I.33
Characterization of Roman Mortars and Plasters in Tarsus (Cilicia-Turkey)

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Abstract Tarsus, located in southern Anatolia (Asia Minor), was one of the important urban-centres of the Roman Province Cilicia. This paper aims to provide an extensive characterization of the mortar and plaster samples from several Roman structures in Tarsus. To determine the properties of the samples, a set of chemical, physical, and mechanical tests were carried out and the results were evaluated. The presence of calcareous aggregates required the use of quantitative microscopic methods to determine the mix proportions. The results showed that all samples are lime mortars with limestone and river sand aggregates. It is also evident that gypsum is a constituent of the binder in most of the samples.

1 Introduction

Tarsus, with its long history reaching to Neolithic period, had become an important settlement for Romans from the 1st century B.C. and held its position for centuries [1]. Excavations and surveys have been carried out on the sites enclosing Roman remains since the 1980s, yet there are no extensive studies regarding the characterization of historic mortars and plasters that were used in these constructions. Samples taken from four Roman sites in the city has been the subject of this paper: The Temple (Donuktaş), Roman Road, Roman Bath, and Cleopatra Gate. Studies on the characterization of historic building materials would obviously support and enrich the scientific research conducted on these sites. Furthermore, such studies would lead to a better understanding of the local construction techniques and allow comparisons to similar sites in Anatolia and the Middle East.
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2 Materials and methods

Thirteen mortar and plaster samples were studied from the four historical sites mentioned above. The Temple (known as Donuktaş) is an extensive structure and one of the most important monuments of the Roman era in the city. It has a rectangular plan with dimensions approximately 103 m x 43 m [2]. DT1 and DT2 are the samples taken from the thick (6.50 m) outer walls of the Temple. RY1 and RY3 were collected from the remains surrounding the Roman Road, which was discovered during the excavations in 1993. Samples RH1, RH2, RH3, RH4, RH5, RH6, RH7 were taken from different levels and parts of the Roman Bath, which is also an outstanding structure of large size and noted for its partly standing dome. KLK1 and KLK2 are samples from the Gate, also known as “Cleopatra Gate,” which had been part of the city walls. The locations and general observations of the samples are shown in Table 1. The samples, weighing approximately 60-80 g, were carefully removed with a chisel from the sound parts of the masonry, labelled, and transferred to the laboratory safely in plastic bags. [3]

<table>
<thead>
<tr>
<th>Sample No</th>
<th>Function/ Location</th>
<th>Construction type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>DT1</td>
<td>Masonry mortar / Wall</td>
<td>Rubble stone +mortar</td>
<td>High strength mortar with white coloured binder and sand aggregate under 2 mm</td>
</tr>
<tr>
<td>DT2</td>
<td>Masonry mortar / Wall</td>
<td>Rubble stone +mortar</td>
<td>High strength mortar with white coloured binder and sand aggregate under 2 mm</td>
</tr>
<tr>
<td>RY1</td>
<td>Masonry mortar / Pavement</td>
<td>Rubble stone +mortar</td>
<td>High strength mortar with yellow-white coloured binder and sand aggregate under 2 mm</td>
</tr>
<tr>
<td>RY3</td>
<td>Joint mortar/ Wall</td>
<td>Brick +mortar</td>
<td>Joint mortar with yellow-white coloured binder and fine sand aggregate and organic additives</td>
</tr>
<tr>
<td>RH1</td>
<td>Masonry mortar / Wall</td>
<td>Rubble stone +mortar</td>
<td>High strength mortar with yellow-white coloured binder and sand aggregate under 5 mm</td>
</tr>
<tr>
<td>RH2</td>
<td>Joint mortar/ Wall</td>
<td>Brick +mortar</td>
<td>Joint mortar with yellow-white coloured binder and sand aggregate under 2 mm</td>
</tr>
<tr>
<td>RH3</td>
<td>Plaster/ Wall</td>
<td>Render over brick +mortar wall</td>
<td>Render with white coloured binder and sand aggregates under 2 mm and lime lumps</td>
</tr>
</tbody>
</table>

Table 1 Descriptions of the samples (DT1,DT2 are taken from The Roman Temple, RY1,RY3 are taken from Roman Road, RH1,RH2,RH3,RH4,RH5,RH6,RH7 are taken from Roman Bath, KLK1,KLK2 are taken from Cleopatra Gate)
This project followed methods and standards proposed in former related studies for the characterization of historic mortars and plasters to analyze and evaluate the samples. Chemical analyses, such as acid loss and ignition loss tests, were carried out in order to understand the properties of binder and aggregates and binder/aggregate ratios [4, 5]. The grading curves of the aggregates were determined by means of sieve analysis, and graded aggregates then were observed under stereo-microscope [4, 5]. The mineralogy of the binder and aggregates was carefully determined through polarized-light microscopy after thin section preparations of the samples and X-Ray diffraction (XRD) analyses [6]. Physical tests were conducted to identify the bulk density and porosity of the samples [7, 8]. In order to understand the mechanical properties, mechanical tests were conducted on irregular lumps by using point-load tester [9].

3 Results and discussion

3.1 Physico-mechanical characteristics

The physical and mechanical properties of the samples are presented in Table 2. The density values ranging between 1.15 and 2.21 g/cm³ are typical for historic mortars and plasters [10]. Porosities are rather variable. This variability is mainly related to binder composition as well as different binder/aggregate ratios. [11]

Compressive strength values have been calculated using the equations in the ASTM standard [9]. The only conflict was the strength conversion index values
used in the calculation of the uniaxial compressive strength (MPa), which were designed for rocks. A suitable index for the mortar samples was calculated by using the correlation between uniaxial compressive strength values and point-load strength values. Cube specimens of adequate size (4x4x4 cm) were cut out of mortar lumps from the samples and subjected to the uniaxial compressive strength test. The irregular lumps of the same samples were tested using point-load tester. The ratios of the two values were calculated, and the median was accepted as the strength conversion index.

The visual analyses are compatible with the compressive strength values. The samples evaluated visually as high-strength mortars with less friability have higher values (3.16 MPa- 4.93 MPa), whereas samples indicated as low-strength mortars show lower values (0.55 MPa -1.84 MPa).

<table>
<thead>
<tr>
<th>Sample</th>
<th>Acid loss (%)</th>
<th>B+CA content (%)</th>
<th>B:CA</th>
<th>B:A Ratio</th>
<th>D (g/cm³)</th>
<th>P (%)</th>
<th>CS (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DT1</td>
<td>70.9</td>
<td>2.41</td>
<td>7.39</td>
<td>53.3</td>
<td>1:3</td>
<td>Ct,G Q,C,V</td>
<td>1.71</td>
</tr>
<tr>
<td>DT2</td>
<td>66.7</td>
<td>4.05</td>
<td>20.77</td>
<td>30.2</td>
<td>1:3</td>
<td>Ct,G Q,C,V</td>
<td>2.21</td>
</tr>
<tr>
<td>RY1</td>
<td>70.4</td>
<td>1.62</td>
<td>7.04</td>
<td>60.2</td>
<td>1:3</td>
<td>Ct Q,C,V,S</td>
<td>2.19</td>
</tr>
<tr>
<td>RY3</td>
<td>80.9</td>
<td>1.47</td>
<td>4.74</td>
<td>74.2</td>
<td>1:3</td>
<td>Ct Q,C,V</td>
<td>1.15</td>
</tr>
<tr>
<td>RY1</td>
<td>75.2</td>
<td>1.05</td>
<td>3.15</td>
<td>68.3</td>
<td>1:2</td>
<td>Ct Q,C,F,V</td>
<td>1.99</td>
</tr>
<tr>
<td>RH2</td>
<td>65.5</td>
<td>0.62</td>
<td>2.49</td>
<td>82.6</td>
<td>1:1</td>
<td>Ct Q,C,F,V</td>
<td>1.49</td>
</tr>
<tr>
<td>RH3</td>
<td>45.6</td>
<td>6.53</td>
<td>1.40</td>
<td>65.5</td>
<td>-</td>
<td>Ct,G Q,F,V</td>
<td>1.38</td>
</tr>
<tr>
<td>RH4</td>
<td>71.5</td>
<td>2.05</td>
<td>5.25</td>
<td>61.6</td>
<td>2:3</td>
<td>Ct,G Q,F,C</td>
<td>1.30</td>
</tr>
<tr>
<td>RH5</td>
<td>68.2</td>
<td>8.34</td>
<td>18.14</td>
<td>36.6</td>
<td>1:3</td>
<td>Ct Q,C,F,V,B</td>
<td>1.86</td>
</tr>
<tr>
<td>RH6</td>
<td>64.6</td>
<td>5.29</td>
<td>14.18</td>
<td>42.2</td>
<td>1:3</td>
<td>Ct,G Q,C,F,V</td>
<td>1.78</td>
</tr>
<tr>
<td>RH7</td>
<td>58.0</td>
<td>0.68</td>
<td>5.11</td>
<td>70.0</td>
<td>1:3</td>
<td>Ct Q,C,F,V,B</td>
<td>1.57</td>
</tr>
<tr>
<td>KKL1</td>
<td>18.5*</td>
<td>16.73</td>
<td>3.84</td>
<td>17.9</td>
<td>-</td>
<td>Ct,G V,Cc</td>
<td>1.54</td>
</tr>
<tr>
<td>KKL2</td>
<td>33.0*</td>
<td>15.89</td>
<td>5.91</td>
<td>18.0</td>
<td>2:3</td>
<td>Ct,G V,Cc</td>
<td>1.80</td>
</tr>
</tbody>
</table>

B:Binder, A:Aggregate, CA: Calcareous aggregate, PBW: Physically bound water, SBW: Structurally bound water, D: Bulk density, P: Total porosity, CS: Compressive strength

*: lime, **: gypsum

Ct: Calcite; G: Gypsum; Q: Quartz; V: Volcanic; C: Carbonates/Limestone; S: Shells; F: Feldspars; B: Brick particles and dust, Cc: Charcoal
3.2 Binder identification and characterization

The XRD results indicate that calcite is the main component of the binder of the samples; however, the presence of gypsum, ranging from traces to very strong peaks, is remarkable in most of the samples (Fig. 1). Quartz is present as a result of the fine aggregate grains passed through a 63 µm sieve.

![XRD pattern of sample KLK1](image)

Fig. 1 XRD pattern of sample KLK1 (G: Gypsum-(Ca(SO₄)(H₂O)₂), C:Calcite-Ca(CO₃), Q:Quartz –(SiO₂))

Dissolving samples in HCl acid to determine binder/aggregate ratios of the mortars is a simple and generally used method [12, 13, 14]. On the other hand, the method is not suitable for mortars with calcareous aggregate, since the aggregates also would dissolve in the solution [15]. The investigation of the thin sections under polarized-light microscope indicates the presence of calcareous aggregates in most of the samples. Hence, quantitative microscopic methods were used to determine the mix proportions [16]. The percentages of calcareous aggregates in the mixtures were also defined by comparative evaluation of the results of acid loss and ignition loss tests. The binder/aggregate ratios are variant, including ratios such as 1:1, 2:3, 1:2, and 1:3. The proportions of calcareous aggregates are shown in Table 2.

KLK1 and KLK2 are two samples containing high amounts of gypsum that did not react and dissolve in HCl (10%) acid. These samples were treated by the chemical method stated by Middendorf and Knöfel [17], and gypsum and lime contents of the binder are given separately in Table 2.

3.3 Aggregate identification and characterization

The mineralogical analysis shows that the aggregates are composed of mainly quartz, limestone, feldspar, and volcanic rocks (Fig. 2). Traces of shells and
charcoal are present in several samples. It is apparent that the aggregates are river sand, and they can be classified by colour into two groups: dark-coloured river sand and light-coloured river sand.

![Thin section image under polarized-light microscope of sample RH6 showing mainly limestone and quartz](image)

**Fig. 2** Thin section image under polarized-light microscope of sample RH6 showing mainly limestone and quartz

The grain size distributions of most of the samples are within ideal ranges when compared to the Fuller curve (Figs. 3, 4, 5). The maximum grain size for these samples is 4 mm. The three samples with coarse aggregates (>8 mm) have been taken either from the core of the walls (DT2-DT3) or the sub-level of the pavement (RY1). The plasters and joint mortars contain finer aggregates despite the presence of coarse grains in samples taken from rubble stone masonry.

![Particle size distribution of the aggregates having the maximum size of 16 mm.](image)

**Fig. 3** Particle size distribution of the aggregates having the maximum size of 16 mm.
4 Conclusions

The aim of this study was to identify and characterize the binders and aggregates of mortars used in four different Roman sites in order to understand the construction techniques in Plain Cilicia.

The results indicate that all samples are lime mortars with limestone and river sand aggregates. The XRD results indicate that the samples with different porosity than that of typical lime mortars contain gypsum as a constituent of the binder. Gypsum content ranges from trace amounts to a high quantity. Samples KLK1 and KLK2 contain much higher amounts of gypsum than the others. After a comprehensive research on the historical background of the site and further studies on the other related monuments of the era in the region, it would be appropriate to identify the mortar containing both lime and a high gypsum content either as a mortar type used in the Roman period or to indicate some medieval repairs.

The aggregates are river sands definitely taken from the several rivers of the region. The presence of calcareous aggregates complicates the evaluation of binder/aggregate proportions and the predictions of binder hydraulicity according
to CO$_2$/H$_2$O ratios. Advanced instrumental analysis, such as SEM-EDS analysis, becomes fundamental for samples with calcareous aggregates in order to understand hydraulic additives. Quantitative microscopic analysis is a convenient method to determine mixing ratios in such cases.

It can be stated that aggregate gradation curves of the samples with higher mechanical properties comply with the Fuller curve.

5 References

8. TS EN 1936 (2001) Turkish Standard, Natural stone test methods - Determination of real density and apparent density, and of total and open porosity.