Water in Ancient Construction

Javier Martínez Jiménez

The importance of water in the Roman world needs no underlining: from aqueducts and sewers, to powering flour mills, mining and, above all, bathing. The importance of water in Roman industries and secondary productions (pottery, textiles, fish sauces, etc.) has also usually been acknowledged in recent research, but without enough detail regarding the sourcing, use, storage, and distribution of water in these facilities. In this context, construction as an industry is no different. Water was necessary at many stages on construction sites, and in the larger projects, the logistics of sourcing, storing and disposing of water must have been quite complex. Furthermore, most of the studies done on the economics of construction[1] have focused on the amounts, sourcing, and expense of all other elements: lime, bricks, tiles, stone, manpower, metal, timber, etc. Perhaps because water is freely sourced and it has no apparent impact on the budget it is felt that water had no economic impact on construction projects. However, stone, lime and timber can be easily stored and, even if heavy, easily transported; water poses, from this perspective, different challenges, especially in those cases when water was needed on site.

In this paper I will address three elements of construction that require water: mortars, plasters, and pisé. From ancient mixing proportion (largely from Vitruvius and Pliny, together with modern reconstructions, and technical recommendations), it may be possible to obtain some volumetric ratios between the final (archaeological) structure and the original amount of water input, which could serve as a stepping platform from which to infer the order of magnitude of water necessary on Roman construction sites.

Pisé

Mud was the earliest material used in construction. Mud structures have been identified in a pre-ceramic site at the Wadi Faynan in Jordan,[2] and it remained in use both structurally and as a binder into the Roman period and beyond. From Pliny we know that structural rammed earth was characteristically used *in Africa Hispaniaque* already in the time of Hannibal, something also evident archaeologically.[3] Mud was also used in the form of pre-fabricated blocks: either uncooked (mudbrick) or baked (bricks, terracottas) forms.

Rammed earth or pisé[4] is the technique by which earth is trampled into a coffering, usually on top of stone or rubble foundations. It is simple and cheap, while offering good insulating properties and, despite what it may seem, is durable. Pisé walls, as calculated from granulometric analyses, are made of clay (15–25%, as more would result in cracks during the drying process), sand to increase the volume

Published in: Elena H. Sánchez López (Ed.), The Role of Water in Production Processes in Antiquity, Panel 3.19, Archaeology and Economy in the Ancient World 21 (Heidelberg, Propylaeum 2020) 11–20. DOI: *https://doi.org/10.11588/propylaeum.572*

Material	Density (kg/m³)
Mortar mix (putty + sand, 1 : 3 vol)	2400
Pisé	1800-2100
Pozzolana	1370
Quicklime (CaO)	3340
Sand	1555
Slaked lime putty ($Ca(OH)_2 + H_2O$)	1600 (fresh) – 1350 (matured)
Water	1000

Fig. 1: Reference table with the densities of the materials discussed in the text.

(40–50%), gravels (0–15%), and silts (20–35%). Lime and straw were sometimes added to improve the physical characteristics of the earth: straw gave further cohesion by diminishing retraction (and cracking) during curing while lime (which partly reacted with the humidity of the clay), improved the hardness.[5]

The way pisé was prepared was by mixing the clay with the aggregates and adding enough water to ensure that the mix absorbed 8–10% of its weight in water – a very stiff mix. Considering that the clays and the aggregates, even if they had been left to cure and dry for several months[6], already had some humidity in them, the amount of water that was necessary to add to the mix appears to have been minimal. Considering the density of pisé, for every cubic meter of earth only between 144 and 210 l of water would have been needed, meaning that an approximate maximum of 15–20% of the final volume of pisé was originally added as water.

Mortars

Lime mortars are a material widely used in construction because of their cementitious properties. This means, that they chemically transform when mixed with water into a paste, as they cure (dry) to become new rigid solids (losing moisture to the air, and carbonising CO_2 from the atmosphere) that bind coarser aggregates together (fig. 2).[7]

Lime mortars are made by mixing quicklime (obtained from burning limestone) with water (a process known as slaking), which results in a slaked lime putty. Slaking requires large quantities of water, which is normally done theoretically in a proportion of 1 : 4, 1 : 3[8] or, more experimentally, 1 : 2.1[9], lime to water, per weight. Considering the densities of both quicklime and of water, these rise up to a 1 : 7 and even 1 : 13 in volume (fig. 3).

This lime putty (which might have been between 60–80% water in volume) could have either been used fresh, or left to cure over a period of time, during which the

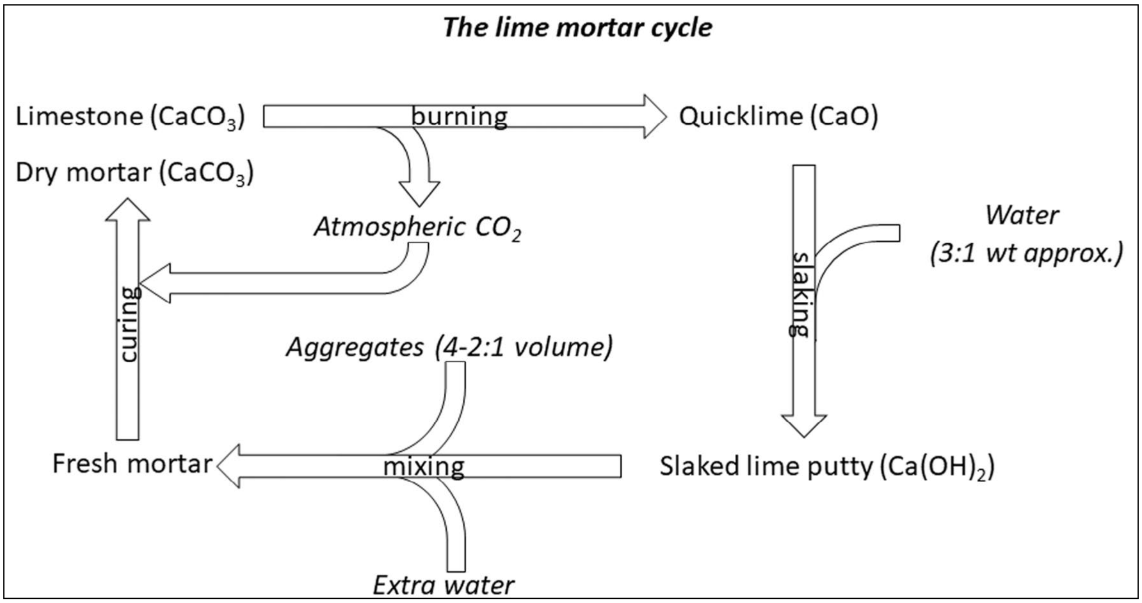

Fig. 2: The chemical cycle of lime mortar.

Quicklime to water volume rations as derived from weight proportions

1:3	**1:2.1**	**1:4**
$m_w = 3 \cdot m_{ql}$	$m_w = 2.1 \cdot m_{ql}$	$m_w = 4 \cdot m_{ql}$
$v_w \cdot d_w = 3 \cdot (v_{ql} \cdot d_{ql})$	$v_w \cdot d_w = 2.1 \cdot (v_{ql} \cdot d_{ql})$	$v_w \cdot d_w = 4 \cdot (v_{ql} \cdot d_{ql})$
$v_w = 3 \cdot (v_{ql} \cdot d_{ql}) / d_w$	$v_w = 2.1 \cdot (v_{ql} \cdot d_{ql}) / d_w$	$v_w = 4 \cdot (v_{ql} \cdot d_{ql}) / d_w$
$v_w = 3 \cdot 3340 \cdot v_{ql} / 1000$	$v_w = 2.1 \cdot 3340 \cdot v_{ql} / 1000$	$v_w = 5 \cdot 3340 \cdot v_{ql} / 1000$
$v_w \approx 10 \cdot v_{ql}$	$v_w \approx 7 \cdot v_{ql}$	$v_w \approx 13 \cdot v_{ql}$
1:3 (wt) = 1:10 (vol)	**1:2.1 (wt) = 1:7 (vol)**	**1:4 (wt) = 1:13 (vol)**

m = mass; v = volume; d = density
$_w$ = water; $_{ql}$ = quicklime

Fig. 3: Conversion of the slaking proportions from weight to volume ratios, as calculated using the formula V = m · d.

density would decrease as the lime expands. Cured appears to have been preferred in Roman times (sometimes after years of curing: Pliny *NH* XXXVI.55). The putty is then mixed with dry aggregates (most commonly sand) in a volume proportion, which varies from 1 : 2 to 1 : 4 [10], to increase the volume and prevent the mix from shrinking when curing.[11] However, traditional masons appear to have applied this 1 : 3 rule to the amount of quicklime, and not of slaked lime putty[12] – perhaps

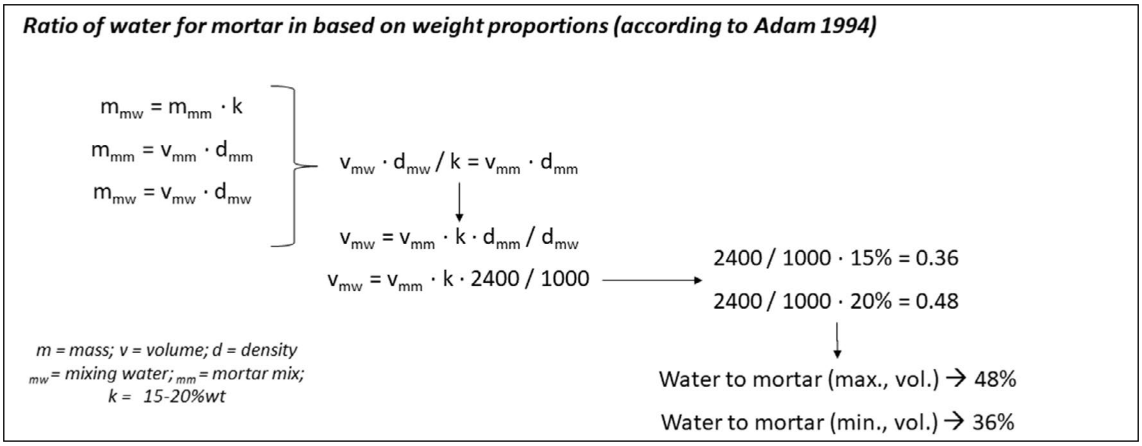

Fig. 4: Calculations for the ratio (percentage) in volume between fresh mortar and the water necessary to mix it, given an ideal mix of putty to sand (1 : 3 vol), where the putty was slaked in a 1 : 3 (wt) mix.

as a way of cost-management from the beginning of the project, and linked to on-site slaking with a 'volcano'. This may account as to why some analyses on Roman concretes show that this 1 : 3 ratio appears to not have been followed.[13] Aggregates absorb water and humidity from the putty during the mixing.[14] In order to correct the rheology, and to counter this water absorbed by the aggregates (ranging between 0.6–8%wt for sand, 10–20%wt for bricks and 10–30%wt for sands), more water is then added to the mix. This amount of corrective water depends too much on the individual circumstances of each mortar mix,[15] and from experimental trials,[16] it appears to be between 15–20% of the final weight of the putty mixed with the aggregates. With the densities of putty and sand, this means that the volume ratio is close to 36–48% of the mortar mix (fig. 4), although this is based on an average density for the mortar mix, and it will vary greatly according to the putty to aggregate ratio and the varying densities of the aggregates themselves.

In some cases (especially in Italy, with the use of local volcanic sands), the dry aggregates added to the lime putty were not chemically inert. Volcanic materials and crushed pottery have pozzolanic properties, which means that they react with the slaked lime, stopping it from carbonising back to limestone, forming a new silicon-based compound. As a result, these mortars cure under water, and are waterproof on land. This was developed during the first century BC in Italy and then spread through the empire.[17] The mixing proportions of putty to aggregate appear to have been the same as with normal lime mortars.

This mortar (whether with pozzolanic materials or not) on its own cannot be used for construction; it has to be a binder. This can be done in a masonry structure (rubble, stone, bricks) or, in "Roman concrete", with coarser aggregate (the *caementa*), which could be used structurally in walls, vaults and domes. These elements also absorb moisture from

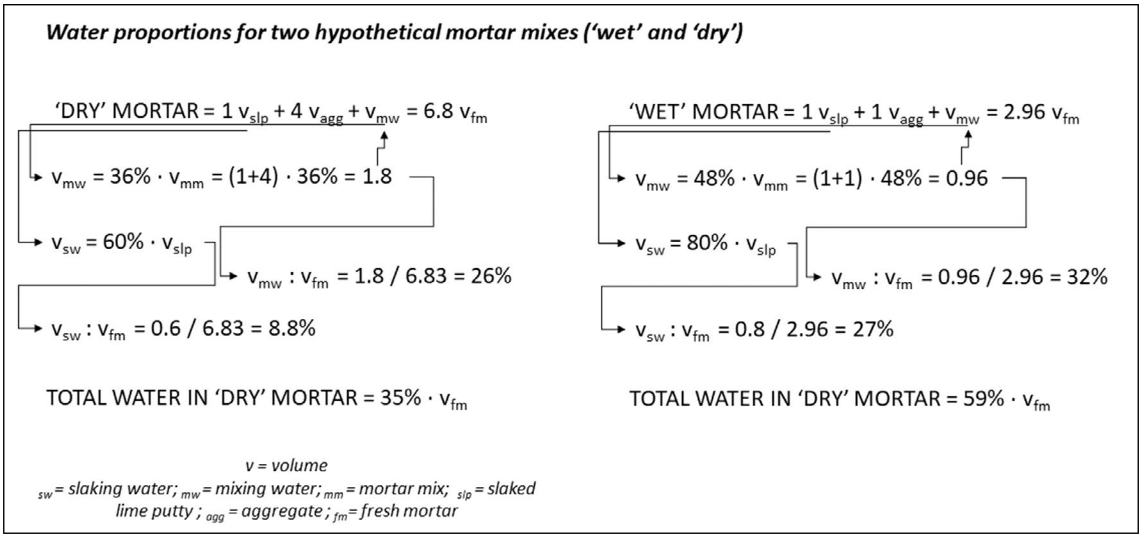

Fig. 5: Overall water consumption necessary (slaking and mixing) for a given volume of fresh mortar.

the freshly mixed mortar. In order to prevent the mortar from drying to quickly (which would cause cracks), it is necessary to soak the *caementa* (especially bricks) and other porous elements in contact with the mortar (like timbers). Furthermore, and depending on the weather, water may need to be splashed over the surfaces. The amount of water needed for this varies according to the absorption properties of each material and the weather conditions, making it impossible to calculate.

For the mix and the slaking, however, it is possible to present these over simplified calculations, based on two different mixes, a 'wet' and a 'dry' mortar. A more detailed study will give more accurate results. But put together, it appears that a standard ideal lime mortar, might have had a 35–60% input as water (fig. 5), plus any excess mortar, variations in the mix proportions, the water added to saturate the *caementa* or to keep the mortar from drying too quickly. The actual range may be closer to 50–75%.[19]

Plaster

Plaster is, like mortar, a substance that can be hydrated into putty, which quickly dries to a solid.[20] Plaster was usually applied on walls to protect it, but was also a way of decorating them, both inside and outside. Because of their exposed nature, plasterworks need to be renovated periodically. Plasters and stuccoes could, furthermore, be painted over or moulded into different shapes, and were applied on timber, stone or bricks.

Most plasters are based on lime and gypsum, the latter having two main advantages: it does not require high-temperature furnaces to become active, and it cures quickly after being mixed with water. Rather than going through a whole calcium cycle, when gypsum ($CaSO_4 \cdot 2H_2O$) is fired it loses part of its internal water ($2\ CaSO_4 \cdot H_2O$), which is then reabsorbed from the hydrated putty forming gypsum again. This is a much quicker process, as already described by Pliny[21] and Vitruvius[22], which is why lime and gypsum were mixed.

Plastering is in itself a complex process, which involves various layers (normally three) of different mixes before the final one is applied; and if to be painted on, this will have to be done on a fourth one. Modern and medieval plasterworks from Iberia were formed as follows:[23] The undercoat was a first (sometimes also a second), rough surface to even and flatten the wall, some 10–15mm in thickness. This was done with a stiff lime mortar, with a 1 : 1 or 1 : 2 lime putty-to-sand volume ratio. The preparation coat was similarly used to create an even surface on which to work the final layer. This gypsum-lime-sand plaster (volume mix of 1 : 2 : 1), was applied in two coats: one rough and the second smoothed, and up to 10mm thick. After this layer cures, it is dampened again before applying the finishing coat, which is much finer, with hardly any sand and either a gypsum-lime mix or only gypsum putty.

All of these mixes had to be hydrated while mixing, probably quite often to prevent the gypsum plaster from drying too quickly. While the lime putty would have been brought on site already hydrated, the gypsum mix would have had to be watered in situ.

Thinking about Water Logistics

Considering the amounts of water proposed in this quick overview, it is now possible to think about the dynamics and logistics of water supply in Roman construction sites. For example, in pisé construction, the amount of water necessary does not seem to have been very big. Furthermore, because each course of coffering needs to be fully dry before the next one can be trampled, and average coffers were no more than three or four planks high, pisé constructions would have only required water at the sporadic moments of mixing the clay.

In mortar construction, however, water is much more abundant in proportion and in frequency, which would require a steady supply at different stages, especially slaking and mixing. Slaking could be done on site, which has the advantage of giving easy access and facilitating the transportation of the lime (which is lighter than the putty). On site it would be possible to slake the lime in pits or vats and allow it to cure for some weeks (certainly not for long years), although not all construction sites would have had enough space to accommodate this (or could secure enough water to do it). Plus, slaking is a very exothermic reaction, and thus dangerous. An alternative to this would be off-site slaking, which would also allow it to cure for as long as necessary and then transport the putty to wherever it was necessary. Adding a middleman such as a putty provider could have added costs to the budget. One of the houses of Pompeii, under repairs at the time of the eruption, had a stack of lime putty, suggestion that this solution appears ideal for small works, when it is only necessary to mix the lime and the aggregate in situ. However, on large construction sites, or at periods of large-scale construction, it might have been necessary to slake the lime on site, together with the mixing. An example of such 'volcano' mixing is depicted in a mosaic in the Bardo museum.[24] At this point, logistics could become more complicated if water was necessary in large quantities – especially over the summer. If the baths of Caracalla serve as an example, there we know that the aqueduct and the cisterns appear to have been the first things to be built.[25]

We should keep in mind that, thanks to the Roman concrete revolution, it was not only walls and vaults built with mortar. The tiles of the roof were bound with it, the floors (either *opus signinum* o mosaic) required mortar; so did the foundations, plastering and whitewashing. Lime and aggregates might have been essential in the budgeting – ultimately dictating the viability of the project,[26] but water was necessary at every stage of the process. Imperial baths and palaces, aqueducts, city walls, amphitheatres, etc. – these are structures in the range of thousands of cubic metres of structural concrete, roofs, decorations, etc.

How water was supplied to such large construction project still needs further research. Most certainly water from wells, rivers or cisterns (and fountains urban contexts) was obtained, but it would make a difference in term of man-hours if water was sourced or stored on site, and if stored, how it was supplied (water wheels? Pipelines? Bucket chains?). Construction in rural contexts (especially aqueducts, which required large amounts of mortar in difficult locations) would have required completely different dynamics and logistics, perhaps with a number of mixing stations and then the mixed mortar was carried to its final place – as can be seen on Trajan's column with fortification efforts.[27]

Lime, sand, timber, stone, bricks, manpower; all of these elements would be tallied in the final budget, but considering the amounts of water involved, more thought needs to be put into the logistics of water supply.

Notes

[1] e.g. DeLaine 1997.

[2] Mithen et al. 2011.

[3] Plin. nat. 35, 48; Uribe Agudo 2006.

[4] Pisé is understudied for the Ancient world. Wright 2005, 90 already pointed out that, "[a]t the present time[,] understanding of this construction is based on ancient reference fitted to modern practice".

[5] Fuentes García 2010, 3.42–3.70.

[6] Fuentes García 2010, 3.70.

[7] Adam 1994, 74 f.; Wright 2005, 46–84.
[8] Goldsworthy – Min 2009; Harper 1934; Lancaster 2005, 53; Wright 2005, 146.
[9] Brune 2010, 336.
[10] Lancaster 2005, 545; Siddall 2010, 166.
[11] At a proportion of 1:5 wt (=1:17 vol), the mix becomes limewash; Adam 1994, 73.
[12] Lynch 2007.
[13] Jackson et al. 2009, 2484.
[14] Oleson et al. 2004, 219.
[15] Brune 2010, 18. 330; but, as a general rule Adam 1994, 74.
[16] Brune 2010, 338.
[17] Mogetta 2013.
[18] Here we are leaving mortars with crushed pottery (opus signinum) aside, as pottery was never used on its own, but mixed with sand, and other aggregates, making the calculations more complicated.
[19] These are in relation to the mortar itself, not necessarily the concrete, which even if forming a monolithic solid, the mortar itself was mixed with coarse aggregate. For opus caementicium, etc., it will be necessary to calculate what proportion of it was caementa and how much mortar.
[20] Wright 2005, 159 f.
[21] Plin. nat. 36, 49.
[22] Vitr. 7, 3, 3.
[23] Malta da Silveira et al. 2007.
[24] Adam 1994, 76 fig. 164.
[25] DeLaine 1997.
[26] Oleson 2010.
[27] Goldsworthy – Min 2009, 237.

Image Credits

Fig. 1–5 by the author.

References

Adam 1994 [1989]
J. P. Adam, Roman Building. Materials and Techniques (London 1994).
Brune 2010
P. Brune, The Mechanics of Imperial Roman Concrete and Structural Design of Vaulted Monuments (PhD Thesis Rochester 2010).
DeLaine 1997
J. DeLaine, The Baths of Caracalla: a Study in the Design, Construction and Economics of Large-Scale Building Projects in Imperial Rome. JRA supplement series 25 (Portsmouth 1997).

Fuentes García 2010
R. Fuentes García, Construcciones de tierra. El tapial, nuevo sistema para construcción y restauración mediante la ´tecnica „tierra proyectada“ (PhD Thesis Granada 2010).
Goldsworthy – Min 2009
H. Goldsworthy – Z. Min, Mortar Studies towards the Replication of Roman Concrete, Archaeometry 51.6, 2009, 932–946.
Harper 1934
E. Harper, Lime slaking, Journal of the American Water Works Association 26.6, 1934, 750–756.
Jackson et al. 2009
M. Jackson – J. M. Logan – B. E. Sceetz – D. M. Deocampo – C. G. Cawood – F. Marra – M. Vitti – L. Ungaro, Assessment of Material Characteristics of Ancient Concretes, Grande Aula, Markets of Trajan, Rome, JASc 36, 2009, 2481–92.
Lancaster 2005
L. Lancaster, Concrete Vaulted Construction in Imperial Rome. Innovations in Context (Cambridge 2005).
Lynch 2007
G. Lynch, The Myth in the Mix. The 1:3 ratio of lime to sand (2007) <http://www.buildingconservation.com/articles/mythmix/mythmix.htm> (accessed 2018).
Malta da Silveira – Veiga – de Brito 2007
P. Malta da Silveira – M.R. Veiga – J. de Brito, Gypsum Coatings in Ancient Buildings, Construction and Building Materials 21.1, 2007, 126–131.
Mithen et al. 2011
S. Mithen – B. Finlayson – S. Smith – E. Jenkins – M. Najjar – D. Maričević, An 11 600 year-old Communal Structure from the Neolithic of Southern Jordan, Antiquity 85.328, 2011, 350–364.
Mogetta 2013
M. Mogetta, The Origins of Concrete in Rome and Pompeii (PhD Thesis Ann Arbor 2013).
Oleson 2010
J. P. Oleson, Harena sine Calce: Building Disasters, Incompetent Architects, and Construction Fraud in Ancient Rome, in: Å. Ringbom – R. Hohlfelder (eds.), Building Roma Aeterna: Current Research on Roman Mortar and Concrete. Commentationes Humanarum Litterarum 128 (Helsinki 2010) 9–27.
Oleson et al. 2004
J. P. Oleson – C. Brandon – S. Cramer – R. Cucitore – E. Gotti – R. Hohlfelder, The ROMACONS Project. A Contribution to the Historical and Engineering Analysis of Hydraulic Concrete in Roman Maritime Structures, IntJNautA 33.2, 2004, 199–229.
Siddall 2010
R. Siddall, From Kitchen to Bathhouse. The Use of Waste Ceramics as Pozzolanic Additives in Roman Mortars, in: Å. Ringbom – R. Hohlfelder (eds.), Building Roma Aeterna: Current Research on Roman Mortar and Concrete. Commentationes Humanarum Litterarum 128 (Helsinki 2010) 152–68.
Uribe Agudo 2006
P. Uribe Agudo, La construcción en tierra en la arquitectura doméstica romana del nordeste de la Península Ibérica, Salduie 6, 2006, 213–23.

Wright 2005
G. Wright, Ancient Building Technology. Technology and Change in History VII 1, 2. Materials (Leiden 2005).