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ORIGINAL PAPER

Mortars and masonry—structural lime and gypsum mortars in Antiquity and Middle Ages

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Abstract
Mortar is of fundamental importance for the building technology. It is used to bind together masonry units and ease the building process. Several building techniques evolved to take advantage of the capacity of mortars to improve cohesiveness and form sound structures. In this paper, I discuss how lime and gypsum mortars were employed from the Antiquity to the Middle Ages. Gypsum mortars offered several advantages due to their adhesive properties and quick setting. Their use as a structural binding agent developed in regions rich in gypsum, and was particularly significant in vault construction. Lime mortars offered different advantages over gypsum ones, particularly in terms of mechanical resistance and resilience to humid conditions. The massive use of lime mortars started with the ancient Romans and continued throughout the centuries as the foremost binding material, until the introduction of Portland cement mortars in the nineteenth century.

Keywords Gypsum mortar · Lime mortar · Masonry · Concrete vaults · Tile-vaults · Brick

Premise

This Topical Collection (TC) covers several topics in the field of study, in which ancient architecture, art history, archaeology and material analyses intersect. The chosen perspective is that of a multidisciplinary scenario, capable of combining, integrating and solving the research issues raised by the study of mortars, plasters and pigments (Gliozzo et al. 2021).

The first group of contributions explains how mortars have been made and used through the ages (Arizzi and Cultrone 2021; Ergenç et al. 2021; Lancaster 2021, this paper). An insight into their production, transport and on-site organisation is further provided by DeLaine (2021). Furthermore, several issues concerning the degradation and conservation of mortars and plasters are addressed from practical and technical standpoints (La Russa and Ruffolo 2021; Caroselli et al. 2021).

The second group of contributions is focused on pigments, starting from a philological essay on terminology (Becker 2021). Three archaeological reviews on prehistoric (Domingo Sanz and Chieli 2021), Roman (Salvadori and Sbrolli 2021) and Medieval (Murat 2021) wall paintings clarify the archaeological and historical/cultural framework. A series of archaeometric reviews illustrate the state of the art of the studies carried out on Fe-based red, yellow and brown ochres (Mastrotheodoros et al. forthcoming); Cu-based greens and blues (Švarcová et al. 2021); As-based yellows and reds (Gliozzo and Burgio 2021); Pb-based whites, reds, yellows and oranges (Gliozzo and Ionescu 2021); Hg-based red and white (Gliozzo 2021) and organic pigments (Aceto 2021). An overview of the use of inks, pigments and dyes in manuscripts, their scientific examination and analysis protocol (Burgio 2021) as well as an overview of glass-based pigments (Cavallo and Riccardi forthcoming) are also presented. Furthermore, two papers on cosmetic (Pérez-Arantegui 2021) and bioactive (antibacterial) pigments (Knapp et al. 2021) provide insights into the variety and different uses of these materials.

This article is part of the Topical Collection on *Mortars, plasters and pigments: Research questions and answers*

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Introduction

In antiquity, mortared construction yielded monumental achievements as much as dry masonry construction. However, while ashlar masonry required huge and heavy stones, mortared construction employed smaller material units. The spread of mortared construction during the Roman empire enabled new forms of architecture and the adoption of vaulted structures.

Over the centuries different binders were used, principally earth mortars, bitumen mortars, lime mortars and gypsum mortars. Most of these binders were developed according to availability of local materials. Their study contributes to the understanding of the structures and forms.

Archaeometry contributes to the understanding of the characteristics of the different binders used for structural mortars and is fundamental for the interpretation of construction history. However, archaeometric studies are sometimes separate from the analysis of the masonry as a whole. With few exceptions, typically resulting from interdisciplinary studies (e.g. Jackson et al. 2014), most archaeometric work on mortars does not focus on why and how mortars affected the construction techniques and the structural conception of a building, on the way the building process contributed to form structurally sound structures, on how much builders were conforming to or departing from best practice.

The understanding of masonry needs a broader approach (Giuliani 2006). Binders, in fact, are not the main contributor to the capacity of a masonry type to withstand stresses. Resistance to stresses and durability depend on many factors, including the selection of materials, their manufacture, the building process, the way the masonry units were assembled and, last but not least, the structural layout of the building (wall thickness, wall height, etc.) and loads.

Mortars worldwide differ considerably one from the other, both in composition and mechanical properties. For this reason, historic masonries offer building solutions that vary widely from region to region and any attempt to reduce them to just a few typologies would compromise the understanding of the specific contribution of regional practices.

In this text, the discussion is centered on the two principal types of binders, lime and gypsum mortars. I will highlight the way materials were selected and assembled to form vertical or horizontal structures. Bitumen mortars, earth mortars and Portland-cement mortars will be not discussed.

In general terms, "quality" of the mortar here is intended as related to its capacity to bind together materials to form a masonry with good resistance to stresses (normal loads or dynamic actions such those generated by external agents, such as wind, subsidence, earthquakes).

Binding materials and construction

In a traditional construction, structural mortars improve the adhesion and cohesion of single units of bricks or stone and contribute to the formation of structures that can stand the pressure of (a) dead loads (i.e. the permanent loads generated by the structure itself), (b) live loads (i.e those imposed loads generated by the use of the structure) and (c) environmental loads (i.e those accidental loads caused by wind pressure, earthquakes, snow, thermal expansion or contraction and settlements). The more the mortar has a binding capacity, the more it will improve the structural behaviour of the structure. The advantage of mortars is that they can adapt to the morphology of masonry units: they can be applied in regular layers between regular courses of bricks or stone ashlars, or fill the space between irregularly cut stones.

In dry masonry structures, stresses are transmitted from stone to stone through contact points. In walls, the heavier the stones are and the smoother and wider the contact faces are, the better the structure will perform. There will thus be no need for a binder, as for example in the ashlar masonry of classical marble architecture. Occasionally, builders adopted thin layers of lime mortar or pure lime to improve the contact between faces imperfectly smoothed, so as to avoid cracking. One Roman example is that of the two travertine blocks forming the capitals of the interior orders of the "curia" at Paestum, where a thin layer of pure lime was used to improve the contact between the two blocks, given the many cavities characterizing the local travertine (personal observation, Vitti 1999). In such cases, the mortar layer is so thin that there is no binding action. It has been suggested by contrast that gypsum mortars adopted in ashlar architecture in Pharaonic Egypt served as lubricant (Arnold 1991).

The smaller and more irregular the stone elements are, the greater the importance of mortar for the transmission of the stresses from stone to stone. The load bearing capacity of the masonry will be proportional to the mechanical and adhesive properties of the mortar, since the binding material will transfer the stresses from one stone to the other and at the same time keep together the single units of the masonry once the mortar has hardened. Thus, a fundamental axiom in masonry construction lies in the relationship between the dimension of the single units and the adhesive capacity of the mortar. The more the mortar gives cohesiveness to the compound, the more the single units can be small, and vice versa, so as mortar loses strength, the single units will need to be bigger and the resistance of the wall will largely depend on the contact points between the stones.

Two examples may help in understanding the axiom. Modern concrete is made with Portland cement as binder, mixed with coarse and fine rock particles (aggregate) and water. The small aggregates form a mortar which is in turn mixed with larger coarse aggregates to form concrete. In concrete, the strong chemical bonds established by the binder and its adhesive capacity mean that the coarse aggregates are 1–3 cm in size (Fig. 1). On the contrary, it is possible to find ancient and historic stonework with large stones, in which the binder acts as a filler between one stone and the other, but does little to create a cohesion and transfer the stresses through the structure. In such constructions the dimension of the stones tends to be as big as possible and gaps between one stone and the other are filled with chippings and splinters (Fig. 2). Masons seek to increase the contact points between stones and mortar is principally used to ease construction.

The way masonry units are assembled is fundamental for the achievement of a sound mortared masonry. A regular and well-compacted masonry reduces deformability and contributes to the durability of the structure. As in modern concrete, that when poured into the formwork is compacted by vibration to increase density and strength, mortared rubble has a higher capacity to resist to stresses if rammed to reduce voids. This principle was not always adopted, as masons took generally more care in forming the exterior elevation of walls, for aesthetic and practical reasons, rather than the core of the walls, sometimes formed by filling the volume between the two elevations. This may have influenced negatively the strength of the wall, even when using a mortar with high adhesive properties.

Fig. 1 Modern concrete wall (Cruilles, Catalonia). The undulating layers of concrete derive from the pouring process. One- to 3-cm size aggregates are entirely bonded by the Portland cement paste

Fig. 2 Masonry with large granite blocks (larger blocks are 50 × 80 × 33 cm) and small stone flints placed at the joints (Kizer House, South Bend, IN). Mortar joints are minimal and stresses are transmitted principally through contact points

Structural mortars can influence the efficiency and costs of the building process. While dry ashlar masonry results from heavy ashlars skilfully hewn and assembled by expert workmanship, a performant—i.e. resistant to high stresses—mortared masonry needs less effort and time to be achieved. The mortar joint can compensate for differences in the form and dimension of the masonry units (Fig. 3), as there is no need for regular contact between surfaces. In an arch, the mortar can form wedges as to have the masonry units (typically bricks) of cuboid form (Fig. 4). In some cases, the advantages offered by the mortar contribute to making the whole building process much quicker, as is the case of tile vaults, since the quick setting of gypsum makes it possible

Fig. 3 Brick-faced Roman concrete (Argos Aqueduct, Greece). Differences in thickness and form of the brick are compensated for by the mortar joint

Fig. 4 Construction of a brick arch with rectangular bricks (Chellah, Morocco). The wedged shape of mortar helps in giving a radial disposition to the bricks

to avoid temporary supports during construction. An example is the 29-m-wide dome of the Cathedral of St. John the Divine in New York, built in 1909 in 15 weeks (Ochsendorf 2010)!

Five main kinds of mortars can be distinguished: (a) Earth mortars, (b) bitumen mortars, (c) gypsum mortars, (d) lime mortars and (e) Portland-cement mortars.

Earth mortars have a low resistance to compression, but when employed for massive mud-brick masonry, they form quite a remarkable structure (Hughes 1983, O'Grady et al. 2018). They differ from other binding agents, insofar as they have similar physical, chemical and mechanical properties as the masonry unit (mud-brick). They can be used unmixed or with organic and inorganic aggregates to form a skeletal structure and to avoid cracking during drying. The properties of mud-brick walls (considerable mechanical resistance in dry conditions, excellent thermal insulation, low-cost production process) made them an ideal construction technique in antiquity, since the Neolithic Age (Rosenberg et al. 2020). Earth mortars can be exceptionally found also in fired-brick walls (Labate et al. 2019) and were used in Medieval and vernacular stone masonry, sometimes mixed with quicklime as a stabilizer (Markley 2018, Minke, 2018, Morton et al. 2019).

Bitumen is a viscous mixture of hydrocarbons, a naturally occurring material, abundant in some regions of the Middle East (Moorey 1994). Bitumen mortars were in use in the Middle-East certainly by 1800 BCE (Forbes 1964, Artioli et al. 2019). These mortars were composed of a mixture of bitumen with chopped straw, clay or sand. Bitumen was mixed with a filler (mineral component) and had good binding property, but low mechanical resistance. Its major quality stood in being impermeable to air and water, thus offering excellent isolation from humidity, a major problem in mudbrick construction. Early examples show that bitumen was also mixed into gypsum (Moorey 1994).

Gypsum is a sulfate and evaporite mineral, most commonly found in layered sedimentary deposits in association with halite, anhydrite, sulfur, calcite and dolomite. Hydrous or non-hydrous calcium sulfates are the main components of gypsum-based products (Lushnikova & Dvorkin 2016). The $CaSO_4 \cdot H_2O$ system consists of five solid phases: gypsum (dihydrate, $CaSO_4 \cdot 2H_2O$), bassanite (hemihydrate, $CaSO_4 \cdot 0.5H_2O$), anhydrite I (α-$CaSO_4$), anhydrite II (β-$CaSO_4$) and anhydrite III (γ-$CaSO_4$). Natural anhydride is rare and can be used without thermal treatment as a binder. The denser crystal structure results in higher mechanical properties. In general, gypsum binders are typically obtained by thermal treatment. Calcination at 135–180 °C produces hemihydrate. Hardening is expressed by the hydration reaction $CaSO_4.0.5H_2O + 1.5H_2O \rightarrow CaSO_4.2H_2O$.

Hemihydrate β is known as plaster of Paris. Its initial setting time starts after 2–6 min from hydration and the hardening process completes after 2 h. Its strength is given by the water-gypsum ratio and is related to the formation of the resulting gypsum crystals and the bond between them (Williamson and Lewry 1994; Lushnikova and Dvorkin 2016).

Three main characteristics of gypsum have influenced its use as a structural binder: its resistance to fire, its quick setting and the fact that it expands while setting, thus increasing cohesion between the masonry units.

Gypsum and lime are frequently mixed and the advantages of the one compensates for the disadvantages of the other (higher mechanical resistance, quicker setting, reduction of shrinkage).

Gypsum dihydrate has a high solubility in water, which makes gypsum unsuitable for use in a humid environment. The addition of lime and pozzolanic admixtures improves water resistance.

Lime mortars were by far the most commonly used mortars, before Portland-cement binders became the most common binder in mortars. Lime binders result from a firing process that produces a reactive material which through a setting and curing process produces chemical stability due to a carbonation reaction. When heated, calcium carbonate ($CaCO_3$) produces quicklime (CaO) and carbon dioxide (CO_2). As water (H_2O) is added to quicklime, it causes an exothermic reaction which forms calcium hydroxide or lime putty ($Ca(OH)_2$). Long-term carbonation occurs when lime putty reacts with carbon dioxide to form calcium carbonate (Ergenç et al. 2021). When pozzolans are used, the mortar achieves hydraulic properties and can set and harden even under water. The addition of pozzolans to lime putty was described by Vitruvius (Vitruvius, *De Architectura,* 2.6.4). Pozzolanic materials react with lime and form cementing binding hydrates and have greater strength and react faster

(Elsen et al. 2011). There are several pozzolanic additives, including volcanic ash, crushed terracotta, plant ash and fly-ash (Charola et al. 2005; Lancaster 2015). Pozzolanic mortars are frequently referred to as hydraulic mortars, and have to be distinguished from mortars containing hydraulic lime, which are obtained from less pure limestones (Ashurst 1997), as in NHL—natural hydraulic limes. If the carbonate contains magnesium (as in sedimentary carbonate rocks composed mostly of dolomite), the binder is a magnesian or dolomitic lime, with slower hydration kinetics.

The mechanical and cohesive qualities of the mortar, as well as its durability, depend on the lime: its composition, porosity, inclusions in the carbonate rock as well as the dimensions of the carbonate rock clasts and the firing temperature and process. Other factors, such as the composition and dimension of aggregates, the amount of water, appropriate immersion into water of masonry units proportionately to their porosity, and external temperature at the time of the masonry production also contribute to durability.

Portland-cement mortar is a modern material that has largely replaced lime mortar (Elsen et al. 2011). Its higher mechanical property and adhesive quality results in a stiffer and cohesive structure (Drougkas et al. 2019). As such, masonry built with Portland cement differs considerably from a traditional masonry.

Before the introduction of industrial process, which has contributed to uniform the building industry with materials tested as to guarantee standardized performance under well-defined conditions, construction depended on multiple factors. Above all, the local availability of materials and other local/regional factors (political and economical context, expertise, knowhow, etc.) determined most of the building practices. Solutions were developed taking advantage of gained experience through a trial and error approach. Masonry was formed considering, inter alia, the capacity of the mortars to bind together the materials and the different types of loads that the building had to resist. As needed, a mortar with reduced binding capacity and durability could be used, without compromising the structural behaviour of the building. For instance, in seismic areas, masonry has to allow minimal deformation as to disperse part of the energy; increasing mortar's mechanical resistance might reduce deformability of the masonry and cause damage to the structure. For this reason, aerial mortars with a higher deformability are frequently coupled with timber reinforcements (Ashurst 1997) (Fig. 5).

Structural lime mortars

The earliest production of lime plaster dates to the Epi-Paleolithic Kebaran (Near East, 12M BCE) and Pre-pottery Neolithic cultures (7.2–6M BCE). Early use of lime-based binders is restricted to plastered surfaces (Kingery et al. 1988). Plasters are well documented in Minoan and Mycenean buildings, as early as the 2nd millennium BCE. In the Minoan palaces, a very hard and amorphous material, composed of stones, clay, lime, crushed potsherds and sometimes entire vases, similar to a slightly hydraulic mortared compound, suggests an early use of mortared material to form horizontal structures (Shaw 1973). Its manmade origin has been questioned, since similar hard and thick levels of cementitious conglomerate can derive from the presence of water sediments occurring over long periods of time on incoherent material.

Contrary to gypsum, bitumen and earth, lime mortars were adopted late as a binding material in Mesopotamian, Egyptian and Mediterranean construction (Arnold 1991; Sauvage 1998; Wright 2005). Structural mortars were used for rubble masonry walls in 5th c. BCE Olynthos (northern

Fig. 5 Mortared masonry wall reinforced with timber ties (Pelion, Greece)

Greece) in humidity conditions (Papayanni and Stefanidou 2007). Pozzolan mortars are documented in the 3rd–2nd c. BCE at Delos, Pella, Argos and other sites in Greece (Stefanidou et al. 2012). In this period, pozzolan and brick-dust mortars were used selectively to reinforce masonry at the base of walls (Pachta et al. 2014). In the Mausoleum of Belevi in Asia Minor (3rd c. BCE), mortar was used to reinforce ashlar masonry by filling the gaps between the stone blocks (Heinz 2017).

The extensive use of structural mortars started in Roman times. Romans used principally pure lime (also referred as air lime, putty lime or non-hydraulic lime), which was derived from pure limestone, i.e. stones with pure calcium carbonate and a minimal amount of non-carbonate minerals (Elsen et al. 2011). Pozzolanic mortars were largely employed in Rome and in the volcanic district around the bay of Naples. Samples of pozzolanic mortars from Pompei show that in some cases they were more friable and incoherent than aerial mortars, possibly because of the production process (Miriello et al. 2010; De Luca et al. 2015).

An earlier example of pozzolanic mortar can be found in the walls of Ravenna (late 3rd c. BCE), built with mortared fired bricks (Manzelli 2001). Analysis of the mortar revealed the use of gypsum along with pozzolanic mortar, with pozzolans imported purposely from near Rome (Costa et al. 2001). The use of fired bricks with binders is to be connected to the tradition of solid brick masonry well documented in southern Italy in the Hellenistic period, i.e. before the Romans expanded to the south of the Italian peninsula. The use of pozzolan mortars may well relate to technical knowledge deriving from Greece (see pozzolanic Hellenistic mortars in Northern Greece).

Several scholars, attracted by the unsurpassed architectural masterpieces of Rome, have investigated Roman mortars and Roman concrete (i.e. the mortared rubble composites in Rome, in Latin *opus caemeticium*) studying their composition and mechanical and chemical properties (Lamprecht 1987; Samuelli Ferretti 1997; Jackson et al. 2009, 2014; Brune et al. 2013). The current view is that the cohesiveness and durability of Roman concrete derive from the materials available locally (limestone, volcanic ash, tuff, pumice) and the way they were sieved, washed, graded into different sizes and mixed. The pozzolanic reactions between calcium hydroxide and volcanic aggregate produced a slightly resilient calcium-aluminium-silicate hydrate (C-A-S-H) binder. Later reactions produced platy calcium-aluminosilicate crystals (strätlingite) which reinforced the interfacial zone between aggregates and binder, and ultimately avoided aging and cracking in the mortar (Jackson et al. 2014). The cohesiveness of Roman concrete, i.e. its capacity to form a united whole, derived also from the selection of the *caementa* (archaeological term adopted to designate the material units—coarse aggregate—assembled with mortar) and the way they were arranged to form concrete.

Studies of sea-water Roman concrete have highlighted how pozzolans from the Baian Region (Naples) were used in different harbours of the Mediterranean (Brandon et al. 2014). The reaction between lime, pozzolans and seawater formed tobermorite and resulted in extremely cohesive and durable mortars. Mortared rubble was formed with pozzolanic mortars and local *caementa*, and poured into a formwork to form breakwaters and docks (Oleson et al. 2004; Jackson et al. 2013; Jackson 2014).

Outside Rome, pozzolanic mortars were produced taking advantage of materials different from volcanic ash (if not available locally), such as crushed terracotta or plant ash (Lancaster 2015). However, pozzolanic mortars were not employed everywhere. Studies of regional mortars, employed in equally remarkable buildings, remain sporadic and insufficient to determine the skills developed in mortar production in the different regions of the empire and how builders were able to generate quality mortars with locally sourced materials. The reason for this is that analysis is connected to conservation projects; thus studies concentrate largely on noteworthy monuments and sites, and lack a programmatic approach. The prejudice generated by the focus on the only treaty on architecture, by Vitruvius (see Jackson and Kosso 2013; Artioli et al. 2019), and the architectural revolution in Rome between Augustus and Hadrian, does not do justice to the earlier examples of mortared construction nor to other regional achievements between 2nd c. BCE and 2nd c. CE. On the other hand, mortars are frequently evaluated without due attention to the role they play in the construction, necessary for understanding the way they really contributed to the achievement of the goals of architectural design and how much they conformed to standard building practice when forming masonry units with a binding agent.

Crushed terracotta mortars (frequently called “crushed brick mortars”) were widely employed since antiquity. Early examples date to the Bronze Age (Theodoriou et al. 2013) . They were extensively employed in Roman and in later periods (see, for instance, studies of Cretan mortars: Maravelaki-Kalaitzaki et al. 2003). Fired clay, due to having high levels of soluble silica and alumina (deriving from the calcination of clay at 600–900°C), can become active in fixing calcium hydrate and increase the binding properties of the mortar. The more contact occurs between fired clay and lime, the more the chemical reaction forming insoluble products with binding properties will form. This is due to the chemical reactions between fired terracotta and lime, which remove any discontinuity between the two materials and form strong bonds (Baronio and Binda 1997). Vitruvius suggested their use whenever volcanic ash was not available (Vitruvius, *De*

Architectura, 5.2.1). Such mortars were increasingly adopted in Late Antiquity and in Byzantine architecture.

It is not easy to determine exactly if these mortars employed ground bricks or, more likely, unusable terracotta ware, amphoras or tiles, so as to take advantage of waste material (Lancaster 2019). It has been observed that some bricks and some clays, independently from the temperature at which they had been fired, do not react. Equally, overfired bricks (such as those produced today) and pottery do not react with lime, because at above 1000°C they lose reactivity. The effective use of crushed terracotta in antiquity shows that empirical knowledge determined which terracotta/bricks to use for these mortars. Structural mortars employing crushed terracotta and terracotta dust were largely adopted after the 4th c. CE. In this period, between 4th and 15th c. CE, an analysis of Byzantine masonries in Greece revealed mortars that include few calcite lumps, few inclusions of charcoal and wood chips (Stefanidou et al. 2012). These structural mortars are reddish in colour, applied to thick horizontal joints and have proved to be durable (Pachta et al. 2014). This tradition of high-resistance mortars persisted in the Greek island throughout the 15th–19th c.

Noteworthy are the mortars of Hagia Sophia in Istanbul (6th–10th c. CE), where the use of pozzolanic mortars is well documented. Their adhesion reactions at the ceramic-matrix interface depended on the dimension and type of ceramic (raw materials, clays and firing temperature) and calcium hydrate content in the mortar (Moropoulou et al. 2002).

The analysis of medieval binders in Pisa shows that air limes were used hand in hand with pozzolanic mortars obtained from highly siliceous materials, such as earth from fossil remains of diatoms (Franzini et al. 1999). In general, early medieval mortars are considered of low quality, because they are brittle and not homogeneous. Viollet-le-Duc believed that this was due to an inappropriate firing process (Viollet-le-Duc 1863). The poor quality of medieval masonry, however, depended largely on the construction process. It is evident that many masonries lacked compactness, given the many cavities in the mortared rubble masonry, and cohesiveness. Some recent studies have shed light on the understanding of mortar production in the Middle Ages, and particularly in the use of mortar mixers (Hueglin 2011). These mixers were adopted in a period of poor workmanship, and disappeared in the 12th c. with the rise of a more organized workforce. This is confirmed by the overall improvement in the quality of mortars (Furlan and Bissegger 1975), in some cases because of the addition of materials that caused pozzolanic reactions (Adams et al. 1992). It can also be ascertained that in some cases gypsum was added to lime mortars to speed up setting, as in Bruges and Chartres (Adams et al. 1992).

Lime-mortared masonry

Romans had adopted lime mortar for preference when building walls and vaults since at least the 2nd c. BCE (Mogetta 2015). Mortars made it possible to speeding construction: "our people, whose object is speed (*celeritati studentes*) care only for the faces, placing [the stones] upright, the middle they stuff with separate layers of broken rubble and mortar. So in the walling three "skins" are raised up, two faces and a middle of "stuffing" (*media farturae*)." (Vitruvius, *De architectura*, 2,8,7, translation Tomlinson 1961). *Caementa* consisted of small coarse aggregates (typically each unit had the dimension of a fist) filling the core of the masonry between the two exterior faces, as described by Vitruvius (Fig. 6). This type of masonry made monumental architecture easier to achieve with less skilled workmanship than ashlar masonry, since the materials were roughly hewn.

Fig. 6 *Opus reticulatum* wall in Capocolonna (Crotone, Italy). The two facings are made with stones cut in pyramidal shape so as to reinforce the bond with the core. Mechanical properties of the wall may decrease if the masonry is roughly assembled

An example is the sanctuary of Fortuna at Praeneste, outside Rome, built in early 1st c. BCE (Steck 2014). The pozzolanic mortars offered a good binding capacity, although still inferior that found in for monumental architecture from the time of Augustus onwards (Jackson and Kosso 2013).

The difference from earlier gypsum- and bitumen-mortared masonry is in the mechanical properties of lime mortars, which ultimately resulted in a sound structure with thinner walls, compared with the massiveness of mud-brick and fired-brick walls. As underlined by Vitruvius and Pliny the Elder, the building techniques developed in the Late Republic were inferior relative to the dry-stone or brick masonry made by the Greeks (Vitruvius, *De architectura*, 2,8,7; Pliny, *Naturalis Historia*, 35. 172). Particularly in the Late Roman Republic, mortared masonry buildings did not have the same structural resistance as earlier architecture (Vitti 2020). The reason for that was the above-mentioned division of the walls into three parts (core and two facings) and the several cavities resulting from the building procedure, since the coarse aggregates were poured with mortar into the space between the two wall facings and were not compacted (Fig. 7). Ordinary masonries were between 30 and 60 cm thick (1 or 2 Roman feet)—variations depended on the presence of vaults and wall height—and were prone to collapse, because the wall facing could detach from the core and the core was not very cohesive. It is thus clear that in the 2nd–1st c. BCE, mortared masonry was far from reaching the cohesiveness of later Imperial masonry and the main advantage offered by mortar was in the building procedures and organization of the construction site.

Early mortared masonry outside Rome shows that Roman builders were challenged by mortars with poor binding capacity, as happened in Patras, a Roman colony in the Peloponnese, Greece. Here, early 1st c. CE mortared rubble was of river stones and lime mortar made with earth-lime mortars. To increase the bond between the facing and the core of the wall, the builders inserted broken tiles into the joints of the exterior elevation (stone-brick reticulate) (Fig. 8). Broken tiles ensured a higher bond than the rounded river stones, because of their roughness and their size, thus acting as headers connecting the external face of the wall to its core. Such solutions exemplify how much the quality of mortar could influence the development of local solutions. Later, during the 2nd c. CE, in Patras and more generally in the Peloponnese, the establishment of a well-organized building industry resulted in the production of excellent mortars, and stone-brick reticulate was no linger used.

Under Augustus (end of 1st c. BCE), some buildings in the capital show a greater expertise in the selection of materials. Mortars began to have higher binding capacity and durability (Jackson and Kosso 2013). This capacity to build structurally sound masonry is reflected in the use of different types of *caementa* and in the building process. The theatre of Marcellus offers a remarkable and well researched example (Jackson et al. 2011). By the 2nd c. CE, Rome had developed an expert building industry and was able to achieve unsurpassed architectural masterpieces. The studies conducted on Trajan's Markets give a good insight onto the extraordinary adhesive quality and resistance to stresses of its masonries (Jackson et al. 2009). The walls of these huge structures were massive, to withstand the extremely high stresses. If aerial mortars had been used, carbonatation would have lasted very long periods. Pozzolan mortars, on the contrary, shortened the curing and hardening process and ultimately guaranteed the speed in construction.

The mortared rubble developed in Rome is often referred to as Roman concrete, and has some specific attributes: the

Fig. 7 Failure of an *opus reticulatum* facing because of the poor bond with the core of the wall. The soundness of the masonry is diminished by the use of river stones and the many hollow spaces in the masonry (Herdonia, Foggia, Italy)

Fig. 8 Stone-brick reticulate in the stadium of Patras (Greece). Bricks are used to reinforce the bond between the facing and the core

use of strätlingite cements, the careful layering of cm-sized coarse aggregates, the density of the compound and the extraordinary high resistance to stresses.

Under Nero, the use of broken tiles and bricks mixed as *caementa* with mortar for concrete structures is connected to the development of the brick industry (Fig. 9). It is at this stage that mortared-brick construction starts to emerge as one of the strongest types of masonry, although in Rome it was still connected to concrete and not to solid brick masonry (Vitti 2020). Fragmented bricks presented a coarse surface to mortar and improved bonding. Moreover, although bricks did not offer strong pozzolanic activity, because the size of the bricks did not allow deep penetration by the binding material, there was a chemical reaction between the surface of the bricks and the mortar which improved the adhesion between the two (Baronio et al. 1997), thus offering greater cohesiveness to the structure.

To increase the bond between core and facing, the use of bonding courses was substantial (a bonding course, is a single or more layers of bricks running right through the thickness of the wall). In Rome, since the end of the 1st c. CE, a single layer of large bricks (*bipedales* 60×60 cm, 2×2 Roman feet) was often used. More commonly, smaller rectangular or square bricks were laid in two or three layers, with a similar purpose, as for instance in Pompei and Herculaneum.

Fig. 9 A typical Roman brick-faced concrete wall with *bipedalis* bonding courses. Broken bricks and stones are used as *caementa* and are layered in horizontal courses, to achieve maximum strength of masonry (Baths of Nero, Pisa, Italy)

Outside Rome, bonding courses were adopted as 3 or 4 brick layers embedded regularly into rubble masonry walls (Righini 1999). In Late antique and Byzantine masonry, this solution was largely adopted and remained in use, with variations, right up until the 19th century (Fig. 10). Headers (units placed with their long side orthogonal to the wall facing) and bonding courses were particularly important for the achievement of higher structural quality in walls (Napolitano and Glisic 2019). Bonding courses also helped to level rubble masonry walls and guarantee compactness.

Solid-brick masonry offered excellent mechanical properties and greater cohesiveness, due to the procedure of adding the materials layer by layer. The structure was made out of modular regular units stacked in layers with regular mortar joints. While early examples from the Bronze Age were typically made with mud bricks and clayish mortar, at a later stage in Mesopotamia, fired bricks were also employed. The neo-Babylonian Ziggurat of Ur—6th c. BCE—had a mud-brick core and a fired-brick facing with bitumen mortar. Solid fired-brick walls are known in the Hellenistic period (Bonetto et al. 2019). Extraordinary example of fired-brick masonry from the Roman period are the late 2nd c. BCE columns of the basilica of Pompei (Vitti 2020). Lime-mortared brick masonry is limited to the pillars, which had to resist concentrated stresses, while the outer walls were all made with rubble masonry. In the 1st c. BCE, other examples are known in Northern Italy, as for instance the Porta Leoni at Verona. Later (13th–19th c. CE), solid-brick structures were used for less massive walls than the Republican Roman fortifications of Northern Italy (3rd–1st c. BCE), in order to

Fig. 10 Brick horizontal bonding courses in a rubble masonry wall (Nicopolis, Greece)

have walls of minimal thickness, but high structural load-bearing capacity, even when roughly executed. Solid brick masonries became widespread in the Middle Ages (Ratilainen 2014). Under Almoravid influence (12th c.), brick masonry was reintroduced extensively in Spain, as in the Giralda of Seville (Vitti 2021).

In a brick masonry, the thickness of the joints varies considerably. Romans used thinner joints, typically between 1 and 2 cm thick (Fig. 11). With joints between 0.5 and 1 cm, brick walls are particularly strong, because of a "tie effect" generated by the adhesion of brick to mortar, which minimizes the greater deformability of mortar (De Cesaris 1996). Testing of brick masonry under compression has shown that a masonry unit made of bricks and lime mortar has a higher compressive strength than the mortar itself, because the mortar is confined within a multiaxial/spatial masonry unit. This "confinement effect" shows that mortars with low compressive strengths can be used in masonry to achieve a compressive strength 10 times higher (Drougkas et al. 2019). This also highlights the advantages offered by lime mortars with low compressive strength in allowing some deformation when under stress, both for the elastic property of the mortar and for the energy absorption of the masonry when mortar crumbles. Samples of the pozzolanic mortars of Justinian's Hagia Sophia have shown that the long curing time of lime mortars allowed the masonry to absorb energy without compromising the structure (Livingston 1993; Moropoulou et al. 2002).

The most important contribution to mortared masonry after Roman times comes in Gothic construction, which was based on mortared stone-blocks to form walls arches and vaults. While walls were built with stones with a fill of mortared rubble, structural elements such as columns, arches, flying buttresses and vaults where built in solid stone. It has been noticed that the mortar thickness varied into the different structural components depending on the stresses (Cassinello 2006). Thinner structural architectural parts, such as columns or ribs, had thinner joints, which resulted in stiffer structural elements. At the center of the stone blocks, grooves cut into the stone (Fig. 12) allowed for additional mortar to better bond the two adjacent blocks. Other parts of the fabric had thicker mortar joints, for example in vaults and walls.

Medieval masonries south of Rome document the persistence of the practice to differentiate between mortars used

Fig. 11 Brick-faced rubble masonry wall of the Roman aqueduct at Argos (Greece). The mortar joint is 2 cm, while the bricks are 4 cm thick. The many hollow spaces in the nucleus show little attention to reaching high compactness in the masonry

Fig. 12 Drums of a column in the Armenian Church of Nicosia (Cyprus) showing the imprint left on the mortar by cross-shaped groove made to increase the mortar joint of an otherwise thin joint. Other grooves have the shape of a trident

for the joints of the wall facing from those used for the core of the wall (Fiorani 1996). Typically, since the mortar in the joints was confined to a minimal height, it required smaller aggregates. Where crushed terracotta was employed for the brick masonry in late antique and Byzantine architecture, joints could be up to 7cm thick.

Lime-vault construction

Vaulted structures were improved by the introduction of mortared construction. In dry masonry vaults, stone voussoirs (wedged shaped elements) required precision stone-cutting to achieve full contact between each adjoining voussoir. Most vaults in Hellenistic architecture (4th–1st c. BCE) in the Greek territories were built in this fashion, as for instance the Macedonian barrel-vaulted chambers. Some 3rd–2nd c. BCE brick-vaults in Reggio Calabria (Southern Italy) were built with voussoir bricks, and made no use of mortar (Vitti 2016). Romans, by introducing lime-mortared construction, started to move beyond dry vaulting. Mortar could be adapted to the irregular surface of roughly hewn or totally irregular stones placed in a radial disposition (Fig. 13). Mortar offered the possibility to ease and speed in construction, in the same way it fostered wall construction. In an arch, the forces are transmitted perpendicular to the stone voussoirs, and generate stresses in compression (Lancaster 2005). Resistance is offered mostly by stones and the mortar is primarily needed to improve contact and transmit the stresses from one stone to the other. Given that mortar has lower mechanical properties than the stone, its thickness was always kept minimal. Early vaults were of medium size, with spans up to 6 m.

A change in vault construction occurred in the late 2nd c. BCE. The so-called *porticus* Aemilia, a huge civic building in Rome, was entirely built in mortared masonry, using small tuff units (Vitti 2020). Here, the 8.30 m vaults were made with small-dimension tuff and mortar up to the level of the haunches, and above this level the intrados was made from small rectangular tuff stones and a core formed by irregular *caementa* placed in abundant mortar. Romans were already experimenting what would have turned out to be a major revolution in vaulting. In imperial Rome (1st–4th c. CE), the *caementa* were layered in horizontal courses from the impost to the crown, a marked departure from earlier vaulting. Mortar played a major role in achieving the necessary cohesiveness. Horizontal layering improved compactness, since *caementa* could be set one by one in the mortar, with appropriate density and avoiding cavities (Fig. 14). These extraordinary vaults were made possible by the exceptional mechanical resistance of the pozzolanic mortars, and proved to be longlasting.

In some of the most exceptional Roman buildings, neither the composition of the mortars, the mixtures of concrete nor the building procedures were uniform throughout the structure, but differentiated so as to increase the structural behavior. Such is the case of vaults, which were exposed to higher stresses. This differentiation entailed materials

Fig. 13 Roman stone barrel vault at Iasos (Turkey) made with thin stones placed radially

Fig. 14 Roman concrete barrel vault. *Caementa* made from red volcanic scoria layered horizontally (Baths of Caracalla, Rome, Italy)

and assembling processes being determined right from the design phase. For instance, in the 2nd c. Trajan's Markets in Rome, mortars and concretes were differentiated in the different parts of the building, and vaults had a higher density (Jackson et al. 2009; Bianchini and Vitti 2017). In general, *caementa* were varied according to the structural needs and materials, such as travertine and leucitite used in the foundations, bricks and other volcanic tuffs in the walls and lightweight stones in the vaults. The mortar compositions varied between the walls and the vaults, as the latter contained pumice aggregates.

Concrete vaulting was problematic outside the capital, as it required knowledge and materials that might not have been always available. In most regions, radial vaulting, either with stone voussoirs, irregular stones or bricks, was preferred (Fig. 13). As vaulting was the most challenging structural element, influencing also the design of the supporting structures, multiple innovative vaulting techniques were developed (Lancaster 2015). In Greece, builders adopted brick vaulting as an alternative to concrete (Fig. 15), since the thin mortar joints between the bricks made it possible to build a strong vault rapidly, without having to delay during the long hardening periods that non-hydraulic mortars need (Vitti 2016).

The origin of solid brick vaulting is to be found in the East (Benseval 1984). In the Middle East, gypsum-mortared vaults are well documented in Parthian architecture. The extensive use of lime-mortared brick vaults started in the Roman period (Vitti 2016) and was then adopted in Byzantine period.

The structural performance of brick arches and vaults was particularly suitable for small- and middle-sized vaults, although between 4th and 6th c. CE several monumental brick vaults were built (Karydis 2011), including Hagia Sophia in Constantinople (Livingston 1993).

Fig. 15 Solid brick arches and vaults in a Roman tomb at Troezen (Greece)

In the Byzantine period, the mortars used in vaults had crushed terracotta aggregates. Terracotta aggregates were selected particularly (but not exclusively) for the vaults. In Thessaloniki, collapsed portions of a vault of a building on Gounari Street show a clear differentiation of mortars between walls and vaults, due to the use of crushed terracotta for the mortar of the brick vault (Stefanidou et al., 2015).

In Middle and Late Byzantine architecture, brick vaults became less massive (Ousterhout 2019): light domes springing from high, perforated drums, took full advantage of the possibilities offered by brick construction.

In later periods, brick vaults and domes spread throughout Europe. The domes of Brunelleschi in S. Maria del Fiore in Florence and Michelangelo in S. Peter's in Rome offer the most remarkable examples.

Gypsum-mortared construction

The English term *plaster* does not have the same meaning as the French term *plâtre.* In English *plaster* denominates the protective layer of mortar used for the facing of masonry, while in French it refers to any construction material derived from the process of calcination of gypsum (powder, paste, or solid panel). The word *plaster*, however, is often used as well for gypsum- or lime-based mortars, making it difficult to distinguish between the two (Wright 1992). It is thus good practice to specify whether gypsum or lime mortar is discussed.

Gypsum was employed in construction in contexts rich in natural stones like alabaster, selenite, gypsite, etc. such as Tell El-Amarna-Egypt (Harrell 2017) or regions such as Aragon-Spain (Sanz Aeauz and Villanueva Dominguez 2009) and Île-de-France-France (Le Dantec 2019). In the Eastern Mediterranean region and the Middle East, where mortared construction developed earlier than in the West, gypsum mortars were common, particularly where fuelling kilns was problematic, because of the scarceness in timber. Theophrastos (end 4th c. BCE) acknowledges that in Cyprus gypsum was commonly used (*Peri ton Lithon* 64-66). Gypsum offered several advantages. It had a shorter and less difficult production process than lime, since it required less energy (lime requires more fuel and more firing time with related added costs. Kingery et al. 1988) and there is no further processing required after firing (lime had to be slaked in order to complete the chemical process which would determine its use as a binding material). Gypsum once fired could be ground and rehydrated straight away, forming a paste which hardened quickly and had good mechanical and adhesive resistance.

Builders who employed gypsum as structural mortar could take advantage of the following characteristics:

a) excellent resistance to mechanical stress, due to the morphology of gypsum after hydration (Wright 1992). Tensile testing on non-calcined gypsite (impure gypsum) from ancient deposits in Amarna (Egypt) show that it was stronger than those calcined (Harrell 2017);
b) quick setting time, which made the building process easier. The hardening process of plaster of Paris is complete in 2 h, when it reaches a compressive strength of 2–7 MPa (Lushnikova and Dvorkin, 2016);
c) an increase of volume during hardening, which helps to bind masonry units (ca. 1% during hardening, with a 0.05–0.1% subsequent shrinkage. Lushnikova and Dvorkin, 2016);
d) excellent fire resistance, due the evaporation of chemically bound water when exposed to fire, thus favouring the use of gypsum for masonries exposed to fire. Hydration during burning enhances porosity and reduces conductance of heat, resulting in an ideal material to protect easily combustible building material (Lushnikova and Dvorkin, 2016);
e) excellent durability, provided that is protected from humidity.

Limitations in the use of gypsum as a binding agent in masonry are its lower resistance to compression and solubility to water (loss of cohesion when wet). The calcined gypsites of Tell El-Amarna have an excellent resistance to water, due to their low hygroscopicity, which explains the finding of intact gypsum cones dating to the 18th Dynasty (New Kingdom 1540–1075 BCE) (Harrell 2017). Also in 16th c. Spain, a twice-fired gypsum was renowned for its excellent properties, including resistance to humidity and hardness (Pérez Sánchez and Sanz Zaragoza 1996) . In Paris, weather-resistant gypsum plasters were used for plastering exterior facades (Le Dantec 2017).

Gypsum-mortared masonry

In ancient Egyptian construction, gypsum is documented in horizontal and vertical joints of ashlar masonry. Early mortars date back to the late Predynastic Period (early 3rd M BCE). Samples of the gypsum have shown that it was fired at very high temperatures (300–500°C), thus forming anhydrite II, which has a very slow setting and low binding capacity. For this reason, it is considered that anhydrite was used principally as a lubricant in construction (Goyon 2004) and not as a binder. A mixture of gypsum and stone ("gypsum concrete") employed in the foundations of 14th c. BCE buildings of Akhenaten at Tell El-Amarna (Harrell 2017) is evidence of a building technique also documented in Archaic and Classical Cyprus (Wright 1992).

Gypsum was already widely employed in the Near East, Cypriot, and Turkey in the Early Neolithic period (Kingery et al. 1988). In the Elamite empire, the use of gypsum-mortared fired-brick masonry is to be found in the "royal tombs" (end 16th c. BCE) (Benseval 1984). It was similarly used centuries later in the "royal tombs" of Assur, in the neo-Assyrian empire (Benseval 1984; Sauvage 1998). In Dura Europos (Syria), the ancient city on the Euphrates, the late 4th c. BCE fortification was built with gypsum rock with a thin layer of gypsum mortar (Adam 2005), similarly to a later example in Hatra (2nd c. CE). In Parthian and Sassanid architecture, the potential of gypsum was expanded further. In the palace of Assur (1st–2nd c. CE) the "pillared hall" (fig. 17) was entirely built with fired-brick masonry bonded with gypsum mortar (Andre and Lenzen 1933). In Sassanid Persia, the use of gypsum is widespread. Early Islamic construction used building techniques developed under the Sassanids.

The use of gypsum concrete in gypsum cementitious mortars in Egypt and Cyprus is an important precedent for lime-mortared rubble (De Magistris 2010). The use of gypsum-mortared masonry found fertile ground in all the countries rich in gypsum (Fig. 16). This tradition is well documented in Spain, particularly in Aragon (Villanueva 2004), where the use of gypsum was influenced by the presence of Arabs in the Iberic peninsula. Aragon and the Ebro Valley document not only brick and stone gypsum-mortared masonry but also rammed-earth (pisé) walls with gypsum mortar joints (Vegas et al. 2009; Mileto et al. 2012). In gypsum-reinforced rammed-earth masonry, gypsum is used as an alternative to slaked lime to improve the even distribution of earth at the corners of each sector, form quoins (wall corners) and protect joints from water infiltration.

In France, gypsum was employed mainly in Provence, East France, and in the Parisian area. In early 13th c. Gothic cathedrals (Chartres and Bourges), gypsum replaced lime mortars in some masonries; it was also mixed with lime as to take advantage of the faster setting time (Adams et al. 1992).

Fig. 16 Gypsum mortared rubble masonry at the Armenian Church at Nicosia, Cyprus

In Paris, gypsum composition is of evaporitic rocks formed in the Early Eocene, with deposits which are 8 m thick south of the Seine river, and reaching 30 m in Montmartre, Montmercy and Vaujours (Le Dantec 2019). The abundance and quality of Parisian plaster (due to various factors including the quality of the rock, firing and subsequent manufacturing process) created a well-established and extremely specialized tradition of the use of gypsum mortars, also when exposed to the elements, hence the term "plaster of Paris". In Paris, the use of gypsum is documented from the middle ages to the 19th c. both for masonry and external plasters. Gypsum mortar was widely employed for half-timbered masonry to mortar the infills between timber elements. Because of its excellent resistance to fire, after the great fire of London (1666), it was imposed by Louis XIV in Paris and was adopted in London (Le Dantec 2017). Gypsum mortar is well documented for masonry (particularly for chimneys, because of its excellent resistance to fire), partition walls (rendering on wooden laths) and the famous plasters made to resemble brick or stone surfaces (as for instance in Place des Vosges). It is with industrialization that gypsum loses quality and skilled workmanship declines.

In northern Europe, it is also documented since the Middle Ages, as in the case of 12th c. Polish examples (Tadeusz 1991).

Gypsum-mortared vaults

Construction with gypsum mortar favoured tile vaulting, a building technique characterized by not needing a provisional timber support (centering) for the construction of the vault. In antiquity, a similar concept may be found in the construction of vaults with terracotta tubes, which also employed gypsum mortar (Lancaster and Ulrich 2014) .

It is in vaulting construction that gypsum mortar offers ideal advantages, because of its adhesive property. In the East, one of the most practical vaulting techniques since antiquity was pitched and vertical brick vaulting (Benseval 1984). Typically built with mud or fired bricks forming arches as thick as the brick's thin side, this technique solved one of the major issues of vaulting, since made it possible to build without centering, and so particularly useful in regions short of timber, such as Mesopotamia. Most of these vaults were laid against an end wall, which offered a support to the first arch (Fig. 17-A).

In the early CE, Parthian architecture offers the most remarkable examples of gypsum-mortared fired-brick vertical vaulting. In the pillared hall of the palace in Assur, vertical brick vaulting was used to connect the pilasters, resulting in freestanding arches (i.e. not laid against an end wall). This was achieved by the builders by interlocking the impost of the arches with the masonry of the abutments and probably using a temporary support (Fig. 17-B). The adhesive properties of gypsum made these arches solid enough to resist the heavy masonry above (Vitti, forthcoming).

The provisional support for building freestanding vertical brick vaults evolved, in Sasanian architecture, into temporary or permanent gypsum arches made with reinforced gypsum cast to form an arch. A remarkable example is offered by the quite small "temple" in Neisar (Kashan, central Iran, 2nd century CE). Here, the stone masonry was made with gypsum mortar (Fig. 18-C). Two details are noteworthy. The arches connecting the pilasters were made with stones cut in the shape of bricks, similar to those found in the pillared hall of Assur, but without the elaborate interlocking of bricks at the impost (Fig. 18-B2). Builders evidently draw inspiration from brick vaulting techniques, but used the abundant local stone. At the same time, in Neisar, they used gypsum reinforced with reeds to form thin arches, as temporary centering for the arches and as permanent guides for the construction of the dome (Benseval 1984), which was achieved by placing eight such thin gypsum arches equally distanced and then filling the area with gypsum-mortared stones (Fig. 18-A).

Sasanian architecture bridged gypsum-mortared construction between Parthian architecture and Islamic architecture, most Umayyad and Abbasid architecture. Similar cast-gypsum arches with radially or vertically gypsum-mortared stones were employed in the Umayyad palace of the Amman citadel and in Qasr al-Kharanah (60 km south of Amman) and, later, in the 8th c. Abbasid Al-Ukhaidir Fortress, in present day Iraq (Arce 2003). These arches became progressively thinner as the expertise in the use of gypsum evolved.

Gypsum mortars thus made possible the reduction of vertical-brick arches to form thin ribs, which eventually formed interlaced ribs supporting a filling above. This technique enhanced the potential of architecture as form, and made it possible to build light weight vaults. Ribs actually replaced the gypsum elements used as guide for vaulting. The art of rib vaulting thus reached new and impressive heights in Persia in the 10th–12th centuries. In dome n. 60 of the congregational Jameh Mosque of Isfahan, dated between 1090 and 1150, ribs were composed of 4 layers of bricks set on edge (soldier position, i.e. with the brick laid vertically with the thin side on the intrados) built according to the principle of vertical-brick vaulting (Galdieri 1983). The abundant gypsum mortar allowed for a very rough detail in execution, showing the advantage of this binding agent (Fig. 19).

The process towards ever lighter vaults culminated with the introduction of tile-vaults. These vaults are still in use nowadays and form thin shells of bricks laid flat, made of two or more layers, and bond with gypsum mortar and without centering. The technique is well documented in Southern Spain since the end of the 12th c. (Zaragozá Catalán, 2012), but the earliest example is the Qubbat al-Barudiyyin in Marrakech, dated 1117. Almoravids are likely to have imported from Persia the use of fire bricks and the technology of gypsum-mortared arches, and from there the technique was introduced into el-Andalus, after its conquest by the Almoravids (Vitti, forthcoming). Peter IV of Aragon (1319–87) noted that the vaulting technique to be "very

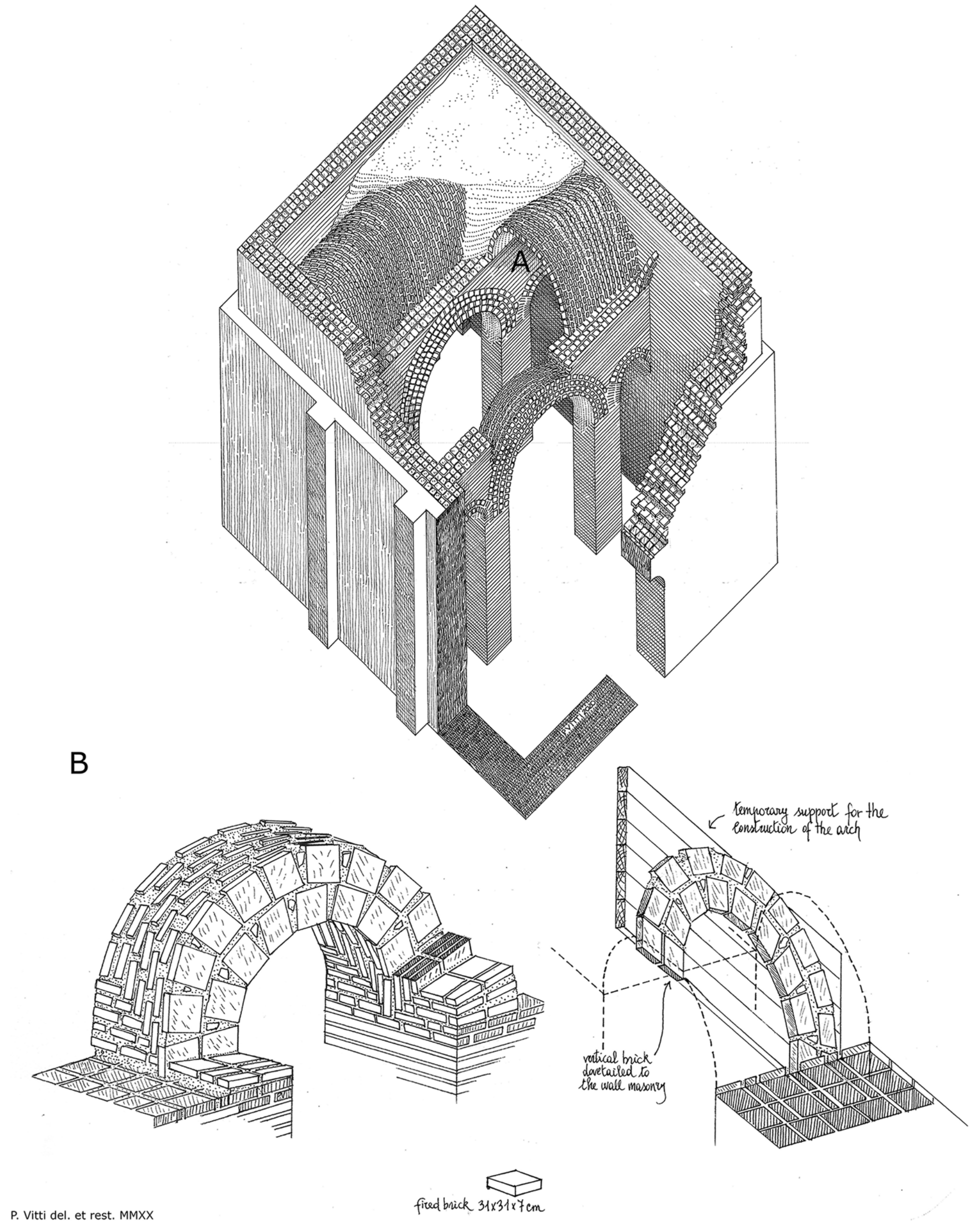

Fig. 17 Axonometric reconstruction of the Pillared hall of the Palace of Assur (first century AD). All the fired-brick masonries are mortared with gypsum. (A) one-brick thick barrel vault; at both ends the brick-arches are inclined towards the wall (pitched disposition), and at the center they were vertical. (B) freestanding vertical-brick arches

profitable, very lightweight and very low-cost work of plaster and brick" (Ochsendorf 2010).

In present-day tile vaults, the mason builds simultaneously two or three brick layers; the first one is mortared with gypsum and serves as a support to the other, typically mortared with lime-cement mortars.

Concluding summary of key concepts

The aim of this paper has been to highlight the role of lime and gypsum mortars in the development of building techniques in Antiquity and Middle Ages. The general assumption is that building techniques were influenced by the different properties of lime and gypsum in forming masonries and vaults. Taking advantage of the chemical bonds, of the manufacturing procedures and of the building techniques, builders adopted different solutions which in some cases advanced the development of new architectural forms.

The key concepts that have been addressed regard the selection of materials, based on local resources, on the building techniques which allow for a better performance of walls and vaults and on the way the binding properties of mortars influenced the construction process.

The mechanical properties of the raw materials played a crucial role, and depended on the availability of local materials. The building industry in Rome was favoured by excellent materials, and particularly the local volcanic ash and tuff, which produced

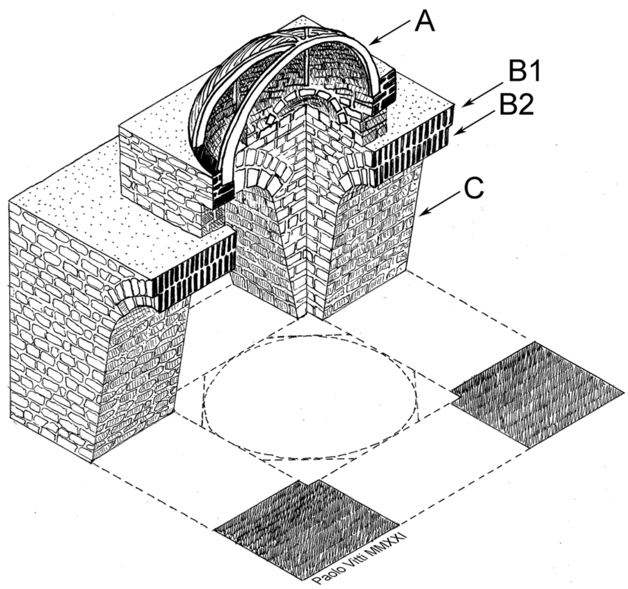

Fig. 18 Axonometric reconstruction of the "Temple" in Neisar (Kashan, Central Iran). The stone masonry and stone vaults are mortared with gypsum. (A) gypsum ribs in the dome. (B1) Vertical stone freestanding barrel vaults composed of two overlapping arches. Vertical stone construction starts at the haunches. The stones have the same form as a fired brick. (B2) The recess on the lower barrel vault was left by a gypsum rib that served as provisional support. The vault was built from the exterior towards the interior. (C) Gypsum-mortared masonry. The pilasters taper to reduce the span of the vault

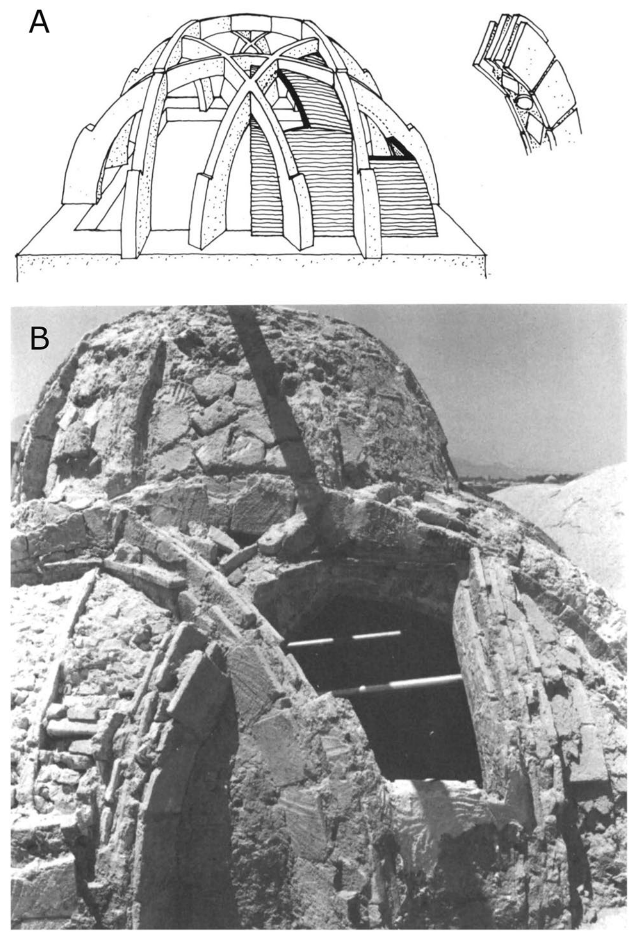

Fig. 19 Rib vault (n. 60) in the Great Mosque in Isfahan: (A) the diagram shows the web of ribs. Each rib is formed with four brick layers placed on edge (soldier position). The detail of the rib shows that the central ribs were recessed, in order to have a decorative pattern inserted in the recess (after Galdieri 1983, figs. 12 and 13). (B) View of the extrados of the vault after the removal of the plaster and later interventions (after Galdieri 1983, fig. 17)

extraordinarily resistant pozzolanic mortars. Export was limited to exceptional projects, as is the case of the pozzolan exported for the 3rd c. BCE fortification of Ravenna or the construction of Roman concrete harbours in Imperial times (Brandon et al. 2014). Only in later times, starting with the 18th c., did export become more common, as in the case of pozzolan and trass which were transported by river to other regions for production of pozzolanic mortars (Gargiani 2013). However, in traditional construction, the majority of the building materials were locally sourced, and inspired regional building techniques which developed through a trial and error process.

As far as the quality of construction is concerned, mention must be made of the fact that structural mortars were not the only component necessary to achieve a sound masonry. Not only the masonry units but also the building procedures and the structural layout affected the final result. Particular emphasis was put on the role of bricks in a mortared masonry. Solid-brick construction (walls, arches and vaults) is actually one of the most widespread building techniques throughout many regions in the world, for it exemplifies the advantages of building with homogeneous horizontal layers which alternate bricks with mortar and the excellent chemical bonds between masonry unit and mortar.

Gypsum mortars were adopted earlier than the lime mortars for construction. Their instability to water favoured their use in dry environments, even if several gypsum plasters show high resistance to the elements. Gypsum mortars were particularly successful in vault construction, because of their quick setting and enabled elimination of formwork (centering).

Lastly is important to stress that studies on mortars should always include information on the masonry units so as to allow scholars to address all the research issues related to the role the structural mortars played in any building being discussed.

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