Journal of Cultural Heritage xxx (2019) xxx–xxx

Available online at
ScienceDirect
www.sciencedirect.com

Elsevier Masson France
EM|consulte
www.em-consulte.com/en

Original article

The ancient *pozzolanic* mortars of the Thermal complex of Baia (*Campi Flegrei*, Italy)☆

Concetta Rispoli[a,*], Alberto De Bonis[a], Vincenza Guarino[a], Sossio Fabio Graziano[a,b], Claudia Di Benedetto[a], Renata Esposito[c], Vincenzo Morra[a], Piergiulio Cappelletti[a]

[a] *Dipartimento di Scienze della Terra, dell'Ambiente e delle Risorse, Università di Napoli Federico II, Complesso Universitario Monte Sant'Angelo, Ed. L, Via Cintia 26, 80126 Naples, Italy*
[b] *Dipartimento di Farmacia, Università degli Studi di Napoli Federico II, Via D. Montesano 49, 80131 Napoli, Italy*
[c] *Dipartimento di Studi Umanistici, Università degli Studi di Napoli Federico II, Via Porta di Massa 1, 80133 Napoli, Italy*

ARTICLE INFO

Article history:
Received 18 January 2019
Accepted 17 May 2019
Available online xxx

Keywords:
Mortar
Roman
Hydraulicity Index
C-A-S-H gel
Terme di Baia
Campi Flegrei

ABSTRACT

Ancient *pozzolanic* mortars show the high technological quality achieved by Roman construction workers, due to their '*excellent state*' of preservation in every environment. These workers well knew that thanks to the combination of lime with specific volcanic products (*pozzolana*), mortar and concrete become hydraulic, allowing underwater hardening and increasing mechanical strength. The use of *pozzolana* in a mortar provides the underwater curing (hydraulic limes) of whatever construction with higher speed compared to carbonation processes of slaked lime. Whenever *pozzolana* is not available, it is substituted by ceramic fragments, which possess similar hydraulic properties. This research focuses, for the first time, on the detailed characterization of mortars coming from the Thermal Complex of Baia, which represents one of the most important archaeological sites in the Campania region. Thanks to several thermal springs, the ancient city of *Baiae* (*Campi Flegrei*) was the holiday resort of the Roman aristocracy. The former *Soprintendenza Archeologia della Campania*, allowed us to perform non-invasive, but representative, sampling of mortars that were characterised by multianalytical methodologies (POM, XRPD, SEM-EDS, TGA, and MIP) providing useful information on possible future activities of restoration. Results confirmed the expertise of Roman workers, who skilfully combined volcanic tuff aggregate, hydrated lime, and ceramic fragments. In particular, the typical zeolitic mineral association of phillipsite > chabazite > analcime found in the tuff aggregate pointed out their provenance from the Neapolitan Yellow Tuff related to the volcanic activity of *Campi Flegrei* of ca. 15 ka BP. The most relevant characteristic detected in all studied samples is the mortar hydraulicity testified by evidences such as reaction rims between *pozzolana* and binder, Hydraulicity Index (HI), and thermal analyses investigation. Also, composition of secondary mineralogical phases in the cementiceous matrix is particularly relevant. Distinctive is the contemporary presence of C-A-S-H gel, calcite and gypsum. C-A-S-H gel is derived from lime/ceramic fragments reaction; calcite is likely related to the partial reaction of underburned lime; and gypsum could be ascribable to the sulphation process of calcite. These secondary minerogenetic products fill pore space and enhance bonding in pumice fragments, thus contributing to long-term durability of mortars.

1. Introduction and research aims

Whenever one thinks of Roman Empire, the mind goes straight to history and literature and not to geological science. However, geology should be definitely taken into account as the great technological progresses of this period were achieved through a skilful and intensive use of available georesources never seen until then. The ability to building roads, aqueducts, temples and monuments was so technologically developed that these manufacts still resist over two thousand years to the strength of subaerial weathering, waves and seawater chemical interactions. Roman craftsmen

☆ This article is part of the special issue "Geosciences for Cultural Heritage", composed of a selection of peer-reviewed papers presented at session S30 of Congress SGI-SIMP 2018. Guest editors: Fabrizio Antonelli (University IUAV of Venice), Alberto De Bonis (University of Naples "Federico II"), Domenico Miriello (University of Calabria), Simona Raneri (University of Pisa), and Alberta Silvestri (University of Padua).

* Corresponding author.
E-mail address: concetta.rispoli@unina.it (C. Rispoli).

https://doi.org/10.1016/j.culher.2019.05.010
1296-2074/

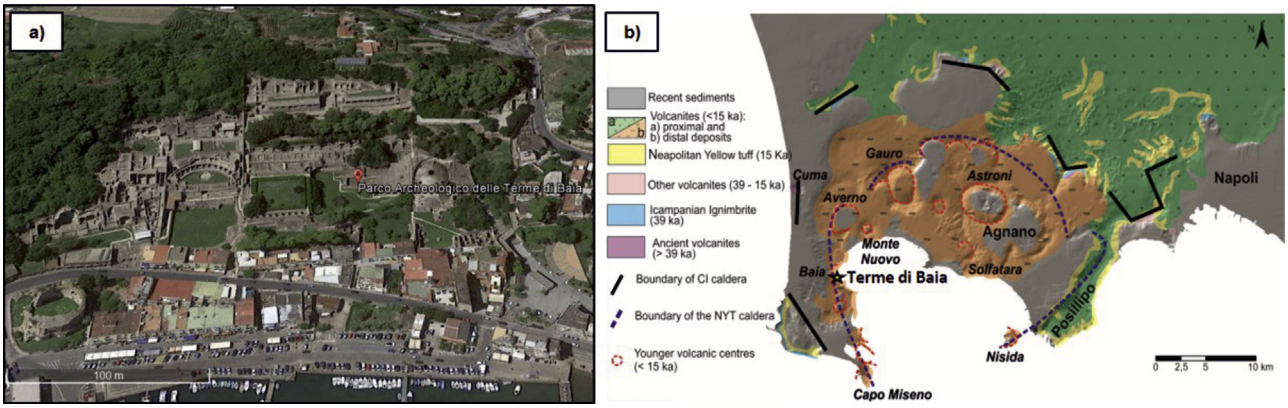

Fig. 1. a: satellite picture of *Terme di Baia*; b: geological sketch map of *Campi Flegrei* [modified after 11].

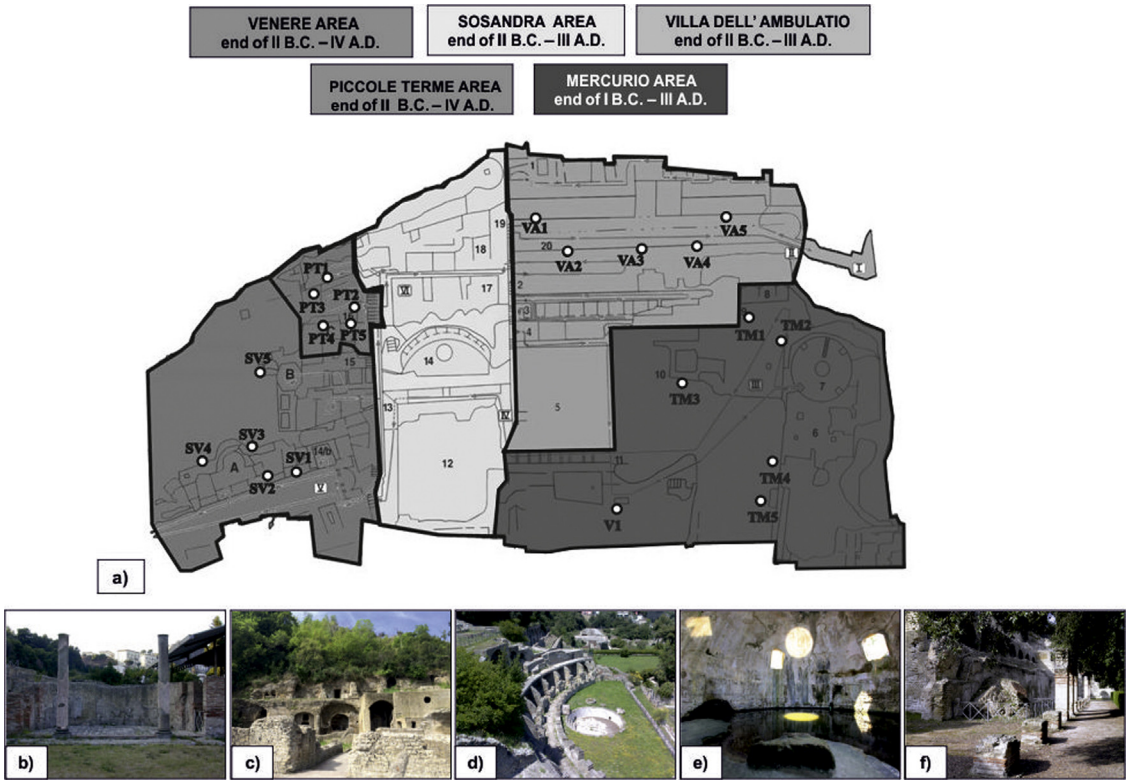

Fig. 2. a: planimetry of Archaeological Park of *Terme di Baia*, along with samples location (modified after [18]); b: *Venere* area; c: *Piccole Terme* area; d: *Sosandra* area; e: *Mercurio* area; f: *Villa dell'Ambulatio* area. SV: *Venere area* samples; TM and V1: *Mercurio* area samples; PT: *Piccole Terme* area samples; VA: *Villa dell'Ambulatio* samples.

knew that thanks to the combination of lime with specific volcanic products (*pozzolana*), mortar and concrete become hydraulic allowing underwater hardening and increasing their mechanical strength [1]. The use of *pozzolana* marked a revolutionary progress in the construction sector, due to the ability of mixture to cure also underwater (hydraulic limes) and with a higher speed compared to carbonation processes of slaked lime.

Whenever volcanic material was not available, fragments of artificial materials (ceramic fragments) with similar hydraulic properties were used [1].

The Department of Earth Sciences, Environment and Resources (DiSTAR) of the Federico II University of Naples, for over twenty years has been engaged in the application mineralogical and petrographic methods for archaeometric studies of several ancient finds and monuments, such as Roman ceramics, mortars and concrete [2–9].

Aim of this study is improving knowledge of Roman construction techniques used for the production of mortar-based materials from one of the most important archaeological sites of the Campania region of Italy: the archaeological park of *Terme di Baia*. The investigation was carried out by means of mineralogical, petrographic and physical techniques to examine in detail microstructural and compositional features of mortars and pointing out: mix design, provenance of raw materials, study of secondary minerogenetic processes. Moreover, the outcomes of this research will also represent a valuable base of information for future activities of restoration of this important archaeological site.

2. Geological and archaeological settings

The archaeological site of *Terme di Baia* (Fig. 1a) is located in the western sector of *Campi Flegrei* volcanic district (Campania

Please cite this article in press as: C. Rispoli, et al., The ancient *pozzolanic* mortars of the Thermal complex of Baia (*Campi Flegrei*, Italy), Journal of Cultural Heritage (2019), https://doi.org/10.1016/j.culher.2019.05.010