Construction Materials Consultants Ltd.

Wallace House, Whitehouse Road, Stirling, FK7 7TA
Tel 01786 434708 Fax 01786 475133
E-mail mail@cmcstirling.co.uk

Report on the Examination and Analysis of Mortar Samples from Stone and Brick Masonry

The Guild Hall, York

Prepared and Approved By

W A Revie

Prepared for

The Earth Stone & Lime Company
Hall Farm
Maltongate
Thornton Dale
Pickering
North Yorkshire YO18 7SA

Date Issued 19th March 2018

Our Ref: M/1844/18
Your Ref: Guild Hall, York
Doc. Ref: M184418R1

Table of Contents

1.0 Introduction

A batch of samples, identified as mortar from the Guild Hall, York, was received from Nigel Copsey of the Earth, Stone & Lime Company, in CMC's Stirling Laboratory on the 18th January 2018. The samples were identified as mortars removed from a selection of locations, representing different areas of construction, and/or repair, of the stone and brick masonry of the Guild Hall, in York. Details of the locations sampled was supplied via email on the 17th January 2018, with this including both marked-up plans, on which the locations of the samples were indicated, and a selection of digital images showing the masonry sampled.

As requested the samples were examined on receipt and a laboratory programme of analysis was proposed, along with an indication of costs. This was provided in the form of a quotation, reference M/Q544/18, dated the 2nd February 2018. Instruction to proceed with the analysis was received via from Nigel Copsey by email on the 3rd February 2018.

The Guild Hall was originally Built in 1445, with several additions and alterations incorporated over time. However, it was severely damaged by fire and bomb blast during the second World War, and was rebuilt in the 1960's. It was, however, considered that most of the samples were from construction that pre-dated the 1960's restoration works.

This report details observations from a macroscopic and microscopic examination of the samples along with the results of analyses carried out on the samples received. The report concludes with comment on the composition of the mortars and the binder type, along with comment on the form in which the mortar was prepared and used.

2.0 Sample

A batch of samples was received in CMC's Stirling laboratory on the 18th January 2018, with the sample submitted by The Earth, Stone & Lime Company. The samples being identified as mortars from a selection of stone and brick masonry on the Guild Hall, York. On receipt in the laboratory the sample details were entered into the sample register and the unique sample reference SR2546 allocated, with the laboratory and Client sample reference reproduced below:

CMC Sample Reference.	Client Sample Reference.	Location/Comment
SR2546-S1	B	Sand Lime Brick Masonry, South East Corner, external wall.
SR2546-S2	C	Ashlar Stone Masonry, North Gable wall of East building.
SR2546-S3	D	Wall of the original Guild Hall, within the Stone lean-to shed.
SR2546-S4	E	Mortar from stone masonry, West outer wall within East lane.
SR2546-S5	F	Sand Lime Brick masonry, Lean-to at South end of East lane.
SR2546-S6	G	Possibly the earliest Ashlar Stone Masonry, N Gable to Hall.
SR2546-S7	H	Brick Masonry, similar to sample "B", three story Building.
SR2546-S8	i	Repair mortar to Ashlar Stone Masonry, West Elevation, Hall.
SR2546-S9	J	Clay Brick Masonry, West Wall, North end of West Wing.

No sample A was received. The digital images and marked up plans are reproduced in Appendix "A" to this report, for reference purposes.

3.0 Methods of Examination and Analysis

All samples were initially submitted to a microscopic examination employing a stereo-binocular microscope at magnifications up to x20, and the salient features recorded.

On the basis of the microscopic analysis the samples were grouped into "like" types, with representative samples from each group prepared and submitted to the following programme of laboratory analysis. With a selection of sub-samples submitted to analysis by X-ray Powder Diffraction (XRD), to aid identification of the binder type employed.

Samples that contained binders that were indicated to contain Portland Cement or be eminently hydraulic lime based mixes were analysed, by the methods of BS 4551: 2005 + A1: 2010 + A2: 2013, with those found to be high calcium or feebly hydraulic limes analysed by the procedures of the SLCT (Scottish Lime Centre Trust).

Where considered appropriate and to enable additional information to be obtained, relating to the fabric condition of the mortar, and the form in which the binder was used, thin sections were prepared. With the sections submitted to a petrographic examination.

4.0 Macroscopic Examination

Observations from the examination of the samples received are presented below, along with a summary of the properties of the samples in their as received condition.

CMC Sample No.	Client Ref.	Mass (gram)	Maximum Dimension (mm)	Comment
SR2546-S1	B	19.02	29.4 x 19.9 x 6.3	Hard dense mortar- possible Hydraulic lime, with lime added used in the form of a quicklime or putty with hydrate.
SR2546-S2	C	8.00	13.8 x 12.7 x 6.3	Small pieces of an Ashlar mortar, putty lime mix.
SR2546-S3	D	95.78	36.9 x 28.7 x 23.1	Hard to very hard compact mortar, possible cement/lime/sand, or a Hydraulic lime with putty lime
SR2546-S4	E	11.92	31.9 x 24.1 x 14.3	Piece of stone, Limestone, Dolostone?
SR2546-S5	F	25.08	38.2 x 24.9 x 11.4	Soft to firm mortar, with large lime inclusions, may be an early Hydraulic lime, quicklime mix?
SR2546-S6	G	11.96	22.9 x 13.9 x 10.8	Ashlar mortar mix, lime putty based, large lime inclusions.
SR2546-S7	H	19.86	27.2 x 20.1 x 10.2	Hard to very hard compact mortar, may be a cement/lime/sand mortar of Hydraulic lime with putty mortar.
SR2546-S8	i	26.25	21.3 x 17.6 x 11.5	Ashlar mortar, putty mix, with stone fragments.
SR2546-S9	J	21.99	29.1 x 13.2 x 12.5	Pointing mortar, hard, compact Possibly a cementitious mortar.

Based on the above and given the quantity of the samples available for analysis, within each group, it was suggested that the following analysis programme be followed:

Analysis by XRD to confirm binder type, samples: B, C, D, E, F, G, H, i & J = 9 No.

Mix composition of samples by wet chemistry or acid digestion: D, F, G & J = 4 No.

Mix composition by BS 4551, samples B, D & J = 3 No.

Thin section examination, samples C, D, F, G & H = 5 No.

A description of Each sample is given in the following sections of the report.

4.1 Sample SR2546-S1 – Sample "B"

This sample is of a hard well compacted and well bonded mortar. Although it was possible to break pieces under persistent finger pressure the mortar broke with an audible "snap", confirming that it was a hard but brittle mortar. The mortar contained a few small lime inclusions, which were rounded and had the appearance of balled hydrate.

Plates No. 1 & 2: The above left plate shows the sample as received, with a few intact pieces along with a quantity of fines. The right plate shows a freshly fractured surface through the thickness of the mortar. The piece in the image had been treated with a phenolphthalein indicator solution to check for carbonation. The mortar was found to be fully carbonated.

Water droplet tests indicated that the mortar had a moderately well-connected pore structure with droplets supported for a short period prior to being absorbed and diffused throughout the matrix.

The colour[1] of the mortar, was found to be 7.5 YR 8/1 "White".

4.2 Sample SR2546-S2 – Sample "C"

This sample consisted of pieces of Ashlar mortar with the appearance of a traditional Ashlar mortar, made from putty, with limestone dust and linseed oil. The mortar was hard and brittle and when snapped and heated emitted a faint odour of linseed oil.

[1] The colour of the mortar samples was determined against the Munsell Soil Colour Charts

Plate No. 3 & 4: The left plate shows the sample as received, with the right plate showing a freshly fractured surface through the thickness of an intact piece.

The mortar was found on testing to be fully carbonated and did not absorb water droplets placed onto its outer or a freshly fractured surface.

The mortar colour was found to be 2.5Y 8/3 "Pale Yellow".

4.3 Sample SR2546-S3 – Sample "D"

Plates No. 5 & 6: The plates above show the condition of the mortar in sample "D". The left plate is the sample, as received, with the right plate showing a fractured surface through one of the larger pieces. Note the abundance of sub-angular to rounded lime inclusions.

The mortar was found on breaking to be hard and was difficult to break under persistent finger pressure, requiring a hammer tap to disrupt. The mortar was compact and on testing was found to be fully carbonated. On placing water droplets on the surface, they were supported for a short period prior to the droplets being slowly absorbed.

The mortar was found to be 10YR 6/2 "Light Brownish Grey" in colour, on a fractured surface.

4.4 Sample SR2546-S4 – Sample "E"

This sample consisted of a piece of stone, limestone, possibly Dolostone, along with a small quantity of mortar fragments and fines also included in the sample.

Plates No. 7 & 8: The left plate shows a view of the sample as received. The right plate shows a close-up of a freshly fractured surface through the stone fragment.

Spot tests indicated that the stone was a limestone, and possibly Dolomitic, with a very fine texture and a well-connected pore structure.

The colour of the stone was found to be 10YR 8/2 "Very Pale Orange".

4.5 Sample SR2546-S5 – Sample "F"

This mortar was variable in hardness, with some pieces soft and others moderately hard. They were all well compacted and all contained large sub-angular to sub-round lime inclusions, which were up to 4.5mm in size.

Plates No. 9 & 10: The left plate shows the sample as received with the right showing a fractured surface trough an intact piece of the mortar, where lime inclusions can be seen.

The mortar is fully carbonated and was indicated to have a well-connected porosity from the water test, with water droplets being rapidly absorbed and diffused throughout.

The colour of the mortar was assessed at 10YR 7/2 "Light Grey".

4.6 Sample SR2546-S6 – Sample "G"

The mortar in sample "G" was an Ashlar mortar, but unlike the other ashlar samples it contained a proportion of natural sand, which was slightly coarser than the normal 'silver sand' (Fine processed Quartz sand) normally associated with this form of putty mortar. There were also lime putty inclusion apparent, which would indicate that the mortar had not been well prepared prior to use.

Plates No. 11 & 12: The left plate shows the sample as received, with the right plate showing a magnified view of one intact piece, where the dense fabric can be seen along with line inclusions, these are arrowed in plate.

The mortar was fully carbonated and displayed a degree of water repellence. On heating a faint odour of linseed oil was apparent.

The colour of the mortar was found to be 10YR 8/2 "Very Pale Brown".

4.7 Sample SR2546-S7 – Sample "H"

Plates No. 13 & 14: The left plate shows the sample as received, with the right plate showing a close-up of the largest fragment, which contains an abundance of lime inclusions.

The mortar is hard to very hard and resisted breaking under firm finger pressure, requiring a hammer impact to disrupt. Lime inclusions measured up to 5.5mm in size and the mortar was fully carbonated.

Water droplet tests confirmed a connected pore structure with the slow absorption of droplets and their diffusion throughout the mortar piece tested.

The colour of the mortar was assessed at 10YR 8/1 “White”.

4.8 Sample SR2546-S8 – Sample “i”

This sample was from another Ashlar mortar, similar to sample “G”, with it being a putty mortar containing a low proportion of quartz aggregate, which were coarser than commonly found, along with putty lime inclusions, up to 3.5mm in size. A low content of linseed oil was also indicated to be present.

Plates No. 15 & 16: View of the sample as received, left plate, and a magnified view of a fractured surface through the thickness of the pointing mortar.

The sample contained some small stone samples, along with the mortar, the stone being similar in appearance to sample “E” and the mortar being an ashlar mortar.

On testing the mortar, it was found to be fully carbonated and water droplets were supported with only minimal absorption observed.

The mortar colour was 10YR 8/2 “Very Pale Brown”.

4.9 Sample SR2546-S8 – Sample “J”

This sample consisted of several pieces of a hard pointing mortar. The longer pieces could only be broken under persistent firm finger pressure whilst the short lengths required a hammer impact to break.

The mortar was hard and well bound and had the appearance of a cementitious mortar.

Plates No. 17 & 18: The left plate shows the intact ribbons of pointing mortar from which the sample was composed. The right plate shows a fresh fracture through the thickness of one of the intact pieces, displaying a well compacted mortar.

The mortar was fully compacted and appeared to contain a patchy air entrainment, and on testing with water droplets it was noted to be porous, with the water droplets slowly absorbed and diffused throughout the thickness of the sample.

The colour of the mortar was assessed at 2.5Y 7/1 "Light Grey".

5.0 Microscopic Examination

Petrographic thin sections were prepared from slices sawn from a selection of pieces of mortar, with the slices aligned to permit the maximum area possible, of the mortar, on the slides.

The samples were prepared for thin sectioning by initially drying them to a constant weight at 60°C prior to impregnating the dried sub-samples with an epoxy resin containing a fluorescent blue dye. One side the impregnated slices were polished and mounted onto glass slides (50mm x 75mm). The mounted samples were then ground and polished to 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, an assessment of microporosity and a clear indication of any crack patterns present, in plane polarised light.

The samples were also mounted into a 'Swift automatic stage' which permitted the determination of the volumetric mix composition, by modal analysis.

The observations from the examination of the samples are presented below:

5.1 Sample SR2546-S2 – Sample "C" - Ashlar Pointing

This sample was composed of small pieces of an Ashlar pointing.

Plate No. 19:

Thin section prepared from a piece of mortar for microscopic examination.

Aggregate

The aggregate is composed of fine crushed limestone flour and is locally observed as balled inclusions of the flour, and as discrete lenses of chalky fines. The dust appears to be from a Dolomitic limestone, with an abundance of rhombs observed within the fines.

A low proportion of fine quartz grains were also observed, but these were rare and, therefore, may be present as contaminants, included in the mix, rather than be indicative of a quartz aggregate addition. The quartz grains are typically finer than 0.04mm and sub-rounded to sub-angular in shape.

Binder

The binder has the appearance of a lime that has been used in the form of a putty, with a relatively uniform paste, albeit there are locally patches of high microporosity where the paste from the putty has not been fully mixed with the dust.

The binder is fully carbonated, with small globular voids that are surrounded by discoloured paste, perhaps an indication of the presence of oil in the mortar as mixed.

There is no evidence of alteration products within the body of the mortar, albeit there is evidence of partial dissolution and the redeposition of calcite on the outer edge. Within this there are fine acicular crystals that would infer that reaction products, from a reaction of the binder and acid rain or other environmental sulphates, had occurred, though this is minimal in the sample examined.

Voids and microcracks

Voids are very rare and are present as small discrete elongated air voids (up to 0.34mm) and small bubbles (typically <0.06mm) entrapped within the paste.

Cracks are rare, and where present are randomly distributed throughout; they range in width from <0.02mm to 0.0.08mm and have the appearance of drying shrinkage cracks.

Cracks connected to the outer surfaces show evidence of binder depletion at their margins confirming water penetration along the crack pathways, and locally the cracks are lined and infilled with redeposited calcite (Calcium carbonate) indicating water migration into the crack paths under service condition.

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

Sample Ref:	SR2546-S2 – "C"
Constituents	**%**
Aggregate	
Quartz	5.6
Rock flour (Whiting)	22.3
Total Aggregate	**27.9**
Binder (Lime)	63.1
Clinker	0
Lime inclusions	5.3
Secondary products/Calcite sulphate, etc	0.3
Total Binder	**72.1**
Total Constituents	**100.0**
Voids	0.6
Crack	0.8
Cracks/Voids	**1.4**
Mix Composition, by volume	
Binder: Aggregate Ratio	
Lime : Whiting : Quartz	**1.0 : 0.3: 0.1**

Table No. 1: Modal Analysis carried out on thin section prepared from sample S2.

Photomicrographs:

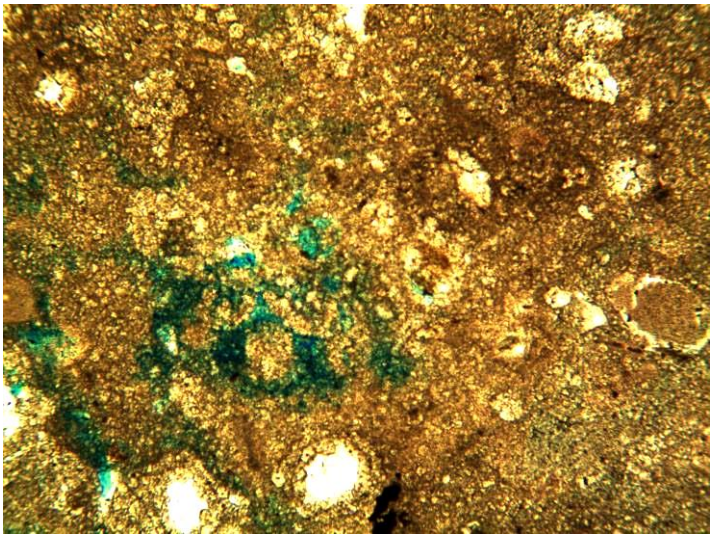

Plate No. 20:

A view in plane polarised light (ppl), of a typical area of the mortar where the chalk components are moderately well distributed throughout the paste, over most of the area in view. Rock flour inclusion (balled and unmixed flour) can be seen in the lower left and upper right side of the paste.
The patchy colour change in the paste around the lower left lime inclusion is considered to be due to the oil in the mortar. There is little microporosity observed in this area of the plate.

Porosity is highlighted by the blue dyed resin. Field of view 1.2mm.

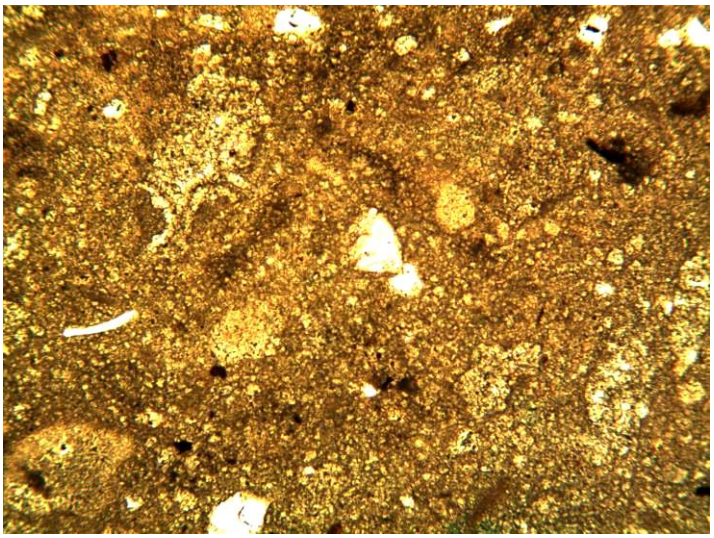

Plate No. 21:

Another view in ppl, of an area of paste containing an abundance of unmixed limestone four and fine quartz aggregates (white in the image) distributed throughout.

The darker areas are small voids and areas of paste rich in oil, which is not uncommon in this type of mortar.

Porosity is highlighted by the blue dyed resin. Field of view 1.2mm.

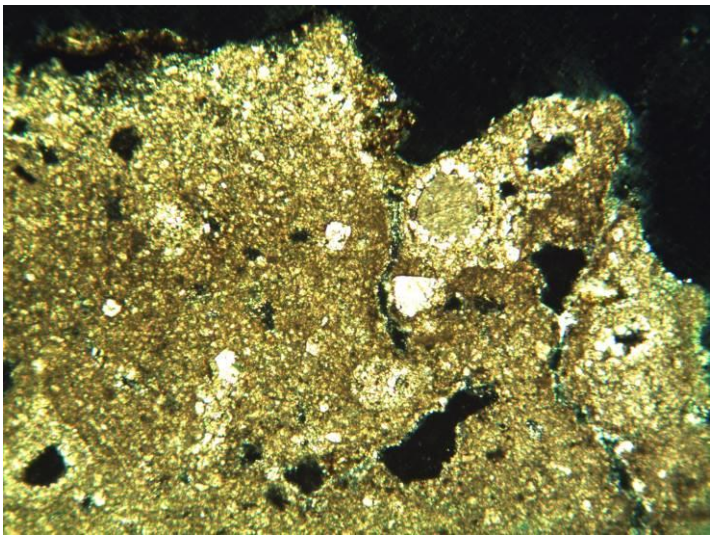

Plate No. 22:

A view in cross polarised light (xpl) of an area at the outer surface of the mortar, where redeposition of lime has occurred along the upper and right edges in the plate. With the voids and crack paths (lower right) coated with redeposited calcite and locally fringed with sulphate minerals, white in image.
Quartz grains are also apparent, along with pockets of rock flour.
Voids and the blue dyed resin appear dark in cross polarised light.
Field of view 1.2mm.

5.2 Sample SR2546-S3 – Sample "D" – Pointing to Original Stonework

Plate No. 23:

Thin section prepared from a piece of mortar for microscopic examination and composition by modal analysis.

This sample was well compacted and hard, resisting breakage under firm finger pressure. The mortar was noted to contain an abundance of lime inclusions, which from their appearance, would infer that the mortar had been made using a quicklime or putty lime.

Aggregate

The aggregates in the mortar sample contains a mixed suite of rock types, including quartz, minor quartzite, flint, igneous rock fragments and limestone, with a proportion of fine brick fragments, and opaque materials (coal/charcoal), along with a small quantity of ash clinker.

The aggregates are sub-angular to sub-round in shape, with a low proportion of elongated aggregate particles also present. In addition, there were fine angular to irregular shaped brick fragments, and coal. The shape and texture of the aggregates suggesting a river or river terrace source for the sand.

The aggregates range in size from 0.02mm to 1.6mm (coarse silt to very coarse sand) in the section examined. As there were no clay or fine silt materials observed, it is again inferred that a water transported material was used as the aggregate.

The aggregates are mostly well bound within the paste. Although peripheral microcracks are locally apparent, they do not appear to be continuous across the section and as such appear to have formed as early plastic shrinkage features.

Binder

The binder is typical of a lime mortar, with an abundance of lime inclusions apparent within the section. A significant number of the inclusions appear to have formed from non-hydraulic quicklime, however there is a small number that contain hydraulic components, with some of the incompletely slaked inclusions retaining a faint imprint of the rock fabric, which appears to be Dolomitic in origin.

Dispersed throughout the paste are fine brick fragments, some of which display alteration features and are surrounded by reaction rims. This may infer that albeit the lime was both hydraulic to a degree, and Dolomitic, a proportion of brick fines had been added to the mortar, most likely as a pozzolan.

The paste is fully carbonated and unhydrated lime inclusions were not observed. The lime inclusions apparent, include both sub-round and sub-angular inclusions, with a proportion having the appearance of having formed from quicklime, with others fully hydrating and appearing as putty inclusions.

The more angular inclusions, however, are typical of particles of incompletely slaked quicklime, at the time of placing. Lime inclusions range in size from 0.3mm to 3.6mm in the section examined, with most of these showing well defined margins with little evidence of diffusion into the surrounding paste, but without displaying perimeter cracking. Whereas, most of the rounded fully slaked quicklime inclusions (putty) display partial diffusion into the surrounding paste.

From the examination of this sample it is indicated that the binder was probably mixed with the aggregate, this in the form of a quicklime, but it was well slaked prior to placing.

Voids and microcracks

Voids are abundant as both entrapped air voids, which are typically round to sub-round in shape and range from 0.08mm to 2.4mm in size, but mostly <1.2mm. Those formed from leaching and binder depletion, are commonly irregular, sub-angular or elongated/ in shape, whereas, entrapped air voids are sub-rounded to elongate in shape. Many of the voids are locally lined by fine fringes of calcite, with uncommon and very localised clusters of gypsum crystals.

Cracks are rare and occur as localised features peripheral to, and linking; larger aggregate particles and incompletely slaked quicklime particles. The cracks are fine, ranging in width from <0.03mm to 0.16mm, and are typical of drying shrinkage features.

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

Sample Ref:	**SR2546-S3 – "D"**	
Constituents	%	
Aggregate	**Inclusions as binder**	**Inclusions as Aggregate**
Quartz & Flint	35.8	35.8
Lithic Fragments	3.4	3.4
Opaque	0.6	0.6
Ash/Brick	11.1	11.1
Lime inclusions & Clinker	-	10.1
Total Aggregate	**50.9**	**61.0**
Binder (Lime)	35.8	35.8
Clinker	3.2	3.2
Lime inclusions	10.1	0
Secondary products/Calcite	0	0
Reaction Products/Gypsum	0	0
Total Binder	**49.1**	**39.0**
Total Constituents	**100.0**	**100.0**
Cracks/Voids	**11.8**	**11.8**
	Total	**Effective**
Binder: Aggregate Ratio	**1.0 : 1.04**	**1.0 : 1.6**

Table No. 2: Modal Analysis carried out on thin section prepared from sample S3.

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 of the mix, relating to its performance as a mortar. Whereas, the total lime content reflects the mix at the time the mortar was made and placed, including the inclusions (both fully slaked and unslaked) as part of the added lime binder.

Photomicrographs:

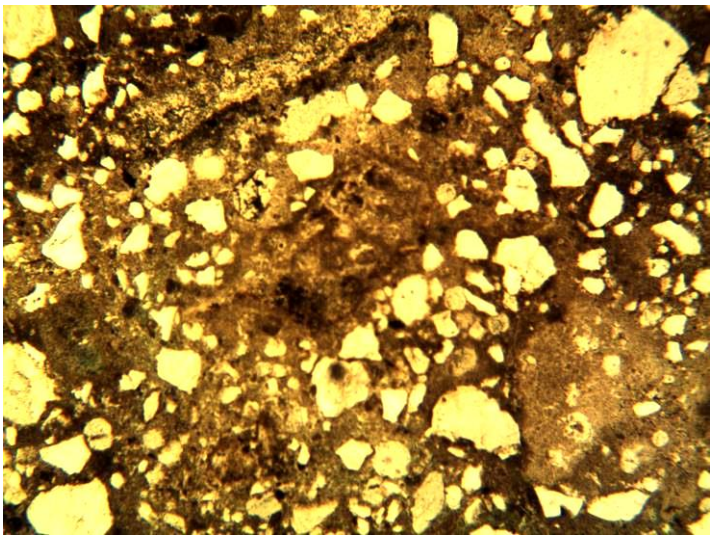

Plate No. 24:

A view in plane polarised light (ppl) showing a typical area of paste within the mortar, with a fully slaked angular lime inclusion, in the centre of the plate, which contains Belite clusters, indicating a hydraulic component in the binder. The aggregates are dominated by quartz in this view However, on the lower right, there is a sub-angular lime inclusion which appears to contain fine quartz grains, but these have not been altered during calcining. The paste within the inclusion has slaked to putty but this has not diffused into the surrounding matrix.

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

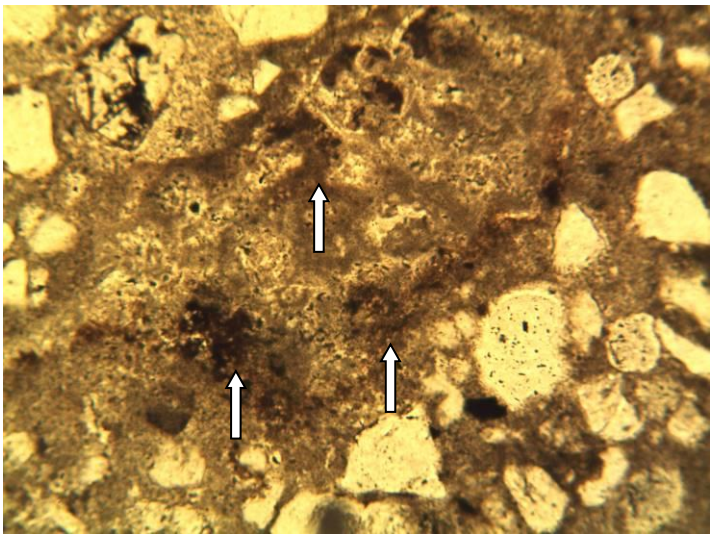

Plate No. 25:

A magnified view of the angular inclusion in the centre of the area in Plate No. 24 above. This view is again in ppl.

Belite clusters can be seen clearly within the inclusion, arrowed in plate, and also within the surrounding paste, confirming that the mortar was made from a hydraulic binder. In addition to this there was both fine brick and ash material observed within the paste, some of which appears to have altered and may have acted as a pozzolan in the mortar.

Porosity and voids are highlighted by the blue dyed resin. Field of view 1.2mm.

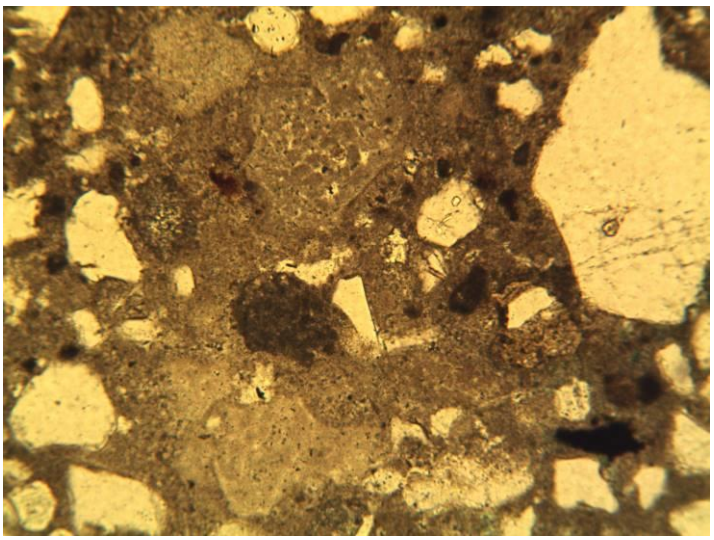

Plate No. 26:

Another view in ppl, of an area containing an abundance of small lime inclusions that appear to be from a non-hydraulic lime, with the inclusions having the appearance of a fully slaked non-hydraulic quicklime. Albeit that in the upper centre, is incompletely burnt it retains some features from the original rock fabric. Ash fragments and fine fragments of coal/charcoal are also present in this view.

Porosity and voids are highlighted by the blue dyed resin. Field of view 1.2mm.

5.3 Sample SR2546-S5 – Sample "F" – Pointing to Sand Lime Brick

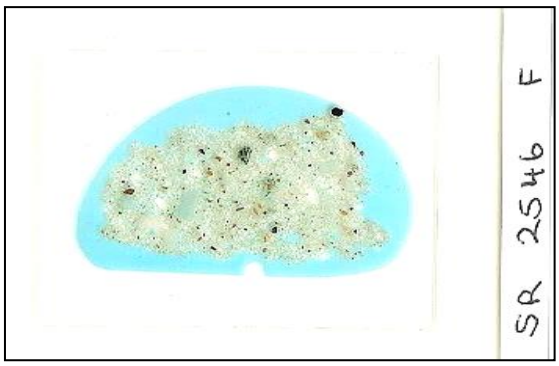

Plate No. 27:

Thin section prepared from a piece of mortar from sample S5 for microscopic examination and composition by modal analysis.

This sample was well compacted but varied in hardness, with the piece selected for examination from a compact but moderately soft fragment of mortar. The mortar was again noted to contain an abundance of lime inclusions, which could be formed from either quicklime or putty lime.

Aggregate

The aggregates in the mortar sample is again comprised of mixed suite of rock types, but in this sample, it is dominated by quartz, with minor quartzite, flint with limestone fragments and some shell fragments. There is also a proportion of ash and opaque materials (coal/charcoal), present, although their abundance is much less in this sample.

The aggregates range in size from 0.06mm to 1.4mm (very fine to coarse sand) in the section examined. The aggregates are relatively clean with no evidence of clay or silt in the sample, which along with the shell would infer a river, estuary or river terrace source.

The aggregates are mostly well bound within the paste and peripheral microcracks are rare, and where present have the appearance of early plastic shrinkage features.

Binder

The binder is again typical of a lime mortar, with a high abundance of lime inclusions within the section. The inclusions have mostly formed from non-hydraulic quicklime, with some incompletely burnt fragments retaining an imprint of the original rock. This indicated that the limestone burnt was an Oolitic Limestone, with no evidence of the Dolomitic limestone present in sample “D”, possibly suggesting that this mortar was from a different period of construction.

The paste is fully carbonated and unhydrated lime inclusions were not observed. The lime inclusions apparent, include both sub-round and sub-angular inclusions, and a number have the appearance of the of having been formed from incompletely slaked quicklime, at the time of mixing and placing.

The presence of a small proportion of ash , which appears to contain components that have reacted with the lime paste, showing features consistent with aluminates commonly associated with hydraulic limes. The ash may have been added as a pozzolan, or accidentally as a contaminant along with the quicklime.

Lime inclusions range in size from 0.5mm to 4.2mm in the section examined, and these display sharp boundaries with little evidence of diffusion into the surrounding paste, inferring that they have performed as aggregate in the mix rather than binder.

From the examination of this sample it is indicated that the binder was incorporated into the mix in the form of a quicklime, but mostly it appears to have been well slaked prior to placing.

Voids and microcracks

Voids are abundant and include entrapped air voids and those formed by leaching of lime from inclusions. The former are typically sub-round to irregular in shape and range from 0.1mm up to 3.2mm in size, but mostly <1.2mm. The larger voids formed by the depletion of lime, are typically sub-angular in shape and up to 2.8mm in size. Some voids, close to contact surfaces, were noted to be fringed with redeposited calcite and locally this is interspersed with fine clusters of sulphate minerals, possibly gypsum.

Cracks are very rare and occur as plastic and early drying shrinkage features. They are fine, and range in width from <0.02mm to 0.10mm. Cracks are free of infilling.

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

Sample Ref:	SR2546-S5 – "F"	
Constituents	%	
Aggregate	**Inclusions as binder**	**Inclusions as Aggregate**
Quartz & Flint	38.2	38.2
Lithic Fragments	1.8	1.8
Opaque	2.4	2.4
Ash/Brick	1.2	1.2
Lime inclusions & Clinker	-	10.9
Total Aggregate	**43.6**	**54.5**
Binder (Lime)	44.9	44.9
Clinker	0	0
Lime inclusions	10.9	0
Secondary products/Calcite	0.5	0.5
Reaction Products/Gypsum	0.1	0.1
Total Binder	**56.4**	**45.5**
Total Constituents	**100.0**	**100.0**
Cracks/Voids	**16.5**	**16.5**
	Total	**Effective**
Binder: Aggregate Ratio	**1.0 : 0.8**	**1.0 : 1.2**

Table No. 3: Modal Analysis carried out on thin section prepared from sample S5.

Photomicrographs:

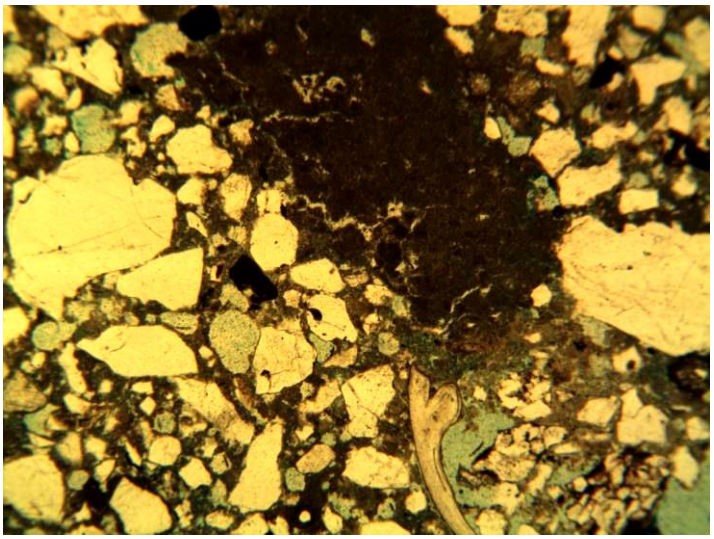

Plate No. 28:

A view in plane polarised light (ppl) showing a typical area of the mortar.

This image is dominated by quartz sand grains encapsulated in the paste, with a large incompletely slaked, and overburnt, lime inclusion, upper centre in plate. A shell fragment can be seen in the lower right.

The paste has the appearance of a non-hydraulic mortar, although with fine ash and coal/charcoal fragments apparent it may perform as feebly hydraulic.

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

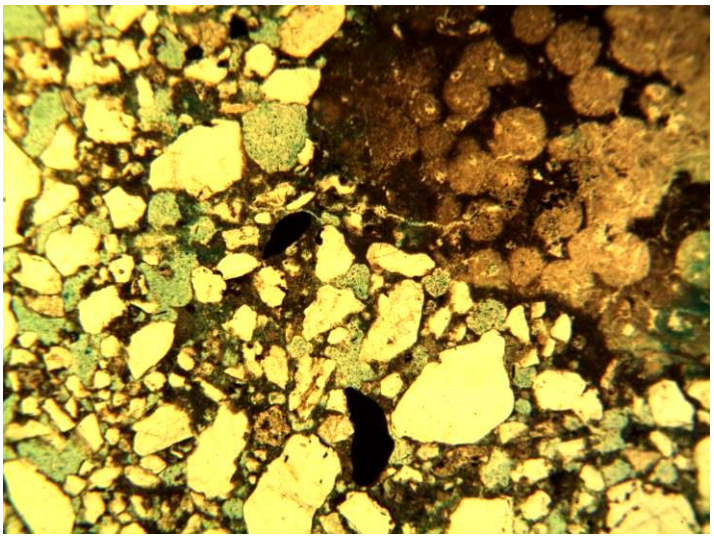

Plate No. 29:

Another view of the mortar again in ppl.

The image shows a partially burnt Oolitic limestone fragment in the upper right abutting a highly porous area of mortar. Although the mortar is dominated by sub-angular quartz grains, encapsulated in a non-hydraulic lime binder, there are patches of the paste that appear to contain ash fragments, which show reaction rims, and this may therefore impart a measure of Hydraulicity (pozzolanic) property to the mortar.

Porosity and voids are highlighted by the blue dved resin. Field of view 2.4mm.

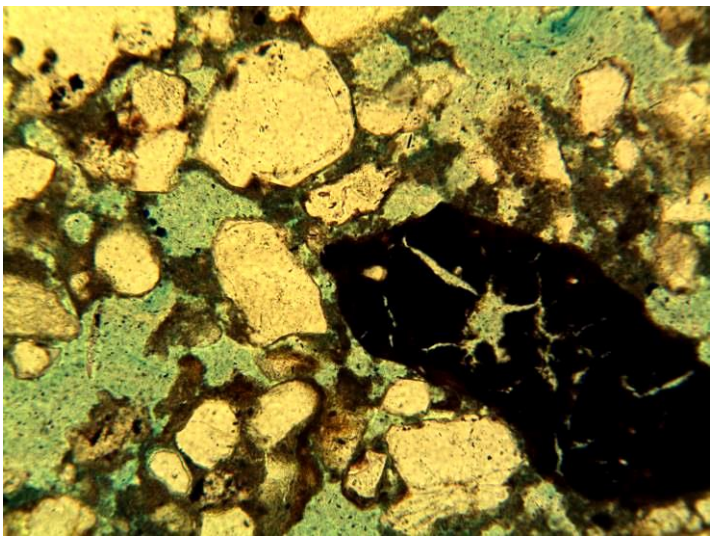

Plate No. 30:

Another magnified view in ppl, of a voided area containing an abundance of small interconnected voids, with quartz aggregates and a dense lime paste.
A partially burnt coal fragment can be seen in the lower right, which may infer that the lime was burnt with coal as the fuel, and that this was present as a contaminant with the quicklime.
A number of the voids retain a fine fringe of redeposited calcite, with, locally, pockets of sulphate minerals.
Porosity and voids are highlighted by the blue dyed resin. Field of view 1.2mm.

5.4 Sample SR2546-S6 – Sample "G" - Possibly Earliest Ashlar Mortar

This sample was composed of small pieces of an Ashlar pointing.

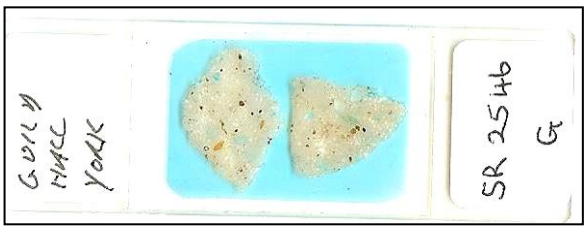

Plate No. 31:

Thin section prepared from representative pieces of mortar for microscopic examination and modal analysis.

Aggregate

The aggregate is predominantly composed of quartz, quartzite, flint and crushed limestone. However, unlike traditional Ashlar mortar the limestone is coarser grained and not as a fine limestone flour (Whiting). The limestone is a Dolomitic limestone, with an abundance of rhombs observed within the fragments and distributed throughout the paste as fines.

The presence of coarse sand grains confirms the observations from the hand specimen, that this Ashlar mortar does not follow the common practice of using a very fine silver sand. The grains are fine to coarse, 0.1mm to 3.4mm in size, but typically finer than 0.6mm, and these are angular to irregular in shape and have the appearance of a processed sand. The crushed limestone is Dolomitic and ranges in size from 2.2mm to <0.02mm.

Binder

The binder has the appearance of a lime used in the form of a putty, albeit one that contains a proportion of incompletely slaked fragments, some of which show fabric that infers a high calcium limestone as the source. The paste is dense and relatively uniform.

The binder is fully carbonated and is locally leached, at the edges of mortar fragments, and along the wider external margin connected crack paths. The edges and crack paths are liberally coated with redeposited calcite. The paste and the lime inclusions have the appearance of a high calcium air lime, with no hydraulic components observed.

Voids and microcracks

Voids are present as discrete elongated air voids up to 0.1.8mm in size and there is evidence of partial dissolution with the redeposition of calcite on the outer edge and lining near edge voids. Fine acicular crystals, typical of sulphate reaction products, were observed within the calcite coatings, and it is considered that these are the result of a reaction between the binder and acid rain, or other atmospheric pollutants. Cracks are present, and these are randomly distributed throughout; they range in width from <0.02mm to 0.1mm and have the appearance of drying shrinkage cracks.

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

Sample Ref:	**SR2546-S6 – "G"**
Constituents	**%**
Aggregate	
Quartz	13.7
Lithic Fragments	2.8
Opaque	3.2
Crushed limestone	16.5
Total Aggregate	**36.2**
Binder (Lime)	49.0
Lime inclusions	13.7
Secondary products/Calcite sulphate, etc	1.1
Total Binder	**63.8**
Total Constituents	**100.0**
Voids & Cracks	5.0
Cracks/Voids	**5.0**
Mix Composition, by volume	
Binder: Aggregate Ratio	
Lime : L/stone : Sand	**1.0 : 0.25: 0.3**

Table No. 4: Modal Analysis carried out on thin section prepared from sample S6.

Photomicrographs:

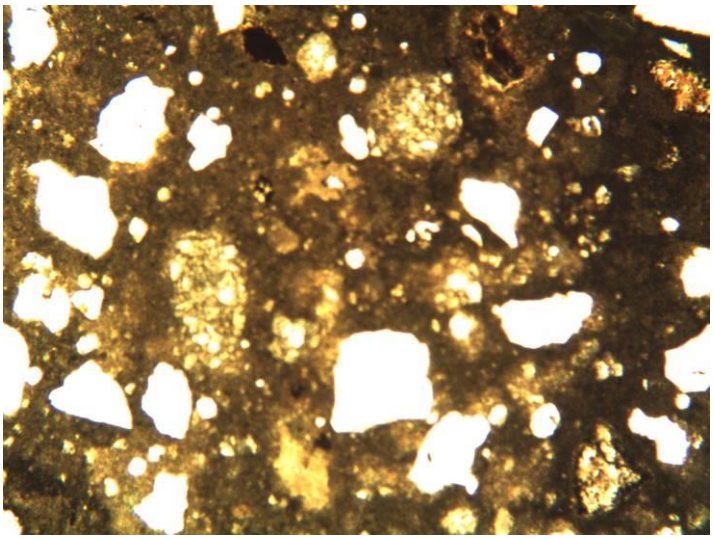

Plate No. 32:

A view in plane polarised light (ppl), of a typical area of the mortar. The sand grains in this view are dominated by angular quartz grains (white in image). The patchy appearance of the paste is due to the presence of crushed limestone fragments and fines are dolomitic in form. The paste is dense and there is little microporosity observed in this area of the plate. The darker zone down the right side of the plate is considered to be an oil rich area of paste. Porosity is highlighted by the blue dyed resin. Field of view 2.4mm.

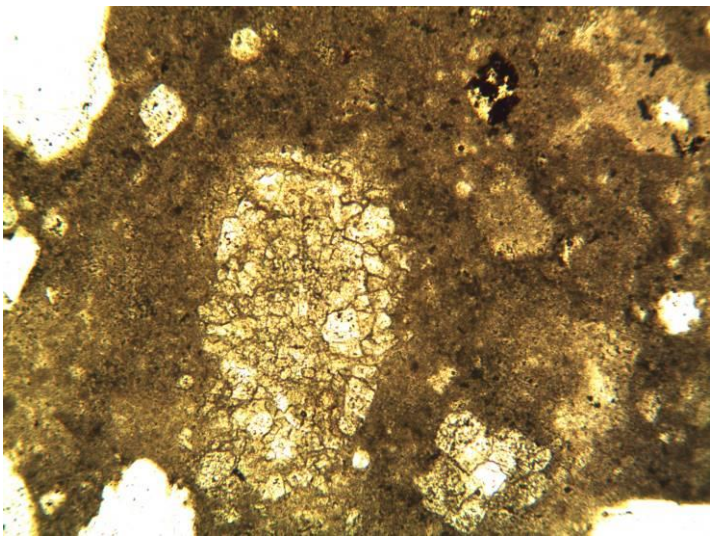

Plate No. 33:

Another view in ppl, of an area of paste surrounding a coarse limestone fragment, left of centre, with smaller fragments and fines (dust) also present distributed throughout the paste.
The paste is dense and there are small patches having a globular appearance, which is typical of that where oil is finely dispersed through the paste. The lighter patches are limestone dust rich zones.

Porosity is highlighted by the blue dyed resin. Field of view 1.2mm.

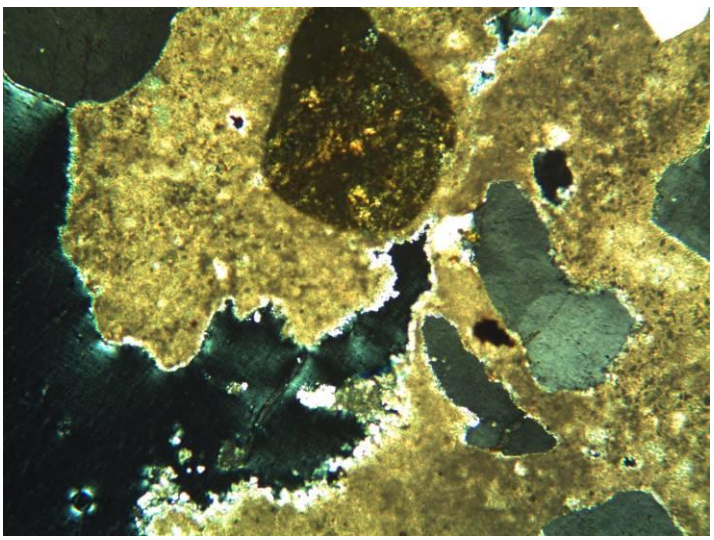

Plate No. 34:

A view in cross polarised light (xpl) of an area at the outer edge of the mortar. Here fringes of reprecipitated lime, white in image, which is now carbonated, can clearly be seen. This is apparent around the edge of the mortar and along edge connected cracks and appears as linings to voids. Locally needle shaped sulphate minerals are also apparent.
Quartz grains (grey in plate) are also apparent, along with a flint particle.
Voids and the blue dyed resin appear dark in cross polarised light.
Field of view 1.2mm.

5.5 Sample SR2546-S7 – Sample "H" – Brick Masonry Mortar

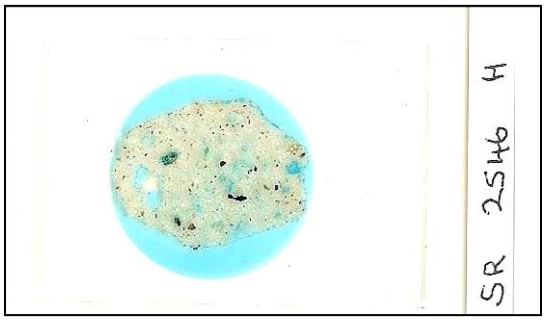

Plate No. 35:

The plate opposite shows the thin section prepared for microscopic examination and composition by modal analysis.

This sample was from a well compacted and hard mortar. The mortar was noted to contain an abundance of large angular lime inclusions, with one of the larger intact fragments selected for examination.

Aggregate

The aggregates in this mortar sample is similar to that in sample "F" and is again comprised of mixed suite of rock types, with quartz, minor quartzite, flint and limestone fragments with some shell fragments also observed. The limestone appears to be dolomitic. A low proportion of ash and opaque materials (coal/charcoal) were also noted, and it is considered that these are likely to be present as contaminants, rather than added as a pozzolan.

The aggregates range in size from 0.1mm to 1.8mm (very fine to very coarse sand) in the section examined. As in sample "F" the aggregates are relatively clean and it is possible that they were obtained from the same, or a similar, source.

Aggregates are fully encapsulated and well bound within the paste and peripheral microcracks are rare.

Binder

The binder is lime and there is an abundance of lime inclusions within the section. Most of the inclusions have formed from non-hydraulic quicklime, however, there are a few inclusions that show the presence of hydraulic components within their fabric, typical of Belite, and Belite was also detected sparsely distributed throughout the paste, although the abundance is low, which would suggest a very feebly hydraulic lime.

Several incompletely burnt and over burnt fragments are present, and as in sample "F" the residual rock imprint suggests the lime was made from an Oolitic limestone.

The paste is fully carbonated and unhydrated lime inclusions were not observed. The lime inclusions apparent, are mostly sub-round to sub-angular in shape, and appear to have formed from the incompletely slaking of quicklime, and incomplete mixing of the putty formed. An abundance of shrinkage cracks, and other features associated with putty mortars were observed the mortar appears to have been very well slaked.

Lime inclusions range in size from 0.4mm to 2.2mm in the section examined, and these displays both sharp boundaries, associated with incompletely burnt and overburnt lime, with others displaying rounded and diffused boundaries, typical of putty inclusions.

Voids and microcracks

The void content is low and where observed they appear to have formed from entrapped air voids, which are sub-round to irregular in shape, ranging from 0.1mm to 0.3mm in size.

Cracks are abundant in this sample and they are typical of that normally associated with putty lime mortars and have formed as plastic and early drying shrinkage of the paste. They are fine, and range in width from <0.01mm to 0.3mm, they meander through the matrix, are discontinuous and connect aggregate and lime inclusions. Many of the cracks have closed due the reprecipitation of calcite, but no gypsum was observed in the section examined.

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

Sample Ref:	**SR2546-S7 – "H"**	
Constituents	%	
Aggregate	**Inclusions as binder**	**Inclusions as Aggregate**
Quartz & Flint	31.2	31.2
Lithic Fragments	2.7	2.7
Shell	2.1	2.1
Opaque	2.8	2.8
Ash	0.5	0.5
Lime inclusions & Clinker	-	12.4
Total Aggregate	**39.3**	**51.7**
Binder (Lime)	47.8	47.8
Clinker	0	0
Lime inclusions	12.4	0
Secondary products/Calcite	0.5	0.5
Reaction Products/Gypsum	0	0
Total Binder	**60.7**	**48.3**
Total Constituents	**100.0**	**100.0**
Cracks/Voids	**4.5**	**4.5**
	Total	**Effective**
Binder: Aggregate Ratio	**1.0 : 0.65**	**1.0 : 1.1**

Table No. 5: Modal Analysis carried out on thin section prepared from sample S7.

Photomicrographs:

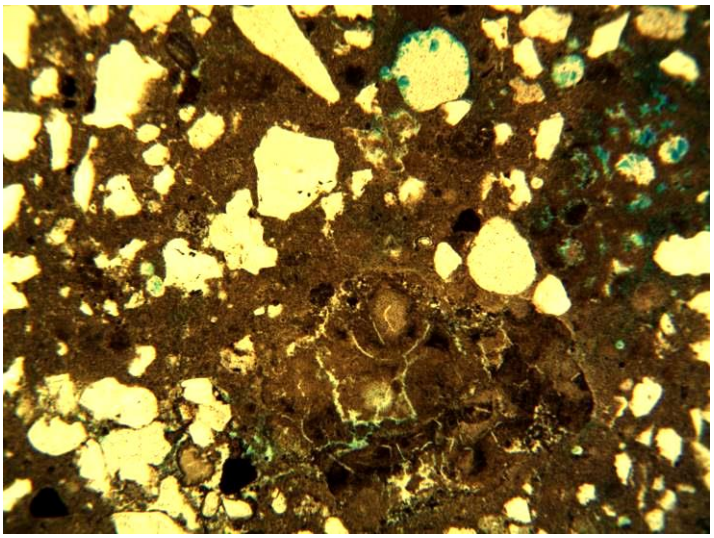

Plate No. 36:

A view in plane polarised light (ppl) showing a typical area of the mortar.

An over burnt inclusion is seen in the lower centre of the plate, with a partially hydrated, but fully calcined Oolitic limestone inclusion seen in the upper right.

The paste has the general appearance of a non-hydraulic mortar, although sparse Belite clusters were observed along with fine ash and the binder may have performed as feebly hydraulic lime.

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

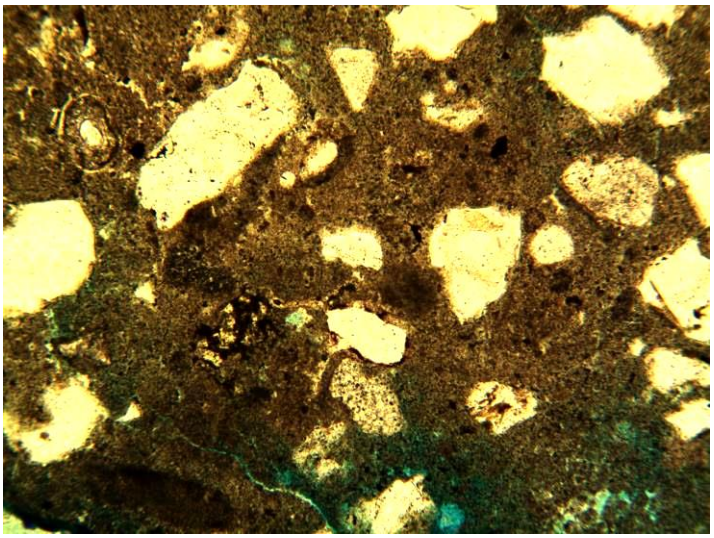

Plate No. 37:

Another view of the mortar ppl.

This image is of an area where an abundance of fine randomly orientated cracks is apparent, some of which have healed. These are a combination of plastic and early drying shrinkage cracks, typical of those normally observed in putty mortars, but here they are finer.

Finely disseminated hydraulic components are apparent distributed throughout the paste. Aggregates are mostly of quartz.

Porosity and voids are highlighted by the blue dyed resin. Field of view 1.2mm.

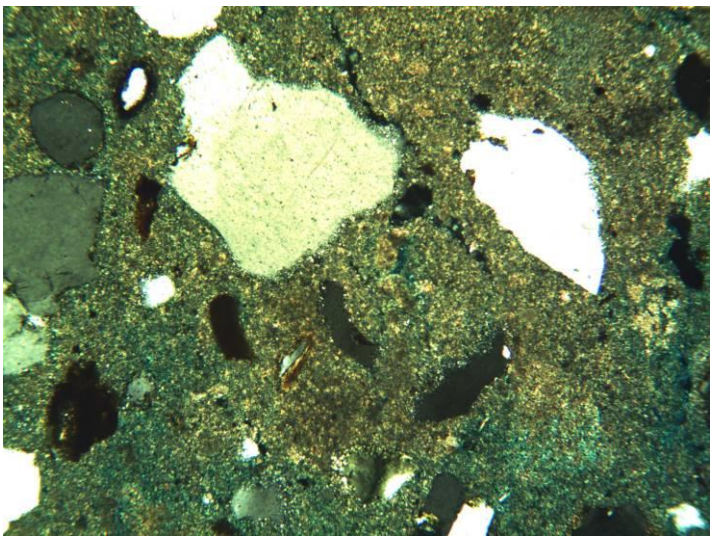

Plate No. 38:

A view in cross polarised light (xpl). This shows that the binder is fully carbonated, this having a speckled granular appearance.
Voids and crack paths are picked out by the incapsulating resin (black in plate).

The aggregates in view are dominated by quartz grains (white and grey in plate).

Voids, opaque materials and the blue dyed resin all appear dark in cross polarised light. Field of view 1.2mm.

6.0 Analysis by X-Ray Diffraction

To assist in the identification of the composition of the binder in the mortar samples, a binder rich sub-sample was prepared from a typical example of each variant received and these submitted to analysis by X-ray Powder Diffraction (XRD).

To achieve this, a representative sub-sample of the mortar was obtained, from each sample, with these ground in an agate mortar and pestle, taking care to minimise crushing of the aggregate. A concentrated binder rich sub-sample was obtained by sieving the sample over a 63µm sieve. The powder collected being back-packed into proprietary sample holders for presentation in the X-Ray Diffractometer.

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. With the digital output from the diffractometer analysed in 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 result obtained are shown in the following appended figures at the end of this report, in the form of a labelled X-ray diffractograms:

Figure No. 5 – SR2546-S1 – "B" Binder from mortar Sand Lime Brick, South East Corner,
Figure No. **6** – SR2546-S2 - "C" Binder from Ashlar Pointing to North Gable, East Building,
Figure No. 7 – SR2546-S3 – "D" Binder from Pointing to Original Guild Hall Wall,
Figure No. 8 – SR2546-S4 – "E" Stone Masonry sample, to check for Dolomite,
Figure No. 9 – SR2546-S5 – "F" Binder ex pointing, Sand Lime Brick on Lean-to in Lane,
Figure No. 10 – SR2546-S6 – "G" Binder ex Earliest Ashlar Masonry, North Gable on Hall,
Figure No. 11 – SR2546-S7 – "H" Binder from Pointing, Brick Masonry, 3 storey Building,
Figure No. **12** – DR2546-S8 – "i" Binder from Ashlar Repair Mortar, W Elevation of Hall,
Figure No. 13 – SR2546-S9 – "J" Binder in Pointing to Clay Brick, West Wall of West Wing.

The most abundant mineral components identified are indicated in the appended diffractogram using the following short-hand notation:

cc = Calcite ($CaCO_3$) Calcium Carbonate, carbonated lime component, also the dominant component of any limestone in the aggregate,
ar = Aragonite ($CaCO_3$) another crystalline form of Calcium Carbonate, commonly associated with shell, but also in leached and redeposited carbonated lime,
va = Vaterite ($CaCO_3$) a further form of ($CaCO_3$) Calcium Carbonate, carbonated lime, also a component of some limestones,
al = Alite (Ca_3SiO_5) *tri*-calcium Silicate, Clinker component in Portland cement and eminently hydraulic lime binders,
be = Belite (Ca_2SiO_4) *di*-calcium Silicate, Clinker component in Portland cement and Hydraulic lime binders,
hy = Hydrocalumite ($Ca_2Al(OH)_6Cl2H_2O$) Calcium Aluminium Chloride Hydroxide Hydrate, hydration product of aluminous lime and white Portland cement binders,
br = Brownmillerite ($Ca_2(Al,Fe)_2O_5$) Calcium Aluminium Iron Oxide, clinker component in some Portland cements and in aluminous hydraulic limes,
hd = Hydromagnesite ($Mg_5(CO_3)_4(OH)_24H_2O$), Magnesium Carbonate Hydroxide Hydrate, weathering product of Dolomitic lime binder, and Dolomitic limestone,
c4 = ($Ca_4Al_2O_6CO_311H_2O$) Calcium Aluminium Oxide Carbonate Hydrate, carbonated hydration product of a hydraulic lime clinker,
gy = Gypsum ($CaSO_42H_2O$) Calcium Sulphate Hydrate, most likely present as reaction product between lime in binder and environmental sulphates,
mo = Monosulphate ($Ca_4Al_2O_6(SO_4)14H_2O$) Calcium Aluminium Sulphate Hydrate, hydraulic clinker and sulphate reaction product,
do = Dolomite ($Ca,Mg(CO_3)_2$) Calcium Magnesium Carbonate, dominant component of Dolomitic limestone and in Dolomitic lime binder,
he = Hematite (Fe_2O_3) Iron Oxide, from the brick or aggregate component,
fs = Feldspar, mostly of the plagioclase group, Albite, with minor Anorthite, common rock forming minerals, components in aggregate,
di = Dickite, Clay mineral of the Kaolinite group of minerals., aggregate component, or present as soiling,
qz = Quartz (SiO_2) dominant component of the sand grains in the aggregates used in the mortar sample.

From the analysis it is indicated that there are several variants of binder present in the samples received. With the Ashlar pointing in the earliest original mortar (Sample "G") indicated to have been produced using a Dolomitic lime binder, whereas, the later Ashlar binders, as represented by sample "C" and "i" are indicated to have been made using a high calcium lime.

The masonry mortar to the older sand lime brick, used in the masonry of the Lean-to, contains a non to feebly hydraulic lime, with the lime being an aluminous Calcium lime, and is, therefore, possibly from later work. As the early mortar work appears to have been carried out using Dolomitic limes.

All other mortars submitted are mostly feebly to moderately Hydraulic lime, with mortars from "B" and "H" being moderately hydraulic with the exception of sample "J", from the Clay Brick masonry, which is indicated to be an eminently hydraulic lime made from a Dolomitic limestone binder.

The binders in the mortars are summarised below:

Ashlar Mortars:

Sample "C" was made from a Dolomitic lime putty.

Samples "G" and "i" were both made using high calcium non-hydraulic lime putties.

Masonry Mortar:

Sample "B" is an eminently hydraulic siliceous lime.

Sample "D" this is a feebly hydraulic Calcium lime with some Dolomitic lime, and ash.

Sample "F" feebly hydraulic, aluminous high calcium lime, along with a proportion of ash.

Sample "H" is from a non to feebly hydraulic lime, with minor silicates present, with ash.

Sample "J" is a Moderately Hydraulic Dolomitic lime, the mix does not contain ash.

Most of the mortars have been affected to some degree by atmospheric sulphates, however, this has resulted in the formation of gypsum and not the potentially disruptive Ettringite, which may have been expected had the mortars contained Portland cement.

The XRD on the stone sample confirmed that this was a Magnesian/Dolomitic Limestone.

7.0 Mix Composition Analysis by Acid Digestion

A total of four samples were prepared for mix composition by acid digestion, these were samples "D", "F", "G" and "i". The results obtained are reproduced below:

Two of the samples were of Ashlar type mortars, one based on non-hydraulic High Calcium binder and the other a Dolomitic lime, with both used in the form of a putty, with the mortar containing a fine filler and a proportion of sand.

The other two mortars submitted for analysis were masonry mortars, with again one incorporating a Feebly Hydraulic Calcium lime binder and one with a Feebly Hydraulic Dolomitic lime binder.

Three samples were submitted to analysis by the methods of BS4551, with the results analysed using data pertaining to modern Hydraulic limes.

The results of the analysis carried out are presented in the following sections:

7.1 Mix Composition Analysis by Acid Digestion

Masonry Pointing and Jointing Mortar from External Masonry:

Sample Ref.	**SR2546-S3 "D"**	**SR2546-S5 "F"**
Weight Proportions		
Binder content (Quicklime)	1.0	1.0
Fine Aggregate (Sand)	2.2	4.9
Volume Proportions		
Binder content (Quicklime)	1.0 (1.0)[1]	1.0 (1.0)[1]
Fine Aggregate (Sand)	0.6 (0.6)	1.4 (0.8)

[1] Values in brackets were determined by modal analysis, see section 5.0 of this report.

The aggregate recovered from the samples, following acid digestion, were found to be as follows, and represented as aggregate filled histograms in the appended Figures No. 1 & 2.

Sample Ref:	**SR2546-S3 "D"**		**SR2546-S5 "F"**	
BS Sieve Size (mm)	**% Retained**	**% Passing**	**% Retained**	**% Passing**
4.00	0	100	0	100
2.00	0	100	0.5	99.5
1.00	2.5	97.5	1.8	97.7
0.500	9.8	87.7	11.8	85.9
0.250	28.0	59.7	38.1	47.8
0.125	26.5	33.2	31.9	15.9
0.063	25.4	7.8	11.5	4.4
Passing 63µm	7.8		4.4	

Ashlar Mortars:

Sample Ref.	**SR2546-S6 "G"**	**SR2546-S8 "i"**
Weight Proportions		
Binder content (Putty lime + Whitening/Dust)	1.0	1.0
Fine Quartz (Silver sand)	0.8	0.3
Volume Proportions		
Binder content (Putty lime + Whitening/Dust)	1.0 (1.0)[1]	1.0
Limestone fines - from Modal Analysis	(0.25)	
Fine Aggregate (sand + some dolomitic limestone)	0.6 (0.3)	0.27

[1] Values in brackets were determined by modal analysis, which permitted separation of sand and dolomitic fines.

The aggregate recovered from the samples, following acid digestion, was found to be dominated by quartz grains, with that in sample "G" being coarser than that in sample "i", see gradings below and in the appended Figures No. 3 & 4.

Sample Ref:	**SR2546-S6 "G"**		**SR2546-S8 "i"**	
BS Sieve Size (mm)	**% Retained**	**% Passing**	**% Retained**	**% Passing**
4.00	0	100	0	100
2.00	5.2	94.8	0	100
1.00	8.2	86.6	5.2	94.8
0.500	30.1	56.5	25.0	69.8
0.250	28.7	27.8	39.0	30.8
0.125	14.8	13.0	18.1	12.7
0.063	6.2	6.8	5.8	6.9
Passing 63µm	6.8		6.9	

7.2 Mix Composition by chemical Analysis

As there was insufficient sample for acid digestion, sub-samples from samples "B", "H" & "J" were submitted to analysis by the methods of BS 4551:2005 + A1:2010 + A2: 2013. The results obtained are reproduced below:

Sample Ref.	**SR2546-S1 – "B"**	**SR2546-S7 – "H"**	**SR2546-S9 – "J"**
Chemical Analysis		**% by mass**	
Insoluble Residue	42.74	54.87	56.24
Soluble Silica (SiO2)	1.23	1.57	5.61
Calcium Oxide (CaO)	21.98	16.13	17.94
Loss on Ignition	25.92	20.84	13.79
Approximate volume Proportions, calculated on the basis of standard assumptions.			
Hydraulic Lime	1.0	1.0 (1.0)[1]	1.0
Sand	0.7	0.5 (0.7)	1.2

Comments

The analytical results presented above were evaluated by the method of BS 4551: 2005 + A1: 2010, on the basis of the following assumptions:

a. The Hydraulic Lime content has been calculated on the basis that an Eminently Hydraulic binder contained 11.9% soluble silica and 59.4% calcium oxide and had a dry bulk density of 1.050 kg/m^3, with a Feebly Hydraulic lime containing 7.6% soluble silica, 66.2% calcium oxide and a bulk density of 845kg/m^3.
b. The sand contained 0.2% soluble silica and no soluble calcium compounds and had a dry bulk density of 1675kg/m3.
c. The mortar contained no mineral admixtures.

However, the results presented above have to be treated with caution as there was insufficient sample allow recovery of the lime for chemical analysis. Therefore, the chemical composition of modern Feebly Hydraulic (NHL2) and Eminently Hydraulic Limes (NHL5), in the form of hydrates have been used in these calculations.

8.0 Summary

The mortars used in the samples appear to have been made from a mixture of binders and this may reflect the time that the works were executed, with these including High Calcium and Dolomitic limes, ranging from non to feebly, moderately and eminently hydraulic.

There is the possibility that some of the mortars may have been mixed using non-hydraulic quicklime, with the Hydraulicity obtained by the addition of a proportion of a hydraulic lime, and/or a pozzolan, such as brick dust and/or ash, in the mortar.

Details of the mixes used in the walls, as represented by the samples, are summarized below:

Masonry Pointing and Jointing Mortar from External Masonry:

Sample Ref.	**"B"**	**"D"**	**"F"**	**"H"**	**"J"**
Volume Proportions					
Binder content (Quicklime)	1.0	1.0	1.0	1.0	1.0
Fine Aggregate (Sand)	0.7	0.6	1.4	0.5	1.2
		By modal analysis			
Binder: Agg. by vol. (Total)		1.0 : 0.8	1.0 : 0.8	1.0 : 0.7	
(Effective)		1.0 : 1.6	1.0 : 1.2	1.0 : 1.1	
Form of Binder	1	2	3	4	5

1 - Eminently Hydraulic Calcium lime used as a hydrate.
2 – Feebly Hydraulic lime as a Calcium with low proportion of Dolomitic quicklime that also contained ash (as a pozzolan?) the mix was dry slaked.
3 – Feebly Hydraulic Aluminous Calcium lime, used as quicklime – dry slaked,
4 – Feebly Hydraulic lime, similar to 3 above, but with silicates present, along with ash.
5 – Moderately hydraulic Dolomitic lime, used in the form of a hydrate.

All of the aggregates in the masonry mortars are quartz rich natural aggregates, and although there are minor differences between them, in samples "B", "D" and "J" they consist of a mixed suite of rocks, with minor limestone, and these may have been obtained from a local pit or terrace source. Whereas, those in samples "F" & "H" also contain significant limestone (Dolomitic) and shell fragments and may be from a river bank or estuary source.

Ashlar Mortars:

Sample Ref.	**"C"**	**"G"**	**"i"**
Volume Proportions			
Binder content (Putty lime = Whitening/Dust)		1.0	1.0
Fine Aggregate (sand + dolomitic limestone)		0.6	0.3
	By modal analysis		
Binder: Dust/Whitening: Agg. (Total)	1.0:0.3:0.1	1.0:0.3:0.3	
Form of binder	Dolomitic lime	High Calcium	High Calcium.
	All used in the form of a Putty		

The main difference between the aggregates used in the Ashlar mortars is that in both samples "G" and "i" they contained a high proportion of natural quartz rich aggregate, along with coarsely crushed Dolomitic limestone. Whereas, sample "C" was typical of a traditional Ashlar mortar, made from putty lime, with a very fine limestone dust (Whiting), with a low proportion of fine pure quartz (silver) sand.

9.0 Replacement Mortars

From the results of the XRD analysis, and the observations from the microscopic examination, it is indicated that the original mortars used in the Guild Hall construction were from a range of mortars containing different binders, see section 8.0 above.

Therefore, in the selection of mixes to be used in conservation/repair works it may be necessary to use more than one mix, although this will be dictated by the extent of the works to be carried out at any given time, the necessity to replace like with like, and the skill of the masons employed to undertake the work, and the time of the year that the works will be carried out.

If it is intended to replicate the original quicklime mortar, given the variation between the mixes analysed, consideration will need to be given to the impact of weathering on the samples submitted, as all were small in size, and the appropriateness of their interpretation, given the proportion of unmixed lime (inclusions) present and the use of Dolomitic limes.

Dolomitic limes are no longer available in the UK and it will be necessary to consider using currently available materials, and, therefore, their substitution with either high calcium limes, Natural Hydraulic limes, or gauged limes, particularly if Hot Mixed Lime Mortar work is considered. However, it is not recommended that Hot Mixed Mortar (HMM) work is considered for repointing work, unless the masons are well skilled, and the pointing is deep packed (>40mm) and that there is sufficient time in the contract for the masons to repeatedly go over the work to press back and close up the joints, with an extended protection and curing regime practiced, both of which will be heavily weather dependent.

Rather than attempt to work with too large a pallet of mixes it is suggested that these be kept to a minimum, with possibly one or two options for each type, Ashlar repointing and general masonry works.

Guidance can be obtained from the current British Standards or Historic England's publication "Practical Building Conservation Series"- "Mortars, Render & Plasters". With consideration of the building location, exposure and weather severity.

The mixes given below are for guidance only, and are based on the analysis of the mortars received, not the building. These will require adjusting, or modifying, on the basis of knowledge of the building, the location, the materials available and the experience and skills if the personnel undertaking the works.

Ashlar:

Either use a proprietary Ashlar mortar based on a High Calcium lime, as provided by most specialist conservation mortar producers. This comprising of lime putty, whiting and silver sand, to which a proportion of linseed oil has been added. If to be site mixed this can be replicated from 1.0 part Putty lime, 0.3 to 0.4 parts whiting, 0.2 parts silver sand (quartz <0.2mm), with a proportion of linseed oil. When adding oil to the mix, first mix the oil with a proportion of hot slaking quicklime, before adding this to the Ashlar mortar mix.

If the works are to be carried out in the cooler months or where adequate protection cannot be guaranteed, along with an appropriate curing regime, consideration should be given to using a proprietary Ashlar mix, either based on, or containing a gauging of NHL2.

Masonry Mortar:

If a HMM is to be considered a mix composed of 1.0 part quicklime to 1.0 part sand by volume, should provide a comparable mortar, particularly if a proportion of a pozzolan (3 to 4% Ash or 5 to 7% Brick Dust), by weight of the binder is added, or a gauging of an NHL (0.3 parts of quicklime by volume, after slaking) is included. This mix would need to be mixed and slaked dry, banked and screened, to remove oversize and unmixed lime, and it would best if slaked with kibbled quicklime, rather than powdered, to match the original condition.

However, the use of such a mix would entail careful preparation and use by experienced skilled craftsmen, and this would require an extended period of curing and aftercare, if it were to perform successfully.

Nonetheless, if a modified mix based on readily available materials is deemed more appropriate, an alternative mix could be prepared that is comprised (by volume) of 1.0 part CL90 quicklime: 0.5 part NHL2 (BS EN 459): to 4 to 5 parts sharp sand. However, it will be necessary to adjust this mix on site as to suit the condition of the masonry and sand available. The following selection of mixes may be considered, dependant on the supplier of the NHL and the grade used:

Otterbein NHL2 (will give the mortar a buff colour)
1.0 part CL90 Quicklime: 0.5 NHL2: 5 Parts sharp sand (2:1:10. Typical 1:2 mix)

St. Astier NHL2
1.0 part CL90 Quicklime: 0.5NHL2: 4.5 parts sharp sand (2:1:9).

Or if it is not intended to use a “Hot Lime” mix, consideration could be given to the use of an NHL sand mix, in which the following mixes may be considered:

Otterbein NHL2
1.0 Part NHL2: 2.5 parts sharp sand.

St. Astier NHL 2
1.0 Part NHL2: 2.2 parts sharp sand.

With respect to sand aggregate for use in the works, local sands should be considered, and as it is unlikely that sands close to those originally used will be available, a processed concrete sand may provide a suitable grading, although it may be necessary to gauge this with a proportion of building sand to arrive at a matching grading and a workable mortar.

Pictorial representations of the aggregates recovered from the samples submitted are appended in Figures No. 1 to 4, and these may be used to aid the matching of the considered sand source and its grading.

10.0 Quality Statement

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

The observations, analysis results reported, and comments offered, relate only to the samples of mortar received from Nigel Copsey of the Earth, Stone & Lime Company, which were identified as having been obtained from the masonry of the Guild Hall, York and received in CMC’s Stirling Laboratory on the 18th January 2018.

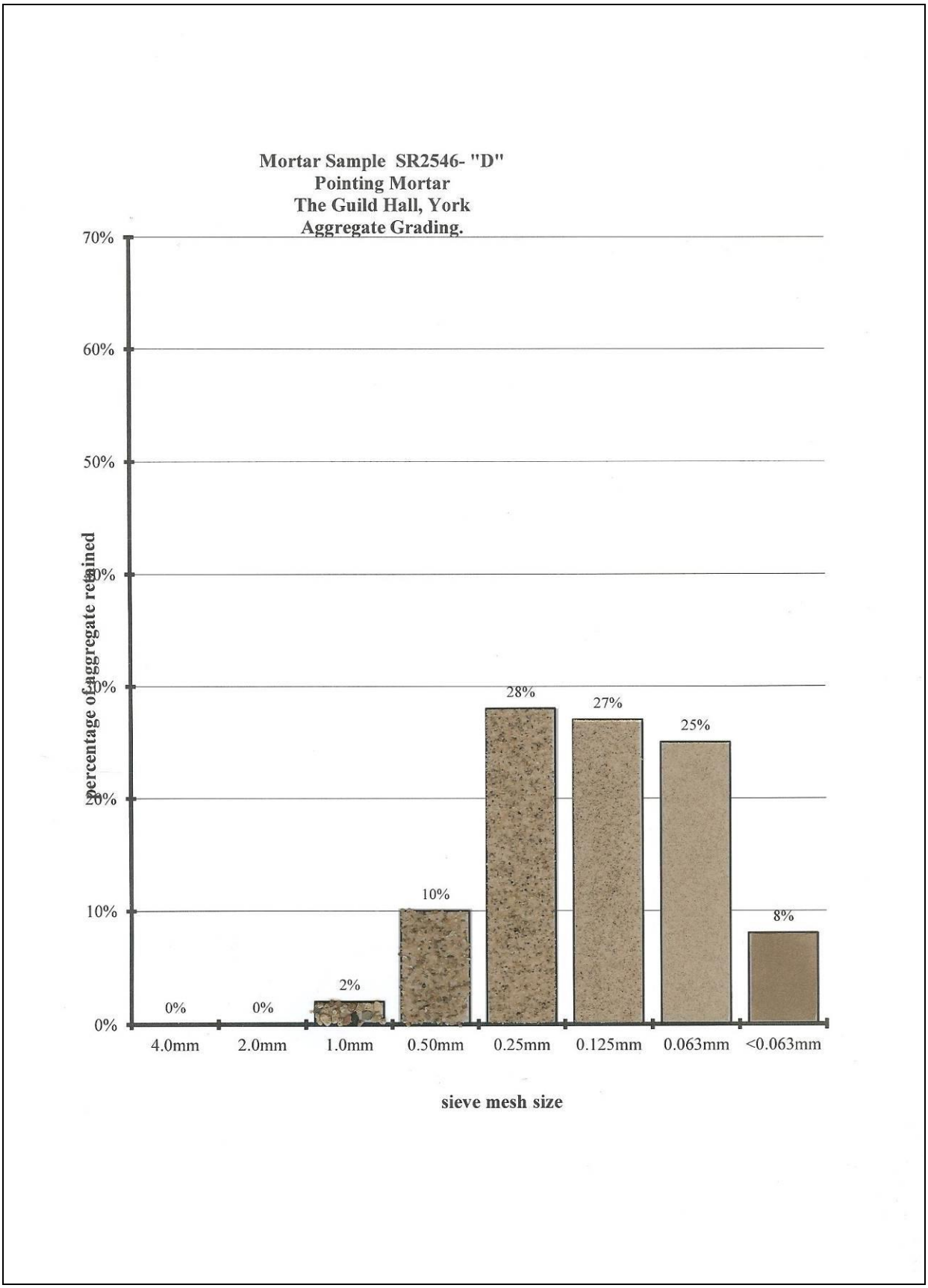

Figure No. 1: Grading of Aggregate from sample SR2546-S3 "D"

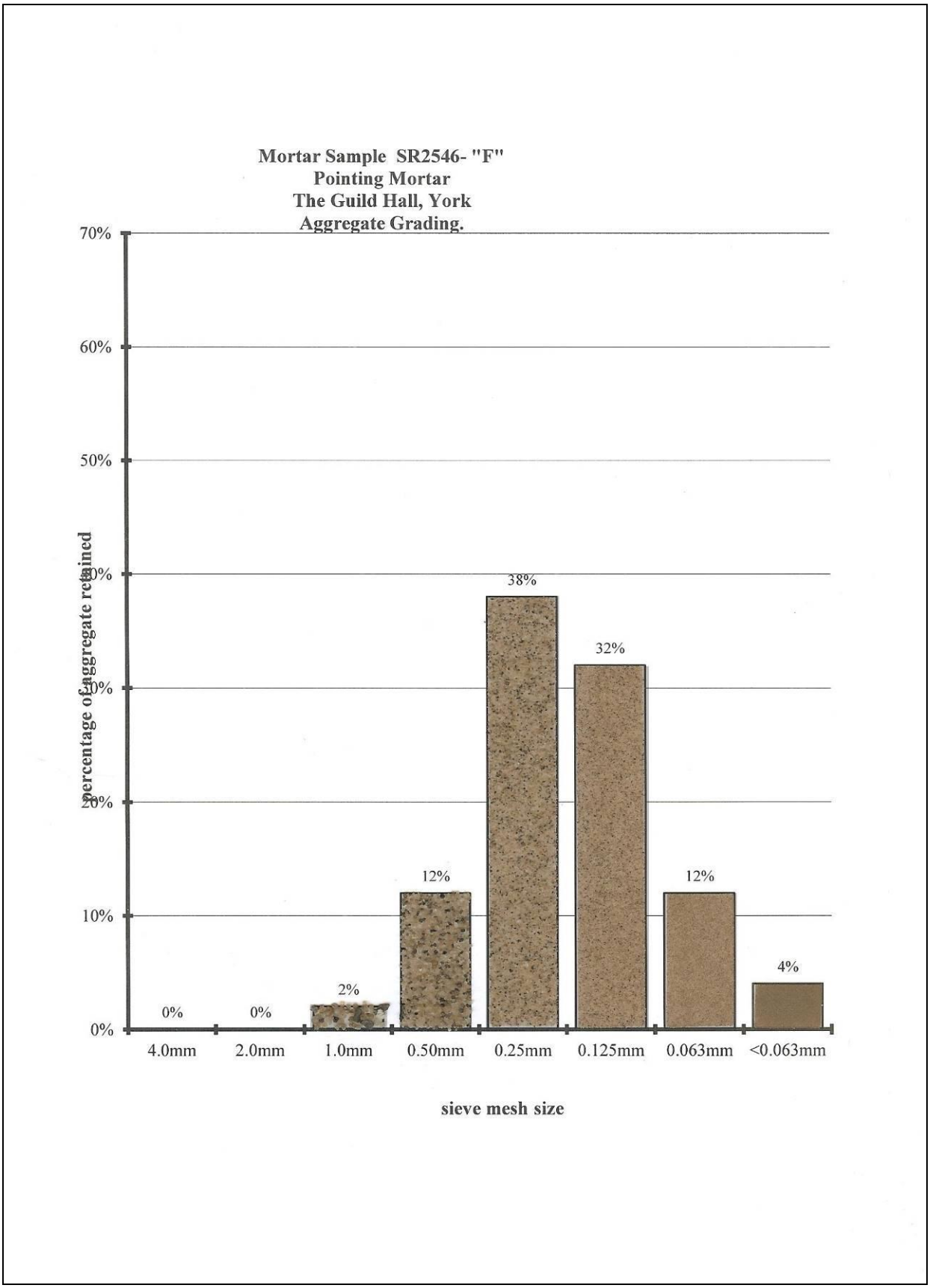

Figure No. 2: Grading of Aggregate from sample SR2546-S5 "F"

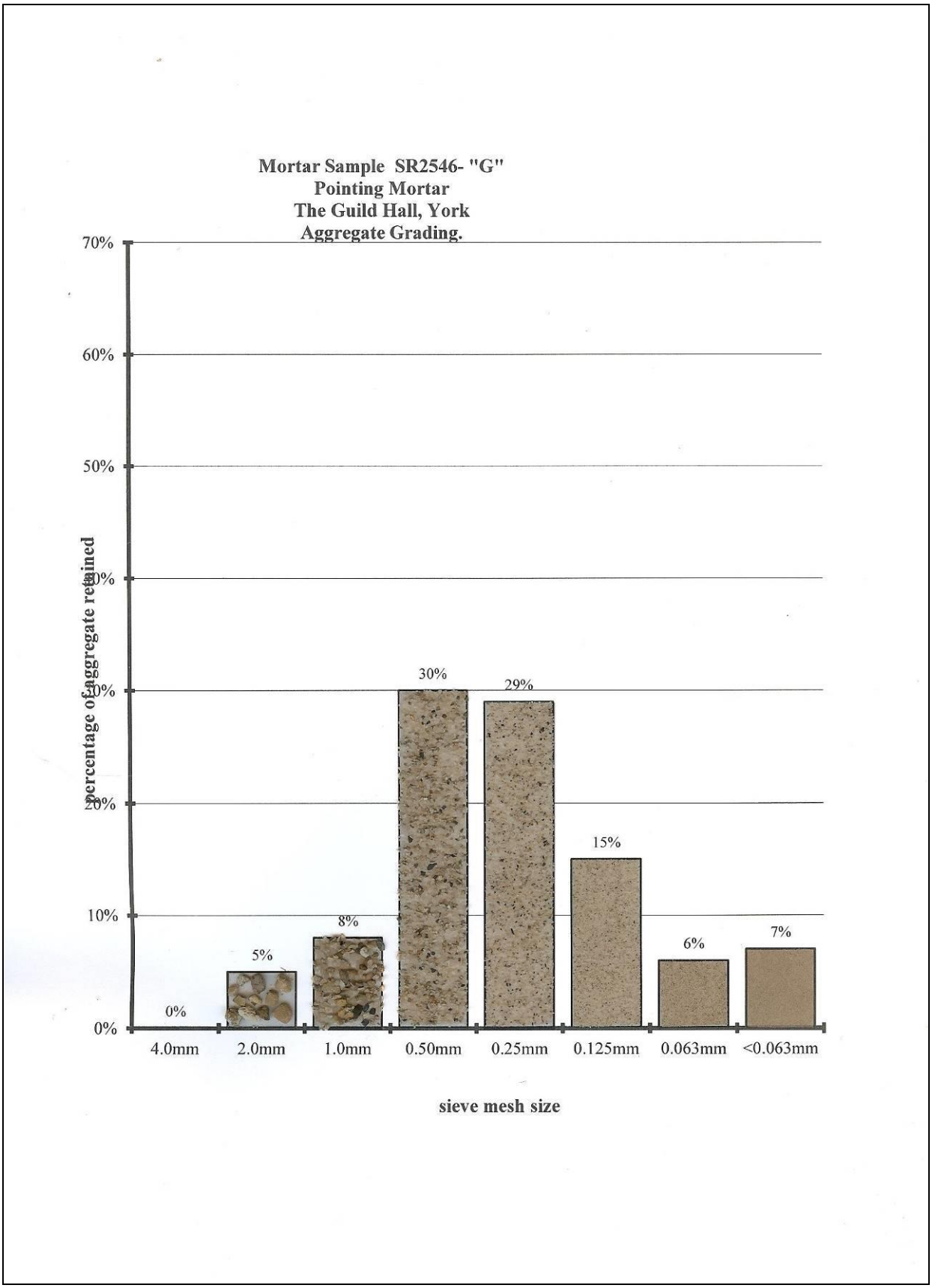

Figure No. 3: Grading of Aggregate from sample SR2546-S6 "G"

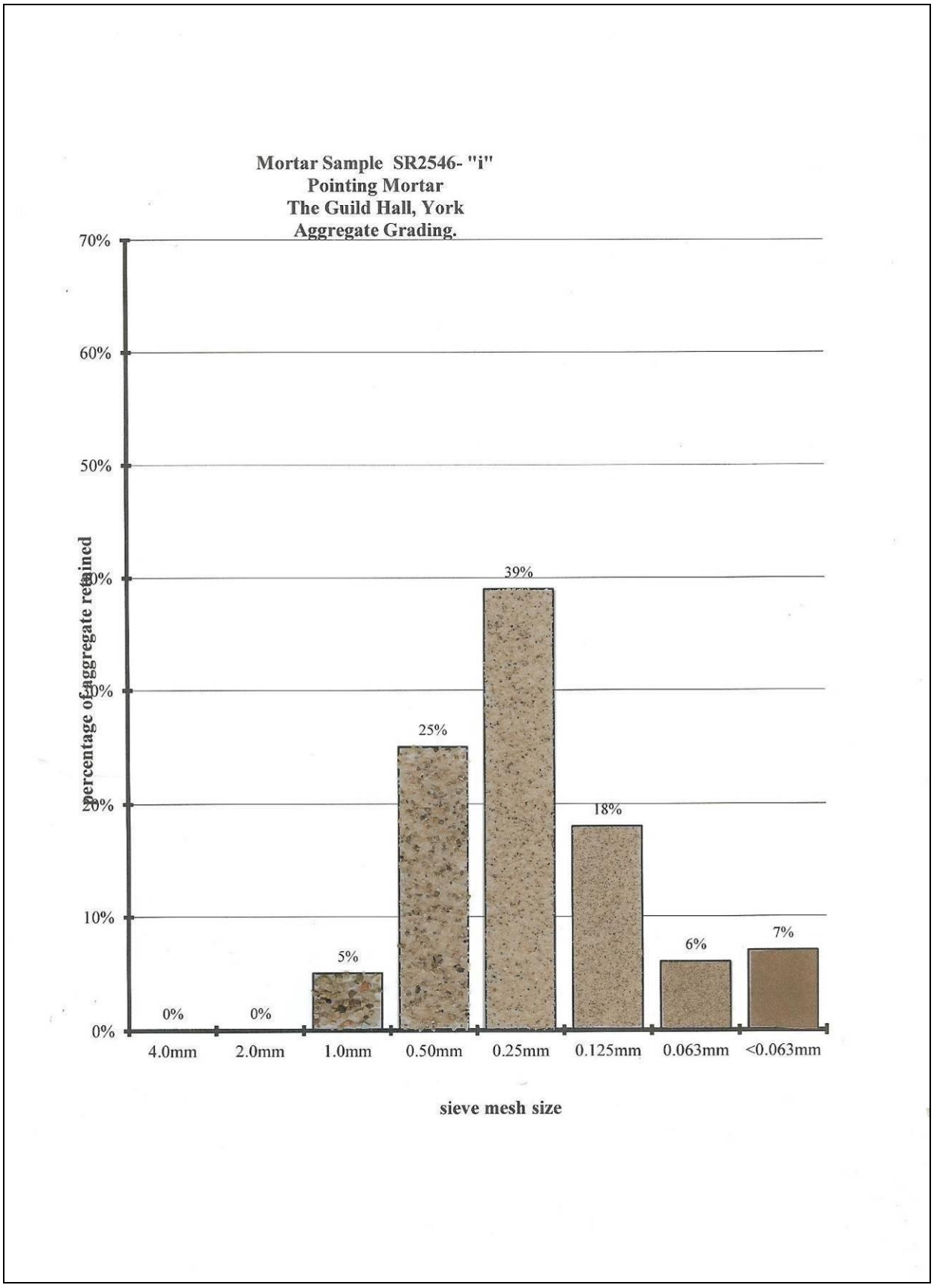

Figure No. 4: Grading of Aggregate from sample SR2546-S8 "i"

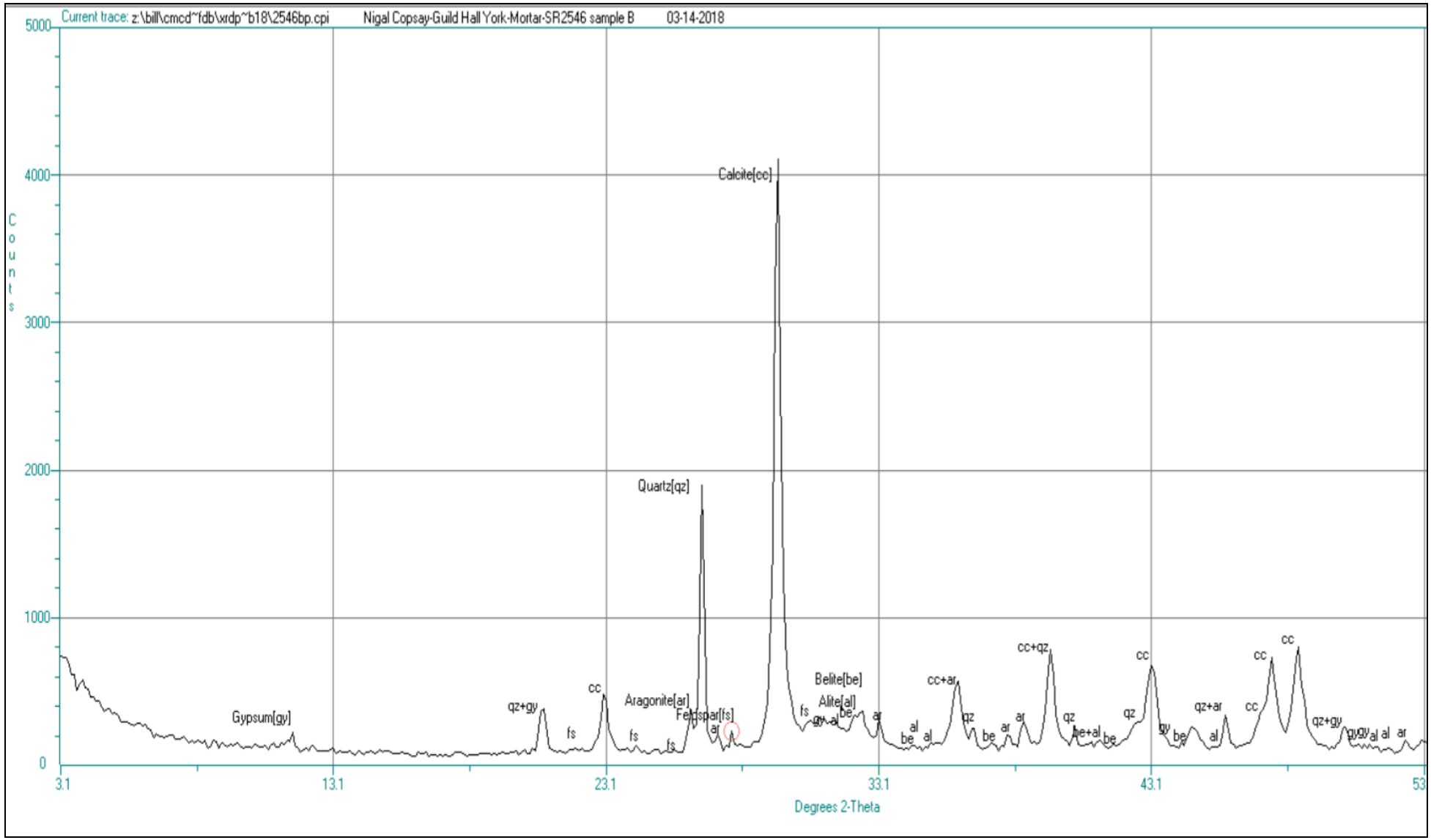

Figure No. 5 – SR2546-S1 – "B" Binder from mortar Sand Lime Brick, South East Corner.

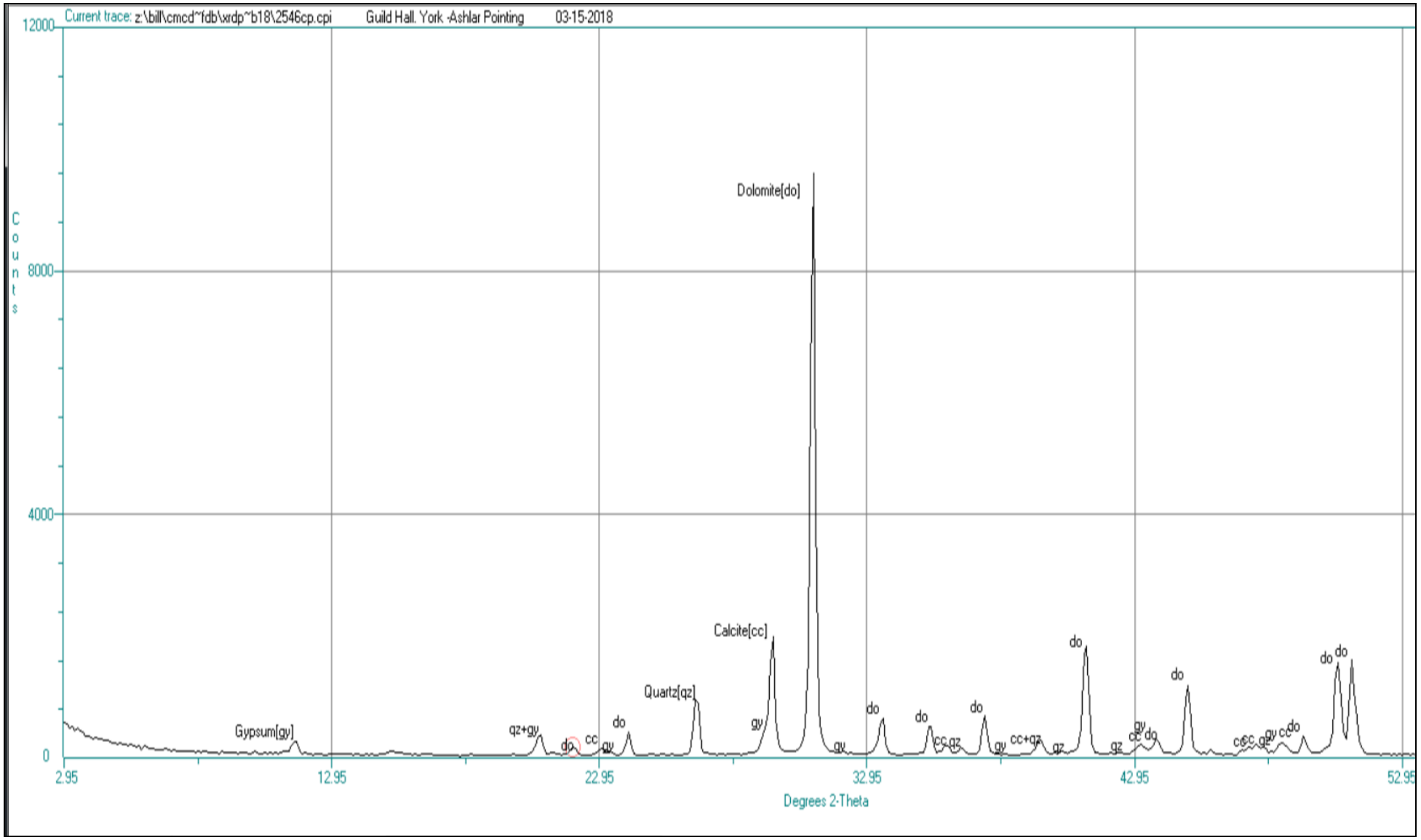

Figure No. 6 – SR2546-S2 - "C" Binder from Ashlar Pointing to North Gable, East Building.

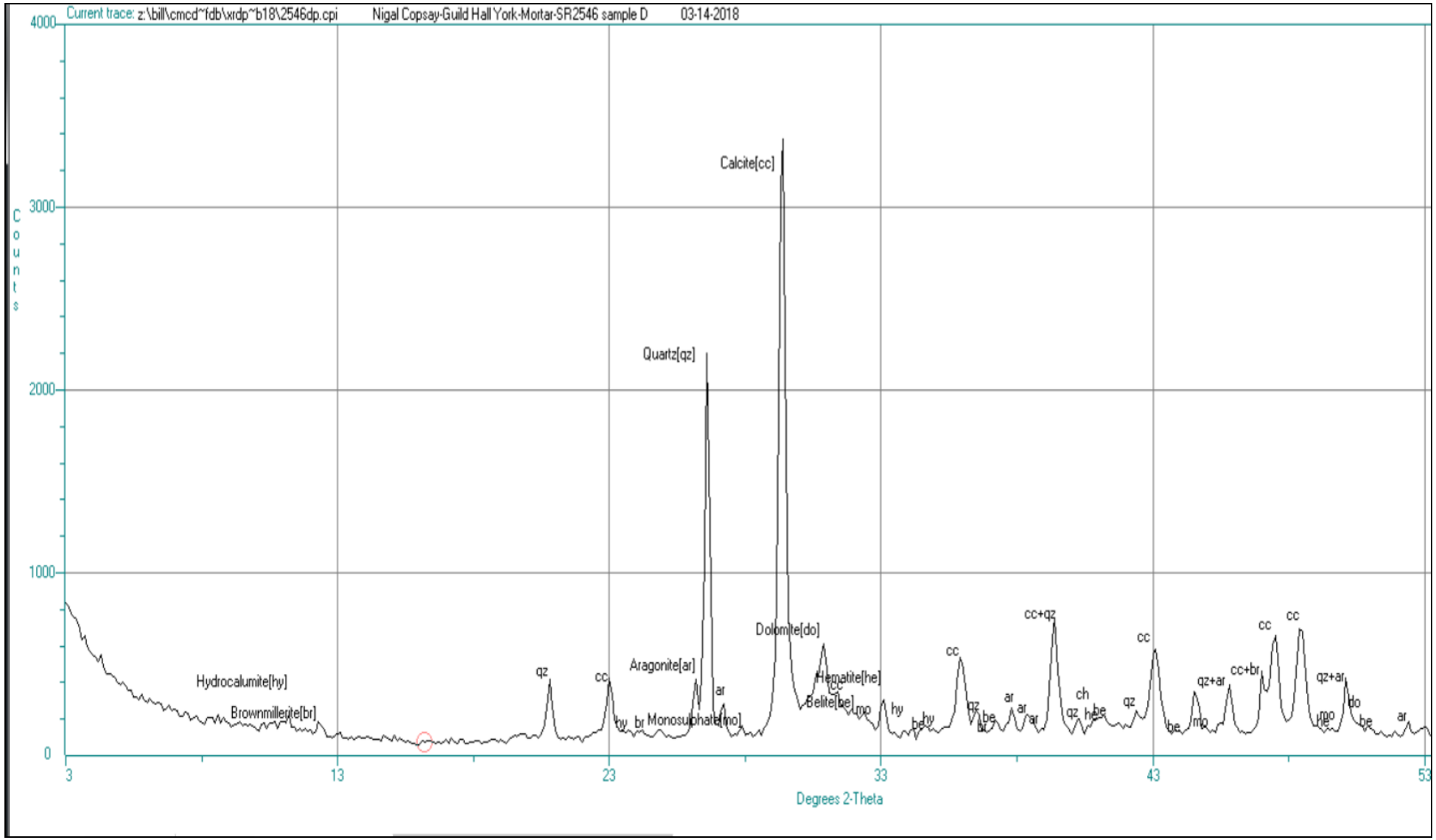

Figure No. 7 – SR2546-S3 – "D" Binder from Pointing to Original Guild Hall Wall.

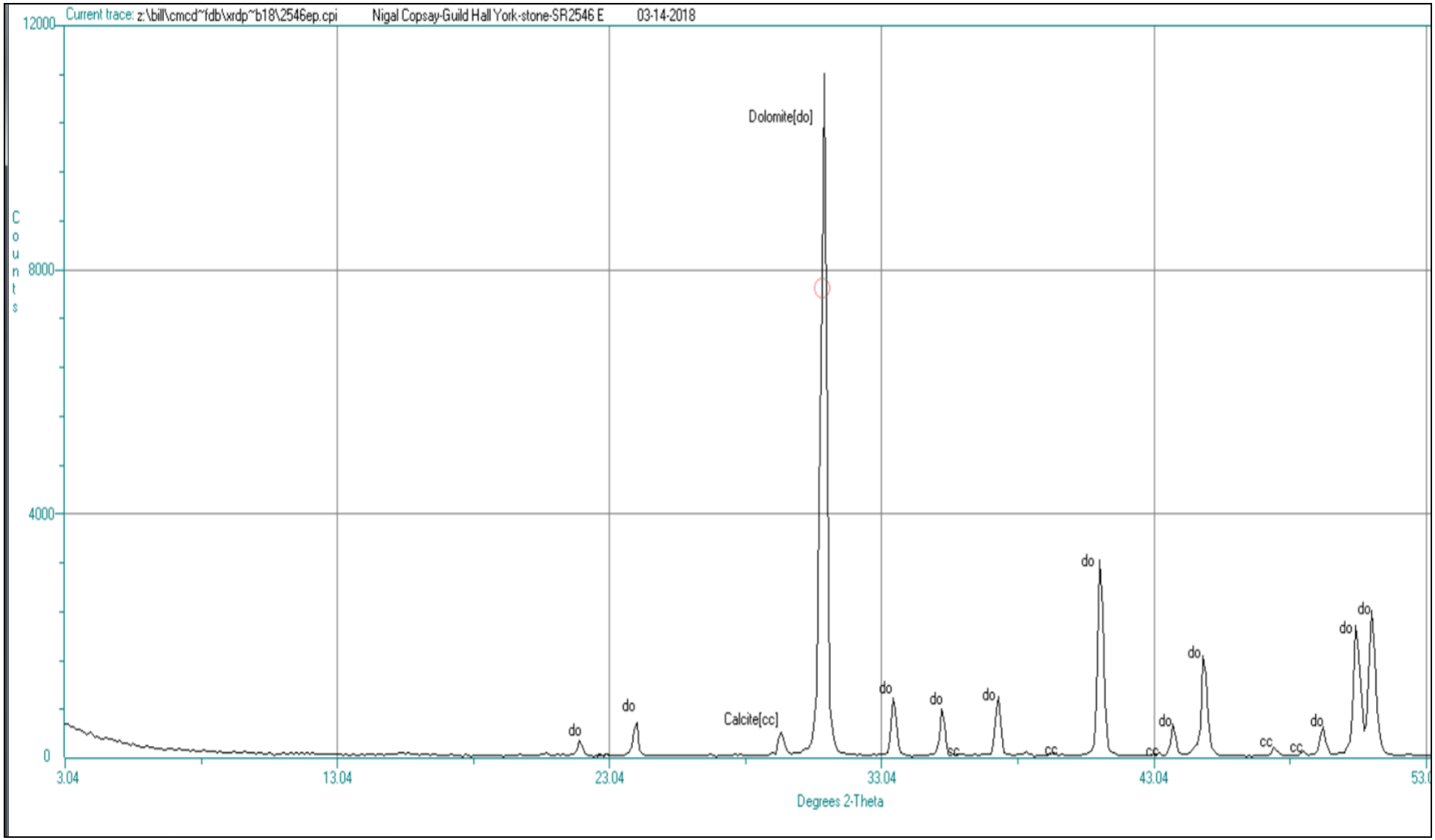

Figure No. 8 – SR2546-S4 – "E" Stone Masonry sample, to check for Dolomite.

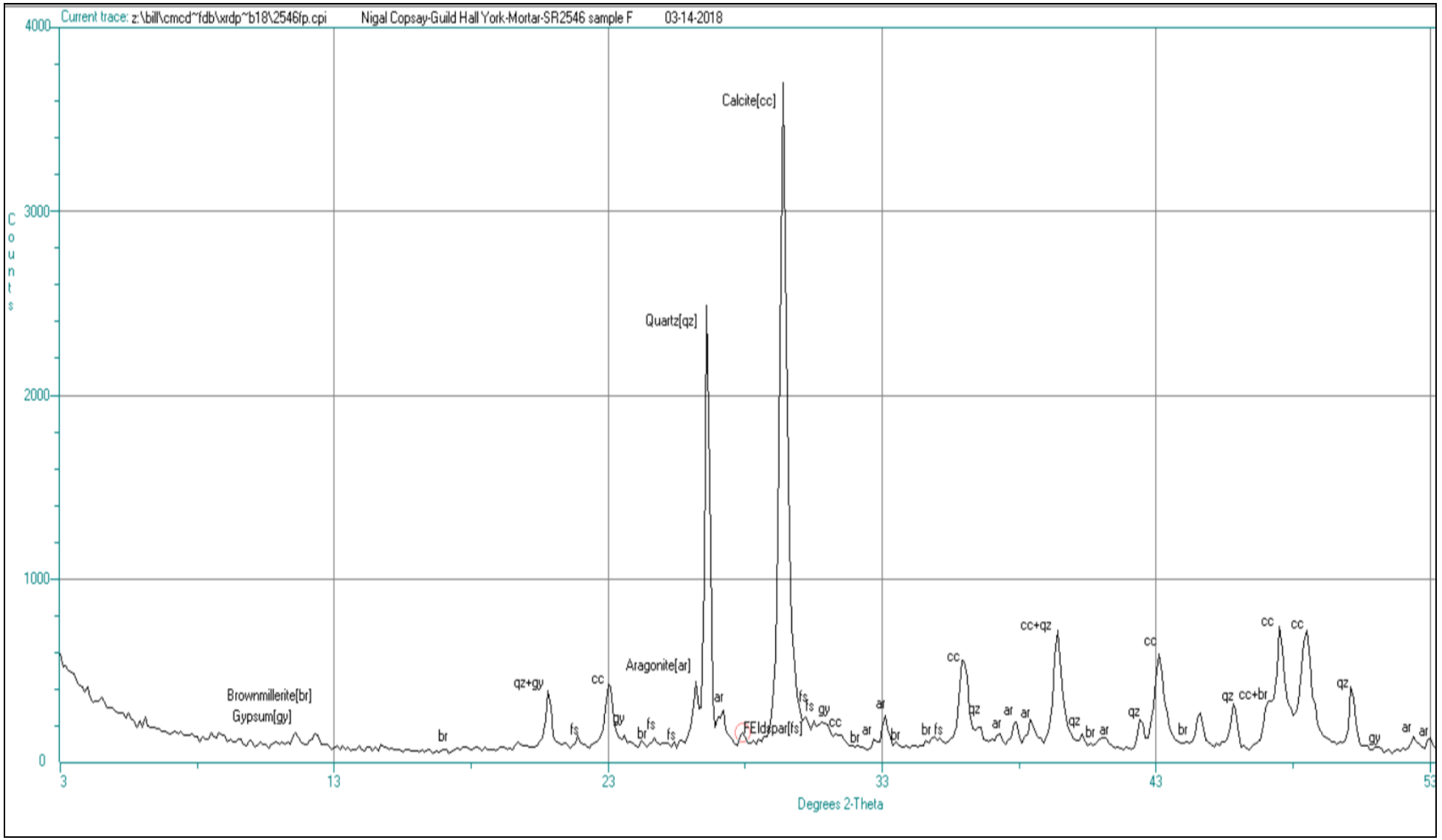

Figure No. 9 – SR2546-S5 – "F" Binder ex Pointing from Sand Lime Brick on Lean-to in Lane.

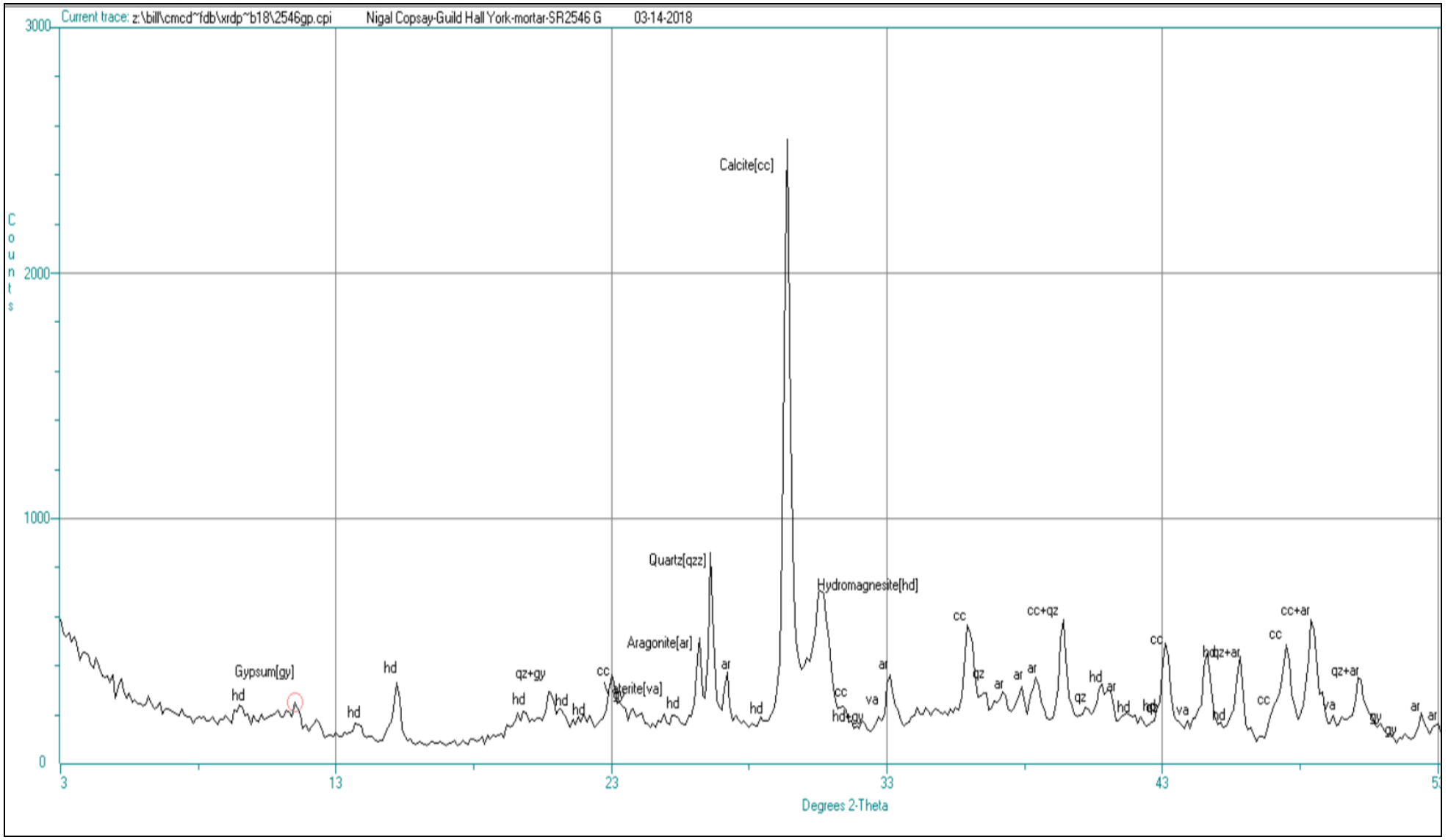

Figure No. 10 – SR2546-S6 – "G" Binder from Earliest Ashlar Masonry, North Gable on Hall.

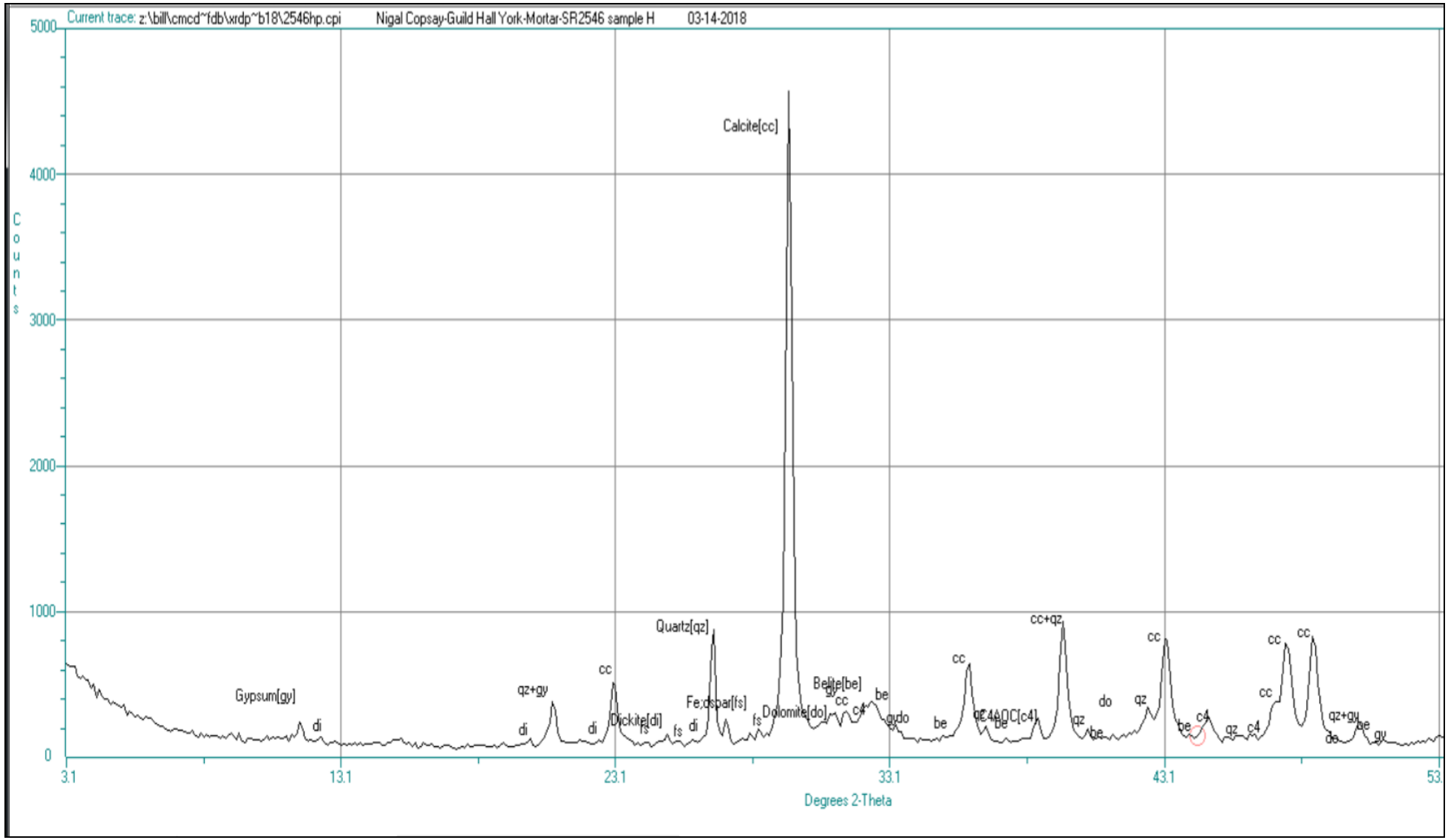

Figure No. 11 – SR2546-S7 – "H" Binder ex Pointing to Brick Masonry, from three storey Building.

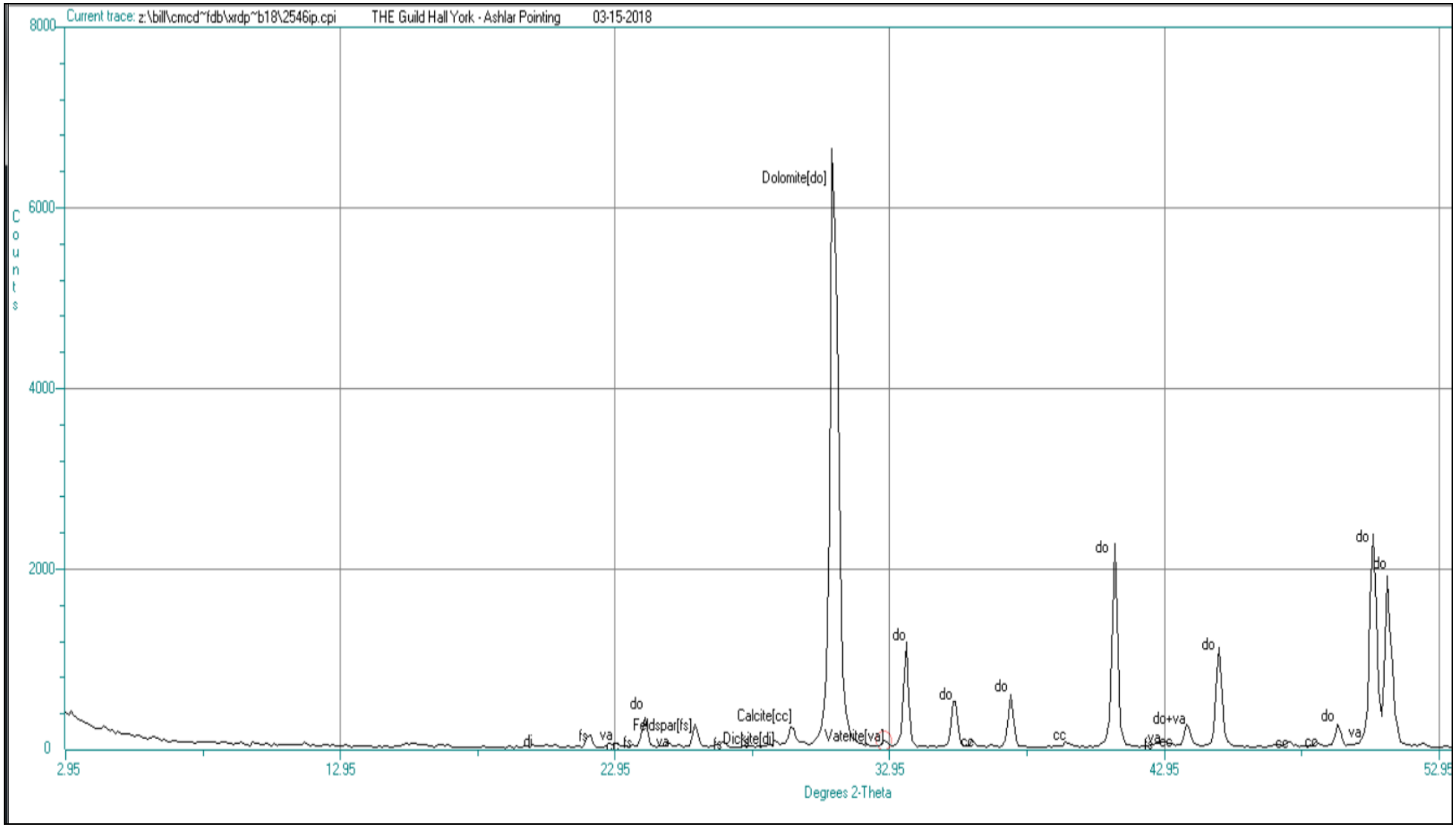

 Figure No. 12 – DR2546-S8 – "i" Binder from Ashlar Repair Mortar, W Elevation of Hall.

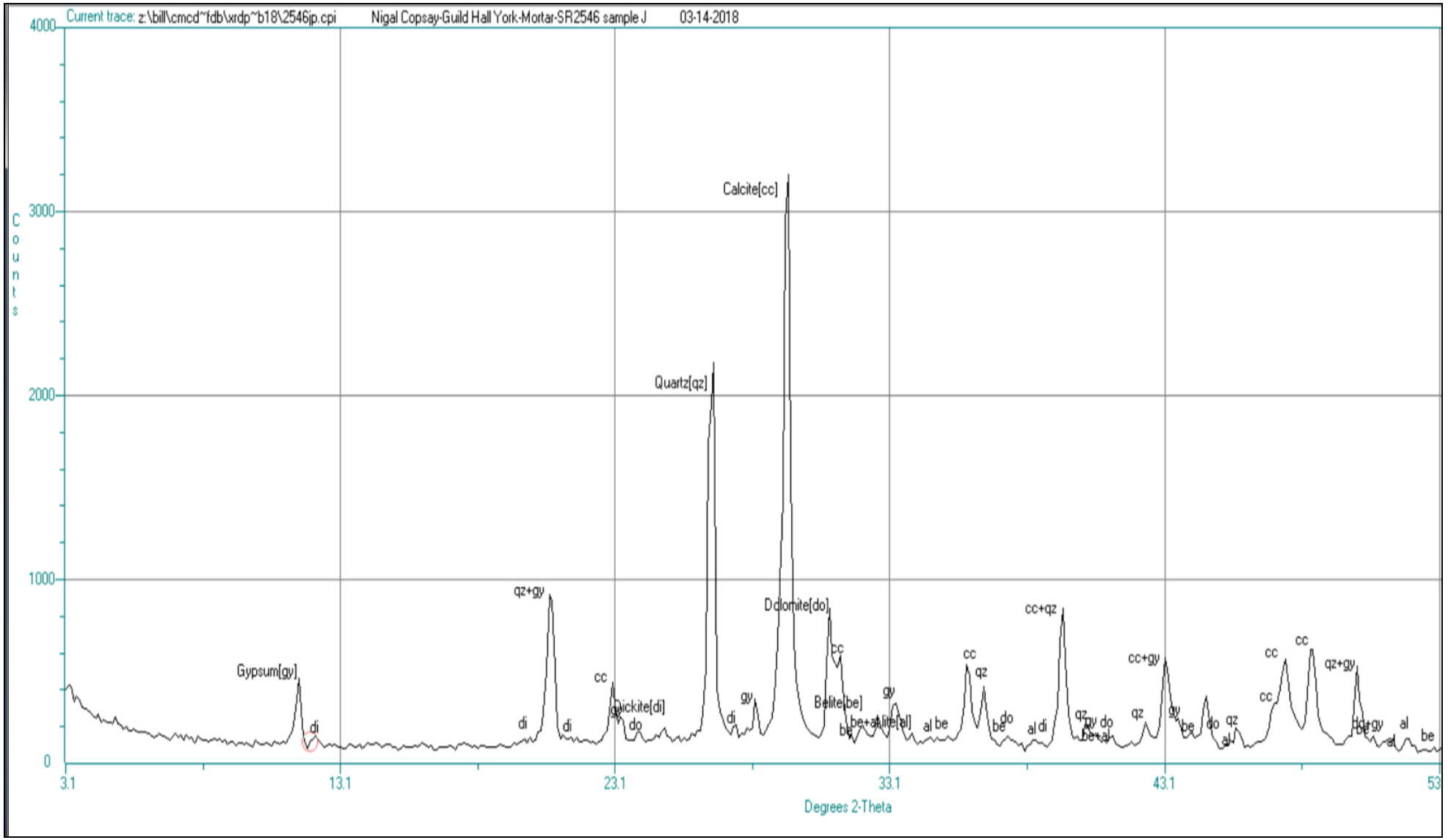

Figure No. 13 – SR2546-S9 – "J" Binder from Pointing to Clay Brick, West Wall of West Wing.

APPENDIX "A"

Sample Locations:	Plates Showing Locations "B" to "J"
Sample Locations:	Figures No. A1 & A2

G) probably earliest masonry – Ashlar Pointing

C) Ashlar Pointing

I) – Ashlar pointing

Also, I)

E)

D) wall of original guild Hall within stone lean-to shed

F)

J)

H)

B) probably same as H)

Figure No. A1: Location of samples B, C, D, E, G, H & i.

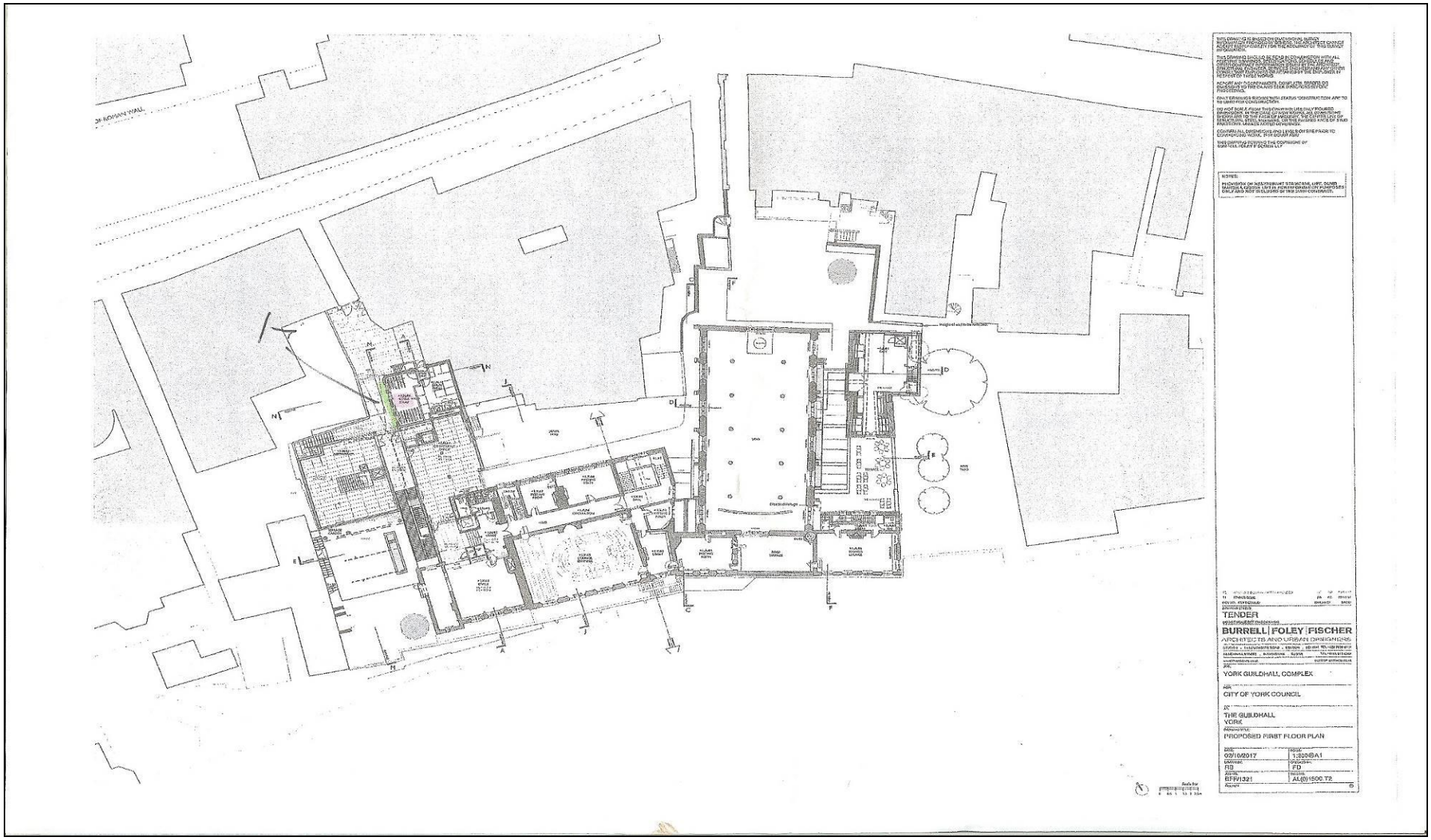

Figure No. A2: Location of sample J.