Contributions of ceramic debris to the chronology of restoration works at water conduits of the Roman aqueduct of Carthage

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ABSTRACT The aqueduct of Carthage is a remarkable hydraulic engineering work built under the Roman emperor Hadrian (second century AD). Aerial water conduits run for 17 km in the plane of river Miliane, but most are subterranean. In view of the importance of this Mediterranean patrimony in architectural archaeology, a study on construction and reconstruction materials plus techniques used along Aqueduct history was developed. The results of a non-destructive study undertaken on ceramic debris collected at the aerial water conduit nearby Mohamedia are reported. Photon-based non destructive techniques — laboratory X-ray diffraction (XRD) and fluorescence (XRF), plus synchrotron radiation micro-fluorescence (B-SRXRF) — were applied for phase identification and chemical characterization. Morphologic observation and analytical data place the chronology of these ceramics between the 11th and the 12th century, thus, in accordance with a Hafsid rehabilitation of that section of the aqueduct.

1. Introduction

The aqueduct of Carthage is a remarkable hydraulic engineering work built under the Roman emperor Hadrian (second century AD) to assure water supply to the capital of *Africa Proconsularis* (Ifriqiya, actual Tunisia). Aerial water conduits run for 17 km in the plane of the river Miliane, but most conduits are subterranean.

The first historically registered restoration of Hadrian's Aqueduct took place after seven decades of use (Rakob, 1979; Ferchiou, 1999), possibly following a natural hazard. Two centuries later, aerial water conduits were destroyed at various places when the Vandals conquered Carthage, but the aqueduct has been reconstructed in the sixth century by the Byzantines.

After the Islamic conquest of Carthage, rehabilitation works were extensively conducted by the Fatimids in the 10th century and by the Hafsids along the 13th century.

In view of the importance of this Mediterranean patrimony in architectural archaeology, a study of construction and reconstruction materials plus techniques used in the Aqueduct was developed under an international research project driven by the European Union.

Chemical features were disclosed for differentiating among four mortar types: early Roman, Byzantine, medieval and modern (Figueiredo et al., 2001).

A mineralogical and chemical study on water conduit mortars and deposited calcareous crusts (Figueiredo et al., 2000) has shown that fine debris of the local mosaic industry displaying hydraulic (pozzolanic) properties were originally used by the Roman constructers. Conversely, a carbon-rich argillaceous mixture was used in further restoration works, occasionally enclosing minute ceramic fragments.

Results of a non-destructive study undertaken on ceramic debris collected at the aerial water conduit nearby Mohamedia are herein reported with the aim of contributing to date restoration works performed at that conduit.

2. Materials

Studied ceramic materials are listed in Table 1. These debris were incorporated in water conduit mortars as fine aggregates, being either pale yellow or red ceramics with varied thickness, some partially covered with a very deteriorated yellowish glaze.

TABLE 1
Description of ceramic debris collected at water conduit mortars of the Aqueduct of Carthage nearby Mohamedia.

<table>
<tr><th rowspan="2">Nr.</th><th rowspan="2">Sample abbreviate description</th><th colspan="2">Crystalline phases</th></tr>
<tr><th>Glaze</th><th>Ceramics</th></tr>
<tr><td>1</td><td>Pale yellow decorated ceramics with weathered green glaze</td><td>—</td><td></td></tr>
<tr><td>2</td><td>Pale yellow ceramics, thick green glaze in the inner surface</td><td>Q + C (tr)</td><td>(?)+ Q (tr)</td></tr>
<tr><td>3</td><td>Fragment of red ceramics with green glazed outer surface</td><td colspan="2">—</td></tr>
<tr><td>4</td><td>Thick pale-yellow ceramic, decorative white & purple glaze</td><td colspan="2">—</td></tr>
<tr><td>5</td><td>Pale reddish ceramics; white glaze in the back, green glaze in the face</td><td colspan="2">—</td></tr>
<tr><td>6</td><td>Red ceramic, remains of yellow (face) and green (back) glaze</td><td colspan="2">—</td></tr>
<tr><td>7</td><td>Pale yellowish ceramics with yellow glaze in both surfaces</td><td colspan="2">C > Q</td></tr>
<tr><td>8</td><td>Pale yellowish ceramics with white glaze in both surfaces</td><td colspan="2">—</td></tr>
<tr><td>9</td><td>Red ceramics; yellowish glaze in both surfaces</td><td>—</td><td>Q & C (tr)</td></tr>
<tr><td>10</td><td>Red ceramics with brownish glaze covering the surface</td><td colspan="2">—</td></tr>
<tr><td>11</td><td>Fragment from a vase handle in pale yellow ceramics covered with highly weathered greenish glaze</td><td>—</td><td>G > C > Q</td></tr>
<tr><td>12</td><td>Thick pale yellow ceramics, dark green glaze in one surface</td><td>Glass> C-D, Q, A?</td><td>—</td></tr>
</table>

A, Anhydrite, CaSO;
C, Calcite, $CaCO_3$;
D, Dolomite, $CaMg(CO_3)_2$;
G, Ghelenite-Äkermanite solid solution, $Ca_2(Al,Mg,Fe)(Al,Si)_2O_7$;
Q, Quartz, SiO_2; tr, phase in trace amount;
(?), unidentified phase.

Decorative incisions and borders were still recognizable in two samples (no. 1 and 2 in Fig. 1) and another sample (no. 11) is clearly a fragment of a vase handle. The remaining debris were too small to allow for an useful morphological identification.

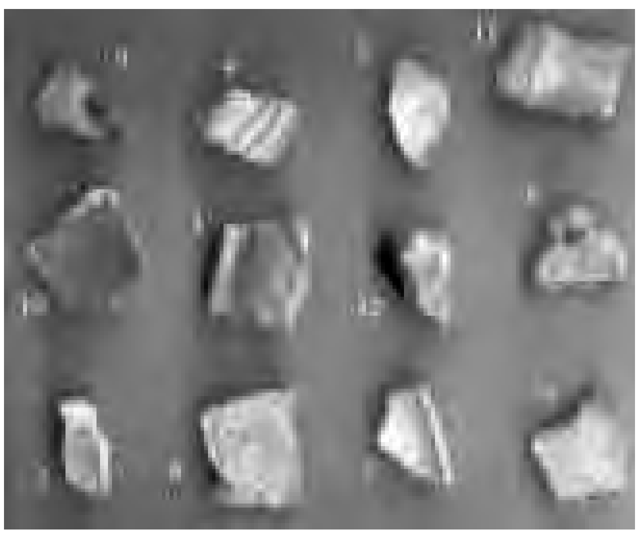

FIG. 1 – Ceramic debris collected at water conduit mortars of the aqueduct of Carthage nearby Mohamedia.

3. Experimental

Exclusively non-destructive methodologies could be used for phase identification and chemical characterization because the ceramic debris had to be returned to the Institute National du Patrimoine in Tunis. Accordingly, the instrumental techniques applied were X-ray diffraction (XRD) for phase identification and X-ray fluorescence (XRF-WDS) spectrometry for bulk chemical constitution, both performed with a laboratory equipment, plus synchrotron radiation micro-fluorescence (B-SRXRF) for elemental analysis, using the photon microprobe of the LURE in Orsay/France.

This synchrotron beam-line (D15 A at the DCI storage ring) is equipped with a Si(Li) detector and the area to irradiate in the sample (down to 0,03 mm^2) is positioned with the aid of a laser-beam by a computer-controlled micrometer stage.

An excitation energy of 21 keV was selected for SRXRF spectra collection. Computer programs developed at the LURE were used for data handling and processing. Peak assignment was based on diagnostic lines - Ka in the X-ray emission spectrum of elements with medium atomic number and La for elements with Z >42.

4. Results and conclusions

Morphological inspection of the most representative fragments suggested that the production of original ceramics could date from the 11th and the 12th centuries. In particular, sample no. 1 (Fig. 1) with a pale greenish glaze in both faces was identified as belonging to a decorated vase, typical from Carthage production in that period (Daoulatli, 1995), therefore in accordance with rehabilitation works historically reported as having been conducted by the Hafsids in the Mohamedia sector of the aqueduct.

The glazes were systematically studied using XRD by directly irradiating the fragment surface. Phase analysis showed variable degrees of devitrification resulting in the crystallization of quartz and occasional development of a carbonate phase (Fig. 2).

Phase composition of the ceramic body denotes incipient firing once the major component phase of recent ceramics — melilite, a solid solution between gehlenite ($Ca_2Al_2SiO_7$) and äkermanite ($Ca_2MgSi_2O_7$) with formula $Ca_2(Al,Mg,Fe)(Si,Al)_2O_7$ — was seldom identified.

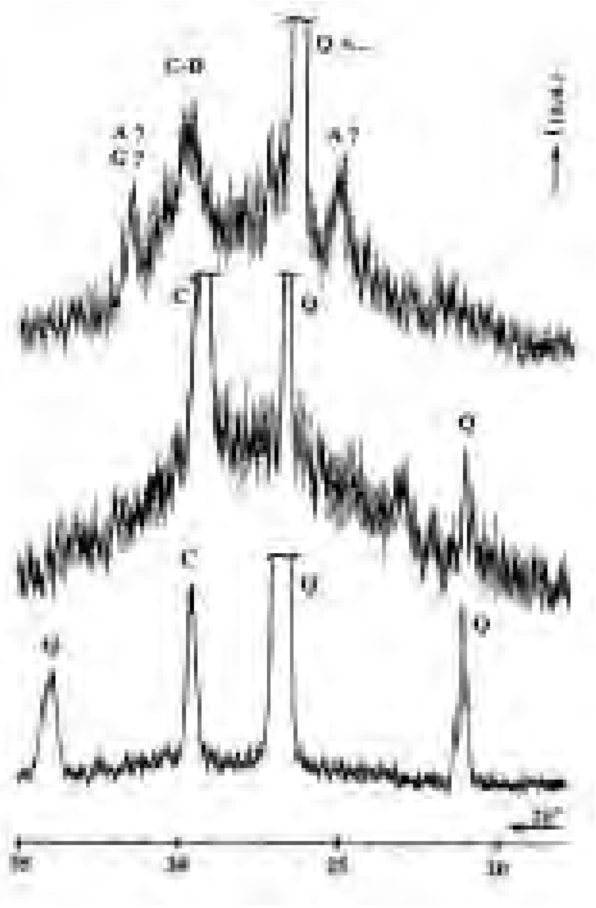

FIG. 2 – X-ray diffraction spectra (Cu ka radiation): a) white ceramic body (nr. 11); b) dark green glaze (nr. 12); c) yellow glaze (nr. 7); d) thick green glaze (nr. 2). A, Anhydrite, $CaSO_4$; C, Calcite, $CaCO_3$; D, Dolomite, $CaMg(CO_3)_2$; G, Ghelenite-Äkermanite solid solution, $Ca_2(Al,Mg,Fe)(Al,Si)_2O_7$; Q, Quartz, SiO_2.

The chemical constitution of the glazes disclosed by synchrotron radiation X-ray fluorescence analysis pointed towards the possibility of establishing characteristics that could contribute to clarify questions concerning the origin or provenance of such ceramics on the basis of relative contents of some major elements (particularly Ca and K) and of the opacifier (SnO_2), fluxes and pigments.

As expected for vitreous decorations dating from the 11th to the 13th century, the studied glazes are all very rich in lead. This conclusion is illustrated by the SRXRF spectra reproduced in Fig. 3.

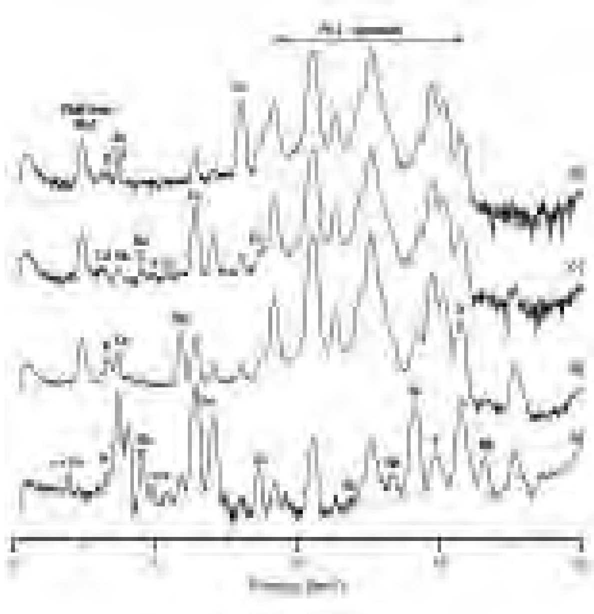

FIG. 3 – *SRXRF* spectra (excitation energy 21 keV, intensity in arbitrary units). Diagnosis lines of identified elements are assigned (Ka or La). a) white ceramic body (no. 11); b) purple glaze (no. 4);); c) yellow glaze over red ceramics (no. 9); d) green glaze (sample no. 1 in Fig. 1). e.p. – escape peak; REE – La, Ce, Nd (in traces).

The highest value of the ratio Sn/Pb — as calculated on the basis of the intensity of diagnosis *L*-lines — was assigned in fragment no. 8; comparatively, low Sn/Pb ratios were found for samples no. 1 (Fig. 3 d), 5 and 9 (Fig. 3 c), denoting a significant decrease in the content of the glaze opacifier in these three fragments.

It was possible to estimate the ratio Pb/Mo despite the difficulties inherent to the quantification of Mo — a possible yellow colouring element — in the presence of a high Pb content under the experimental conditions used for SRXRF spectra collection. Unexpectedly, fragments with yellow glaze displayed a low value, while a relatively high Pb/Mo ratio was found for sample no. 4 with purple decoration, rich in potassium and containing manganese.

Yellow colouring is also hardly ascribed to Sb- or Cd-based pigments because these elements were seldom detected by SRXRF. An exception is the glaze in sample no. 9 as illustrated by the SRXRF spectrum reproduced in Fig. 3 c. Once the studied glazes are all Pb-rich, the yellow tonality may then be due to the incipient formation of lead carbonate, despite such phase having not been detected by XRD.

The ratio Ca/K was found to be higher in pale-yellow ceramics (e.g., sample no. 11, clearly depicted in the corresponding SRXRF spectrum reproduced in Fig. 3 a), while red fragments displayed comparatively higher contents in Ti and in some trace elements — namely, Rb and Zr.

The green colour of some glazes was ascribed to the presence of copper (e.g., in sample no. 1, Fig. 3 d), once no other green-colouring ions were present — like chromium or nickel. Purple colouring of glaze decorations in sample no. 4 is possibly connected with the presence of manganese (possibly in Mn^{6+} state), well expressed in the SRXRF spectrum (Fig. 3 b).

Summarizing: morphological inspection, combined with non-destructive chemical and phase analysis of ceramic debris collected at the Mohamedia sector of the Aqueduct of Carthage has provided a confirmation of the historical suggestion concerning important rehabilitation works conducted by the Hafsids in early medieval times.

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NOTES

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