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 Pointing Mortar & Plaster Samples

The Anglican Cathedral Church of the Redeemer

City of Calgary, Alberta, Canada

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 31st October 2016

Our Ref: M/1736/16
Your Ref:
Doc. Ref: M173616R1-rev1

Table of Contents

1.0 Introduction

Following a discussion on the analysis of historic mortars with Nigel Copsey of The Earth, Stone & Lime Company, who are Consultants to Macdonald & Lawrence providing expertise in traditional building technology and materials, a cost estimate for the analysis of mortars was provided, by email. The costs were for the analysis of mortar samples for mix composition, including, where possible, the form and type of binder used in the mortar production.

Subsequently samples of mortar and plaster identified as having been sampled from the Anglican Cathedral Church *of the* Redeemer, in the City of Calgary, Alberta, Canada, were received CMC's Stirling Laboratory. Information was also provided by Nigel Copsey, by email, on the background to the construction of the Cathedral and the locations from where the samples were obtained, along with instruction to proceed with the analysis of the samples submitted.

This report details observations from a macroscopic and microscopic examination of the samples along with the results from analysis carried out on the two samples received. The report concludes with an interpretation of the results giving the mix composition of the materials examined and details of the type and form in which the binders were employed in their production.

2.0 Samples

Two samples were received in CMC's Stirling laboratory on the 5th September 2016, with the samples submitted by Nigel Copsey of The Earth, Stone & Lime Company. On receipt in the laboratory the sample details were entered into the sample register and the unique sample reference SR2418 allocated, with the laboratory and Client sample references reproduced below:

CMC Sample Ref.	Client Sample No.	Location/Comment
SR2413 – S1	S1	Pointing Mortar,
SR2413 – S2	S2	Plaster.

3.0 Methods of Examination and Analysis

Following an initial examination of the samples received, it was proposed that they be submitted to the following programme of examination and analysis:

Both samples were initially examined; weighed, measured and photographed, in the as-received condition. Following logging a representative sub-sample was extracted from each with this dried to a constant weight at 70°C to permit the as-received moisture content to be determined.

The samples were also submitted to a detailed examination with the aid of a stereo-binocular microscope, at magnifications up to x 20 to assist in assessing their as received condition. During this examination, small sub-samples were exposed to a range of indicator solutions and reagents to assist in assessing their composition.

Following the initial examination a binder rich sub-sample was prepared from each sample for analysis by X-ray Powder Diffraction (XRD). This form of analysis was employed to aid identification of the type of binder used in each of the mortar samples and permits an assessment of whether there were any reaction products present that may indicate whether the mortar had undergone chemical attack from environmental pollutants or other contaminants.

A petrographic thin section was also prepared from intact pieces from both samples S1and S2, with these submitted to a microscopic examination with an Olympus BH2 polarised light microscope to assist in clarifying the form in which the binder was used, and to confirm the mix composition and permit an assessment of the structure of the mortar fabric.

The mix composition was initially determined on both samples by acid digestion, following the procedures of the Scottish Lime Centre Trust, with grading of the recovered aggregate. However, as sample S1 was indicated, both from the results of the XRD analysis, and from the microscopic examination of the petrographic thin section, to contain hydraulic components a further sub-sample was analysed by the methods of British Standard BS 4551: 2005 + A1: 2010 +A2 2013 "Mortar - Methods of Test for Mortar and Screed - Chemical Analysis and Physical Testing ".

4.0 Macroscopic Examination

Observations from the examination of the samples are presented in the following sections of this report, with a summary of the properties of the samples, as received, given below:

CMC Sample Ref	Client Ref	Mass Received (grams)	No. of Pieces	Size of Largest Intact Piece (mm)	Colour[1] Sample Munsell Chart	Moisture content % by dry mass
SR2418 - S1	S1	23.7	3 fragments	38.9 x 16.4 x 14.2	Gley1 10Y 8/1"Light Greenish Grey"	1.1
SR2418 - S2	S2	14.9	1 fragment	32.0 x 23.6 x 9.9	5Y 8/1 "White"	0.9.

Images of the building from the samples were obtained and the location from which sample S1 was obtained was provided by Nigel Copsey and these are reproduced below:

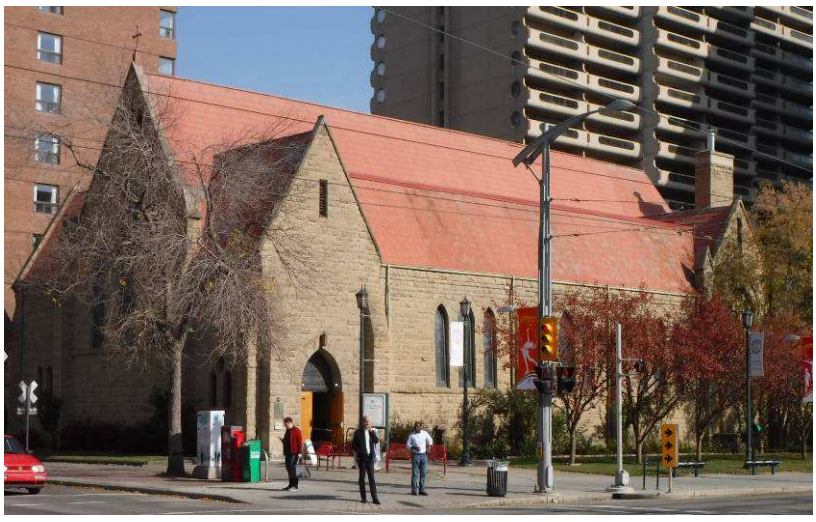

Plate No. 1:

The Anglican Cathedral Church *of the* Redeemer, City of Calgary, Alberta Canada, from which the samples were obtained.

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

Plate No. 2: Location of pointing sample S1

Plate No. 3: Close-up of eroded stone and bedding mortar

From an examination of the mortar joints in plates supplied it would appear that the pointing and bedding mortars contained either limestone aggregates or lime inclusions (unmixed binder) and if correct the latter could infer that the mortars were mixed as a "Hot Lime", however, to clarify this the samples received were to be examined in greater detail.

Observations from a visual examination of the samples as received are presented below:

4.1 Sample SR2413 - S1: Pointing Mortar

This sample is from a mortar that is firm, moderately hard and locally brittle. The mortar is well compacted with no obvious voids observed in the hand specimen, although the mortar was found, from a water droplet test, to display a well connected porosity. The mortar was noted to be binder rich and contain sparse light coloured inclusions, which measured up to 2.4mm, although the majority ranged from 0.2mm to 1.2mm in size.

A phenolphthalein indicator test provided a negative response suggesting that the binder was fully carbonated throughout its thickness. Oxidising agents also produced a negative response indicating that there were no organic components within the thickness of the mortar sample tested.

The paste was generally uniform with the aggregate well encapsulated in, and surrounded by, the paste with the abundance and appearance of the mortar suggesting a binder rich mix. The inclusions observed are variable in shape and texture and some were noticeably hard and these may these may be either limestone aggregate or infer the presence of under burnt or overburnt lime particles. Therefore, to assist in clarifying whether the inclusions were the residue from an incompletely slaked quicklime, or the residue from a putty lime from which all of the over/under burnt fragments had not been screened before use, or a pre-slaked quicklime run to a hydrate, used unscreened, or if they are simply aggregate particles, a petrographic thin section was prepared to permit a more detailed examination.

There is also evidence of water percolation with localised leaching and redeposition of binder components within the near surface pore structure on one surface, presumably an outer, or possibly a masonry contact, surface, all other sample surfaces were free of any redeposited material.

Plates No. 4 & 5: The left plate shows the sample as received, with a lightly soiled surface with localised redeposited (leached) binder encapsulating the soiling on one surface. The largest mortar piece was firm to the touch but could be broken under firm finger pressure and once disrupted it could be further powdered under moderate finger pressure. The plate on the right shows a close-up of a freshly fractured surface through the largest fragment, where a sub-angular inclusion can be seen arrowed in the plate, with the inclusion surrounded by an area of paste rich matrix.

The intermediate sized piece retained a darker outer surface and this was also marginally harder than the other two pieces in the sample, but there is insufficient to permits its analysis on its own, The hardness may simply be due to a reaction with surface absorbed pollutants or the redeposition of binder leached from deeper within the joint.

4.2 Sample SR2413 - S2: Plaster

This sample consisted of a single piece of plaster which was again binder rich, visually richer than that in sample S1, with features that would infer that it had been perhaps also placed in a more workable (wetter) condition and the aggregates appeared finer graded. There was no evidence of inclusions in the hand specimen examined.

The plaster was again hard and brittle, but unlike sample S1, when broken the mortar in this sample could be disrupted and powdered under light to moderate finger pressure. The plaster was also found, from the phenolphthalein indicator test to be carbonated throughout its thickness, with tests employing oxidising agents again producing a negative response.

The plaster displayed a well connected pore structure, with the rapid absorption of water droplets placed onto both a freshly fractured and as placed contact surfaces.

It was noted on fracturing that the plaster contained lengths of wood fibre, with these randomly orientated and randomly distributed throughout the sample received. It is, therefore, possible that the wood fibre (coarse sawdust) had been added to the plaster rather than be present as a contaminant. Perhaps added in lieu of hair, as a reinforcement. The wood fibres ranged in length from 3.8 to 7.2mm with widths ranging from 0.12 to 0.36mm. However, given the small size of the sample, it is possible that this was obtained from an area where the plaster that had been contaminated at time of placing.


Plates No. 6 & 7: The left plate shows the condition of sample S2 as-received, with the right plate showing a magnified view of a freshly fractured surface through the thickness of the plate, where it was noted that the mortar contained an abundance of fine wood fibres, which given its distribution may infer that had been added purposefully to the plaster.

5.0 Microscopic Examination

Petrographic thin sections were prepared from both samples S1 and S2, with the samples aligned to permit the maximum area possible on the slides.

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

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

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

5.1 Sample SR2413 - S1: Pointing Mortar

Aggregate

The aggregates are composed mainly of limestone fragments, along with a proportion of quartz grains, chalcedony, indeterminate weathered metamorphic particles with minor feldspar and shale. The limestone is dominated by calcareous limestone/marble along with dolomitic limestone and siliceous limestone.

The aggregates are mostly sub angular to sub-round in shape with a low abundance of angular fractured grains, the latter displaying minor internal fracturing but these are in trace proportions and would infer a proportion of crushed aggregate in the sand. A proportion of the aggregate particles show alteration of weaker minerals, to varying degrees, with these having the appearance of pre-encapsulation features, however, there inclusion do not appear to be detrimental to the performance of the mortar.

The aggregates are well bound within the paste and although peripheral microcracks are observed, where present, these do not appear to inhibit the aggregate/paste bond. The aggregates range in size from 0.03mm to 1.8mm (coarse silt to fine sand) in the section examined.

Binder

The binder is typical of a lime mortar that was made with a high binder content, i.e. a binder rich mortar. The paste has the appearance of a non-hydraulic lime over most of the area of the section. However, locally there are clusters of hydraulic components present, which would suggest either the addition of a lime having a hydraulic component, or an early Portland cement, to a non-hydraulic lime mortar, or the use of a binder prepared from a randomly variable limestone deposit. The hydraulic components are observed in the form of unhydrated clinker, with, where observed, this mostly in the form of fine to coarse Belite clusters, with Ferrite, and as partially hydrated pseudomorph clinker grains. There is one large sub-rounded inclusion which has the appearance of an overburnt lime, measuring 3.2mm x 1.4mm in area, which was observed to contain coarse clinker, i.e. Belite, Ferrite, and possibly Calcium Aluminates, confirming that some of the limestone had been calcined at a temperature sufficient to produce a proportion of hydraulic lime clinker.

The paste also displays random patches of high microporosity and is transected by a network of very fine shrinkage crack, consistent with a lime rich mix that had undergone early plastic and early drying shrinkage, common in binder rich putty mixes.

The paste is fully carbonated and there is an proportion of lime inclusions present, but where observed these have the appearance of having formed from both incompletely slaked quicklime and putty, the latter possibly indicating a high degree of slaking of the quicklime, but these have not all diffused into the surrounding paste.

The lime inclusions range in size from 0.3mm to 3.2mm in the section examined, with these being round to sub rounded shape, with diffused (or partially diffused) margins, typical of that associated with putty lime, whilst others show well defined angular margins with little evidence of diffusion into the surrounding paste. Although the latter is a feature normally associated with a mortar mixed in the form of a "Hot Lime" where the quicklime was added to the sand and slaked in place. However, the absence of any evidence of peripheral compaction or spherical air voids concentrations, adjacent to particles, would infer that the mixed material had probably been dry-slaked and allowed to cool before being screened (to remove the coarser unslaked particles and oversized aggregate) and remixed prior to placing with the mortar placed as a cold mix. A few of the underburnt inclusions retain an imprint of the original rock fabric, which although confirming that the limestone burned to produce the binder contained both non-siliceous and siliceous limestone it was noted that their texture and composition appeared to differ from that of the calcareous aggregates in the mortar, in that they are not dolomitic, nor display the metamorphic imprint apparent in many of the limestone particles in the aggregate. This suggesting the limestone used in the binder production was probably from a different source to that from which the aggregates had originated.

Voids and microcracks

Voids are very rare but where present are as discrete entrapped air voids which are typically irregular in shape and up to 0.65mm in size. The voids are mostly free on linings, with the exception of those adjacent to one outer or masonry contact surface, where they contain fringes of fine calcite, with localised clusters of gypsum crystals.

Cracks are abundant and meander through the paste linking voids, aggregate and lime inclusions, with the crack network extending across the full width of the section. The cracks are very fine, ranging in width from <0.02mm to 0.1mm, and are typical of drying shrinkage features. The cracks are mostly free of linings and they do not appear to have acted as channel ways for the migration of percolating waters, in the section examined.

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

Sample Ref:	**SR2413-S1**	
Constituents	**%**	
Aggregate	**Inclusions as binder**	**Inclusions as Aggregate**
Quartz	9.5	9.5
Lithic Fragments	6.5	6.5
Calcareous Silicates	10.3	10.3
Limestone (Calcite)	15.8	15.8
Dolomitic Aggregate	7.7	7.7
Lime inclusions	-	4.4
Total Aggregate	**49.8**	**54.2**
Binder (Lime)	41.1	41.1
Clinker	4.7	4.7
Lime inclusions	4.4	0
Secondary products/Calcite and silica	0	0
Total Binder	**50.2**	**45.8**
Total Constituents	**100.0**	**100.0**
Voids	3.2	3.2
Crack	5.8	5.8
Cracks/Voids	**9.0**	**9.0**
	Total	**Effective**
Binder: Aggregate Ratio	**1.0 : 0.99**	**1.0 : 1.18**

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

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

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

Photomicrographs:

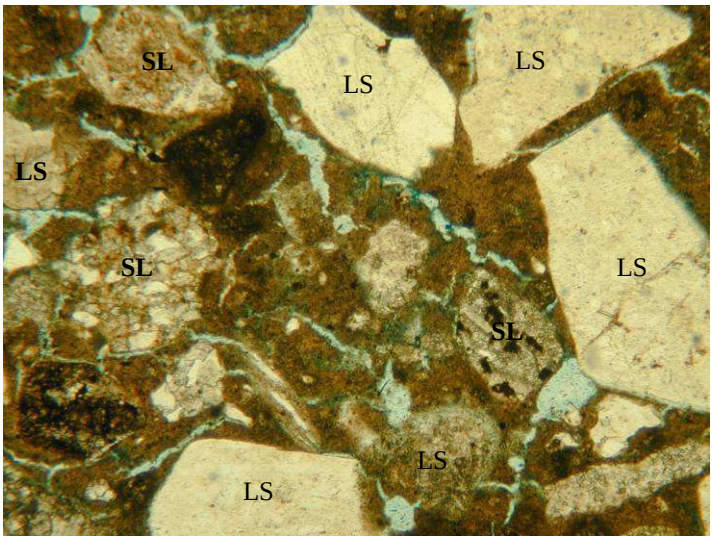

Plate No. 8:

A view in plane polarised light (ppl) showing a typical area of the mortar paste and the aggregate distribution. Aggregates are dominated by limestone (LS) and siliceous limestone fragments (SL) with minor chalcedony and other lithic fragments.
The paste is relatively dense and uniform throughout; and is coloured light to dark brown in this plate. The paste is transected by a number of fine shrinkage cracks which is a common feature in putty lime and hot lime mortars.
Porosity is highlighted by the blue dyed resin.
Field of view 2.4mm.

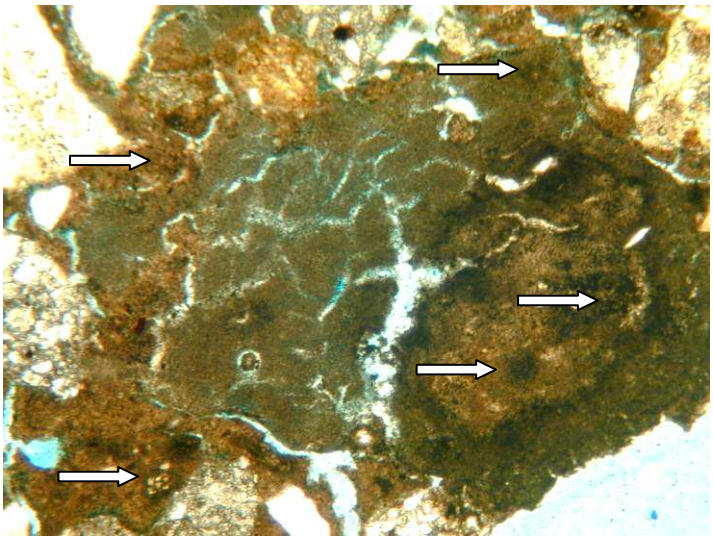

Plate No. 9:

Another view in ppl. A lime inclusion can be seen filling the centre of the plate. The inclusion is partially hydrated, on the left side of the inclusion with a kernel of unhydrated and partially overburnt limestone in the right side of the inclusion. The lime is locally diffused into the surrounding paste. It can be seen, at higher magnification that the unhydrated material contains a low proportion of clinker components, and these can also be seen in the surrounding paste, arrowed in plate.
Porosity is highlighted by the blue dyed resin.
Field of view 2.4mm.

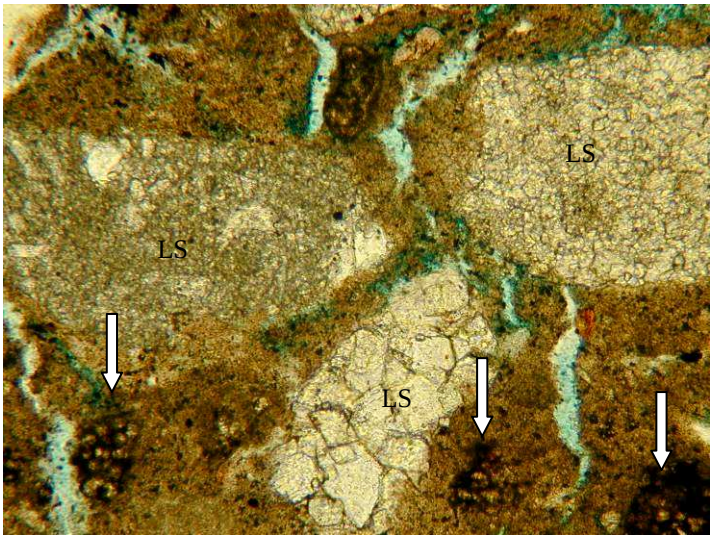

Plate No. 10:

A magnified view in plane polarised light, this image again shows limestone aggregate particles (LS). The upper right and left particles being dolomitic, with the lower centre being siliceous.

Belite clusters (hydraulic components) can be seen in the lower centre, lower left and right in the plate, these are arrowed in the plate for ease of identification. Note that the Belite observed is very coarse grained, typically 0.04mm to 0.2mm in size.

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

5.2 Sample SR2413 - S2: Plaster

Aggregate

The aggregates in this sample are similar to that in S1 with regards to mineralogy although the grain size is much finer and there are more quartz grains present and although the aggregate is again dominated by limestone the proportion of dolomitic limestone and siliceous limestone present are in trace proportions, with only trace proportions of chalcedony and feldspar observed in the sample examined.

The aggregates are dominated by sub-round to sub-angular particles, some of which show weathered margins, where weaker minerals have altered to clays, with rounding and water worn surfaces, observed in the recovered aggregate, suggesting a river bank or pit sand source.

The aggregates are well encapsulated in the binder and peripheral cracks are rare.

Binder

The binder is typical of a lime which was gauged with plaster (Plaster of Paris - Hemi-Hydrate) with the lime used in the form of a well slaked hydrate, or a well mixed putty lime, however, given the absence of lime inclusions and the presence of areas of high porosity within the paste, it is likely that the paste was used in the form of a putty.

The paste is fully carbonated and unhydrated clinker is rare. However, where observed clinker is in the form of partially hydrated pseudomorph grains, but these were only observed in one small area of the paste and it is possible that they were incorporated in the mix as a contaminant. No lime inclusions were observed in the section examined.

In addition to the lime paste, gypsum was also observed as crystal growths within voids and as fine disseminated crystals distributed throughout the paste. Given the abundance of the gypsum and its even distribution it is most likely that the binder was gauged with a proportion of gauging plaster at the time of mixing, perhaps to act as an accelerator, to aid setting. .

Voids and microcracks

Voids are again rare but where present are mostly in the form of irregular entrapped air voids and sub-round shaped water formed voids, with these ranging from 0.04 to 0.8mm in size. Most of the sub rounded voids are filled to partially infilled with secondary growths of gypsum.

Cracks are scarce and where observed they are very fine and mostly occur at outer surfaces from where they meander into the paste locally linking aggregate. The cracks are very fine, ranging in width from <0.02mm to 0.06mm, and are typical of drying shrinkage features, all contain secondary linings of gypsum.

Fibres

A proportion of wood fibre was observed distributed throughout the section, with these measuring up to 1.8mm x 0.8mm to 0.2mm in width, in the section examined.

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

Sample Ref:	SR2413-S2
Constituents	**%**
Aggregate	**Inclusions as binder**
Quartz	14.1
Lithic Fragments	2.8
Calcareous Silicates	7.2
Limestone (Calcite)	13.6
Dolomitic Aggregate	2.4
Total Aggregate	**40.1**
Binder (Lime)	52.4
Clinker	0.3
Lime inclusions	0
Gypsum	7.2
Total Binder	**59.9**
Total Constituents	**100.0**
Voids	3.8
Crack	1.9
Cracks/Voids	**5.7**
Wood fibre	**2.1**
	Total
Binder: Aggregate Ratio	**1.0 : 0.67**

Table No. 2: Modal Analysis from a thin section prepared from sample S2, as there are no lime inclusions present in the mortar examined the found mix composition (total) is the same as the effective mix composition. The gypsum content determined from the point count is likely to be a significant underestimation, as the gypsum is finely disseminated throughout the binder and is below the resolution of the optical microscope.

The following photomicrographs show the condition of the mortar pieces examined:

Photomicrographs:

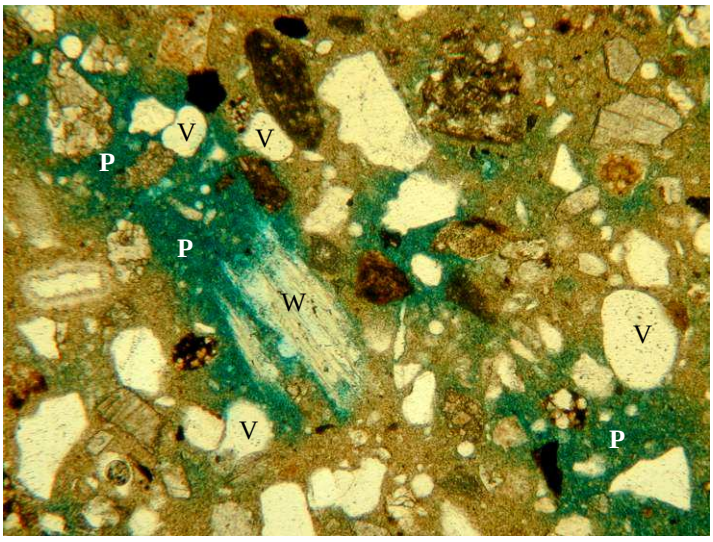

Plate No. 11:
A view in plane polarised light (ppl) showing a typical area of the mortar, note that the paste (brown colour) is relatively uniform in this image with sparse small air voids (V in plate) apparent.
The paste is free of the crack pattern normally associated with putty lime mortars and was also noted to contain porous (P) areas (highlighted by blue dye penetration).
Aggregates in this view are dominated by quartz (white in plate) limestone and lithic fragments.
A wood fragment can be seen on the left of centre (W in plate)

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

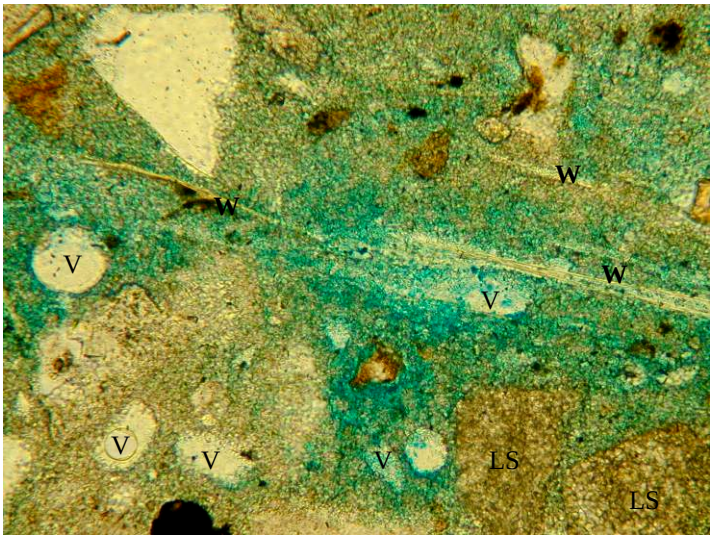

Plate No. 12:

Another view in ppl, at higher magnification, showing an area of the paste with fine wood fibres (w) and a micro porous area of paste extending across the centre of the plate.

The paste contains fine gypsum crystals diffused throughout the area in view. Voids are typically rimmed by calcite and gypsum crystal fringes (V). The aggregates in view are mostly limestone (LS)

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

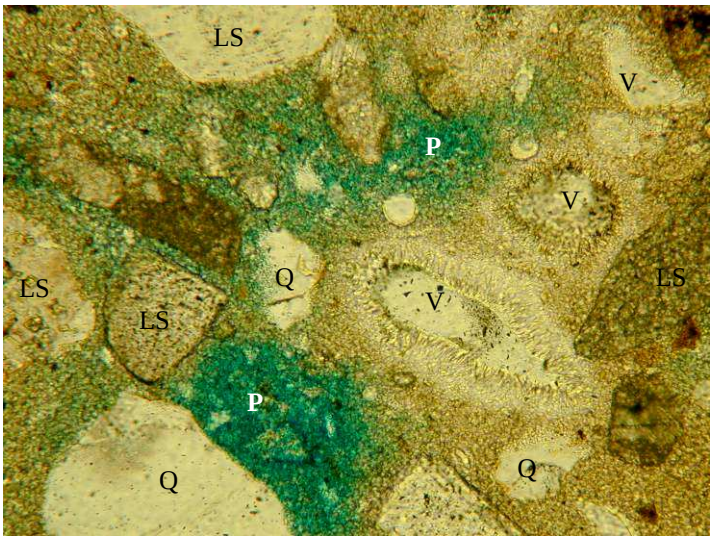

Plate No. 13:

A view in ppl, of a paste rich area with patches displaying high microporosity (P).

Several voids can be seen with these all retaining a thick rim of redeposited calcite and gypsum (V).

The aggregates in view are mostly limestone (LS) and quartz (Q)

Porosity is highlighted by the blue dyed resin.

Field of view 1.2mm

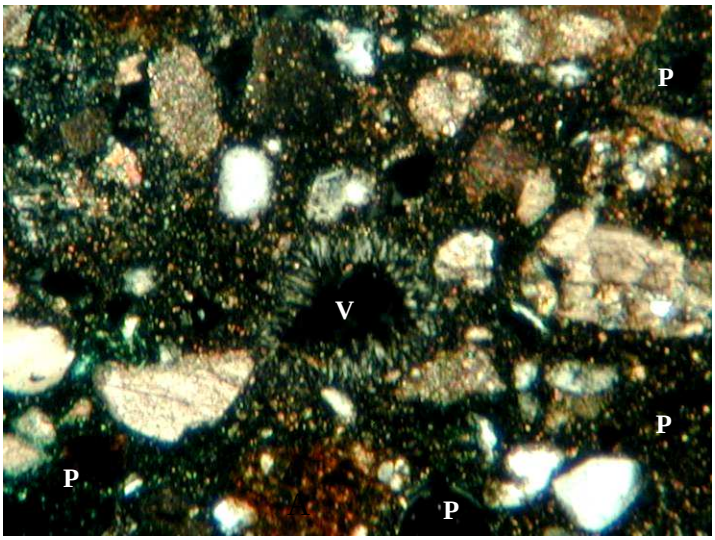

Plate No. 14:
A view in cross polarised light (xpl), of a paste rich area, with a mixed suite of aggregate particles, evenly distributed throughout.

A gypsum rimmed void can be seen within the centre of the image (V) with patches of matrix displaying micro porosity zones at the lower left and upper and lower right (P). The paste is fully carbonated and can be seen to have gypsum distributed thouighout, seen as the light coloured spotting throughout the paste.

Voids and the blue dyed resin 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 binder in both samples and to confirm if they were mineralogically similar, a binder rich sub-sample was obtained from both samples with these prepared for analysis by X-ray Powder Diffraction.

To achieve this, a sub-sample was obtained from each and this disaggregated in an agate mortar and pestle, care being taken to minimise the crushing of aggregate particles as possible. The majority of the aggregate was removed by screening the powdered samples over a 63µm sieve. With the powder collected 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 55° 2θ in steps of 0.1° 2θ at a rate of 1° 2θ/minute using CuKα radiation. The results are shown in the following figures which are appended to this report, in the form of labelled X-ray diffractograms:

Figure No. 1 – SR2413-S1 - Pointing Mortar Sample,
Figure No. 2 – SR2413-S3 - Plaster Sample.

The most abundant mineral components identified are indicated on the diffractograms using the following short-hand notation:

cc = Calcite ($CaCO_3$) Calcium Carbonate, carbonated lime binder component, also the dominant component of the limestone, which is the dominant component of the aggregate,

la = Larnite (Ca_2SiO_4) *di*-Calcium Silicate, hydraulic component in hydraulic lime binders and in Portland type cements,

gy = Gypsum ($CaSO_4 2H_2O$) Calcium Sulphate Hydrate, can be present as reaction product between environmental pollutants and the lime in the binder (S1) and as a gauging added to plaster (S2),

ba = Bassanite ($CaSO_4 0.5H_2O$), Calcium Sulphate Hemi-Hydrate, the form in which Gypsum is used as a plaster as a gauging added to lime plaster, indicating that a proportion is still present in the plaster, in the unhydrated state, not uncommon in gauged plasters,

ca = Calcium Aluminium Oxide Hydrate ($Ca_4Al_2O_6C_3 11H_2O$), carbonated hydraulic component of the binder,

qz = Quartz (SiO_2 component of the aggregate, both as quartz grains, quartzite and in siliceous limestone fragments,

do = Dolomite ($Ca\ Mg\ (CO_3)_2$) Limestone aggregate component in the fine aggregate,

fe = Feldspar, mostly Albite from the Plagioclase group of minerals detected in sample,

On the basis of the results from the XRD analysis it is indicated that the binders in both samples differed. The absence of Alite, but with Belite and Calcium Aluminates in sample S1 it was concluded that this was most likely a hydraulic lime binder rather than a Portland cement gauged lime. Whereas that in the Plaster, sample S2, was a gypsum gauged non-hydraulic lime.

Sample S1 appears to have been affected by environmental sulphates, i.e. acid rain or ground waters, or sulphates from the masonry, with this reacting with lime in the binder, resulting in the low gypsum content detected in the sample.

The proportion of Gypsum and Bassanite present in sample S2 was determined by Rietveld Refinement and found to be in the region of 21% of the total sample.

7.0 Mix Composition

On the basis of the results from the XRD analyses, the mix composition of the samples was initially determined by acid digestion using the method of the Scottish Lime Centre Trust (SLCT). However, given the presence of calcareous aggregates in the samples the acid used was a 5% concentration rather than the 10% solution normally used, and the dwell time in the acid kept to a minimum, with the digestion stopped as soon as all of the binder appeared to have been consumed. Standard densities for the relevant components have been used in the calculation of the mix compositions. The aggregate residue from the acid digestions was recovered, dried and sieved through a nest of British Standard sieves to permit the particle size distribution of the aggregate to be determined. The grading results are presented below in tabular form and as particle filled histograms in Figures No. 3 and 4, at the end of this report.

The results obtained from the analyses are reproduced below, however, it must be borne in mind when using the sand graphs to match potential sand sources for use in the works, that the recovered aggregates have been treated in acid and any grain coatings present may have been partially depleted, or perhaps bleached, and this may have affected, to some degree, the colour of the recovered sand grains.

7.1 Sample SR2413 - S1: Pointing Mortar

From the analysis of this mortar it was found that the soluble binder: Aggregate ratio was 1.0:0.6. With the mix composition, calculated on the basis of a feebly to moderately hydraulic lime, used both in the form of a quicklime and a hydrate, were calculated and these are reproduced below.

1 part lime Quicklime to 0.9 parts aggregate, or 1 part hydrate to 0.7 parts aggregate, by weight

or

1 part lime Quicklime to 0.33 parts aggregate, or 1 part hydrate to 0.4 parts aggregate by volume.

The aggregate recovered from the sample were graded and the results are presented in the following table, and in the form of an aggregate filled histogram, see Figure No. 3:

BS Sieve Size (mm)	% Retained	% Passing
2.00	0	100
1.00	4.0	96.0
0.500	30.1	65.9
0.250	38.4	27.5
0.125	8.6	18.9
0.063	4.6	14.3
Passing 63µm	14.3	

The aggregates are dominated by limestone with minor Quartz, Quartzite, Chalcedony and a trace proportion of Feldspar. The majority of the aggregate grains display water worn surfaces although there is a low abundance that displays sharp angular features consistent with crushed aggregate particles.

As a check on the mix composition for different degrees of hydraulicity the proportion of soluble silica and soluble calcium was determined along with the Loss on Ignition and Insoluble residue, following the methods of BS4551. The results obtained would infer the following mix composition for limes having a range of hydraulicity

Chemical Analysis	**% by mass**
Insoluble Residue	38.68
Soluble Silica (SiO2)	2.07
Calcium Oxide (CaO)	35.38
Loss on Ignition	23.40

Mix composition	**By Mass**		**By Volume**	
Hydraulicity	**Binder**	**Aggregate**	**Binder**	**Aggregate**
Feebly	1.0	1.4	1.0	0.7
Moderately	1.0	2.3	1.0	1.0
Eminently	1.0	2.7	1.0	1.4

On the basis of the above and the XRD analysis this would tend to infer that the binder had a hydraulicity that could be classed as moderate, which is consistent with the hardness and firmness of the mortar sample received.

7.2 Sample SR2413 - S2: Plaster Sample

On the analysis of sample S2 the soluble binder: Aggregate ratio was found to be 1.0:0.9 and on this basis the following mix proportions were calculated on the basis of total binder (lime + Gypsum) to aggregate:

1 part lime hydrate + Gauging Plaster to 1.2 parts aggregate,
1 part lime putty + Gauging to 0.7 parts aggregate by, weight
or
1 part lime hydrate + Gauging Plaster to 0.45 parts aggregate
1 part lime putty + Gauging Plaster to 0.57 parts, by volume.

Where the gauging plaster was added in the form of Bassanite at a dosage of 1 part lime to ** parts Bassanite.

The results of the grading analysis are presented in the following table, and in an aggregate filled histogram in Figure No. 4.

BS Sieve Size (mm)	**% Retained**	**% Passing**
2.00	0	100
1.00	0	100
0.500	0	100
0.250	15.3	84.7
0.125	38.5	46.2
0.063	19.9	26.3
Passing 63µm	26.3	

The aggregates differ from those in sample S1 in that they are much finer graded and although they are again dominated by limestone, only minor quartz and trace proportions of chalcedony and feldspar were present in the recovered aggregate from this sample.

The proportion of Gypsum and Bassanite (3.1%) present in sample S2 was determined by Rietveld Refinement and found to be in the region of 21% of the total plaster sample, which in a mortar having a total binder content of 60% gives an approximate gauging of the binder of 35% gypsum. This equates to 31.3% hemihydrate of the binder by mass, or 1 part lime putty to 0.6 parts anhydrite by volume.

8.0 Summary

On the basis of the examination and analysis of the mortar samples submitted it was indicated that the samples represent two different mortar mixes. These are summarised below for comparison:

CMC Ref: **Client Ref**	**SR2413-S1** **S1**	**SR2413-S2** **S2**
Source	**Pointing Mortar**	**Plaster**
Binder type	Feebly to moderately Hydraulic Lime used as Dry-Slaked Quicklime	Non Hydraulic Lime used in the form of a putty lime Gauged with Hemi-Hydrate
	Binder : Aggregate	**Lime : hemi-Hydrate : Aggregate**
By Mass	1.0:0.9	1.0:0.5:1.0
By Volume	1.0:0.33	1.0:0.54:0.78
Visual Volume (Total)	1.0:0.99	1.0:0.67 (Binder:aggregate)
Visual Volume (Effective)	1.0:1.18	
Wood Fibre		approximately 2% of mix by volume

Sample Ref:	**SR2413-S1**	**SR2413-S2**
BS - EN Sieve Size (mm)	**% Retained on Sieve**	
2.00	0	0
1.00	4.0	0
0.500	30.1	0
0.250	38.4	15.3
0.125	8.6	38.5
0.063	4.6	19.9
Passing	14.3	26.3

Table No. 3: Comparison of the sand grading on aggregates recovered following acid digestion.

From an examination of the thin sections prepared from the samples it was observed that they both show different properties with these sufficient to infer that they were made from different binder materials at different proportions.

In sample S1 the binder appears to be a moderately hydraulic lime that was probably incorporated with the sand in the form of a quicklime, however, the mortar had not been used in the form of a Hot-Lime mortar, with the slaked lime and sand probably stored dry (after slaking) for a period and then screened to remove oversize aggregates and any oversized unslaked lime inclusions, prior to being remixed and used as a cold lime mortar. i.e. a Dry Slaked Hot-Lime Mortar (HLM) but used cold.

Whereas, from an examination of sample S2 it was indicated that the plaster sample was made from a non-hydraulic lime, mixed in the form of a putty to which a gauging of gypsum (in the form of a Hemi-Hydrate) had been added. The absence of lime inclusions, and plastic/drying shrinkage features would infer that the binder had not been used in the form of a quicklime but as a lime putty. The plaster was gauged with Hemi-Hydrate at a dosage of 1 part lime putty to 0.54 parts hemihydrate by volume, with a proportion of wood chip (2%) apparently added to the mix, perhaps in lieu of hair reinforcement.

These comments are offered on the basis of the observations made on the samples received and if the results are to be used to replicate mortars for use in conservation works the users should satisfy themselves that the samples submitted are representative of the materials in the building.

9.0 Quality Statement

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

The observations and analysis results reported and comments offered relate only to the two samples received from Nigel Copsey of the Earth, Stone & Lime Company, which were stated to be from the Anglican Cathedral Church *of the* Redeemer, City of Calgary, Alberta, Canada, received for examination and analysis on the 5th September 2016.

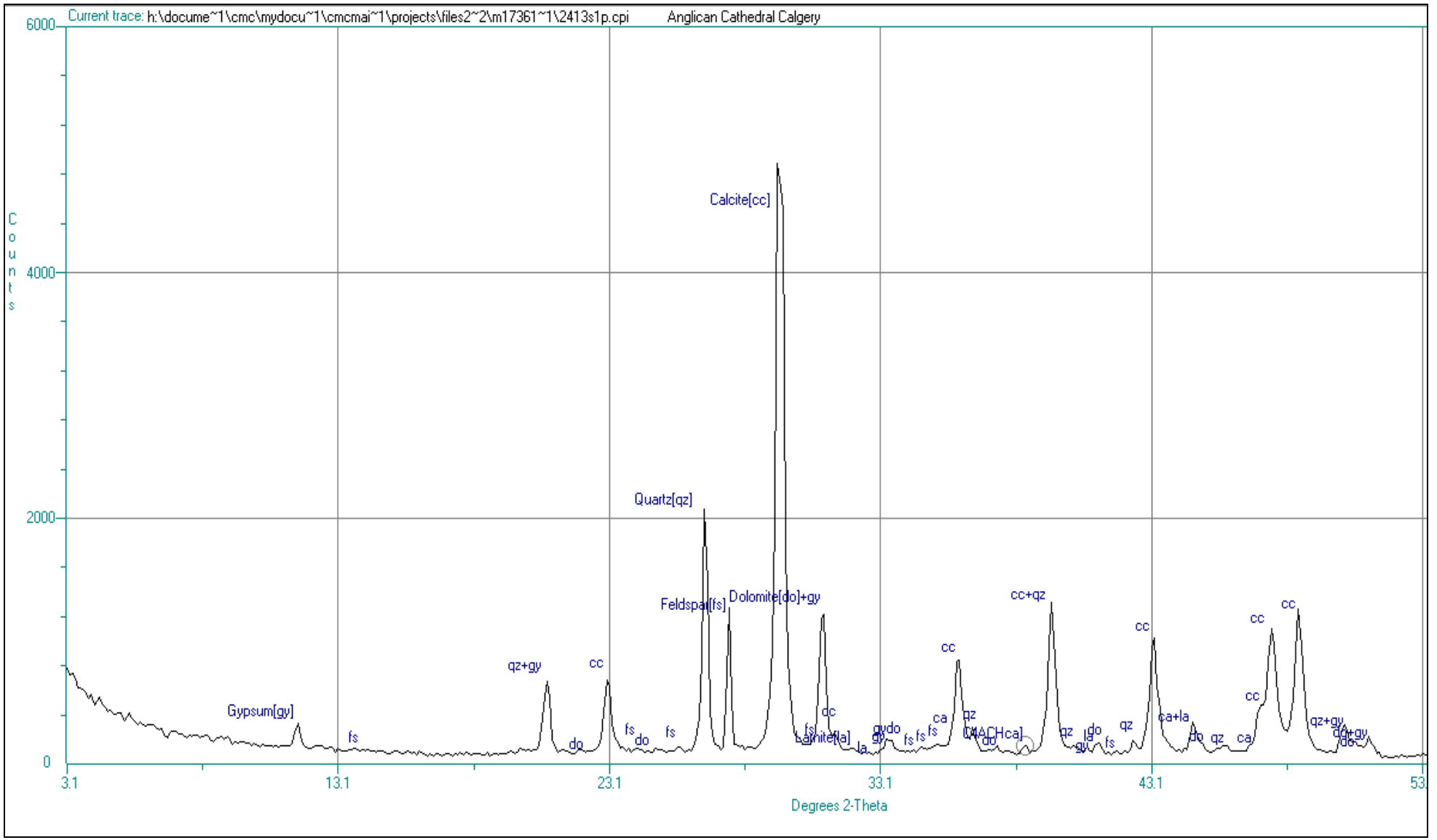

Figure No. 1 – SR2413-S1 - Pointing Mortar Sample.

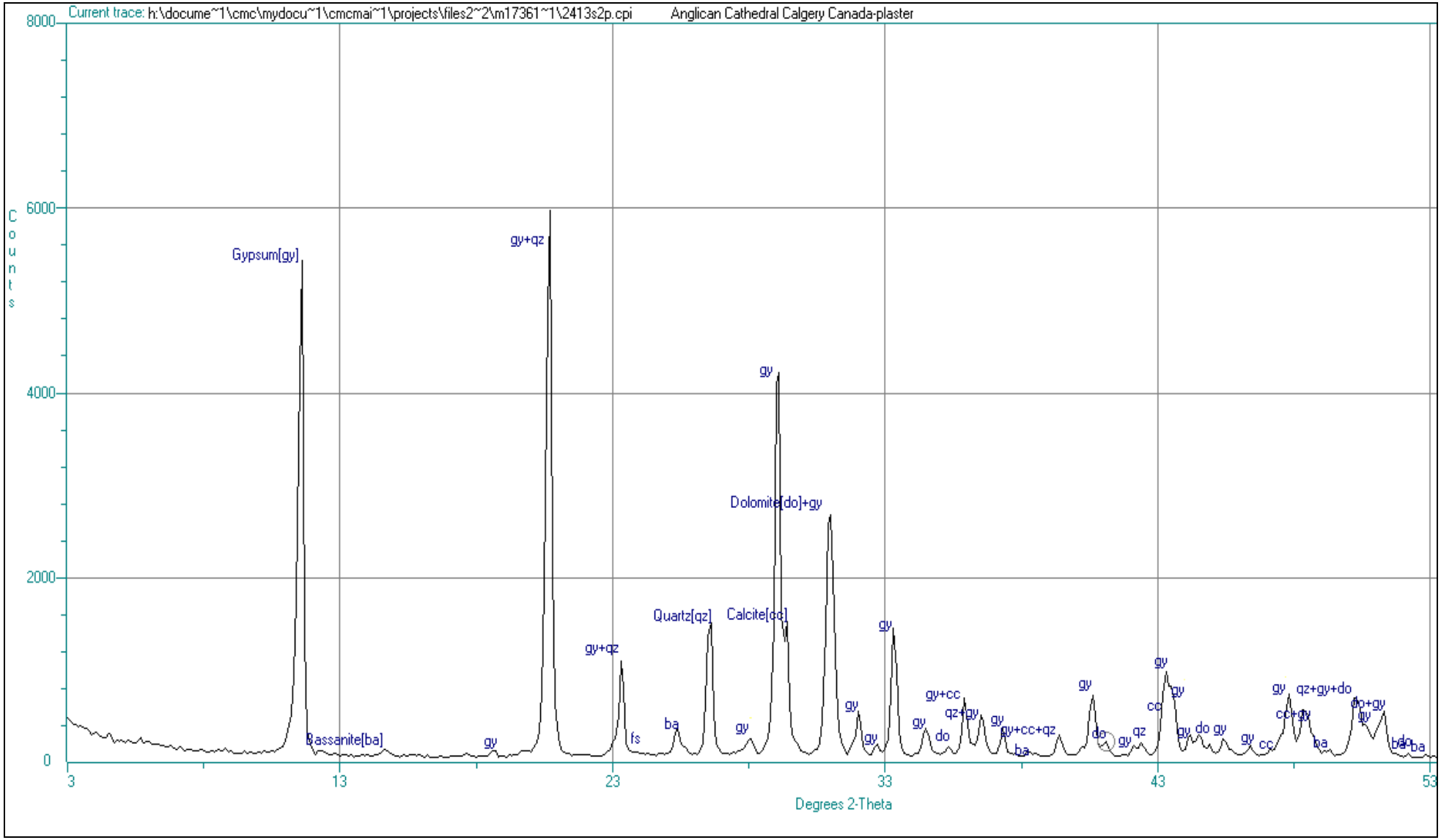

Figure No. 2 – SR2413-S2 - Plaster Sample.

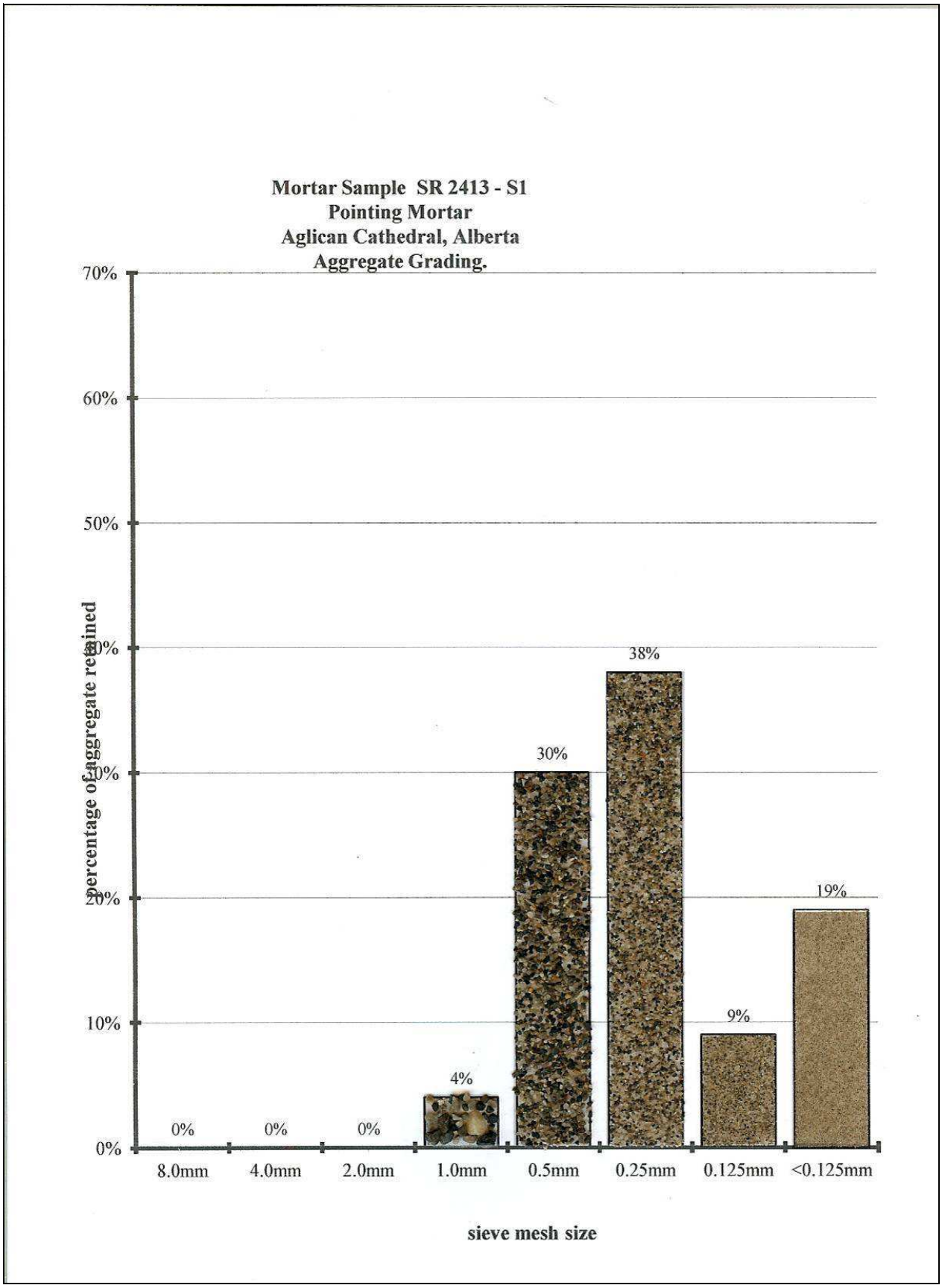

Figure No. 3: Aggregate grading – Sample SR2413-S1 – Pointing Mortar

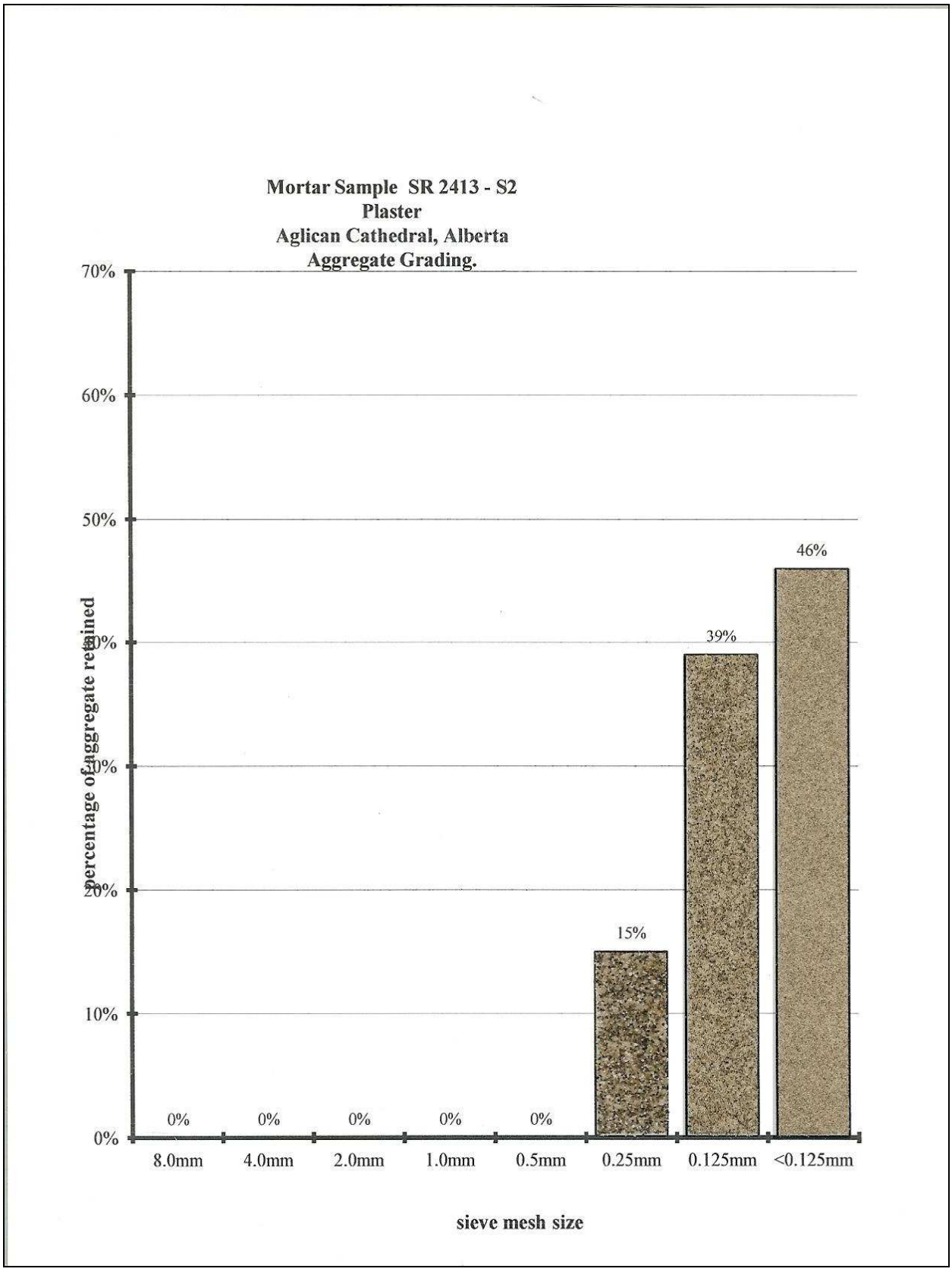

Figure No. 4: Aggregate grading – Sample SR2413-S1 – Plaster Sample