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GEOLOGICAL ORIGIN OF THE REAGENTS CONSTITUTING THE ROMAN MORTAR, ACCORDING TO VITRUVIUS

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Abstract

It was established that the volcanic sands, around Rome, have physical properties, which make them correspond to the *harenae fossiciae* described by Vitruvius (II, 4). However, Vitruvius states that the best of all sands extracted from volcanic tuffs is what he calls the tuff *carbunculus* "carboncle" or *materia excocta*, which is a "soft volcanic tuff calcined by underground fire". He also claims that it is found geologically in Etruria, in the volcanic area located in the north of Rome. Vitruvius uses this volcanic sand exclusively for concrete masonry, whereas regular pozzolana from Napoli (*pulvis*) is especially employed for marine piers. He described, as a geologist, the formation of construction materials starting from volcanic fire and, as an architect and engineer, the reasons for which the volcanic reagents react so well with lime. Thus the volcanic tuff *carbunculus* refers to a pyroclastic rock traversed by degassing pipes, called "fossil fumaroles".

Keywords: Apparatuses (*opus caementicium*), Roman concrete, Construction History, Geology, Historical Period: Antiquity, History of Science, Materials (volcanic sand, pozzolana, lime), Treatises, Manuals, Quarry, Vitruvius

Introduction

Roman architects constructed concrete buildings such as the Coliseum, the Pantheon in Rome, or the cathedral Hagia Sophia in Constantinople (Byzantine period). According to the Roman architect Vitruvius, lime (*calx*), volcanic sand (*harena fossicia*), potsherds (*testa*), and rubble (*caementa*) were the ingredients of the *structura caementicia* "concrete". Rubble and stones used in Roman concrete, coined *caementa*, and came from volcanoes such as the Vulcini volcanic complex, the Monti Cimini, the Monti Sabatini, and the Colli Albani. Since the XIXth century, volcanic sand deposits have been known in Rome and in

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Lazio (GUILLAUME 1877 ; BLAKE 1947 ; LUGLI 1957 ; ANDERSON 1997 ; LANCASTER 2005 ; JACKSON and MARRA 2006). The volcanic sand, also called pozzolana in archaeological literature, is a local product found in the Colli Albani volcano district (LANCASTER 2005). It comes stratigraphically in three varieties/layers :

- 1) *pozzolana rossa* (red, 1600-1900 kg/m³) is the lowest layer,
- 2) *pozzolana nera* (black, 1340 kg/m³) is the second layer,
- 3) *pozzolanella* (grayish, 1360-1670 kg/m³) on the top was the first to be exploited, but it was an inferior product for concrete.

The “volcanic sands” (*harenae fossiciae*)

The red and black pozzolanas were exploited by means of underground tunnelling. They were extracted in the valleys such as the Marrana della Caffarella, Fosso di Tor Carbone and Fosso delle Tre Fontane (south and east of Rome). Known layers of *pozzolana rossa* up to ten m are located near the basilica of San Paolo fuori le Mura. Of course, the best known volcanic product is the pozzolana of Puozzoli (bay of Naples), called by Roman architect Vitruvius *puluis* “powder”. Current geological and archaeological researches have focused on the volcanic sands located around Rome. It was established that these volcanic sands have physical properties, which make them correspond to the *harenae fossiciae* described by Vitruvius (II, 4). Thus, the descriptions given by roman authors on these materials relate to a geological reality by color and extraction.

Vitruvius (II, 4, 1) describes the characteristics of *harena fossicia* “volcanic sand” :

In caementiciis autem structuris, primum, est de harena quaerendum, ut ea sit idonea ad materiam miscendam neque habeat terram commixtam. Genera autem harenae fossiciae sunt haec : nigra, cana, rubra, carbunculus. Ex his quae in manu confricata fecerit stridorem erit optima ; quae autem terrosa fuerit non habebit asperitatem. Item si in uestimentum candidum ea coniecta fuerit, postea excussa uel icta id non inquinaret neque ibi terra subsiderit, erit idonea.

“Now in concrete structures we must first inquire about the sand, that it be suitable for mixing material into mortar, and without the admixture of earth. Now the kinds of volcanic sand are these : black, white, red, and from carbuncle. Of these, that which makes a noise when rubbed in the hand will be best ; but that which is earthy will not have a like roughness. Also, if it is covered up in a white cloth, and afterwards shaken up or beaten, and does not foul it, and the earth does not settle therein, it will be suitable.” ¹

Vitruvius (II, 4, 3) distinguishes the volcanic/pozzolanic sand used in concrete and the other used in stucco :

Fossiciae uero celeriter in structuris siccescunt, et tectoria permanent, et concamerationes patiuntur, sed eae, quae sunt de harenariis recentes. Si enim exemptae diutius iacent, ab sole et luna et pruina concoctae resolvuntur et fiunt

terrosae. Ita cum in structuram coiciuntur, non possunt continere caementa, sed ea ruunt et labuntur oneraque parietes non possunt sustinere. Recentes autem fossiciae cum in structuris tantas habeant uirtutes, eae in tectoriis ideo non sunt utiles, quod pinguitudine eius calx commixta propter uehementiam non potest sine rimis inarescere. Fluuuatica uero propter macritatem uti signinum liaculorum subactionibus in tectorio recipit soliditatem.

“But quarry volcanic sand quickly dries in buildings, and the surface lasts ; and it admits of vaulting, but only that which is fresh from pit. For if after being taken out it lies too long, it is weathered by the sun and the moon and the hoar frost, and is dissolved and becomes earthy. Thus when it is thrown into the rubble, it cannot bind together the rough stones, but these collapse and the loads give way which the walls cannot maintain. But while fresh volcanic sand has such virtues in buildings, it is not useful in plaster work ; because owing to its richness, the lime when mingled with straw cannot, because of its strength, dry without cracks. But river sand because of its fineness (like that from Signia), when it is worked over with polishing tools, acquires solidity in the plaster.”

Vitruvius (II, 4, 3) clearly explains the use of *harena fossicia* for terrestrial architecture. The Roman architect (II, 6, 1) describes the properties of the true *pozzolana* :

Est etiam genus pulueris, quod efficit naturaliter res admirandas. Nascitur in regionibus Baianis <et> in agris municipiorum, quae sunt circa Vesuuium montem. Quod commixtum cum calce et caemento non modo ceteris aedificiis praestat firmitates, sed etiam moles, cum struuntur in mari, sub aqua solidescunt.

“There is also a kind of powder which, by nature, produces wonderful results. It is found in the neighbourhood of Baiae and in the lands of the municipalities round Mount Vesuvius. This being mixed with lime and rubble, not only furnishes strength to other buildings, but also, when piers are built in the sea, they set under water.”

That is why he distinguishes between *pozzolana* (*puluis*) and volcanic sand (*harena fossicia*) :

Vtraque autem sunt egregia in structuris, sed alia in terrenis aedificiis, alia etiam in maritimis molibus habent uirtutem.

“Both are excellent in walling. But some materials have advantages in buildings on land, and others in piers built into the sea.”

Vitruvius thus distinguishes three kinds of *harenae* for terrestrial construction and classifies them according to their extraction origin :

- *harena fossicia*, *carbunculus* “volcanic sand”,
- *harena fluuuatica*, “river sand” (quartz, limestone, etc.),
- *harena marina* “sea sand” (quartz, limestone, etc.).

The best of all *harenae fossiciae* : the *carbunculus*

Thus, the descriptions given by roman authors on these materials relate to a geological and archaeological reality (BLAKE 1947 ; LUGLI 1957 ; LANCASTER 2005 ; JACKSON and MARRA 2006). What about the *carbunculus* ? The best of all *harenae fossiciae*, as Vitruvius (II, 6) states, is extracted from a volcanic tuff called *carbunculus* “carboncle” or *materia excocta*, which is a “soft volcanic tuff calcined by underground fire”. He also claims that it is found geologically in Etruria, in the volcanic area located in the north of Rome. Vitruvius uses this volcanic sand exclusively for concrete masonry, whereas regular pozzolana von Napoli (*pulvis*) is especially employed for marine piers. The nature of the *carbunculus* and Vitruvius’ conceptions about volcanism used in construction remained unclear and was not taken seriously. One reason was that this text seemed to be unclear, ambiguous and above all metaphorical. In this paper, our philological, geological and materials science study will provide the exact translation of the technical Latin terms employed by Vitruvius. Thus, Vitruvius described the formation of construction materials starting from volcanic fire and, as an architect and engineer, the reasons for which the volcanic reagents react so well with lime.

How construction materials get their properties according to Vitruvius

The word *carbunculus* “volcanic tuff, volcanic sand, carboncle” is found four times in *De architectura* : II, 4, 1 ; II, 6, 6 (bis) ; VIII, 1, 2. It is a keyword for understanding the geological context of chapter 6 of the book II. In this chapter, Vitruvius explains why and how the mixture of pozzolana and lime can set under water. Flames burn both materials : pozzolana by volcanic fire under the earth, lime in a kiln by artificial fire. For Vitruvius (II, 2), each substance in Nature has four elements : *terra* “earth”, *aqua* “water”, *aer* “air” and *ignis* “fire” and their proportions determine their physical properties (hardness, softness, etc.). The volcanic/artificial fire destroys the coherence of any stone : lime is the result of expelled air and water from limestone (Vitruvius II, 5) whereas roman lava (*peperino*), containing more earth and water than air and fire, withstands better fire and weathering (Vitruvius II, 7, 2). For Vitruvius, any substance (stone, mineral, metal) which has been fired in a kiln, such as lime, or has undergone the volcanic fire, gets new physical or chemical properties for architecture and engineering (DAVIDOVITS 2003 ; DAVIDOVITS 2007).

Vitruvius develops his theory on volcanism in the sixth chapter of Book II. The flames from the depths of the earth come in contact with the ground and the subterranean stones. In 2, 6, 6, the flames burn out what is soft and tender in stones, but leaves what is rough (*quod est molle et tenerum, exurit, quod autem asperum relinquit*). Thus are born volcanic (hard/soft) tuffs, pumice sand, pozzolana. Those stones, containing at the beginning the four elements, have lost one element “water” or more, such as limestone becoming quick lime in a kiln. According to his theory of volcanism, these rocks have been weathered, not by water but by the underground flames, and this is the only alteration that our author is talking about in the sixth chapter of Book II.

These volcanic materials got fascinating chemical properties for Vitruvius : volcanic tuff

(*tofus*) and pozzolan (*puluis*) are mixed with lime (*calx*) to form a hydraulic concrete that sets under the seawater. According to the Vitruvian chemistry, those three ingredients are “elementarily” unstable – they have lost elements – thus chemically reactive.

Of course, volcanic fire alters the appearance of any volcanic stone like pumice, as states Vitruvius (II, 6, 2) :

Ardores autem esse in his locis etiam haec res potest indicare quod in montibus Cumanorum Baianis sunt loca sudationibus excauata in quibus uapor feruidus ab imo nascens ignis uehementia perforat eam terram per eamque manando in his locis oritur, et ita sudationum egregias efficit utilitates. Non minus etiam memorantur antiquitus creuisse ardores et abundauisse sub Vesuuio monte et inde euomuisse circa agros flammam. Ideoque tunc quae spongia siue pumex Pompeianus uocatur excocto ex alio genere lapidis in hanc redacta esse uidetur generis qualitatem.

“In the hills of Baiiae which belong to Cumae sites (bay of Naples) are excavated for sweating-rooms. In these, hot vapour rising deep down perforates the soil by the violence of its heat, and passing through it rises in these places, and so produces striking advantages in sweating-rooms. Not less also let it be recorded, that heats in antiquity grew and abounded under Mount Vesuvius, and thence belched forth flame round the country. And therefore now that which is called “sponge-stone” or Pompeian pumice seems to be brought to this general quality from another kind of stone when it is subjected to heat.”

The pumice of Pompei (*pumex Pompeianus*) is a light construction material too.

What are the physical appearances and properties of the volcanic tuff/sand called *carbunculus*, found in Etruria (north of Rome) ? In archaeological literature, the stone *carbunculus* is described as a volcanic tuff of Etruria, called either “nenfro” or “tufo peperino” trachytic/tephrito-leucitic ignimbrite or a peperite from which volcanic sand can be extracted (BLAKE 1947 ; LUGLI 1957 ; MOTTANA and CRESPI 1993). Vitruvius II, 6, 6 writes :

Ergo quibus locis non sunt terrosi montes sed genere materiae, ignis uis per eius uenas egrediens adurit eam ; quod est molle et tenerum, exurit, quod autem asperum relinquit. Itaque uti Campania exusta terra cinis, sic in Etruria excocta materia efficitur carbunculus. Vtraque autem sunt egregia in structuris, sed alia in terrenis aedificiis, alia etiam in maritimis molibus habent uirtutem. Est autem materiae potestas mollior quam tofus, solidior quam terra, qua penitus ab imo uehementia uaporis adusta, nonnullis locis procreatur id genus harenae, quod dicitur carbunculus.

“Therefore where ever mountains are not of earth but of a stony kind, the force of fire escaping through the veins burns it up. It burns out what is soft and tender, but leaves what is rough. Therefore just as in Campania, burnt-out earth becomes ashes (pozzolana), so in Etruria, charred stone becomes soft volcanic

tuff. Both materials are excellent in walling. But the volcanic sand called 'carbunculus' have advantages in buildings on land, and the pozzolana in piers built into the sea. The nature of this volcanic stone is softer than tufa, more solid than the earth ; and when this is burnt deep down by the violence of vapour, there is generated in some places that kind of volcanic sand which is called *carbunculus*."

This text is very difficult to translate for classical philologists and architects who thought that this text was metaphorical. In order to understand it, I have to focus on the keywords, which describe the hardness of these volcanic tuffs. Vitruvius compares two stones : the true pozzolana of Puozzoli (*puluis*) and the best of the volcanic sand, *carbunculus*. Both have different architectural applications (*puluis* "pozzolana" for piers built into the sea and *carbunculus* for buildings on land) because they have undergone the volcanic fire differently. *Puluis* "pozzolana" is a *cinis* "ash", a *terra exusta* "burnt-out earth". The passive past participle *exusta* comes from the verb *exurere* "to burn, to destroy by fire". *Carbunculus* is a *materia excocta* "stony charred material". *Excocta* is the passive past participle of the verb *excoquere* "to cook at high temperature" especially in a furnace. In Vitruvius (VII, 4, 3), this verb is used to refer to the firing of lime. But here, this text shows that this verb is used in a volcanic (natural) meaning : like for Pompeian pumice that is the result of volcanic heat (*pumex Pompeianus excocto ex alio genere lapidis*).

Vitruvius often compares the volcanic activity to a limekiln (DAVIDOVITS 2003). For him, fire destroys and decomposes the elements of any stone but in a furnace or found in a volcano. Technical vocabulary of lime is used to depict metaphorically volcanism. Thus, in a figurative sense, the verb *excoquere* means "to calcine in a volcano". Volcanism described by Vitruvius is not characterized by eruptions, but it occurs indirectly, through the underground sulfur vapours – which provide heat for sweating (Vitr. II, 6, 1) – and boiling water sources located in Etruria.

A limekiln produces several kinds of lime, some too calcined, others not burnt enough, while others are good. Similarly, there are volcanic materials, which have been too much or too little calcined by volcanic and underground fire. Vitruvius provides a classification of volcanic/calcined rocks that have undergone the subterranean fire. In this classification (from the most calcined to the least), pozzolan is at the top while volcanic sand is at the bottom :

- Pozzolan : *cinis* "ash", *terra exusta* "burnt out earth",
- Pumice of Pompeii : *genus lapidis excoctum* "a kind of calcined rock",
- Carboncle : *materia excocta* "calcined rocky material",
- Volcanic sand: *harena fossicia* "extracted volcanic sand".

The more the stone has been exposed to fire, the more the stone induration is low (from volcanic ashes to soft tuff). For Vitruvius, stone appearance, thermal water, testimonials found in ancient texts demonstrate how local materials have been exposed to subterranean volcanism, and consequently have acquired the suitable properties for concrete construction.

How to recognise the *materia excocta* “charred volcanic tuff”/*carbunculus* ?

Vitruvius (II, 6, 6) describes the geological environment that characterises *carbunculus* outcrop :

Ergo quibus locis non sunt terrosi montes sed genere materiae, ignis vis per eius uenas egrediens adurit eam; quod est molle et tenerum, exurit, quod autem asperum relinquit. [...] Est autem materiae potestas mollior quam tufus, solidior quam terra, qua penitus ab imo uehementia uaporis adusta, nonnullis locis procreatur id genus harenae, quod dicitur carbunculus.

“Therefore where ever mountains are not of earth but of a stony kind, the force of fire escaping through the veins burns it up. It burns out what is soft and tender, but leaves what is rough. [...] The nature of this volcanic stone (*carbunculus*) is softer than tufa, more solid than the earth; and when this is burnt deep down by the violence of vapour, there is generated in some places that kind of volcanic sand which is called *carbunculus*.”

According to this text, Vitruvius provides geological hints, which make it possible to locate the *carbunculus* visually. Since it is *materia excocta*, the volcanic tuff, from where the sand *carbunculus* is extracted, has veins through which volcanic fire modifies the hardness of the rock. According to Vitruvius, the volcanic vapours dissolve soft parts of the rock, by creating pores and veins that run through the volcanic tuff *carbunculus*. The volcanic tuff is not very indurated (“softer than tufa, more solid than the earth”). Is the *carbunculus* appearance related to a geological reality or is it a metaphorical sentence as claimed by classical philology ?

In September 1996, during the European industrial research program GEOCISTEM, I was in charge of the archaeological project (sampling roman mortars in Italy) and I visited with geologists of the program a quarry of volcanic tuff in Paringianu near Cagliari (Sardigna) ². Paringianu tuff is a volcanic comenditic tuff, from a pyroclastic flow (volcanic context: ignimbrites, rhyolites). This tuff is very indurated (composition: plagioclase, potassic feldspar, pyroxene, glass matrix and montmorillonite). But closed to the quarry, where hard building stone is extracted, there is a place where the comenditic tuff is not indurated at all, even if it has the same chemical and mineralogical composition. It is a volcanic “sand” and can be extracted as such. How can the different induration be explained ?

The geologists taught us that there are gas pipes running through the soft tuff layer (two m thick). They showed long empty tubes which looked like veins in the stone. They explained that after the volcanic eruption and pyroclastic flow, if the ignimbrite cools slowly, the stone gets a good induration, but if it cools too quickly, the stone degases. The gas contained in the ignimbrite escape through pipes and the stone become soft : volcanic “sand” can be extracted by hand. This phenomenon is known in geology as “fumarole pipes”, “fluidisation pipes” or “gas pipes” (WALKER 1971; SHERIDAN 1979; CAS and WRIGHT 1987, 190-193.). Those pipes appear in thick ignimbrite sheets. In cross section, they appear as vertical empty columns containing coarse lithic and pumice fragments depleted of fine ash

by gas streaming. The vertical pipes are often oxidised and, in some cases, can be enriched in economically important ore deposits by vapor phase crystallisation. This process cements the interstitial fragments so that the pipes are often resistant to erosion. In Italy, in the volcanic sites around the lakes (Bolsena, Vico) of Etruria, gas pipes have been noticed in the ignimbritic tuffs. Famous examples of huge (> two m in length) pipes are in the ignimbrite of Real Grande (Cerro Galan caldera, Argentina), in the Mazama ignimbrite (stratovolcano Mt. Mazama, Crater Lake, United States).

Conclusion

For Vitruvius, the best construction reactive material is *carbunculus* sand. This explains why he felt important to expose his volcanism theory in order to provide the necessary information for the civil engineers. Since it is *excocta materia*, the volcanic tuff of Etruria has veins through which the hot vapors modify the structure of the rock : the soft parts disintegrate by creating pores and veins. For a volcanic tuff, a very intense firing creates the pozzolan, whereas with less flames, it becomes carbunculus tuff, which is “softer than tufa, more solid than the earth”.

Chapter 6 of Book II is the oldest description of fumarole pipes in an ancient text. This text describing degassing pipes in a volcanic tuff can be a personal observation of Vitruvius in Etruria, northern Italy, where he stayed with the caesarean legions probably between 59-58 and 50 B. C. (CORSO 1983).

The relationship between the actual “gas pipes” and the “veins” of the Vitruvian text of II, 6, 5-6 is correlated. As an example, in Paringianu (Sardinia), indurated tuff is extracted as a building stone. Not far away, the same (degassed) tuff disintegrated into volcanic sand, but it has more cohesion than the earth surface of the quarry. This difference of induration is exactly what Vitruvius writes : *est autem materiae potestas mollior quam tofus, solidior quam terra*, “the nature of this volcanic stone (*carbunculus*) is softer than tufa, more solid than the earth”.

Notes

1. The latin text is from VITRUVIUS 1999 and the translation is adapted from VITRUVIUS 1983.
2. European industrial research program GEOCISTEM (BRITE-EURAM BE 7355 33). GEOCISTEM: Cost Effective Geopolymeric Cements for Innocuous Stabilisation of Toxic Elements (1994-1997). Persons involved in the program :
 - European Commission, Bruxelles, project Brite-Euram BE-7355-93, contract BRE2-CT93-0559 ;
 - Joseph Davidovits, scientific co-ordinator, Geopolymer Institute et Cordi-Géopolymère SA, Saint-Quentin, France ;
 - Philippe Rocher, B.R.G.M., Orleans, France ;
 - Athos Rinaldi, Laviosa Chimica Mineraria Spa, Livorno, Italy ;
 - Carlo Marini, Department of Earth sciences, University of Cagliari, Italy ;

- Sando Tocco, Department of Earth sciences, University of Cagliari, Italy ;
- Domingo Gimeno, Faculty of Geology, University of Barcelona, Spain ;
- Zelimir Gabelica, Department of Chemistry, University of Namur Belgium ;
- Luigi Buzzi, Cementi Buzzi Spa, Casale Monferrato, Italy ;
- Frédéric Davidovits, CERLA, University of Caen, France.

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