

An Unfinished Pompeiian Construction Site Reveals Ancient Roman Building Technology

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This file contains all reviewer reports in order by version, followed by all author rebuttals in order by version.

Version 0:

Reviewer comments:

Reviewer #1

(Remarks to the Author)

The article is very interesting, based on the exceptional excavation of a construction site still in progress in Pompeii at the time of the eruption of Mount Vesuvius. It convincingly demonstrates how quicklime was pre-mixed with dry pozzolan before adding water in the creation of Roman concrete. To enhance the article, it would be interesting to compare the data with other lime mortars from Pompeii recorded in other chronological contexts. Indeed, one might wonder whether the use of quicklime might not be part of the urgency of rebuilding after the 62-63 AD earthquake. An emergency technique? Or was it a technique that was already widespread in Pompeii's buildings before the major rebuilding required by the 62-63 AD earthquake? The question remains.

Figure 7 is very instructive, but the workers' clothing needs to be corrected. Not a toga, but a tunic (see, for example, the famous Via Labicana fresco for the workers' clothing).

Reviewer #2

(Remarks to the Author)

The ms on Unfinished Pompeiian Construction Site Reveals Ancient Roman Building Technology is highly interesting for the archeology and geochemical community as it refers to a unique past environment for studying historical building techniques. The main novelty is based on the excavation of a "frozen" Roman construction site to discover "hot mixing" technique to be actively used for binding material. This technique can provide advanced conditions/properties such as fast reactive high T formation/setting conditions and self-healing reactions. I like this approach/outcome! The ms is well organized and well written and methods are properly described. My main concern is about the excessive length of the present contributions, which is accompanied with several repetitions and comments/discussion points not being always in the focus of the main scope. Thus, I would like to see the contribution to be published in Nature Communications but only with major revision to shorten its length and by considering the comments below.

Specific comments:

(1) Abstract: Rephrase "... that calcium-rich phases originating from lime clasts diffuse and form reactive rims around volcanic pumice, producing a wide range of reaction products." The phases are not diffusing, but the dissolved ions gained from dissolution are.

(2) Although the ms is mostly well written, it could be shortened in several cases to be focused on the main issues and to be not repeating (see general comment above):

For instance, to be deleted:

- End of discussion: "The work conducted here both enhances our understanding of ancient building practices ... and the conservation of ancient structures."

- Intro: "Their road systems, for example, were an ... achieved through these construction innovations."

- The whole intro is too excessive.

(3) to be revised: "... where the reaction of the lime with the Si- and Al based compounds in the pozzolana forms stable and insoluble C-A-S-H." C-A-S-H phases are not stable (e.g. being amorphous) and not insoluble (e.g. strongly depending on the environmental conditions like pH), but they are chemical resistant in common building exposure settings.

- (4) Kinetics in "To gain additional insights into the chemical and kinetic history"
- (5) Isotopes (Fig. 4 and text): The slope documented in the literature is not 1:1, but is 0.6 to 0.7(!) as depending on complex reaction kinetics and mechanisms.
- (6) Discussion on isotope signatures misses aspect on the local source of H₂O, which is also highly relevant for potential shift in O isotope composition of the final CaCO₃.
- (7) Change and cyclic fluctuation of ¹⁸O and ¹³C values may record restoration activities:
<https://www.scopus.com/record/display.uri?eid=2-s2.0-84924452714&origin=recordpage>
- (8) Rephrase first sentence of chapter "Post-pozzolan aggregate/matrix interfacial remodeling"

Reviewer #3

(Remarks to the Author)

The article provides important new insights to further characterize the role played by the "hot mixing" method in Roman concrete construction, i.e. the practice of pre-mixing dry quicklime with pozzolans before adding water in the manufacturing of structural mortars. This fabrication process has thus far been studied primarily in the context of medieval and early modern architectural history and applied particularly to modern conservation projects (as clear from the articles cited in bibliography). In previous studies, the authors have argued that this is the "secret" behind the durability of Roman concrete structures, since it would endow the mortars with self-healing properties (whereby the calcite-rich lumps interspersed within the matrix would be subject to long-term dissolution, releasing fluids into the surrounding pore network that would react with the reactive surfaces of volcanic glass and recrystallize, sealing any cracks). On this basis, they have experimented with adding quicklime to Portland cement mixes to create a modern self-healing concrete that would be inspired by Roman precedent. (In reality, most forms in Roman concrete architecture worked only in compression, so the development of cracks did not create any major structural issues if buttressing was adequate; the problem, as is well known, affects reinforced concrete construction to a much greater degree.) The authors now interpret the newly discovered evidence from Pompeii discussed in the article as confirmation that hot lime mixing was the "primary method" in Roman times (p. 13), concluding that slaked lime would normally have been added only to repairs and finishing mortars (mainly to enhance the building medium workability). As highlighted on pp. 3-4, this finding would upend the conventional view that historians derive from the 1st century BCE author of the only Roman architecture handbook known to us: after advising on the best types of stones to be fired for making lime, Vitruvius notes that pit sand, or river sand and crushed pot sherds, can be mixed in after the quicklime has been slaked (*cum ea erit extincta*; De arch. 2.5.1). Significantly, the prescribed use of slaked lime for concrete masonry is also attested in surviving building contracts, such as the *Lex Puteolana parieti faciendi* of 105 BCE, which enforced specific instructions for the making of the structural mortar (CIL I2 698; II. 37-38 *calx restincta*).

The archaeological context presented in the first part of the article, House IX.10.1 in Pompeii, is indeed remarkable for the level of detail that has been recorded during the excavations. Recovering archaeological traces of active construction sites featuring accumulations of building materials and features associated with the logistics of construction is a relatively rare opportunity, though not as uncommon as the authors lead the reader to believe (for recently documented examples, see the proceedings of the *Arqueologia de la Construcción* workshops, with five volumes published between 2008-2016, or the 2023 collection *Archeologia del cantiere edile: temi ed esempi dall'Antichità al Medioevo*). The finds in question are well dated stratigraphically, since they clearly belong to the post-62 CE phase of Pompeii, a short-lived period in which much of the town's infrastructure was undergoing renovation due to the extensive damages caused by an earthquake. (Incidentally, the features under discussion are much later in date than the time of Vitruvius, who composed his treatise in the 20s BCE, and may refer to practices that became common in a subsequent phase of concrete construction; strictly speaking, then this evidence cannot be used to refute Vitruvius). Traces of the phenomenon, however, are documented elsewhere at the site. Spinazzola's excavations on Via dell'Abbondanza, for example, revealed remains of temporary lime kilns installed within private properties to meet the higher demand (e.g., Casa del Sacello Iliaco I.6.4., where piles have also been found of what J.-P. Adam, *Roman Building and Techniques*, ch. 3, identifies as gypsum; could these be chunks of quicklime?). On this building phase more broadly, it would be useful to point readers to Maiuri, *L'ultima fase edilizia di Pompeii* (1942) and now H. Dessales (ed.), *Ricostruire dopo un terremoto: Riparazioni antiche a Pompei* (2022).

On a related note, the authors should acknowledge that the construction project described in this study was fairly limited in scope compared to other major building enterprises that were still in progress in other parts of Pompeii, most famously the Sanctuary of Venus (on which see, e.g., Battiloro et al. in *Fasti Online* 425, 2018), let alone other imperial buildings in the broader Roman Empire, for which the *chaîne opératoire* reconstructed by the authors in fig. 7 on p. 14 (hot mixing in small batches) may not have been practical or sustainable, given the much higher volumes of materials involved and the size of the structures to be built, for which lifting large and heavy pottery vessels full of hot mortar by hand, as depicted in the sketch, would hardly be feasible. In these cases, the availability of open space would have indeed allowed to transport quicklime directly to the building site, thus saving on transportation costs due to the lighter weight and loss of volume. The recently documented example of the Roman theater at Augst shows numerous mortar-mixing pits being used in different phases of modification of the building. One of them contained layers of set lime featuring partially slaked lumps at the bottom, and is relevant for this study because it has been interpreted as the remains of a mixing pit for hot lime mortars (T. Hufschmid, "Provincial-Sized Monumentality: The Construction Site of the Roman Theatre of Augusta Raurica (Switzerland)", in *Architectures of the Roman World: Models, Agency, Reception*, ed. by N. Mugnai, Oxford 2023, p. 105). The rest may have been standard slaking pits (of the kind documented by Traini as containing dry lime). In theory, lime could also be slaked right at the kilns (along the Lattari Mountains, in the case of Pompeii) and distributed locally to smaller sites that lacked space already in the form of lime putty, contained in recycled amphorae (the slaking of lime directly in amphorae, as described by the authors, does not seem a particularly practical solution, not the least because the vessel type is not really suited to stand in an upright position, and the narrow neck limits the ability to mix water and quicklime). As a side note, the

fact that the pile of pre-mixed dry materials was found in close proximity to a pile of ground terracotta raises the question of whether they were being used to fabricate floors rather than walls (the issue is not discussed).

A noteworthy outcome of the study is the development of a systematic analytical method to differentiate between lime clasts of different origin (i.e., between quick lime and slaked lime), both macroscopically (presence or absence of cracking and expansion; type of distribution within the matrix, cited on p. 12) and at elemental level (isotopic analysis). I leave it to experts in geochemistry to comment on the methodology and the potential to reproduce the experiment. In this respect, it may be useful to note that, as reported in the literature, Pompeian mortars may incorporate calcite inclusions occurring naturally in the volcanic ash deposits of Mount Vesuvius [e.g., Miriello, D et al. 2010. "Characterisation of Archaeological Mortars from Pompeii (Campania, Italy) and Identification of Construction Phases by Compositional Data Analysis." *Journal of Archaeological Science* 37 (9) (September):2207–23. doi:10.1016/j.jas.2010.03.019; see especially figs. 5-6]. Petrographic description of the mortar samples by a geologist should be expected in a study of this kind, also in relation to the provenance of the "pozzolana". Granted that the study has identified C-A-S-H phases in the materials, it would make a difference in the archaeological interpretation to know whether the builders used reworked local alluvial and coastal sands, well selected products of Vesuvius (such as the tephritic foam lavas from the Civita volcanic formation on which the building lies) or unconsolidated levels of the Neapolitan yellow tuff formation, whose use has been observed for land construction in Imperial-era buildings at Pompeii [see, e.g. Secco et al., "Mineralogical clustering of the structural mortars from the Sarno Baths, Pompeii: A tool to interpret construction techniques and relative chronologies." *Journal of Cultural Heritage* 40 (2019) 265–273]. In general, a contextualization of the results within the state of the art of mortar studies in Pompeii, which are not represented in the bibliography, would be recommended (Oleson's and Jackson's work with the ROMACONS project has no direct relevance for Pompeii).

Finally, another observation that may have an impact on the broader interpretation and conclusions regards the structural function of the walls from which the samples were collected. So far, the use of pre-mixed dry materials has been confirmed for Wall 1, a small non-load bearing party-wall, whereas the addition of slaked lime is reported from the facing of Wall 2, a load-bearing wall that delimited the house and supported the roof (as shown in figs 1-2; but the W2 sample seems to come from a square buttress that abutted the perimetral wall, not from the wall itself; thus, fig. S1 is misleading). Additional evidence (e.g., by testing different structural features within the house, including walls that predated the 62 CE renovation phase, as well as other well-dated public monuments) seems necessary to demonstrate whether hot mixing was indeed prevalent in Roman-era construction at Pompeii (as stated on p. 14). These walls stood for only a few months before being destroyed and/or buried by the 79 CE eruption, so we really don't know whether the Pompeian structure built with this formulation would have lasted as long as the Baths of Caracalla.

Minor details:

p. 1: "The development and widespread implementation of Roman concrete further revolutionized and accelerated the construction of aqueducts and road systems." Some of the most spectacular Roman aqueducts are built with ashlar masonry (think of the Pont du Gard). Hydraulic mortar may have played a role but its use for waterproofing is not inherently Roman and has a wide diffusion. See *Mortiers et hydraulique en Méditerranée antique*, <https://doi.org/10.4000/books.pup.39790>. Similarly, role of concrete construction in road building was limited (and certainly not the case for the Via Appia).

p. 1: "Beginning in the 3rd century BCE, Romans began incorporating pyroclastic rocks from volcanic sources such as the Phlegrean Fields, Vesuvius, and the Albani Hills as aggregates and pozzolanic cementitious binder in these concretes." Romans in Rome were not building with concrete in the 3rd century BCE (ashlar architecture was the predominant technique). Other craft communities in areas incorporated under Roman control might have, but evidence is scarce and only picks up in the middle of the 2nd century BCE (see Mogetta 2021 cited in n. 2 for an overview).

p. 1: "Neapolitan Yellow tufa" (and elsewhere). The correct geologic term for the volcanic stone is tuff (tufa refers to sedimentary rocks consisting of concretionary carbonates).

p. 3: calc extincta should be calx extincta.

p. 5: "piles of concave tiles (coppi)". Coppo (pl. coppi) is a modern Italian word; Latin term is imbrex.

p. 6: "pile of finely ground cocchiopesto". Cocchiopesto typically refers to the finished mortar containing ground terracotta. Better to say "pile of finely ground terracotta."

Figure S1: "Viccola Occidentale" should read "Vicolo Occidentale"

Version 1:

Reviewer comments:

Reviewer #1

(Remarks to the Author)

The article has been significantly improved. The additional bibliographical references are appreciated. On the state of the art of studies on Pompeian mortars, it is worth adding

A. Coutelas 2020, "Lime mortar typology," in H. Dessales ed., *The Villa of Diomedes. The making of a Roman Villa in Pompeii*, Paris, pp. 259-266.

The reference added to the *lex parieti* of Pozzuoli is valuable, but it contains an error: not "*Lex Puteolana de pariete faciendo*" (cf. p. 3), but : "*Lex parieti faciendo*" (*puteolana* does not appear in the title of the inscription). It would be appropriate to refer to CIL X 1781 = CIL I2 698 = CIL I 577, the reference to the "*calx restincta*" is in lines 38-39.

The reference added in n. 39 is incorrect, not: Amato, V. *Ricostruire dopo un terremoto: riparazioni antiche a Pompei*. (Centre Jean Bérard, Naples, 2022), but H. Dessales ed., *Ricostruire dopo un terremoto: riparazioni antiche a Pompei*.

Reviewer #2

(Remarks to the Author)

Well done revision, and ms is ready for acceptance from my view.

Reviewer #3

(Remarks to the Author)

I appreciate the authors' engagement with the review and their careful consideration of all the points and issues raised in it. The expanded discussion of the context of Pompeian mortar studies and the additional evidence included in the revised submission (new analysis of W3; petrological analysis of thin sections; further observations on the absence of natural calcite inclusions in the samples) improve the original argument significantly from an archaeological perspective. There is clearly a lot more work to do in Pompeii and beyond to characterize the development and diffusion of hot-mixing fabrication methods in Roman concrete architecture more broadly, and especially its application to large scale building projects. This study will provide an important point of reference for future research.

Minor fixes in the newly added paragraphs:

p. 3, second paragraph "*calcis restincta*" should be "*calx restincta*" (use nominative)

p. 3 second-to-last paragraph "suggests alternative or complementary methods may have been in use in 72 CE" 72 CE should probably read 62 CE if related to the date of the earthquake.

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Point-by-point response to the reviewers' comments

Color-coding:

Original comments are in black

Responses are in red

Revised text is in blue

REVIEWER COMMENTS

Reviewer #1 (Remarks to the Author):

The article is very interesting, based on the exceptional excavation of a construction site still in progress in Pompeii at the time of the eruption of Mount Vesuvius. It convincingly demonstrates how quicklime was pre-mixed with dry pozzolan before adding water in the creation of Roman concrete.

To enhance the article, it would be interesting to compare the data with other lime mortars from Pompeii recorded in other chronological contexts. Indeed, one might wonder whether the use of quicklime might not be part of the urgency of rebuilding after the 62-63 AD earthquake. An emergency technique? Or was it a technique that was already widespread in Pompeii's buildings before the major rebuilding required by the 62-63 AD earthquake? The question remains.

We appreciate this valuable perspective. We have added a sample of an existing wall that had been previously dated before the 62 AD construction phase, and have included its analysis which further supports a more widespread usage of quicklime (sample W3).

Figure 7 is very instructive, but the workers' clothing needs to be corrected. Not a toga, but a tunic (see, for example, the famous Via Labicana fresco for the workers' clothing).

Reference image: <https://www.der-roemer-shop.de/media/image/product/1/md/tunika-der-roemer-kurzarm-creme-biologischer-baumwollstoff.jpg>

We thank the reviewer for pointing out this detail, and we have updated Figure 7 as requested.

Reviewer #2 (Remarks to the Author):

The ms on Unfinished Pompeian Construction Site Reveals Ancient Roman Building Technology is highly interesting for the archeology and geochemical community as it refers to a unique past environment for studying historical building techniques. The main novelty is based on the excavation of a “frozen” Roman construction site to discover “hot mixing” technique to be actively used for binding material. This technique can provide advanced conditions/properties such as fast reactive high T formation/setting conditions and self-healing reactions. I like this approach/outcome! The ms is well organized and well written and methods are properly described.

My main concern is about the excessive length of the present contributions, which is accompanied with several repetitions and comments/discussion points not being always in the focus of the main scope. Thus, I

would like to see the contribution to be published in Nature Communications but only with major revision to shorten its length and by considering the comments below.

We thank the reviewer for their constructive comments, and have significantly shortened the manuscript as requested, particularly in the Introduction section, by removing or condensing the background material on Roman engineering examples. We have also removed repetitive text and streamlined the narrative to be more focused.

Specific comments:

(1) Abstract: Rephrase "... that calcium-rich phases originating from lime clasts diffuse and form reactive rims around volcanic pumice, producing a wide range of reaction products." The phases are not diffusing, but the dissolved ions gained from dissolution are.

We have edited the abstract to reflect that the dissolved ions, and not the phases, are diffusing. As suggested by the reviewer, the text now reads:

"The analysis of reaction rims around volcanic pumice aggregates demonstrates aggregate/matrix interfacial remodeling, where calcium ions originating from the dissolution of lime clasts diffuse and remineralize, producing amorphous phases and various polymorphs of calcium carbonate (including calcite and aragonite)."

(2) Although the ms is mostly well written, it could be shortened in several cases to be focused on the main issues and to be not repeating (see general comment above):

For instance, to be deleted:

- End of discussion: "The work conducted here both enhances our understanding of ancient building practices ... and the conservation of ancient structures."
- Intro: "Their road systems, for example, were an ... achieved through these construction innovations."
- The whole intro is too excessive.

We thank the reviewer for these helpful suggestions and have shorted both the Introduction and Discussion, as requested.

(3) to be revised: "... where the reaction of the lime with the Si- and Al based compounds in the pozzolana forms stable and insoluble C-A-S-H." C-A-S-H phases are not stable (e.g. being amorphous) and not insoluble (e.g. strongly depending on the environmental conditions like pH), but they are chemical resistant in common building exposure settings.

We thank the reviewer for bringing this detail to our attention. As the paragraph in question discusses the crystalline phases, our intention was to describe the properties of partially crystalline C-A-S-H. To clarify this point, we have revised this sentence as follows:

"In the presence of water and lime, this mixture forms calcium aluminum silicate hydrates (C-A-S-H) through pozzolanic reactions, which are responsible for the material's long-term strength and durability^{8,12-17},"

(4) Kinetics in "To gain additional insights into the chemical and kinetic history"

We have updated the kinetics section to include the grinding curve method for archaeological mortars described by Chu et. al, and added additional text discussing the results and their implications, as follows:

"Using the same metrics as in ⁴³, the ν_2 and ν_4 vibrational modes in the samples, located at approximately 870 cm^{-1} and 713 cm^{-1} , respectively, were analyzed after different durations of mechanical grinding in order to identify the extent of crystallinity of the carbonate phases. The ν_2 and ν_4 normalized values were plotted (see Fig. 4 (left)) for both the modern quicklime (mQL) and slaked lime (mSL) references and the ancient (PM, W1, W3, IX10S-20, and IX10S-26) samples. A notable difference in the grinding curve slope was exhibited between the mQL and mSL samples, which was subsequently used as a reference to group the archaeological samples into quicklime (red box) or slaked lime (blue box) precursors (Fig. 4 (left)). Since the ν_2 and ν_4 vibrational modes are most sensitive to in- and out-of-plane lattice distortions, the shallower slope in the mSL and IX10S-20 samples suggests that $\text{Ca}(\text{OH})_2$ underwent less extensive reconfiguration of its crystal structure over time (likely through hydration and carbonation), which would lead to the formation of more ordered phases which can be disrupted by an applied strain. In contrast, the steeper slope in the mQL sample implies a lower starting degree of order, and a more structurally uniform, but disordered material, where ν_4 changes minimally with progressive grinding. The alignment of the PM, W1, and W3 samples with the mQL reference line strongly supports the presence of carbonated quicklime as a raw material in these samples, which is suggestive of a rapid crystallization process. "

(5) Isotopes (Fig. 4 and text): The slope documented in the literature is not 1:1, but is 0.6 to 0.7(!) as depending on complex reaction kinetics and mechanisms.

We thank the reviewer for bringing this to our attention and we have updated the text to indicate that there are two potentially relevant slopes from the kinetic fractionation processes. CO_2 hydration has a slope of 0.6-0.7 (a negative shift of $\delta^{13}\text{C}$ by 19-23 permil and $\delta^{18}\text{O}$ by 14-15 permil at maximum fractionation). CO_2 hydroxylation has a slope of 1 and a negative shift of $\delta^{13}\text{C}$ by 26-31 permil and $\delta^{18}\text{O}$ by 27-30 permil at maximum fractionation. Hydroxylation is expected to dominate at high pHs (above 8.5-9), at higher temperatures because of OH^- activity, and faster precipitation rates, conditions that are all likely important for isotopic fractionation during hot mixing. We have added a paper by Botteger and Kubicki, 2021 to this section. To clarify these points, we have updated the manuscript as follows:

"Equilibrium precipitation would have values near the origin, depending on local water composition, whereas the combined kinetic isotope effects from hydration of atmospheric CO_2 , which follows a slope of $\sim 0.6-0.7$ in a $\delta^{13}\text{C}$ vs. $\delta^{18}\text{O}$ plot, and hydroxylation of atmospheric CO_2 which follows a slope of ~ 1 , have a maximum negative $\delta^{13}\text{C}$ shift of 26-31‰ and $\delta^{18}\text{O}$ of 27-30‰. The relative importance of each kinetic process is pH dependent; in hot mixing, which occurs at high-pH in water-limited conditions, hydroxylation is likely to be a dominant process⁴⁸ providing an independent method to differentiate between carbonation conditions (Fig. 4 (right))."

(6) Discussion on isotope signatures misses aspect on the local source of H_2O , which is also highly relevant for potential shift in O isotope composition of the final CaCO_3 .

We thank the reviewer for bringing this to our attention and we have updated the manuscript as requested in two locations, when we first introduce the processes responsible for determining isotopic composition and when we report the slaked lime samples isotopic composition:

“These values suggest precipitation closer to isotopic equilibrium, with the $\delta^{13}\text{C}$ reflecting dissolved inorganic carbon and $\delta^{18}\text{O}$ reflecting precipitation from local water at ambient conditions.”

“In samples IX10S-20 and MR, the isotopic signature is closer to expected equilibrium and likely reflects the presence of abundant water, slower carbonation, and equilibrium fractionation with dissolved inorganic carbon and the isotopic composition of the local water used in slaking^{49,52}.”

(7) Change and cyclic fluctuation of ^{18}O and ^{13}C values may record restoration activities:
<https://www.scopus.com/record/display.uri?eid=2-s2.0-84924452714&origin=recordpage>

While we acknowledge that modern restoration activities could indeed be captured in the isotopic record, the samples collected and used in the present study were collected shortly after excavation, and thus exclude any modern interventions. We have updated the text accordingly to reflect this point:

“Importantly, these samples were collected prior to modern restoration efforts, so the isotopic variations reflect original construction practices rather than post-depositional interventions.”

(8) Rephrase first sentence of chapter “Post-pozzolanic aggregate/matrix interfacial remodeling”

We apologize for any potential confusion and had updated the text as requested for additional clarity::

“Across PM, MR, W1, W2, and W3, reaction rims were observed; Fig. 5 illustrates the reaction rims present around pumice particles in the mortar, offering details about the long-term chemical processes within the volcanic aggregate-matrix interfacial zones.”

Reviewer #3 (Remarks to the Author):

The article provides important new insights to further characterize the role played by the “hot mixing” method in Roman concrete construction, i.e. the practice of pre-mixing dry quicklime with pozzolans before adding water in the manufacturing of structural mortars. This fabrication process has thus far been studied primarily in the context of medieval and early modern architectural history and applied particularly to modern conservation projects (as clear from the articles cited in bibliography). In previous studies, the authors have argued that this is the “secret” behind the durability of Roma concrete structures, since it would endow the mortars with self-healing properties (whereby the calcite-rich lumps interspersed within the matrix would be subject to long-term dissolution, releasing fluids into the surrounding pore network that would react with the reactive surfaces of volcanic glass and recrystallize, sealing any cracks). On this basis, they have experimented with adding quicklime to Portland cement mixes to create a modern self-healing concrete that would be inspired by Roman precedent.

(In reality, most forms in Roman concrete architecture worked only in compression, so the development of cracks did not create any major structural issues if buttressing was adequate; the problem, as is well known, affects reinforced concrete construction to a much greater degree.)

We thank the reviewer for this important observation regarding load-bearing in ancient Roman concrete structures. It is true that many Roman constructions were loaded primarily in compression and employed architectural strategies such as buttressing to mitigate structural stress. However, we suggest that this does not negate the value or purpose of self-healing processes observed in ancient mortars.

Self-healing was indeed not required for structural integrity under compressive loads, but rather that the observed microstructural cement evolution (including the dissolution of lime clasts and reprecipitation of mineral phases) demonstrates a durability strategy that would have contributed to the long-term durability of these structures, especially in the presence of moisture, freeze-thaw cycles, or minor structural settling. The presence of self-healing features in mortars likely improves aggregate/binder interfacial zones, reduces permeability and prevents surface degradation, which would have been beneficial even in non-reinforced, load-bearing contexts.

While the Romans may have indeed been unaware of these additional self healing benefits which were achieved through the use of hot mixing (as their motivations were likely primarily driven by the faster setting times which are a critical feature of the hot mixing process), the secondary self-healing benefits have likely contributed to their millenia-scale durability and have provided intriguing inspiration in the development of modern concrete formulations.

The authors now interpret the newly discovered evidence from Pompeii discussed in the article as confirmation that hot lime mixing was the “primary method” in Roman times (p. 13), concluding that slaked lime would normally have been added only to repairs and finishing mortars (mainly to enhance the building medium workability). As highlighted on pp. 3-4, this finding would upend the conventional view that historians derive from the 1st century BCE author of the only Roman architecture handbook known to us: after advising on the best types of stones to be fired for making lime, Vitruvius notes that pit sand, or river sand and crushed pot sherds, can be mixed in after the quicklime has been slaked (cum ea erit extincta; De arch. 2.5.1).

Significantly, the prescribed use of slaked lime for concrete masonry is also attested in surviving building contracts, such as the Lex Puteolana parieti faciendo of 105 BCE, which enforced specific instructions for the making of the structural mortar (CIL I2 698; ll. 37-38 calx restincta).

We thank the reviewer for highlighting this valuable resource. We have incorporated a citation to the Lex Puteolana in our revised manuscript introduction, acknowledging that the contract specifies calx restincta in structural mortar preparation in 105 BCE. However, we have also clarified that this evidence predates the construction period described in the paper by nearly two centuries. As such, our findings point to diversification in mortar preparation methods, and this temporal distinction is now more emphasized in the manuscript to reflect that Vitruvian and epigraphic standards may not represent a fixed canon throughout the period, as well as that slaked lime may not have been the sole lime source. To clarify these points, the manuscript has been updated as follows:

“Evidence of slaked lime being used in masonry mortar is also fairly limited, with a notable example found in *Lex Puteolana de pariete faciendo*, an inscription from 105 BCE in Puteoli detailing the use of “*calcis restincta*”, interpreted to refer to slaked lime³⁰. ”

The archaeological context presented in the first part of the article, House IX.10.1 in Pompeii, is indeed remarkable for the level of detail that has been recorded during the excavations.

Recovering archaeological traces of active construction sites featuring accumulations of building materials and features associated with the logistics of construction is a relatively rare opportunity, though not as uncommon as the authors lead the reader to believe (for recently documented examples, see the proceedings

of the *Arqueologia de la Construcción* workshops, with five volumes published between 2008-2016, or the 2023 collection *Archeologia del cantiere edile: temi ed esempi dall' Antichità al Medioevo*).

We thank the reviewer for these important insights and references. The main conclusions from both of these references underscore the importance of on-site material accumulations and construction logistics features—such as lime kilns and tool marks—as indicators of organized building activity. While such findings are not entirely uncommon, this study adds an extremely well preserved site that enriches our broader understanding of ancient construction processes and the socio-technical organization behind them. We updated the text to highlight these sources and added the new references as suggested:

“The discovery of tools and raw materials from these ancient construction sites that are preserved *in situ* is uncommon, with most sites being fragmentary, containing only isolated lime kilns, slaking pits, or scattered debris layers^{4,5}”

“Recent research on mortars from Pompeii has advanced significantly through the use of interdisciplinary and multi-scale characterization approaches, deepening our understanding of materials selection and construction logistics in this ancient Roman city. These analytical investigations have revealed a diverse use of raw materials, including locally collected volcanic ash and pozzolans, and have characterized both original Roman mortars and later restoration phases^{32–34}. Statistical and mineralogical analyses, such as discriminant and principal component analysis, have further enabled researchers to differentiate between construction periods, identify technological choices, and trace the evolution and diversity of mortar recipes across time and applications (such as structural, decorative, and flooring mortars)^{35–37}.”

The finds in question are well dated stratigraphically, since they clearly belong to the post-62 CE phase of Pompeii, a short-lived period in which much of the town’s infrastructure was undergoing renovation due to the extensive damages caused by an earthquake. (Incidentally, the features under discussion are much later in date than the time of Vitruvius, who composed his treatise in the 20s BCE, and may refer to practices that became common in a subsequent phase of concrete construction; strictly speaking, then this evidence cannot be used to refute Vitruvius).

We thank the reviewer for bringing attention to this detail, and we have updated the discussion to emphasize that as this site is a different era of construction than Vitruvius, there may have been undocumented changes in mortar mixing techniques and material selection in the years since his treatise. We have softened the phrasing to show that the evidence presented in the paper cannot be a direct refutation of Vitruvius, and have changed this original section (“...this hot mixing theory and the historical usage of quicklime directly contradicts Vitruvius’ descriptions, highlighting a gap in our understanding of Roman construction techniques, as the writings of Vitruvius have long been considered authoritative sources on the matter”) of the ms to now read:

“While supported through modern research efforts focused on both the analysis of ancient Roman concretes and the behavior of their Roman-inspired modern concrete analogs¹⁵, this hot mixing theory and the historical usage of quicklime departs from Vitruvius’ descriptions and suggests alternative or complementary methods may have been in use in 72 CE, highlighting a knowledge gap in our understanding of Roman construction techniques.”

“This study significantly advances our understanding of Roman construction technology by providing multiple lines of evidence for the use of quicklime in a hot mixing process, a method that appears to contradict the traditionally accepted interpretations of Vitruvius’ writings.”

Traces of the phenomenon, however, are documented elsewhere at the site. Spinazzola's excavations on Via dell'Abbondanza, for example, revealed remains of temporary lime kilns installed within private properties to meet the higher demand (e.g., Casa del Sacello Iliaco I.6.4., where piles have also been found of what J.-P. Adam, *Roman Building and Techniques*, ch. 3, identifies as gypsum; could these be chunks of quicklime?).

The material piles found in Casa del Sacello Iliaco (aka Casa del Larario D'achille) have been analyzed and confirmed to be gypsum, not quicklime. Thus, these material piles cannot be fully used as evidence of a lime kiln, as it represents very limited evidence that most likely pertains to gypsum, and not lime processing (confidential information, publication pending).

On this building phase more broadly, it would be useful to point readers to Maiuri, *L'ultima fase edilizia di Pompeii* (1942) and now H. Dessales (ed.), *Ricostruire dopo un terremoto: Riparazioni antiche a Pompei* (2022).

We thank the reviewer for this suggestion and have added these references as requested. (new references 39 and 40 in the revised text).

On a related note, the authors should acknowledge that the construction project described in this study was fairly limited in scope compared to other major building enterprises that were still in progress in other parts of Pompeii, most famously the Sanctuary of Venus (on which see, e.g., Battiloro et al. in *Fasti Online* 425, 2018), let alone other imperial buildings in the broader Roman Empire, for which the chaîne opératoire reconstructed by the authors in fig. 7 on p. 14 (hot mixing in small batches) may not have been practical or sustainable, given the much higher volumes of materials involved and the size of the structures to be built, for which lifting large and heavy pottery vessels full of hot mortar by hand, as depicted in the sketch, would hardly be feasible.

We appreciate the reviewer's concern regarding the applicability of these findings to larger-scale projects. We have added an acknowledgment of the limitation given by the scale of this project in the discussion as follows:

“The results from the present study suggest the common use of hot mixing techniques for several different applications at the investigated excavation site. While for larger-scale imperial constructions, the logistics of conducting batch hot mixing may have posed challenges, evidence from large-scale sites like Augusta Raurica suggests that hot mixing was still effectively employed, supported by extensive on-site mixing platforms and prearranged material staging areas³¹”

All of these observations point to the potential scalability of this technology, and records of the time have reported the usage of pulley systems at construction sites that were likely needed to transport the hot material. We have further updated the sketch (Fig. 7) to incorporate a pulley lifting system, which is supported by various historical records.

In these cases, the availability of open space would have indeed allowed to transport quicklime directly to the building site, thus saving on transportation costs due to the lighter weight and loss of volume.

This is a great point since the quicklime stones are about half of the weight of raw limestone.

The recently documented example of the Roman theater at Augst shows numerous mortar-mixing pits being used in different phases of modification of the building. One of them contained layers of set lime featuring partially slaked lumps at the bottom, and is relevant for this study because it has been interpreted as the remains of a mixing pit for hot lime mortars (T. Hufschmid, 'Provincial-Sized Monumentality: The Construction Site of the Roman Theatre of Augusta Raurica (Switzerland)', in *Architectures of the Roman World: Models, Agency, Reception*, ed. by N. Mugnai, Oxford 2023, p. 105). The rest may have been standard slaking pits (of the kind documented by Traini as containing dry lime).

We thank the reviewer for bringing this reference to our attention and have added it to the current manuscript, along with additional text regarding the potential implications of these findings:

“Furthermore, recent excavations and analyses, such as those at Augusta Raurica in Switzerland, have uncovered mortar mixing pits with partially slaked residues, which were interpreted as evidence for hot mixing practices in larger-scale Roman construction³¹.”

“While for larger-scale imperial constructions, the logistics of conducting batch hot mixing may have posed challenges, evidence from large-scale sites like Augusta Raurica suggests that hot mixing was still effectively employed, supported by extensive on-site mixing platforms and prearranged material staging areas³¹.”

In theory, lime could also be slaked right at the kilns (along the Lattari Mountains, in the case of Pompeii) and distributed locally to smaller sites that lacked space already in the form of lime putty, contained in recycled amphorae (the slaking of lime directly in amphorae, as described by the authors, does not seem a particularly practical solution, not the least because the vessel type is not really suited to stand in an upright position, and the narrow neck limits the ability to mix water and quicklime).

We appreciate the reviewer providing this context and perspective. While this may be a plausible theory, our introduction focuses on what evidence has at present been found in the archaeological site of Pompeii. In this context, it should be noted that in the manuscript, we do acknowledge that it is unlikely that slaking occurred exclusively in amphorae.

In the original manuscript, we include the following statement in the introduction “One of the most prevalent surviving forms of lime slaking evidence can be found in encrustations of lime on (both intact and broken) amphorae, in quantities that are considered insufficient to be the sole calcium source in the mortar. It is therefore generally accepted that lime was likely slaked in small amounts in these amphorae for usage in other construction projects, such as for decorative work or flooring (13, 26).”

That being said, our current data also provides evidence of lime encrustations in found amphorae, consistent with small-scale slaking operations. It is important to note however, that these slaked lime encrustations are compositionally different from the quicklime granules found in other amphorae, which is why we mention this theory. It should also be noted that other references have shown broken amphorae being used for lime storage and transport (such as J. Adam 1984 fig 160 p. 131). Furthermore, the amphorae that we discovered have necks removed in order to enlarge the opening and facilitate mixing (as shown in Fig 7).

As a side note, the fact that the pile of pre-mixed dry materials was found in close proximity to a pile of ground terracotta raises the question of whether they were being used to fabricate floors rather than walls (the issue is not discussed).

We thank the reviewer for their comment and interest in this issue. Indeed, in the same vicinity, we discovered different types of premixed dry materials. In the original manuscript, we focused only on the pre-mixed pile of quicklime and pozzolans in Room 14 (Sample PM, the room used for wall construction), but in the updated version of the manuscript we extended the analysis to the pile of the dry premixed materials in the Room 2, where a pile of finely ground terracotta was also present. We have added the results of the chemical and petrographic analysis for the lime in the Room 2 pile (IX10S-26) and added a brief discussion on its potential application in floor construction. The captioning for Fig. S13 reads:

“The morphology of the lime clast (exhibiting high porosity and internal cracking) is consistent with previously described quick-lime containing samples. The presence of primarily Ca and Si, with smaller quantities of Al and Fe, support that this is a pre-mixed pile of sand and lime. The location of this pile (in close proximity to a pile of ground terracotta, see Figure 1 Room 2), as well as the archaeological context of the construction in the atrium, suggests it was likely used for flooring applications.”

A noteworthy outcome of the study is the development of a systematic analytical method to differentiate between lime clasts of different origin (i.e., between quick lime and slaked lime), both macroscopically (presence or absence of cracking and expansion; type of distribution within the matrix, cited on p. 12) and at elemental level (isotopic analysis). I leave it to experts in geochemistry to comment on the methodology and the potential to reproduce the experiment.

In this respect, it may be useful to note that, as reported in the literature, Pompeian mortars may incorporate calcite inclusions occurring naturally in the volcanic ash deposits of Mount Vesuvius [e.g., Miriello, D et al. 2010. “Characterisation of Archaeological Mortars from Pompeii (Campania, Italy) and Identification of Construction Phases by Compositional Data Analysis.” *Journal of Archaeological Science* 37 (9) (September):2207–23. doi:10.1016/j.jas.2010.03.019; see especially figs. 5-6].

We appreciate this perspective and the new source, and agree that the volcanic origin of aggregate materials warrants close scrutiny. However, based on crystallinity, morphology, and pores filling nature, we maintain that the different calcium carbonate phases (calcite and aragonite) and amorphous phases observed filling the pumice vesicles are the result of *in situ* precipitation rather than inherited volcanic fragments. Our petrographic thin-section observations (from samples W1, W2, W3, and PM) reveal a diverse range of carbonate-rich clasts, marble-like clasts, and limestone grains from alluvial sands. Given that metamorphosed carbonates (marble) and calc-silicate (skarn) xenoliths can occur in Plinian deposits associated with Somma-Vesuvius activity, they require closer examination. However, the observed textural properties of the thoroughly investigated lime clasts, such as grain size (coarser than volcanic aggregate), porosity and fractures, inhomogeneous birefringence, and a distinct reaction rim with the binder, allowed us to confidently state that the lime clasts were part of the mix-formulation (a conclusion supported by the geologist Celestino Grifa, who has been added to the author list (see below). Furthermore, the dry pre-mixed pile found in Room 2, probably intended for flooring applications (conclusion based on the presence of an adjacent pile of ground terracotta), is also characterized by the addition of quicklime to other dry mortar components, suggesting a similar materials processing strategy using different pozzolanic ingredients, and thereby reinforcing the

notion of hot mixing. To clarify these points, we have included the Miriello et al. 2010 reference to the document, as follows:

“The amorphous, Ca- and Al-rich phases are likely the result of *in situ* precipitation rather than inherited volcanic calcite inclusions, as evidenced by the lack of crystalline characteristics typical of volcanic minerals, and the presence of zoned, reaction interfaces around the pumice fragments, which is incompatible with inherited detrital grains⁴⁹”

Petrographic description of the mortar samples by a geologist should be expected in a study of this kind, also in relation to the provenance of the “pozzolana”.

We sincerely thank the reviewer for their comments. As a result, we have involved Prof. Celestino Grifa in the updated manuscript (and has been added as a coauthor), who analyzed the thin sections of our mortar-based materials.

Considering the petrological features of the volcanic aggregate, we are confident that the ancient artisans utilized local pyroclastics, as indicated by the presence of mineralogical markers related to Somma-Vesuvius activity, such as the widespread leucite-bearing lithics. Only one sample suggests the use of alluvial sand sourced from the surrounding areas of Vesuvius. The specific mineralogy and sources of pozzolana has been added to the supplemental material section.

“All samples are characterized by the presence of volcanic aggregates, primarily composed of coarser aphyric to poorly porphyritic pumices and leucite, diopside, and plagioclase-bearing lava lithics (Fig S8 a, b). These volcanic components are consistently accompanied by loose crystals of zoned plagioclase and diopside (Fig S8 c, d), sanidine, and phlogopite, indicating a similar sourcing of the sandy-sized aggregate raw materials across most of the samples. The petrological features of the samples recall the use of pyroclastic deposits from the Somma-Vesuvius environs.”

Granted that the study has identified C-A-S-H phases in the materials, it would make a difference in the archaeological interpretation to know whether the builders used reworked local alluvial and coastal sands, well selected products of Vesuvius (such as the tephritic foam lavas from the Civita volcanic formation on which the building lies) or unconsolidated levels of the Neapolitan yellow tuff formation, whose use has been observed for land construction in Imperial-era buildings at Pompeii [see, e.g. Secco et al., “Mineralogical clustering of the structural mortars from the Sarno Baths, Pompeii: A tool to interpret construction techniques and relative chronologies.” *Journal of Cultural Heritage* 40 (2019) 265–273].

In general, a contextualization of the results within the state of the art of mortar studies in Pompeii, which are not represented in the bibliography, would be recommended (Oleson’s and Jackson’s work with the ROMACONS project has no direct relevance for Pompeii).

We thank the reviewer for this recommendation. We agree that the specific context of Pompeii merits deeper engagement, and have expanded our references and contextual framework to incorporate several relevant Pompeii-specific studies, including:

- Miriello, D. et al. Characterisation of archaeological mortars from Pompeii (Campania, Italy) and identification of construction phases by compositional data analysis. *J. Archaeol. Sci.* 37, 2207–2223 (2010).

- Franceschini, M. M. N. et al. Raw materials and building technologies in the public buildings of Pompeii after the earthquake of 62/63 CE: A diachronic analysis of mortars. *Case Stud. Constr. Mater.* 21, e03943 (2024).
- Kilian, R., Borgatta, L. & Wendler, E. Investigation of the deterioration mechanisms induced by moisture and soluble salts in the necropolis of Porta Nocera, Pompeii (Italy). *Herit. Sci.* 11, 72 (2023).
- De Bonis A, Graziano SF, Morra V, et al. New compositional data on ancient mortars and plasters from Pompeii (Campania, Southern Italy): Archaeometric results and considerations about their time evolution. *Mater Charact.* 2018;146:336-350.
- Simone D, Previato C, Secco M, et al. Phasing the history of ancient buildings through PCA on mortars' mineralogical profiles: The example of the Sarno Baths (Pompeii). *Archaeometry.* 2022;64(1):87-108.
- Dilaria, S., Previato, C., Secco, M., & Busana, M. S. (2025). A Semi-Automated Machine-Learning Tool for Assessing Building Phases: Discriminant Analysis of Mortars from the 2022 Excavation at the Sarno Bath Complex in Pompeii. *Heritage*, 8(2), 51. <https://doi.org/10.3390/heritage8020051>
- Dilaria, S. et al. Phasing the history of ancient buildings through PCA on mortars' mineralogical profiles: the example of the Sarno Baths (Pompeii). *Archaeometry* 64, 866–882 (2022).
- Secco, M. et al. Mineralogical clustering of the structural mortars from the Sarno Baths, Pompeii: A tool to interpret construction techniques and relative chronologies. *J. Cult. Herit.* 40, 265–273 (2019).

We have added a few sentences of contextualization into the background as follows:

“Recent research on mortars from Pompeii has advanced significantly through the use of interdisciplinary and multi-scale characterization approaches, deepening our understanding of materials selection and construction logistics in this ancient Roman city. These analytical investigations have revealed a diverse use of raw materials, including locally collected volcanic ash and pozzolans, and have characterized both original Roman mortars and later restoration phases^{32–34}. Statistical and mineralogical analyses, such as discriminant and principal component analysis, have further enabled researchers to differentiate between construction periods, identify technological choices, and trace the evolution and diversity of mortar recipes across time and applications (such as structural, decorative, and flooring mortars)^{35–37}.”

Finally, another observation that may have an impact on the broader interpretation and conclusions regards the structural function of the walls from which the samples were collected. So far, the use of pre-mixed dry materials has been confirmed for Wall 1, a small non-load bearing party-wall, whereas the addition of slaked lime is reported from the facing of Wall 2, a load-bearing wall that delimited the house and supported the roof (as shown in figs 1-2; but the W2 sample seems to come from a square buttress that abutted the perimetral wall, not from the wall itself; thus, fig. S1 is misleading).

We appreciate this important clarification. To resolve the issue of structural context, we have revised Fig. S1 to clearly indicate the precise sampling location for W2 and its relation to the exterior wall. We also have expanded our sampling to include new mortar specimens from core load-bearing walls (the new analysis of W3, an existing structural wall pre-dated before these more recent repairs), which is discussed as follows:

“The alignment of the PM, W1, and W3 samples with the mQL reference line strongly supports the presence of carbonated quicklime as a raw material in these samples, which is suggestive of a rapid crystallization process.”

“The uniformity in aggregate composition, reaction rims, and lime clast characteristics observed in petrographic analyses across the PM, MR, W1, W2, and W3 samples suggests a shared material source (likely from the surrounding Somma-Vesuvius region), and consistent preparation methods. The similarity in mineralogy and structure between PM and W3 is particularly notable, as it demonstrates that material from this pre-mixed raw material pile was not only consistent with actively repaired or built features (as in MR and W1), but was also employed in the production of structural masonry. The widespread presence of coarse, birefringent lime clasts with high internal porosity and internal cracking that are characteristic of incomplete slaking supports our proposed usage of hot mixing across sample contexts.”

“The similarity between PM, W1, W3, and IX10S-26 and the mQL samples supports the notion that the ancient samples formed through a hot-mixed process with a controlled, gradual carbonation environment that stabilizes the microstructure.”

Additional evidence (e.g., by testing different structural features within the house, including walls that predated the 62 CE renovation phase, as well as other well-dated public monuments) seems necessary to demonstrate whether hot mixing was indeed prevalent in Roman-era construction at Pompeii (as stated on p. 14). These walls stood for only a few months before being destroyed and/or buried by the 79 CE eruption, so we really don't know whether the Pompeian structure built with this formulation would have lasted as long as the Baths of Caracalla.

We have also included analyses on another wall (W3) that predated the 62 CE renovation phase, which also provides evidence for hot mixing.

Minor details:

We have revised the manuscript text to address all of the minor details edits listed below:

p. 1: “The development and widespread implementation of Roman concrete further revolutionized and accelerated the construction of aqueducts and road systems.” Some of the most spectacular Roman aqueducts are built with ashlar masonry (think of the Pont du Gard). Hydraulic mortar may have played a role but its use for waterproofing is not inherently Roman and has a wide diffusion. See *Mortiers et hydraulique en Méditerranée antique*, <https://doi.org/10.4000/books.pup.39790>. Similarly, role of concrete construction in road building was limited (and certainly not the case for the Via Appia).

We have removed mentions of road-building in the context of Roman concrete, and have instead focused on wall construction.

p. 1: “Beginning in the 3rd century BCE, Romans began incorporating pyroclastic rocks from volcanic sources such as the Phlegrean Fields, Vesuvius, and the Albani Hills as aggregates and pozzolanic cementitious binder in these concretes.” Romans in Rome were not building with concrete in the 3rd century

BCE (ashlar architecture was the predominant technique). Other craft communities in areas incorporated under Roman control might have, but evidence is scarce and only picks up in the middle of the 2nd century BCE (see Mogetta 2021 cited in n. 2 for an overview).

We have revised the text as suggested.

p. 1: “Neapolitan Yellow tufa” (and elsewhere). The correct geologic term for the volcanic stone is tuff (tufa refers to sedimentary rocks consisting of concretionary carbonates).

We thank the reviewer for this catch and have changed each occurrence of “tufa” to “tuff”.

p. 3: calc extincta should be calx extincta.

We have revised the text as suggested.

p. 5: “piles of concave tiles (coppi)”. Coppo (pl. coppi) is a modern Italian word; Latin term is imbrex.

We have revised the text as suggested.

p. 6: “pile of finely ground cocchiopesto”. Cocchiopesto typically refers to the finished mortar containing ground terracotta. Better to say “pile of finely ground terracotta.”

We have changed the manuscript to read “pile of cocchiopesto (finely ground terracotta)”.

Figure S1: “Viccola Occidentale” should read “Vicolo Occidentale”

We have revised the text as suggested and updated the figure.

Point-by-point response to the reviewers' comments

Color-coding:

Original comments are in black

Responses are in red

Revised text is in blue

REVIEWER COMMENTS

Reviewer #1 (Remarks to the Author):

The article has been significantly improved. The additional bibliographical references are appreciated. On the state of the art of studies on Pompeian mortars, it is worth adding A. Coutelas 2020, "Lime mortar typology," in H. Dessales ed., The Villa of Diomedes. The making of a Roman Villa in Pompeii, Paris, pp. 259-266.

We thank the reviewer for this recommendation, and have added more references to H. Dessales throughout the text that encompass the A. Coutelas work.

The reference added to the lex parieti of Pozzuoli is valuable, but it contains an error: not "Lex Puteolana de pariete faciendo" (cf. p. 3), but : "Lex parieti faciendo" (puteolana does not appear in the title of the inscription). It would be appropriate to refer to CIL X 1781= CIL I2 698 = CIL I 577, the reference to the "calx restincta" is in lines 38-39.

We thank the reviewer for this comment, and have applied the correction in the text.

The reference added in n. 39 is incorrect, not: Amato, V. Ricostruire dopo un terremoto: riparazioni antiche a Pompei. (Centre Jean Bérard, Naples, 2022), but H. Dessales ed., Ricostruire dopo un terremoto: riparazioni antiche a Pompei.

We appreciate the reviewer bringing our attention to this detail, and have edited the reference to show the correct H. Dessales source.

Reviewer #2 (Remarks to the Author):

Well done revision, and ms is ready for acceptance from my view.

We thank the reviewer for their positive feedback!

Reviewer #3 (Remarks to the Author):

I appreciate the authors' engagement with the review and their careful consideration of all the points and issues raised in it. The expanded discussion of the context of Pompeian mortar

studies and the additional evidence included in the revised submission (new analysis of W3; petrological analysis of thin sections; further observations on the absence of natural calcite inclusions in the samples) improve the original argument significantly from an archaeological perspective. There is clearly a lot more work to do in Pompeii and beyond to characterize the development and diffusion of hot-mixing fabrication methods in Roman concrete architecture more broadly, and especially its application to large scale building projects. This study will provide an important point of reference for future research.

We thank the reviewer for their constructive feedback and have applied the suggested edits.

Minor fixes in the newly added paragraphs:

p. 3, second paragraph "calcis restincta" should be "calx restincta" (use nominative)

The text now reads "detailing the use of "calx restincta", interpreted to refer to slaked lime"

p. 3 second-to-last paragraph "suggests alternative or complementary methods may have been in use in 72 CE" 72 CE should probably read 62 CE if related to the date of the earthquake.

We thank the reviewer for noticing this detail and have corrected it. The text now reads "suggests alternative or complementary methods may have been in use in 62 CE, highlighting a knowledge gap in our understanding of Roman construction techniques."