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Examination and Analysis of Mortar Samples from Stone Masonry Construction

Vindolanda Roman Fort, Hadrian's Wall

Bardon Mill, Hexham, Northumberland

Prepared & Approved by

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1.0 Introduction

Two samples of mortar were delivered to CMC's Stirling laboratory by ********** ******* on the 28th September 2016. The samples were delivered to CMC with the request that they be examined and analysed to establish the components from which each of the mortars were made and determine their mix composition.

The samples were stated to have been removed from original masonry construction from two areas within the Vindolanda Roman Fort, which is situated to the South of Hadrian's Wall in Northumberland. The samples were removed from the construction by Archaeologists working on the Fort.

This report presents observations from the examination of the samples received, along with the results of the analyses carried out, concluding with a summary of our observations.

2.0 Samples

Two samples were received from ********** ********, who delivered them to CMC's Stirling laboratory on the 28th September 2016. The samples were stated to be from areas of original masonry within the Vindolanda Fort complex.

On receipt in the laboratory the sample details were entered into the sample register and the unique sample reference SR2422 allocated. The samples were further identified by the Client's sample reference, which is reproduced below along with details of the sample locations:

CMC Sample Ref.	Client Sample Ref.	Description/Location
SR2422-S1	Sample 1	Pre Hadrian, 100AD, removed from Bath House
SR2422-S2	Sample 2	AD 213 Fort Wall, sampled from the Rampart backing.

3.0 Methods of Examination and Analysis

The samples, as received, were initially measured, weighed and photographed, prior to being submitted to a microscopic examination with the aid of a stereo-binocular microscope at magnifications up to x 20.

Following the initial examination representative sub-samples were obtained from each sample and these dried in an air circulating oven at 60°C, to a constant weight to permit their as-received moisture content to be determined.

From the dried material sub-samples were prepared and these submitted to acid digestion following the procedures of the Scottish Lime Centre Trust (SLCT) for determination of acid soluble binder content. This also permitted the recovery of the sand for examination and grading.

The aggregate recovered from the acid digestion were graded through a nest of British Standard sieves to enable the particle size distribution to be determined.

Additional binder rich sub-sample were also prepared from each samples, with these disaggregated by grinding them in an agate mortar and pestle, taking care not to crush the aggregates, with binder rich sub-samples obtained by sieving the disaggregated material over a 63µm sieve. The powders passing the sieve were submitted to analysis by X-Ray Diffraction to assist in identifying the type of binders used in the mortars and establish if there were any deleterious reaction products present.

Petrographic thin sections were also prepared from the samples to permit a comparison of the mortar fabric in the two samples and to aid an understanding of the methods of mortar preparation and subsequent in-service performance.

4.0 Macroscopic Examination

Details of the samples as received are reproduced below:

Sample Ref.	Mass of sample (gram)	Size of largest intact piece (mm)	Colour of Mortar Munsell Soil Colour Chart
SR2422-S1	235.0	93.4 x 89.3 x 45.3	10YR 7/3 "Very Pale Brown"
SR2221-S2	231.4	109.1 x 54.6 x 35.3	2.5Y 4/3 "Olive Brown"

Observations from a macroscopic examination of the samples as received are presented in the following sections of this report:

4.1 SR2422-S1 – Pre-Hadrian - 100AD, Bath House

This sample is well compacted and moderately hard to locally hard and the aggregates are well bonded within the matrix of the mortar. The mortar could not be disrupted under firm finger pressure and required a hammer impact to disrupt an intact piece. However once disrupted the mortar could be further broken and aggregates plucked from the paste under firm to persistent finger pressure.

On testing freshly fractured surfaces with a phenolphthalein indicator solution it was indicated that the mortar was fully carbonated. The colour of the mortar was assessed and found to be 10YR 7/3 "Very pale brown" in colour[1]. The as-received moisture content was measured at 1.9% by dry mass.

Water droplet tests indicated that the paste was porous, with water droplets readily absorbed and diffused through the mortar fabric. However, in the hand specimen, there was no obvious signs of binder depletion due to water migration through the sample.

The aggregates are angular to sub-angular in shape, and dominated by clay tile fragments and limestone with a low proportion of quartz in the fine fractions. There is also an abundance of burnt fragments and fine particles of tile or pottery within the paste, perhaps suggesting the addition of a ground tile and ash as a pozzolan.

[1] The colour of the mortars was assessed by comparison against the Munsell Soil Colour Charts.

Plates No. 1 & 2: The above plates show the condition of the sample as received in the laboratory, with the left plate showing the outer surface of the mortar, which retained algae and moss adhering to its surface and penetrating into surface connected voids. The presence of the organic growths and surface soiling inferring that this mortar sample was removed from a section of masonry exposed at the surface. The right plate shows the inner masonry contact surface, where large tile/brick fragments along with a large limestone fragment appear to form the main aggregate components.

Plate No. 3: The image opposite shows a sawn surface cut through the thickness of the largest intact piece of the mortar, where again it can be seen that the dominant aggregate in the sample is crushed clay tile/brick and limestone, see upper right.

Plate No. 4: The image on the left shows the piece of the mortar from which the petrographic thin section was prepared.

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4.2 SR2422-S2 – Fort Walls - 213AD, Rampart Backing

This sample was from a heavily weathered piece of mortar, which was found on examination to be easily disrupted under light to moderate finger pressure.

Plates No. 5 & 6: The left plate shows the sample, as received, with the sample orientated to show what appears to be an outer surface which retained soiling and organic growths. The plate on the right is of what appears to be an inner, fractured, surface where the mortar although discoloured by alteration and soiling due to weathering, does not support any organic colonisation.

The mortar in this sample was sufficiently different to sample S1 as to infer that it was from a totally different mortar, made at a different time and from different materials and this would concur with the information supplied with the sample, i.e. that it was from a separate period of construction.

Plate No. 7: Close-up of the weathered inner fractured surface of the sample as received showing the condition of the matrix and the aggregates.

Plate No. 8: A magnified view of a sawn surface cut through the thickness of the largest piece of mortar for thin section preparation. However, the matrix was sufficiently friable for material in contact with the blade to be lost during cutting, and therefore the entire piece was impregnated with a resin, to consolidate the sample, prior to another cut being taken for petrographic thin section preparation.

On testing the freshly sawn surface with an indicator solution it was again indicated to be fully carbonated. The mortar absorbed water droplets placed onto its surface very quickly and it was indicated that the fabric was highly porous, which is consistent with the observations from the macroscopic examination which identified significant dissolution of binder with reprecipitation within the fabric of the mortar.

The aggregates in this sample were dominated by quartz along with sandstone fragments, quartzite and indeterminate lithic fragments. The aggregates were sub-round to sub-angular in shape, with the finer particles displaying smooth water worn surfaces. This may infer that it was a mixture of partly crushed material and a natural river, or bank, sand.

5.0 X-Ray Diffraction Analysis

Representative binder rich sub-samples were obtained from both mortar samples and these prepared for analysis by X-Ray Powder Diffraction (XRD). This was to enable the binder type used in the mortars to be determined.

The sub-samples were initially disaggregated in an impact mortar, sieved to remove as much of the aggregate particles as possible with the remaining matrix material ground in an agate mortar and pestle to pass a 63µm sieve, with the fines collected for analysis.

The powdered samples were back-packed into proprietary sample holders in preparation for presentation in the diffractometer. This technique was employed to ensure, as near as possible, the completely random orientation of the crystalline components required to give true peak intensities in the diffractograms.

The prepared samples were analysed in a Philips X-ray Diffractometer fitted with a single crystal monochromator, set to run over the range 3° to 60° 2θ in steps of 0.1° 2θ at a rate of 1° 2θ/minute using CuKα radiation. The digital output from the diffractometer were analysed in by a computer program, which matched the peak positions against the JCPDS International Standard Mineral Data-base sub-files using a search window of 0.1°. The results of the analyses carried out are shown in the following figures, appended to this report, in the form of labelled X-ray diffractograms.

After analysing the results a further sub-sample was obtained from sample S1, with this limited to a few lime inclusions, which were picked from the matrix. The inclusions were ground to pass a 63µm sieve, with the powder deposited on a glass slide in the form of an acetone suspension, which was evaporated to dryness in preparation for analysis. The sample was analysed under the same machine conditions as the original samples.

Figure No. 3 – SR2422 S1 – Pre-Hadrian - 100AD, Bath House, matrix sample,

Figure No. 4 – SR2422 S1 – Pre-Hadrian - 100AD, Bath House, inclusion sample,

Figure No. 5 – SR2422 S2 – Fort Walls - 213AD, Rampart Backing, matrix sample.

The most abundant crystalline components are identified in the diffractograms by the following short-hand notation:

cc = Calcite ($CaCO_3$) Calcium carbonate, carbonated binder component, also main component of limestone,

va = Vaterite ($CaCO_3$) Calcium carbonate, carbonated binder component, commonly associated with redeposited lime and also present as a component of limestone,

su = Sualumite ($Ca_2Si_2O_5(OH0_2H_2O)$ Calcium Silicate Hydroxide Hydrate, c-s-h phase found in some hydration components, reaction of the lime with pozzolan,

gr = Grossular ($Ca_3Al_2(SiO_2)_2(OH)$) Calcium Aluminium Silicate Hydroxide, an AFm phase, possibly product of a reaction between lime and pozzolan added to mortar,

qz = Quartz (SiO_2) dominant component of the fine fractions of the aggregate, also present in clay brick and tile fragments,

fs = Feldspar, common rock forming mineral with those detected being from the plagioclase group of miners, aggregate or soiling component,

mi = Muscovite mica, common rock forming mineral, also found in sands and clays derived from mica bearing rocks, aggregate or soiling component,

ka = Kaolinite, common clay mineral, formed from the alteration of feldspar minerals,

di = Dickite, another clay mineral of the Kaolinite group, aggregate or soiling component,

he = Hematite (Fe_2O_3) Iron Oxide, component of the aggregate, within red sandstone and/or brick fragments, or as an ore mineral in the sediments used for aggregate,

py = Pyrite (FeS_2) Iron Sulphide, naturally occurring sulphide mineral commonly found in Limestone and other sedimentary and metamorphic rocks, and their sediments derived from them.

Based on the results from the XRD analysis, on the samples submitted to analysis, it is confirmed that the binders used in the production of both mortars, as represented by the samples received, albeit separated in time by approximately 150 years, were both similar in that they were both indicated to be non-hydraulic high calcium limes.

From the mineralogical composition of the mortar in sample S1, and from the lime inclusion picked from the same sampled, it can be confirmed that the lime used was a high calcium air lime, which contained no hydraulic components. A further XRD analysis carried out on a piece of limestone present as an aggregate also confirmed that this was dominated by calcite with trace proportions of aragonite (probably from the shell within the limestone) along with dolomite, from alteration veins within the rock. It may, therefore, be suggested that the limestone aggregate encapsulated within the mortar was from the same source as the limestone used to produce the binder.

The presence of both AFm and c-s-h phases, albeit in trace proportions in the sample of concentrated fines from the matrix in sample S1, would infer that there has been a reaction between the ground clay tile and ash/clinker, in the fines, with the lime of the binder, with this producing the strength and durability apparent in this sample of mortar.

The presence of pyrite was minimal and there were no sulphate reaction products detected in the sample analysed. Trace proportions of Pyrite is commonly found in limestones of the form observed in the sample.

The binder in sample S2 is again a high calcium lime with no hydraulic components detected in the mortar analysed. However, in this sample there were no pozzolanic materials detected with only common aggregate components observed, which were noted to contain a significant proportion of clay minerals. It may therefore be concluded, that in the absence of tile/brick fragments and ground tile (burnt clay) within the fines that this mortar was made using a non-hydraulic lime and an as-dug sand which contained a proportion of clay, or alternatively a proportion of clay had been added to the mortar, perhaps to increase its cohesiveness.

The hematite detected in this sample, may be from the decay of red sandstone, or pyrite, or other iron rich minerals included in the mortar, within the aggregates.

6.0 Analysis by Acid Digestion

6.1 SR2422-S1 – Pre-Hadrian - 100AD, Bath House

As it was indicated from the visual examination, and the results of the XRD analysis, that this mortar was made from a non to feebly hydraulic lime the sample was analysed by acid digestion.

Additionally from the examination of the intact pieces and the abundance of lime inclusions, including both partially burnt and partially hydrated lime, it was considered that the mortar was most likely mixed and placed in the form of a Hot Slaked mortar. As the quicklime appeared to have been reasonably well slaked, the mix composition is reported for a non hydraulic lime binder, in the form of a quicklime. With values for a hydrate mix also given, on the basis that it may have been initially dry slaked and remixed, as a Hot lime mixed mortar, placed cold.

Lime Aggregate Ratio = 1.0 : 1.6, which equates to a mix having the following proportions:

1 part binder to 2.9 parts aggregate by weight for a Quicklime mix,
or
1 part binder to 0.8 parts aggregate by volume, for a Quicklime mix.

Which would equate to the following for a mix prepared using a Hydrate lime binder.

1 part binder to 2.1 parts aggregate by weight for a Hydrate lime mix,
or
1 part binder to 0.7 parts aggregate by volume, for a Hydrate lime mix.

The aggregate recovered from the sample, following acid digestion, was graded through a nest of British Standard sieves, to permit the particle size distribution to be determined. The results of the grading analysis are presented in the following table, with a pictorial representation of the aggregate grading given in the form of an aggregate filled histogram in Figure No. 1. The grading of the recovered aggregate was as follows:

BS Sieve Size (mm)	% Retained	% Passing
8.00	28.7	71.3
4.00	8.1	63.2
2.00	14.9	48.3
1.00	12.4	35.9
0.500	5.0	30.9
0.250	5.9	25.0
0.125	5.8	19.2
0.063	5.5	13.7
Passing 63µm	13.7	

The aggregate particles greater than 4mm are predominantly of sub-angular pieces of broken clay tile/brick, with between 4mm and 0.5mm the grains are comprised of crushed limestone fragments, and fine tile/brick fragments, whereas below 0.5mm the aggregates are dominated by sub-rounded quartz grains with fine clay tile/brick fragments and a trace proportion of indeterminate lithic fragments. The fines in the aggregate appear to be from a natural quartz rich sand, which display water worn surfaces and this may therefore have been obtained from a river or river terrace source

6.2 SR2422-S2 – Fort Walls - 213AD, Rampart Backing

From the analysis of mortar sample S2 it was found that the mix proportion was as follows, with the binder again indicated to have been used in the form of a non-hydraulic lime, the proportions are, as for sample S1, are quoted for both for a quicklime and a lime hydrate, though from the microscopic examination the hydrate mix is more likely:

Lime Aggregate Ratio = 1.0 : 1.6, which equates to:

1 part binder to 2.8 parts aggregate by weight for a Quicklime mix,
or
1 part binder to 0.75 parts aggregate by volume, for a Quicklime mix

With following producing a similar mortar based on a Hydrate lime binder:

1 part binder to 2.0 parts aggregate by weight for a Hydrated lime mix,
or
1 part binder to 0.7 parts aggregate by volume, for a Hydrated lime mix.

The aggregates recovered from the acid digestion were again graded through a nest of Standard sieves with the following particle size distribution obtained; see the table below and the aggregate filled histogram presented in Figure No. 2.

BS Sieve Size (mm)	% Retained	% Passing
8.00	0	100
4.00	3.7	96.3
2.00	8.5	89.8
1.00	7.5	80.3
0.500	8.9	71.4
0.250	13.3	58.1
0.125	19.8	38.3
0.063	14.1	24.2
Passing 63µm	24.2	

The aggregates in sample S2 differ from those in sample S1, and they are predominantly of sub-round to sub-angular particles of quartz, limestone, sandstone, and quartzite, along with a minor proportion of shale and coal fragments. The aggregates contained a high proportion of material passing the 63 µm sieve which is mostly of silt and clay, which would infer that the aggregates were from an as-dug material from a clayey sand deposit, or that the aggregate was purposely mixed with a proportion of clay, to produce a clay-lime mortar.

7.0 Microscopic Examination

To ascertain what differences there were between the mortars from the two ages of construction, petrographic thin sections were prepared from representative sub-samples from both samples S1 and S2, with the samples aligned to permit the maximum area possible on the slides.

The samples were prepared for thin sectioning by initially impregnating the dried sub-samples with an epoxy resin containing a fluorescent blue dye. The thin sections were prepared by polishing one side the impregnated sample and mounting them onto glass slides (50mm x 75mm). The mounted samples were then ground and polished to give a thickness of approximately 30microns. The microscopic examination of the thin sections was undertaken using an Olympus BH2 Polarised light microscope, fitted with a Digital Camera, to permit the recording of images of areas of note for record purposes.

The presence of dyed epoxy resin enables detailed analysis of void distribution in plane polarised light as well as permitting an assessment of microporosity and a clear indication of any crack patterns present.

Thin section examination is also used to determine the details of the aggregate properties and aggregate distribution within the binder. In addition a visual assessment of the proportion of the materials in the binder can be determined, such as volume of paste, aggregate content and unhydrated clinker. The observations from the examination of the samples are presented below:

7.1 SR2422-S1 – Pre-Hadrian - 100AD, Bath House

Aggregate

The aggregate fragments are composed mainly of limestone fragments, with a significant proportion of clay tile/brick fragments along with a minor proportion of quartz grains, and a low proportion of fine ground burnt clay material with a trace of ash.

The aggregates are mostly sub angular in shape with a low abundance internal micro fracturing, these appear to be pre-encapsulation features and would infer that the coarse aggregate fraction were obtained by the crushing/breaking of larger pieces. The fine quartz grains are sub-round in shape and display smooth water worn features and this may have been obtained from a river or river terrace source.

The aggregates are well bound within the paste and although peripheral microcracks are observed, where present, these do not appear to inhibit the aggregate/paste bond, as there is evidence of suturing by redeposited calcite and, therefore, their presence does not appear to have a detrimental effect on the performance of the mortar. The aggregates range in size from 18.0mm 0.6mm for the limestone and 8.4mm to <0.04mm for brick and <0.42 for the quartz grains in the section examined.

Binder

The binder is typical of a lime mortar that was made with a high binder content, i.e. a binder rich mortar. The paste has the appearance of a non-hydraulic lime. However, there are fine pozzolanic components present; composed of ground clay tile/brick and other fine materials that has the appearance of ash. The presence of the pozzolanic materials and its form would infer that a reaction had occurred between the lime with this imparting a measure of hydraulicity to the mortar. The paste and the lime inclusions were observed to be fully carbonated.

There is an abundance of lime inclusions present, and where observed some of these have the appearance of completely slaked quicklime and incompletely burnt limestone. A proportion of the inclusions have not diffused into the surrounding paste and retain sharp delineating margins, suggesting that they have performed as aggregates, not binder.

The paste displays random patches of high microporosity and voids, but a low abundance of shrinkage cracking, which would have been expected had the mortar been made with a putty lime. Clusters of elongated and spherical air bubbles appear to be concentrated adjacent to some of the inclusions, which is consistent with quicklime slaked within the mortar and it may be that these had formed from steam generated from the slaking process.

The lime inclusions range in size from 10.4mm to 0.3mm in the section examined, with these being angular to sub-angular in shape, with the margins either being clear or partially diffused, typical of that associated with mortars made from quicklime which was slaked with the aggregate, rather than run as a putty before use.

There is very little, but localised, evidence of binder depletion due to water percolation, with this limited to the margins of cracks and voids, which are mostly partially lined or infilled with reprecipitated calcite.

Voids and microcracks

Voids are abundant but where present are observed as discrete entrapped air voids which are typically irregular in shape and up to 5mm in size, but typically less than 0.6mm. The voids are locally fringed with redeposited calcite, which was also observed infilling aggregate peripheral shrinkage cracks.

Cracks although rare are present, and where observed appear to have functioned as water transportation channel ways, with many now sealed by redeposited calcite. the cracks tend to be fine, ranging in width from <0.02mm to 0.3mm, and are typical of drying shrinkage features meandering through the paste linking voids, aggregate and lime inclusions.

The results of a point count (modal) analysis are presented in the following table:

Sample Ref:	**SR2422-S1**	
Constituents	**%**	
Aggregate	**Inclusions as binder**	**Inclusions as Aggregate**
Quartz	2.4	2.4
Clay Tile/Brick fragments	8.0	8.0
Limestone	37.2	37.2
Lime inclusions	-	10.1
Total Aggregate	**47.6**	**57.7**
Binder (Lime)	31.3	31.3
Pozzolanic Material	5.1	5.1
Lime inclusions	10.1	-
Secondary products/Calcite	5.9	5.9
Total Binder	**48.0**	**42.3**
Total Constituents	**100.0**	**100.0**
Voids & Porosity	8.6	8.6
Crack	1.7	1.7
Cracks/Voids	**10.3**	**10.3**
Binder: Aggregate Ratio	**Total**	**Effective**
	1.0 : 0.9	**1.0 : 1.36**

Table No. 1: Modal Analysis carried out on thin section prepared from sample S1.

The effective binder content is calculated on the basis that the inclusions are acting as aggregate rather than as binder and is probably a truer measure of the binder content regarding its performance as a mortar. Whereas the total lime content is a reflection of the mix at the time the mortar was made and placed, including the inclusions (both fully slaked and unslaked) as part of the lime binder added.

The following photomicrographs are included to show the condition of the mortar in the section examined:

Photomicrographs:

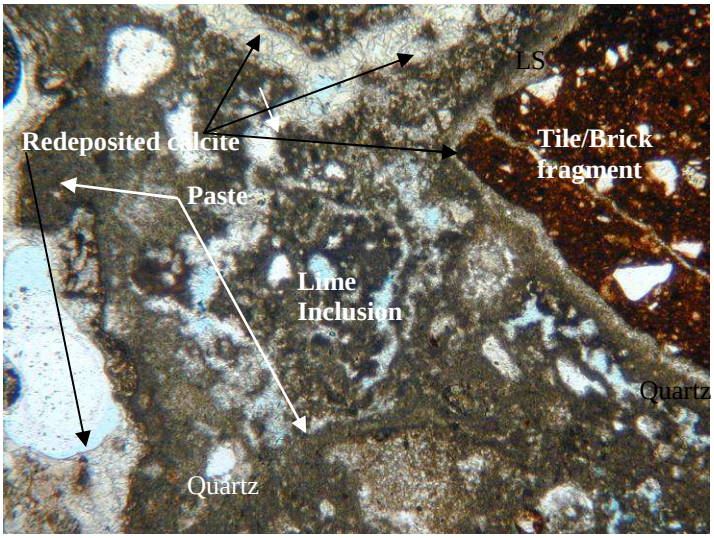

Plate No. 9:

A view in plane polarised light (ppl) showing a typical area of the mortar paste and the aggregate distribution. Aggregates are dominated by crushed clay Tile/Brick fragments in this view.
The paste is relatively dense and uniform and is coloured light to dark grey in this plate. The paste is transected by a number of fine shrinkage cracks which are infilled with redeposited calcite. An area of high microporosity surrounds a partially disrupted lime inclusion in the centre of the plate
Porosity is highlighted by the blue dyed resin. Field of view 2.4mm.

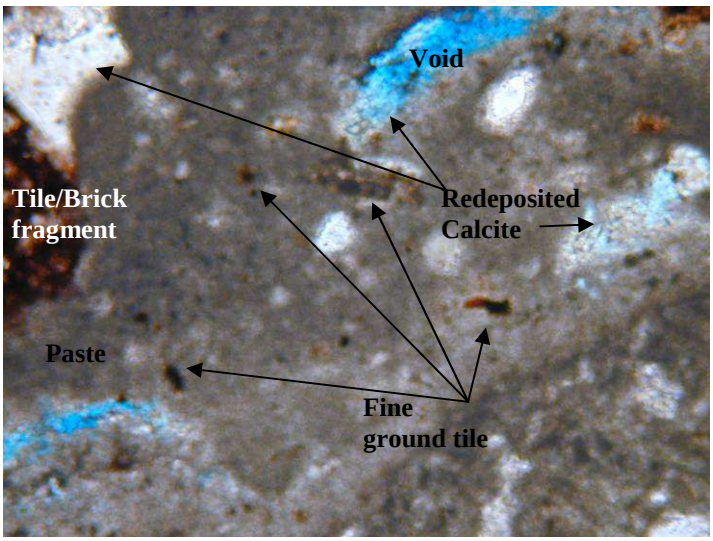

Plate No. 10:

Another view in ppl. A magnified view in plane polarised light, this image shows fine fragments of ground clay tile/brick distributed through the paste, some are diffuse in appearance, possibly indicating a reaction with the lime.
The paste in this view is mostly dense with minor shrinkage cracks which show varying degrees of suturing with redeposited calcite
A fragment of clay tile/brick can be seen on the left side of the plate.
Porosity is highlighted by the blue dyed resin. Field of view 1.2mm.

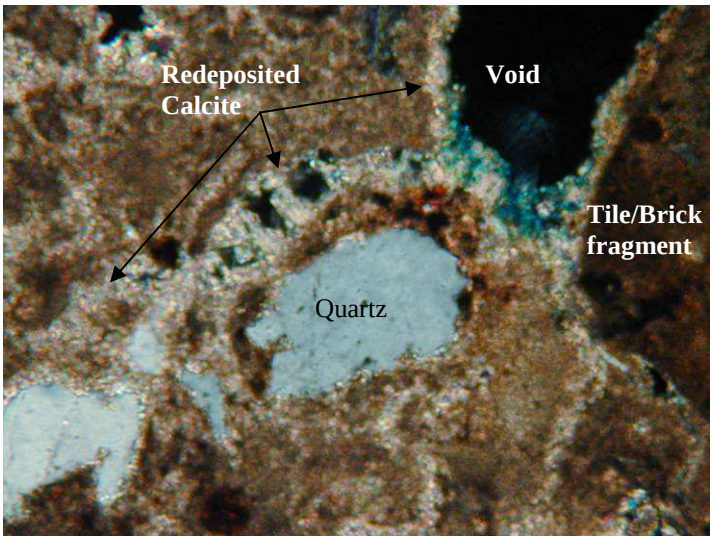

Plate No. 11:

Another magnified view in cross polarised light (xpl). This image shows an area of paste towards the edge of the sample where there is an abundance of reprecipitated calcite suturing and healing crack paths.
The surrounding paste is compact and although there is no evidence of any clinker components, there are a few grains of ground tile/brick apparent (reddish brown in colour), some of which have diffuse margins.
Porosity, voids and the blue dyed resin all appear dark in cross polarised light.
Field of view 1.2mm.

7.2 SR2422-S2 – Fort Walls - 213AD, Rampart Backing Aggregate

The aggregates are dominated by sandstone fragments, along with quartz, with minor quartzite, limestone and igneous rock fragments, along with trace proportions of shale and coal. A noticeable proportion of clay minerals were also observed with these either coating aggregates or existing as balled clay inclusions.

The aggregates are mostly sub angular to sub-round in shape with a number of the sub-angular fragments displaying internal fracturing. The fracturing observed are pre-encapsulation features and would infer that the coarse aggregate particles contains a proportion of crushed material.

Where the aggregates are surrounded by paste they are well bound within the paste. The aggregates range in size from 22mm to <0.3mm.

The aggregates contained a high proportion of material passing the 63 µm sieve which is mostly of silt and clay, which would infer that the aggregates were from an as-dug material from a clayey sand deposit, or that the aggregate was purposely mixed with a proportion of clay and silt, to produce a clay-lime mortar.

Binder

Due to the high degree of leaching and redeposition apparent within this sample it is not possible to clearly determine what form the binder was used in the production of the mortar. Where sufficient paste is apparent there was no evidence of hydraulic components or pozzolanic material in the mix.

The paste displays a high porosity and an abundance of entrapped air voids; however all are lined to locally infilled with redeposited calcite.

The paste is fully carbonated, and although lime inclusions were observed they were randomly distributed throughout the section and were mostly disrupted. The lime inclusions range in size from 1.0mm to 0.4mm in the section examined, with these being sub rounded to sub-angular in shape, with either diffused margins or surrounded by a 'crust' of overburnt lime. Some of the inclusions also displayed features that are typical of that associated with balled hydrate inclusions.

It is therefore possible that the mortar had been made from a slaking quicklime mixed with the aggregate, in a semi-dry condition, and the mix possibly stored and remixed prior to use, as in a hot mix, used cold mortar. This was not an uncommon practice where a proportion of wet clay was added to the mortar.

Voids and microcracks

Voids were abundant and it is likely given their abundance, shape and size that the mix has been affected by a significant degree of binder depletion and redeposition, suggesting prolonged periods of water percolation trough the binder. It is also possible, given the void distribution and presence of channel ways, that the mortar was placed in a particularly wet (over workable) condition. The voids are typical of entrapped air and water voids and are typically irregular to sub-round in shape and up to 12mm in size. The voids are mostly lined or infilled with fringes of fine to coarse reprecipitated calcite crystals.

Shrinkage cracks were apparent within the sparse intact paste rich zones with these ranging in width from <0.02mm to 0.16mm, and these are typical of drying shrinkage features. All cracks are filled with calcite linings.

The results of a point count (modal) analysis are presented below:

Sample Ref:	**SR2422-S2**	
Constituents	**%**	
Aggregate	**Inclusions as binder**	**Inclusions as Aggregate**
Quartz	7.4	7.4
Sandstone fragments	29.1	29.1
Limestone	3.9	3.9
Quartzite	2.0	2.0
Shale, Coal & indeterminate	1.8	1.8
clay	7.9	7.9
Lime inclusions	-	6.3
Total Aggregate	**52.2**	**58.5**
Binder (Lime)	22.2	22.2
Clinker	0	0
Lime inclusions	6.3	-
Secondary products/Calcite and gypsum	19.3	19.3
Total Binder	**47.8**	**41.5**
Total Constituents	**100.0**	**100.0**
Voids	13.0	13.0
Crack	2.2	2.2
Cracks/Voids	**15.2**	**15.2**
	Total	**Effective**
Binder: Aggregate Ratio	**1.0 : 1.09**	**1.0 : 1.41**

Table No. 2: Modal Analysis carried out on thin section prepared from sample S2.

If the clay had been added as a binder component the mix, in the sample examined, would have been in the region of:

Lime: Clay: Aggregate 1.0: 0.16 : 0.93 (Total) or 1.0 : 0.19 : 1.22 (Effective).

The following photomicrographs are included to show the condition of the mortar in the section examined:

Photomicrographs:

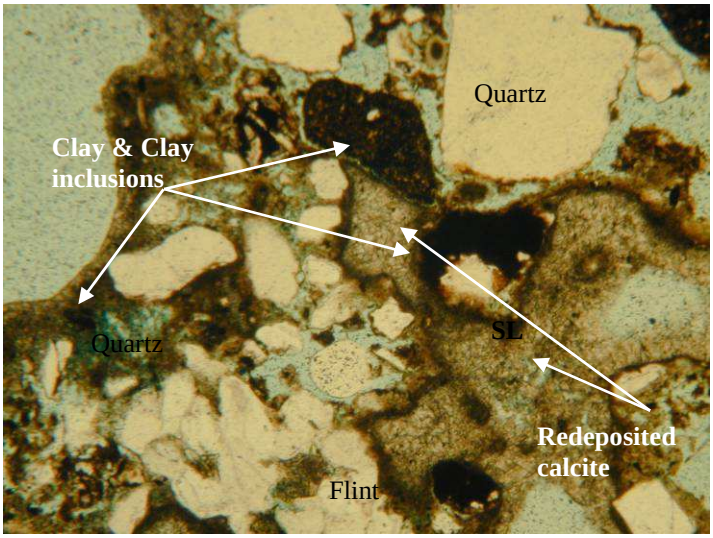

Plate No. 12:

A view in plane polarised light (ppl) showing a typical area of the mortar paste and the aggregate distribution. Aggregates are dominated by Quartz in this view, with quartzite and a limestone fragment.
The paste is locally dense, where compressed between sand grains, left side of plate. Mostly the centre and right side of the plate show an area where the paste is depleted and replaced by redeposited calcite.

Porosity is highlighted by the blue dyed resin. Field of view 2.4mm.

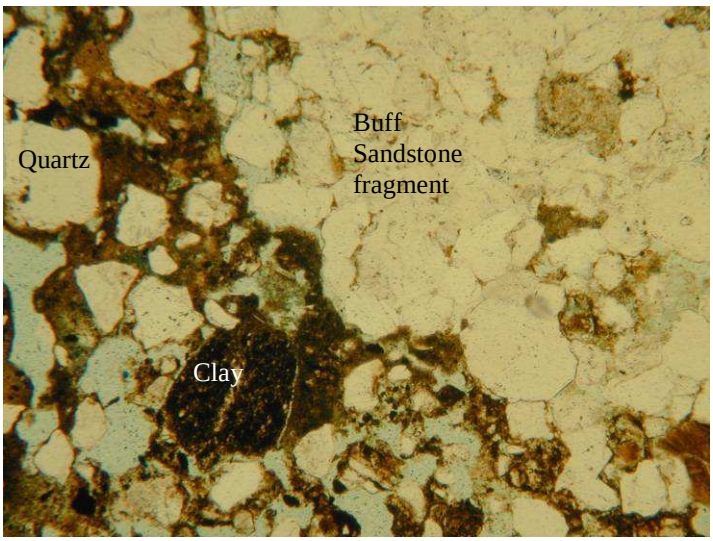

Plate No. 13:

Another view in ppl. This area is dominated by a large sandstone fragment, centre to right of the plate. The sandstone is a buff to white sandstone which contains clay, mica and iron oxide/hydroxide. It can be seen that the paste is well bonded to the sandstone at this location, with the paste discoloured by, and containing, an abundance of clay. Minor cracking can be seen, and where this occur they are sutured by fine fringes of calcite.
Porosity is highlighted by the blue dyed resin. Field of view 2.4mm.

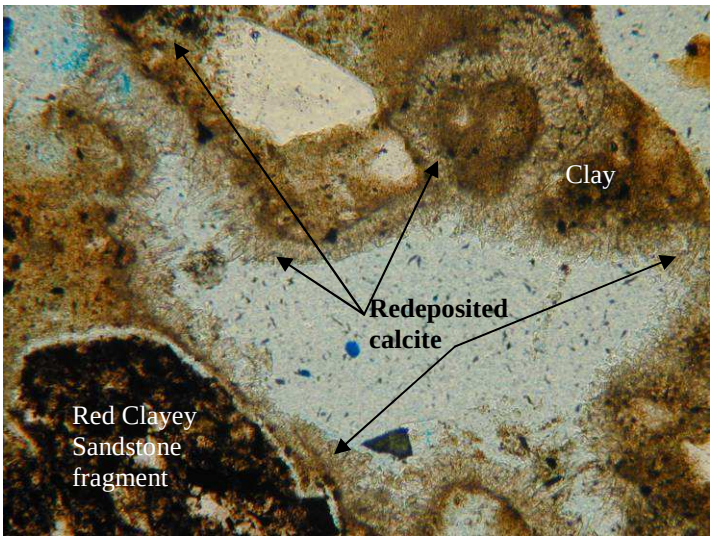

Plate No. 14:

A magnified view in plane polarised light, this image a shows a heavily voided area of the mortar, where aggregate grains are held within a patchy paste framework and welded together by fringes of coarse calcite crystals.
Locally there are small patches of clay, upper right side of plate.
A fragment of a sub-round red sandstone pebble can be seen in the lower left of the plate.
Porosity is highlighted by the blue dyed resin. Field of view 1.2mm.

8.0 Summary

The mortars used in the samples submitted for analysis appear to have been both made from a non- hydraulic lime binder. Although the aggregates in both differ, with that in sample S1, from the Bath House containing crushed clay Tile/Brick both as an aggregate, and as a pozzolan, along with a proportion of crushed limestone, whereas that in sample S2 is mostly of natural aggregate, dominated by sandstone, but with a proportion of clay. The latter not apparent in sample S1.

Although both mortars are lime mortars, in all other respects they differ with that in sample S1 appearing to have been strong and resilient, whereas that in sample S2 is soft and friable and appears only to be intact due to the suturing affect of reprecipitated calcite, i.e. lime leached from the binder, transported in percolating waters and reprecipitated within voids, cracks and zones of porous fabric.

Sample S1 displays all the characteristics of a mortar that was prepared from mixing quicklime with the aggregate and slaking them together, with this possibly placed as a hot mixed mortar. Whereas, sample S2, although heavily leached would appear, from the remnants of remaining fabric, to possibly again have been mixed hot, but probably stored and used as a remixed mortar at a later date.

The mixes used are summarized below:

Sample Ref	**S1**	**S2**
Location.	**Bath House**	Rampart Backing
Age	100AD	213AD
	Mix Composition (by acid digestion)	
Hydraulicity	Non-Hydraulic	Non-Hydraulic
Form of Mixing	Hot Lime Mortar	Hot Mix, used cold
Binder:Agg by vol. Quicklime binder	1.0 : 0.8	1.0 : 0.75
Binder:Agg by vol. Hydrated lime binder	1.0 : 0.7	1.0 : 0.7
	By modal analysis (total)	
Binder: Agg. by vol.	1.0 : 0.9	1.0 : 1.1

The aggregate gradings are also grouped below, for comparison:

Sample Ref.	**S1**	**S2**
BS Sieve Size (mm)	**% Retained**	
8.00	28.7	0
4.00	8.1	3.7
2.00	14.9	8.5
1.00	12.4	7.5
0.500	5.0	8.9
0.250	5.9	13.3
0.125	5.8	19.8
0.063	5.5	14.1
Passing 63µm	13.7	24.2

Sample S1 is in a sound condition and appears to have had limited impact from environmental weathering or age related decay, whereas sample S2 is severely affected. It is likely that if undisturbed that the mortar represented by sample S1 if undisturbed should continue to perform satisfactorily. The mortar represented by sample S2 is susceptible to decay and disruption in response to weathering.

9.0 Quality Statement

We confirm that in the preparation of this report we have exercised reasonable skill and care.

The comments offered and reported herein relate to the two mortar samples received from ******** ******** on the 28th September 2016 which were stated to have been obtained from two separate areas of masonry construction at the Vindolanda Roman Fort, near Hadrian's Wall, Northumberland.

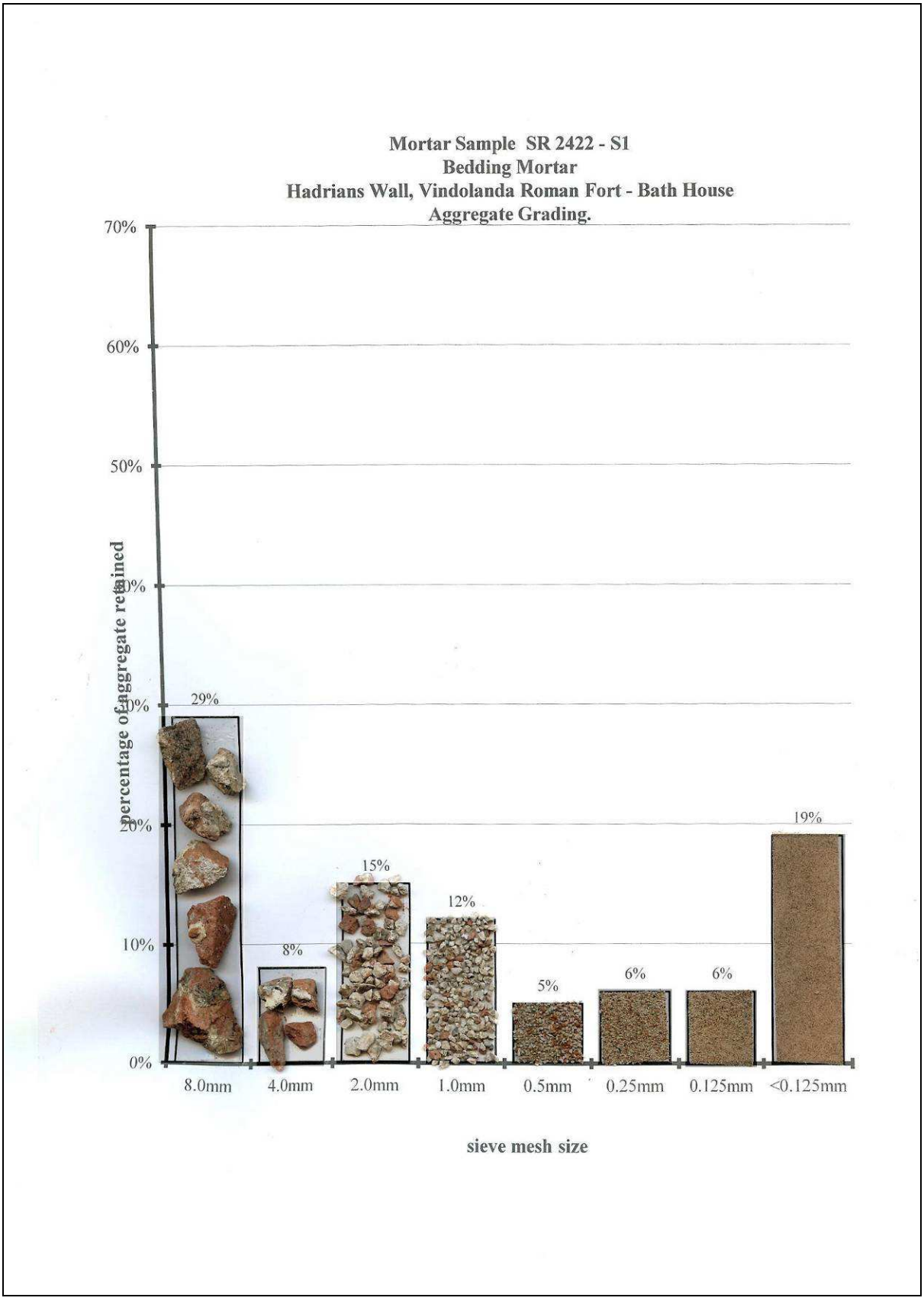

Figure No. 1 – SR2422 S1 – Recovered Aggregate – Particle Size Distribution

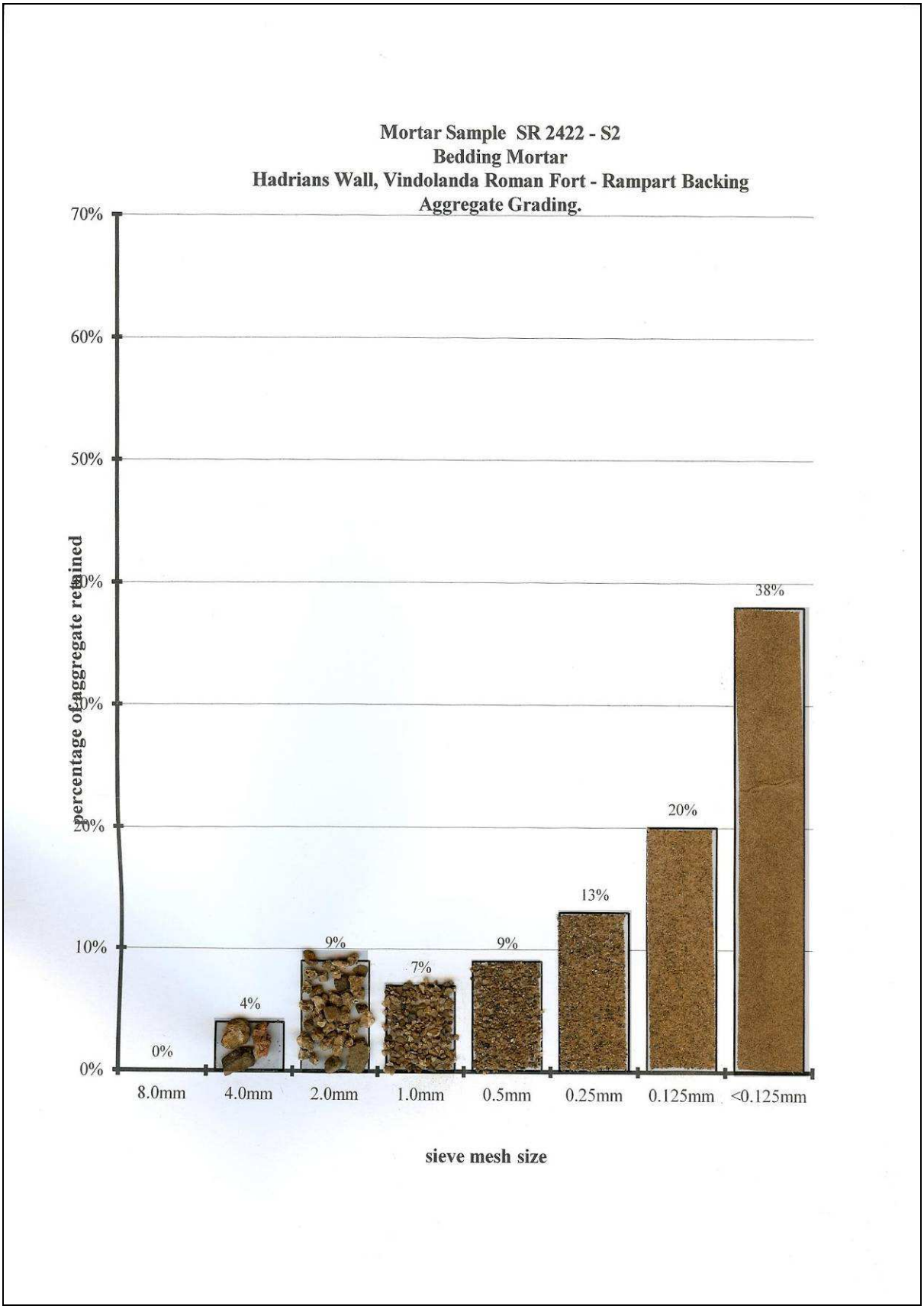

Figure No. 2 – SR2431 S2 – Recovered Aggregate – Particle Size Distribution

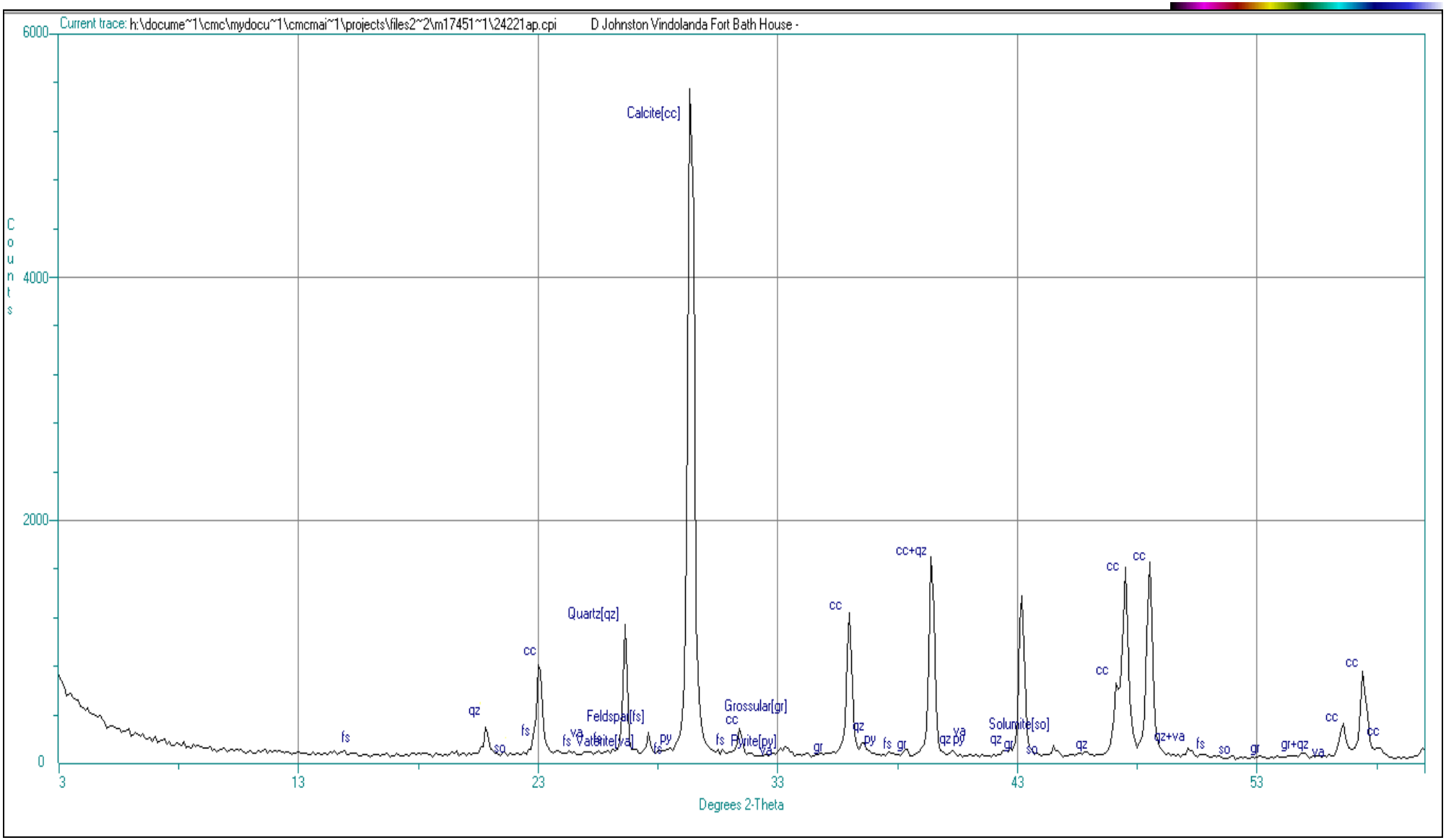

Figure No. 3 – SR2422 S1 – Pre-Hadrian - 100AD, Bath House, matrix sample.

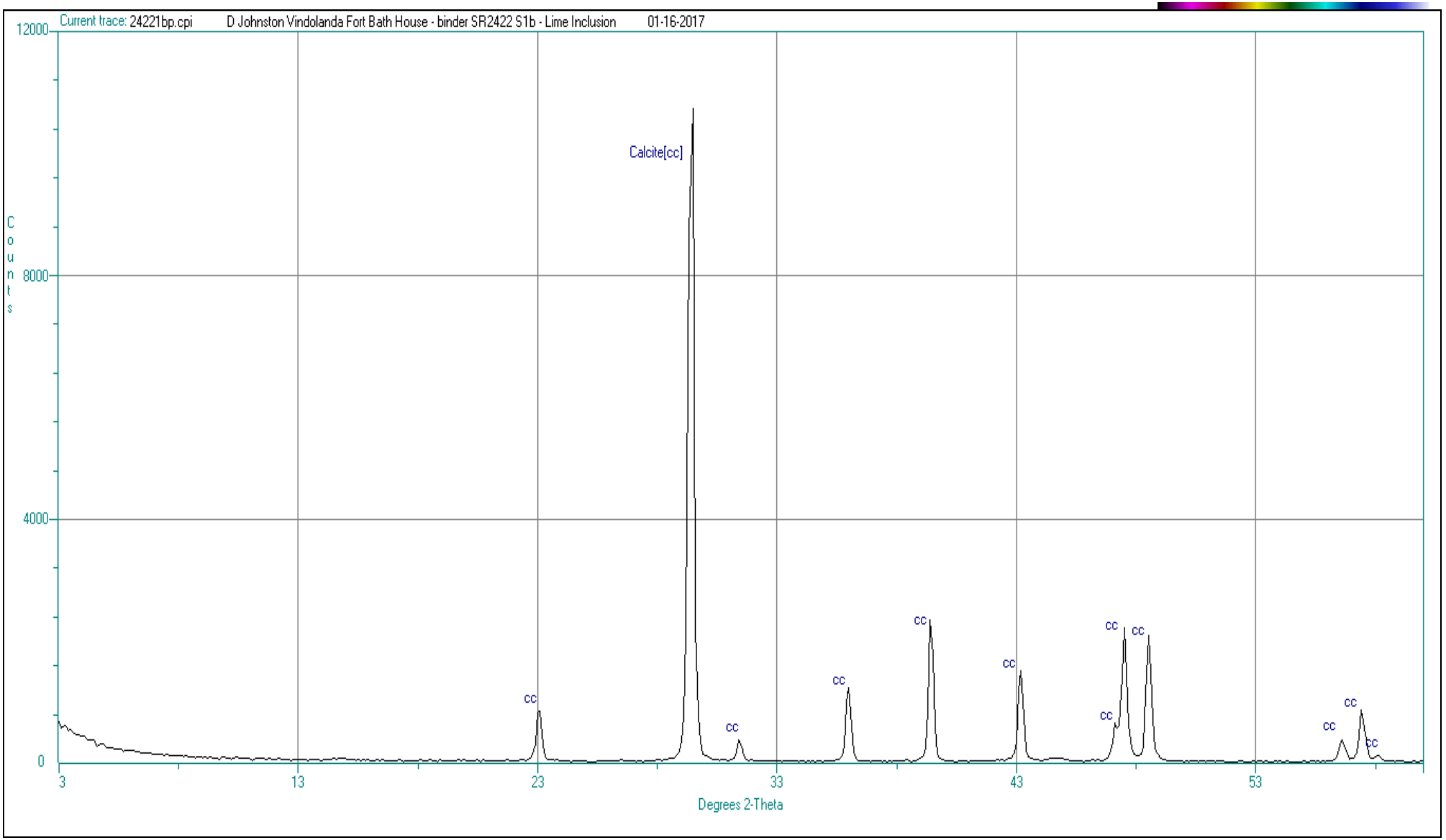

Figure No. 4 – SR2422 S1 – Pre-Hadrian - 100AD, Bath House, inclusion sample.

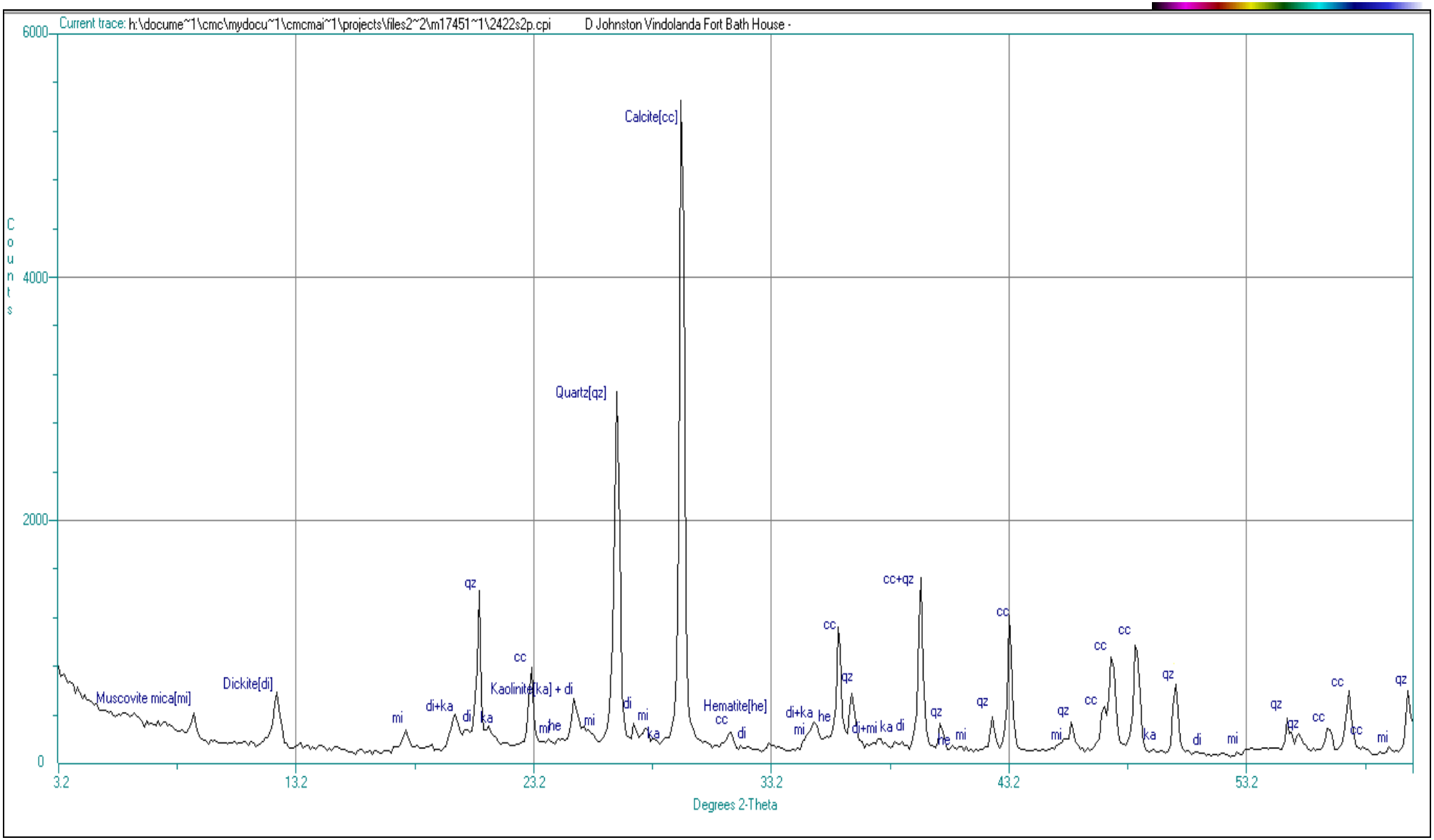

Figure No. 5 – SR2422 S2 – Fort Walls - 213AD, Rampart Backing, matrix sample.