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 a Selection of Mortar Samples

Rudge Memorial Chapel, Lincoln Nebraska, USA

Prepared and Approved By

W A Revie

Prepared for

Berggren Architects
1201 "O" Street
Suite 302
Lincoln
NE 68508
United States of America

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1.0 Introduction

An e-mailed enquiry was received from Douglas Elting of Berggren Architects by CMC on the 30th May 2019. The enquiry related to the analysis of mortar samples from the Rudge Memorial Chapel, Lincoln, Nebraska. Following further email exchanges, a batch of samples from the Chapel were received in CMC's Stirling Laboratory on the 25th June 2019.

The samples received consisted of 10 No. mortar samples, plus a small piece of limestone from the masonry used in the construction of the Chapel. The mortar samples were removed from a selection of locations, and included both pointing and bedding mortars.

We were advised that the Rudge Memorial Chapel was constructed in the early 1930's from Indiana Limestone with a clay tile backup, with the results of the mortar analysis required to assist in the selection of mortars for use in conservation works at the Chapel.

On receipt in the laboratory the samples were examined, and a suggested laboratory programme of analysis, along with an indication of costs, was submitted, see CMC's quotation, reference M/Q601/19. However, due to a mix-up at the laboratory this not issued until the 11th March 2020, following an enquiry from Mr Elting on the 10th March 2020. Instruction to proceed with the analysis was received by email from on the 12th March 2020.

This report presents observations from the examination of the samples along with the results of analyses carried out, concluding with comment on the composition of the mortars and the binder type(s) and aggregates employed in their production.

2.0 Sample

A batch of samples was received in CMC's Stirling laboratory on the 25th June 2019, with the samples identified as masonry mortars from a selection of locations on the Rudge Memorial Chapel, Lincoln, Nebraska. The samples being submitted by Berggren Architects.

On receipt in the laboratory the sample details were entered into the sample register and the unique sample reference SR2736 allocated. Details of the sample are given below:

Sample No.	Location/ Description/Comment
SR2736-S1	Exterior, S.E #1 – Pointing Mortar,
SR2736-S2	Exterior S.E.#2 – Pointing/Bedding Mortar,
SR2736-S3	Exterior N.W. FDN #3 – Pointing Mortar,
SR2736-S4	Exterior N.W. Wall #4 – Pointing Mortar,
SR2736-S5	Interior S.E. Arch – Pointing Mortar,
SR2736-S6	Interior Mortar @ W. Side – Aisle, Grey,
SR2736-S7	Basement Mortar – In Tile,
SR2736-S8	Salt – Mortar – Basement,
SR2736-S9	NDCS 1
SR2736-S10	NDCS 2
SR2736-S11	Limestone Chip with Adhering Mortar.

In addition, a digital image was obtained to give an indication of the form of construction involved and its service environment, see following plate:

Plate no. 1: The Rudge Memorial Chapel, Wyuka Cemetery, Lincoln, Nebraska.

3.0 Methods of Examination and Analysis

On receipt in the laboratory all samples were initially submitted to a microscopic examination employing a stereo-binocular microscope at magnifications up to x20, and a sample log prepared. During this examination representative sub-samples were exposed to a selection of reagents, dilute acids and indicator solutions and the response observed.

To permit comparison of the different mortars and permit grouping samples into similar types for analysis, a binder rich sub-sample was prepared from all of the samples, with these submitted to analysis by X-ray Powder Diffraction (XRD). This to aid identification of the binder type employed and to ascertain whether the mortars had been affected by any potentially disruptive reactions, such as those arising from salt attach and weathering.

Due to the limited quantity in some samples the observations from the microscopic analysis, and XRD analyses, were used to group samples into “like” types, to permit representative samples to be prepared for the following laboratory programme:

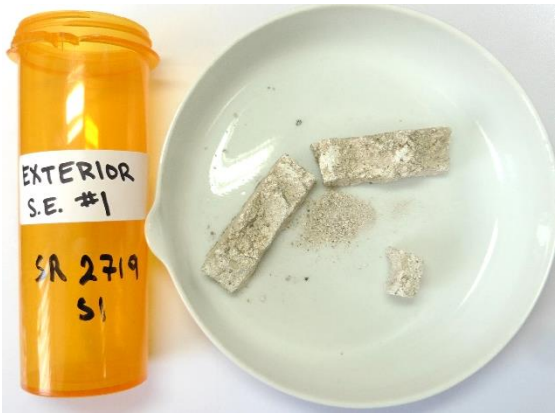
Samples that contained binders which were indicated to contain Portland Cement or likely to be eminently hydraulic lime-based mortars were analysed, by the methods of BS 4551: 2005 + A1: 2010 + A2: 2013. With those found to be high calcium or feebly to moderately hydraulic limes analysed by acid digestion,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

Where considered appropriate, and an intact sufficient sample, of sufficient size, was available, petrographic thin sections were prepared to enable additional information to be obtained, relating to the fabric condition of the mortar, and the form in which the binder was used at the time of mixing. The thin sections prepared were submitted to a microscopic examination in the Polarised light microscope.

4.0 Macroscopic Examination

During the initial examination of the samples, the size, weight and condition of each sample was recorded and entered into a sample log. A copy of the log was submitted to Berggren Architects along with the quotation for the analysis of the mortars, to assist them in assessing the proposed laboratory programme. Images of the samples received are reproduced below for reference.

Plates No. 2a & b: Sample S1- Exterior S.E. #1 – 65.6 gram.



Plates No. 3a & b: Sample S2 - Exterior S.E. #2 – 36.8 gram.

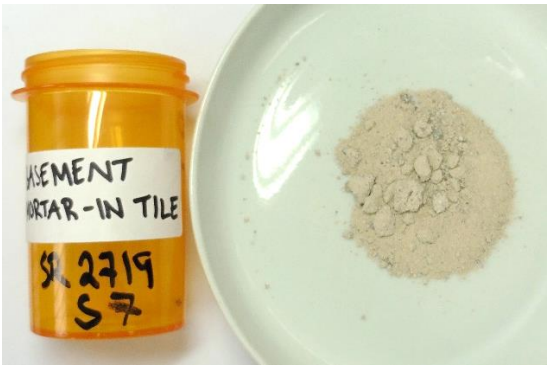
Plates No. 4a & b: Sample S3 - Exterior N.W. FDN #3 – 13.4 gram.

Plates No. 5a & b: Sample S4 - Exterior N.W Wall #4 – 22.9 gram.

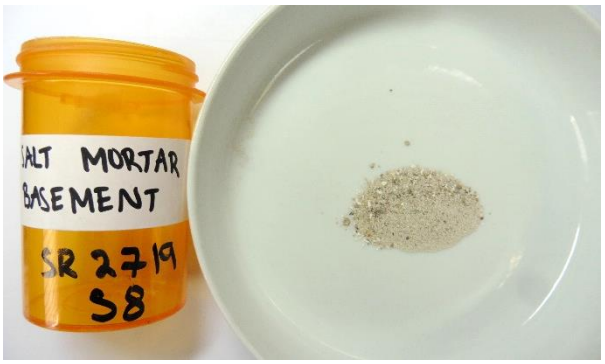
Plates No. 6a & b: Sample S5 - Interior S.E. Arch – 42.5 gram.

Plates No. 7a 7 b: Sample S6 - Interior Mortar @ West Side - Aisle, Grey – 82.3 gram.

Plates No. 8a 7 b: Sample S7 - Basement Mortar – In Tile – 13.4 gram.



Plates No. 9a & b: Sample S8 - Salt – Mortar- Basement – 2.2 grams.



Plates No. 10a & b: Sample S9 - NDCS 1 – 11.0 gram.

Plates No. 11a & b: Sample S10 - NDCS 2 – 10.5 gram.

Plates No. 12a & b: Sample S11 - Limestone fragment from Masonry – 0.3 gram.

A copy of the sample log is attached, see Appendix "A" to this report.

However, the proposed laboratory programme submitted on the 11th March 2020 was further modified on the basis of the XRD analyses and the quantity of sample available for the analysis methods to be employed.

The revised programme included for the following:

Mix composition of samples by acid digestion was limited by the quantity of materials available and included:

Samples S1, S6 and S9 - 3 No. samples were analysed by this method.

Mix Composition by BS 4551: 2005 + A2: 2013

Samples S3 and S5 - 2 No. samples for analysis.

In addition, a thin section was prepared from samples S1, S4 and S9, along with the sample of limestone, the latter to confirm the type of limestone used in the masonry. This would also permit clarification of whether the source of any limestone aggregate within the mortar was the same as that used for masonry. Similarly, if there were incompletely calcined lime inclusions present it may be possible to assess if the lime was made from the same type of limestone. The thin sections would also permit comment on the condition of the fabric of the mortar.

5.0 Analysis by X-Ray Diffraction

To assist in the identification of the components in the mortar samples, along with helping to determine the type of binder employed, a binder rich sub-sample was prepared, from each sample received, and these submitted to analysis by X-ray Powder Diffraction (XRD).

To achieve this, a representative sub-sample of the mortar was ground in an agate mortar and pestle, taking care to minimise crushing of the aggregates present.

A concentrated binder rich sub-sample was obtained by sieving the powdered samples over a 63µm sieve and collecting the material passing the sieve for analysis. The powder collected was then back-packed into proprietary sample holders for presentation in the X-Ray Diffractometer. This technique was used to ensure, as close as is practicable, the random orientation required to give true peak intensities in the diffractograms.

As the aggregate in all samples appeared similar, a sample of the aggregate, after removal of the binder, was also prepared from one sample (Sample S6) to assist in clarifying the mineralogy of the aggregate.

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 55° 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 figures, appended to this report, in the form of labelled X-ray diffractograms:

Figure No. 4 – SR2736-S1 – Exterior, S.E. #1 – Pointing Mortar,
Figure No. 5 – SR2736-S2 – Exterior S.E. #2 – Pointing/Bedding Mortar,
Figure No. 6 – SR2736-S3 – Exterior N.W. FDN #3 – Pointing Mortar,
Figure No. 7 – SR2736-S4a – Exterior N.W. Wall #4 – Pointing & Bedding mortar - Bedding,
Figure No. 8 – SR2736-S4b – Exterior N.W. Wall #4 – Pointing & Bedding mortar - Pointing,
Figure No. 9 – SR2736-S5 – Interior S.E. Arch – Pointing Mortar,
Figure No. 10 – SR2736-S6a – Interior Mortar at West Side – Aisle, Grey,
Figure No. **11** – SR2736-S6b – Aggregate from sample of Interior Mortar at West side – Aisle,
Figure No. 12 – SR2736-S7 – Basement Mortar – In Tile,
Figure No. 13 – SR2736-S8 – Salt – Mortar – Basement,
Figure No. 14 – SR2736-S9 – NDCS 1,
Figure No. **15** – SR2736-S10 - NDCS 2.

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

cc = Calcite ($CaCO_3$) Calcium Carbonate, carbonated lime binder 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 formed from leached and redeposited carbonated lime,

va = Vaterite ($CaCO_3$) a further crystalline form of Calcium Carbonate, commonly found in limestone and found in carbonated paste in mortars and in redeposited leached lime,

po = Portlandite ($Ca(OH)_2$) Calcium Hydroxide, hydrated uncarbonated lime from binder and as a hydration product from cement clinker,

al = Alite (Ca_3SiO_5) *tri*-calcium Silicate, Clinker component in Portland cement and some eminently Hydraulic lime binders,

be = Belite (Ca_2SiO_4) *di*-calcium Silicate, Clinker component in Portland cement and most Hydraulic lime binders,

ge = Gehlenite ($Ca_2Al_2SiO_7$) Calcium Aluminium Silicate, clinker component in some hydraulic limes and Portland type cements, common in white cements,

br = Brownmillerite ($Ca2(Al, Fe)_2O_5$) Calcium Aluminium Iron Oxide, clinker component in hydraulic limes and in some Portland type cements,

ett = Ettringite ($Ca_6Al_2(SO_4)_3(OH)_{12}26H_2O$) Calcium Aluminium Sulphate Hydroxide Hydrate, Hydration product in Portland cement binders and as a sulphate reaction product,

qz = Quartz (SiO_2) Silicon Oxide, dominant component of the aggregates used in all of the mortar samples,

cr = Cristobalite (SiO_2) Silicon Oxide, high temperature form of quartz, aggregate component,

fs = Feldspar, common rock forming mineral, with Anorthite from the Plagioclase group of minerals, along with Alkali feldspars, Sanidine and Orthoclase also present.

mi = Muscovite mica, common rock forming layer-lattice mineral, aggregate component,

th = Thenardite (Na_2SO_4) Sodium Sulphate, alkali sulphate deposited from ground water, leached from clay tile or other environmental sources, or a reaction product.

From the analysis it is indicated that there are several binder variants present in the samples analysed. These are grouped below along with a description of the form of binder indicated to have been used in the production of the mortars submitted.

Samples SR2736--S1, S2, S4a (bedding), S6, S7 and S10: All samples appear to be very feebly hydraulic lime mortars, with, from a visual examination, the binders apparently used in the form of a hydrate. The hydraulic component, in all, appears to be Brownmillerite (Calcium aluminate) and its abundance in the binder is low to very low. Therefore, it may be that the binders used were 'effectively' classed as non-hydraulic. The degree of hydraulicity in the binders is variable, but very low in all samples examined, and this is considered, most likely, to be a function of the presence of trace quantities of clays and/or feldspars in the limestone that was burnt in the production of the lime.

Samples SR2736-S4b (pointing) and S8: both of these mortars are again considered to be hydraulic limes. With sample S4 being moderately to eminently hydraulic, whereas sample S8 is feebly to moderately hydraulic. It would be necessary to determine the chemistry and calculate the hydraulicity index to clarify further. However, the sample quantity was too small to permit this to be determined, at his time.

Samples SR2736-S3, S5 and S9: all appear to be based on a Portland cement type binder, with, possibly a proportion of lime hydrate added to the mix, in samples S3 and S5. Sample S9 having the higher Aluminate content (Gehlenite) may have contained a white cement as the binder, and this may be from a newer repair mortar.

The data from the XRD analysis was further processed by Rietveld Refinement, with the results obtained presented below:

Sample Ref. SR2736	**S1**	**S2**	**S3**	**S4a**	**S4b**	**S5**
Client Sample Ref	**#1**	**#2**	**#3**	**#4**	**#4**	**SE Arch**
			Proportion by Mass			
Calcite	78.3	61.5	25.2	40.8	45.9	76.8
Aragonite				3.9		
Vaterite			10.8			
Portlandite					2.5	1.5
Alite			2.4		1.2	7.5
Belite			1.3		2.7	2.8
Gehlenite					1.6	
Brownmillerite	0.8	0.5		0.4		
Ettringite			3.4		0.6	
Quartz	13.3	23.0	42.1	31.9	23.0	5.8
Cristobalite						
Feldspar (Anorthite)	2.3	5.0	7.0	12.0	9.0	3.0
Feldspar (Albite)						
Feldspar (Sanidine)	5.3	10.0	7.8	11.0	13.5	
Feldspar (Orthoclase)						2.6
Muscovite mica						
Thenardite						
Total	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**

Table No. 1a: Rietveld Refinement on XRD

Sample Ref. SR2736	**S6a**	**S6b**	**S7**	**S8**	**S9**	**S10**
Client Sample Ref	**W. Aisle**	**W. Aisle**	**In Tile**	**Salt**	**NDCS1**	**NDCS2**
			Proportion by Mass			
Calcite	57.3		51.2	40.7	48.5	52.8
Aragonite						
Vaterite						
Portlandite					1.6	
Alite					1.4	
Belite				0.2	0.7	
Gehlenite					0.5	
Brownmillerite	1.3		1.1	2.4		1.6
Ettringite					1.0	0.8
Quartz	23.4	65.1	27.6	28.4	28.1	28.3
Cristobalite	0.5	0.2	0.2	0.3	0.1	0.7
Feldspar (Anorthite)	4.9	14.4	5.8	6.5	5.4	5.9
Feldspar (Albite)						
Feldspar (Sanidine)	3.9	9.5	4.7	1.5	4.6	
Feldspar (Orthoclase)	8.7	10.8	9.4	3.4	6.9	9.9
Muscovite mica					1.2	
Thenardite				16.6		
Total	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**

Table No. 1b: Rietveld Refinement on XRD

From the XRD analysis it is also confirmed that sample SR2736-S8 had been affected by salts, with the dominant salt present being an alkali

6.0 Mix Composition Analysis

A total of three samples were prepared for mix composition by acid digestion, these were samples SR2736 – S1 and S6, i.e. those having more than sufficient material to permit acid digestion, with recovery of aggregate, for grading analysis. In addition, sample S9 was also submitted for mix composition, by this method, to permit aggregate recovery for grading analysis. However, due to its small sample size, and its similarity to sample S10, a composite of S9 & S10 was employed in the analysis.

A further two samples were submitted to analysis by the methods of BS4551, however, the results obtained should be used with caution, and for comparative purposes only, as the results of the analysis are calculated on the basis of data pertaining to modern Portland cements and hydrated limes, and these are likely to differ, possibly significantly, from the cements, or hydrated limes, used at the time of construction.

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

6.1 Mix Composition Analysis by Acid Digestion

Sample Ref.	**SR2736-S1**	**SR2736-S6**	**SR2736-S9**
Source of Mortar	**Exterior Pointing**	**Interior Mortar**	**NDSC1+2**
Binder Type	**Non-to feebly Hydraulic**		**Cement**
Lime : Aggregate Ratio	1.0 : 3.0	1.0 : 4.1	1.0 : 3.2
Weight Proportions – Quicklime Mixes			
Binder content	1.0	1.0	1.0
Fine Aggregate (Sand)	3.9	5.4	4.3
Volume Proportions			
Binder content	1.0	1.0	1.0
Fine Aggregate (Sand)	1.5	2.1	2.5

The mix proportions are calculated on the basis that the binder was used in the form of a hydrate and that no quicklime or puttylime inclusions were present in the mortars examined.

The result of the grading analysis on the recovered aggregates are presented in the table below and as aggregate filled histograms in the appended Figures No. 1, 2 & 3.

Sample Ref:	**SR2736-S1**		**SR2736-S6**		**SR2736-S9**	
BS Sieve Size (mm)	**Retained %**	**Passing %**	**Retained %**	**Passing %**	**Retained %**	**Passing %**
8.00	0	100	0	100	0	100
4.00	0	100	0	100	0	100
2.00	2.9	97.1	0.8	99.2	0	100
1.00	16.7	80.4	5.8	93.4	2.1	97.9
0.500	27.8	52.6	29.3	64.1	25.2	72.7
0.250	27.2	25.4	35.4	28.7	36.9	35.8
0.125	13.0	12.4	16.8	11.9	23.3	12.5
0.063	4.0	8.4	4.2	7.7	4.5	8.0
Passing 63µm	8.4		7.7		8.0	

Table No. 2: Aggregate grading (on recovered aggregate)

Based on the particle size distribution, and the very similar mineralogy, it is concluded that the aggregates used in all of the mortars analysed originated from the same source.

All have a moderate to relatively high fines content, which may suggest that the sand was used as dug, or if processed, it contained a proportion of aggregate dust arising from the processing procedure. The fines, passing the 63µm sieve were analysed by XRD and found to be dominated by quartz with feldspar minerals, no clay minerals were detected.

6.2 Mix Composition by chemical Analysis

As from the XRD analysis it was indicated that some samples may contain a Portland cement, or a Portland cement and lime hydrate as the binder. Those with sufficient material for the analysis procedure were selected and submitted to analysis by the methods of BS 4551:2005 + A1:2010 & A2: 2013.

This analysis was carried out on samples prepared by CMC, on behalf of CMC, by QED Independent Testing and Consultancy Limited of Leicester.

The results reported were processed by CMC with the mix compositions determined reported below:

Results of the mix composition as determined by BS4551 are as follows:

Sample Ref. No.	**SR2736-S3**	**SR2736-S5**
Chemical Analysis	**% by mass**	
Insoluble Residue	77.66	71.93
Soluble Silica (SiO2)	4.57	2.84
Calcium Oxide (CaO)	8.26	13.48
Loss on Ignition	8.15	10.23
Calculated composition of the sample expressed to the nearest 0.5% by mass on dry mass.		
Portland Cement	14.0	15.0
Lime Hydrate	-	6.5
Aggregate	86.0	78.5
Approximate volume Proportions calculated on the basis of the standard assumptions.		
Portland Cement	1.0	1.0
Lime Hydrate		1.1
Aggregate	5.3	4.5
Mortar Classification (Table 4)	*Type iii.*	
(Table 7)		*Type iii.*

Comments

The analytical results presented above were evaluated by the method of BS 4551: 2005 + A1: 2010 + A2: 2013, on the basis of the following assumptions:

i. The cement content has been calculated on the basis that the cement contained 20.5% soluble silica and 64.5% calcium oxide and had a dry bulk density of 1450 kg/m^3.

ii. The hydrated lime contained 75.6% calcium oxide, no soluble silica compounds and had a dry bulk density of 575kg/m^3

iii. The sand contained 0.2% soluble silica and no soluble calcium compounds and had a dry bulk density of 1675kg/m^3.

iv. The mortar contained no mineral admixtures such as PFA, GGBFS or silica fume.

On the basis of the analysis carried out it is indicated that sample S3 was made using a Portland cement binder with no Lime added, whereas sample S5 was a Portland Cement/Lime/Sand mix.

7.0 Microscopic Examination

Petrographic thin sections were prepared from representative samples that contained intact pieces of mortar which could be used in the preparation of the thin sections.

The samples were prepared for thin sectioning by initially drying them to a constant weight at 60°C, in a vacuum oven, prior to being impregnated with an epoxy resin containing a fluorescent blue dye.

One side the impregnated slices were cut and polished then mounted onto glass slides (25mm 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 onto a 'Swift automatic stage' which permitted the determination of the volumetric mix composition, by modal analysis.

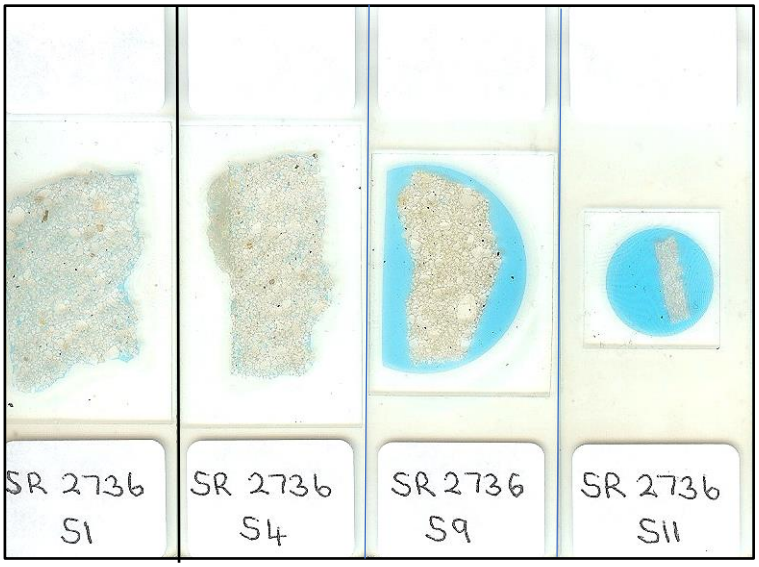


Plate No. 13: Thin sections prepared from mortar samples S1, S4, S9 and limestone fragment S11.

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

7.1 Sample SR2736-S1 – Exterior S.E. #1 – Ponting Mortar

This sample was composed of three intact pieces of mortar all from a single length of pointing mortar. The largest piece was used in the preparation of the thin section.

Aggregate

The aggregate in this sample is dominated by quartz with feldspar, including Plagioclase, Sanidine and Orthoclase, along with a low proportion of altered igneous rock fragments, microcrystalline silica (chert) and trace proportions of limestone and indeterminate altered rock fragments.

The grains are sub-angular to sub-around in shape and most display abraded margins with the source possibly a glacio-fluvial deposit. Sand grains range from 0.02mm to 2.2mm in the section examined.

A very low proportion of chlorite clay minerals were also observed, but in trace proportions, incorporated within altered minerals.

The sand is a quartz rich natural sand with a low proportion of lithic fragments.

Binder

The binder is relatively uniform throughout, and has the appearance of a non-hydraulic lime, in which small incompletely mixed (balled) hydrate form lime inclusions were observed. These are typically 0.04mm to 0.3mm in size. The inclusions, along with small microporous area where the paste has a marked granular texture, mostly abutting irregular aggregate particles, would suggest that the binder had been used in the form of a lime hydrate, rather than as a putty or a quicklime.

The paste is fully carbonated, and displays an abundance of short shrinkage cracks, typical of those observed in non-hydraulic lime mortars, which stiffen and 'set' due to the loss of free moisture.

There is no evidence of alteration products within the body of the mortar, and, in the sample examined, there is only very minor evidence of dissolution of binder, with very localised redeposition of calcite within fine cracks and rimming some voids.

Voids and microcracks

Voids are minor and are present as small, very localised, sub-rounded to irregular features typical of entrapped air voids, as placing artefacts. There was no evidence of entrained air in the sample examined. Voids range in size from 0.05mm to 0.95mm.

Cracks are abundant, and are randomly distributed throughout the fabric; they range in width from 0.01mm to 0.04mm and up to 1.1mm in length. The cracks are mostly discontinuous and connect aggregate particles, and locally voids. They have the appearance of plastic shrinkage cracks that have further developed in response to drying shrinkage. None of the cracks observed had functioned as fluid migration pathways.

Most cracks and most voids are free of secondary minerals, although locally there are fine fringes of redeposited calcite partially lining voids and rimming coarse aggregate particles, although there was no evidence of fluid migration through the mortar sample.

The abundance of cracks but minor redeposited calcite would infer that the mortar had been placed at a moderate to moderately low workability.

Modal Analysis

The results of a point count (modal) analysis carried out on the thin section are presented in the following table:

Sample Ref:	SR2736-S1	
Constituents	**%**	
Aggregate	**Inclusions as binder**	**Inclusions as aggregate**
Quartz	42.7	42.7
Feldspar	12.1	12.1
Igneous rock fragments	5.5	5.5
Chert	2.7	2.7
Opaque	0	0
Lime Inclusions	-	2.6
Total Aggregate	**63.0**	**65.6**
Binder (Lime Paste)	33.1	33.1
Clinker	0	0
Lime Inclusions	2.6	-
Secondary products/Calcite	1.3	1.3
Total Binder	**37.0**	**34.4**
Total Constituents	**100.0**	**100.0**
Voids	3.1	3.1
Crack	4.5	4.5
Total: Cracks + Voids	**7.6**	**7.6**
Mix Composition, by volume		
	Total Binder	**Effective Binder**
Binder: Aggregate Ratio	**1.0 : 1.7**	**1.0 : 1.9**

Table No. 3: Modal Analysis carried out on thin section prepared from sample S1.

The effective binder content is calculated on the basis that any inclusions present 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:

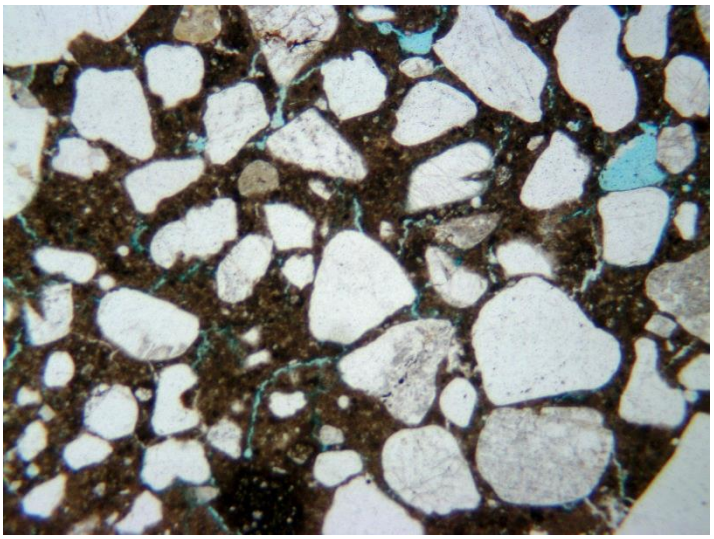


Plate No. 14:

A view in plane polarised light (ppl), of a typical area of the mortar where the fabric is consistent across the whole sample. It is well compacted and uniform throughout. Local entrapped air voids can be seen along with an abundance of fine shrinkage cracks, both highlighted by the blue impregnation resin. Most of the sand grains in view are quartz (white in section), with feldspar and minor igneous grains and also apparent.

Porosity is highlighted by the blue dyed resin.

Field of view 2.4mm.

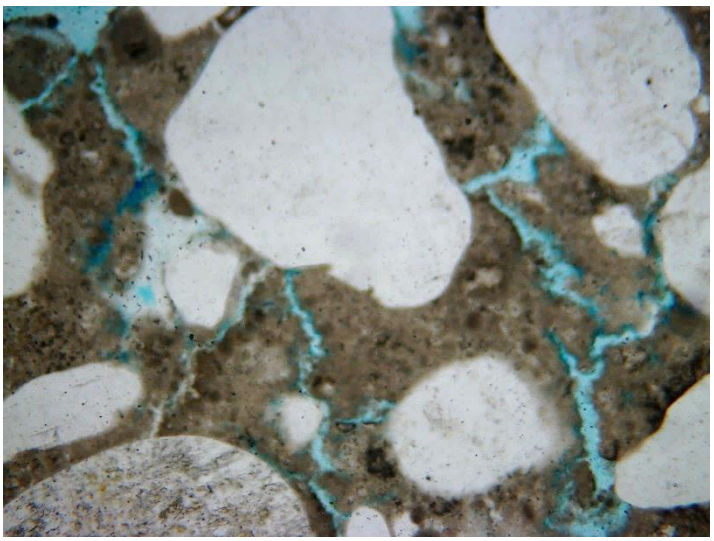


Plate No. 15:

Another view in ppl, of an area of paste containing small balled lime inclusions, centre right and lower centre left. These show a clotted or granular appearance, typical in hydrate mixes. The aggregates in view are again dominated by quartz, with minor feldspar.
Cracks are abundant and those in the right side of the plate locally contain thin rims of redeposited calcite.

Porosity is highlighted by the blue dyed resin.

Field of view 1.2mm.

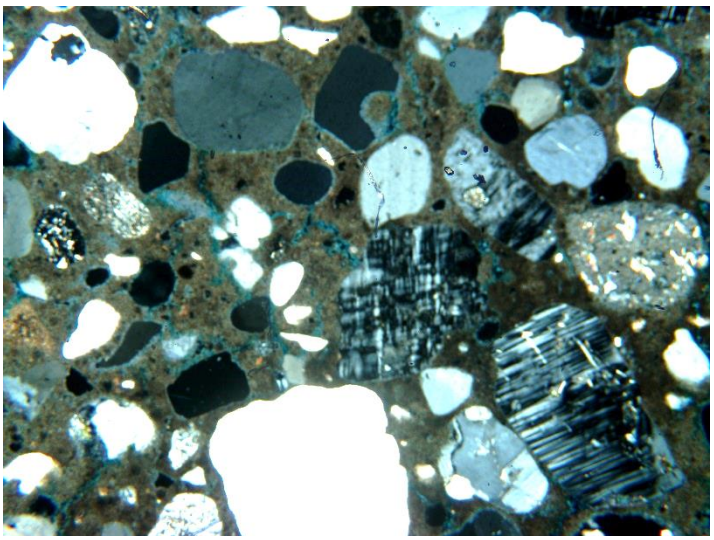


Plate No. 16:

A view in cross polarised light (xpl) of an area of the mortar. Although the paste is dense and well compacted there are a concentration of small voids in the upper centre, extending down to lower left, black in plate. Minor shrinkage cracks are also apparent. The paste is fully carbonated and most of the voids in view are rimed with redeposited calcite (light fringes). Aggregate grains are again dominated by quartz, with an abundance of feldspar and minor igneous fragments present.
Voids and the blue dyed resin appear dark in cross polarised light.

Field of view 2.4mm.

7.2 Sample SR2736-S4 – Exterior N.W. Wall #4 – Pointing Mortar

This sample was well compacted and moderately hard, resisting breakage under firm finger pressure. The thin section was prepared from one of the larger firmer fragments, which was noted to retain a thin piece of limestone from the stone masonry adhering to one edge.

The section was cut across a piece of mortar including both pointing and bedding mortars.

Aggregate

The aggregates in the mortar sample consist of a mixed suite of rock types, as in sample S1 these are again dominated by quartz, but with a significant proportion of feldspar particles, along with chert and minor indeterminate rock fragments.

The aggregates are sub-angular to sub-round in shape, with a low proportion of elongated aggregate particles also present. The shape and texture of the aggregates possibly suggesting a glacio-fluvial deposit as the source for the sand.

Aggregates range in size from <0.02mm to 3.2mm, and all are well bound within the paste, with the aggregate in the pointing and bedding mortars being very similar, and are likely to be from the same source.

Binder

The bedding mortar apparent in this sample is very similar to that in sample S1, with no hydraulic components apparent, although there are angular lime inclusions formed from concentrations of balled hydrate.

Whereas, although the paste in the pointing mortar also has the appearance of a lime rich binder, there is also an abundance of hydraulic clinker grains apparent throughout the section. The occurrence and distribution of the clinker is such as to infer that the mortar is a hydraulic lime mix rather than a cement lime sand mix.

The clinker is variable in coarseness ranging from 0.04mm to 0.45mm in size, with the particles being angular to sub-round and locally irregular in shape. The clinker contains Alite with Belite bound with interstitial ferrite (mostly C_4AF), along with an abundance of Belite clusters and minor Gehlenite also present.

The coarseness of the clinker and the abundance of Belite over Alite would infer that the binder was most likely a moderately to eminently hydraulic lime, rather than a Portland type cement.

Although the paste is carbonated this is patchy, and locally coarse Portlandite crystals were observed infilling pores in microporous areas, lining voids and concentrated around the perimeter of adjacent aggregate particles.

Voids and microcracks

Voids are rare within both mortars and appear as entrapped air voids, which are typically irregular to sub-round in shape and range from 0.2mm to 0.9mm in size.

Cracks are rare and occur as localised features connecting coarse aggregates and locally voids. The cracks are fine and <0.02mm in width and typical of early drying shrinkage features. The cracks are generally free of linings.

Modal Analysis

The results of a point count (modal) analysis, carried out only on the pointing mortar are presented in the following table:

Sample Ref:	**SR2736-S4**	
Constituents	%	
Aggregate	**Inclusions as binder**	**Inclusions as Aggregate**
Quartz	46.0	46.0
Feldspar	9.8	9.8
Igneous rock fragments	4.5	4.5
Chert	5.3	5.3
Opaque	0	0
Lime Inclusions	-	2.1
Total Aggregate	**65.6**	**67.7**
Binder (Paste)	22.8	22.8
Clinker	5.9	5.9
Lime Inclusions	2.1	-
Portlandite	2.2	2.2
Secondary products/Calcite	1.4	1.4
Total Binder	**34.4**	**32.3**
Total Constituents	**100.0**	**100.0**
Voids	3.9	3.9
Crack	0.4	0.4
Total: Cracks + Voids	**4.3**	**4.3**
Mix Composition, by volume		
	Total	**Effective**
Binder: Aggregate Ratio	**1.0 : 1.9**	**1.0 : 2.1**

Table No. 4: Modal Analysis carried out on thin section prepared from sample S4.

Photomicrographs:

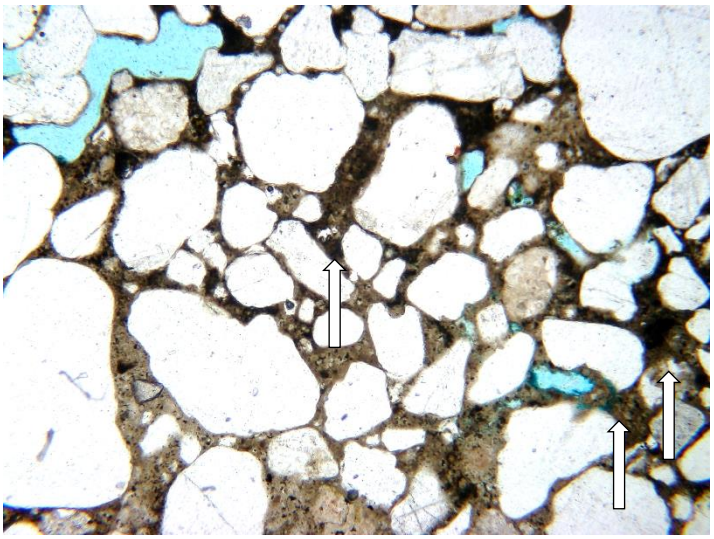


Plate No. 17:

A view in plane polarised light (ppl). This shows a typical area of the mortar, at a transition zone, with the paste in the lower half of the plate carbonated, whist that in the upper part is not fully carbonated.

Distributed throughout the paste, though unevenly, are clinker grains, with these dominated by Belite clusters, examples are arrowed in plate. The aggregates in view are mostly of quartz, with feldspar and minor lithic fragments.

Porosity is highlighted by the blue dyed resin.

Field of view 2.4mm.

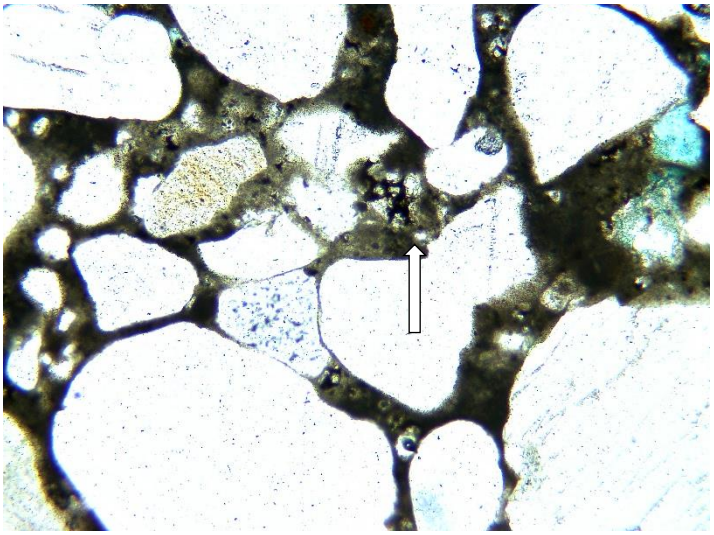


Plate No. 18:

A magnified view of a binder rich area of the mortar. Here the paste appears darker as it is predominantly uncarbonated, with invasive carbonation in the upper left. A coarse clinker particle can be seen in the centre of the plate, arrowed, this is composed of Alite and Belite, in a Ferrite groundmass. There are an abundance of smaller clinker grains and partially hydrated clinker in this view, indicating a relatively high binder content. Aggregates are again dominated by quartz grains, with feldspar

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

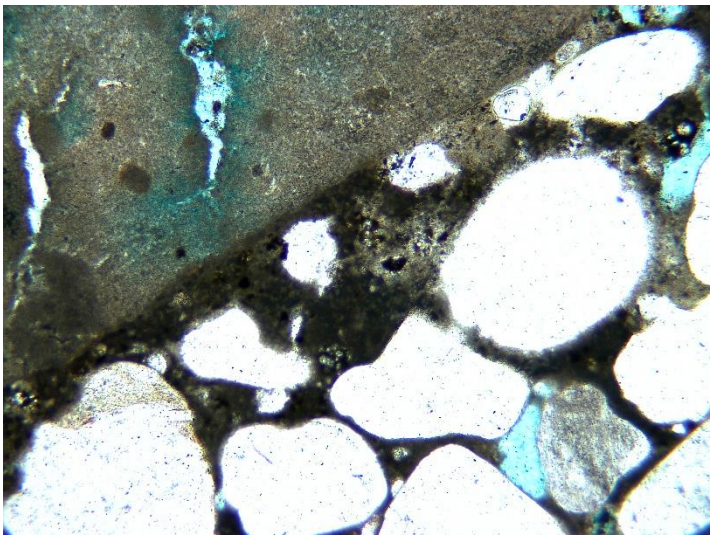


Plate No. 19:

A view in plane polarised light (ppl), of the interface between the pointing, lower part of plate, and the bedding mortar, upper left. The interface cuts diagonally across the field of view, with the bedding mortar dominated by the lime paste, showing typical shrinkage cracking.

The paste in the bedding is again clinker rich close to the interface but less so further away, not uncommon where the pointing had been applied to a dry bedding mortar. Aggregates are mostly of quartz in this view.

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

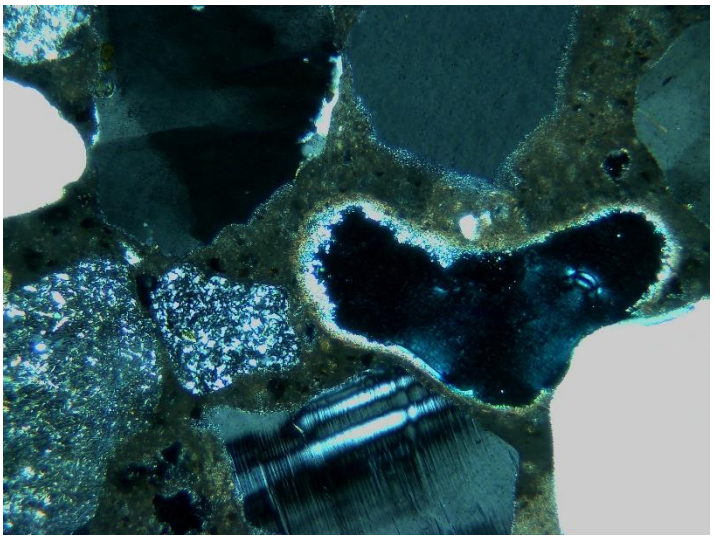


Plate No. 20:

A view in Cross polarised light (xpl), of an area of dense paste in which the void in the centre right is rimmed with coarse Portlandite crystals, mostly on the left side, with this having converted to Calcite at the mid-point of the void, with both Portlandite and calcite present at the right side. The surrounding paste is mostly uncarbonated with small pseudo morphs of partially hydrated clinker fragments distributed throughout. Aggregates are dominated by quartz, with feldspar, chert and an igneous fragment.

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

7.3 Sample SR2736-S9 – NDCS 1

This sample is well compacted and the intact pieces hard to moderately hard, resisting breakage under firm finger pressure. The mortar in this sample is similar with regard to hardness and texture to that in the pointing mortar in sample S5.

Aggregate

The aggregates are again dominated by quartz grains with Plagioclase Feldspars, along with alkali feldspars such as Sanidine and Orthoclase. In addition, there is a proportion microcrystalline silica (chert) and altered rock fragments observed.

The grains are sub-angular to sub-around in shape and most display abraded margins with the source most likely the same as those in samples S1 and S4. The sand grains range in size from 0.04mm to 3.9mm.

The sand is a quartz rich natural sand with a proportion of lithic fragments, with the fines found on analysis to again be dominated by quartz with feldspar but also to contain trace proportions of muscovite mica, sodalite and stishovite. (determined by XRD).

Binder

The mortar paste is dense and mostly carbonated with no lime inclusions or concentrations of hydrate observed. However, a significant proportion of clinker grains were, however, observed distributed throughout with these predominantly of Belite clusters along with Alite and Belite clinker, and as it was noted that the latter is low in ferrite, which along with the presence of Gehlenite would suggest a white cement as the binder.

The clinker is relatively fine with the particles ranging from 0.02mm to 0.1mm in size, with a high proportion of partially hydrated pseudo morph grains also apparent, indicating that the binder is well hydrated.

Although the paste is mostly carbonated there are small patches of partially carbonated paste, particularly in dense clinker rich areas where medium to coarse Portlandite crystals are observed concentrated around the perimeter of adjacent aggregate particles.

Voids and microcracks

Voids are rare and where observed are entrapped air voids, which are typically irregular in shape, being compressed between aggregate particles. The voids measure from 0.03mm to 1.0mm in size. The voids were noted to contain a patchy fine lining of secondary minerals, with both coarse Portlandite and Calcite noted to be present.

Cracks are very rare with that observed appearing to be a localised feature, connected to an outer surface, from where it extends into the fabric to depth of 4.8mm. The crack skirts aggregate particles and ranges in width from 0.04mm, at the surface, to <0.01mm at a depth of 2.2mm, and is typical of an early plastic and drying shrinkage feature. The crack contains patchy portlandite lining its margins at depth with calcite lining the outer section.

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

Sample Ref:	SR2736-S9	
Constituents	%	
Aggregate	**Inclusions as binder**	**Inclusions as Aggregate**
Quartz	50.7	50.7
Feldspar	10.2	10.2
Igneous rock fragments	4.6	4.6
Chert	3.7	3.7
Opaque	0.1	0.1
Lime Inclusions	-	0
Total Aggregate	**69.3**	**69.3**
Binder (Paste)	24.0	27.0
Clinker	3.9	3.9
Lime Inclusions	0	-
Portlandite	1.0	1.0
Secondary products/Calcite	0.8	0.8
Total Binder	**30.7**	**30.7**
Total Constituents	**100.0**	**100.0**
Voids	2.3	2.3
Cracks	0.6	0.6
Total: Cracks + Voids	**2.9**	**2.9**
Mix Composition, by volume		
	Total	**Effective**
Binder: Aggregate Ratio	**1.0 : 2.3**	**1.0 : 2.3**

Table No. 5: Modal Analysis carried out on thin section prepared from sample S9.

Photomicrographs:

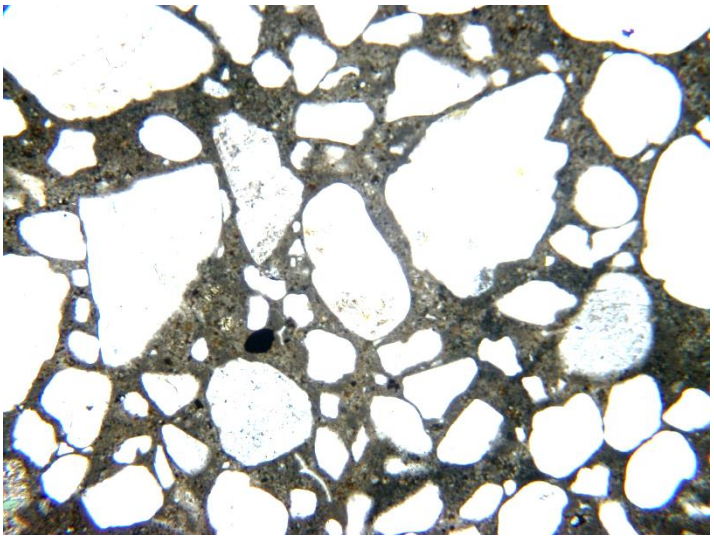


Plate No. 21:

A view in plane polarised light (ppl). This shows a typical area of the mortar. The paste in view is well compacted and relatively dense and mostly carbonated. There is an abundance of clinker apparent distributed throughout the paste, with this dominated by Belite with minor Gehlenite in the area in view. The aggregates are dominated by quartz in this view, with minor feldspar along with trace proportions of igneous rock fragments.

Porosity is highlighted by the blue dyed resin.

Field of view 2.4mm.

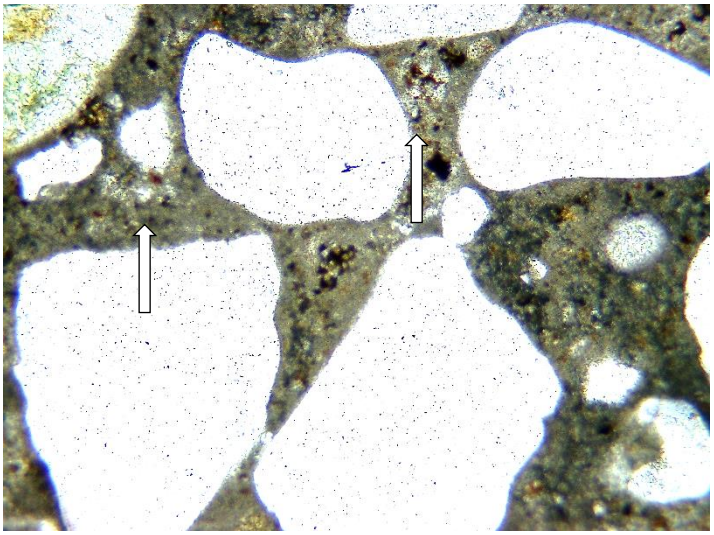


Plate No. 22:

Another view, at higher magnification, of a binder rich area of the mortar where an abundance of cement clinker can be seen, with Alite and Belite dominant along with trace proportions of Gehlenite. Belite clusters can be seen clearly within the paste, with Alite also present, upper centre, left upper quarter and centre right, examples are arrowed in plate, note the low Ferrite content in the cement clinker (normally dark brown/black). The aggregates in view are mostly of quartz.

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

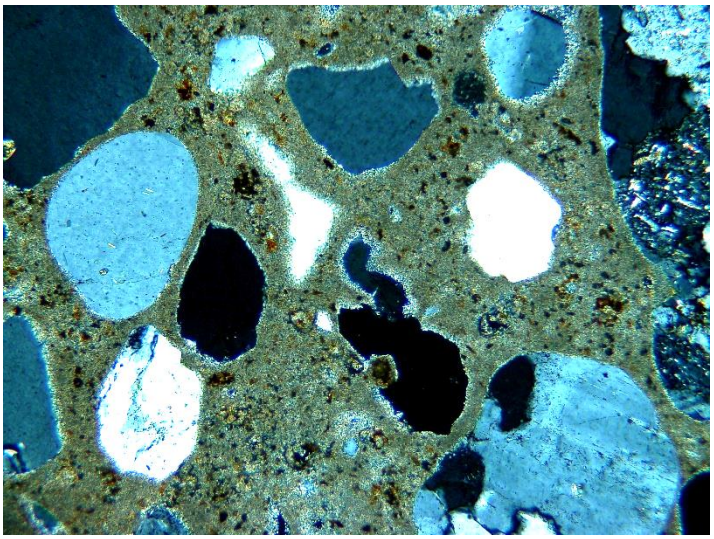


Plate No. 23:

A view in Cross polarised light (xpl), of an area containing fine clinker grains distributed throughout and with a void in the lower centre of plate. The void is rimmed with medium to coarse Portlandite crystals. The clinker in view is very fine and is dominated by Belite clusters many of which also show partial hydration. Aggregates are dominated by quartz, with feldspar and an altered igneous fragment, right side of plate.

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

7.4 Sample SR2736-S11 – Limestone Chip from Wall Masonry

This sample consisted of a small sliver of limestone from the masonry from which the Chapel was constructed.

The limestone is composed of fragmented, abraded and micritised biogenic debris. The fragments are well sorted, with an obvious absence of finely crystalline calcite mud (micrite) and a small range in particle size.

Fragments, include echinoderms, bryozoa, the micritised rims of brachiopods/bivalves, foraminifera and indeterminate bioclasts. Commonly the fossil debris is represented by micrite and the internal parts of the fossils are replaced by blocky calcite. Ooliths are preserved in only trace amounts. The fragments are well cemented by calcite. This ranges from poikilotopic calcite, where bioclastic material is enclosed in one crystal, and blocky, to drusy, where isolated voids are rimmed with separate crystals.

The limestone was indicated by comparison against data obtained on line, to be typical of Indiana Limestone.

Photomicrographs:

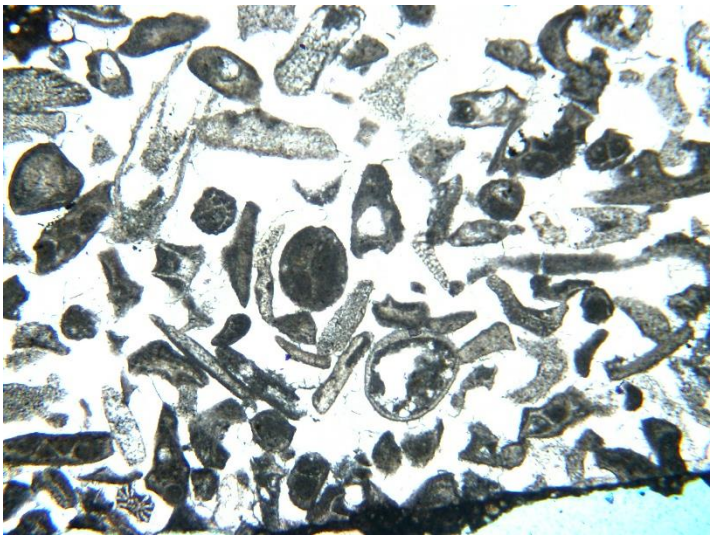


Plate No. 24:

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

The rock fabric is relatively dense with low microporosity apparent.

The bioclasts can be clearly seen bound within a calcite matrix.

Porosity is highlighted by the blue dyed resin.

Field of view 2.4mm.

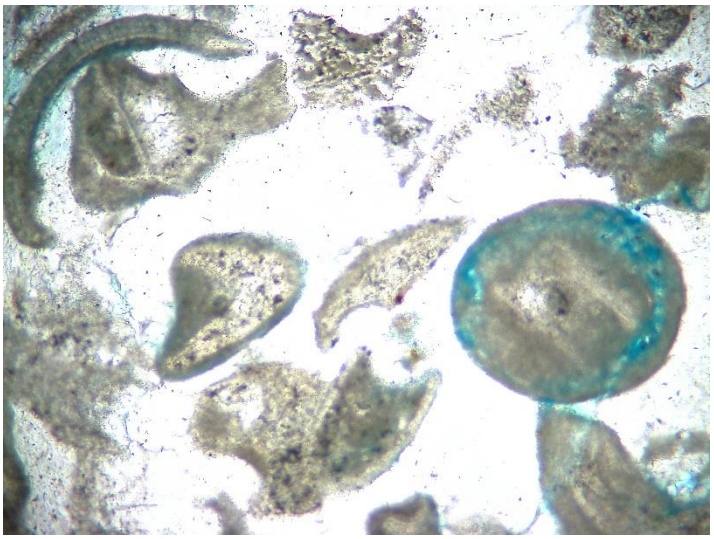


Plate No. 25:

A view in plane polarised light (ppl) at higher magnification to give clearer detail of the bioclastic debris from which the limestone is formed.

Porosity is highlighted by the blue dyed resin.

Field of view 1.2mm.

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 some of the pointing mortars perhaps from later repointing work/repairs.

The binders detected range from non to feebly hydraulic Calcium limes mostly as bedding mortars but locally also in pointing. The lime used in the form of a hydrate.

It is also considered that some of the mortars, S4b (pointing) and S8, had been mixed using a moderate to eminently hydraulic lime, again in the form of a hydrate.

Whereas, samples S3 and S9 appearing to have been made with a Portland cement type binder and a natural sand, whereas sample S5 is a cement/lime and sand mix.

Sample S9 has the features that would infer that the mortar had been made with a white cement and this may represent a later repair.

None of samples contained any Dolomitic limes.

Details of the mixes are summarized below:

Sample Ref.	**S1**	**S4b**	**S6**	**S9**	**S3**	**S5**
Volume Proportions (by acid digestion)						
Binder content	1.0		1.0	1.0		
Fine Aggregate (Sand)	1.5		2.1	2.5		
Volume Proportions (by Chemical Analysis)						
Binder content					1.0	1.0
Lime content					-	1.1
Fine Aggregate (Sand)					5.3	4.5
By modal analysis						
Binder: Agg. by vol. (Total)	1.0:1.7	1.0:1.9		1.0:2.3		
(Effective)	1.0:1.9	1.0:2.1		1.0:2.3		

Aggregates

All the aggregates in the masonry mortars are quartz rich natural aggregates, with only minimal difference in particle size between samples and as the mineralogy is similar, it is therefore likely that they had all been obtained from the same, or very similar, local source.

Knowledge of the local geology would be required to assess this further, to identify the source and determine if the mineral variations are such as to infer different sources, or periods of construction.

In addition to the above it was confirmed that sample S8 (Salt – Mortar ex Basement) had been affected by sulphates with those identified being an alkali sulphate. This if confined can be disruption to the expansive nature of these salts as the precipitate and grow. They also tend to by hygroscopic and can be deliquescent and, if to be removed, should be dry brushed off the building fabric, and disposed of away from the building.

9.0 Quality Statement

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

The observations, analysis results, and comments offered herein, relate only to the samples of mortar received from Berggren Architects on the 25th June 2019, which were identified as materials removed from the fabric of the Rudge Memorial Chapel, Lincoln, Nebraska, USA.

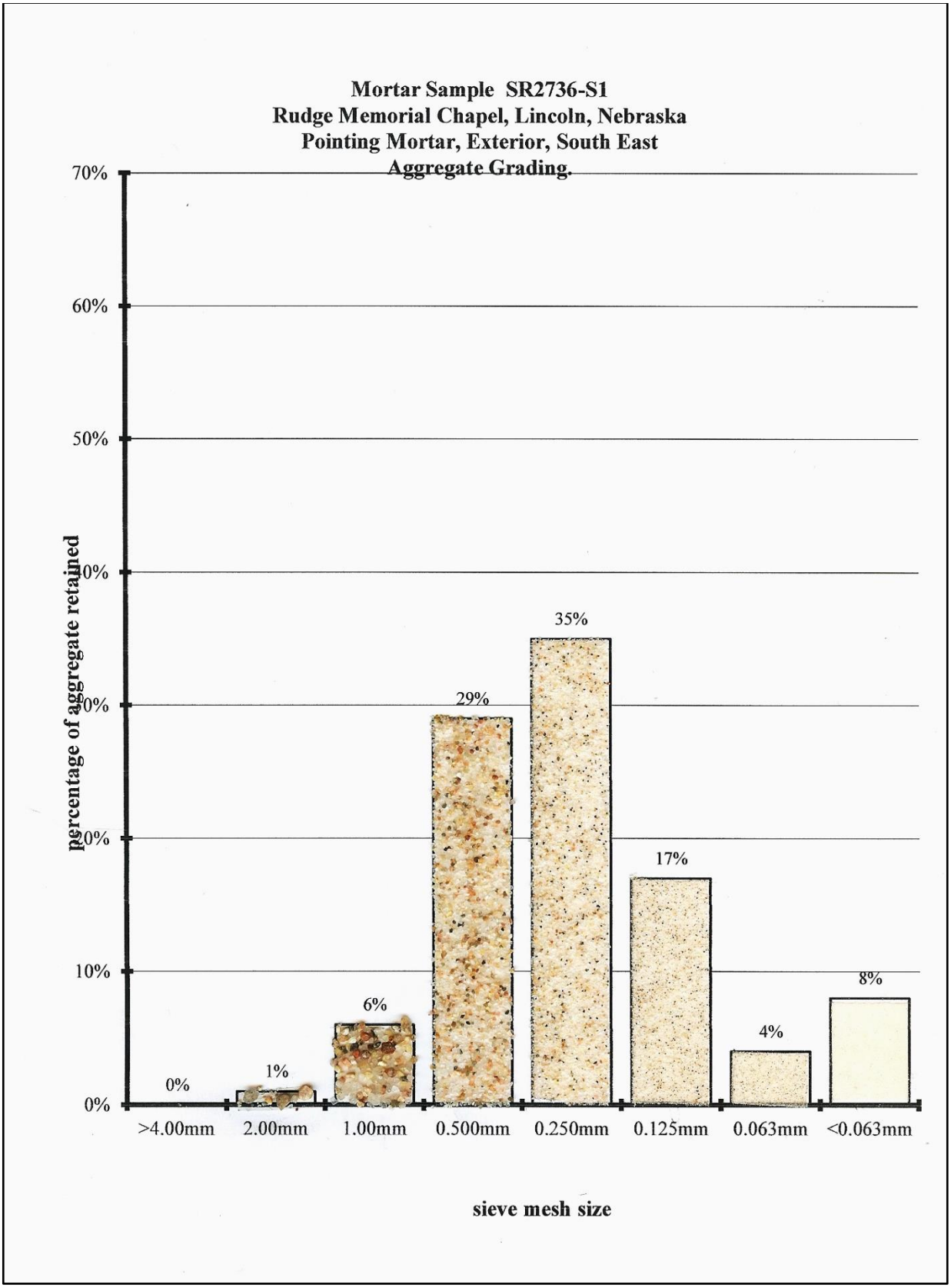


Figure No. 1: Grading of Aggregate from sample SR2736-S1

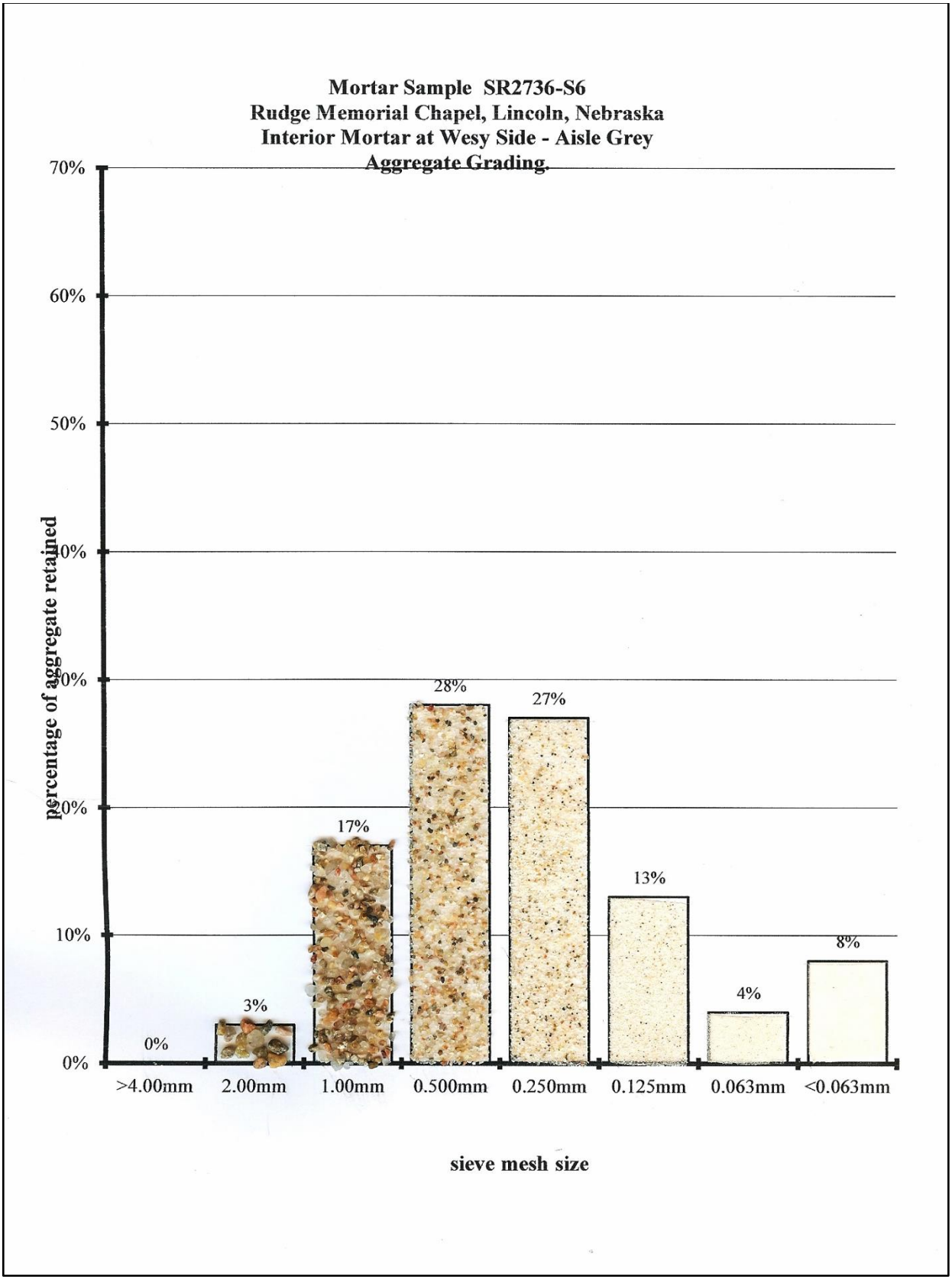


Figure No. 2: Grading of Aggregate from sample SR2736-S6

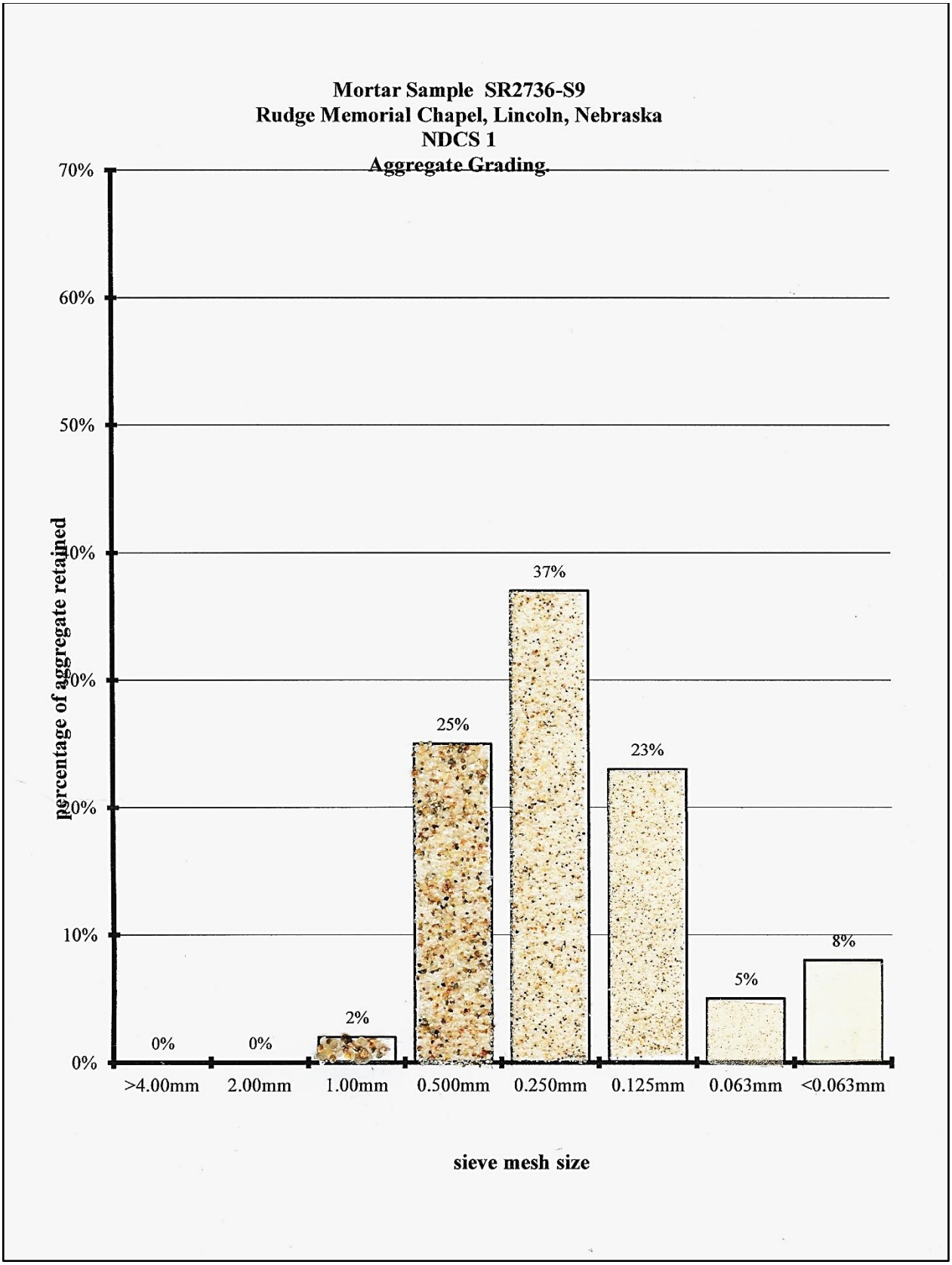


Figure No. 3: Grading of Aggregate from sample SR2736-S9

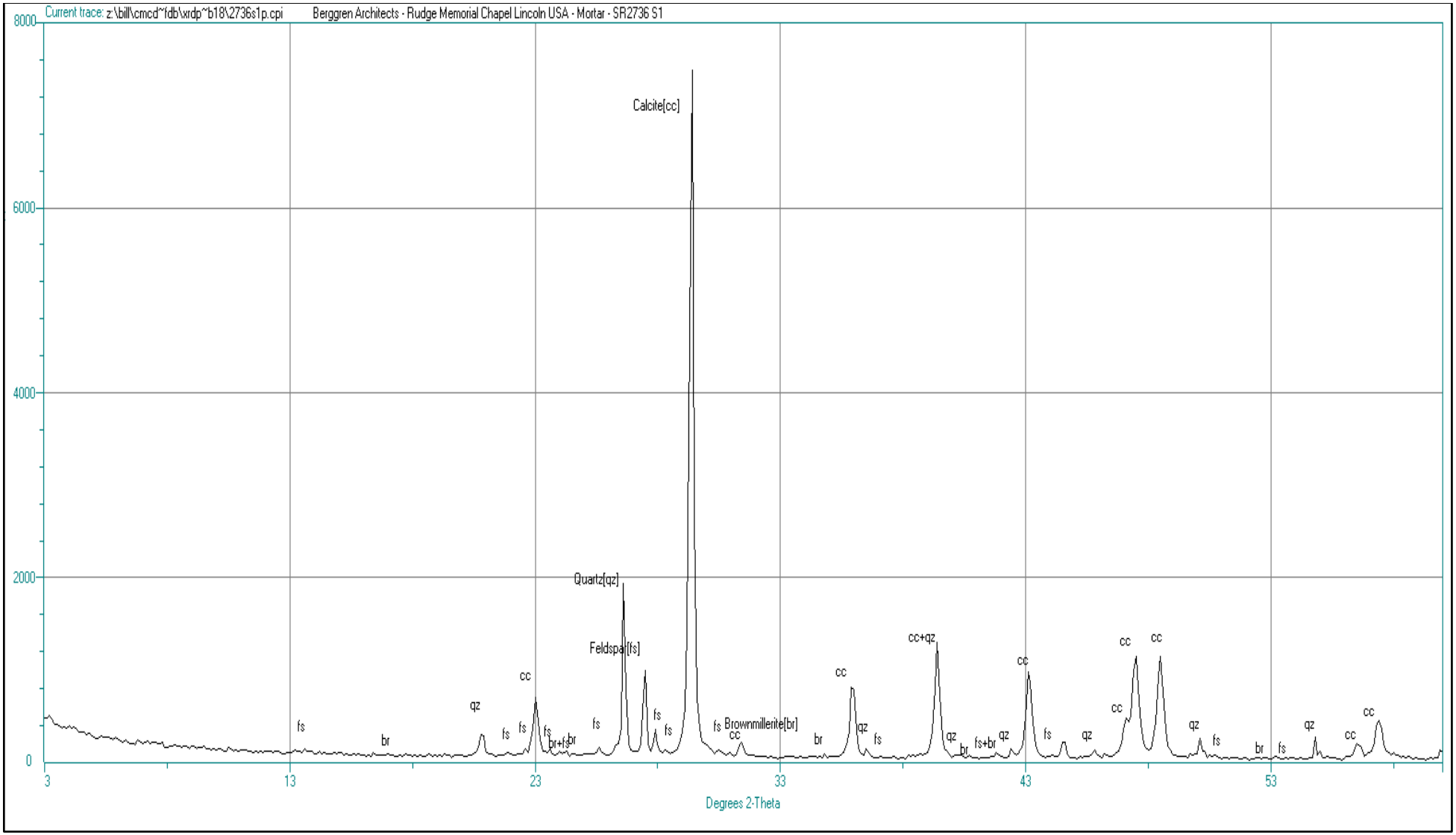


Figure No. 4 – SR2736-S1 – Exterior, S.E. #1 – Pointing Mortar.

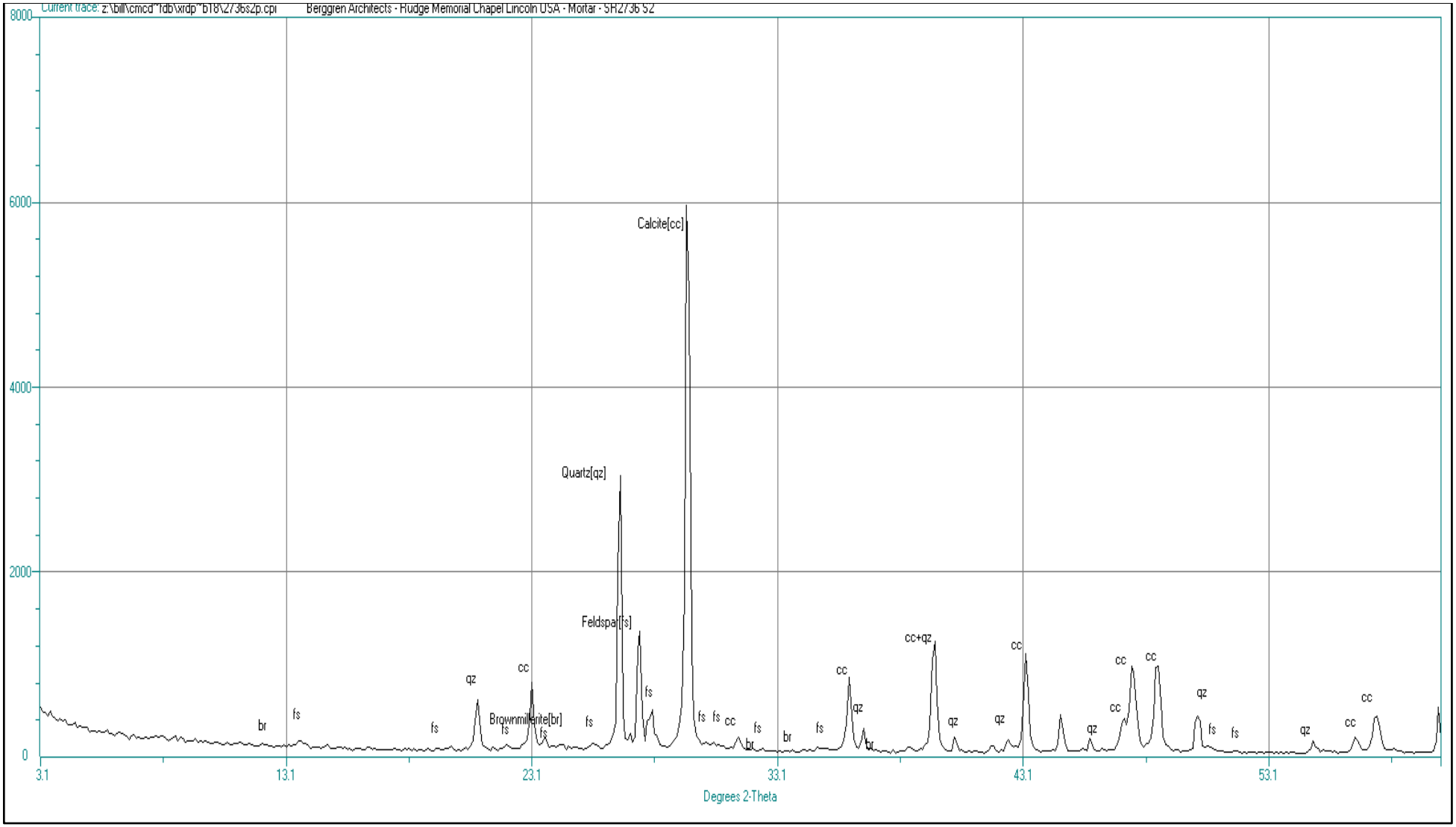


Figure No. 5 – SR2736-S2 – Exterior S.E. #2 – Pointing/Bedding Mortar.

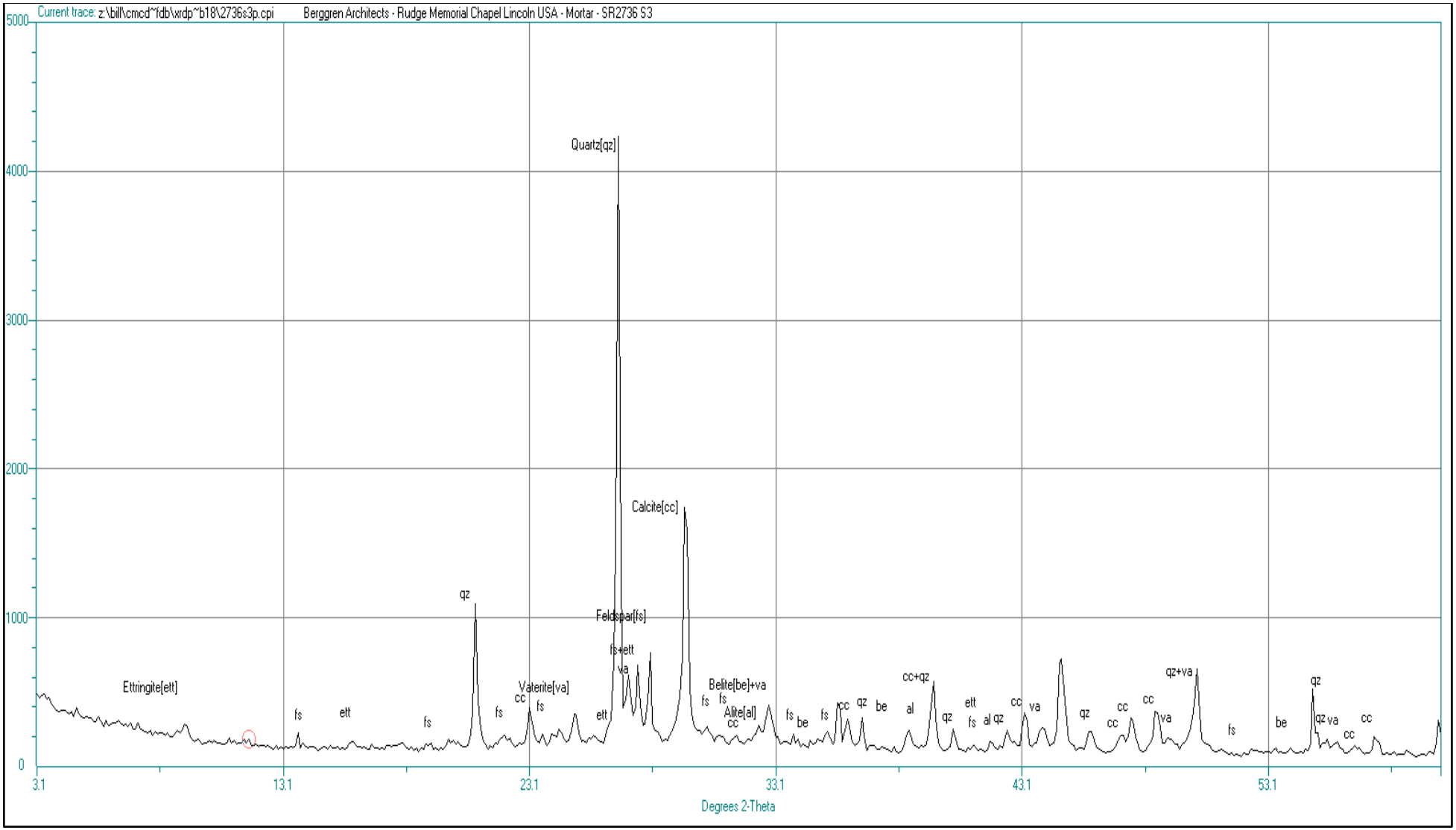


 Figure No. 6 – SR2736-S3 – Exterior N.W. FDN #3 – Pointing Mortar.

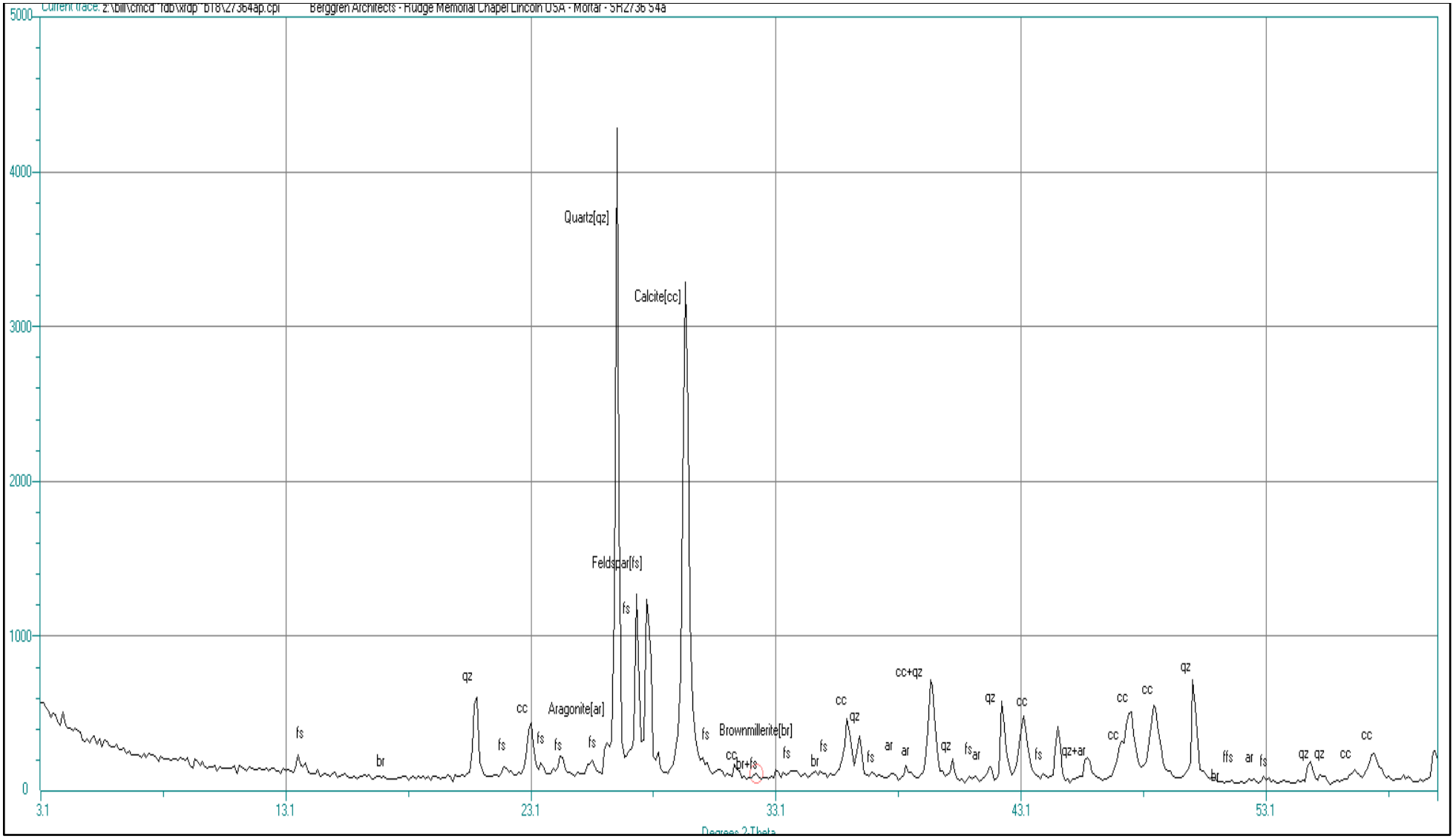


Figure No. 7 – SR2736-S4a – Exterior N.W. Wall #4 – Pointing & Bedding mortar - Bedding.

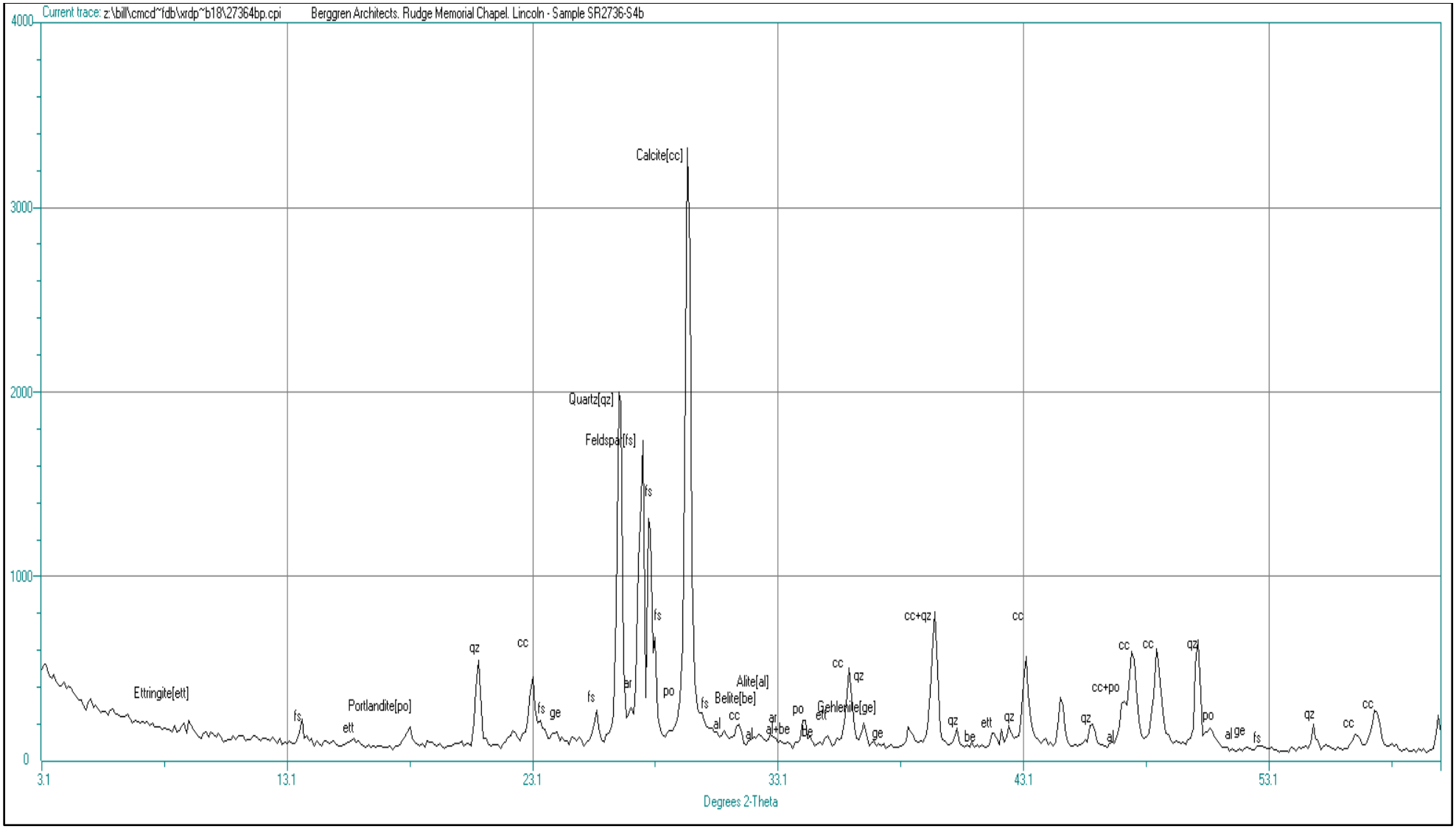


 Figure No. 8 – SR2736-S4b – Exterior N.W. Wall #4 – Pointing & Bedding mortar - Pointing.

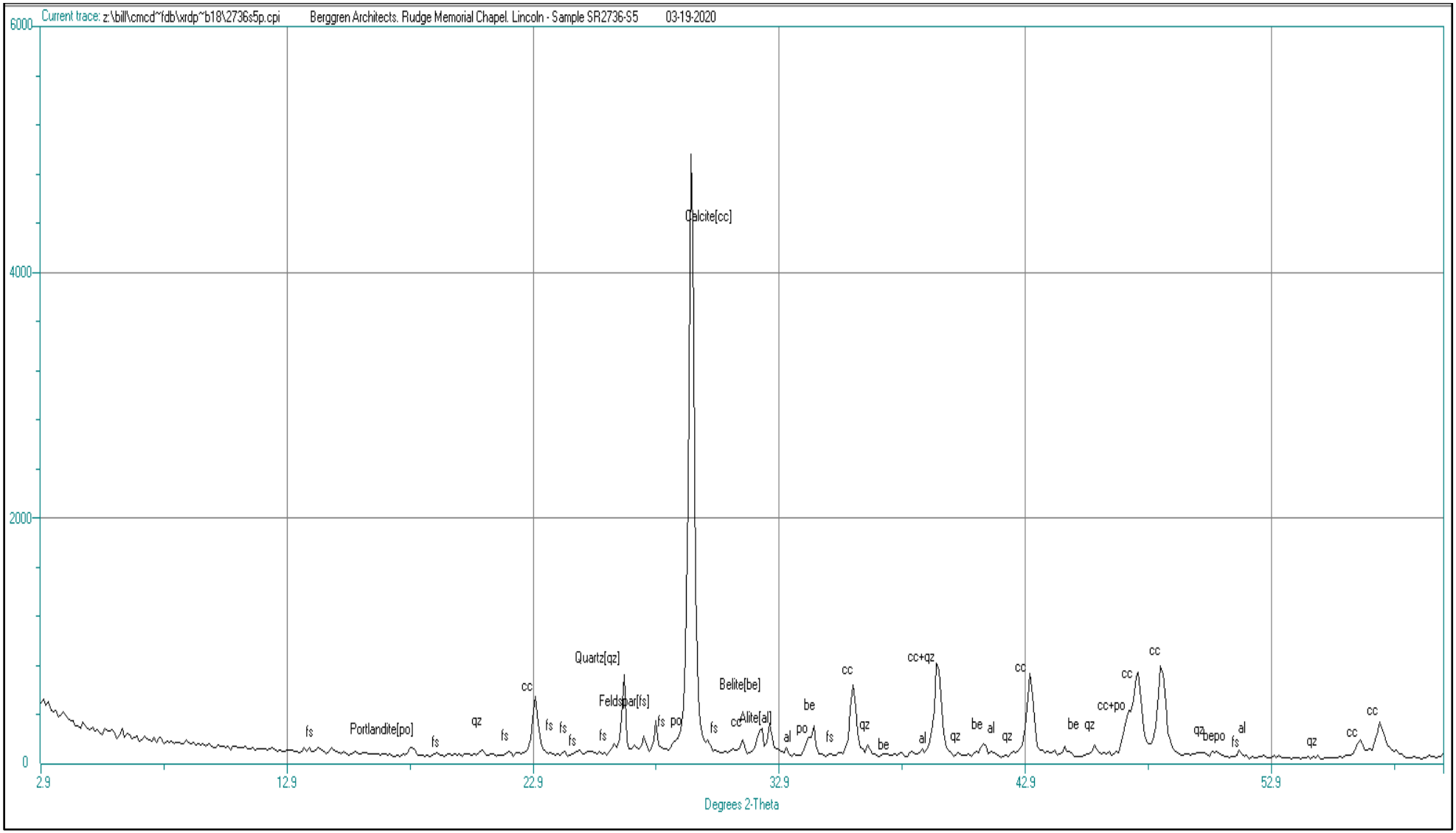


Figure No. 9 – SR2736-S5 – Interior S.E. Arch – Pointing Mortar.

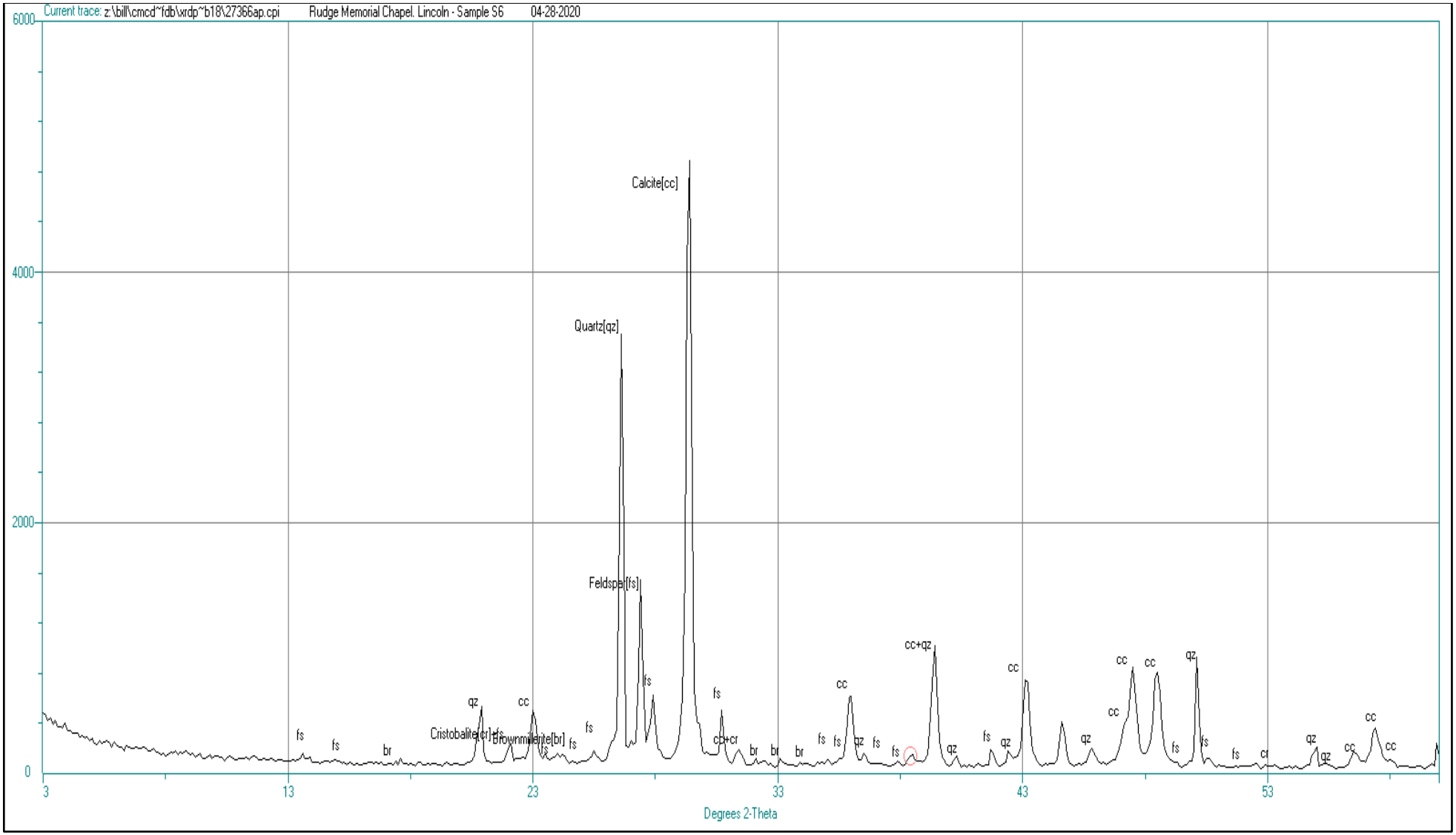


 Figure No. 10 – SR2736-S6a – Interior Mortar at West Side – Aisle, Grey.

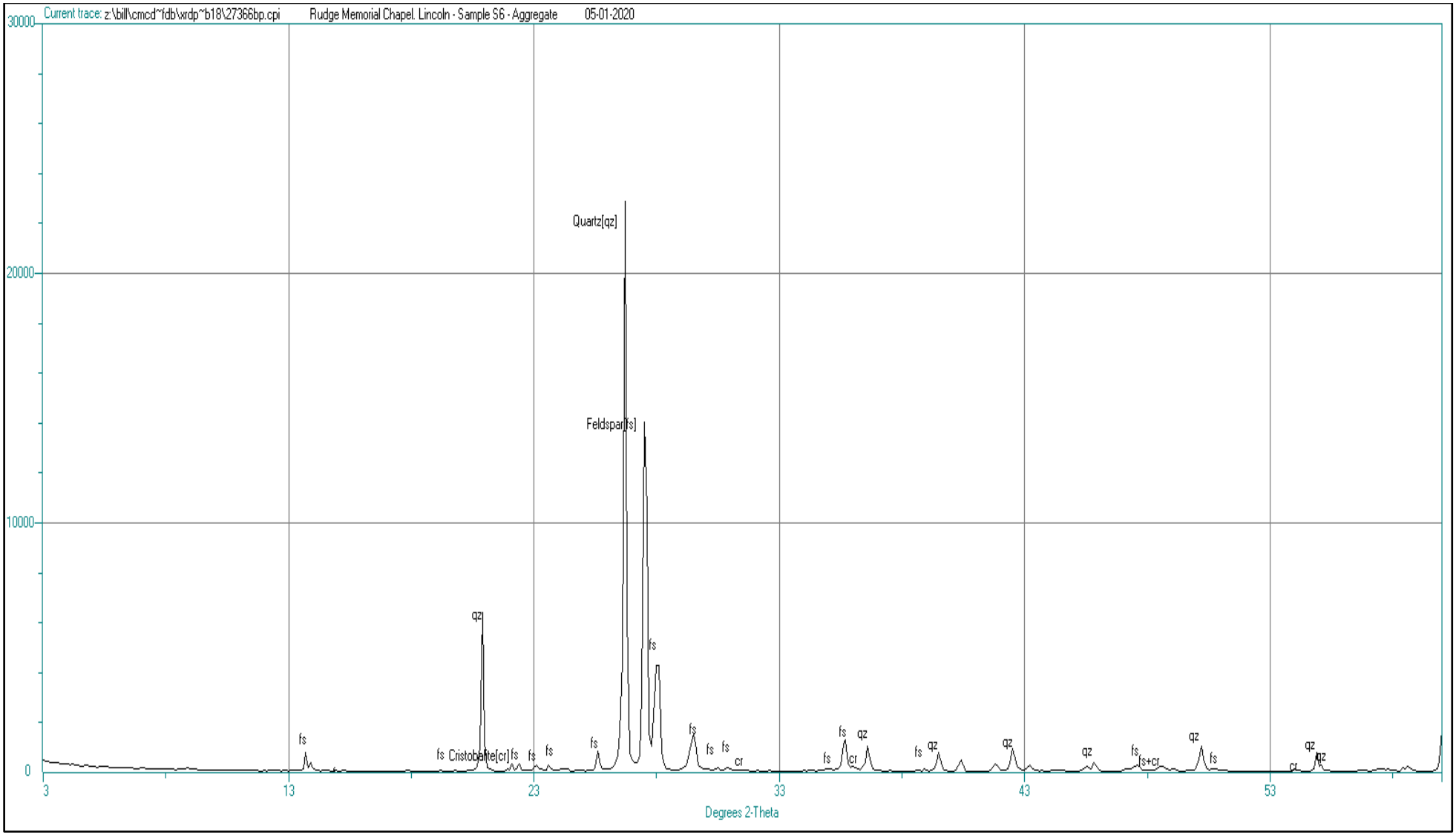


Figure No. 11 – SR2736-S6b – Aggregate from sample of Interior Mortar at west side – Aisle.

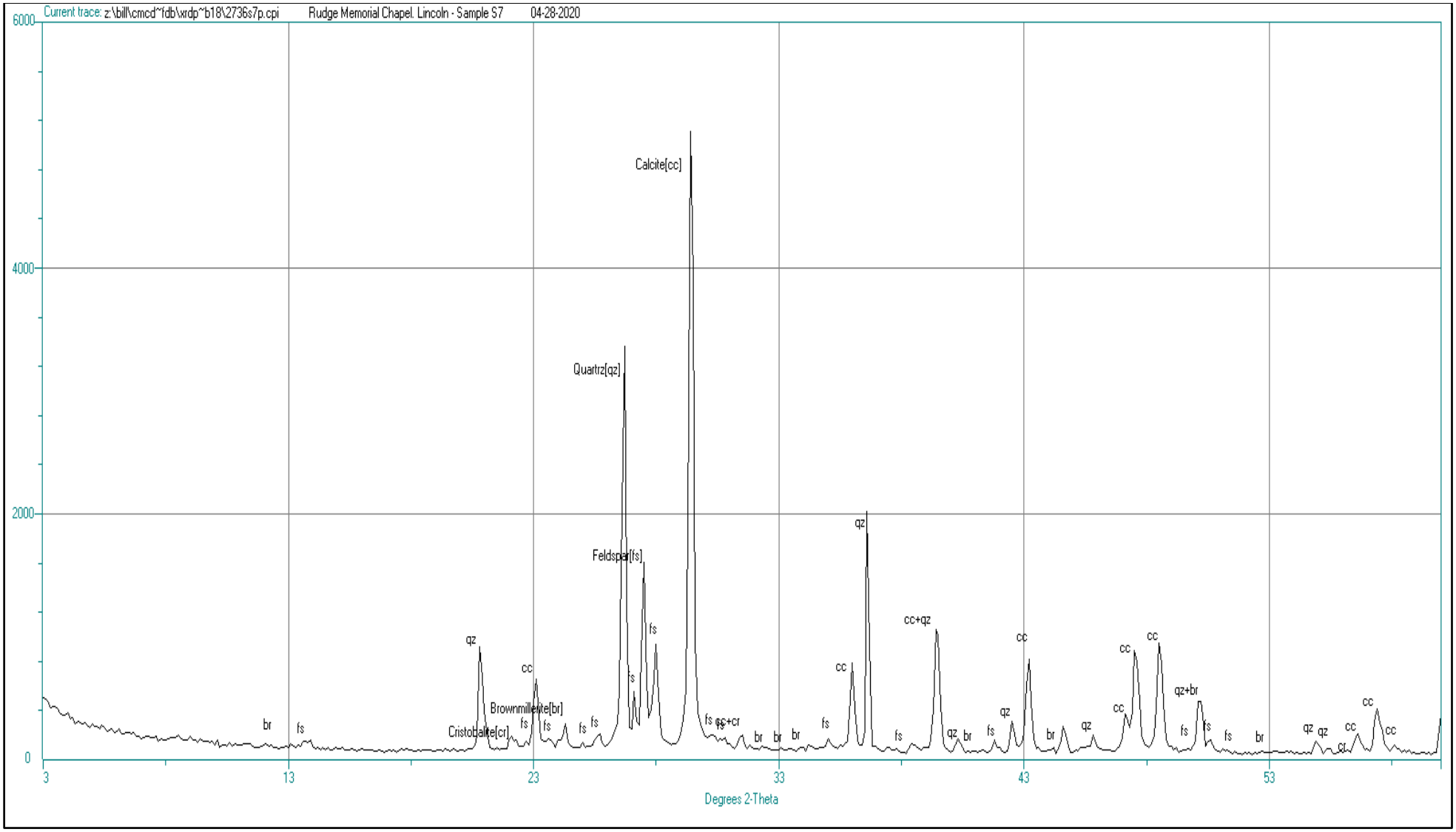


Figure No. 12 – SR2736-S7 – Basement Mortar – In Tile.

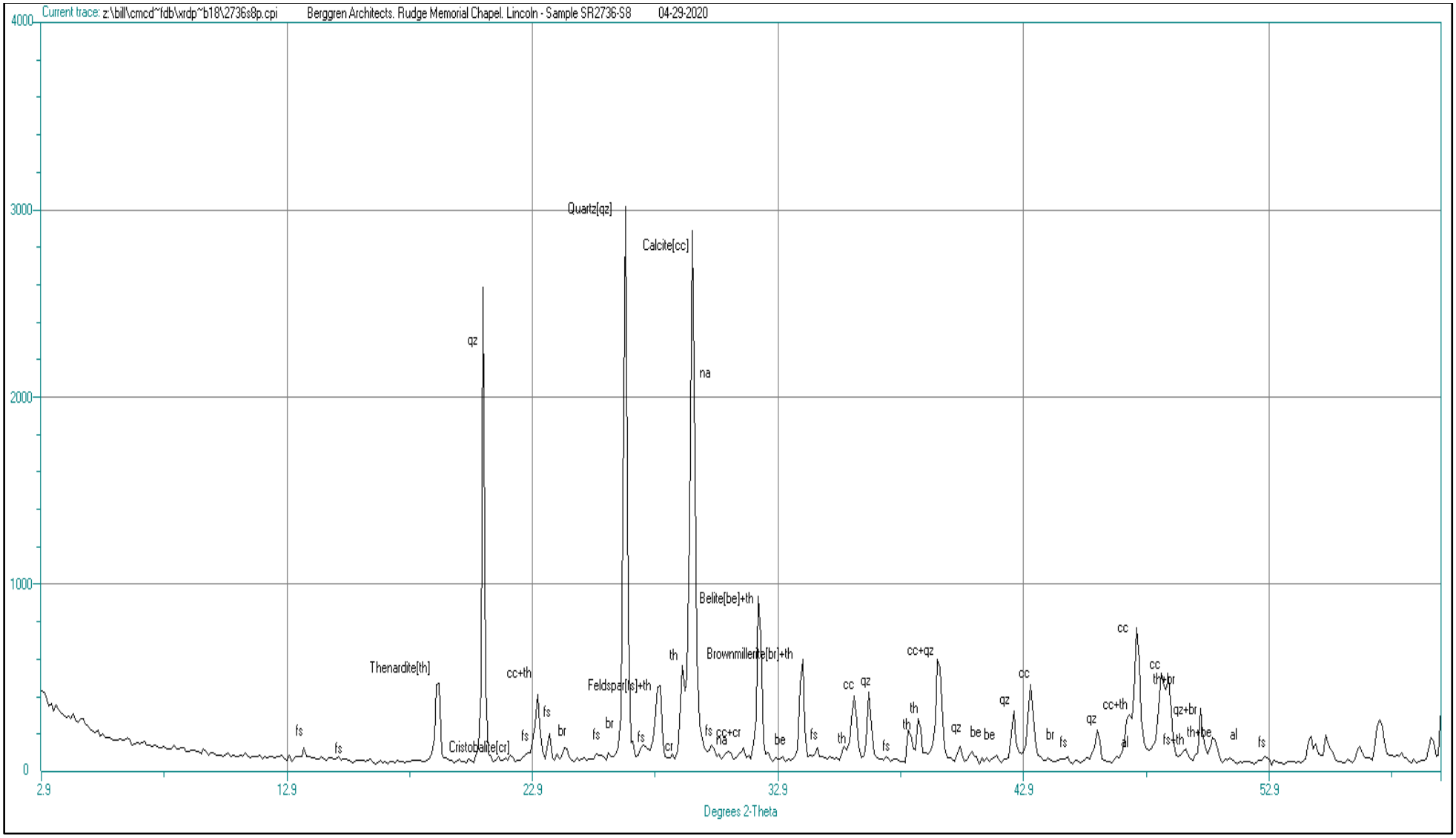


Figure No. 13 – SR2736-S8 – Salt – Mortar – Basement.

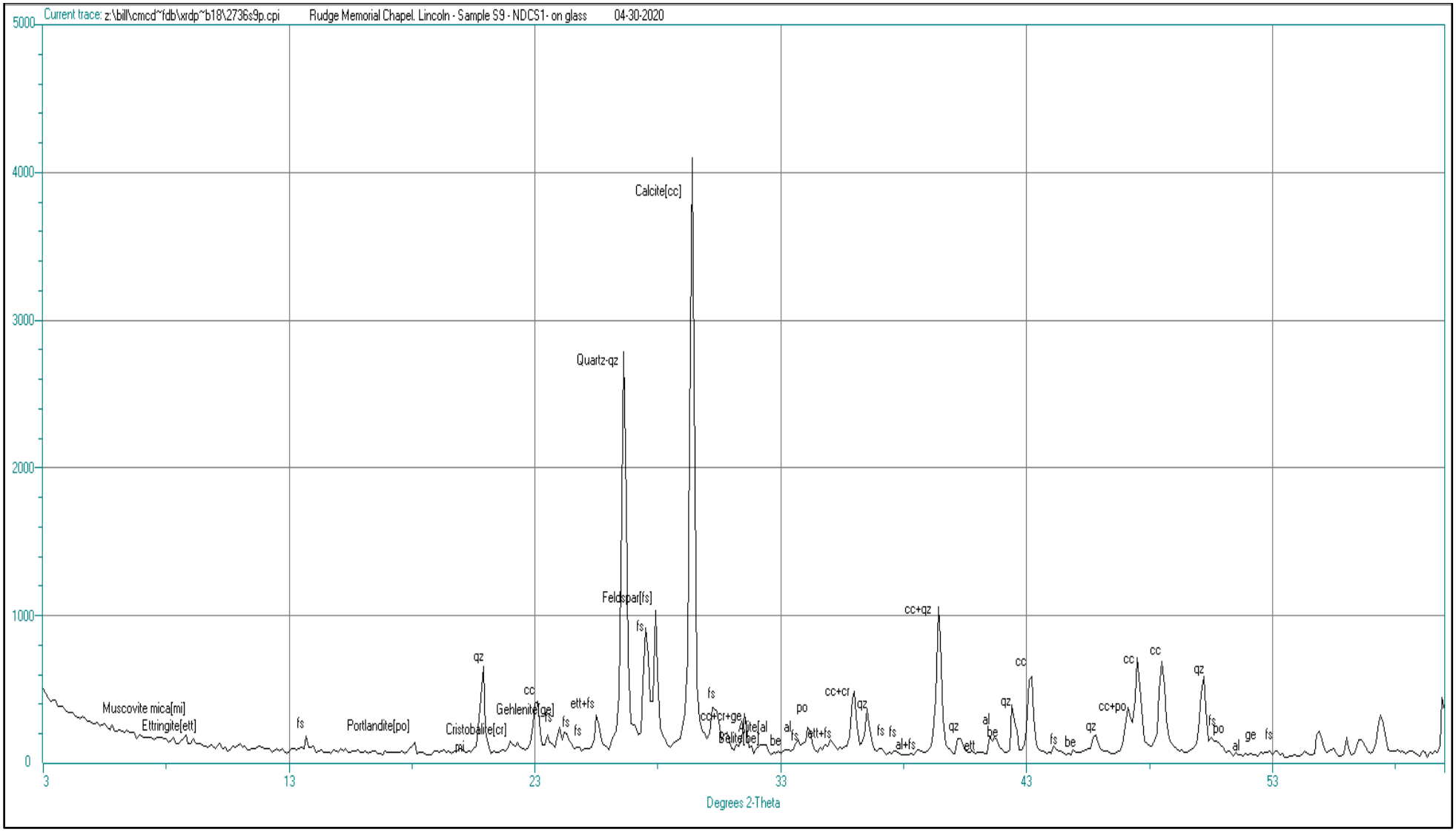


Figure No. 14 – SR2736-S9 - NDCS 1.

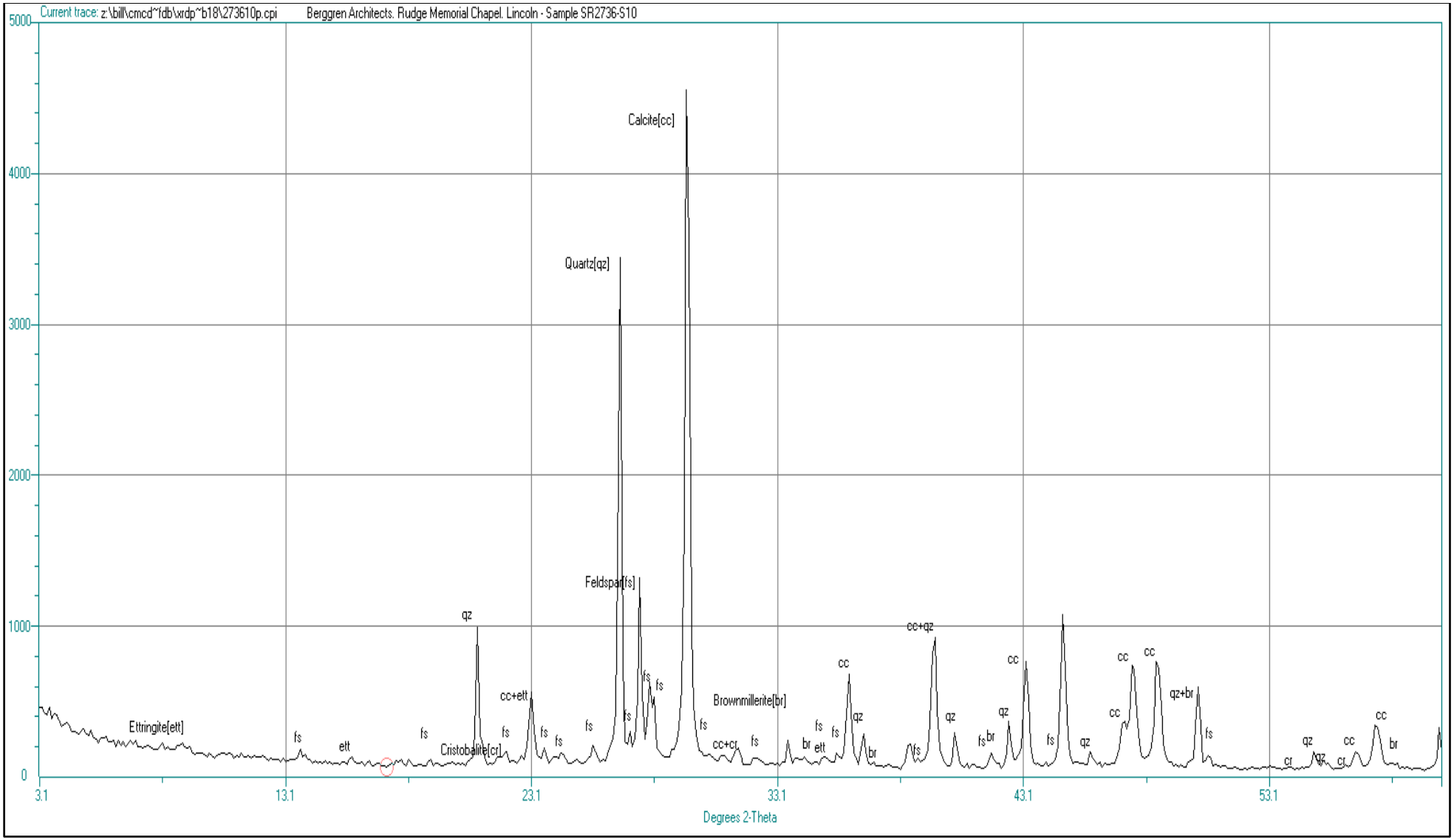


Figure No. 15 – SR2736-S10 - NDCS 2.

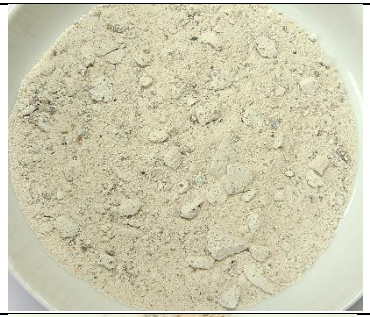
APPENDIX "A"

Sample Log

Sample No.	Location/ Description/Comment
SR2736-S1	Exterior, S.E #1 – Pointing Mortar,
SR2736-S2	Exterior S.E.#2 – Pointing/Bedding Mortar,
SR2736-S3	Exterior N.W. FDN #3 – Pointing Mortar,
SR2736-S4	Exterior N.W. Wall #4 – Pointing Mortar,
SR2736-S5	Interior S.E. Arch – Pointing Mortar,
SR2736-S6	Interior Mortar @ W. Side – Aisle, Grey,
SR2736-S7	Basement Mortar – In Tile,
SR2736-S8	Salt – Mortar – Basement,
SR2736-S9	NDCS 1
SR2736-S10	NDCS 2
SR2736-S11	Limestone Chip with Adhering Mortar.

Laboratory Sample Record Sheet
Project Ref – M/2014/19
Sample Ref – SR 2736

Sample Ref.	As Received weight (g)	Dimensions of largest piece of mortar (mm)	Photo	Colour Munsell Soil Colour Charts	Comments
S1	65.6	59.8 x 24.6 x 21.2		"White"	**Exterior S.E. #1 – Pointing Mortar** The sample consisted of three pieces of a hard well bound mortar. The mortar pieces resisted breaking under firm finger pressure and required an impact to disrupt. On testing a freshly fractured surface with a phenolphthalein indicator solution the mortar was found to be fully carbonated throughout its thickness. No lime inclusions were observed. Aggregates are from a natural quartz rich sand, having a maximum grain size of 2.9mm, and all display water worn surfaces.
S2	36.8	48.0 x 16.2 x 11.0		"White"	**Exterior S.E. #2 – Pointing/Bedding Mortar** A sample comprising small intact fragments of mortar and a quantity of fines. The mortar appears visually to be very similar to that in sample S1 above. The largest intact piece could be broken under firm finger pressure and on testing the freshly fractured surface it was again found to be fully carbonated. Aggregates are again from a water transported natural quartz rich sand with a maximum grain size of 3.1mm. No lime inclusions were observed in this sample.
S3	13.4	38.7 x 17.9 x 12.3		2.5Y 8/1 "White"	**Exterior N.W. FDN #3 – Pointing Mortar** Again, this sample was composed of small fragments and fines. The largest intact fragment was hard, as in sample S1. The outer surface of the intact fragments was coated in a grey coloured granular soiling, with indications of long-term water percolation through the mortar/stone interface. The mortar is soft to moderately hard, with small angular lime inclusions apparent. The mortar is also carbonated and the aggregates are again from a natural sand, similar to samples S1 & 2.

Sample Ref.	As Received weight (g)	Dimensions of largest piece (mm)	Photo	Colour Munsell Soil Colour Charts	Comments
S4	22.9	37.7 x 20.8 x 17.8		"White to Greyish White"	**Exterior N.W. Wall #4 – Pointing Mortar** This sample consists of five intact fragments and a quantity of fines. There are two different mortars in this sample with most being from a hard-repointing mortar, which is only partially carbonated and may be from a white cement pointing, or hydraulic lime. Small pieces of a soft to moderately hard white internal mortar adheres to the harder fragments. Aggregates are again similar to that in sample S1.
S5	42.5	33.4 x 18.4 x 8.0		"White"	**Interior S.E. Arch – Pointing Mortar** This sample contains both intact fragments and fines from the same mortar. The mortar is moderately hard and non-friable and appears to be binder rich. It is fully carbonated and has the appearance of a binder rich mortar. However, the intact fragments were noted to display a water proof property. Aggregates are again from a natural quartz rich sand, having a maximum grain size of 1.7mm. No lime inclusions were apparent in the fragments examined.
S6	82.3	17.1 x 11.1 x 6.4		"White"	**Interior Mortar @ W. Side – Aisle Grey** This sample is mostly of disaggregated mortar fines with a quantity of small mortar fragments. From an examination of the fragments and the fines it is considered that this mortar was similar in composition to that in sample S5 above. Water repellence was noted on some of the fragments but not on all, some of which displayed a high microporosity. The fragments are carbonated as are the fines. Aggregates are again similar to those apparent in the other samples. There were no lime inclusions observed in the fragments examined.
S7	13.41	11.9 x 9.8 x 5.1		7.5 YR 8/1 "White"	**Basement Mortar – In Tile** Another sample which is composed mostly of fines with a few small fragments of intact well bound mortar. The intact pieces are variable with respect to hardness and the colour of the fines is greyer than those in samples S5 & 6 and may be weathered/altered. The sample is fully carbonated and the fragments do not display any water repellent properties. Aggregates are, however, similar to those in the other samples examined.

Sample Ref.	As Received weight (g)	Dimensions of largest piece (mm)	Photo	Colour Munsell Soil Colour Charts	Comments
S8	2.2	Fines only		5Y 8/1 "White" Sand grains	**Salt – Mortar – Basement** Sample is composed essentially of aggregate grains, which are from a natural quartz rich sand having a maximum grain size of 2.7mm. Small fragments of binder are present, with the largest piece measuring 1.4mm, but mostly finer than 0.25mm. the binder may be a lime as the fragments are relatively soft to moderately hard, but they could be powdered with ease. The sample was identified as "Salt - Mortar" Analysis would be required to confirm salts.
S9	11.01	34.7 x 16.5 x 13.4		10YR 8/1 "White"	**NDCS 1** The mortar in this sample is similar to the outer pointing mortar in sample S4. The mortar is hard and well compacted. On testing the mortar, it was found to be fully carbonated and it was noted from water droplet tests that the mortar had a low porosity with the droplets slowly absorbed. Aggregates are again from a quartz rich natural sand, with the grains displayed water worn surfaces, and is similar to that in other samples examined.
S10	10.47	28.7 x 9.1 x 8.0		10YR 8/1 "White"	**NDCS2** This sample is visually similar to sample S9, with the intact pieces being moderately hard, well compacted and when broken, did so with an audible 'snap'. The mortar is fully carbonated and displays a low porosity. Aggregates are again a fine quartz rich natural sand. The binder has the appearance of either a Natural hydraulic lime or a cement/lime/sand mortar, and no lime inclusions were observed within the fabric of the mortar.
S11	0.29	18.5 x 5.5 x 3.3		"White"	**Limestone Chip with Adhering Mortar** This sample consisted of a single small fragment of a crystalline limestone, with a thin coating of mortar along one edge.