Vitruvian marine concrete and experimental archaeology

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Summary

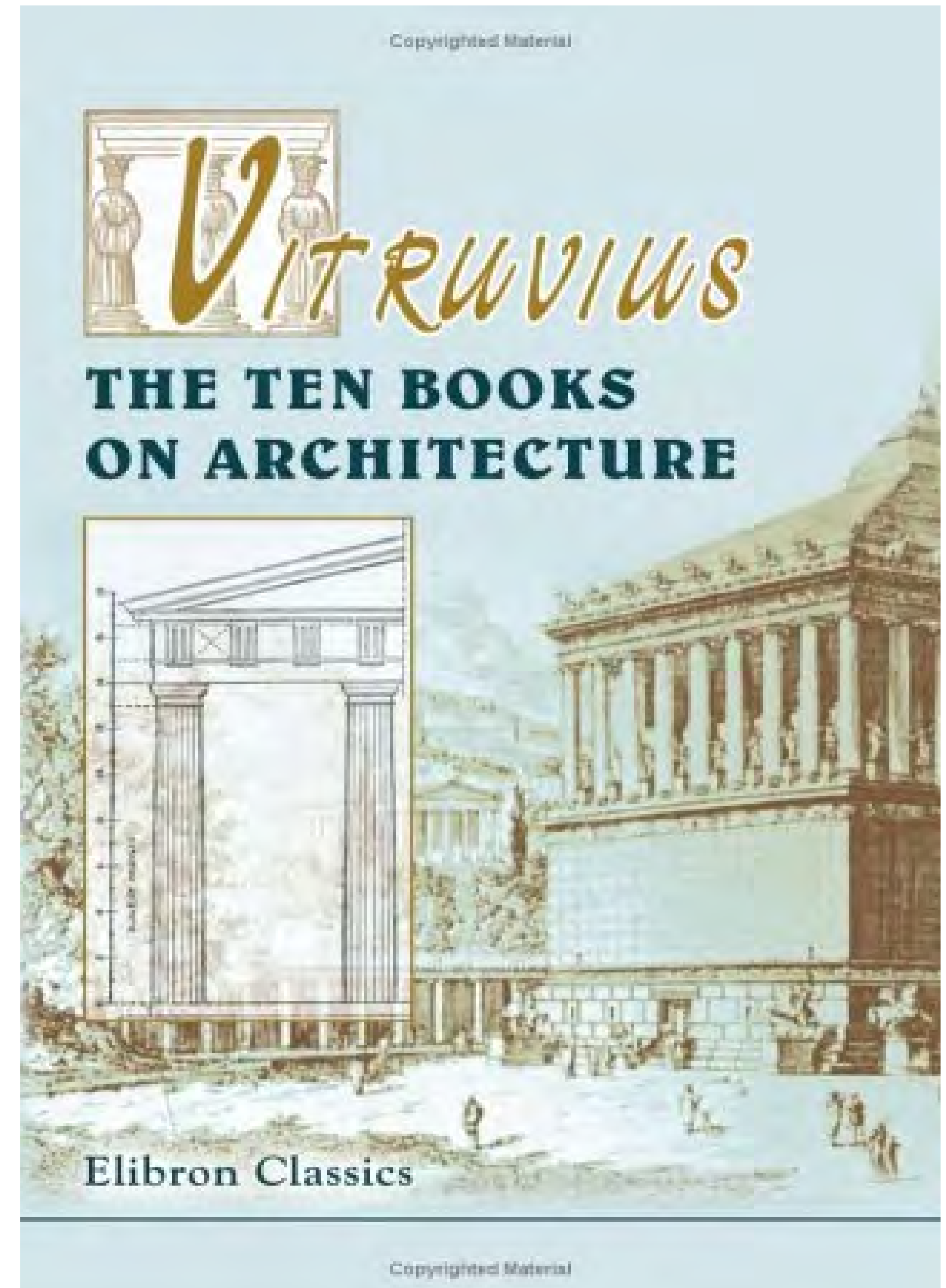
1. Roman geology and pier construction
2. « Roman Maritime Concrete Study » (ROMACONS) full-scale reconstruction:
    - 8 m^3 pier foundation (*pila*) in Brindisi (Italy),
3. Conclusion and references

Harbour facilities in Mediterranean sea

- During the Roman period, trade in Mediterranean sea enabled construction of harbour facilities
- It coincided almost exactly with the wide use of hydraulic concrete (Gotti, Oleson 2008)
- Examples : bridge, pier, fish breeding (Pompei)...

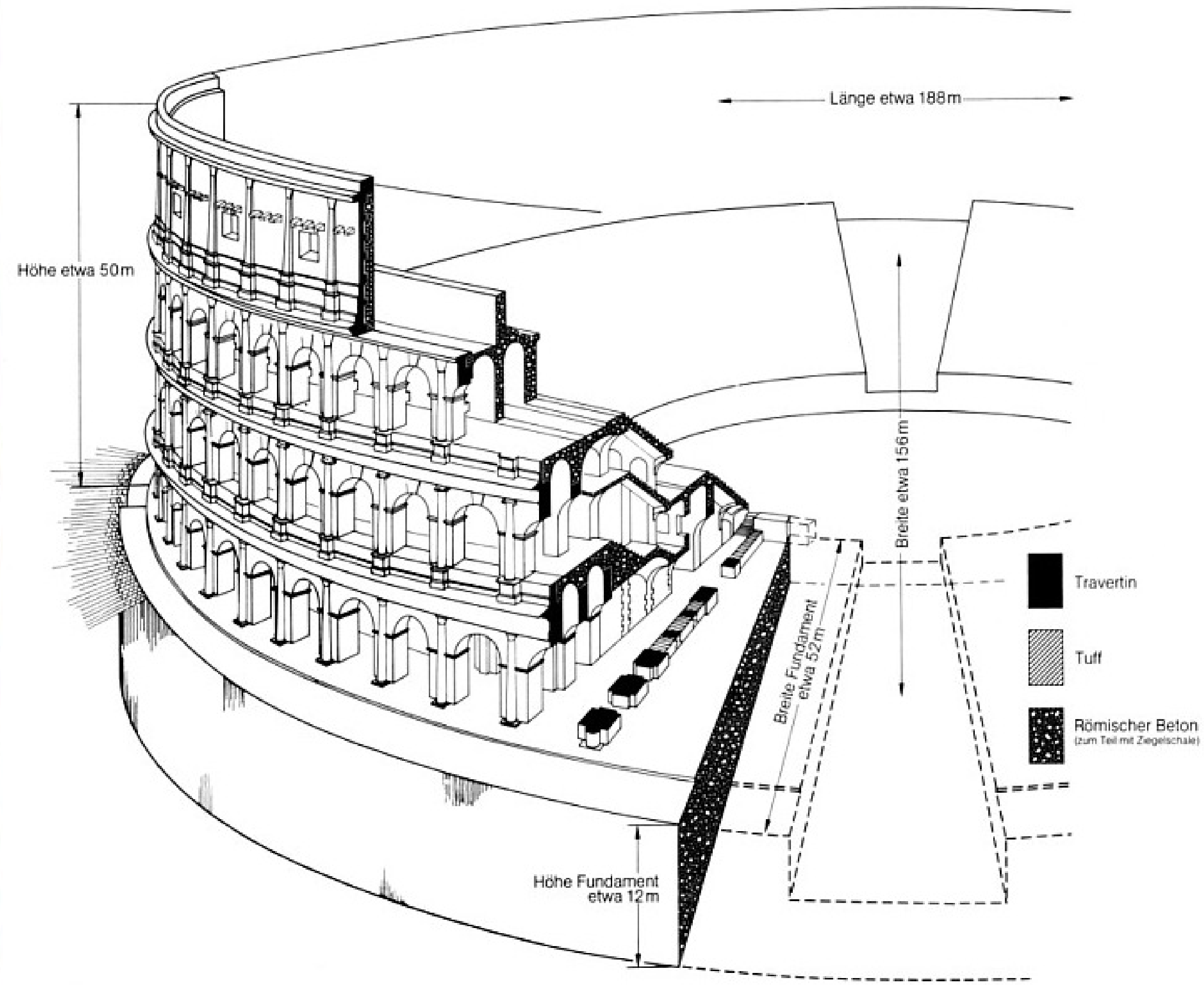
Vitruvius

- Roman architect, author of *De architectura* (25 B.C.).
- The only complete architectural treaty to survive from classical antiquity
- His treaty has recipes for making cement and concrete



Roman Concrete

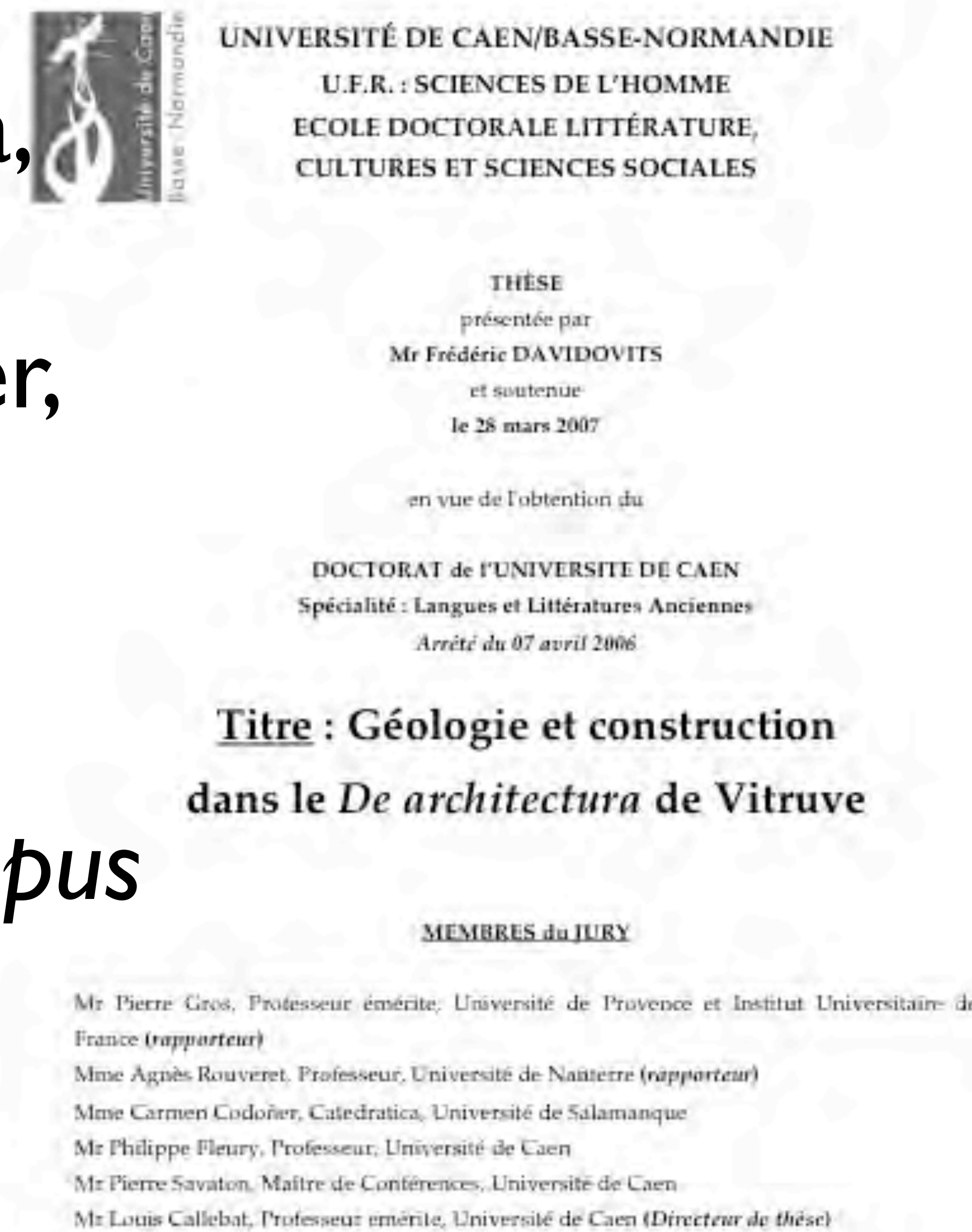
Roman Pantheon



Colosseo

Study of 53 latin and greek words in Vitruvius' work

- stone, rubble, sand, pozzolana,
- adobe, baked brick, lime, plaster,
- Pigments, mortars and coating
- Concrete: *opus caementicium*, *opus signinum*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Titre : Géologie et construction dans le *De architectura* de Vitruve

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Study through 3 research perspectives

1. Lexicography (latin translation)
2. Archaeology
3. « Hard sciences »: geology, civil engineering, science materials…

Keywords of Roman concrete according to Vitruvius

- Lime, hydraulic lime: *calx*
- Sand for concrete : *harena fossicia*
  « volcanic sand »
- Sand for coatings: *harena fluviatica*
  « river sand »

Key words of roman concrete for Vitruvius

- *Caementum* « rubble »
- *Testa* « crushed metakaolin (kaolinitic clay, calcined at 750 °C) »
- *Pulvis* « pozzolana »

Hydraulic concrete

- Concrete which sets without CO_2
- Lime (*calx*) + « pozzolana »
- Pozzolana:

    1. *pulvis* (*puteolanus*) = « powder of Puozzoli »
    2. *harena fossicia* = « volcanic sand »
    3. *testa* = crushed metakaolin

Lime for coating, Pompei

Puozzoli

Puozzoli

Villa Poppea in Oplontis: volcanic ashes

Villa Poppea in Oplontis: pozzolana

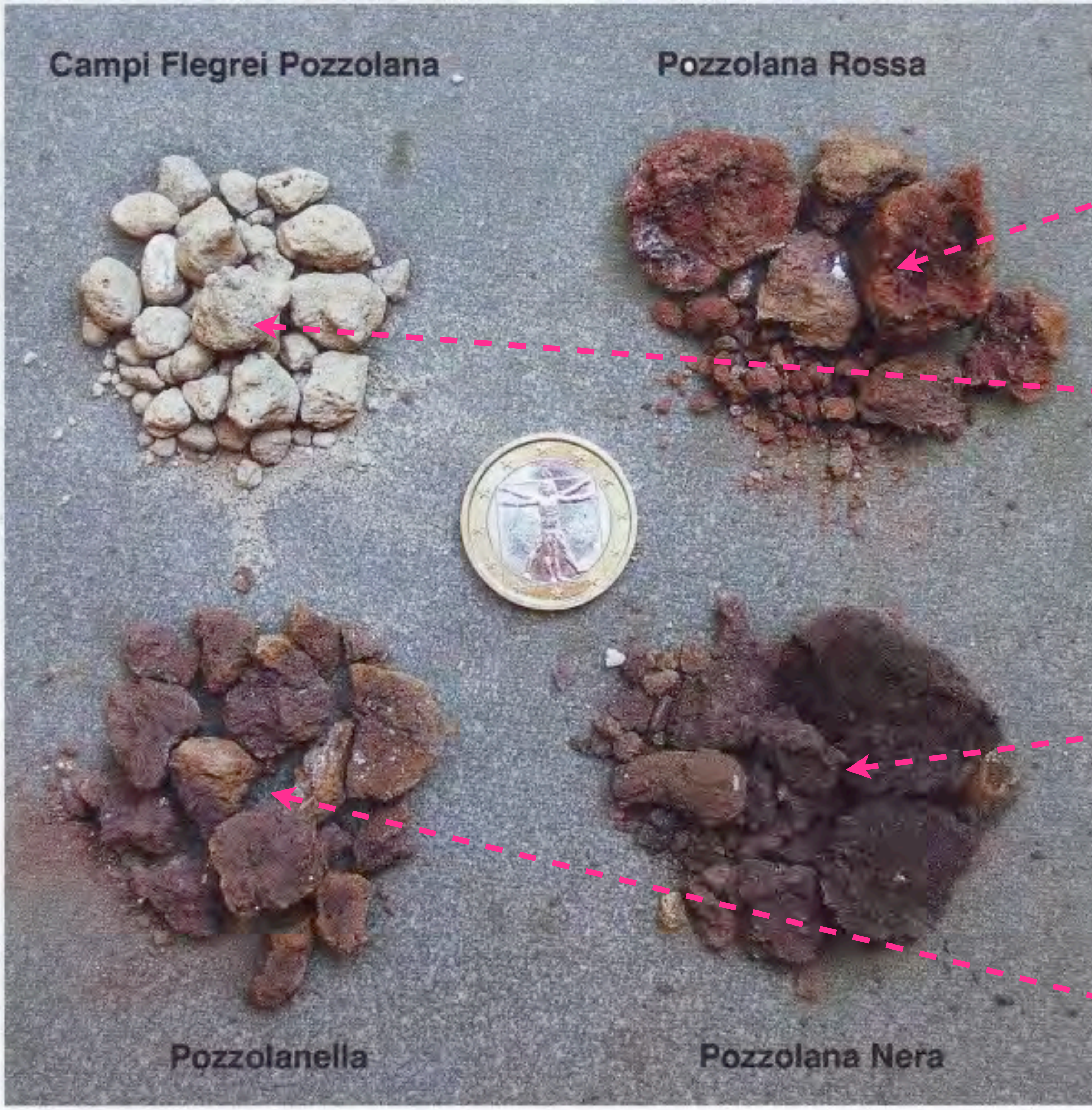


PLATE III. Four types of pozzolana showing the difference in color between them. The Campi Flegreian pozzolana (*pulvis puteolanus*) at upper left is easily distinguishable from the other pozzolanas quarried near Rome. (Euro = 2.3-cm dia)

Harena fossicia rubra: reddish volcanic sand

Pulvis « true pozzolana »

Harena fossicia nigra: reddish volcanic sand

Harena fossicia cana: grayish volcanic sand

After Lancaster 2005

Properties *of harena fossica*

For Vitruvius (II, 4, 3) volcanic sand is the standard of construction: “But quarry volcanic sand quickly dries in buildings (*Fossiciae uero celeriter in structuris siccescunt*), and the surface lasts (*et tectoria permanent*); and it admits of vaulting (*et concamerationes patiuntur*), but only that which is fresh from pit (*sed hae quae sunt de harenariis recentes*).”

Distinction between true pozzolana and volcanic sand

Vitruvius II, 6, 1: *Utraque autem sunt egregia in structuris, sed alia in terrenis aedificiis, alia etiam in maritimis molibus habent virtutem.*

« Pozzolana and volcanic sand are excellent in walling. But the latter have advantages in buildings on land, and pozzolana in piers built into the sea. »

Pozzolana in Vitruvius

- Vitruve II, 6, 1: *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 wonbderful 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 alos, when piers are built in the sea, they set under water. » (F. Granger)

Vitruvian theory of 4 elements

- Each substance in Nature has four elements: *terra* "earth", *aqua* "water", *aer* "air" and *ignis* "fire »
- Their proportions determine their physical properties (hardness, softness, etc.)

Vitruvian theory of 4 elements

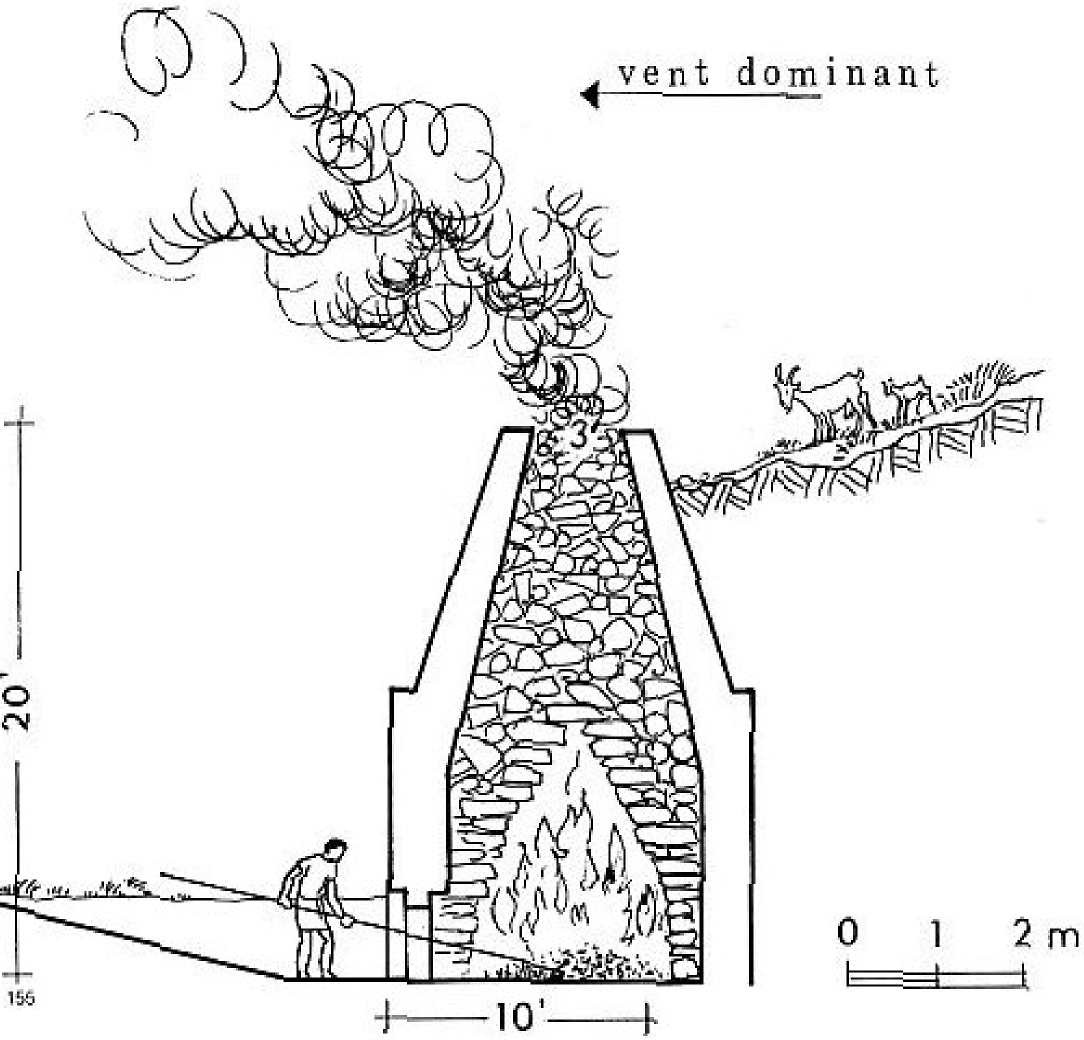
- The volcanic/artificial fire destroys the coherence of any stone,
- Lime is the result of expelled air and water from limestone (Vitr. II, 5) whereas roman lava containing more earth and water than air and fire, withstand better fire and weathering (Vitr. II, 7, 2).

Vitruvian theory of 4 elements

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).

Kiln = volcanism

How does materials gain their physical properties ?



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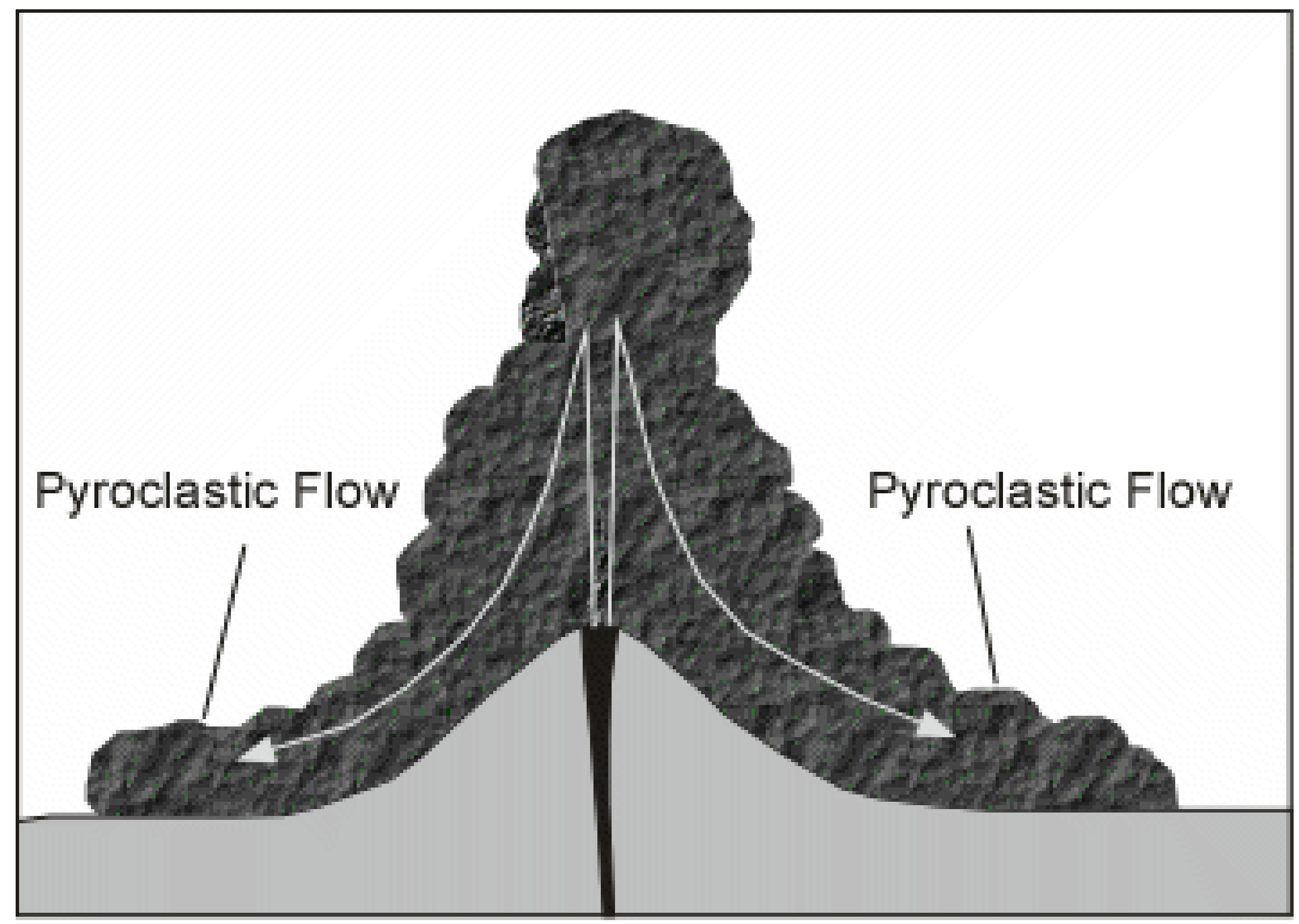


Limekiln = Volcano

List of natural material for mortar/concrete

- 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”

List of artificial materials for mortar/concrete

- *Calx* « lime »
- *Testa* « calcined kaolinitic clay at 750 °C, metakaolin »
- All those materials have been charred by natural (volcanism) or artificial fire (kiln)

Vitruvius V, 12, 2-3

2. Eae autem structurae quae in aqua sunt futurae uidentur sic esse faciendae uti portetur puluis a regionibus quae sunt a Cumis continuatae ad promuntorium Mineruae iisque misceatur, **uti in mortario duo ad unum respondeant.**

3a. Deinde tunc in eo loco qui definitus erit, arcae stipitibus robusteis et catenis inclusae in aquam demittendae destinandaeque firmiter. Deinde inter ea ex trastillis inferior pars sub aqua exaequanda et purganda, et **caementis ex mortario materia mixta quemadmodum supra scriptum est, ibi congerendum**. Denique compleatur structura spatium quod fuerit inter arcas. Hoc autem munus naturale habent ea loca quae supra scripta sunt.

Vitruvius V, 12, 2-3

« 2. The masonry which is to be in the sea must be constructed in this way. Earth (pozzolana) is to be brought from the district which runs from Cumae to the promontory of Minerva (Sorrento), and **mixed, in the mortar/mixing tank, two parts to one of lime**.

3a. Then in the place marked out, cofferdams formed of oak piles and tied together with chains, are to be let down into the water and firmly fixed. Next, the lower part between them under the water is to be levelled and cleared with a platform of small beams laid across and the work is to be carried up with **stones and mortar as above described, until the space for the structure between the dams is filled**. Such is the natural advantage of the places described above. »

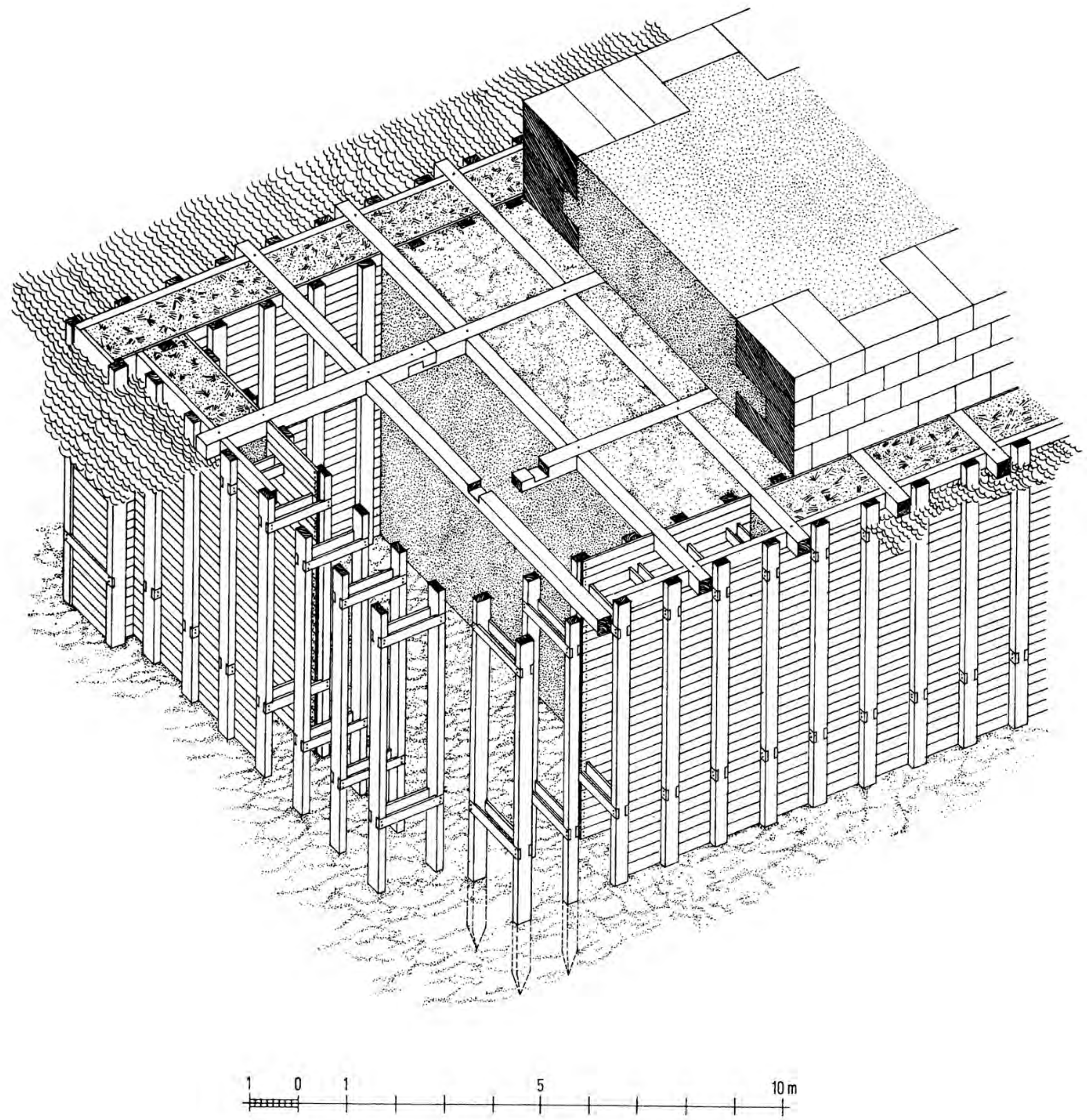
Materials and tools

- *puluis a regionibus quae sunt a Cumis continuatae ad promunturium Minervae* « Earth/ pozzolana brought from the district which runs from Cumae to the promontory of Sorrento »
- *calx* « quicklime »
- *materia* « binder made from 2 of pozzolanea (*puluis*) and 1 of lime (*calx*) ».
- *caementum* « volcanic tuff »
- wood cofferdams
- *mortarium* « mixing tank ».

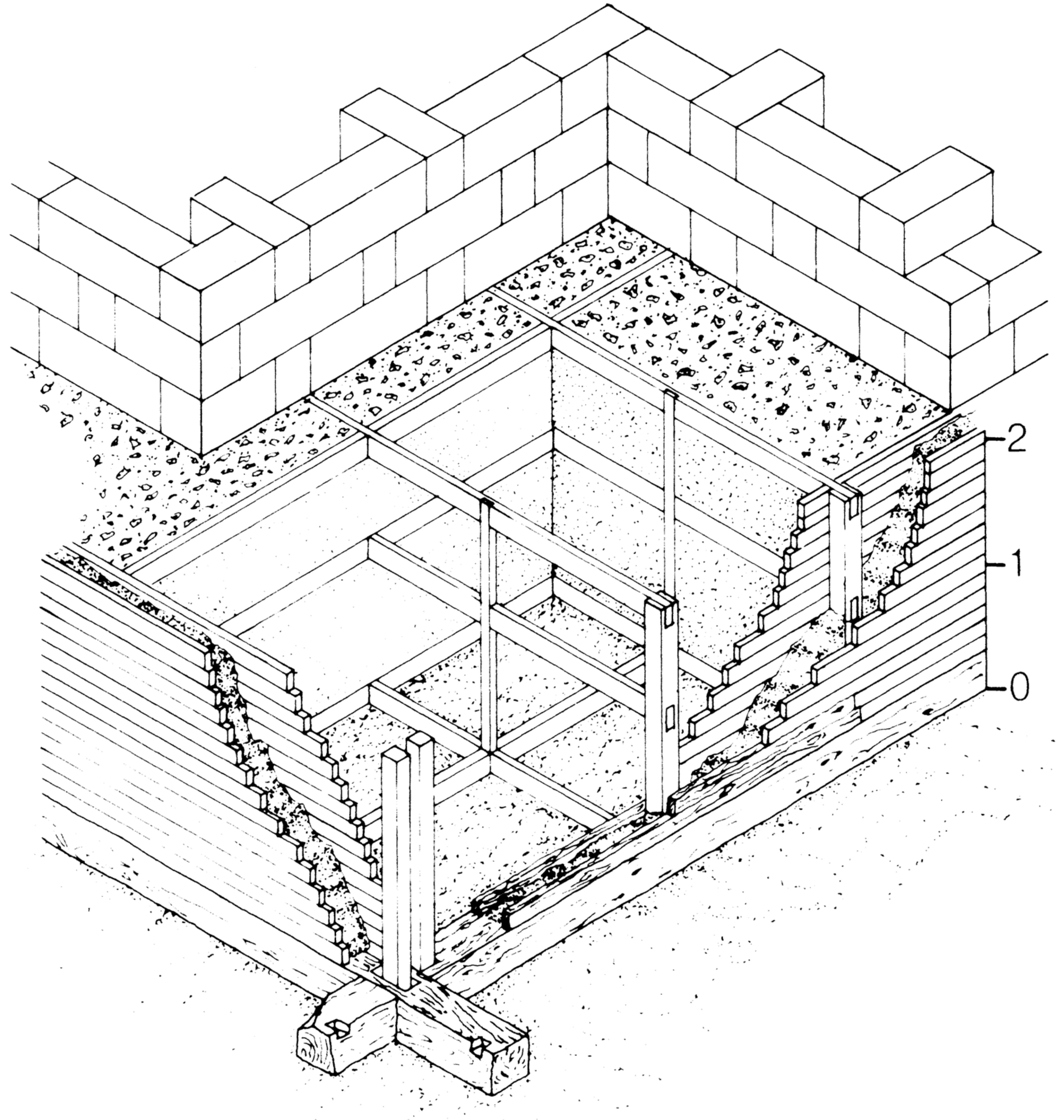
Fabrication des môles

- *miscere puluerem uti in mortario duo ad unum respondeant* «mix in the mixing tank, two parts to one of lime »
- *arcas stipitibus robusteis et catenis inclusas, in aquam demittere destinareque firmiter* « let down into the water cofferdams formed of oak piles and tied together with chains and firmly fixed »
- *deinde interea ex transtilis inferiorem partem sub aqua exaequare et purgare* « next, level the lower part between them under the water and clear with a platform of small beams laid across »
- *et caementis, ex mortario materia mixta quemadmodum supra scriptum est, ibi congerere* « carry up the work with stones and mortar as above described »

- chemical reactions of slaking lime in the cofferdam: *cum tres res consimili ratione ignis uehementia formatae in unam peruenerint mixtionem, repente recepto liquore una cohaerescerunt et celeriter umore duratae solidantur neque eas fluctus neque uis aquae potest dissoluere* (2, 6, 1)
    - « therefore, when three substances (volcanic tuff, quicklime, pozzolana) formed in like manner by the violence of fire come into one mixture, they suddenly take up water and cohere together, they are quickly hardened by the moisture and made solid, and can be dissolved neither by the waves nor the power of water ».
    - Slaking lime by seawater produce the chemical phenomenons described by Vitruvius 2, 6, 1-4.
- *complere structura spatium, quod fuerit inter arcas* « fill the space for the structure between the dams ».



Double dam according to Vitruvius (5, 12) ;
scale 1/150 (Schläger 1971)



Dam of « G zone » in *Caesarea Maritima* (Haifa, Israel); drawing : R. L. Vann (Oleson 1988)

ROMACON experiment

- In september 2004, ROMACON's team (Robert Hohlfelder Univ. of Colorado, Christopher Brandon architect London, J. P. Oleson Univ. of Victoria Canada) wanted to build a pila « pier » in Brindisi harbour (Italy).
- The cement firm *Italcementi* provided the materials: slaked lime, pozzolana and volcanic rubbles from Bacoli (Naples) and planks.

Figure 1. C. Brandon examines the completed form before filling. (R. L. Hohlfelder)

- Ratio of lime/pozzolana: 1/2.
- The binder was very stiff that would not dissipate when dropped into the inundated form.
- The mortar was far toor viscous to poured down a tremie-tube like
- That is why the binder was lowered into the form using a wicker basket with two drop lines along with a trip line.

Figure 2. Mortar is lowered into the form using a wicker basket with two drop lines along with a trip line. (R. L. Hohlfelder)

Figure 3. R. L. Hohlfelder stands on the concrete on the morning after the last mortar and aggregate had been placed in the form. (J. P. Oleson)

- Each layer had a thickness of approximately 20 cm then the surface was tamped using rakes,
- Volcanic rubble was thrown randomly « in an effort to cover the entire surface of the mortar unseen beneath the murky surface within the form » and tamped.
- 8 m^3 concrete made after 273 man-hours of work.
- Concrete sampling were taken after 3, 6 and 12 months.

Results

- Use of napolitan pozzolana as in *Caesara Maritima* (Oleson, Branton 1992).
- Samples show that compressive strength result is interesting after a year: between 4,5 and 5,6 MPa (Gotti *et al.* 2008).
- Binder formula take up Vitruvius' recipe (1 lime / 2 pozzolana), but ratio is better with a reformulated ratio est meilleure avec 1/2,7 from a *pila* of villa of Domitii Ahenobarbi in Santa Liberata (Grosseto, Italy).

- « We have shown that the Vitruvian formula for pozzolanic concrete in fact produces a more or less appropriate result, although a slightly higher ratio of pozzolana to lime results in properties more in line with the ancient sample tested so far.» (Gotti, and al. 2008)
- « It may be that Vitruvius was following some ideal academic rule, rather than existing practise. »
- According to the authors, a better formula was designed by later roman engineers during first century A. D.
- However « further research by the authors may lead to new or revised conclusion. »

- Something is missing in Gotti, Oleson 2008: la « quicklime » *calx viva*.

- Vitruvius (2, 6, 4) reformulates description of hydraulic concrete setting with the concept of *ieiunitas*, « desiccation / elementar instability » inside lime, tuff and pozzolana.

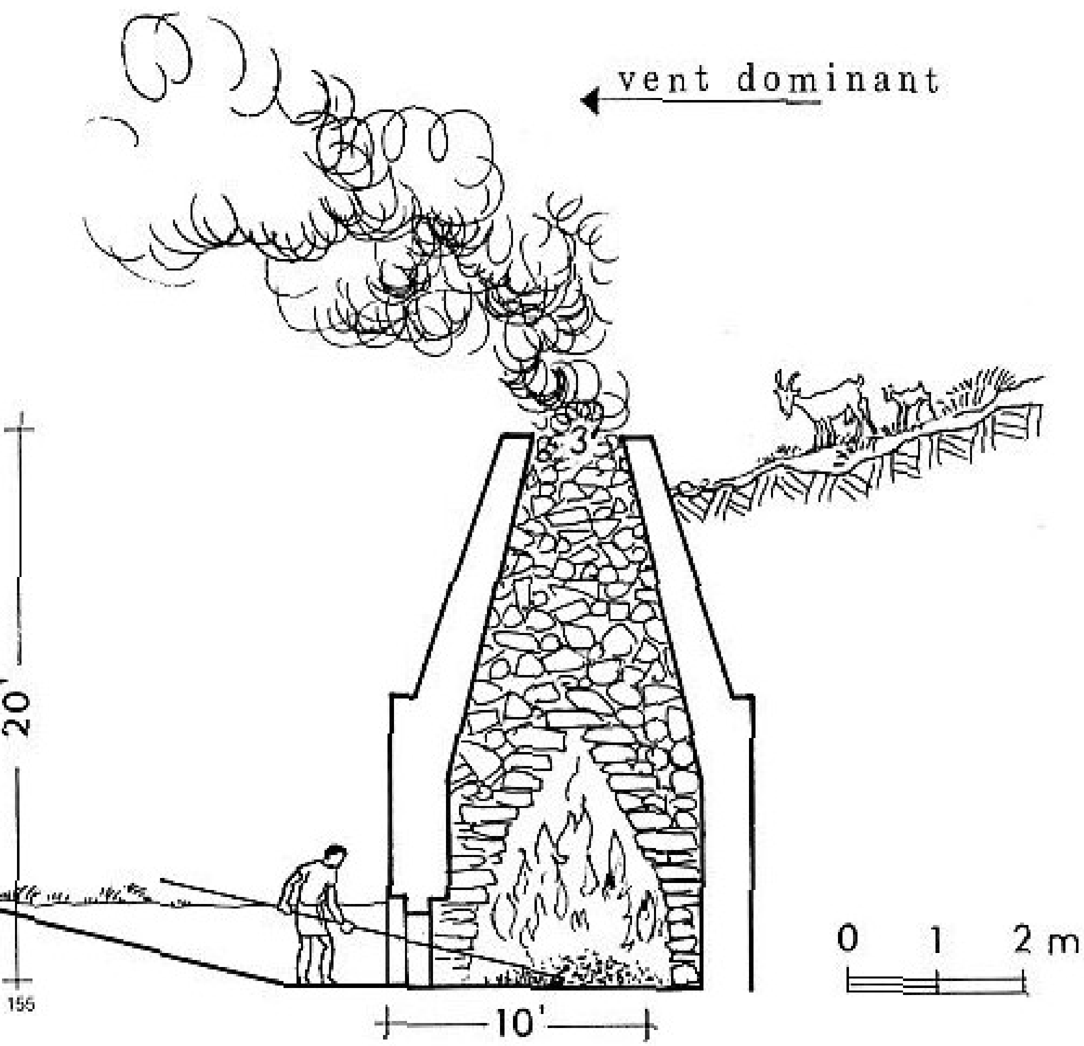
- « Therefore, when unlike and unequal substances are caught together and brought into one nature (*dissimilibus et disparibus rebus correptis et in unam potestatem conlatis*), the hot desiccation (of the expelled « water element » *calida umoris ieiunitas*), suddenly saturated with (sea)water (*aqua repente satiata*) seethes together (*conferuescit*) with the latent heat in the bodies affected (*communibus corporibus latenti calore*), and causes them to combine vehemently (*et uehementer efficit ea coire*) and to gain rapidly one strong solidity (*celeriterque unam soliditatis percipere uirtutem*). »

- chemical reactions of slaking lime in the cofferdam: *cum tres res consimili ratione ignis uehementia formatae in unam peruenerint mixtionem, repente recepto liquore una cohaerescerunt et celeriter umore duratae solidantur neque eas fluctus neque uis aquae potest dissoluere* (2, 6, 1)

- « therefore, when three substances (volcanic tuff, quicklime, pozzolana) formed in like manner by the violence of fire come into one mixture, they suddenly take up water and cohere together, they are quickly hardened by the moisture and made solid, and can be dissolved neither by the waves nor the power of water ».

- Slaking lime by seawater produce the chemical phenomenons described by Vitruvius 2, 6, 1-4.

How does materials gain their physical properties ?



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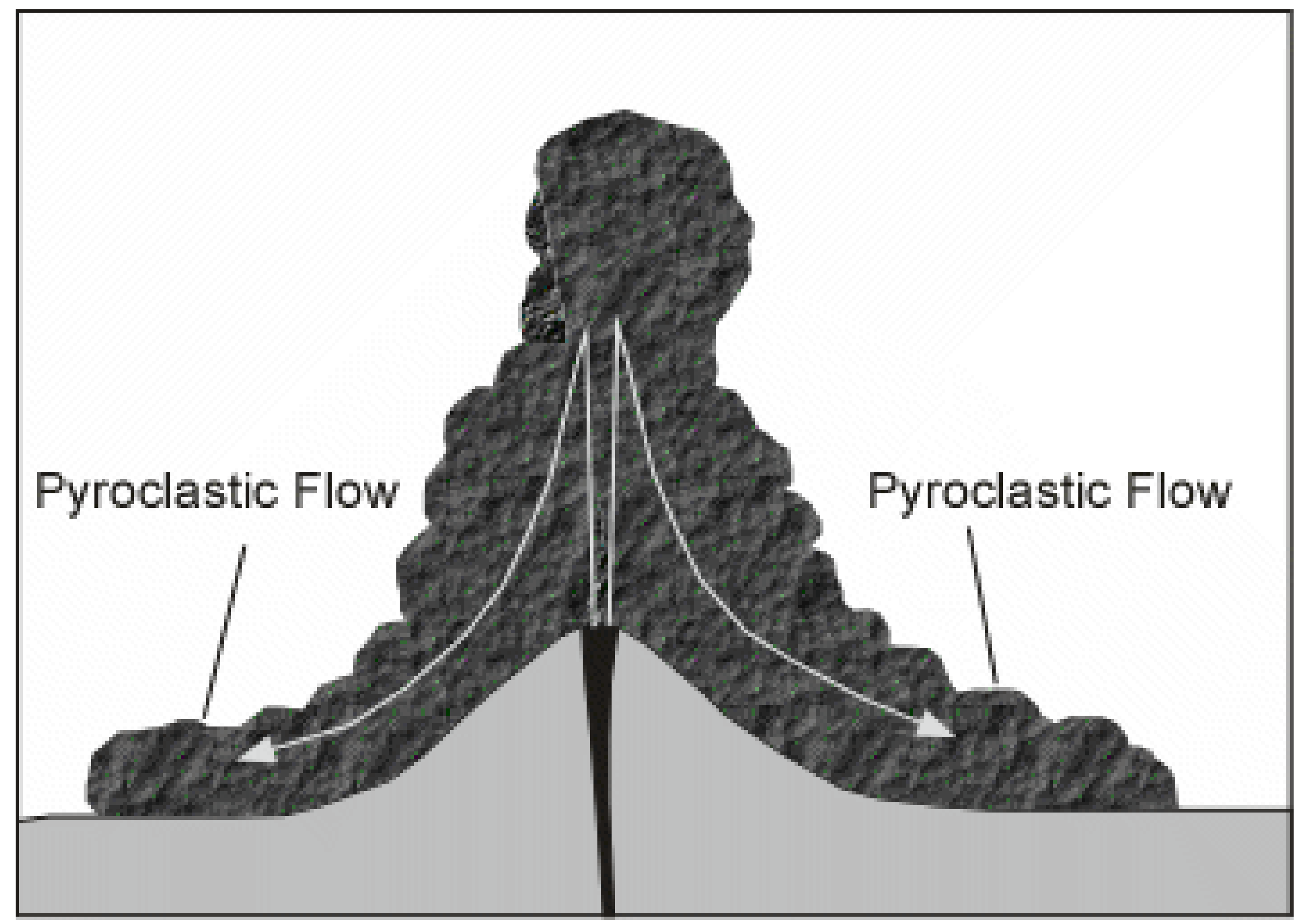

Limekiln = Volcano

Quicklime in hydraulic concrete

- Presence of quicklime is in the verb « to seethe » (*confeuerscit*) when tuff, quicklime and pozzolana are poured in seawater.
- Exothermic reactions are evidence for quicklime.
- Construction logistics is to be rethought
- *Mortarium* « mixing tank » instead of mortar where mixing is done.

Quicklime in hydraulic concrete

- This was discovered in 2005-2007 in Vitruvius text during my Ph. D. redaction.
- In 2017, Marie D. Jackson (Univ. of Utah) (Jackson *et alii* 2017): « An adiabatic model of exothermic heat evolved during hydration of lime and production of pozzolanic C-A-S-H binder in a 10 m2 by 6 m tall *Baianus Sinus* breakwater in the Bay of Pozzuoli, indicates that elevated temperatures, 65–95 °C, persisted for 2–3 yr. »

Appendix Table 1

Roman texts describing the geologic materials and cementitious processes of marine concrete, translations (Oleson 2014)

	English Translation	Interpretation
Vitruvius 30–22 BCE *de Architectura* 2.6.1	There is a kind of powdery earth (*pulvis*) that by its nature produces wonderful results. It occurs in the neighborhood of Baiae and the territory of the municipalities around Mount Vesuvius. This material, when mixed with lime and rubble (*calce et caemento*) not only furnishes strength to other buildings, but also, when breakwaters (*moles*) are built in the sea, they set underwater… Thus, when these three substances (pumiceous ash (*pulvis*), lime (*calx*), and tuff (*tofus*)) formed in a similar manner by the strength of fire are brought together in one mixture, and suddenly they are put into contact with [sea-] water, they cohere into a single mass, quickly solidifying, hardened by the moisture, and neither the effect of the waves nor the effect of water can dissolve them.	Hydration of lime and pumiceous volcanic ash from the Campi Flegrei (and Vesuvius) volcanic districts (Fig. 2) with seawater created pozzolanic reactions that produce cementitious hydrates, mainly C-A-S-H, and rapid solidification of massive concrete structures that resisted the erosive action of seawater and the force of impact of storm waves in the marine environment.
Vitruvius 30–22 BCE *de Architectura* 2.6.4	Therefore, when dissimilar and incompatible materials [lime (*calx*), pumiceous ash (*pulvis*), and tuff (*tofus*) are taken and mixed in a moist environment the urgent need of moisture suddenly satiated by [sea-] water seethes with the latent heat in these substances and causes them to gather into a unified mass and gain solidity quickly.	Exothermic heat evolved from the production of C-A-S-H binder through pozzolanic reaction of lime, pumiceous ash, and seawater led to rapid solidification of the marine concrete.

Appendix table 1 (Jackson *et alii* 2017)

Conclusion

- The idea (Vitruvius is a pure theorician and not an engineer) is false: Vitruvius' recipes for concrete are operative, but they can be improved.
- Logistics for mixing quicklime with pozzolana: dry mixing ?
- Seawater extinguishes lime.
- ROMACON experiment established that the concrete set for one year.
- One year long for setting is unoperative for a military use: Vitruvius V, 12, 4 write that normal concrete should take 2 months minimum for setting.

@

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