have damaged the Aqueduct in the earlier period after its construction. Nevertheless, the fact that it has been restored after only 70 years of use may well be indicative that such an event might have occurred; it is a question for the Historians to solve.

Beyond eventual earthquakes (quite sure in view of an active transverse geologic fault) and repeated destruction during war periods, anthropogenic actions like stone stealing during centuries for current building and other practices still going on nowadays, play a major role in degradation processes affecting the monument. Indeed, daily pasturing activities underneath arches and nearby pillars, plus an intense traffic along two highways parallel to the aerial part of the Aqueduct and a railway perpendicularly cutting the conduit at the initial part (sector A in fig. 1), all contribute decisively to the damage state attained at the end of the XX century and dramatically calling for urgent interventions at various levels.

3 MATERIALS AND CONSTRUCTION/RECONSTRUCTION TECHNIQUES

The diversity of construction/reconstruction testimonies is nicely documented by Ferchiou (1999a) who also provided a quite exhaustive inventory of the problematic that should be tackled under the Prospective Study on the Aqueduct of Zaghouan-Carthage (Ferchiou, 1999b): building materials (varieties and properties) and their alterations (physical/mechanical, chemical by environmental actions or heating/burning); location of stone quarries and chronology of exploitation; contributions of materials knowledge to archaeologic dating; indirect assessment of water composition along time: techniques used in recent restorations (1859-1862 and actual); influence of tectonics and geomorphology on the structural behaviour of the monument. Some of such questions could indeed be successfully treated.

3.1 Original Roman construction

The Aqueduct is an open document for architects and engineers to learn what has been taught by Vitruvius in De Architectura about Roman construction materials and techniques, particularly books II on materials and VIII on water/aqueducts – see for instance a recent re-edition (1995) of the first translation from the original Latin by Claude Perrault in 1673. The study of materials and the knowledge of construction and reconstruction techniques will certainly contribute to implement rehabilitation measures that may guarantee the durability of the remnants of the Aqueduct of Carthage for centuries to come with great cultural profit for future generations.

Figure 2 : Sector C (see fig. 1) of the Aqueduct of Carthage viewed E-W close to the river Miliane.
An *ex-libris* of the monument is the sector labeled C in fig. 1, where a series of impressive Roman pillars about 20 m high stand for a few hundred meters along GP 3 road (fig. 2). Traditional Roman arches with pentagonal wedge-shape blocks assembled into a full semicircle with no interlinking mortar are still standing, as well as in other sectors of the Aqueduct (fig. 3).

The ashlar blocks (lithologic elements) are mainly sandstones, occasionally limestones, presenting varied states and degrees of surface alterations and pathologies. They have been carefully cut and dimensioned to build pillars with uniform cross section, square or rectangular, where two rows of stones form a structure in *opus quadratum* way with sharp joints and no linking mortar, as usual filled by pieces of stone mixed with a lime-and-sand mortar, *opus caementicium*. A reaction interface mortar/stone is clearly apparent.

Despite multiple fractures due to having fallen from a great height, fragments of such mortars spread in the terrain along all sectors of the Aqueduct display a remarkable consistency and a high mechanical strength, thus certifying the recognized high quality of lime mortars from Antiquity.

### 3.2 Medieval (islamic) construction techniques

Very little is known about the eventual reconstruction of the Aqueduct by the Byzantines following the recover of Carthage in the year 534 by Bélisaire (Khosrof, 1999).
Extensive rehabilitation works were conducted after the Islamic conquer and a large number of pillars and arches plus water conduits have been built in a way substantially different from the Roman construction technique (fig. 4).

The material used was a mixture of lime and reddish argillaceous earth with hydraulic properties (pisé) and the pillars were built using wood moulds progressively displaced from bottom to top. After a section had dried, a thin layer of chalk or lime was spread over the surface before starting the new section. Such construction technique may be inferred from fallen blocks (fig. 5).

3.3 Reinforcement walls

Perpendicular walls reinforcing pillars along sector C of the Aqueduct raise important dating questions. Indeed, if most of them are clearly Hafsid constructions in the usual pisé, a Roman original construction is hardly acceptable for those faced with ashlar blocks. A good example is reproduced in fig. 6 where such a wall sustains a pillar between two clearly non original arches.

It is opportune to recall the possible – even not historically reported - occurrence of seismic events shortly after the Roman Aqueduct construction.

Figure 5: Fragment of an Hafsid pillar displaying marks of the wood bars from the mould in the exposed surface

Figure 6: Reinforcement walls in sector C (viewed E-W)
3.4 Materials

The problematic concerning materials ranges from the original building stones, namely, their provenance, actual surface deterioration and bulk state of degradation - topics charged to other partners of the Concerted Action (Alvarez et al., 2000a,b) - to the mortars, and these present a great diversity: mortars in concrete from the original Roman construction, mortars filling joints and consolidating ashlar blocks (restoration works under Severus? or Byzantine?), medieval mortars in pisé (Fatimid and Hafsid periods of rehabilitation) and modern mortars, either with lime (19th century) or with Portland cement (since the fifties) as hydraulic binders.

The Authors have undertaken a mineralogical and chemical characterization of building materials with emphasis on masonries and mortars using current instrumental techniques, preferably non-destructive like optical observation under a stereomicroscope and direct X-ray diffraction (XRD) spectra collection or X-ray fluorescence (XRF) scanning for elemental qualitative analysis. Destructive methodologies included bulk chemical analysis by XRF spectrometry in wavelength dispersive mode (XRF-WDS) and thermal analysis (simultaneous TG-DTA).

Recommended standardization of sampling and analysis procedures (Chiari et al., 1996) was carefully observed. Pore size distribution measurements were spared for the moment and mechanical strength tests have not been performed due to the required large sample dimensions.

Table 1 lists the chemical composition of typical mortars and binding materials. Torba is a traditional binding material used in the Magreb, composed of an yellow-reddish soil clay mixed with lime and salt as minor additive, that displays efficient hydraulic properties (Ferchiou, 1999b).

<table>
<thead>
<tr>
<th>Sample nr. &amp; description</th>
<th>SiO₂</th>
<th>Al₂O₃</th>
<th>Fe₂O₃</th>
<th>MgO</th>
<th>CaO</th>
<th>Na₂O</th>
<th>K₂O</th>
<th>TiO₂</th>
<th>P₂O₅</th>
<th>SO₃</th>
<th>LOI</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 - Stone joint masonry</td>
<td>69.96</td>
<td>1.65</td>
<td>0.54</td>
<td>n.d.</td>
<td>15.95</td>
<td>0.35</td>
<td>0.18</td>
<td>n.d.</td>
<td>0.06</td>
<td>0.46</td>
<td>10.85</td>
</tr>
<tr>
<td>2 - Hydr. lime masonry*</td>
<td>55.30</td>
<td>2.92</td>
<td>0.71</td>
<td>n.d.</td>
<td>24.84</td>
<td>0.50</td>
<td>0.80</td>
<td>n.d.</td>
<td>0.05</td>
<td>n.d.</td>
<td>14.89</td>
</tr>
<tr>
<td>3 - Mortar (fallen block)</td>
<td>36.82</td>
<td>1.46</td>
<td>0.41</td>
<td>0.42</td>
<td>33.55</td>
<td>0.37</td>
<td>0.17</td>
<td>n.d.</td>
<td>0.07</td>
<td>0.19</td>
<td>26.51</td>
</tr>
<tr>
<td>4 - Mortar (pozzolanic?</td>
<td>36.60</td>
<td>4.31</td>
<td>0.84</td>
<td>0.47</td>
<td>35.69</td>
<td>0.24</td>
<td>0.46</td>
<td>n.d.</td>
<td>0.04</td>
<td>n.d.</td>
<td>21.34</td>
</tr>
<tr>
<td>5 - Roman mortar (a)</td>
<td>28.37</td>
<td>4.65</td>
<td>1.18</td>
<td>0.55</td>
<td>37.54</td>
<td>2.09</td>
<td>0.64</td>
<td>0.04</td>
<td>0.05</td>
<td>0.16</td>
<td>24.73</td>
</tr>
<tr>
<td>6 - Hafsid mortar</td>
<td>21.45</td>
<td>3.74</td>
<td>2.30</td>
<td>1.00</td>
<td>37.96</td>
<td>0.24</td>
<td>0.03</td>
<td>0.05</td>
<td>0.18</td>
<td>0.19</td>
<td>32.86</td>
</tr>
<tr>
<td>7 - Conduit mortar (b)</td>
<td>20.79</td>
<td>4.56</td>
<td>2.05</td>
<td>1.00</td>
<td>38.61</td>
<td>0.20</td>
<td>0.41</td>
<td>0.13</td>
<td>0.06</td>
<td>0.13</td>
<td>32.07</td>
</tr>
<tr>
<td>8 - Hafsid mortar (pillar)</td>
<td>19.18</td>
<td>2.79</td>
<td>1.01</td>
<td>0.95</td>
<td>40.30</td>
<td>1.04</td>
<td>0.15</td>
<td>0.03</td>
<td>0.16</td>
<td>0.36</td>
<td>34.03</td>
</tr>
<tr>
<td>9 - Actual torba (c)</td>
<td>12.66</td>
<td>2.34</td>
<td>0.86</td>
<td>0.94</td>
<td>44.94</td>
<td>0.44</td>
<td>0.25</td>
<td>n.d.</td>
<td>0.05</td>
<td>n.d.</td>
<td>37.54</td>
</tr>
<tr>
<td>10 - Torba (sector A)</td>
<td>3.47</td>
<td>3.84</td>
<td>0.94</td>
<td>1.46</td>
<td>48.35</td>
<td>0.32</td>
<td>0.45</td>
<td>n.d.</td>
<td>0.10</td>
<td>n.d.</td>
<td>41.07</td>
</tr>
</tbody>
</table>

MnO values were all below 0.01%. * Hydraulic lime masonry from a 19th century building in Lisbon (a) sample collected by Fadila Guedari, Dept. Geology, Tunis Univ.; (b) conduit masonry with carbon fragments (supposedly Hafsid); (c) sample provided by Naidé Ferchiou, Inst. Nat. Patrimoine, Tunis.

Special attention has been focused on water conduits illustrated in fig. 7. Settled over a coarse-grained mortar (opus incertum) building up the conduit basement and walls (specus), stands a layer of well beaten mortar with crushed small aggregates (opus signinum), usually covered with an impervious thin layer of a very fine and compact masonry.

The incorporation of pozzolana in the original impermeable layer (Roman stucco) seems probable in view of the extensive use of this hydraulic natural material (Eittel, 1954). Following this technique for waterproofing the conduit, later rehabilitations have been made using a carbon-rich fine masonry of torba with small red brick and other ceramic fragments (Figueiredo et al., 2001). Fig. 8 depicts such composite layer construction.

Deposited calcitic crusts were chemically studied by using synchrotron radiation to induce X-ray fluorescence at a microscale (µ-SRXRF) with the purpose of ascertaining the presence of trace elements that might be indicative of water provenance (Figueiredo et al., 2000).
Figure 7: View of the water conduit, sector A, at the beginning of the aerial part of the Aqueduct.

Phase analysis by X-ray diffraction to assess the mineralogical constitution of studied mortars showed them to be composed of calcite and quartz, irrespective of the period of manufacture. Additional diffraction peaks of low intensity could be noticed in many diffraction spectra, occasionally allowing for the identification of minor crystalline phases like gypsum or vaterite and aragonite, both calcium carbonate polymorphs that have been quoted as carbonation products of aged mortars incorporating hydraulic components (McConnell, 1960). A slight uplifting of spectrum background indicated the presence of still amorphous material in samples from mortars filling joints between ashlar blocks in apparently Roman pillars, thus suggesting later restoration works.

Simultaneously, an increase in relative intensity of quartz diffraction line at 4.26 Å was remarked. This effect could be explained through the presence of a less common silica phase – tridymite, known to form as a result of crystallization from the glassy phase in volcanic ashes and other pozzolanic materials.

Figure 8: Fallen water conduit at the beginning of section A of the Aqueduct. (a) opus incertum; (b) original opus signinum displaying a surface layer rich in red brick fragments (the stucco is not perceptible under actual magnification); (c) possible restoration (Roman opus or Hafsid masonry?); (d) surface crust of calcite deposited from flowing water.
3.5 Modern and recent rehabilitations

Reconstructions works latter than 1852 (modern, about 1950) were performed with smaller stone blocks and a lime mortar as binder. They are easily noticed as illustrated by fig. 9.

Even easier to identify are a few regrettable restorations conducted in the nineties using Portland cement mortars.

Extensive reconstruction of the monument was in course last May to prevent further structural hazards.

Some works were mainly intended to consolidate dangerous fractures close to some arches and to fix pillars in serious risk of falling down. Fig. 10 illustrates a pillar under rehabilitation were original Roman construction techniques are well evidenced, namely at the conduit base.

In parallel to punctual and urgent interventions, a large-scale rehabilitation of the Aqueduct was under way, definitely burying the testimonies of previous construction and reconstruction techniques (fig. 11).
AN EASY TEST FOR MORTAR TYPE IDENTIFICATION

In the course of present study, a quick-and-easy test was devised for assessing the type of mortar – Roman, Byzantine, Hafsid (medieval) and modern - from a small mass of sample.

A comment is worthwhile making at this point concerning the usefulness and applicability of bulk chemical analysis when studying ancient masonries, mortars and concretes. These composite building materials are quite heterogeneous due both to manufacture techniques and raw materials. It is practically impossible to perform an efficient separation of components in most cases and not seldom the mortars display a significant variability of binder-to-sand ratio.

Chemical data obtained by XRF analysis of samples collected at the aqueduct of Carthage provided values ranging from 91 to 98 (\%(w/w)) for the sums CaO+SiO$_2$+loss-on-ignition (LOI). Accordingly, a simple evaluation of phase constitution could be established on the basis of experimental LOI values.

The results obtained are partially summarized in table 2 and show a good agreement with phase composition calculated from bulk chemical analysis, conjugated with results of phase analysis performed by X-ray diffraction. From the values of calcite-to-quartz ratios listed in last column, a distinction between original Roman mortars (Ca/Qz ~ 1.5) and Byzantine (or Severus?) material (Ca/Qz ~ 0.3-0.8) seems clear.

Conversely, much has still to be understood about medieval mortars that present a large span of Ca/Qz ratios (2.7 - 5.7) – the latter being just the value for an analysed sample of actual torba.

The fine mortar of a water conduit also deserves a comment. The addition of pozzolanic material to a lime-rich mortar seems highly probable in view of a high Ca/Qz ratio when compared to a current Roman mortar.

In a similar way, the value of Ca/Qz ratio for the conduit mortar containing fragments of carbon (ashes) certifies a medieval origin.

Table 2: Phase composition of mortars as estimated from the loss-on-ignition (samples ordered by increasing experimental LOI values)

<table>
<thead>
<tr>
<th>Sample nr. - description / Aqueduct sector in fig. 1</th>
<th>LOI (%(w/w))</th>
<th>Ca</th>
<th>Qz</th>
<th>Ca/Qz</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 - Mortar filling a joint between pillar stones / E</td>
<td>10.87</td>
<td>25</td>
<td>75</td>
<td>0.3</td>
</tr>
<tr>
<td>11 - Mortar filling a joint between roman blocks / C</td>
<td>18.62</td>
<td>43</td>
<td>57</td>
<td>0.8</td>
</tr>
<tr>
<td>12 - Mortar filling a joint between pillar stones / C</td>
<td>14.82</td>
<td>34</td>
<td>66</td>
<td>0.5</td>
</tr>
<tr>
<td>2 - Hydraulic lime masonry (19th century, Lisbon)</td>
<td>14.89</td>
<td>34</td>
<td>66</td>
<td>0.5</td>
</tr>
<tr>
<td>3 - Roman mortar from an opus incertum block / E</td>
<td>26.51</td>
<td>60</td>
<td>40</td>
<td>1.5</td>
</tr>
<tr>
<td>5 - Roman mortar (opus signinum) / A</td>
<td>26.94</td>
<td>61</td>
<td>39</td>
<td>1.6</td>
</tr>
<tr>
<td>13 - mortar (opus incertum) collected at the Bardo</td>
<td>31.81</td>
<td>73</td>
<td>27</td>
<td>2.7</td>
</tr>
<tr>
<td>7 - Conduit mortar with a carbon-rich layer * / C</td>
<td>32.07</td>
<td>73</td>
<td>27</td>
<td>2.7</td>
</tr>
<tr>
<td>6 - Conduit mortar nearby Mohammedia / A</td>
<td>32.86</td>
<td>75</td>
<td>25</td>
<td>3.0</td>
</tr>
<tr>
<td>8 - Hafsid mortar (fallen block at GP3 road / B)</td>
<td>34.03</td>
<td>77</td>
<td>23</td>
<td>3.3</td>
</tr>
<tr>
<td>14 - Hafsid mortar from a fallen block / B</td>
<td>35.79</td>
<td>82</td>
<td>18</td>
<td>4.6</td>
</tr>
<tr>
<td>15 - Hafsid mortar (filling from a pillar) / E</td>
<td>36.29</td>
<td>83</td>
<td>17</td>
<td>4.9</td>
</tr>
<tr>
<td>4 - Water conduit fine mortar (pozzolanic?)</td>
<td>36.60</td>
<td>84</td>
<td>16</td>
<td>5.2</td>
</tr>
<tr>
<td>16 - Hafsid mortar (recent fracture in a pillar) / B</td>
<td>36.69</td>
<td>84</td>
<td>16</td>
<td>5.2</td>
</tr>
<tr>
<td>17 - Hafsid mortar (filling from a pillar) / E</td>
<td>36.79</td>
<td>85</td>
<td>15</td>
<td>5.7</td>
</tr>
<tr>
<td>9 - Torba (sample provided by N. Ferchiou)</td>
<td>37.54</td>
<td>85</td>
<td>15</td>
<td>5.7</td>
</tr>
</tbody>
</table>

* Analysed material free from carbon particles. Ca - Calcite; Qz - Quartz
5 FINAL COMMENTS

There is still much to be learned about materials and techniques employed at the Aqueduct of Carthage since its original Roman construction. Nevertheless, the knowledge the understanding of the monument gained through the study herein briefly described will already allow for a future implementation of rehabilitation measures where the intervention(s) can take into due account the problematic of materials compatibility and durability (Binda et al., 1996). The retrieval of traditional building and manufacture techniques is also highly desirable.

This is the only way of saving this precious architectural (engineering) heritage of the Mediterranean basin for the cultural benefit of generations to come. Otherwise, ad hoc restorations will continue to take place without safeguarding testimonies of the original aqueduct and former historic reconstructions.

ACKNOWLEDGEMENTS

The financial support of EU is gratefully acknowledged, as well as the local support of Tunisian Colleagues – S. Kohsrof, N. Ferchiou and F. Guedari - for conducting two visits and further exchanging information about the Aqueduct. Thanks are also due to other partners of the Concerted Action, particularly the Coordinator J.L. Briansó (Autonomous University of Barcelona/Spain) and the Colleagues A. Alvarez and R. Estrada from UAB.

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