Roman buildings: mortar, hydraulic mortar and pozzolanic concrete in the Gulf of Naples, Campania – Italy

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Abstract

The aim of article is to summarise the information published with regard to research carried out into mortar and concrete materials in relation Roman buildings in the gulf of Naples, Italy.

The region due to its geological formation and the historical significance of Roman cities and its monuments implicated in multidisciplinary studies on the raw materials and Roman construction technologies for an in-depth knowledge of the composition of geomaterials degraded in time and structural problems with a view to restoring the archaeological heritage.

The article describes the case studies of two geographic areas in particular, the sites of the Phlegrean Fields (Puteoli, Baia, Misenum) and the Vesuvius area (Pompeii, Herculaneum, Stabia, Surrentum). The results showed that important complexes and monuments have a composition of mortars and conglomerates which is found to match what is indicated by the sources and that malfunctions made in different chronological periods do not always retain the same composition. Futhermore, results confirmed that Roman engineers extensively used local geomaterials such as volcanic and sedimentary aggregates mixed with hydrated lime.

Introduction

Recipes for mortar-based building materials may change over time and differ in various construction and restoration phases. They normally reflect craftsmen's knowledge, availability of raw materials, and also the importance of the building in which they are found.

The use of particular materials and certain constructive techniques has allowed to preserve Roman buildings to this day; these monuments that are part of our Cultural Heritage require accurate and specific restoration work.

The Romans developed the technology of building with burnt-lime mortars to a very high level; they developed a sophisticated empirical understanding of the effects of production methods and mortar additives.

Knowledge of components (mortars, binders and stone materials) of ancient wall structures is therefore crucial for the preservation of archaeological monument.

Ancient literary source (*Vitruvius* and *Plinius Secundus*) give us many information about Roman tecnologies. In his handbook of architecture *Vitruvius*, in the 1th century B.C., describes many materials, designs, and types of construction, and he occasionally turns to the process itself.

The author describes the terms for various aspects of architecture as well as architectural practice. The provision of special materials such as *pulvis Puteolanus,* a characteristic material of the volcanic formation of the Phlegrean Fields, which was mainly used to make hydraulic mortar and to realize maritime infrastructures.*Vitruvius* suggests the utility of concrete in constructing buildings with vaulted roofs. The ancient *pulvis Puteolanus* apparently originated in the region around *Puteoli*, as the name suggests, and around the Bay of Pozzuoli in the Phlegrean Fields volcanic district near *Baiae*, as stated by *Vitruvius*. This same origin is specified by *Strabo*, Pliny, and Seneca (Passages 12, 14, 16). *Plinius*' handbook contains a rich store of miscellaneous information relevant to ancient technology too.

For this reason the aim of some researches is to investigate, by means of laboratory tests, the mechanical features of pozzolanic mortar of Phlegrean Fields and Vesuvian sites (Figure 1) to make a reproduction of mortars having physical, mechanical and chemical compatibility to the original mortars, by using natural materials.

Increasing sophistication in conservation, mirrored by increasing technical understanding of traditional and other modern man made building materials resulted in greater demands for better performance of materials used in conservation and restoration and their compatibility with historic originals.

These elements can be useful for structures built with similar techniques and are absolutely indispensable to safeguard the monumental heritage of Vesuvian sites and Phlegran Fields, constantly threatened by eruptions, earthquakes and age-long alternation of positive and negative phenomena of bradyseism capable to submerge a significant part of the ancient settlements to a depth of 15 meters below sea level.

Figure 1 – Roman cities in the Gulf of Naples.

Materials

Mortars were usually inhomogeneous because they were produced manually. The study of ancient mortars and concrete is therefore of twofold interest: mortars provide information on raw materials and technologies available at the time of production; knowledge of the main physical properties of a mortar and its state of conservation is a prerequisite for the process of restoration and conservation. Science methodologies can be used to measure the main characteristics and properties of ancient mortars and their components (binder and aggregate). Since it is not always possible to measure directly all properties of binders and aggregate fractions, some properties are obtained through data processing.

Mortar

The use of cement works spread to Rome and Campania from the 3rd century B.C. through Oriental and Hellenistic influences; Previously only the binder was clay while the lime mortar was introduced by the Romans (Giuliani 2006).

Mortar generally indicates a dough of earth and grain or straw, or land mixed with inerts or lime and sand or puddle (*materia ex calce et harena* Plin. N.H. 35, 169); In Roman times generally the dough was composed of sand and grass in ratio of 2:1 and water. The abundance of water in the dough is an element that differentiates the ancient conglomerate from the modern one. Vitruvius (2, 5, 1-2) indicates the proportions of the components to make good mortar (table 1).

Plinius Secundus (N.H. 36, 176) instead, shows that many buildings collapsed because the right amount of lime mixed with water was not met.

Hydraulic mortar instead served to make quick water intake and the Romans obtained it by mixing fat lime and *pulvis puteolanus* (pozzolan) or adding ceramic fragments (brick or pottery) to lime and sand. The mortar thus obtained began to grip after four days even if completely immersed in the water.

Table 1 – Ancient proportions (by Vitr. 2, 5, 1; Plin. N. H. 36, 175)

Pure lime paste	Quarry sand	Sea or river sand	Pozzolan	Sea or river sand and brick fragments
1	3			
1		2		
1			2	
1				3 (2 sand + 1 brick)

Opus caementicium

The name comes from stone fragments joined to mortar to form the compound. Its composition is described by *Vitruvius* (Vitr. 5, 12, 5).

Cocciopesto
It is a mixture of lime, sand or pozzolan and homogeneously distributed brickwork breaks, giving mortalities hydraulic properties. It was used as a waterproofing layer of wall structures placed in damp environments and as a coating of tanks.
This mixture, even if used as a lining or floor covering, is a concrete composite; In layers of a certain thickness it has a traction-resistance capacity.

Opus signinum
It is a conglomerate that is often identified with the cocciopesto and it is mentioned by *Vitruvius* when it speaks of the construction of the tanks (8, 6, 14); The same passage is quoted by *Plinius Secundus* (*N.H.* 35, 173) and by Columella (R.R. 9,1) for rainwater tanks in wildlife farms.

Roman buildings in the gulf of Naples

Roman cities along the Gulf of Naples emerged in an area whose volcanic geological features were crucial for the supply of raw materials used for the construction of ancient roman buildings and maritime structures.
Vitruvius, writing in the first century BC, described a powder that produced 'wonderful' results when added to a simple lime-water mix. This 'powder', composed of tuffs derived from the volcanic province of Phlegrean Fields on the Gulf of Naples, enabled mortars and concretes to set in the presence of sea water and, in addition, to produce stronger structures than those built with lime cement alone. The tuffs were quarried from the vicinity of the modern town of Pozzuoli. The Romans called this material *pulvis puteolanis,* dust of Puteoli, Puteoli being the Latin name for Pozzuoli, which in turn has given the modern term 'pozzolana', widely applied to all additives to cements that produce a hydraulic set. The unique properties of this material were probably discovered as the local tufts, scoria and lavas were the aggregate of choice for the construction of the harbours and the port at Roman *Puteoli* (Lippiello 2011).

The Campi Flegrei (*Phlegrean Fields*)
The coastline of the Campi Flegrei is a geologically active area: bradyseism, frequent earthquakes, fumaroles and bubbling mud pots, and the occasional smell of sulphur are constant reminders of the defining presence of Campi Flegrei and Mt. Vesuvius. This area, located to the west of Naples and *ca.* 200 km south of Rome, is part of an ancient caldera in the Campi Flegrei (Phlegraean Fields) volcanic district. It was bounded by the Roman colony of *Puteoli* to the east and *Misenum*, the home of Rome's Western Mediterranean fleet, to the west. August's interest in the Phlegrean Fields district gave rise to the expansion of coastal cities and to the enormous development of port and road infrastructures, thus developing new building technologies using local raw materials.

Puteoli
The city was founded by the Romans after the Second Punic War, as part of a political plan of colonial foundations at strategic points of control of the coast of Campania in particular, became one of the most important harbour cities of the Roman Empire, for the strategic importance of its port. Archaeological Superintendence helped to enrich the knowledge of the ancient Roman city of *Puteoli*; in particular the archaeological surveys carried out since the nineties of the last century, as part of a large project to re-qualify and enhance Rione Terra, a promontory on which the late Roman Republic colony was allocated, allowed to acquire important information about the Roman city (Figures 2-3).
The archaeological investigations have allowed us to deepen the study of the building techniques from the foundation of the Roman colony to the 3th-4th century A.C., when the promontory was abandoned. The project, founded in 2004 by a multidisciplinary collaboration, analyzed mortars used in the northeast of the area (Imperatore and Proietti 2004).
The typological identification of building techniques is not only a useful support for documentation of digging data and for the diachronic evolution of mortars (i.e. verifying whether over the centuries there have been variations in the binder component) but it is an important element for diagnostics and preservation of ancient building. Mortar analysis has been useful in identifying components and their percentages to reproduce and use them in restoring patches.
The analysis found that ancient mortars are made up of a lime-based binder and a siliceous aggregate of volcanic origin, pozzolanic or volcanic sand coming from the territory. A clear change in aggregate-binding ratio was observed in the transition between the late republican age and the Augustan age (Paternoster et al. 2007).

Baia
The ancient *Baiae*, famous for its beauty and thermal water springs, was the holiday resort of the Roman aristocracy. The surrounding hills and the coastal coastline were occupied by luxurious villas whose owners are famous by literary sources. This area due to bradyseism has dramatically changed its coastal profile and some of these residential villas have been submerged (Figure 4).
Now the remains of the city lie underwater along up to a distance of 400–500 mt. far from the modern shoreline. Here, over the years, the restoration of sectors of several buildings

Figure 2 – *Rione Terra in Pozzuoli*, view from the sea.

Figure 3 – *Rione Terra*, Roman Building, detail.

Figure 4 – *Baia*, Roman submerged building, detail (Photo by ASNA archiv).

has been carried out: the Villa with entrance as a prothyrum, Villa dei Pisoni, a sector of the so called *Via Herculanea* and the Building with porticoed courtyard near *Portus Iulius*.

The hydrothermal and volcanic phenomena prompted scholars to experiment innovative methods of conservation and protection of archaeological heritage through the analysis of geomaterial and building techniques used in this area; In particular innovative restoration and conservation methods have been applied to underwater Roman buildings that require special conservation measures due to its characteristics.

To date, multidisciplinary studies focused on the analysis of the ancient mortars of the archaeological complex "Thermae di Baia" and some Roman buildings of the underwater parks of the Baia.

The archaeological site of "Villa a Protiro" (*Prothyrum Villa*) is located at 5 mt. depth; the rooms composing the Villa extend for 40 mt. along the road, flanked by *thermae*, *tabernae* and other villas; however, its real size should have been larger. The name "prothyrum" is derived from the presence of two stuccoed column shafts, no longer in existence, that were placed on two short partition walls built in front of the threshold. Sampling (12 mortars) was performed on several walls of the archaeological complex. The results obtained

from petrographic analysis, showed the presence of different technology of production of mortars in term of type of aggregate, aggregate-binder ratio. In some samples they are marble fragments, testifying the Roman marble re-use in the mixture of mortars. In particular, there is a good correlation between the location of sampling sites within the different residential rooms and the minero-petrographic, morphologic and chemical features of the analysed fragments. This study is crucial since the most recent guidelines of scientific and international cultural heritage protection bodies agree in promoting underwater archaeological and historical heritage. (La Russa et al. 2015).

The so called archaeological complex "Terme di Baia" is an archaeological park extending along 40.000 sq.m. and it is divided in five sections: *Villa dell'Ambulatio, Mercurio* area, *Sosandra* area, *Piccole Terme* and *Venere* area that embrace patrician residences and a thermal complex (Figure 5).

A multidisciplinary group works to improve the knowledge of Roman construction techniques by means of detailed microstructural and compositional examinations of cementitious binding matrix and aggregates aiming at pointing out provenance of raw materials, mix-designs proportioning and secondary minerogetic processes.

Mineralogical-petrographic characterization of samples confirmed that Roman engineers extensively used tuff aggregate, hydrated lime, and *cocciopesto*. The main aggregate is *cocciopesto*, characterized by a mixture of lime, *pozzolana* and a part of the inert formed by shattered tiles, bricks and pottery. It is exactly the presence of *cocciopesto* which confers hydraulicity to the mortar (Rispoli et al. 2016).

The port facilities of the *Lacus Baianus* and *Portus Iulius* have been the subject of the ROMACONS project, because these structures do represent the first significant effort of building on a large scale in the sea (Figure 6).

The first site that we investigated was the entrance channel to *Baianus Lacus*, distinguished by two long moles or breakwaters. Each mole is about 9.5 mt. wide, while the channel between them is about 32 mt. wide. A similar location selected for coring was the entrance channel to the now submerged harbour of *Portus Iulius*. This installation was the first one built in the Italian peninsula specifically to serve as a base for a naval fleet. It was constructed clandestinely in the early 30s B.C. by Marcus Agrippa (Brandon et al. 2014).

Figure 5 – *Baia*, Archaeological complex of "Terme di Baia" (Photo by ASNA archiv).

Misenum

Misenum was the harbour of Rome's Western Mediterranean fleet. In the territory of Agrippa made significant engineering infrastructures linked to road and aqueducts.

The *Piscina Mirabilis* was the terminal point of Serino aqueduct; it is a water resevoir, with rectangular shape by

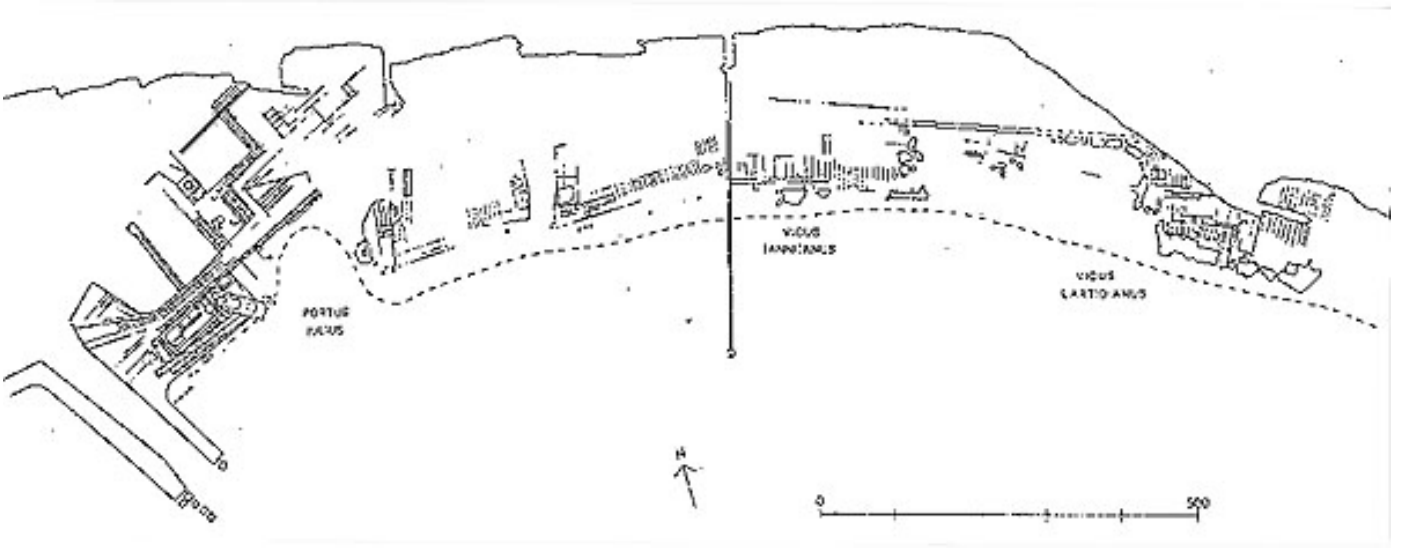

Figure 6 – *Lacus Baianus* and *Portus Iulius* (Photo by Miniero 2010).

a capacity of 12000 cbm water. It's 15 mt. high, 72 mt. long and 25 mt. wide. The internal space is based of 48 cross-shaped pillar, located on four lines, making five corridors with a barrel vault; the access was built by two stairs held by three archs, located in NO and SE corners. Next to the west entrance the intake pipe is located to allow the water supply. In the ground of the short corridor there is a little escavated basin with a depth of 1,10 mt., with an exit hole on the right end, that probably was used as settling tank.

The walls were built in *opus reticulatum* with lanes of bricks in the middle and pillar of tuff block, they have a coat of cocciopesto with a curb at the base to prevent infiltrations (Figure 7).

Mineralogical and petrographic examinations performed on geomaterials from the *Piscina Mirabilis* point out that hydraulic raw material was mixed with the lime for casting the mortars.

The main aggregate is cocciopesto, characterized by a mixture of lime, pozzolana and part of the inerts formed by shattered tiles, bricks and pottery. It is exactly the presence of cocciopesto which confers hydraulicity to the mortar. In fact, this component plays a pozzolanic reaction or reacts with free lime, forming hydraulic compounds, with long-term stability and water resistance. Extremely interesting is the composition of the cementiceous binding matrix, with the contemporary presence of gel-like C-S-A-H, derived from the reaction between lime and cocciopesto, calcite, gypsum, and, finally, tobermorite (Rispoli et al. 2015).

The Vesuvian sites

The eruption of Mount Vesuvius in 79 A.C. has allowed to preserve the Roman cities located at the foot of the volcano. The remarkable state of preservation of the murals and decorative structures in recent years has focused on the safeguarding of sites through multidisciplinary and international projects.

Pompeii

The site for the particular circumstances that have led to a remarkable state of preservation of the wall painting of public and private buildings has always been the subject of multidisciplinary teams, as well as the excavation campaigns to investigate the construction phases preceding the 79 A.C., they continue to enrich the knowledge of the ancient city (Figure 8).

Numerous international teams and diagnostic projects carried out by the Superintendence have deepened the study of the mortars of some public and private buildings in the city to identify the raw materials used in the mixture. Because they are artificial materials, mortars have diverse compositional and material characteristics, as a result of different construction needs and the technological knowledge of the workers who produced them.

The *Garum* Workshop is located in the *Regio* I of the archaeological site of *Pompeii* (I, XII, 8) and was devoted to the manufacture, storage and sale of *garum* famous Roman fish sauce. Probably the building was originally a private residence, later transformed into a workshop (De Luca *et al.* 2014).

D*omus of Octavius Quartio* occupies the entire *insula* 2 of *Regio* II in Pompeii, representing one of the most important domus of the archaeological site. An interdisciplinary approach has been adopted in order to plan conservative, preventive and restoration actions aimed at the requalification of *Pompeii* within the frame of "Grande Progetto Pompei" program. The *domus* was investigated by means of a multi-analytical and multi-disciplinary survey in order to define the state of conservation of the masonries. The method here proposed started with a precise mapping by laser-scanner that provided a precise measured-base for mapping geomaterials,

Figure 7 – *Misenum, Piscina Mirabilis*.

Figure 8 – *Pompeii*, Archaeological site, detail.

weathering forms and damage categories (Grifa et al. 2016).
The House of the Vestals, an ancient elite house in Pompeii (*Regio VI, insula 1*), shows different types of mortar.
Another research describes the compositional characterisation of coccciopesto and natural pozzolanic mortars sampled in the *Regio* VI area of the archaeological site of Pompeii, with particular reference to the Casa di Pansa in *Insula* 6 and Casa 17 in *Insula* 2. (Miriello *et al.* 2010).
Ariadne's House or "dei Capitelli Colorati", is located in the *Regio* VII, *insula* 4, in a privileged location at the center of the city, less than 100 meters from the forum. With 1700 sq.m., it is one of the biggest stately *domus* of the private Pompeian architecture (Pèrez *et al.* 2013).

The raw materials used in the mortars are related to the geology of the area and are fully compatible with the pyroclastic deposits of the Vesuvius.
The mortars were characterised by their aggregate-binder ratio, the mineralogy of the aggregate, which was fully compatible with that of the pyroclastic deposits of Vesuvius, and the composition of the binder, which revealed pozzolanic hydration phenomena caused by the reaction of natural pozzolana and cocciopesto with hydrated lime.
These data may be useful in the future to prepare mortars of high compatibility for use in restoration operations or detailed studies on the provenance of the raw materials used for their preparation.

Herculaneum
The Herculaneum Conservation Project is a public-private initiative to conserve and enhance the Roman city of Herculaneum and HCP team carried out an extensive sampling campaign across the site of both original and restoration mortars, used during the nineteenth and twentieth century excavation and restoration campaigns (Figure 9).
The composition and quality of the original construction mortars used in Herculaneum's walls do not only have archaeological value, but are also fundamental for understanding the structural capacity of the wall itself. This study will not only increase knowledge about the site but will also contribute to the conservation of Herculaneum and other open-air archaeological sites, thanks to the development of works strategies that consider quality, cost and time parameters when working with each type of mortar identified. (De Vita et al. 2010; Leone et al. 2016).
Stabiae
Ancient *Stabiae* is located on the Pianoro of Varano, a plateau in the junction between the Lattari Mountains carbonate ridge and the Sarno River flood plain. This settlement nowadays consists of several *otium villae* and rustic villas. During its life span, this otium villae complex was subjected to several geological risks related to the seismic and volcanic activity of this area, such as the earthquake in 62 A.C. Subsequently, it was completely buried by pyroclastics (several metres thick) from the 79 A.C. eruption, and subsequent slope instabilities, which in turn altered the ancient coastline. Villa San Marco is a huge building of approximately 11,000 sq.m., of which only a part has been excavated (Figure 10).
The other important materials of the mixtures have a volcanic origin. The source of such sand can be ascribed to the southern Bay of Naples where the Somma-Vesuvius finger-print can be easily recognised. As far as the volcanic aggregate is concerned, the mortar-based materials were made using a recipe of lime and volcanics, both available in the Vesuvius environs. The comparison with published research on mortar-based materials from other sites of the Vesuvius environs confirmed a wide utilisation of local raw materials (Izzo *et al.* 2016).

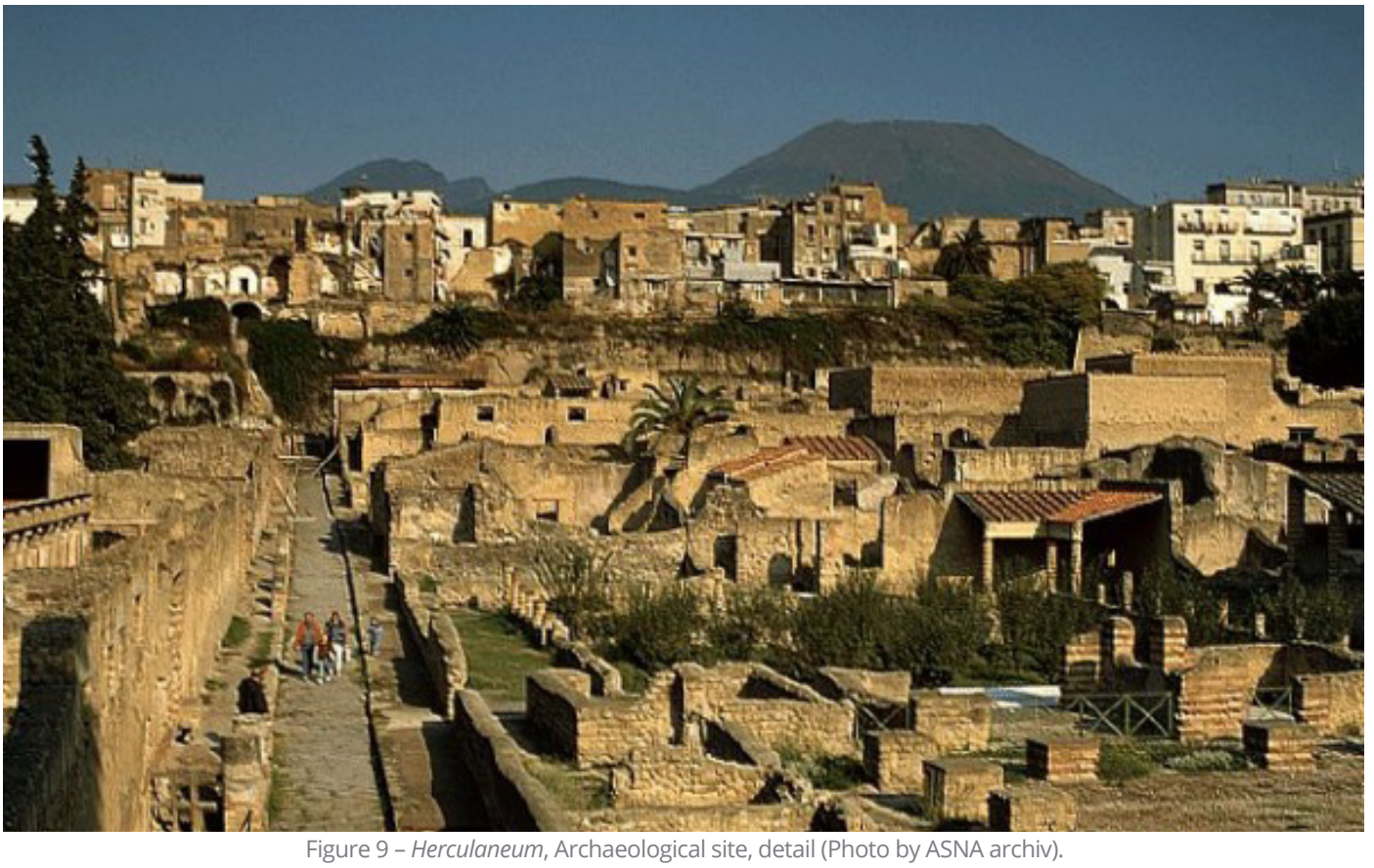

Figure 9 – *Herculaneum*, Archaeological site, detail (Photo by ASNA archiv).

Figure 10 – *Stabiae*, Villa San Marco, detail.

Surrento Peninsula

Remains of a Roman villa are visible near the eastern side of the Marina d'Equa bay, at the foot of the promontory of Vico Equense, in the Sorrento peninsula.

Rooms were seriously damaged by sea erosion and for this reason is almost impossible to recognize the original building plan. The villa was certainly damaged by the Vesuvius eruption of the year 79 A.C., whose products covered the stairs of access to the residence by the sea. The decoration of the Roman villa is documented by some sporadic marble findings, now kept at the National Archaeological Museum of Naples.

Geomaterials from the *Villa*, in particular mortars, are here studied in order to improve the knowledge on raw materials used to produce mortars, as well as their alteration products. Mineralogical and petrographic examination, performed on mortars from *Villa del Pezzolo,* evidenced that hydraulic raw material was mixed with lime for casting the mortars.

The volcanic aggregates were represented by some grey tuff fragments and leucitic scoria (Rispoli et al. 2016).

Conclusions

Multidisciplinary studies have shown that Roman buildings located in the Gulf of Naples, both public and private, were constructed using mortars produced with local raw materials; the area falls into two volcanic districts, the Campi Flegrei and Vesuvio, which have prime materials ideal for the composition of mortars and concretes so much to be cited by the literary sources (*Vitruvius* and *Plinius Secundus*). Results also showed that within the same for a given chronological period, differently quality mortars could be used, (perhaps due to the function of the building or to the wealth of the owner), and that qualitatively and quantitatively different mortars were used over the centuries and this could be associated with the use of certain building techniques over the centuries and could have affected the structural solidity of buildings.

Lastly, the pozzolan of the Phlegrean Fields has been identified in the maritime concrete infrastructures of the ports of the eastern Mediterranean and *Portus* near Rome (Stanislao et al. 2011; Brandon et al. 2014), proving that this raw material was also exported especially to make harbor and maritime infrastructures solid and resistant, as the hydraulic capabilities were better, just as *Vitruvius* prescribed.

References

Brandon C. J., Hohlfelder R. L., Jackson M. D., Oleson J. P. (eds.) 2014, *Building For Eternity. The History And Technology Of Roman Concrete Engineering in the sea*, Oxford & Philadelphia.

De Luca R., Miriello D., Pecci A., Domínguez Bella S., Bernal Casasola D., Cottica D., Crisci G. M. 2014, *Mortar plaster from the Garum workshop at Pompei (Italy): an archeometric study*, VIII Congresso Nazionale di Archeometria, Scienze e Beni Culturali: stato dell'arte e prospettive, Bologna 5 - 7 Febbraio.

De Vita A., Pesaresi P., Puglisi V. 2010, *Overview of the 100 Mortars Project at the Archaeological Site of Herculaneum*, J. Válek, C. Groot, J. J. Hughes (eds.), 2nd Historic Mortars Conference HMC2010 and RILEM TC 203-RHM Final Workshop 22-24 September 2010, Prague, Czech Republic.

Giuliani C. F. 2016*, L'edilizia nell'antichità*, Roma. SBN 9788843037094.

Grifa C., Barba S., Fiorillo F., Germinario C., Izzo F., Mercurio M., Musmeci D., Potrandolfo A., Santoriello A., Toro P., Langella A. 2016, *The Domus Of Octavius Quartio In Pompeii: Damage Diagnosis Of The Masonries And Frescoed Surfaces*, International Journal Of Conservation Science, Volume 7, Special Issue 2, 885-900.

Imperatore V., Proietti L. M. 2004, L'applicazione della diagnostica alle malte antiche del Rione Terra di Pozzuoli, Catalano L., Frunzio G. (eds.),La Diagnostica per la Tutela dei Materiali e del Costruito, 4 dicembre 2003, Sito reale di San Leucio (Ce), Napoli, 159-164.

Izzo F., Arizzi A., Cappelletti P., Cultrone G., De Bonis A., Germinario C., Graziano S. F., Grifa C., Guarino V., Mercurio M., Morra V., Langella A. 2016, *The art of building in the Roman period (89 B.C. – 79 A.C.): Mortars, plasters and mosaic floors from ancient Stabiae (Naples, Italy),* Construction and Building Materials 117, 129–143.

La Russa M. F., Ruffolo S. A., Ricca M., Rovella N., Comite V., Alvarez de Buergo M., Crisci G. M., Barca D. 2015, *Archaeometric approach for the study of mortars from the underwater archaeological site of Baia (Naples) Italy: Preliminary results*, Periodico di Mineralogia, 84, 3A (Special Issue), 553-567, DOI: 10.2451/2015PM0031.

Leone G., De Vita A., Magnania A., Rossi C. 2016, *Characterization of archaeological mortars from Herculaneum*, Thermochimica Acta 624, 86–94.

Lippiello M. 2011, *Pozzolanic Cementum of The Ancient Constructions in "Campi Flegrei" Area*, International Journal of Architectural Heritage, 5, 84–100.

Miniero P., *La villa romana inglobata nel Castello Aragonese di Baia : campagna di scavo 2003-2004.* in Gasparri C., Greco G., Pierobon Benoit R. (eds), Dall'immagine alla storia : studi per ricordare Stefania Adamo Muscettola Pozzuoli (Napoli): Naus, 2010, 303-316.

Miriello D., Barca D., Bloise A., Ciarallo A., Crisci G. M., De Rose T., Gattuso C., Gazineo F., La Russa M. F. 2010, *Characterisation of archaeological mortars from Pompeii (Campania, Italy) and identification of construction phases by compositional data analysis*, Journal of Archaeological Science 37, 2207-2223.

Paternoster G., Proietti L. M., Vitale A. 2007, *Malte e tecniche edilizie del Rione Terra di Pozzuoli. L'età romana.* Pozzuoli, ISBN 88-74313748978887 4313747.

Pérez M. C., García-Diego F. J., Merello P., D'Antoni P., Fernández-NavajasA., Ribera i Lacomba A., Ferrazza L., Pérez-Miralles J., Baró J. L., Merce P., D'Antoni H., Curiel-Esparza J. 2013, *Ariadne´s house (Pompeii, Italy) wall paintings: A multidisciplinary study of its present state focused on a future restoration and preventive conservation*, Materiales de Construcción Vol. 63, 311, 449-467.

Rispoli C., Graziano S. F., De Bonis A., Cappelletti P., Esposito R., Talamo P. 2015, *The Piscina Mirabilis: caracterization of geomaterials*, IMEKO International Conference on, Metrology for Archaeology and Cultural Heritage, Benevento, October 22-23, 266- 270.

Rispoli C., Graziano S.F., Guarino V., De Bonis A., Esposito R., Budetta T., Morra V., Cappelletti P. 2016, *Characterization of ancient mortars: preliminary results from Villa del Pezzolo, Sorrento Peninsula, Italy*, IMEKO International Conference on, Metrology for Archaeology and Cultural Heritage, Torino, Italy, October 19-21, 151-156.

Stanislao C., Rispoli C., Vola G., Cappelletti P., Morra V., De' Gennaro M. 2011, *Contribution to the knowledge of ancient Roman seawater concretes: the Phlegrean pozzolan adopted in the construction of the harbour at Soli-Pompeiopolis (Mersin, Turkey), Periodico di Mineralogia*, Special Issue Devoted to Prof. Franco Enrico, 80:3 (Special Issue), 471-488. [DOI:10.2451/2011PM0031]