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ORIGINAL PAPER

Production, transport and on-site organisation of Roman mortars and plasters

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Abstract
This paper examines the role of mortars and plasters in the construction process during the Roman period and seeks to elucidate the chaîne opératoire from the production of the main ingredients — lime and aggregate — to their application in structures, based on archaeological, visual and archaeometric data. As well as looking at the actual processes involved, it also considers the functional requirements of the mortars and plasters and the economic implications of their use, especially the nature and cost of transport, which may have led to particular choices being made by Roman builders; it also considers the supply of materials in terms of the logistics of construction. The emphasis is on mortared rubble construction, which was a particular development of the Roman period from the second century BCE and required much larger quantities of lime than previous building techniques. Attention is also paid to the human actions involved and the tools employed.

Keywords Lime · Aggregate · Mortar · Roman construction · Chaîne opératoire

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; Vitti 2021). An insight into their production, transport and on-site organisation is further provided by this paper. 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 Mediaeval (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. 2021); 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 2021) 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

Since mortars and plasters are in themselves composite materials, and mortar itself is an essential part of another composite material, their role in the construction process is necessarily complex. First, Roman architects or builders had to identify suitable sources of raw materials for the binder (usually lime in the Roman period but also gypsum) and aggregate. These then had to be extracted and given any preliminary processing at the extraction site, before their transport to the construction site, where any further on-site preparation occurred, before the mortar or plaster was mixed and then finally used in construction or decoration. Malacrino (2010, 61–76) gives a brief recent introduction to the subject, while Coutelas (2019) and Traini (2013) both provide excellent detailed overviews, with Traini providing the more detailed bibliography but with a narrower focus on the lime component; Coutelas is mainly concerned with ancient Gaul and Traini with Roman Italy, although both range more widely over the area of the Roman empire and its successors in Europe, North Africa and the Near East.

General considerations

Although the use of mortars and plasters in the ancient and early mediaeval worlds has long been recognised, the detailed processes which formed the chaîne opératoire for construction and decoration have only relatively recently become an important focus for archaeologists (see Coutelas 2008 for a good overview). The general monograph of Adam (1984) provided an accessible summary for a wider audience while also giving a general account of the processes of construction and rendering using lime-based mortars and plasters; the work has been translated into several languages and still provides a starting point for many students. Lamprecht (1984) is an early study of Roman mortared rubble construction including archaeometric studies of the mortars. The operation of limekilns and the production of lime in general have been a particular area of interest since the pioneering study by Baradez (1957), followed up by Sölter (1970) and especially in the 1980s by Dix (1982) and Adam and Varene (1985), who showed the importance of ethnographic studies for understanding the production cycle.

Interest in the logistics of supply and the economics of use developed in the late 1990s following the publication of this author's study of the Baths of Caracalla in Rome (1997), although few concentrate on mortar (see Camporeale 2011 for a rare example). Since the 1990s, there has also been an increasing number of scientific studies of ancient mortars and plasters which have contributed greatly to our understanding of the sources of raw materials, the types of recipes used and the interaction between the components at a microscopic level (e.g. Jackson et al. 2007; Marra and D'Ambrosio 2013; Wehby Murgatroyd 2016; Columbu et al. 2019; Coutelas 2019; Dilaria et al. 2019), all of which have implications for the construction process and the relation between the specific recipes and the function of the mortar or plaster. These have been matched with archaeological studies focusing on the organisation of mortar production and use on building sites (e.g. Loustaud 1983; Coulthard 1999; Coutelas 2005; Coutelas and Hourcade 2016; Guyard et al. 2008), although the evidence for this is generally less frequently preserved.

Overall, evidence for mortar in the ancient construction process is heavily weighted towards what can be deduced from the finished product, with direct evidence in the archaeological record of the actual processes surprisingly rare in relation to the volume of construction which took place. This is true even in the case of lime kilns, which provide the bulk of the direct evidence for production. Because the processes and practices continued through the mediaeval period and into the nineteenth — and in some places the twentieth — century, historic images and records plus ethnographic studies are often used to fill out or interpret the ancient evidence.

Physical requirements

In the period under question, there is ample evidence that the mortars used for a binder in mortared rubble construction, for mortar floors and for wall plaster, deployed the same range of basic raw and processed materials. The differences came at the final stages of use, where the choice of recipe and the manner of applying the material related to its specific function. It is clear from the ancient written sources (see Lancaster 2021) that at least by the first century BCE, ancient builders had developed some firm ideas about the qualities and nature of the raw materials required for making the best mortars and plasters for different functions, and of the effects of using substitutes. Their preference for lime made from pure calcitic limestone, identified by the whiteness and hardness of the source limestone, meant that it was often brought from considerable distance, while the aggregate was most likely to be local, both inert sands and natural pozzolans as well as crushed terracotta, although imported pozzolans were also used. All of these had different implications in terms of sourcing, preparation and transport.

We should remember that these preferences were not based on any scientific analysis as we know it but on empirical observation, experience and experimentation. It is also clear that the reality, as identified through modern scientific analysis of mortars and plasters, does not always match up to the prescriptions of the ancient sources (Coutelas 2019), something that in itself throws interesting light on ancient building practices and the role of economics in the construction process.

Scheduling the supply of materials for mortar

The need to assemble all the constituents for making mortar or plaster on site at the appropriate time has substantial implications for the logistics of the construction process. This is especially the case where mortar forms a key element in creating the structural envelope, as was common from the second century BCE onwards with the development and extensive use of mortared rubble construction (usually but misleadingly called 'concrete') using lime-based mortars in Rome and central Italy (see Vitti 2021). Since mortar occupies about a quarter to a third of the volume of good-quality mortared rubble construction (DeLaine 2001; Camporeale 2011), this development brought about a large increase in the amount of lime needed in urban areas, some of which — like Rome — did not have suitable limestones locally. Since mortar or plaster was needed at all stages of construction from the foundations to finishing, establishing and maintaining a supply of lime may have been one of the priorities at the very inception of any building project and vital for extra-large ones like city walls, permanent military camps (e.g. at Tipasa, Baradez 1957), infrastructure projects like aqueducts or harbour works and major public buildings (e.g. the Baths of Caracalla in Rome, DeLaine 1997, 111–114 and 189–191). Once construction began, all the materials for mortar had to be available separately on site and already prepared, with a chain of supply established to replenish them, since once the mortar itself was mixed, it needed to be used within a very short space of time; this is particularly true for mortars using pozzolans in the aggregate. Changes to the composition of the mortar within a single building project can therefore reflect not only technical requirements and different phases of construction, but also problems with or alterations to the supply of materials, substantial breaks in construction or changes in the workforce (Coutelas 2012a). Efficient sourcing of the ingredients of the mortar, combined with the relatively rapid curing times for the pozzolanic mortars of Rome, allowed an impressive speed of construction; masons' marks on the brick-faced walls of the early second century Baths of Trajan in Rome indicate that 15 m of vertical wall were erected in only 2 months (Volpe and Rossi 2012).

Sources, production and transport of primary materials

Aggregates

Of the two main components which make up lime mortars and plasters, it is the aggregate that provides much of the volume and is the more variable component. The variability arises from two distinct and at times contradictory requirements: function and economy, the latter dictated largely by accessibility and available transport routes.

The most economical way of sourcing aggregate was to use whatever local materials were the most abundant and the easiest to extract but still fulfilled the need for fine-grained material essential to the creation of the mortar (for an overview Coutelas 2009, 64–70). The use of local sands and gravels in mortars for bulk construction, even when the quality of resultant mortar is poor, reflects this economic mentality; examples are discussed by Coutelas for several sites in Gaul (Coutelas 2005; 2011; 2012b), by Dilaria and Secco (2018) for Aquileia and by Cardoso et al. (2014) for Ammaia in Lusitania (Portugal). It may also reflect, at a distance, the tradition, previously common throughout the area of the Roman empire, of earth construction and mortars which were made from local soils and clays. In some cases, further processing may have been necessary, including sieving to remove coarser (or sometimes finer) particles or washing to remove clay and soil impurities (Coutelas 2009), but careful choice of natural deposits would have avoided this in many cases, depending on the use to which the mortar was being put.

The use of local materials for mortars employed in bulk construction appears to have been the origin of the use in Rome of the pozzolanic pit sands (*harena fossicia*), which had such important repercussions for Roman architecture and engineering (Jackson et al. 2007); the famous *pulvis puteolanus* from the Bay of Naples presumably had a similar origin, as in both cases there was a local volcanic geology and a relative dearth of ordinary inert sands. An interesting study by Marra et al. (2016) of some of the earliest mortared rubble structures identified in and around the city shows that the aggregates in the earliest mortars came from nearby outcrops or the construction site itself and included debris from working the rubble, itself a tuff of volcanic origin. In other examples, the pit sand appears to have become mixed with tuff debris as a result of the two strata interfacing at the quarry. Towards the end of the second century BCE, there appears to have been a change to using a different — and more effective — pit sand deposit (*pozzolana rossa*) on the outskirts of the city, which fits with the revised date for the start of wide-spread construction in mortared rubble in Rome (Mogetta 2015), requiring a more reliable and predictable supply than simply using what was closest to hand. Nevertheless, Wehby Murgatroyd's study (2016) of closely contemporary mortars from the second century CE Ostia, the port of Rome, shows that even so close to Rome aggregates in otherwise similar mortars used different mixtures of materials of volcanic origins, and not just the *pozzolana rossa*, with no effect on the mechanical quality of the resultant mortars.

The use of pozzolans has long been one of the main interests in scientific research into Roman mortars, and it is increasingly the case that the use of sources besides those of Rome or the Bay of Naples can be identified. Lancaster (2015, 22–26; 2019) gives an overview of other places in the Roman empire where local sources of volcanic materials were used in mortar, from the Rhineland in the west to eastern Turkey, for example, at Sagalassos (Callebaut et al. 2000), while Brandon et al. (2014) discuss this in relation to the pozzolans used in harbour works around the Mediterranean. Other naturally occurring pozzolans of volcanic origin in Italy not included in Lancaster's survey include those from the Euganean Hills west of Padua, used for the theatre and amphitheatre of the Roman city (Bonetto et al. 2021), and from the Vulsini volcanic district in Tuscany (Marra and D'Ambrosio 2013). At Nora in Sardinia, ground obsidian was also used as a pozzolan, which Columbu et al. (2019) argue came not from its primary source but from abundant deposits of obsidian tool-making waste from prehistoric contexts around the city.

In the Roman period, it is usually hard to identify the precise extraction sites of these materials, when abundant local sources were used and/or small quantities were required for minor projects. In areas of continued habitation, larger quarries for aggregates were also commonly obliterated by later construction, as was happening already in antiquity. Excavations in the House of Amaranthus at Pompeii revealed a series of pits in the natural volcanic soil some at least of which appear to have been quarries to extract aggregate for either mud brick or (more likely given the first century BCE date) for mortar (Fulford and Wallace-Hadrill 1999), but this is a rare find. At Rome, because the pozzolan deposits are intercalated between those of lithoidal tuffs, the aggregate was frequently obtained from underground galleries which can still be identified, with examples from the Aventine (Marra et al. 2016), the Esquiline outside Servian walls from the second century BCE (Serlorenzi 2014) and from the south-east of city (Buccellato and Coletti 2014). Large piers of the material were left to support the strata above, and little extra shoring seems to have been used. These pozzolans can be quarried simply using a pick, and given that the galleries appear to have been at least 2 m wide, the material could be loaded directly into carts or panniers on pack animals at the quarry face. Some idea of the process of working of these quarries in the Roman period can be deduced from much later sources, in particular from De Marchi (1894), when it appears that very similar methods were in use.

In contrast to these naturally occurring materials, the other main types of aggregates used in lime mortars — the crushed terracotta and plant ash — were both waste products which were used for their pozzolanic actions particularly, but not universally, to exploit their ability to resist moisture (Coutelas 2019; Lancaster 2012). These two materials would have been very different to source; waste terracotta products were more abundant in urban situations, manure and crops in rural ones. Siddall (2011) has demonstrated in the case of the baths at Corinth that the ground terracotta came from pottery, particularly low-fired ceramics such as those used for amphorae and coarsewares, rather than from bricks or roof tiles which tended to be fired at a higher temperature and were both more difficult to process and less reactive in the mortar. The overwhelming use of the material was in surface treatments, including pointing the joints of masonry, wall plasters and the fixing base for marble and other wall veneer, mortar floors and the lining of water features including aqueduct channels, cisterns, fountains and basins in baths.

Even this volumetrically limited use of crushed terracotta would have required, in all but the smallest applications, an organised system for collecting and possibly marketing the discarded ceramics. This would not be surprising given that amphorae had other uses in the construction industry; whole, they were used to build enclosure walls (Serlorenzi 2010) or in drainage schemes (Carbonara et al. 2018), while broken pieces were common as part of fills on building sites; they were also used as containers for building materials (see below). The waste ceramic for mortar then had to be crushed or ground, although there is not the evidence to say whether this happened at the collection point or the building site; much may have depended on the quantities required. For large quantities at least, it is feasible that animal- or even water-powered mills were employed, using similar technology to that used for milling grain. Although crushed terracotta was sometimes used in mortar for construction, for example, in the later second century CE bouleuterion at Smyrna (Turkey) (Felekoğlu et al. 2016) where it was clearly used for its structural properties, the difficulty of obtaining the necessary quantities of material and the cost of processing may have been limiting factors for more general use in areas which did not have natural pozzolans. The continued use of crushed terracotta in plasters and floors, either on their own or combined with local pozzolans, perhaps reflects the inherent conservatism of builders working in an empirical tradition despite the hydraulic properties of the natural pozzolans (e.g. Rispoli et al. 2020).

Lime

There is overwhelming scientific evidence that in the main Roman period, when the use of lime-based mortars for rubble construction was at its height and very widely spread over the empire, the preference was to use the purest calcitic limestones available to burn for lime as recommended by Vitruvius (see Lancaster 2021). At Ammaia, a Roman town in Portugal, Cardoso et al. (2014) have shown active selection for this material on the part of Roman builders. Although in the earliest buildings a clay-based mortar was used, builders soon turned to using calcitic limestone, even though this had to be imported from an as yet unknown source, rather than making the lime from the local dolomitic limestone, the latter only being employed in the post-Roman period. Nevertheless, examples have been identified where in the absence of better material, limestone marls with a high clay content and even the shells of marine and riverine molluscs were employed (Suméra 2009; Dilaria et al. 2019). In late antiquity and the mediaeval period, lime kilns often used debris from ruined or surplus buildings, including marble from statuary, funerary monuments, inscriptions and veneer. These appear frequently in urban centres (see e.g. Venditelli and Ricci (2015) for Rome; Lenzi (1998) for Ostia; Bonnie (2016) for Galilee; Del Moro 2008 for Cyrene) but are also found in decommissioned Roman rural villas, exploiting both marble and limestone building elements, as part of a broader practice of late antique and early mediaeval recycling, often for church building (Munro 2016).

The general process of lime-burning in antiquity has been well-described in the modern literature (e.g. Adam 1984, 65–71; Dix 1982; Traini 2013, 31–48; Suméra 2009), and there is ample evidence, both archaeological and from depictions, for example, on the mid-twelfth century mosaic from the south side of the nave of the Cappella Palatina in Palermo (Fig. 1), to show that the techniques did not vary enormously in later periods, even persisting until very recently in traditional lime-burning areas (for examples, see Adam 1984, 68–70; Wurch-Kozelj and Kozelj 1999). The archaeological evidence for actual limekilns is however relatively thin for the early- to mid-Roman periods compared with late antiquity and the mediaeval period; Traini (2013, 49–82) provides a useful catalogue with bibliography for the area of the Roman empire, while new finds are constantly extending the evidence (e.g. Traxler et al. 2018).

While quicklime could be produced by the simple burning of limestone in an open space, the resultant temperatures were not high enough to result in a complete calcination, and the lime produced was contaminated by ash and charcoal from the fuel (Traini 2013, 32–33). As the process leaves few visible traces, it was probably more wide-spread in the Roman period than is often assumed (for an example, see Coulthard 1999). The most common form of lime-kiln in the archaeological record is that described by the Roman senator Cato the Elder in the mid-second century BCE (see Lancaster 2021), taking the form of a broad truncated cone of circular or elliptical plan, with one, or occasionally two, accesses to the outside at ground level for adding fuel and removing ashes, often with a ledge running around the inside at the base, and sometimes a pit in the centre for collecting the ashes (Fig. 2). The lowest stones (referred to as the charge) were laid initially over some kind of formwork or corbelled to form a rough vaulted firing space which would be self-supporting once the props burnt away during firing, and then the rest of the charge was gradually added over this.

Fig. 1 Mid-twelfth century mosaic from the south side of the nave of the Cappella Palatina in Palermo (Sicily), showing the building of the Tower of Babel. To the left, a worker loads fuel into a lime kiln. At the bottom right, a man works lime in a lime-slaking basin, while beside him, another worker shovels lime into a basket being raised to the second level of the structure. At the third level, the man on the right holds a mason's trowel. Photo author

Fig. 2 Late second century CE lime kiln no. 9, Lauriacum, Emms (Austria), aerial view. The kiln is built into the natural conglomerate, and the combustion chamber (top) and access to the stoke hole (below) are built from rubble. The edge of the ash pit can be seen just above the stole hole, and the floor of the access corridor is discoloured by ash and charcoal. From Traxler et al., 2018, 103, courtesy S. Traxler

Excavated examples have a lower diameter ranging from 2 to 7 m, with 3–4 m being the most common. Cato's kiln, with a diameter of just under 3 m, would have had a volume of about 20 m3, producing perhaps 14–15 m^3 of usable quicklime, while Baradez (1957) estimated that the largest of the kilns at Tipasa (Algeria), an ellipse with long axis around 6 m in diameter, had a volume of 90 m^3 able to produce 65 m^3 of quicklime.

Many of the excavated examples of the Roman period are of single kilns, mainly in rural areas and arguably serving the needs of villas or other rural settlements, and this is the context of Cato's kiln. Some at least of the lime would have been used in agriculture rather than for construction (Dix 1982). These are unlikely, however, to have been able to serve the needs of large urban centres or major infrastructure projects, yet relatively few limekilns have been found in Roman cities; those for the baths at Vieil-Evreux (France) are an exception (Guyard et al. 2008). Rather, they tend to be located at or near the limestone quarries and in rural areas where fuel was more easily found. The hilly area around Lucus Feroniae, along the Tiber north of Rome, has provided several examples of sites with multiple kilns directly adjacent to the quarries, in one case organised in pairs to allow for a more efficient firing cycle (Fontana 1995; Savi Scarponi 2013); most show evidence of use over a long period of time and can be interpreted as commercial enterprises serving the needs of Rome. The existence of subsidiary structures connected to the kilns, as at Lucus Feroniae, reinforces the interpretation of these as permanent installations producing for a market rather than for occasional or intermittent use supplying the needs of a rural estate. A similar phenomenon has been found in the Swiss Jura (Coutelas 2009, 56) and at several sites in Gaul, one at Touffréville with 16 permanent kilns of different periods demonstrating a long period of exploitation (Coulthard 1999), although the particular market for the lime is far from clear. Large groups of kilns have also been found near military sites or at least operated by Roman legionaries, along the northern *limes* and at Tipasa (Algeria); the best known are those at Iversheim (Sölter 1970), with a row of five kilns plus one slightly later, while the most recently discovered, at Lauriacum/Emms (Traxler et al. 2018, 2019), had 12 kilns each 3–4 m in diameter (Fig. 2). While these have usually been interpreted as serving the needs of the Roman army in the building of fortresses, the group of at least 10 kilns at Krivina, in northern Bulgaria, dating to the later first century CE has no clear relation to any major military sites of that date using mortar in construction (Vagalinski 2011), and as at Touffréville no obvious market can be determined. This author (1997, 189) has calculated that at least 21 large kilns each producing 60 m^3 quicklime and operating 14 cycles per year over four years were needed for the Baths of Caracalla, strongly suggesting that lime producing on this military scale would have been needed to serve the requirements of a city the size of Rome.

All these kilns are of the periodic kind, that is, they need to be filled, fired and then emptied before the cycle can begin again. While historic figures for firing cycles vary greatly (see DeLaine 1997, 112 note 48 for examples), Baradez (1957) suggested that only three firings per month would be feasible in his study of the kilns at Tipasa. This fits with experimental firings at Iversheim, which took 6–7 days including the cooling, plus 3 days for loading and unloading (Sölter 1970, 35–40); larger kilns would have taken longer to load, fire and unload, so that perhaps 12–14 firings were possible in the drier months of the year (cf. Delaine 1997, 112–114). The longer the firing, the more likely that the limestone would be completely calcined and the resultant quicklime of better quality. At some sites, notably Lucus Feroniae (Fontana 1995) and Tipasa (Baradez 1957), there is an arrangement of several normal-sized kilns of 3–4 m in diameter plus one much larger one, which suggests some kind of distinction in the production cycle, but whether this was for different destinations for the lime or simply to create a more flexible structure of supply can no longer be determined. Relatively few known production sites based at quarries have facilities for slaking lime (see below), which seems to have been done mainly at the construction site (Suméra 2009, 58).

Lime burning also has a large fuel requirement, which has been roughly estimated at 1.5–3 tonnes of wood per m^3 of lime, depending on the type and degree of moisture (DeLaine 1997, 113; Suméra 2009, 40–42). The general use of oak and other hardwoods has been confirmed by Vaschalde et al. (2013) for Roman and mediaeval lime kilns in southern France, based on a study of charred wood from kilns. Local availability, however, appears to have informed the choice of species used, and there is evidence that smaller materials, including typical Mediterranean shrubby plants like rosemary and juniper, and even chaff or dried animal dung, were also used at some point in the firing cycle. The gathering of fuel must have been an important part of the lime-burning operation for the sites with large banks of kilns, while for individual smaller kilns on rural estates, some at least could be accumulated from general arboriculture or other estate activities.

Transport

It has been estimated that one of the major elements in the cost of construction was the transport of building materials (DeLaine 1997, 219), but this depended on the weight and volume to be transported, the distance, the form of transport and the available infrastructure. Russell (2013) provides a thorough analysis of the problem in relation to building stone, much of which also applies to the components of mortar and plaster, in particular for mortared rubble constructions where the volumes of mortar were considerable. This made the burning of limestone at source an obvious solution, as it reduces the weight by about 44%. The natural pozzolans of Rome and the Bay of Naples weigh roughly 1 tonne per m^3, coarse dry sands and loose gravel about 1.5 tonnes per m^3 and quicklime 1.1–1.5 tonnes, depending on the limestone used (Giuliani 1990, Table 7.1).

Land transport was much more expensive than water, and there was a closer relation between cost and weight over land than by water. Although both aggregates and quicklime could be carried by pack animals, the volumes required suggest that wagons, drawn by oxen or mules, were the usual mode for overland transport, with a maximum load of 1–2 tonnes for standard carts. This did, however, require a fairly smooth and level surface, so that proximity to good roads was important for any materials that had to be moved over any distance. River transport downstream may have cost about a tenth of land transport or a fifth if movement upstream was involved, while sea transport may have cost 30–40 times less and involved much larger loads. Since transferring loads from one means of transport to another added extra labour and cost, solutions involving the fewest transhipments may have been preferred.

Direct evidence of transport solutions for aggregates is almost non-existent, but the relatively short distances involved in most cases indicate that the norm would have been to use carts, with the material being loaded directly at the quarry and unloaded at the building site without any need for transhipment. One of the pozzolan quarries identified by Buccellato and Coletti (2014) south of Rome and just 1 km from Tiber might have used the river, but this would have required two extra transhipments and an up-river journey, making the 12-km land journey along the major highway of the via Ostiensis a more likely solution. Some aggregates made longer journeys. The natural pozzolans found loose as ballast in the hold of a sunken ship at Pisa (Marra and D'Ambrosio 2013), dated to the first decades of the first century CE (Camilli 2012), came from the Vulsini volcanic district in Tuscany via the river Fiora, along an established commercial water trade route with a river port and a sea port connected to the important town of Vulci. According to Jacopo Bonetto, unpublished research by the University of Padua has demonstrated that these pozzolans from the Bay of Naples were used in the construction of the large baths and theatre at Aquileia. The closeness of the various sources of these pozzolans to the sea must have been an important factor in their exploitation. Trade in pozzolans from the Bay of Naples, used for harbour works, is a special case discussed in Brandon et al. (2014, 223–226), who argue for a major trade in the material across the Mediterranean.

The situation was rather different for lime, which in the early- to mid-Roman periods was generally produced at the quarry site where fuel could also be easily acquired and often had to be transported longer distances than aggregates (for an overview, see Suméra 2009, 58–60). It is not therefore surprising that many of the known limekilns are situated very close to major rivers such as the Tiber (Fontana 1995; Savi Scarponi 2013), Rhine (Sölter 1970) and Danube (Vagalinski 2011). Since neither production nor construction sites were generally directly beside a river, some transport by cart would have been necessary at each end of the journey, with the additional transhipments involved. At the same time, river transport for lime was not always possible; the lime for the Villa of the Quintilii via Appia south of Rome has been shown to come from the Monti Cornicolani to the east of the city (Fichera et al. 2015), where river transport via the Tiber would involve two sections of road transport scarcely if any shorter than direct road transport, plus the extra transhipments. Transporting quicklime, as seems generally to have been the case, saved on weight but posed other problems. The material is both caustic and had to be protected from moisture to prevent premature slaking which would make it unusable for construction. It therefore needed to be transported in some form of container, such as heavy sacks or large baskets. Things could go wrong; the Greek philosopher Theophrastos, writing in the early third century BCE, recounts the tale of a ship carrying lime and textiles which caught fire after the lime became wet (cf. Traini 2013, 83).

On-site storage and preparation of materials

Efficient use of manpower in construction requires that all the necessary materials are at hand. Depots of building materials are therefore a normal feature of construction sites, including modern ones, but can be hard to identify in the archaeological record. This is partly due to the fact that piles of dry materials, including aggregates, may leave little or no trace once incorporated in the structure, and partly due to their location in open areas which are less likely to be the focus of modern excavations (Guyard et al. 2008; cf. Spera et al. 2011 for a mediaeval example). The bulk of the archaeological evidence relates to lime-slaking pits and basins, which were generally dug into the working surface and preserved by being buried at the end of the building project and/or reused as rubbish pits (see the catalogue in Traini 2013, 95–102). The villa at Brachaud, near Limoges, provides a rare example of a work depot with both lime-slaking pits and an area for aggregate marked out by an edge of tile, the two separated by only a couple of metres (Loustaud 1983, Fig. 6). Pompeii also provides examples on a small scale, for example, in what appears to be interrupted building works at the House of Amaranthus, with a pile of pozzolanic aggregate and lime, mortar and crushed terracotta stored in amphorae (Fulford et al., 1995-96). The final necessary element is water for slaking lime and mixing mortar, yet this is rarely discussed in the archaeological context.

Aggregates

Since the proportion of aggregate to lime in most Roman mortars was around 3:1 by volume, considerable areas needed to be set aside for storing aggregates on large building sites. Alternatively, and particularly for major building projects, stocks of aggregate needed to be replenished on a regular basis if the construction schedule was not to be delayed. The variability of composition in mortars and plasters using the same basic materials, whether sands, natural pozzolans or crushed terracotta (e.g. Di Benedetto et al. 2018), presupposes that some degree of processing and sorting of aggregates took place on site, which would have added another level to the supply chain, and required space for working the different materials and storing them separately.

The evidence that aggregates for mortar and especially plaster were sorted for size is clear, although little discussed in terms of the construction process. Davey (1974) is an exception; he grouped the maximum size of aggregates in construction mortars from the province of Britannia into sizes that would have fit through sieves of *uncia* (c. 24.5 mm) in mortar floors and foundations, *digitus* (c. 18.5 mm) in wall mortars and *semiuncia* (12.3 mm) in plasters. At Ostia, from personal observation, the largest aggregate in mortar for ordinary facing brickwork would also pass through a *digitus* screen, while in fine-work used for decorative brick facing the maximum is generally less than 2 mm, possibly derived from a tenth of a *digitus* sieve (Fig. 3). In the Villa of the Quintilii just outside of Rome, the largest aggregate in the mortar for the core would have fit through an *uncia* screen (Fichera et al. 2015, Fig. 4b). A similar distinction between core and facing can be seen in the Baths of Caracalla in Rome (DeLaine 1997, 140). In the amphitheatre at Aquileia, a *semiuncia* sieve seems likely for general construction and a very fine one for laying brick (Dilario and Secco 2018, 183–185).

Lime slaking

Both Suméra (2009, 50–58) and Traini (2013, 83–91) give good overviews of the process of turning quicklime into slaked lime through the addition of water, to make the essential component in lime mortars and plasters. The limited evidence available suggests that the usual process of slaking lime was by fusion, involving adding water gradually to a layer of quicklime while mixing it continually with a long-handled draw-hoe (one with a blade at right angles to the handle) until the lumps of quicklime disintegrated. This process appears to be what is being shown on a late antique mosaic from Oued R'mel (Tunisia, now in the Bardo Museum; Adam 1984, Fig. 164); although the mosaic has considerable lacunae, it clearly shows a man pouring water

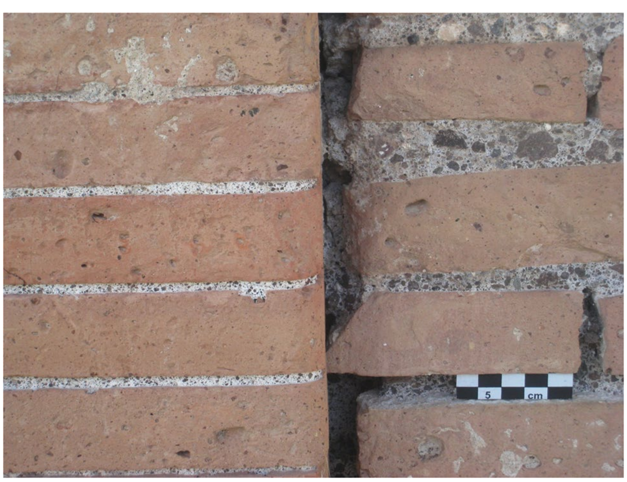

Fig. 3 Construction detail, Casa a Giardino, Ostia (Italy), built in the 120 s CE. On the right, part of wall showing standard brick facing, with mortar having a pozzolan aggregate which would go through a *digitus* sieve; on the left, the adjacent decorative pilaster, an integral part of the same structure, with very narrow joints requiring the pozzolan to be put through a fine sieve. Photo courtesy S. Camporeale

Fig. 4 Lime-slaking basin, Molesme 'Sur-les-Creux' (Côte-d'Or, France), early first century CE. The floor of the basin is made of planks of fir. From Coutelas 2005, Fig. 1, courtesy A. Coutelas

from an amphora onto a pile of white material which is being worked with a draw hoe by a largely lost figure. Fully slaked lime, if kept away from air, is more stable than quicklime, and if covered, it can be stored for long periods. The benefit of storing lime before use was to make sure that the process was complete and no lumps of quicklime remained which might react explosively when further water was added in the making of mortar and in particular plaster.

The limited archaeological evidence for the Roman period indicates that on the whole, lime slaking took place at the building site, whether this was the location of the lime kilns or not. Lime slaking/storage pits have generally not been well-recorded or published. Loustaud (1983) was one of the first to discuss the phenomenon, examining 8 basins from ancient Limoges and a nearby villa; although the evidence has grown since then, Traini (2013, 95–102) only catalogues 22 from Roman and late Roman sites, not all entirely convincing, although he notes that this is not an exhaustive list. Most of the reliable examples are from domestic contexts and are fairly small, with a longest dimension of about 1 m. The largest of those discussed by Loustaud (1983) measured 1.4 × 2.4 m, with a volume of 1.58 m^3, and relates to villa baths. Some of these basins were pits dug into the earth and lined with tiles and/or wooden planks (Fig. 4); others were of masonry and lined with cocciopesto. Traini and Mannelli (2013) report a much larger basin, 1.88 × 2.65 m and 1.82 m deep and lined with cocciopesto, which served the construction of the late second/early third century CE baths on the slopes of the Palatine in Rome, although there is no direct evidence to show that it was in fact used for slaking or storing lime. A basin of this capacity could hold 5 m^3 of slaked lime, enough to make c. 20 m^3 of mortar at the normal proportion of 1:3. To put this in perspective, the amount of slaked lime required for the Baths of Caracalla in Rome was over 100,000 m^3, which would have needed a basin of this size being filled over 20,000 times over the course of construction. It is clear that we have not yet found any major installations for lime-slaking on imperial building sites.

A number of sites recorded by Loustaud (1983) have two lime-slaking basins, one larger than the other; he argues, on the basis of ethnographic parallels, that the larger was used for the primary slaking and the second for refining the resultant product to ensure complete slaking and to remove impurities such as fragments of carbonated lime, which could be caused by the reuse of lime-slaking pits and basins; such fragments have been identified in archaeometric studies of mortars. Alternatively, the basins could have been used for different qualities of slaked lime, the larger for mortar and the smaller for plaster, where the complete slaking of the lime was more critical. The fact that such basins have been found still containing lime has led Loustaud (1983, 149) to suggest that this was a deliberate act to preserve lime for later maintenance.

Putting in place

The process of building with mortar and plaster varied to some degree with the size, nature and importance of the project. We should not expect to find the same qualities of mortar or the same care in applying it on small domestic restoration works as on large public buildings. Nevertheless, the basic organisation of work was presumably similar and dictated by the physical requirements of the site and the project. The wall painting from the Tomb of Trebius Justus in Rome (Fig. 5; Marucchi 1911) is the only surviving example from the Roman world of builders working on a brick-faced mortared rubble wall. The scene is remarkably modern: there are five workmen, wearing the short tunic of the slave or labourer, with two bricklayers standing on scaffolding on either side of a wall, while one labourer carries a load of mortar up a ladder in half an amphora, another carries a load of bricks or rubble in a basket, and a third mixes mortar using a long-handled draw-hoe. The scene can be broken down into three essential actions: mixing the mortar, transporting the materials to the workface and putting in place.

Mortar and plaster mixing

While any aggregate processing and lime slaking needed to be carried out in advance of construction, mortar and plaster preparation had to take place concurrently with construction or decoration, especially when pozzolans were being used as such mortars begin the curing and hardening processes very quickly.

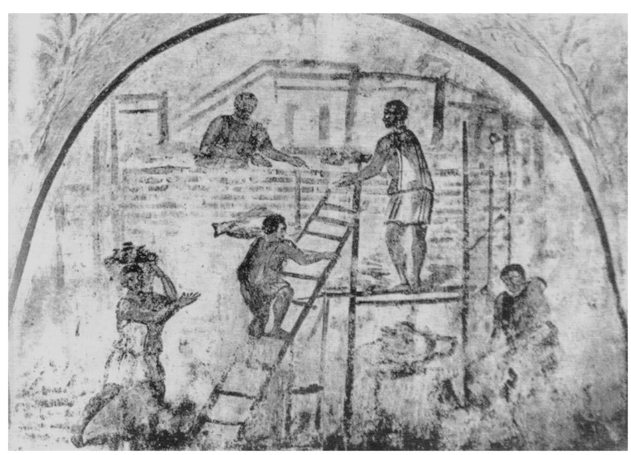

Fig. 5 Wall painting showing a scene of builders at work from the Tomb of Trebius Justus, Via Latina (Rome), fourth century CE. Two men on scaffolding either side of a brick-faced wall are laying bricks using masonry trowels. To the left, a man carries a basket full of rubble or bricks, while to his right, another man climbs a ladder with a halved amphora of mortar on his shoulder. To the right, a man mixes mortar with a draw-hoe. From Marucchi 1911, Fig. 5

The recipes for mortar mixes in the written sources (see Lancaster 2021) are given as whole ratios such as 1:2 or 1:3 lime to aggregate by volume, and these proportions are roughly confirmed by archaeometric analyses (e.g. Wehby Murgatroyd 2016) although there is much variation. Such proportions could be achieved simply on site by using a basket-load as a measure, which would account for at least some of the variability in the results. Baskets appear on both the Oued R'mel mosaic and the Trebius Justus wall painting, as well as on Trajan's Column in Rome, as standard elements in construction scenes, usually as containers for moving materials, but there is no reason that they could not be used at the same time for measuring. Romans used a *modius* for measuring grain, but these would not have been feasible to use on building sites; this author (1997, 107) however has estimated that the baskets on Trajan's Column would have contained around two *modii* or roughly a cubic Roman foot (0.026 m^3).

The process of mortar mixing is well described by Traini (2013, 103–112; cf. Coutelas, 2008, 2009, 71–72). It can be seen at the lower right-hand corner of the scene from the Tomb of Trebius Justus (Fig. 5) and reappears frequently in mediaeval representations of building sites. A measured quantity of aggregate was arranged on a flat piece of ground in a rough circle with a well in the centre, the appropriate quantity of slaked lime is placed in the centre, and the aggregate is mixed into the lime using the same kind of draw hoe as used in lime slaking, with limited water used as required to obtain the right consistency of the paste (see Adam 1984, Fig. 163, for a reconstruction drawing). In order to produce the best mortar or plaster, the mixing needed to be thorough. Coutelas (2008) provides examples from a number of sites to show that mortar-mixing areas were often reused, and this may have been the way in which small fragments of old mortar found their way into fresh (for an example, see Dilaria and Secco 2018). There is no evidence that Roman builders used the kind of mortar-mixing machines which have been identified for mediaeval building sites (Bianchi 2011), although this may simply be due to the absence of evidence.

Moving mortar and plaster around the construction site

Over the short distances involved in most building sites, human portage was the most basic and most flexible way of moving the different ingredients from the stockpiles and lime-slaking or storage pits to where the mortar was mixed and then moving the mortar to the workface (for a summary, see DeLaine 1997, 107). Except possibly on very large building sites such as the imperial baths, pack animals and wagons would require extra manpower for loading and unloading and might simply clutter the site unnecessarily. Over short distances, a man can carry a load of around 50 kg or even more, around the same as a small donkey. There is no evidence that Romans used wheelbarrows, but some form of simple two-wheeled cart may have been used instead; nevertheless, the same reservations as for pack animals or larger wagons apply.

In the wall painting from the Tomb of Trebius Justus, a distinction is made between the man on the ground, who appears to have a basket load of bricks or rubble, and the man on the ladder, who appears rather to be carrying the mortar in half an amphora. The caustic nature of both lime and mortar would make this a sensible choice; the use of amphorae to store lime and mortar observed at Pompeii (see above) suggests that this was common practice. In addition, the open nature of a longitudinally halved amphora would make the mortar easier to access for the mason than the more closed form of a basket.

Using mortar in construction

Mortared rubble masonry

The construction process for mortared rubble is generally well-understood; Adam (1984, 125–150) provides a useful if brief introduction. It is, however, rarely if ever discussed specifically from the point of view of how the mortar is used. Overall, the construction process can be divided into three stages: laying foundations, laying the facing and core of the walls and laying the vaults (if used). At each stage, the work could be done well or done poorly. Generally, what has been preserved has been so by virtue of being at the better end of the scale; the very poor quality of some of the construction at Pompeii, and in particular the weakness of much of the mortar, is a reminder that not all Roman construction was of high quality. The following applies to the higher end of the construction spectrum.

The fundamental principle of Roman mortared construction is that the rubble is laid in mortar, rather than being mixed into the mortar before being put in place. Even in foundations, where the sides of the foundation trench, whether just earth or timber shoring, served to contain the mass of rubble and mortar, all the evidence points to the rubble being either roughly laid or thrown into the trench in layers alternating with mortar and then rammed down to compact the mass and remove air pockets (cf. Dilaria and Secco 2018, 184). The mortar therefore was not liquid and could not be poured like modern concrete.

The walls above ground were generally constructed as two faces with a central core, either with short vertical sections of the external faces being put in place and then the core or the two rising together (Fig. 6). The ability of the pozzolanic mortars of Rome and central Italy to cure and gain strength rapidly, and the use of relatively narrow mortar joints, meant that the work could proceed rapidly without the need for any supporting formwork, although this may not

Fig. 6 Construction detail, Grandi Horrea, Ostia (Italy), late second century CE phase. Section and face of wall, from left to right: section through neatly coursed brick facing; section through roughly coursed core; neatly coursed brick facing. Photo author

Fig. 7 Brick facing, Grandi Horrea, Ostia (Italy), late second century CE phase. Detail showing vertically struck joints (indicated by arrows); elsewhere, the surface of the mortar has deteriorated. Photo author

have been the case everywhere (cf. Camporeale 2011). As with the foundations, the core was laid more or less roughly in courses alternating with mortar but generally without any further consolidation, and it is not uncommon to see gaps between individual pieces of rubble where the mortar has not penetrated (cf. DeLaine 2001, 234). Laying the facing required more careful work than laying the core and sometimes used a less coarse mortar, especially for finely finished work. The detail depended on the shape and form of the facing materials used, but the basic process was to bed each facing element into a horizontal layer of mortar; for larger elements, such as rectangular blocks or reticulate pieces, mortar was first applied to the side of the element which was to be in contact with the piece previously put in place as in modern bricklaying, while the triangular bricks used in mid-imperial construction in Rome and Ostia were often laid simply on the mortar bed, creating narrower horizontal than vertical joints (see Fig. 6). The mortar had to be of a consistency that would give way slightly when the facing element was put in place, ensuring good contact between the two, without flowing too much out of the joint. In the best construction, the horizontal joints are of fairly uniform thickness while still allowing for variations in the thickness of the facing element; this suggests that the workmen maintained a uniform consistency of mortar and used a specific amount for each course, even though this amount could vary both within a single building for different functions (Fig. 3) and from one building to another.

The mortar in the joints was then finished in various ways, being struck either vertically to be flush with the plane of the wall (Fig. 7) or at an angle or slightly hollowed out. Coutelas (2012b, 173–175) provides examples of both weather-struck joints, where the mortar slopes in from top to bottom and double-struck joints which slope towards in both directions away from a central ridge of mortar. In mortared rubble construction using irregular pieces or where the quality of the bulk of the mortar in the core was poor, the joints between the facing pieces could be finished at a second stage called pointing, using a different quality of mortar and even almost pure lime putty to protect the structural integrity of the core and/or to establish a smooth outer face, sometimes for decorative purposes (Coutelas 2005, 332–334; 2009, 78–82).

Mortar was used in vaulting with the shape defined by wooden formwork which also supported the structure of the vault against gravity until it had cured sufficiently to be self-supporting (see Lancaster 2005). Although in early Roman vaults the rubble was set radially, in later buildings in central Italy where strong pozzolanic mortar was used, the rubble was laid horizontally in the mortar exactly like the wall-core, and it is often difficult to say where the wall ended and the vault started. The main difficulty in using mortared rubble for vaults appears to have been separating the supporting formwork from the underside of the vault once it had cured. One solution used in Rome and Ostia was to cover the formwork with one or two layers of brick, which remained attached to the underside of the vault when the formwork was removed; elsewhere the mortar skin on the vaults has often preserved the size and shape of the timbers used for formwork (Lancaster 2005, 22–50; Coutelas and Hourcade 2016).

Trowels

The main tool for laying and finishing mortar in construction was the leaf- to rhomboid-shaped builder's trowel, which has remained in use to the present day. Relatively few actual examples have survived from antiquity, and there are a small number of depictions, the earliest of which is on the relief of the *structor* (builder) Diogenes at Pompeii. Gaitzsch (1980,133–147) provides a catalogue of 83 examples from Italy and the north-western provinces, to which can be added one from the Roman veteran colony of Cuicul (Tunisia) now in the museum of Djemila (Belhout 2019, cat. No. and Fig. 14); imprints of a pointed trowel have also been found in mortar pointing at Cassinomagus (Coutelas 2012b, Fig. 50). Gaitzsch divides them into six types based on the basic shape, with variants defined mainly by the different length to width ratios, while within each type, the trowels vary also in length and breadth. This rather masks the functional aspect of his types, which he otherwise divides into masons' trowels (54 out of the 83), pointing trowels — some also used in plasterwork (26 out of the 83), and three 'pointed' (or 'English') trowels, the latter being the familiar form currently used by archaeologists. A further separation between pointing and plasterers' trowels can be made (Fig. 8). Gaitzsch found no examples from the Greek period and associated the development of the tool, and of local and specialised variants, to the growth of mortared rubble construction in the Roman period. The range of shapes and sizes can be paralleled in early twentieth century trowels, for example, those advertised in the catalogue of the specialist company Forges de Mutzig (1929) which gives the place of use as well as the function of the different types. The wall painting from the Tomb of Trebius Justus in Rome (Fig. 5) is to my knowledge the only surviving representation from antiquity which shows a trowel being used by builders, but such scenes are relatively common in mediaeval construction scenes (Fig. 1).

Harbour works

The production of mortar and laying of mortared rubble for harbour works were rather different to those for land-based

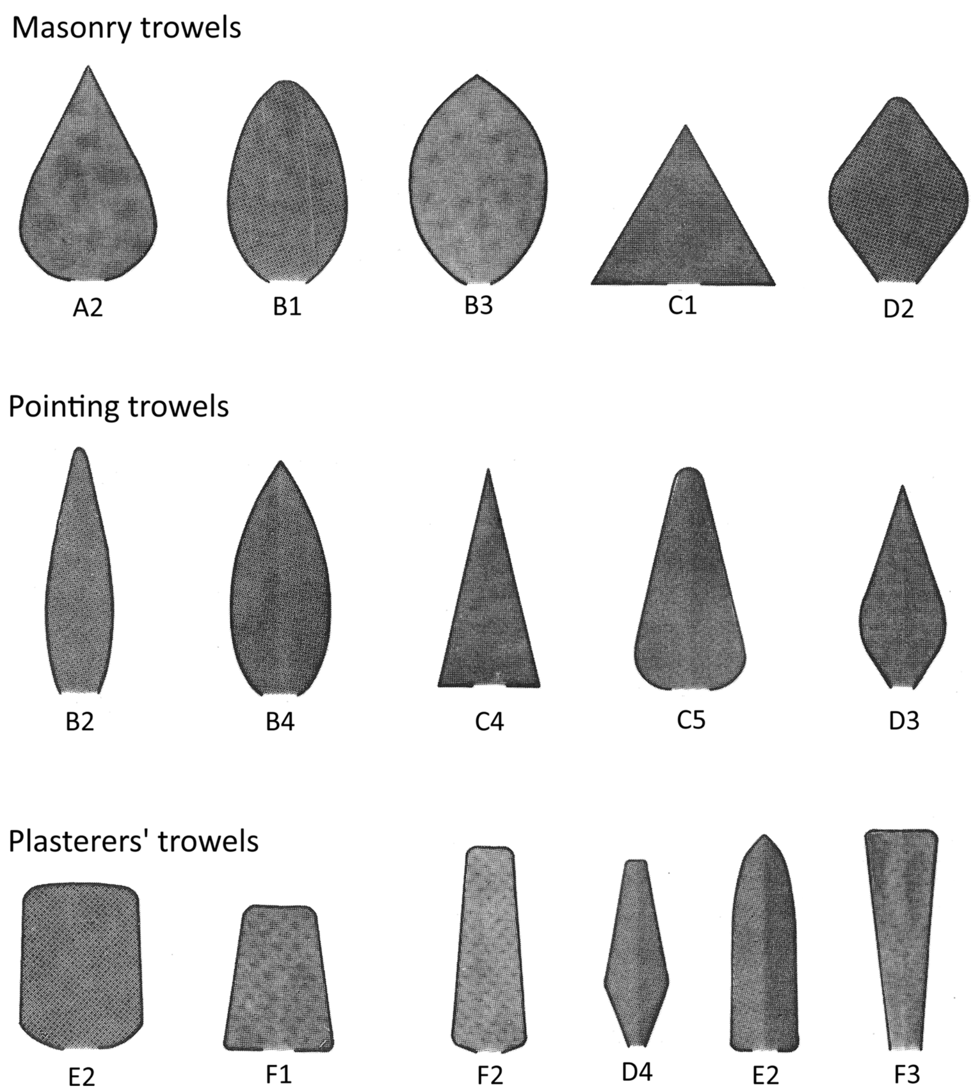

Fig. 8 A selection of Roman masonry, pointing and plasterers' trowels, first to fourth centuries CE. A2 and B1 are the most common forms, while the pointing and plasterers' trowels are relatively rare. Adapted from Gaitzsch 1980, 139

structures, as described in the ancient sources (see Lancaster 2021) and discussed in Brandon et al. (2014, especially 143–222). The success of mortared rubble harbour works depended on the mortar. Nearly all of those tested by Brandon et al. (2014, 161) fall in the range of 55–60% mortar by volume, compared with around 35% for land structures. Jackson (in Brandon et al. 2014, 164–166) argues that in some harbour works either quicklime or aged slaked lime, in the form of small granules, may have been mixed with the pozzolan either dry or with a small amount of water, only fully hydrating in the seawater once put in place, although many questions remain. In two out of the three types of formwork used to create harbour structures discussed by Brandon (in Brandon et al. 2014, 191–222), success depended on the use of hydraulic pozzolanic mortar which would cure and continue to gain strength when completely submerged. Alternatively, harbour works needed to use cofferdams created in situ, which allowed the structure to be built in a dry environment. Otherwise, the process appears to have been very similar to that used in the construction of foundations, although in at least some cases, the degree of compaction is less, reducing the strength of the mortared rubble, presumably due to the difficulties of working underwater.

Plastering and finishing

The final stage of construction often involved adding a separate coating to built surfaces, all of which involved some form of lime-based plaster or mortar. This includes mortar floors, rendering coats for walls, the supporting base for marble and stone veneer and mosaics on floors and walls, and special hydraulic treatments designed to waterproof a variety of structures especially aqueducts, cisterns, fountains and industrial basins. Coutelas (2009, 87–121, cf. Büttner and Coutelas 2011) provides a good starting point for understanding how mortar was adapted for these different types of use in the context of ancient and mediaeval Gaul, and see Adam (1984, 216–234) for a more general account.

Wall coverings nearly always consist of at least two layers, and more normally three, rather than the seven recommended by Vitruvius (see Lancaster 2021); Di Benedetto et al. (2018) provide a good example from central Italy. The first (anchorage) layer was the thickest, as much as 50 mm in some cases, as it had to even out the face of the wall. The mortar was applied to the wall using a trowel, with the surface left rough to help the second layer to adhere; the large particles of poorly sorted aggregate in the mix encouraged this further. The second layer usually contained smaller and better-sorted aggregate and was given a flat finish probably using a float, as was the very thin final layer composed of lime with little or no aggregate, which could be left plain or painted. The application of this final layer is shown in a relief from Sens (Uffler 1971; reconstruction drawing Adam 1984, Fig. 522), while a few wooden floats, looking remarkably like modern ones, have been found in excavations as well as examples of scrapers used by plasterers (Gaitzsch 1980, 11–18). For utilitarian purposes, the aggregate was often crushed terracotta, and there was no fine finishing coat, although, as can be seen in many places at Pompeii, red pigment was sometimes applied to the surface.

Mortar floors, made with or without crushed terracotta aggregate, generally included more and larger aggregate which helped give the mortar more strength than similar plasters; they were also often compressed to improve density and resistance, especially important for cisterns and other water features. Bedding layers for veneer, on the other hand, were often little different to the mortars used in masonry, while those for mosaic usually had a top layer of almost pure lime, sometimes with added fine aggregate, into which the individual mosaic tesserae were set.

Concluding summary of key concepts

The focus of this paper is the chaîne opératoire of the construction process from the production of the main ingredients — lime and aggregate — to their application in structures in the Roman period. First, Roman architects or builders had to identify suitable sources of raw materials for the binder (usually lime) and aggregate. These then had to be extracted and given any preliminary processing at the extraction site, before their transport to the construction site, where further preparation occurred, before the two components were mixed to form the mortar or plaster which was then used in construction or decoration. The emphasis here is on mortared rubble construction, which was a particular development of the Roman period from the second century BCE and required much larger quantities of lime than previous building techniques.

The processes which formed the chaîne opératoire for construction have only recently become the focus of academic interest, and evidence for identifying the details of this sequence of events is uneven. It requires an interdisciplinary approach, and much has to be deduced by working back from the finished product, while direct archaeological evidence of the actual processes is relatively rare, and the detail has not always been recorded or published. As well as archaeological and archaeometric evidence, literary sources, ancient representations and ethnographic studies all contribute. The production of lime is the best understood and has been the focus of considerable literature, as have the components and working of pozzolanic mortars, both those using natural pozzolans and those using pozzolanic waste products, especially crushed terracotta.

The archaeometric identification of the ingredients of surviving mortars and plasters provides evidence for the choices by builders, in terms of the functional requirements but also, and in many cases perhaps primarily, in terms of the economics of construction. Local geological settings, the physical environment especially the ready availability of fuel and their relation to the building site in terms of transport routes, appear to have been primary factors affecting choice. In terms of extraction and preparation of materials, the archaeological evidence shows that well-established technologies were used, especially notable in relation to the production of lime; the main difference is in the scale of productive units, presumably for very large building projects or to serve a major urban market as a commercial venture. Limestone appears to have been most often transported as quicklime, presumably due mainly to the advantage gained by its weight reduction.

The main secondary processing which took place at the construction site was the slaking of the lime and the sorting of the aggregate, by sieving or crushing, to obtain the required size for particular functions both in mortars and surface treatments. Controlling the supply and processing of the basic ingredients played an important part in the logistics of construction. The mortar or plaster mix was then varied by adding different aggregates in different proportions to the slaked lime, allowing for a range of possible uses from essentially the same few raw ingredients. Techniques of using mortar and plaster in the construction process can be reconstructed from limited visual evidence and archaeological finds of tools and the marks left by them in the mortar. All the evidence points to methods which largely survived into the mediaeval period and beyond and can still be recognised in traditional construction today.

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Data availability Unless otherwise indicated, all sources are published.

Code availability N/A

Declarations

Conflict of interest The author declares no competing interests.

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