Restoration techniques using 1930's Portland cements at Porte de l'Est in the Roman city-wall of Aventicum, Switzerland

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Abstract

Historic masonries using hydraulic cements were extensively used for construction and restoration at the turn of the 20th century. Different cements such as Roman (or natural) cements, natural Portland cements or dolomitic cements, were used according to their local availability and the choice or experience of architects and workers. The Roman city Aventicum (now Avenches) was built at the beginning of the 1st century AD. Unique in Switzerland and classified as of national importance, the Roman wall of Aventicum was built during the second half of the 1st century AD. 5.5 kilometres long, this vast perimeter crowned the capital of the Helvetians and showed the power of Rome. Subsequent to a large campaign of archaeological and restoration works initiated from 1845, the Porte de l'Est, one of the four original main entrances of the city, was restored in the 1930s with the construction of a protection wall above the Roman vestiges. The walls were made of artificial and joined stones composed of concrete and finishing mortar imitating local natural stones. This study presents first the technological details of the artificial stones made of different natural Portland cements. Although the cements differ in the sulfate content, the microscopy exams show very good compatibility properties within the successive layers with a strong interface and no internal sulfate reaction leading to degradation.

Introduction

The use of Portland cement is controversial because of reversibility issues in conservation and restoration of cultural heritage objects. The incompatibility issues of Portland-type cement materials applied on stones or joints are usually stated by conservators and the scientific community [1-5]. Cement concrete and mortars are identified in many objects built and restored between 1850-1950, during which they were preferentially used for economical (rapid production compared to stone art) and technical (strength, presumable resistance to freezing and aggressive environments) purposes. The durability of Portland cement-based materials is illustrated in many historic structures [6-8] or stone imitation works [9]. This article presents the case of Porte de l'Est in Avenches (CH), where the 1930's conservation strategy of Roman vestiges mostly used Portland cement to produce protection walls and aesthetic mortars. The article details the techniques used and the characterization of concrete and mortars based on microscopy.

Historical context

During the 1st century AD, the colony of Aventicum manifested its status as a city by acquiring a wall more than 5.5 km long, 7 m high, including battlements, and 2.4 m wide. The structure was equipped with seventy-three towers, a round path with several entrances, including two monumental gates. It still defines the territory occupied by the former capital of the Helvetians [10]. With its impressive dimensions and its layout still visible in many places, the wall is one of the most important Roman buildings in Switzerland. The monument has recently been the subject of an in-depth study to consider its restoration [9].

In 1885, the Pro Aventico Association was founded to highlight Roman monuments and monitor archaeological excavations. Three architects followed one another in different stages of wall restoration (1898 Mayor, 1907 Naef, 1916 Bosset). From 1899, particular care was taken to preserve the original wall (the restorations should not be confused with Roman masonry). The joints were distinguished by a different treatment and the boundaries were marked by a mortar tinted "red ochre" [11]. The execution and reconstruction of successive cement screeds protecting the wall heads were also widely discussed by the protagonists [11-14]. After several tests, regulations were developed requiring that the walls must keep their ruined appearance and the roof, while playing its protective role, must be limited to representing a horizontal section of the wall while remaining aesthetic. At Porte de l'Est, the elevations were first restored in natural stone rubble -Jura limestone rubble for the smaller elevation and Jura limestone with shell sandstone blocks for the larger- before being raised with artificial stone. The distinction between the original part and restitution was then ensured by the distinction between the building materials.

In 1916, a systematic phase of raising the walls of Porte de l'Est began under the direction of L. Bosset. The first mention of artificial stone was made in his diary from June 6 to 14, 1916[10]. A first imitation stone vault was cast on a semi-circular formwork in 1917 [14]. Its raw surfaces were then cut, and false joints were carved to give it the appearance of the original stone apparatus (Figure 1a). From 1925 to 1929, the first major works using exclusively artificial stone were carried out. The documents describing these interventions best are the archival photographs in which we can see the construction of the buttresses in large apparatus of the corridors of the door (1925) imitating shell sandstone (Figure 1b) and the pillars of the tower (1926) imitatiing Jura limestone (Figure 1c and 1d), as well as the laying of imitations of yellow limestone rubble for the small apparatus.

The use of artificial stone having then become relevant (cast vaults, rubble imitating Jura limestone, large blocks imitating shell sandstone or Jura limestone), all masonry was therefore restored and enhanced with this material. Only the protective screeds were still made of natural stones. 1935 marked the end of the reconstruction work on Porte de l'Est. No information is given on the origin of the binders and aggregates used during the work. The restoration work on the Roman theatre in Aventicum was also carried out by the same

[10] *« On prépare des moellons de parement et on en fabrique en pierre artificielle »[14]*

company, Righetti, under Bosset's direction in 1926-1930. The techniques used on these two sites were different, but it is believed that the same cement suppliers, mentioned in [6], may have been used for Porte de l'Est. The technique of artificial stone casting is well documented.

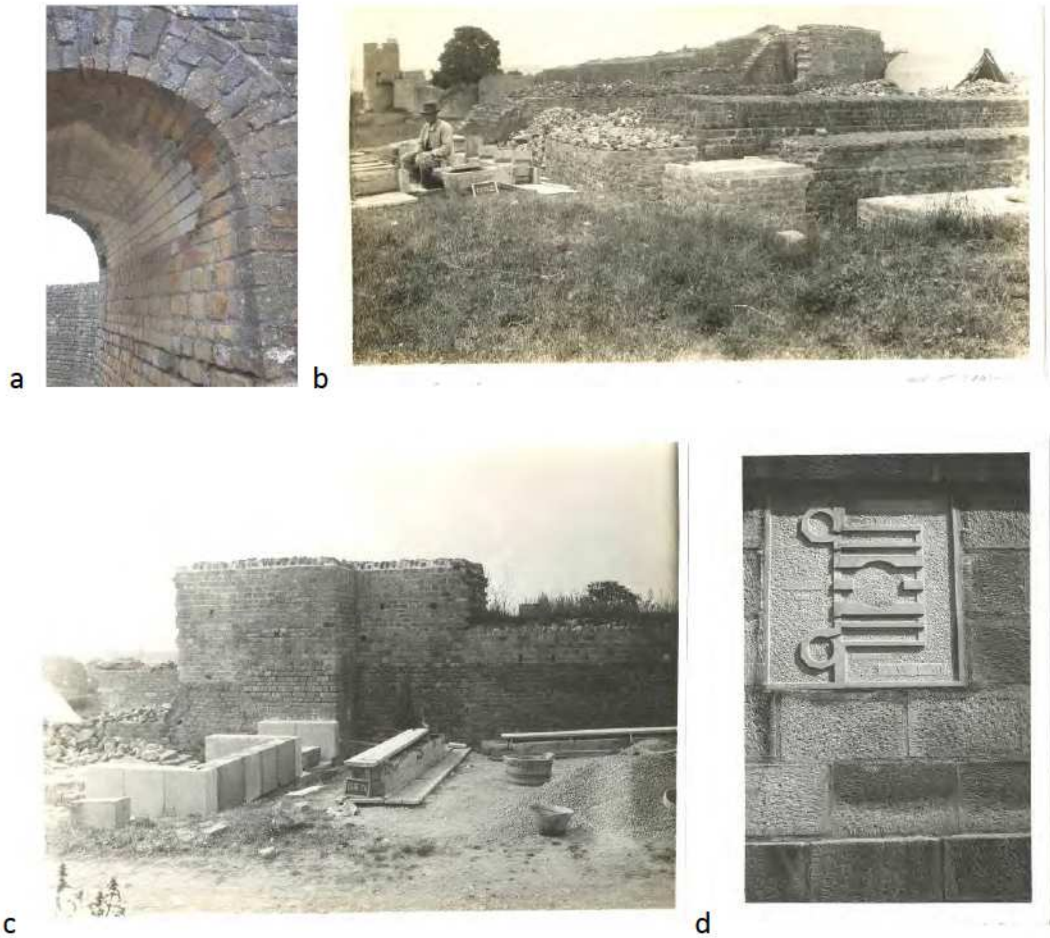
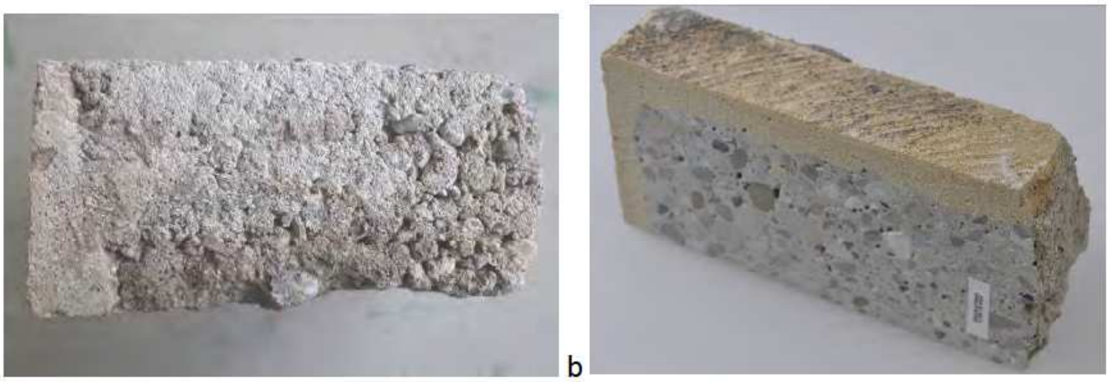


Figure 1. Application of artificial stones in Aventicum, a: stone vault (1917), b: large apparatus buttresses imitating shell sandstone (1925), c: pillars of the tower imitating Jura limestone (1926), d: artificial stone imitating Jura limestone (1935)

The procedure consisted in vigorously compacting a thin and fairly dry mortar against one or more of the vertical walls of a formwork, depending on whether ashlar stones (Figure 2a) or corner stones (Figure 2b) were produced. This 2-3 cm thick compact layer of surface mortar was tinted in the mass so that it could be cut to give it the appearance and relief of the original stones (Figure 1d and Figure 2b). A layer of coarse concrete was then poured into the mould, which tightens the surface cement and holds it in place during setting (Figure 1b, Figure 1c, Figure 2). Modules were manufactured to clamp up to six blocks of the correct size. The photographs from 1925-1926 illustrate the process of making large masonry blocks imitating shell sandstone (Figure 1b) and Jura limestone (Figure 1c); in Figure 1c, the restitution of one of the pedestals is illustrated by the blocks of its base, ready to receive the second level: the simultaneous formwork of six blocks covered with a board and the aggregates with screens. A large formwork allowing the manufacture of at least ten blocks at a time is also observed in the background.



a b

Figure 2. a: ashlar stone, b: corner stone

Samples and methods

In 2012, four cores (35 mm diameter and approx. 130 mm long), labelled M1 to M4, were sampled from different artificial stones. Figure 3 shows the cross section of the cut cores where the sections prepared for microscopy are marked by red dashed lines. The four samples present two or three different layers, each with a distinct texture (grain size, colour), between which interface appears more or less clearly. The areas of interest, shown by red squares in Figure 3, were sampled and impregnated with epoxy resin to create polished sections for microscopic analyses. A Philips Quanta 200 microscope was used for structural analysis of mortars. EDX microanalyses were performed by a Bruker AXS Quantax spectrometer, for chemical identification (point and elementary distribution) of the main phases observed. No analysis was performed on the core of M4, its composition having been considered comparable to that of M1 and M2.

Microscopy results

The analysis focused on the porosity, the nature of cement and the hydration products of the two or three presentative layers and interfaces of the samples M1 to M3.

Sample M1 and M2

Figure 5 shows the difference of porosity observed though the samples M1 and M2. The porosity progressively decreases from the core of concrete (layer 3) to the finishing layer (layer 1). The latter appears relatively porous, with many compaction voids related to casting and poorly dense hydration products.

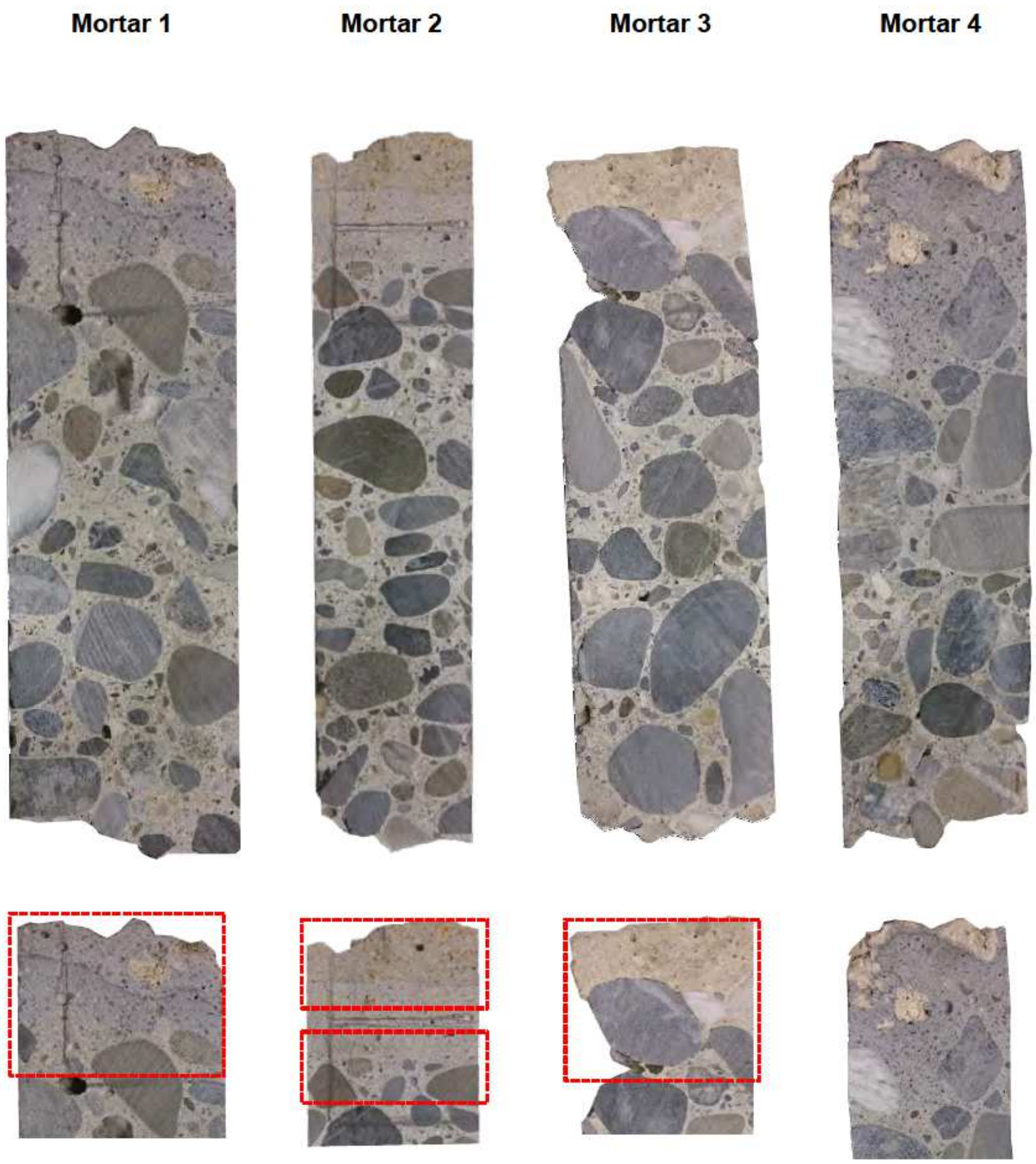


Figure 3. Cross section of samples M1 to M4

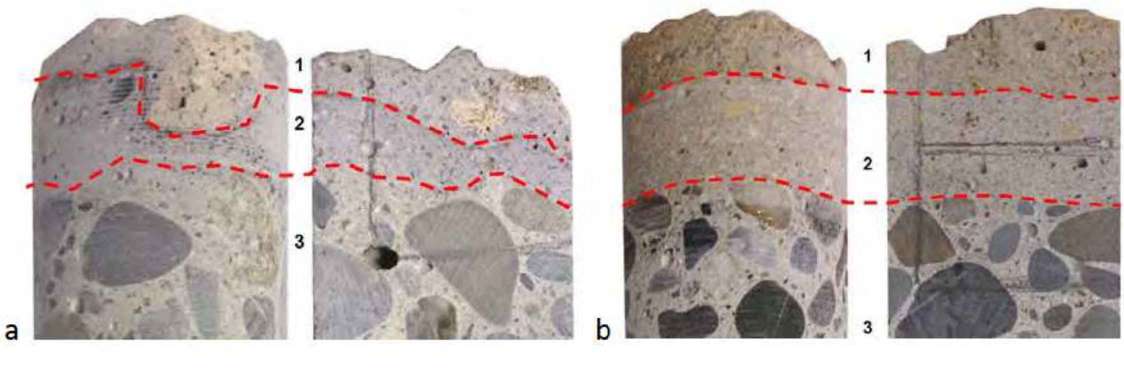
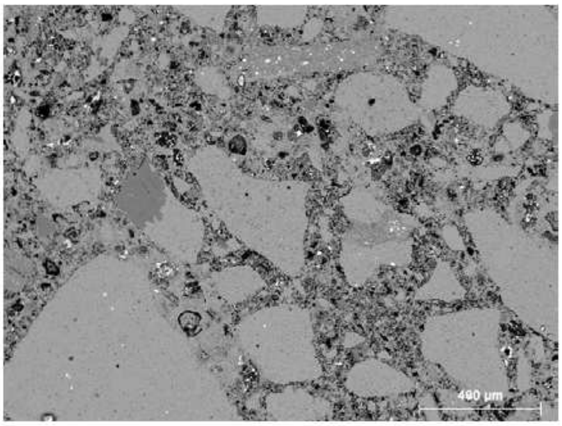
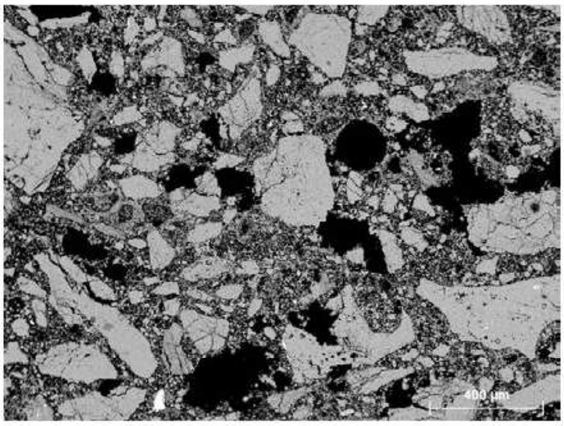


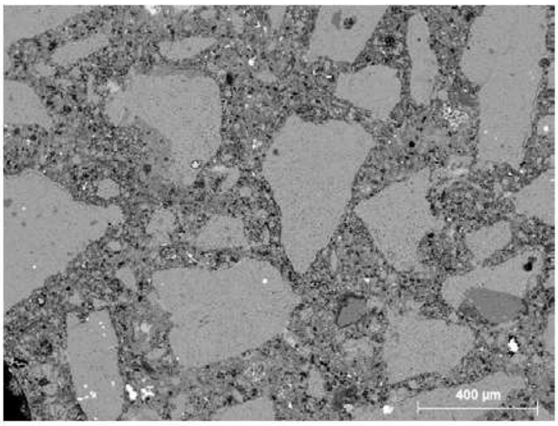
Figure 4. Finishing mortar (1), bonding mortar (2) core (3), a: sample M1, b: sample M2



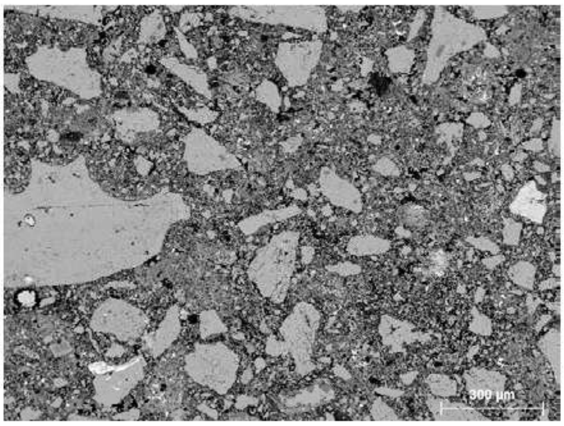
Layer1: finishing mortar M1



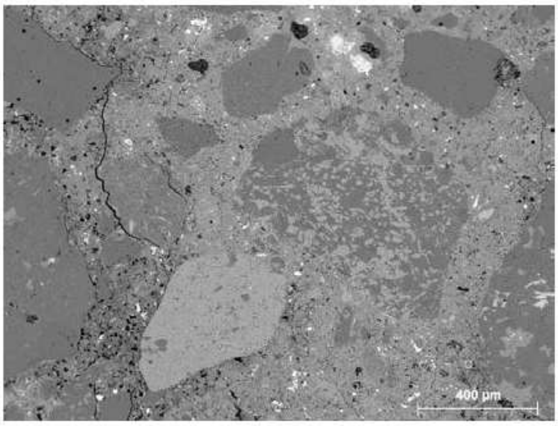
Layer1: finishing mortar M2



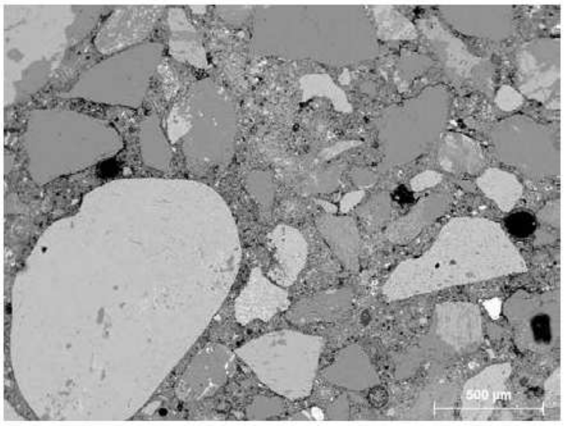
Layer 2: bonding layer M1



Layer 2: bonding layer M2



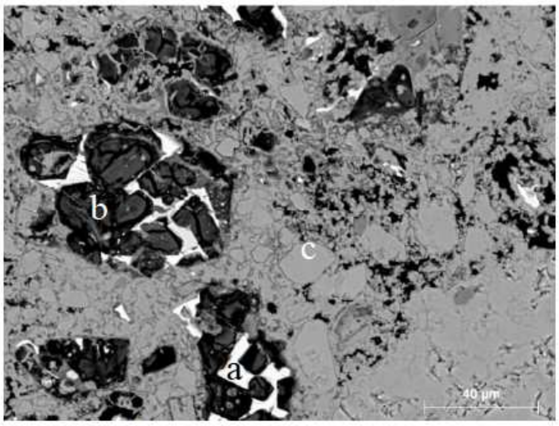
Layer 3: core in concrete M1

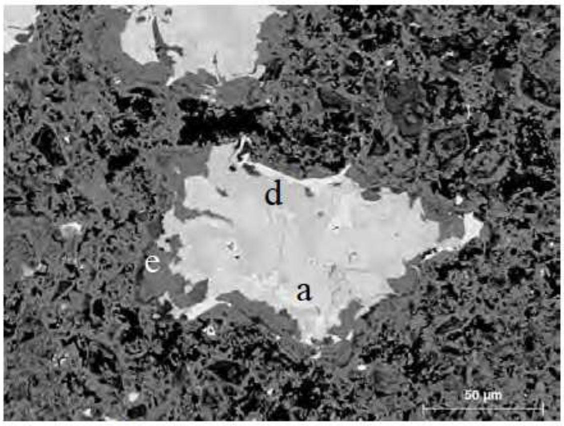


Layer 3: core in concrete M2

Figure 4. Microstructure and porosity of the different layers, sample M1 and M2

Figure 6 details presentative cement grains observed in the different layers of samples M1 and M2. Results are interpreted for each layer in the dedicated section of the article. The distribution of calcium, silica, aluminium and sulfur on both sides of the interfaces (marked by the red dashed line) between the different layers are given in the elemental mapping for sample M1 and M2 (Figure 7 and Figure 8, respectively). The mappings mainly illustrate the difference in the sulfur content between the finishing and the bonding mortars. The latter contains the highest sulfur content among the three materials. The difference in Ca, Si and Al distribution mainly originates from the nature of the aggregates.

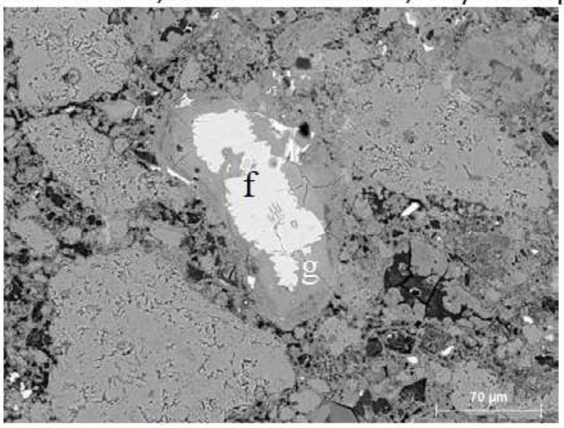


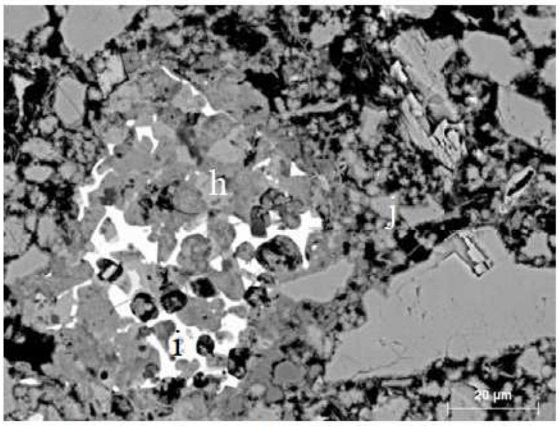


Layer 1: finishing mortar M1

Layer 1: finishing mortar M2

a :unhydrated ferrite, b: silica gel subsequent to decalcified calcium silicates, c: powder from addition of crushed stone, d: calcium aluminates, e: hydration products C-S-H

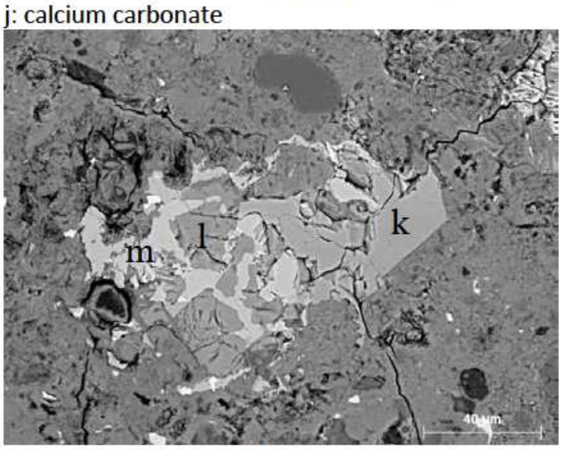


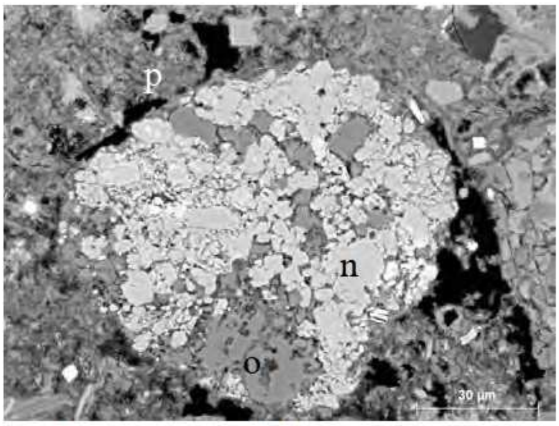


Layer 2: bonding mortar M1

Layer 2: bonding mortar M2

F: tricalcium silicates C_3S, g: hydration products C-S-H, h: anhydrous phase Ca-Al-Si, i: unhydrated ferrite, j: calcium carbonate





Layer 3: core in concrete M1

Layer 3: core in concrete M2

k: phase from the melilites group (possibly alumino-akermanite from the chemical analysis), l: calcined clay with wt% composition K_{26}-Si_{17}-Al_{17}-O_{41}, m: tricalcium silicates C_3S, n: phases with wt% composition Ca_{18}-Si_{17}-Al_{13}-Fe_9-O_{43} , o: non calcined albite, p: C-S-H

Figure 6. Details on cement grains of the different layers, sample M1 and M2

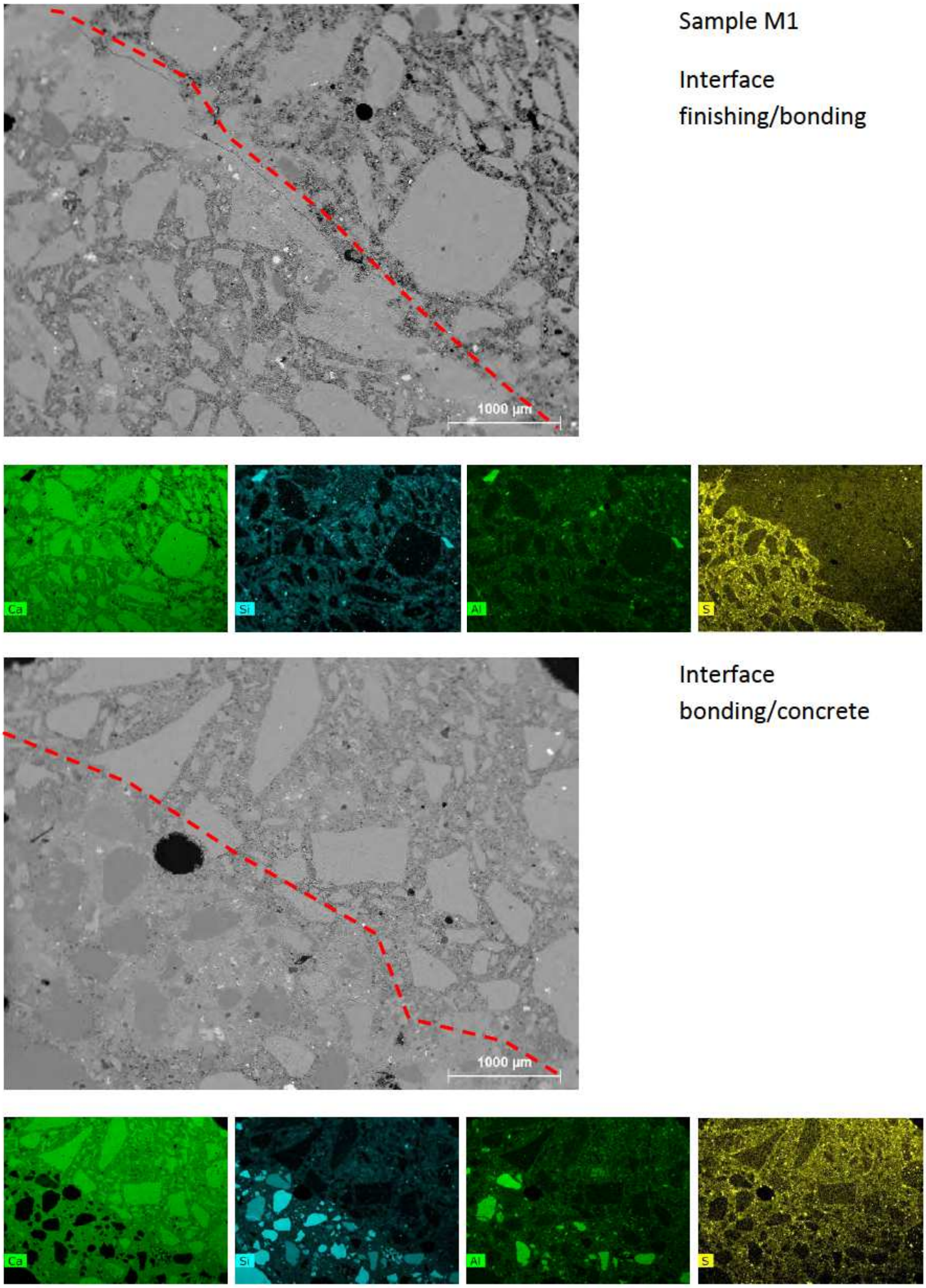


Figure 7. Interface between the different layers, including elemental mapping (Ca, Si, Al, S), sample M1

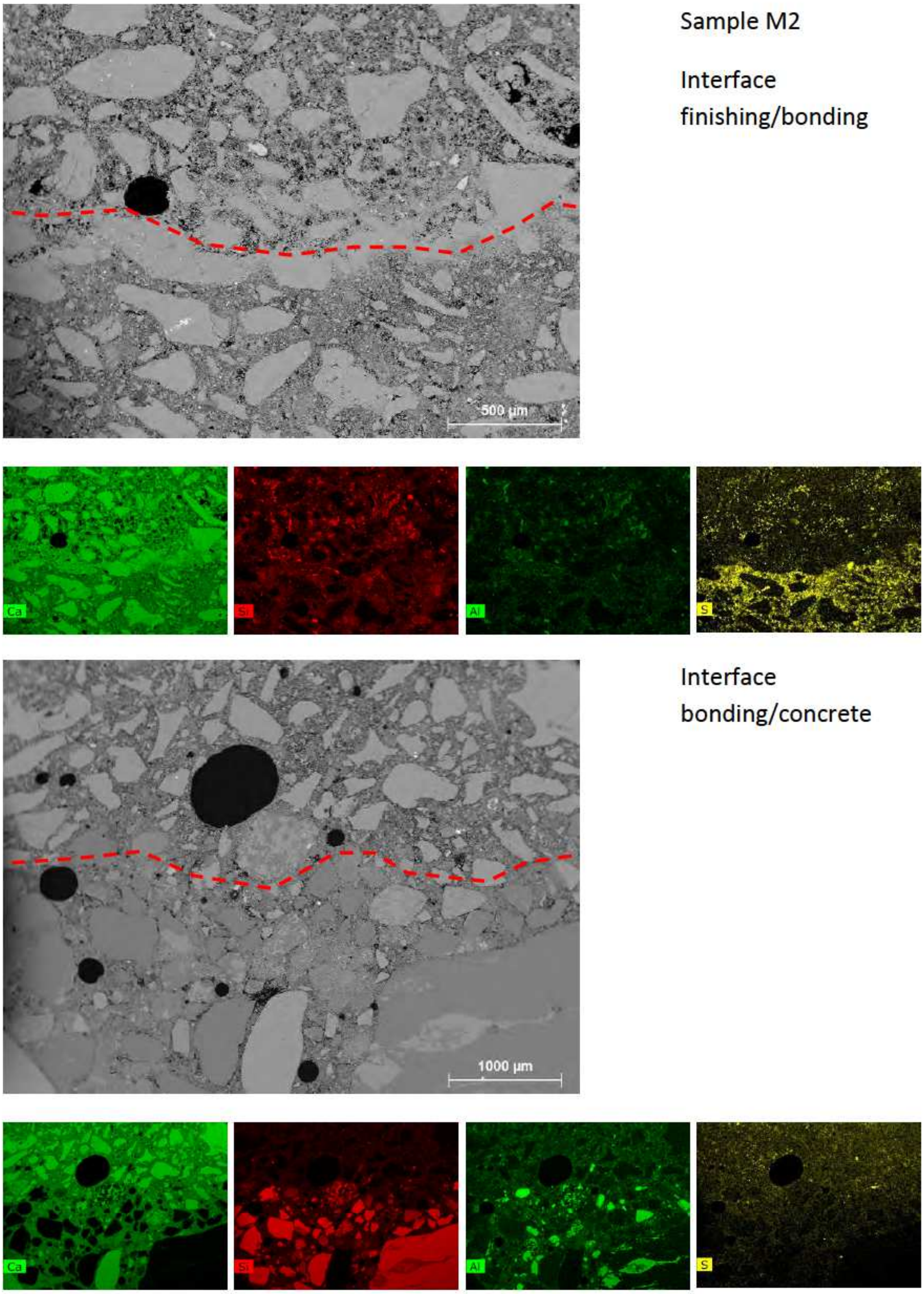


Figure 8. Interface between the different layers, including elemental mapping (Ca, Si, Al, S), sample M2

The analysis only focused on the finishing mortars, assuming that the concrete core is comparable to that of samples M1 and M2. A difference of porosity is observed within the finishing layer (Figure 10). This results from the presence of an existing crack at the interface with concrete, leading to strong leaching and carbonation of hydration products and remnants of anhydrous cement grains, in which the calcium silicates decalcified to form an amorphous silica gel (Figure 11, caption d).

Sample M3

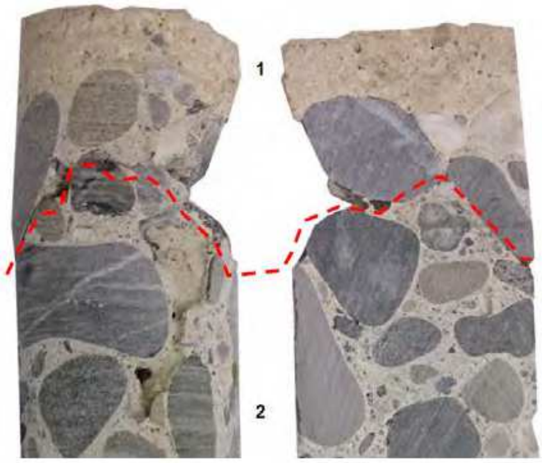


Figure 9. Finishing layer (1) and core (2), sample M3

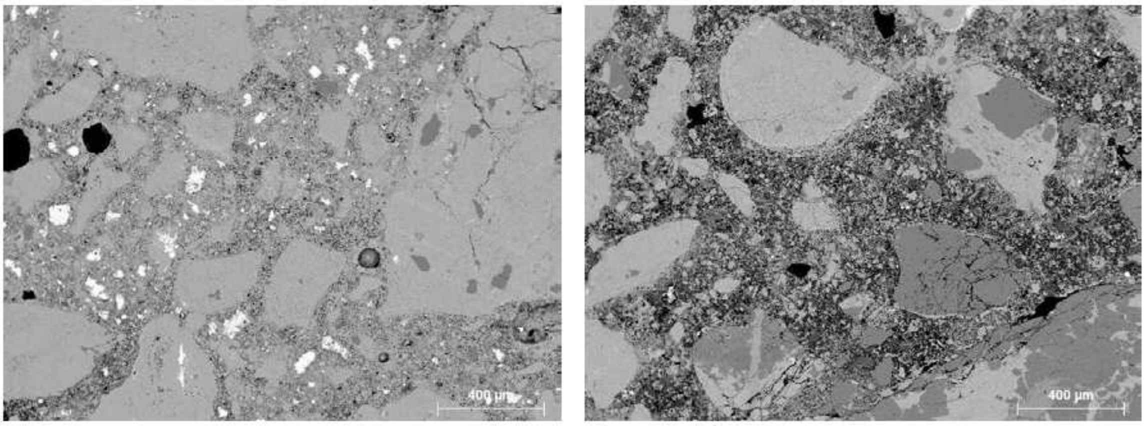
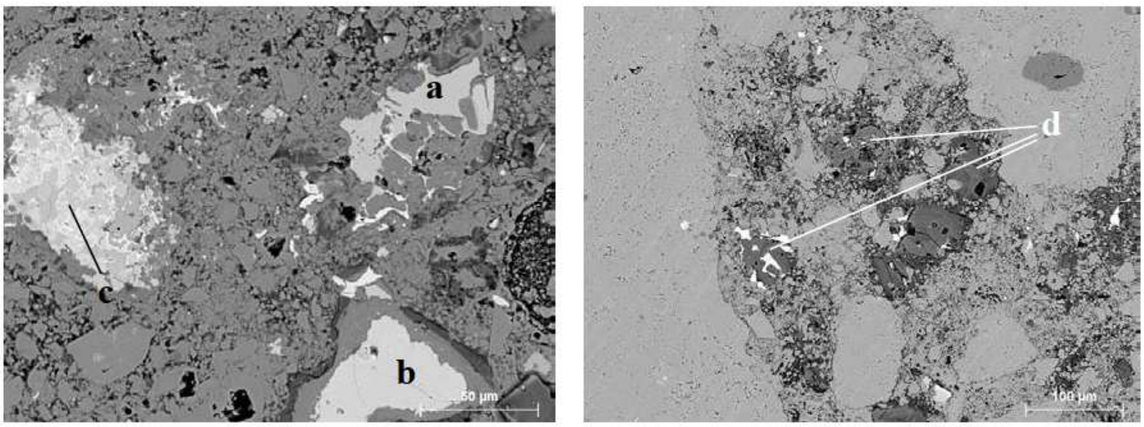


Figure 10. Microstructure and porosity within the finishing layer, sample M3, left: external area, right: near cracked interface with concrete



a: calcium aluminium C_4A type, b: calcium silicate C_2S, c: grain with C_2A, C-A-(S) and ferrite, d: decalcified C_2S in a cement grains

Figure 11. Details on cement grains within the finishing mortar, sample M3. Left: external area, right: near-cracked interface with concrete

Interpretations

Based on the microscopic observations, the cementitious materials used to produce artificial stones are interpreted below.

The inner core is composed of a concrete with a grain size of 0-2 cm, composed of Portland-type cement and mainly siliceous aggregates. This concrete has a sound and dense microstructure, without any sign of degradation. Many anhydrous cement grains are still present in the matrix. The cement has a mineralogy comparable to that of modern Portland cements, with calcium silicate phases (remaining C_2S) included in solid solutions of the calcium aluminate type (C_3A, C_2A, C_4AF) and the presence of thick and dense inner C-S-H at the boundary.

The intermediate bonding mortar is observed in samples M1 and M2. This mortar remains fairly porous despite the high degree of cement hydration. Finely ground residue (shred from shell sandstone with a calcareous matrix) is evenly distributed in the mortar. The cement is referred to as Portland type because of the high temperatures (>1300°C) identified. The composition of the cement grains is identical to that of the cement used for micro-concrete and finishing mortar. However, the elementary mapping of sulfur (Figure 7 and Figure 8 clearly indicates a sulfate-bearing cement, comparable to modern Portland cements. Within the bonding mortar, sulfur is homogeneously distributed, incorporated into the hydrated phases of the cement (in the form of calcium mono-sulfo-aluminate and calcium tri-sulfo-aluminate ettringite) covering the inner walls of the trapped air pores. The elementary mapping indicates a clear interface, without any diffusion of sulfur through the different layers.

A tinted finishing mortar, including stone powder to imitate local natural materials, covers the bonding mortar (samples M1 and M2) or is directly applied on the concrete (sample M3). In the three samples, the finishing mortar is made of Portland cement. Unlike the concrete and the finishing mortar, this cement is free of sulfates (clear interface without diffusion of sulfur, highlighted by elemental mapping). The microstructure of the finishing mortar is more porous in comparison with the subsurface layers. A large reserve of cement grains is visible and decalcified under the effect of atmospheric carbonation and ambient humidity. The decalcification of calcium silicates yields to a silica gel and a ferrite phase skeleton. Such carbonation level can result from the low compactness of the mortar. The granular filler of the mortar is composed of siliceous limestone sand and the same crushed limestone as that of the bonding mortar.

Portland cement phases predominate in the three different layers. Seldom cement grains with remnants of calcium carbonate, non-calcined clay materials, or albite, possibly indicate a single source of marl calcined in a shaft kiln although rotary kilns were introduced in 1904 in the Swiss production of artificial Portland cements [16].

Figure 5 indicates a porosity progressively decreasing from the core (concrete) to the finishing mortar (except for sample M3, subject to leaching and carbonation subsequent to cracking at the interface). This difference probably originates from the casting and finishing techniques. The finishing mortar was first cast as thin layers in the formworks. A dry composition of this mortar, strongly compacted against the formwork walls, can explain the nature and shape of pores observed in the samples. The three layers (micro-concrete, bonding, finishing) are compatible and adhere to each other. The presence of progressively porous mortars on a denser concrete structure contributes to the stability of the interfaces and protects the masonry structure [1]. The mortars and concrete are chemically compatible, even though the presence of sulfates is detected and confined to the intermediate bonding mortar only. No diffusion of sulfates through the inner micro-concrete or the outer finishing mortar is observed. Similarly, no degradation related to an internal sulfate reaction between the different layers is identified.

Conclusions

This study presents a consistent application of the first "Portland" cements for the 1930’s conservation of Roman vestiges of the Porte de l’Est in Avenches. The restoration ethics of Jacques Mayor and his successors Albert Naef and Louis Bosset is remarkable for the end of the 19th century, a period when national and international charters and conventions have not yet been established. There is early implementation of the principles of the Venice Charter (1963), in particular Articles 9 and 12 on authenticity. The technique of artificial stones was systematically used to imitate local sandstone and limestone and recreate parts of walls designed on the basis of archaeological works. The overall durability of the walls is good despite local degradations due to rising dampness. At least two types of Portland cements were used and differentiated by the initial sulfate content. Sulfate is predominantly present in the bonding mortars and in lesser amounts in the core made of concrete. The choice of cement could have been motivated by the setting regulation required for the cast of concrete and the bonding layer. In contrast, the finishing layer contains no sulfate, suggesting the use of rapid cement to produce the finishing render imitating stone. The physical and chemical compatibility criteria are verified between the different concrete and mortars. The microscopy analysis reveals both a sound microstructure of each layer of the wall (core and external mortars) and compatibility at their interface, with good physical adherence and no diffusion of sulfate. Local masonry works are planned to restore local surfaces of walls suffering from rising dampness. Roman cement mortar with addition of tuff-stone is suggested to create a new finishing mortar.

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