CHARACTERISTICS OF BYZANTINE-PERIOD LIME MORTARS AND PLASTERS FROM THE ANAIA CHURCH (KADIKALESI)

1 INTRODUCTION

Historical lime mortars and plasters were produced using non-hydraulic lime and natural or artificial pozzolanic aggregates. Amorphous silica and alumina in the structures of pozzolans react with lime in the presence of water, and calcium silicate hydrate (CSH) and calcium aluminate hydrates (CAH) that provide hydraulic properties of lime mortars and plasters; mineralogical and chemical compositions, microstructural properties of binders, aggregates and limes; and pozzolanic activities of aggregates were determined using RILEM test methods, XRD, SEM-EDS and TGA. Mortar samples were comprised of natural aggregates whereas lime plasters were made of brick aggregates. Analyses revealed that plasters were slightly less dense and more porous than mortars due to the porous structure of the brick aggregates. All mortars and plasters were hydraulic due to the use of highly reactive pozzolanic aggregates. The basic physical properties, raw-material compositions, mineralogical and chemical compositions of mortars and plasters were found to be similar throughout the construction periods spread over different centuries. These similarities revealed the conscious knowledge of the lime mortar technology during the Byzantine period in Western Anatolia.

Keywords: Byzantine period, hydraulic lime mortar, pozzolan, characterization

In this study, Byzantine-period lime mortars and plasters used in the Anaia Church in Kuşadası- Aydın were examined in order to determine their characteristics and investigate the continuity of the lime mortar technology through centuries in the Anaia Church. The results will also contribute to future conservation studies at the site. Basic physical properties, raw-material compositions and hydraulic properties of lime mortars and plasters; mineralogical and chemical compositions, microstructural properties of binders, aggregates and limes; and pozzolanic activities of aggregates were determined using RILEM test methods, XRD, SEM-EDS and TGA. Mortar samples were comprised of natural aggregates whereas lime plasters were made of brick aggregates. Analyses revealed that plasters were slightly less dense and more porous than mortars due to the porous structure of the brick aggregates. All mortars and plasters were hydraulic due to the use of highly reactive pozzolanic aggregates. The basic physical properties, raw-material compositions, mineralogical and chemical compositions of mortars and plasters were found to be similar throughout the construction periods spread over different centuries. These similarities revealed the conscious knowledge of the lime mortar technology during the Byzantine period in Western Anatolia.

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Ključne besede: bizantinsko obdobje, hidravlična apnena malta, pucolan, karakterizacija

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Church is of great importance as it exhibits an architectural and symbolic value comparable to the monumental structures from Constantinople (Istanbul), the Byzantine capital city.

Three construction periods were determined in the Anaia Church, taking into consideration the spatial organization, construction techniques, materials and architectural elements such as ambo and synthronon (Figure 1). The first construction period (Early Byzantine in the 5–6th centuries) with three naves, a naos, a narthex and atrium spaces covered with a wooden roof was considered.6

There had been three major earthquakes that severely damaged the Church in 1039, 1040 and 1056 with the intensities of grades VII and VIII according to the MSK-64 intensity scale.10 Following these earthquakes, the damaged north and south facade walls of the naos and narthex were rebuilt and strengthened with buttresses during the second construction period between the 11–13th centuries (the Middle Byzantine period).6,11 The Middle Byzantine period additions can be distinguished due to the differences in the wall bonding techniques, recessed brick technique and the separations between the wall joints. The third construction period was determined to be between the 13th and 14th centuries (the Late Byzantine period) due to sharp wall separations and different bonding techniques. In this period, the Church was extended with the baptistery, cisterns and outer narthex. Besides, the naos walls and buttresses, and inner narthex buttresses were built to strengthen the Church structure.6,11

2 EXPERIMENTAL PART

In this study, 9 lime mortar (M) and 5 lime plaster (P) samples were taken from the baptistery (Ba), cistern I (C), cistern II (C), naos (N), outer narthex (O) and substructure (S) of the Anaia Church which were dated to different construction periods (Figure 1). The sampling was carried out on the undeteriorated parts of the Church.

Experimental studies were carried out to determine the basic physical properties, raw material compositions and hydraulic properties of the lime mortars and plasters; mineralogical and chemical compositions, microstructural properties of binders, aggregates and limes; as well as pozzolanic activities of the aggregates via the RILEM test methods, XRD, SEM-EDS and TGA.

The basic physical properties of the lime mortars and plasters were determined with RILEM tests that described their bulk density and porosity values.12 The raw material compositions defined by the lime/aggregate ratio and the particle size distributions of the aggregates were determined by dissolving carbonated lime (CaCO3) with a diluted hydraulic acid (5%), washing, drying and sieving the aggregates. The mineralogical compositions of the finely ground aggregates, binders and limes of less than 53 μm were detected using X-ray diffraction (XRD). XRD analyses were done using a Philips X-Pert Pro X-ray diffractometer with CuKα radiation, operating at 40 kV and 40 mA in a range of 5–60° with a scan speed of 0.08 °/s. The chemical compositions of the aggregates, binders and limes were determined via a scanning electron microscope (SEM) coupled with an X-ray energy dispersive system (EDS). SEM-EDS analyses were carried out with a Philips XL 30S FEG on pellets obtained from powder samples pressed with a pressure of 980.665 MPa (10 t/cm²). Semi-quantitative results for the chemical compositions were obtained by averaging the data derived from three distinct areas of the samples following the k-ratio protocol. The data were collected without using a standard sample. The results were also

![Figure 1: Plan showing the construction periods of the Anaia Church and sample locations](image-url)
used to calculate the hydraulic HI (Equation (1)) and cemen-
tation CI (Equation (2)) indices to identify the hy-
draulicity of the lime lumps.\textsuperscript{13,14}

\[
HI = \frac{\%Al_2O_3 + \%Fe_2O_3 + \%SiO_2}{\%CaO + \%MgO} \quad (1)
\]

\[
CI = \frac{(2.8 \cdot \%SiO_2 + 1.1 \cdot \%Al_2O_3 + 0.7 \cdot \%Fe_2O_3)}{(\%CaO + 1.4 \cdot \%MgO)} \quad (2)
\]

The pozzolanic activities of the aggregates were de-
termined by measuring the differences in electrical con-
ductivity taken before and after the addition of fine ag-
gregates (< 53 μm) into the saturated calcium hydroxide
solution (Ca(OH)\textsubscript{2}).\textsuperscript{15} Electrical-conductivity differences
higher than 40 mS/m indicate that aggregates are pozzolan, while a value of 120 mS/m indicates that ag-
gregates have good pozzolanicity.\textsuperscript{15} Pozzolanic activities
were also evaluated with the chemical compositions us-
ing the ASTM C618-03 standard. According to this stan-
dard, the SiO\textsubscript{2} + Al\textsubscript{2}O\textsubscript{3} + Fe\textsubscript{2}O\textsubscript{3} content of pozzolanic
materials should be above 70 %.\textsuperscript{19}

The hydraulic properties of mortars and plasters were
determined by measuring the differences in electrical con-
ductivity due to the loss of chemically bound water (H\textsubscript{2}O) of hydraulic prod-
ucts between 200–600 °C (H\textsubscript{2}O) and the release of car-
dioxide (CO\textsubscript{2}) via TGA.\textsuperscript{16} Accordingly, a
CO\textsubscript{2}/H\textsubscript{2}O ratio lower than 10 indicates the hydraulic
character of mortar or plaster.

Microstructural properties and morphologies of the
mortars and plasters were specified with a scanning elec-
tron microscope (SEM) coupled with an X-ray energy
dispersive system (EDS) (Philips XL 30S FEG). Analy-
ses were carried out on polished and broken surfaces of
lime mortars using the secondary electron (SE) and
backscattered electron (BSE) modes at different magnifi-
cations in order to examine the general microstructure of
the mortars, properties of pozzolan-binder interfaces and
microstructural characteristics of pozzolans.

### 3 RESULTS AND DISCUSSION

#### 3.1 Basic physical properties and raw-material com-
positions of lime mortars and plasters

Macroscopic investigations revealed that all the lime
mortars consisted of natural aggregates and had a greyish
color, whereas the lime plasters were composed of brick
aggregates and had a pinkish color. All the samples were
sound with a stiff and compact appearance.

The lime mortars with natural aggregates had higher
density and lower porosity of 1.54–1.73 g/cm\textsuperscript{3} and
31–37 %, respectively (\textsuperscript{1}Table 1\textsuperscript{)}. However, the lime plas-
ters with brick aggregates were less dense and more po-
rous with values of 1.30–1.42 g/cm\textsuperscript{3} and 43–47 %, re-
spectively (\textsuperscript{1}Table 1\textsuperscript{}). These differences may be explained
with the porous structure of brick aggregates.\textsuperscript{17,18} It is
known that the porous structure of brick aggregates en-
hancess the resistance of plasters to deterioration, making
them ideal materials, especially for water-related struc-
tures.\textsuperscript{17}

Lime/aggregate ratios by weight were found to be be-
tween 1/3–4/3 for the plasters, 1/2–1/1 for the Early
Byzantine lime mortars, and between 4/3–5/3 for the
Middle and Late Byzantine buttress mortars (\textsuperscript{1}Table 1\textsuperscript{}). These differences might be due to either the use of lime
as the binder or the existence of calcareous based parti-
cles in aggregates. Previous studies showed that a higher
amount of the binder provides better bonding between
the structural components and a greater mechanical
strength in lime mortars.\textsuperscript{20–24} The buttresses were thought
to be added to the Anaia Church after the earthquakes
that took place in the Middle and Late Byzantine peri-
ods.\textsuperscript{6} The mortars used in the construction of the but-
tresses may have been produced with a higher lime/ag-
gregate ratio to provide a higher strength to resist future
earthquakes.

The particle-size distribution of aggregates is another
important feature in defining the raw-material composi-
tions of lime mortars and plasters since it is known that

\begin{table}
\centering
\begin{tabular}{|c|c|c|c|c|c|c|}
\hline
Period & Sample & Location & Function & Aggregate type & Density (g/cm\textsuperscript{3}) & Porosity (%) & Lime/aggregate (by weight) \\
\hline
Early Byzantine & BaM1 & Baptistry wall & Mortar & Natural & 1.72 & 31 & 0.78 \\
& BaM2 & Baptistry wall & Mortar & Natural & 1.63 & 36 & 1.10 \\
& NM2 & Naos wall & Mortar & Natural & 1.66 & 34 & 0.86 \\
& SM1 & Substructure arch & Mortar & Natural & 1.62 & 37 & 1.14 \\
& SM2 & Substructure buttress & Mortar & Natural & 1.72 & 32 & 0.51 \\
& SM3 & Substructure vault & Mortar & Natural & 1.58 & 37 & 1.14 \\
\hline
Middle Byzantine & NM1 & Naos buttress & Mortar & Natural & 1.67 & 35 & 1.44 \\
& NM3 & Naos buttress & Mortar & Natural & 1.73 & 31 & 1.66 \\
& OP1 & Outer narthex wall & Plaster & Brick & 1.31 & 43 & 1.15 \\
& OP2 & Outer narthex wall & Plaster & Brick & 1.42 & 44 & 1.04 \\
& CP1 & Cistern I wall & Plaster & Brick & 1.34 & 48 & 0.72 \\
& CP2 & Cistern I wall & Plaster & Brick & 1.36 & 44 & 1.38 \\
& CP3 & Cistern II wall & Plaster & Brick & 1.30 & 46 & 0.37 \\
& NM4 & Naos buttress & Mortar & Natural & 1.54 & 34 & 1.36 \\
\hline
\end{tabular}
\caption{Physical properties and raw-material compositions of the lime mortars and plasters}
\end{table}
the particle sizes of aggregates effect the physical properties, durability and mechanical strength of mortars. The natural aggregates of Kadıkalesi had higher amounts of aggregates with sizes of > 1180 μm (4–37 %), and also aggregates of 1180–500 μm (8–21 %), 500–250 μm (5–32 %), 250–125 μm (3–14 %), 125–53 μm (2–7 %) by weight, and lower amounts of aggregates of < 53 μm (0.5–2 %) by weight. Within the distribution of brick aggregates, the weight percentages of the aggregates of the sizes > 1180 μm (10–19 %), 500–250 μm (9–17 %), 1180–500 μm (4–12 %) were lower; and the weight percentages of the aggregates with the sizes of 250–125 μm (5–12 %), 125–53 μm (6–12 %) and < 53 μm (0.5–5 %) were higher when compared with the distribution of natural aggregates. Consequently, the aggregates had a wide range of particle sizes, enhancing the mechanical strength of the mortars.

3.2 Characteristics of the lime used in the production of mortars and plasters

White nodules of a few millimeters in the lime mortars and plasters were considered as “lime lumps”, which might have occurred during the mixing of lime and aggregate. Since lime lumps were considered to represent lime, their chemical and mineralogical compositions were accepted to be the same as those of the raw material. In the XRD patterns of the lime lumps from all the periods, only sharp calcite peaks were identified (Figure 2c). The SEM-EDS analysis indicated that lime lumps mainly consisted of large amounts of CaO (97–98 %) and smaller amounts of SiO2 (0.6–1.2 %), MgO (0.6–0.9 %), Na2O (0–0.1 %), Al2O3 (0.4–0.6 %), K2O (0–0.2 %) and were without TiO2 or Fe2O3.

Hydraulic and cementation indices were calculated using the chemical compositions according to the Boynton formula. Hydraulic-index (HI) values lower than 0.1, and cementation-index (CI) values lower than 0.3 demonstrate a non-hydraulic character of lime. HIs and CIs of the lime lumps of the Anaia Church mortars were found to be between 0.01–0.02 and 0.03–0.04, respectively. The mineralogical and chemical compositions and HI and CI values showed that the lime used in the production is non-hydraulic and fat. Micritic calcite crystals smaller than 5 μm were observed in SEM images (Figures 2a and 2b). This may indicate that the lime had been used after a long aging.

3.3 Characteristics of the natural and brick aggregates used in mortars and plasters

The pozzolanic activities of the aggregates were determined by following the electrical conductivity differences in the saturated calcium hydroxide solution before and after the addition of fine samples (< 53 μm). Electrical conductivity differences were found to be between 150–800 mS/m for the natural aggregates, and between 570–709 mS/m for the brick aggregates (Table 2). The

Figure 2: Typical lime lump (SM2 sample) consisting of micritic calcite crystals: a) SEM 5000x, b) SEM 20000x, c) XRD pattern (C: calcite 86-2334)
Table 2: Chemical and mineralogical compositions and electrical-conductivity differences (E.C.D.) of the aggregates

<table>
<thead>
<tr>
<th>Period</th>
<th>Sample</th>
<th>Major oxide compositions (%)</th>
<th>Mineralogical compositions</th>
<th>Pozzolanic activity</th>
<th>E.C.D. (mS/m)</th>
<th>SiO₂+ Al₂O₃+ Fe₂O₃ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Na₂O</td>
<td>MgO</td>
<td>Al₂O₃</td>
<td>SiO₂</td>
<td>K₂O</td>
</tr>
<tr>
<td>Early Byzantine</td>
<td>BaM1</td>
<td>0.60 ± 0.08</td>
<td>2.29 ± 0.02</td>
<td>11.26 ± 0.72</td>
<td>75.77 ± 1.55</td>
<td>2.25 ± 0.10</td>
</tr>
<tr>
<td></td>
<td>BaM2</td>
<td>1.86 ± 0.42</td>
<td>2.23 ± 0.44</td>
<td>12.71 ± 0.72</td>
<td>73.47 ± 1.70</td>
<td>2.77 ± 0.27</td>
</tr>
<tr>
<td></td>
<td>NM2</td>
<td>0.62 ± 0.11</td>
<td>4.21 ± 0.39</td>
<td>16.07 ± 0.24</td>
<td>66.90 ± 0.24</td>
<td>3.20 ± 0.04</td>
</tr>
<tr>
<td></td>
<td>SM1</td>
<td>0.66 ± 0.12</td>
<td>4.39 ± 0.42</td>
<td>15.47 ± 0.54</td>
<td>66.80 ± 1.08</td>
<td>3.19 ± 0.06</td>
</tr>
<tr>
<td></td>
<td>SM2</td>
<td>2.34 ± 0.41</td>
<td>0.80 ± 0.15</td>
<td>16.87 ± 1.32</td>
<td>69.53 ± 0.50</td>
<td>2.83 ± 0.63</td>
</tr>
<tr>
<td></td>
<td>SM3</td>
<td>0.63 ± 0.16</td>
<td>3.02 ± 0.33</td>
<td>12.54 ± 0.15</td>
<td>74.38 ± 0.65</td>
<td>2.79 ± 0.83</td>
</tr>
<tr>
<td>Middle Byzantine</td>
<td>NM1</td>
<td>0.78 ± 0.11</td>
<td>3.27 ± 0.19</td>
<td>14.11 ± 0.35</td>
<td>69.74 ± 0.67</td>
<td>3.40 ± 0.99</td>
</tr>
<tr>
<td></td>
<td>NM3</td>
<td>0.80 ± 0.16</td>
<td>3.02 ± 0.40</td>
<td>13.56 ± 0.83</td>
<td>71.53 ± 1.18</td>
<td>3.11 ± 0.10</td>
</tr>
<tr>
<td></td>
<td>OP1</td>
<td>0.99 ± 0.12</td>
<td>1.35 ± 0.14</td>
<td>13.60 ± 0.30</td>
<td>73.41 ± 0.66</td>
<td>2.89 ± 0.83</td>
</tr>
<tr>
<td>Late Byzantine</td>
<td>OP2</td>
<td>0.99 ± 0.21</td>
<td>2.08 ± 0.14</td>
<td>16.76 ± 0.20</td>
<td>67.20 ± 0.73</td>
<td>3.76 ± 1.23</td>
</tr>
<tr>
<td></td>
<td>CP1</td>
<td>0.52 ± 0.12</td>
<td>2.07 ± 0.10</td>
<td>10.41 ± 0.52</td>
<td>78.15 ± 1.23</td>
<td>2.13 ± 0.20</td>
</tr>
<tr>
<td></td>
<td>CP2</td>
<td>0.49 ± 0.08</td>
<td>2.98 ± 0.18</td>
<td>14.40 ± 0.13</td>
<td>66.12 ± 0.49</td>
<td>3.04 ± 0.10</td>
</tr>
<tr>
<td></td>
<td>CP3</td>
<td>0.47 ± 0.13</td>
<td>3.07 ± 0.12</td>
<td>12.06 ± 0.70</td>
<td>71.90 ± 0.53</td>
<td>2.60 ± 2.96</td>
</tr>
<tr>
<td></td>
<td>NM4</td>
<td>0.37 ± 0.07</td>
<td>2.24 ± 0.17</td>
<td>15.27 ± 0.39</td>
<td>71.48 ± 0.86</td>
<td>3.27 ± 0.85</td>
</tr>
</tbody>
</table>

The number of pluses represents the abundance of mineral peaks. (Q: quartz, A: albite, M: muscovite, Cl: clinopyroxene, O: orthoclase, H: hematite)

Figure 3: TAS diagram showing geochemical origins of the fine natural aggregates
results greater than 120 mS/m revealed that both the natural and brick aggregates used in the mortars and plasters from all periods exhibited highly reactive pozzolanic properties.15

SEM-EDS analyses revealed that the natural aggregates in lime mortars were mainly composed of large amounts of SiO₂ (66.8–75.8 %), moderate amounts of Al₂O₃ (11.3–16.9 %) and smaller amounts of Fe₂O₃ (4.4–7.4 %), MgO (1.8–4.4 %), K₂O (2.2–3.4 %), Na₂O (0.4–2.3 %), CaO (0.6–1.8 %) and TiO₂ (0.6–1.5 %) (Table 2). The SiO₂ + Al₂O₃ + Fe₂O₃ content of the natural aggregates was in a range of 89.75–92.47, indicating their pozzolanic property.19

Possible geochemical classes of fine natural aggregates (< 53 μm) were evaluated using the total alkali-silica (TAS) diagram according to the major oxide compositions.29 According to the TAS diagram, all fine natural aggregates from the Middle and Late Byzantine period and some from the Early Byzantine periods (BaM1, NM2, SM1, SM2) were classified as the dacite group, while two of the Early Byzantine samples (BaM2, SM3) were in the rhyolite group (Figure 3). The fine natural aggregates from the dacite group were composed of quartz, albite, muscovite and clinochlore, while the fine natural aggregates from the rhyolite group also contained orthoclase (Figures 4b and 4d), (Table 2).

The use of volcanic aggregates was a common practice in the ancient Hellenistic, Roman and Byzantine settlements in western Anatolia that has rich igneous rock resources.18,30–32 Future interdisciplinary studies may provide more precise information about the provenance of natural aggregates. Determining the sources will also be necessary for the mortars to be produced for the conservation works in the future.

The chemical compositions of the brick aggregates used in the Middle and Late Byzantine lime plasters mainly consisted of large amounts of SiO₂ (66.1–78.2 %), moderate amounts of Al₂O₃ (10.4–16.8 %) and smaller amounts of Fe₂O₃ (4.0–7.8 %), MgO (1.4–3.1 %), K₂O (2.1–3.8 %), Na₂O (0.5–1.0 %), CaO (0.8–4.1 %) and TiO₂ (0.6–1.0 %) according to SEM-EDS (Table 2). Smaller amounts of CaO indicated that all the brick aggregates were produced from Ca-poor clay sources. The SiO₂ + Al₂O₃ + Fe₂O₃ values were found to be in a range of 88.35–93.14, indicating a pozzolanic property as determined with the electrical-conductivity analysis.19

The XRD analysis demonstrated that the brick aggregates were mostly comprised of quartz, albite and muscovite. Different mineral phases of the brick aggregates were used to predict their firing temperatures. At firing temperatures exceeding 900 °C, amorphous substances begin to disappear and pozzolanic activities are lost. The pres-

Figure 4: SEM images and XRD diffraction patterns of the aggregates: a) brick SEM 2500x, b) brick XRD, c) natural SEM 2500x, d) natural XRD (A: albite 76–1819, Cl: clinochlore 79–1270, H: hematite 87–1166, M: muscovite 84–1302, Q: quartz 85–0798)
ence of mineral phases such as mullite (= 1000 °C), cristobalite (= 1200 °C) or wollastonite (= 900–1050 °C) indicated high firing temperatures. Pozzolanic properties and the absence of high-temperature minerals suggested that the firing temperature did not exceed ≈ 900 °C in all the brick aggregates.

Microstructural properties of the aggregates were determined with SEM-EDS. SEM images showed that brick aggregates had a more porous structure than natural aggregates. The microstructure of the brick aggregates also exhibited little vitrification, confirming low firing temperatures during their production. Both aggregates also exhibited little vitrification, confirming low firing temperatures during their production. Both aggregates were comprised of amorphous particles with an irregular morphology, which can be associated with their pozzolanic properties (Figures 4a and 4c). These amorphous substances could not be determined with the XRD patterns since their non-crystalline structure did not give any indicative peaks.

### 3.4 Characteristics of the binders of mortars and plasters

Fine mortar and plaster matrices, finer than 63 μm, consisted of small grain-sized aggregates and carbonated lime was defined as the "binder". Binders are the parts that provide high strength and hydraulic characteristics to mortars. The SEM-EDS analysis revealed that the binders comprised of natural aggregates had a larger amount of CaO (67.0–87.2 %) and small amounts of SiO2 (6.9–20.3 %) and Al2O3 (2.2–6.4 %), while the binders with brick aggregates consisted of a larger amount of CaO (36.4–64.9 %) and moderate amounts of SiO2 (19.5–34.5 %) and Al2O3 (9.2–14.1 %) (Table 3).

In the XRD diffraction patterns of the binders with natural or brick aggregates, calcite originating from lime; and quartz, albite and muscovite originating from aggregates were determined (Figures 5b and 6b), (Table 3). Mineralogical compositions of the binders indicated similar characteristics throughout different periods. Hydraulic products like calcium silicate hydrates (CSH) and calcium aluminate hydrates (CAH) formed as the result of the reaction between the pozzolanic aggregates and lime binder could not be detected due to their amorphous structure.

Hydraulic properties of the binders were determined by calculating the percentages of weight losses between 200–600 °C and 600–900 °C, detected via TGA. The weight losses between 200–600 °C were due to structur-
ally bound water (H₂O) of the hydraulic products (CSH, CAH), while the losses between 600–900 °C were caused by a CO₂ release during the decomposition of carbonate lime. The CO₂/H₂O ratio between 1 and 10 indicated the hydraulic character of the mortars. 16 The CO₂/H₂O ratios were found to be between 5.2–10.0 by weight for the mortars composed of natural aggregates and between 2.7–4.8 by weight for the lime plasters composed of brick aggregates (Table 3). These results revealed that all the binders exhibited hydraulic properties. The hydraulicity of the binders may be attributed to the use of highly reactive natural and artificial pozzolanic aggregates in their production.

SEM images of the binders showed strong bonding between the lime and aggregates, which was an indicator of a pozzolanic reaction and hydraulic properties. Also, there was no microcrack formation or irregularity at the interfaces (Figures 5a and 6a) (Tables 4 and 5).
4 CONCLUSIONS

Byzantine-period lime mortars and plasters used in different construction phases of the Anaia Church are stiff and compact materials that survived for centuries, preserving their original characteristics. All the lime mortars were produced from natural aggregates of a volcanic origin with lime/aggregate ratios between 1/2–5/3, whereas all the lime plasters consisted of brick aggregates with lime/aggregate ratios between 1/3–4/3. The only exception was the mortars used for the buttresses added to the church to strengthen its structure after the earthquakes in the 11th century, with a higher lime/aggregate ratio of 4/3–5/3.

Non-hydraulic and fat lime had been used for the mortar and plaster production after a long aging period. Natural aggregates of mortars were probably mainly obtained from the local rhyolite and dacite sources. Brick aggregates were manufactured from Ca-poor clays at low firing temperatures between 800–900 °C. All the natural and brick aggregates used in the mortars and plasters exhibited highly reactive pozzolanic properties. Due to the use of pozzolanic aggregates in their production, mortars and plasters had hydraulic characteristics.

It is remarkable that the basic physical properties, raw-material compositions, chemical and mineralogical compositions of the lime mortars and plasters used in different construction periods of the Anaia Church, which is a Byzantine structure, were similar and have not changed over the centuries. These similarities reveal that the knowledge of the use of the local raw-material resources and the mortar production technology was intentionally transferred over the centuries during the Byzantine period.

The production of new lime mortars and plasters to be used in the future conservation works in the Anaia Church should be physically, chemically and minerallogically compatible with the original mortar and plaster properties determined by this study. For this purpose, possible local lime, natural pozzolan and clay sources should be investigated and their suitability for the use in the mortar and plaster production should be fully examined. Furthermore, special production of brick aggregates should be carried out and these aggregates should be fired at low temperatures.

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