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ORIGINAL ARTICLE

The analysis of two historic fired artificial stonewares: Coade stone (18th–19th centuries) and a recent discovery from Oxnead Hall, Norfolk (16th–17th centuries)

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Abstract

Coade stone has played a significant role in architectural and ornamental design since its inception in the early 18th century. It is well known that earlier, experimental, architectural stoneware products existed, but few of these have been studied in detail scientifically, and only one major analytical study of Coade stone has appeared in the literature. This paper presents a new spectroscopic analysis of Coade stone along with that of a newly discovered sample from Oxnead Hall in Norfolk where it known that Sir Clement Paston experimented with artificial stone in the late 16th century. The results demonstrate that it is possible to differentiate between the two variants on the basis of both the raw materials used and the different phases formed in their production processes.

KEYWORDS

artificial stone, ceramics, Coade stone, spectroscopy, stoneware

INTRODUCTION

The successful development of fired ceramic artificial stone under the thriving business woman Eleanor Coade (1733–1821) in mid-18th-century London provided a new medium for the construction of moulded design features for incorporation into architecture and for garden statuary in estates and buildings across Britain and beyond. Coade stone was endlessly adaptable, enabling architectural and sculptural embellishment in any style according to taste, chiefly neoclassical but also the Gothic,

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Egyptian, funerary, armorial or indeed commercial. The ability to prepare and cast complex and ornate designs in stonewares using moulds had several advantages over the carving of natural stone analogues in creation time, reliability of dimensions, and cost and ease of assembly. Crucially, the high degree of vitrification during firing of these artificial composites also improved weathering properties over their natural counterparts, which recommended them for immediate application for external structures. The use of artificial moulded stoneware in place of carved blocks of marble and cast lead or bronze also lent itself admirably to the vogue for the placement of garden statuary in formalised garden settings. The pale colour achieved was from the first used to market fired artificial stone as a preferred alternative to natural stone (contemporary artificial alternatives such as earthenware, plaster or lead all needed to be painted to mimic stone).

Coade stone was a fired ceramic, relying for its hardness to vitrification caused by high-temperature firing, as opposed to a cast composition which achieves hardness through chemical reaction with the air. The Coade formula was never patented, not least because the size of aggregate must have varied somewhat according to the size of the object. It is therefore possible that samples of Coade stone from objects of varying sizes would yield slightly differing results. Analyses to date have focused on chemical composition rather than aggregate size, which could form a useful topic for further analysis.

Eleanor Coade produced her eponymous artificial stone by the acquisition of Daniel Pincot's ailing factory in London first in 1769 upon which she built a successful business, marketing her products under the names of Coade and Coade & Sealy, until her death in 1822. Thereafter William Croggon continued the Coade artificial stone business, diversifying into the production of scagliola, until he died in 1835. His son, Thomas Croggon, could not keep the business going after 1837, after which the Coade method dissipated into simpler, less labour-intensive terracotta compositions, as successful manufactures such as John Blashfield (1800–90) and Mark Blanchard (1816–92) acquired the Coade moulds, mostly working in terracotta. In contrast, Sir Clement Paston of Oxnead Hall produced his artificial stone in the mid to late 16th century and this continued into the 17th century.

The Coade formula, built upon other artisanal developments in stoneware production from the late 17th century, was at first closely guarded and shrouded in mysticism and secrecy. The composition adopted by Coade was roughly based upon the following recipe: 10% stoneware grog, 10% crushed flint, 10% fine Reigate river sand, 10% soda glass and 60% white potter's ball clay from Devon (Fowler, 1850: 215–216; Freestone et al., 1985; Freestone, 1991). These raw materials were mixed with water into a paste, moulded appropriately and fired at about 1100–1150°C in coal-fired kilns for four days (Figure 1) (Freestone 1985: 296; Kelly, 1990). Eleanor Coade initially called her artificial ceramic stone *lithodipyra*,

FIGURE 1 The work yard of Coade's artificial stone manufactory, Lambeth, *c.*1800. Note the workmen grinding and mixing raw materials (London Metropolitan Archives © City of London)

which is Greek for 'twice-fired stone'; the term *lithodipyra* refers to the fact that Coade stone contains significant proportions of grog (recycled pre-fired waste stoneware) and ground soda glass. The size of the Coade kilns used in the firing process was commented on by Llewellyn Jewitt from which it was deduced that large composite artefacts could be fired in one piece (Jewitt, 1878). The historical background to the development of Coade stone has been surveyed by Kelly (1990) and Stanford (2016). The former text comprehensively describes the location of most known examples of surviving Coade stone architectural features and statuary, one of the largest examples of which is the lion statue standing on Waterloo Bridge in London, which was created and assembled by Coade's successor at her Lambeth manufactory, William Croggan, in May 1837, and weighs 14 tons and whose state of preservation upon exposure to the polluted atmosphere of 19th-century London can only be described as remarkable.

However, it would be manifestly incorrect to assume that Eleanor Coade was the first inventor of an artificial stone ceramic to be used in architectural construction as several apparently less successful ventures are recorded historically from some two centuries before. One of these relates to Sir Clement Paston of Oxnead Hall in Aylsham, Norfolk. The manor of Oxnead was acquired by William Paston in 1419 (Richmond, 1990, *passim*); Sir Clement Paston (by 1523–1598) inherited the estate and undertook extensive restructuring of the house and gardens between 1567 and 1580 (Figure 2). The family fortunes declined somewhat afterwards and, in 1732, upon the death of Sir William Paston, 2nd Earl of Yarmouth, Oxnead Hall was demolished and sold off for building materials, retaining only one service range as a farmhouse (Howard & Town, 2018). The residual debris contained several moulded and fired artificial structural features in a buff/grey hollowed-out, limestone-like stone. Nathaniel Bacon in December 1575, wrote that (Hassell-Smith et al., 1978/79):

> Mr Clement Paston, in building a house of lat here in Norfolk, burnt in killes [kilns] with his brick all the stuf which served for his windowes (except two or three speciall windowes which he mad of free stone) & and for the jammbes and manteltres & toppes of his chimneis, moulds at certain skantlins being made for that purpose. Thei show as free stone & (as I am told) hetherto have decaied nothing at all. I shall make enquiries for those mouldes at certain skantlins which served Mr Paston.

It seems clear that Sir Clement Paston had created successfully an artificial fired ceramic stone some two centuries before the Coade manufactory. It has also been pointed out that Paston would have

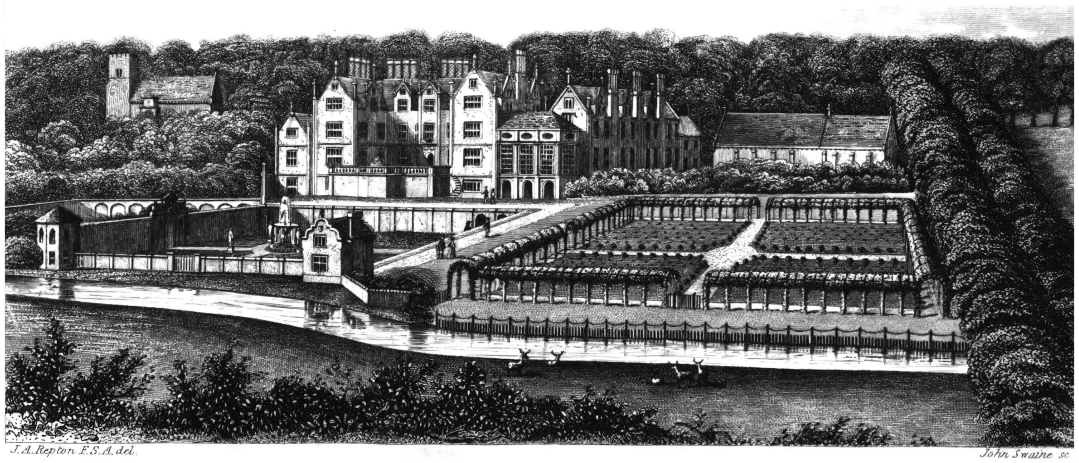

FIGURE 2 Suggested reconstruction of how Oxnead Hall in Norfolk would have looked in the mid-17th century, viewed from the south-east (engraved by John Swain after a watercolour by John Adey Repton for the *Gentleman's Magazine*, January 1844)

had access to most of the raw materials required for his artificial stone locally, including grog from the ancient Roman pottery and mortaria site at Brampton across the River Bure from Oxnead, riverbed estuarine clays similar to secondary ball clays in composition, glass and flint (Knowles, 1977: 216–219). It must be stressed that these fired ceramic artificial stone composites are entirely different from cement and the very durable Roman concrete, *opus caementicum*, which comprised a volcanic dust called *pozzolano* mixed with lime and pieces of rock and brick mixed into a paste with water and cured atmospherically (Ushizima et al., 2020; Xu et al., 2021).

Recent archaeological investigations were undertaken at Oxnead Hall in an attempt to compile a basic construction chronology for the house, barns and stables, as well as looking for evidence for any historical applied decoration and original architectural features. The survey included a detailed examination of the remaining buildings and outbuildings, and also examined a selection of the small finds and demolition rubble discovered on site (Champion, forthcoming). Although much of the general demolition rubble was used to level sections of the site, the present owners have amassed an extensive collection of material. Amongst the large quantity of 16th-century brick fabric were noted a small number of examples of what at first appeared to be worked freestone, that had been used for external decorative features such as window surrounds and plinths. However, closer inspection revealed that the substance was an artificial substitute that had been moulded and fired to replicate the appearance of stone.

Here we have analysed specimens of Coade stone and Oxnead stone using elemental and molecular spectroscopic techniques and have determined their phase compositions by X-ray diffraction: the prime objective is to investigate whether the Oxnead stone is truly an artificial ceramic fired stoneware which precedes Coade stone by some two centuries and to verify if the later Coade stone is of the same composition. Although Coade stone has been studied previously by scanning electron microscopy (SEM)/energy-dispersive X-ray spectroscopy (EDAXS), and a comparison made with later simulated stone such as Blashfield and Doulton in the period 1850–90 using portable X-ray fluorescence (XRF) spectroscopy, this is the first time that the earlier Oxnead stone has been subjected to a chemical analysis to facilitate its comparison with later Coade stone specimens (Karran & Colston, 2016).

SAMPLES

The samples were recovered from two locations at the site, one of which was an intact area of demolition rubble dating from the early 18th-century destruction of the hall. The material is a pale buff/grey, fine-grained, fabric—reminiscent of a high-quality limestone—that showed very little sign of weathering despite having been exposed to the elements for several centuries, and subsequently buried (Figure 3). The rear of each piece had also had a quantity of fabric removed, being scooped out by hand, leaving the finger marks present, thereby reducing both the weight of each individual piece and ensuring a more consistent result during the firing process. The larger example had been damaged on one corner, revealing the inner fabric, and it was from here that a small drilled sample was taken for analysis to limit the possibility of surface contamination.

Two samples of Coade stone were provided from a 1780s' gate cap (Figure 4) at Eleanor Coade's seaside villa in Belmont in Lyme Regis, Dorset (owned and restored by the Landmark Trust): one from its outer face and one from its inner face, to determine whether a finer mix was used for the fair face compared with apparently rougher 'packing' to bulk up the thickness. The samples analysed by Freestone in the late 1980s also came from this gate post.

A third sample came from a fragment of a Coade stone wing given to Caroline Stanford by Coade Stone Ltd, modern-day conservators of Coade stone and who closely follow the Coade method and formulation.

Analysis

The SEM/EDAXS analyses were carried out using a scanning electron microscope (TESCAN VEGA, Czech Republic) equipped with an energy dispersion spectrometer (Link X-Max 50, Oxford

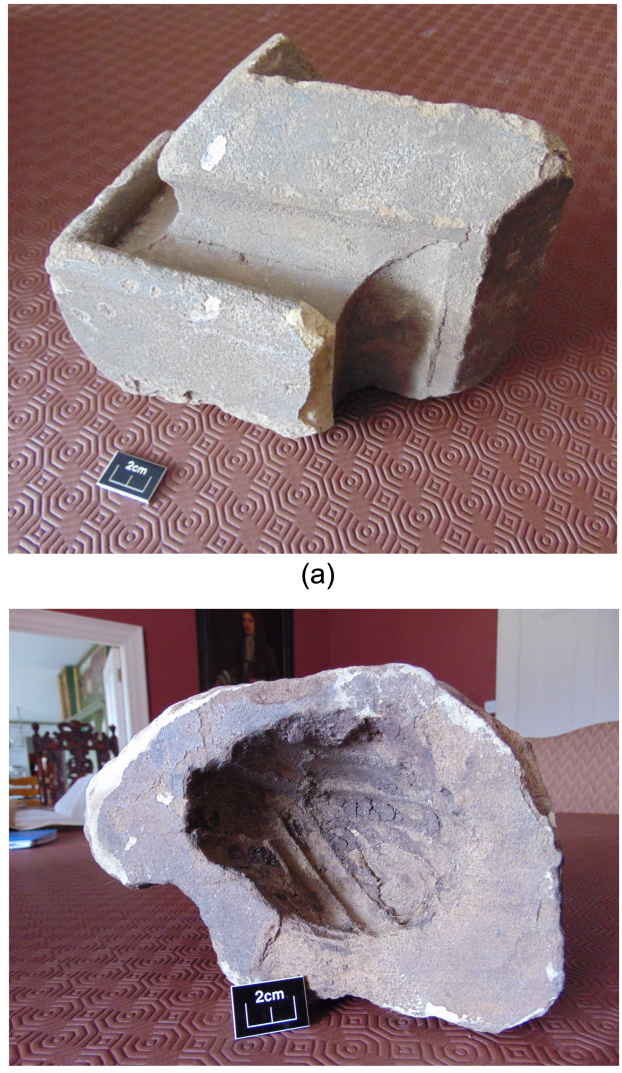

FIGURE 3 An example of the artificial moulded stonework discovered at Oxnead Hall. Mould lines are still visible on the surface, and there is little evidence of weathering: (a) front face; and (b) reverse face clearly showing where the excess material has been removed from the body of the moulding to reduce the weight and ensure consistency during the firing process

Instruments, UK) calibrated against the SPI set of standards (SPI supplies, USA), operating at 15 kV, with a beam current of 6 nA.

The XRD analyses were carried out using a PANalytical X'Pert Pro diffractometer (PANalytical, the Netherlands), equipped with a diffracted beam monochromator and multichannel detector (CuKα radiation, 40 kV, 30 mA, 3–70° 2θ, step scanning at 0.02°/100 s). The records were analysed using X'Pert HighScore 3.0e software, equipped with the PDF-2 database.

The Raman spectroscopic analyses were carried out using a Renishaw InVia Reflex spectrometer (Renishaw, UK) coupled with a microscope (Leica, Germany). The spectrometer is equipped with a thermoelectrically cooled CCD detector. Excitation was provided by a 514.5 nm Ar laser (power approximately 20 mW at source). To achieve enhanced signal-to-noise ratios of the Raman signal, 10–30 scans were typically accumulated, each of 20 s exposure time. Spectra were recorded within

FIGURE 4 An 18th-century Coade stone gate cap from Eleanor Coade's own seaside villa at Belmont in Lyme Regis, Dorset, which she acquired in 1784 (photo: Caroline Stanford)

TABLE 1 SEM/EDAXS data for elemental oxides/% in Oxnead and Coade stone samples

Specimen	SiO_2	Al_2O_3	MgO	CaO	Na_2O	K_2O	P_2O_5	TiO_2	Fe_2O_3	Cl^- reference	
Oxnead	39.5	14.3	1.3	14.6	1.0	1.5	0.5	0.4	5.3	0.1	Present work
Coade stone	57.0	30.3	0.5	0.8	1.0	3.1	0.0	1.1	1.3	0.2	Present work
Coade stone	60	30	0.5	1.4	1.3	2.8	0	1.2	1.4	0	Freestone (1991)

Note: The elemental oxide percentages for the Oxnead and Coade stone specimens in the current work are averaged between the analyses for the independent grog and matrix regions, representing up to five determinations for each specimen, identified in the SEM experiment. Measurements were also made for the glassy regions; these are discussed in the text.

the 100–2000 cm^{-1} spectral wavenumber range with an operational spectral resolution of 2 cm^{-1}. A polystyrene standard was used to verify the internal wavenumber calibration. Spectral analysis and treatment, such as baseline correction, were performed using the GRAMS/AI 9.1 software package. Comparison of spectral band wavenumbers was facilitated using the RRUFF database of minerals.

RESULTS AND DISCUSSION

Only one previous study in the literature has given the percentage composition of the raw material components in Coade stone, using SEM/EDAXS, which cited the following data: SiO_2 60%; Al_2O_3 30%; TiO_2 1.2%; FeO 1.4%, MgO 0.5%; CaO 1.4%; Na_2O 1.3% and K_2O 2.8% (Table 1) (Freestone et al., 1985: 299; Freestone, 1991: 135). The work of Karran and Colston, using a portable XRF instrument, gave data for 26 elements in major, minor and trace concentrations of which the presence of ten elements were used in the discrimination between Coade and later 19th-century artificial stone products, but the percentage compositions of silica, alumina, calcia, magnesia etc. were not provided (Karran & Colston, 2016: 292). It was noted, however, that the Fe content of Coade stone at 0.62% (equivalent to an Fe oxide percentage of about 0.8%) was significantly less than that of the other two Victorian stone samples from Blashfield and Doulton, these comprising approximately twice as much Fe oxide in content. This correlates well with the comment in the early literature that Coade stone used white clays and extremely fine white river sand, which would both be anticipated to be low in their Fe oxide content.

A comparison of the data obtained by Freestone for Coade stone using SEM/EDAXS and in the current work as shown in Table 1 reveals that the two sets are in very good agreement with each other. The new data presented here for Oxnead stone indicate some definitive differences, which can be summarised as follows: Oxnead stone has a significantly smaller percentage of silica and alumina than Coade stone, being respectively 39.5% versus 57% for silica and 14.3% versus 30.3% for alumina.

Other differences are that the calcia in Oxnead stone is significantly higher in percentage than that of Coade stone, being 14.6% versus 0.8% respectively, and other minor component differences being manifest as magnesia 1.3% versus 0.5%, potash 1.5% versus 3.1%, titania 0.4% versus 1.1% and Fe oxide 5.3% versus 1.3%, respectively for Oxnead stone and Coade stone. The minor elemental oxide changes reflect the different sourcing of the clays used in the raw material, perhaps the most significant of these being the 400% change in Fe oxide content which can be ascribed to the use of ordinary sand for the Oxnead stone raw materials compared with the higher quality fine quartz river sand that was a characteristic of Coade stone production. The higher silica content of Coade stone can be ascribed to the use of glass frit as a raw material in comparison with Oxnead stone. Previous analysis has shown that the glass used in the Coade composition was the common soda lime bottle glass of the period, which was high in lime and low in alkalis. These additional fluxing agents and alkalis counteracted the otherwise weakening effect of a relatively high proportion of the more inert grog, sand and flint (Freestone, 1991:137). Lambeth was an area of glasshouses and glass grinders in the 18th century so the inclusion of ground glass possibly represents an efficient recycling of glass waste.

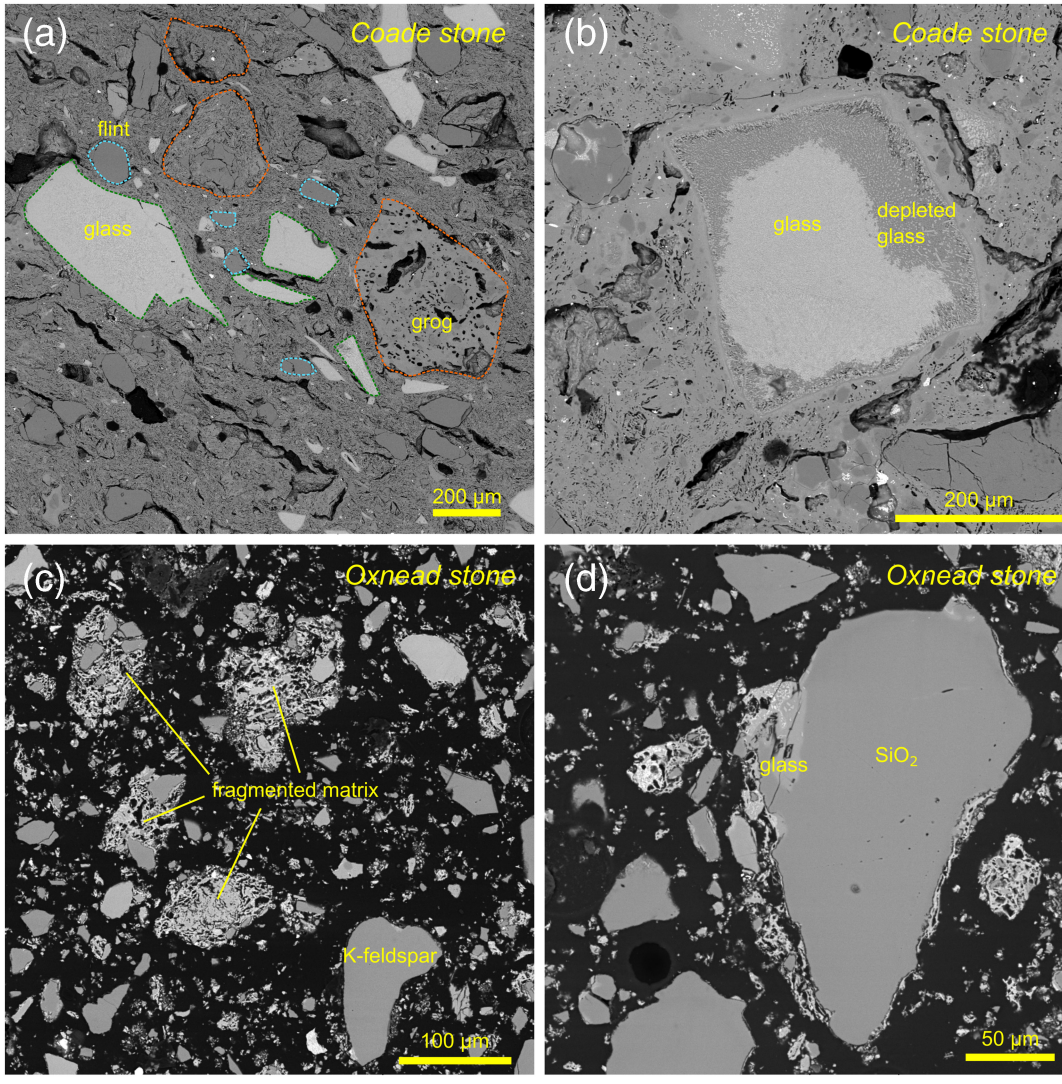

FIGURE 5 SEM micrographs of genuine Coade stone and the Oxnead stone samples

This is manifest in the SEM micrographs which show glassy areas that are rich in silica (evaluated as 63% in the SEM/EDAXS measurements) which have also partly crystallised into diopside and wollastonite phases and have also become depleted in calcium. The high alumina content of Oxnead stone reflects the use of different secondary clays in its raw materials (Figure 5).

The XRD data acquired from the specimens of Oxnead and Coade artifical stone clearly indicate that they are of different phase composition (Table 2); the phase composition of the Coade specimen is indicative of it being fired at a higher temperature than the Oxnead analogue with the presence of mullite, which has been recorded as a characteristic signature in hard paste porcelain kiln fired ceramics (Colomban, 2013; Colomban et al., 2020; Edwards, 2021). On the other hand, the presence of wollastonite in the Oxnead specimen shows a similarity with some soft paste porcelain compositions which have been fired at significantly lower temperatures in the kiln. An indicated higher firing temperature agrees well with the process used by Eleanor Coade in the mid- to late 18th century for her Coade stone

TABLE 2 XRD data for Oxnead and Coade stone specimens

Specimen	Mineral phase identified	Formula
Oxnead	Quartz	SiO_2
	Sanidine	$KAlSi_3O_8$
	Albite	$NaAlSi_3O_8$
	Wollastonite	$CaSiO_3$
	Diopside	$MgCaSi_2O_6$
	Rutile	TiO_2
Coade stone	Mullite	$Al_6Si_2O_{13}$
	Cristobalite	SiO_2
	Na/K feldspar	$(Na,K)AlSi_3O_8$
	Sillimanite	Al_2SiO_5
	Diopside	$MgCaSi_2O_6$
	Rutile	TiO_2

TABLE 3 Raman spectroscopic data cm^{-1} and mineral species identified for Oxnead and Coade stone specimens

Specimen	Mineral species identified	Formula	Raman spectral bands cm^{-1}
Oxnead	Quartz	SiO_2	464
	Haematite	Fe_2O_3	212, 275
	Feldspar	$KAlSi_3O_8$	285, 514
	Rutile	TiO_2	451, 612
	Wollastonite	$CaSiO_3$	635, 970
	Carbon	C	1304, 1596
	Glass	Silicates	500 br, 1000 br
Coade stone	Quartz	SiO_2	464
	Haematite	Fe_2O_3	212, 275
	Rutile	TiO_2	451, 612
	Anatase	TiO_2	
	Carbon	C	1304, 1596
	Diopside	$MgCaSi_2O_6$	
	Cristobalite	SiO_2	
	Mullite		

production process. Likewise, the presence of sanidine in the Oxnead samples is also indicative of a lower firing temperature as used for soft paste versus hard paste porcelains and the presence of cristobalite (the high-temperature stable form of quartz) in the Coade samples suggests the higher processing temperatures that would have been achieved in the Coade stone firing process. Both Coade and Oxnead specimens contain rutile, which is present in the sedimentary clays used in the raw materials and the quartz would have been derived from the fine river sand used as a raw material component. Diopside is present in both and indicates the presence of a magnesium elemental presence in both stone formula-

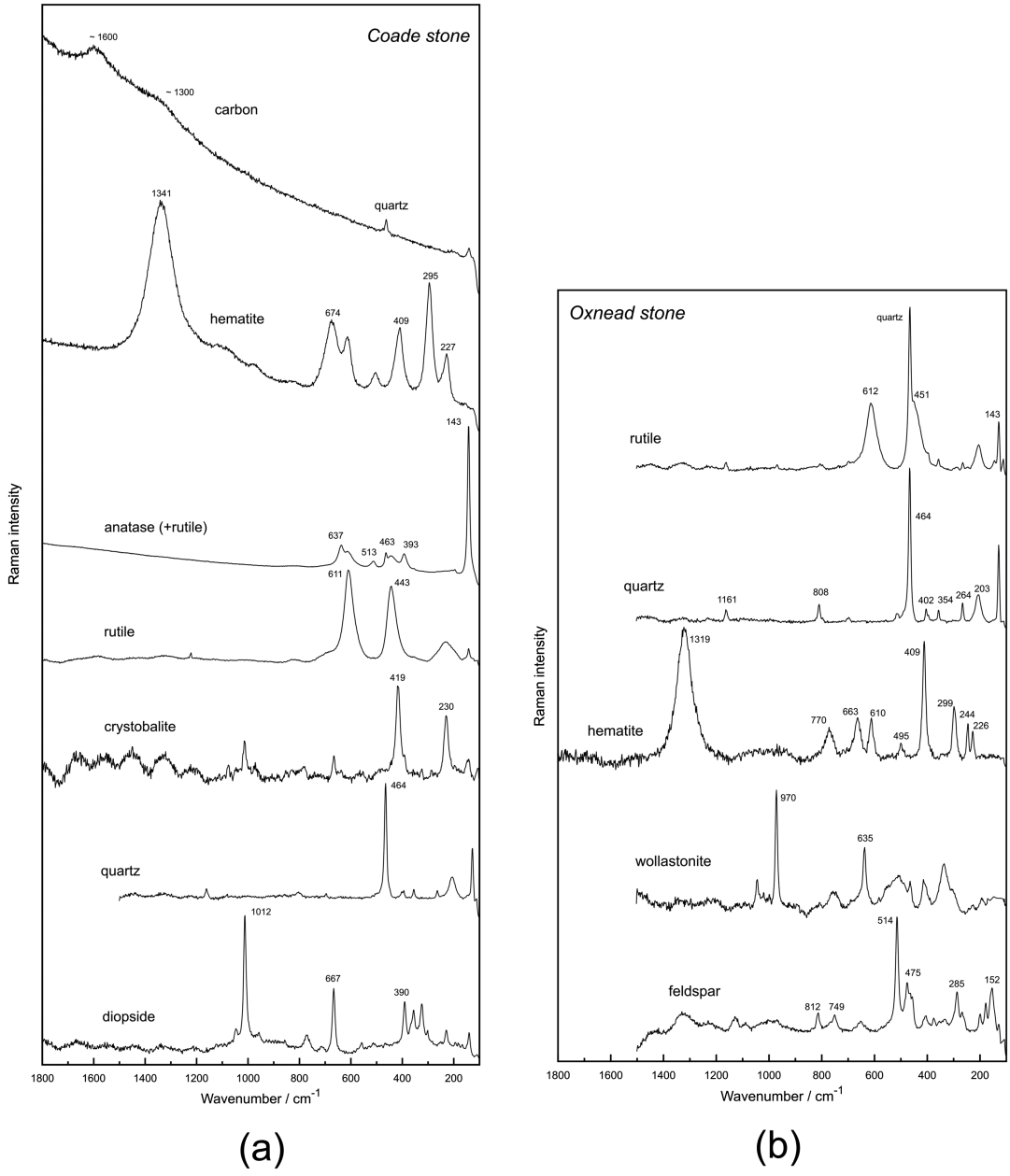

FIGURE 6 Raman spectra for various components located in (a) the Coade stone samples; and (b) the Oxnead stone samples

tions, probably arising from a talc silicate component in the clays used. The presence of a glass additive in each stone is inferred from the amorphous background observed in the XRD data.

Finally, the Raman spectroscopic data (Table 3) comprising characteristic band wavenumbers confirms the XRD data assignments and provides another analytical differentiation between the Oxnead and Coade stone specimens (Figure 6). Again, feldspar is seen in the Raman spectrum of Oxnead stone, and wollastonite confirms its lower temperature production process compared with the higher temperature mullite formation in Coade stone. The higher temperature form of silica, cristobalite, is also identified in Coade stone from the Raman spectrum.

The identification of the mullite phase in Coade stone is a definitive indicator of the high kiln temperature adopted in its synthesis. Another significant discovery is the low concentration of Fe (III) oxide in its composition reflecting the careful selection of the sand and clay components: this generates the similarity between Coade stone and other stonewares and porcelains, but Coade stone is differentiated from porcelain by its lack of translucency to transmitted light and coarseness of aggregate. The characterisation of the minerals and phases found in the production of Coade stone, stonewares, terracottas, and porcelains is accomplished by the Raman spectroscopic analysis of the molecular signatures which then facilitates the interpretation of the kiln procedures and of the temperatures attained in the synthetic processes (Edwards et al., 2022). The miniaturisation of Raman spectroscopic instrumentation is now seeing applications for direct on-site and in-field archaeological excavations, which are being adopted for the non-invasive selection of specimens for further studies in the laboratory (Jehlička & Culka, 2019).

CONCLUSIONS

The current work, which reports the first analysis of the early Oxnead stone and its comparison with Coade stone from the 1780s, demonstrates that it is possible to differentiate between them on the basis of both the raw materials used and the different phases formed in their production processes. It can thus be confirmed that Coade stone used a significantly higher ceramics production temperature than its earlier Oxnead analogue and that this is reflected in the presence of mullite and cristobalite in the former and wollastonite in the latter specimens. This suggests that while the Coade formulation was a consciously refined and manufactured formulation of recognised ingredients specifically sourced from elsewhere, the Oxnead mix was essentially a chance, artisanal discovery based upon materials to hand at a single site. The Oxnead sample therefore cannot considered a true prototype for the manufactured Coade product, with its inclusion of ground glass.

Further insight into the Coade manufacturing process is yielded by the consistency of the results for the fair and inner faces of the Coade gate cap (samples 1 and 2). This indicates that a single mix was used throughout a Coade piece, a useful insight in comparison to earlier manufacturers. For example, Richard Holt, who took out a patent (No. 447) for fired artificial stone in 1722, left a deposition dated 1730 describing his process in which he recommended a skim of finely ground composition over a filling of coarser material (BL Add. MS 11394, f. 46; Stanford, 2016). Examples of Holt's wares have yet to come to light.

This analysis affords a distinctive basis for the identification of synthetic ceramics used in historic buildings and projects that may at some stage have involved a recycling initiative from earlier buildings which archaeological restoration projects of ancient building structures may encounter. Finally, it needs to be emphasised that of the three analytical techniques adopted here Raman spectroscopy can be used entirely in a non-destructive analytical mode which would be beneficial for undamaged ceramic statuary for which conservators may be unwilling to excise even small specimens.

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DATA AVAILABILITY STATEMENT

The data that supports the findings of this study are available in the material of this article.

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