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Report - 78470/K

REPORT ON THE PETROGRAPHIC EXAMINATION OF THREE MORTAR SAMPLES (Site: Sunlight House, Manchester; Project Ref. Project Ref 002579WJ476)



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This report comprises

Cover page

6 pages of text

Appendix A – 3 pages of petrographic descriptions

Appendix B – 3 pages of photographs illustrating the samples

Appendix C – 8 pages of photomicrographs of the thin sections

Appendix D – 5 pages of petrographic procedures and glossary

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For the attention of Mr Toni Howarth

20 November 2024

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REPORT ON THE PETROGRAPHIC EXAMINATION OF THREE MORTAR SAMPLES (Site: Sunlight House, Manchester; Project Ref. Project Ref 002579WJ476)

1 INTRODUCTION

Three small mortar samples advised to be from Sunlight House, Manchester were provided for analysis on 28 October 2024. It was requested that the samples be examined to identify their constituents and to assist in the replication of the mortars at site with modern materials. Instructions to proceed with the analysis were submitted under Purchase Order No. 002579/WJ476 23 October 2024.

2 SAMPLES

The following samples were provided for analysis:

Laboratory reference	Client / site reference	Mass, g
K19563/1	Atkinson Street - Sample 1	1.03
K19563/2	Little Quay Street - Sample 2	6.35
K19563/3	Courtyard - Sample 3	1.50

3 TEST METHODS

The petrographic testing was carried out in accordance with BS 1881-211, 2016¹. A summary of the procedures followed and a glossary of terms used in the description of the samples are given in Appendix D. In brief, the following work was carried out.

- (i) The samples were examined as received and photographed.
- (ii) A longitudinal fluorescent resin impregnated thin section was prepared from the most deteriorated inner ends of each core representing the cores between their inner surfaces and maximum depths of 67mm. Each thin section measured about 45x67mm.
- (iii) The thin sections were examined with a Zeiss petrological photomicroscope and the distribution of porosity and microcracking was assessed from an examination of the thin sections in fluorescent light using the petrological microscope.

4 PETROGRAPHIC EXAMINATION RESULTS

4.1 Visual description of the samples

Visual descriptions of the samples as received are given in Table A1 in Appendix A and photographs illustrating the samples as received are given in Appendix B.

4.2 Petrographic description of the aggregate

A petrographic description of the aggregate in each core is given in Table A2 in Appendix A.

4.3 Petrographic description of the paste

A petrographic description of the paste in each core is given in Table A3 in Appendix A. Photomicrographs illustrating the typical appearance of the paste in the thin sections are given in Appendix C.

¹ BS 1881-211:2016 Testing concrete. Procedure and terminology for the petrographic examination of hardened concrete

5 SUMMARY - ATKINSON STREET - SAMPLE 1

5.1 Mortar types - Atkinson Street - Sample 1

The sample includes two types of lime mortar and a modern Portland cement-based mortar.

The two lime-based mortars differ mainly in terms of their aggregate contents with the Type 1 lime mortar containing only traces of aggregate and the Type 2 lime mortar containing an abundant fine sand.

The Portland cement based mortar contains fine quartz sand.

5.2 Aggregate characteristics - Atkinson Street - Sample 1

The aggregate characteristics in each mortar type are compared in the table below.

Lab. Ref.	K19563/1		
Client Ref.	Atkinson Street - Sample 1 – Aggregate characteristics		
Mortar type	<i>Type 1 lime mortar</i>	<i>Type 2 lime mortar</i>	<i>Portland cement mortar</i>
Sand type	Quartz sand (trace)	Quartz sand	Quartz sand
Estimated grading	Note 1	Fine	Fine
Nominal maximum size	0.3	0.3	0.3
Dominant particle types	Quartz	Quartz	Quartz

Note 1: Very little aggregate present.

5.3 Matrix characteristics - Atkinson Street - Sample 1

The aggregate characteristics in each mortar type are compared in the table below.

Lab. Ref.	K19563/1		
Client Ref.	Atkinson Street - Sample 1 – Matrix characteristics		
Mortar type	<i>Type 1 lime mortar</i>	<i>Type 2 lime mortar</i>	<i>Portland cement mortar</i>
Binder type	Hydraulic lime	Hydraulic lime	Portland cement resembling OPC
Calcium silicates and Portland cement	Moderate amounts calcium silicate particles composed of belite. Traces of calcium silicate particles that contain alite, possibly indicating the presence of traces of white Portland cement.	Moderate amounts calcium silicate particles composed of belite. Traces of calcium silicate particles that contain alite, possibly indicating the presence of traces of white Portland cement.	Moderate amounts of unhydrated Portland cement grains
Carbonation	Fully carbonated	Fully carbonated	Almost fully carbonated
Alteration	None seen	None seen	None seen

6 SUMMARY - LITTLE QUAY STREET - SAMPLE 2

6.1 Mortar types - Little Quay Street - Sample 2

The sample consists of a single type of mortar with a blend of fine quartz sand and crushed limestone that is probably crushed Portland stone in a hydraulic lime binder. The composition of the mortar is such that it superficially resembles Portland stone.

6.2 Aggregate characteristics - Little Quay Street - Sample 2

The aggregate characteristics are summarised in the table below.

Lab. Ref.	K19563/2
Client Ref.	Little Quay Street - Sample 2
Mortar type	<i>Hydraulic lime mortar</i>
Aggregate type	Blend of Quartz sand and crushed limestone resembling Portland stone
Estimated grading	Fine
Nominal maximum size	0.6
Dominant particle types	Quartz and Limestone

6.3 Matrix characteristics - Little Quay Street - Sample 2

The aggregate characteristics are summarised in the table below.

Lab. Ref.	K19563/2
Client Ref.	Little Quay Street - Sample 2
Mortar type	<i>Hydraulic lime mortar</i>
Binder type	Hydraulic lime
Calcium silicates and Portland cement	Traces calcium silicate particles composed of belite. Very rare calcium silicate particles that contain alite, possibly indicating the presence of traces of white Portland cement.
Carbonation	Fully carbonated
Alteration	None seen

7 SUMMARY - COURTYARD - SAMPLE 3

7.1 Mortar types - Courtyard - Sample 3

The sample consists of a single type of mortar with a blend of fine quartz sand and crushed limestone that is probably crushed Portland stone in a hydraulic lime binder. The composition of the mortar is such that it superficially resembles Portland stone.

7.2 Aggregate characteristics - Courtyard - Sample 3

The aggregate characteristics are summarised in the table below.

Lab. Ref.	K19563/3
Client Ref.	Courtyard - Sample 3
Aggregate type	Blend of Quartz sand and coal ash dust
Estimated grading	Fine
Nominal maximum size	0.3
Dominant particle types	Quartz and Ash

7.3 Matrix characteristics - Courtyard - Sample 3

The aggregate characteristics are summarised in the table below.

Lab. Ref.	K19563/3
Client Ref.	Courtyard - Sample 3
Binder type	The sample size is too small to reliably identify binder type. Traces of the outlines of particles resembling early Portland cement can occasionally be found. The mortar matrix also contains patches of microcrystalline gypsum ^{Note 1} .
Calcium silicates and Portland cement	Traces calcium silicate particles composed of belite. Very rare calcium silicate particles that contain alite, possibly indicating the presence of traces of white Portland cement. The presence of Portland cement is uncertain.
Carbonation	Uncarbonated with patchy calcite deposition
Alteration	Substantial alteration has occurred with some evidence of sulfate-related deterioration and weakening due to moisture ingress and calcite deposition.

Note 1: This may originate from historic atmospheric sulfur contamination. The possibility of calcium sulfate binder cannot however be ruled out.

8 REMARKS

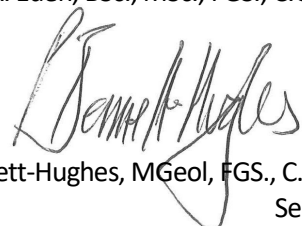
The above concludes the requested programme of testing. Please do not hesitate to contact us if we can be of any further assistance in this matter.

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For the attention of Mr Toni Howarth

for GEOMATERIALS RESEARCH SERVICES
(part of Sandberg LLP)


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20 November 2024

Samples can only be retained for a period of two months from the date of issue of the report unless we are instructed otherwise. Samples can be returned or retained for a further charge.
Opinions and interpretations expressed herein are outside the scope of UKAS accreditation.

APPENDIX A – PETROGRAPHIC DESCRIPTION OF THE SAMPLES

PETROGRAPHIC EXAMINATION OF MORTAR - BS 1881-211, 2016

TABLE A1 OF 3: PETROGRAPHIC DESCRIPTION OF THE SAMPLES

Sandberg Ref.	K19563/1		
Client Ref.	Atkinson Street - Sample 1		
Condition of sample	Broken fragments ranging up to about 15mm containing three types of mortar as described below.		
Mortar type	Type 1 lime mortar	Type 2 lime mortar	Portland cement mortar
Summary of mortar constituents	Hydraulic lime with traces of chert and quartz sand particles.	Hydraulic lime with fine quartz sand	Portland cement binder with fine quartz sand
Overall colour of mortar	Yellowish white	Yellowish white	Medium greyish brown
Occurrence	Thin layer up to about 1.5mm thick consisting mainly of matrix with only traces of aggregate	The most abundant mortar type	Occurs beneath the Type 1 mortar
Aggregate			
<i>Coarse aggregate (>4mm particles)</i>	None seen	None seen	None seen
<i>Estimated BS EN 13139 sand grading classification</i>	To few sand particles present to estimate the grading. The largest sand particle measures 0.3mm	Fine 0/0.3	Fine 0/0.3
<i>Particle shape</i>	Subrounded	Subrounded	Subrounded
<i>Sand grain coatings</i>	None seen	None seen	None seen
<i>Major rock types (>20% of aggregate)</i>	Quartz	Quartz	Quartz
<i>Minor rock types (5-20% of aggregate)</i>	Feldspar	Quartzite	Quartzite
<i>Trace rock types (<5% of aggregate)</i>	-	Feldspar	Feldspar
Matrix			
<i>Binder type</i>	Hydraulic lime (high hydraulicity)	Hydraulic lime (high hydraulicity)	Portland cement – resembles OPC
<i>Undispersed lime / lime lumps</i>	Minor rounded fragments of undispersed lime	Minor rounded fragments of undispersed lime	None seen
<i>Portland cement and calcium silicates</i>	Moderate amounts calcium silicate particles composed of belite. Traces of calcium silicate particles that contain alite, possibly indicating the presence of traces of white Portland cement.	Moderate amounts calcium silicate particles composed of belite. Traces of calcium silicate particles that contain alite, possibly indicating the presence of traces of white Portland cement.	Moderate amounts of unhydrated Portland cement grains
<i>Carbonation</i>	Fully carbonated	Fully carbonated	Almost fully carbonated, other than the unhydrated cement grains
<i>Microporosity</i>	High	High	High
<i>Alteration of matrix other than carbonation</i>	None seen	None seen	None seen

PETROGRAPHIC EXAMINATION OF MORTAR - BS 1881-211, 2016

TABLE A2 OF 3: PETROGRAPHIC DESCRIPTION OF THE SAMPLES

Sandberg Ref.	K19563/2
Client Ref.	Little Quay Street - Sample 2
Condition of sample	Broken mortar fragments with a maximum dimension of about 30mm
Mortar type	Lime mortar
Summary of mortar constituents	Hydraulic lime binder with crushed Portland stone and fine quartz sand
Overall colour of mortar	Light yellow
Aggregate	
<i>Coarse aggregate (>4mm particles)</i>	None seen
<i>Estimated BS EN 13139 sand grading classification</i>	Crushed limestone 0/0.6 (fine) Sand 0/0.3 (fine)
<i>Particle shape</i>	Angular to subrounded (the sand particles are more rounded in shape than the limestone particles)
<i>Sand grain coatings</i>	None seen
<i>Major rock types (>20% of aggregate)</i>	Limestone ^{Note 1} , Quartz
<i>Minor rock types (5-20% of aggregate)</i>	Quartzite
<i>Trace rock types (<5% of aggregate)</i>	Feldspar
Matrix	
<i>Binder type</i>	Hydraulic lime
<i>Undispersed lime / lime lumps</i>	Rare rounded fragments, typically <0.1mm in diameter.
<i>Portland cement and calcium silicates</i>	Traces calcium silicate particles composed of belite. Very rare calcium silicate particles that contain alite, possibly indicating the presence of traces of white Portland cement.
<i>Carbonation</i>	Fully carbonated
<i>Microporosity</i>	High
<i>Alteration of matrix other than carbonation</i>	None seen

Note 1: Resembling Portland stone / oolitic limestone.

PETROGRAPHIC EXAMINATION OF MORTAR - BS 1881-211, 2016

TABLE A3 OF 3: PETROGRAPHIC DESCRIPTION OF THE SAMPLES

Sandberg Ref.	K19563/3
Client Ref.	Courtyard - Sample 3
Condition of sample	Broken mortar fragments with a maximum dimension of about 8mm and abundant loose sandy debris
Mortar type	Early Portland cement mortar
Summary of mortar constituents	Early Portland cement binder with coal ash dust and fine quartz sand. Many of the fragments contain abundant microcrystalline gypsum
Overall colour of mortar	Medium reddish brown
Aggregate	
<i>Coarse aggregate (>4mm particles)</i>	None seen
<i>Estimated BS EN 13139 sand grading classification</i>	Coal ash 0/0.1 (fine) Sand 0/0.3 (fine)
<i>Particle shape</i>	Angular to subrounded (the sand particles are more rounded in shape than the ash particles)
<i>Sand grain coatings</i>	None seen
<i>Major rock types (>20% of aggregate)</i>	Quartz, Coal ash
<i>Minor rock types (5-20% of aggregate)</i>	Quartzite
<i>Trace rock types (<5% of aggregate)</i>	Feldspar
Matrix	
<i>Binder type</i>	The sample size is too small to reliably identify binder type. Traces of the outlines of particles resembling early Portland cement can occasionally be found. The mortar matrix also contains patches of microcrystalline gypsum ^{Note 1} .
<i>Undispersed lime / lime lumps</i>	None seen
<i>Portland cement and calcium silicates</i>	The presence of Portland cement is uncertain.
<i>Carbonation</i>	Calcite deposition is occurring indicating the ingress of moisture containing dissolved CO ₂ .
<i>Microporosity</i>	High
<i>Alteration of matrix other than carbonation</i>	Substantial alteration has occurred with some evidence of sulfate-related deterioration and weakening due to moisture ingress and calcite deposition.

Note 1: This may originate from historic atmospheric sulfur contamination. The possibility of calcium sulfate binder cannot however be ruled out.

APPENDIX B – PHOTOGRAPHS ILLUSTRATING THE SAMPLES AS RECEIVED

Figure B1

Sample K19563/1

Atkinson Street - Sample 1

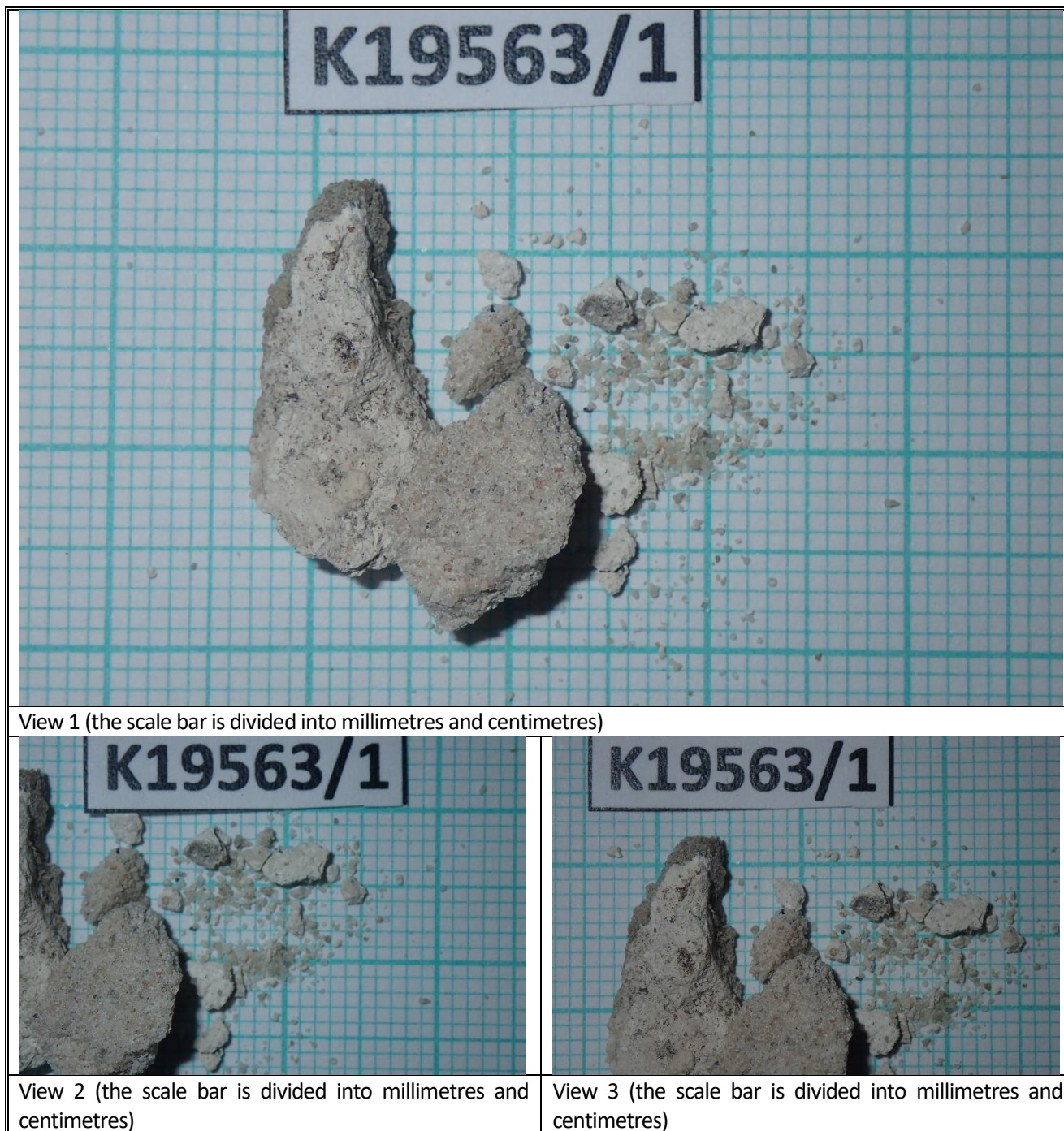
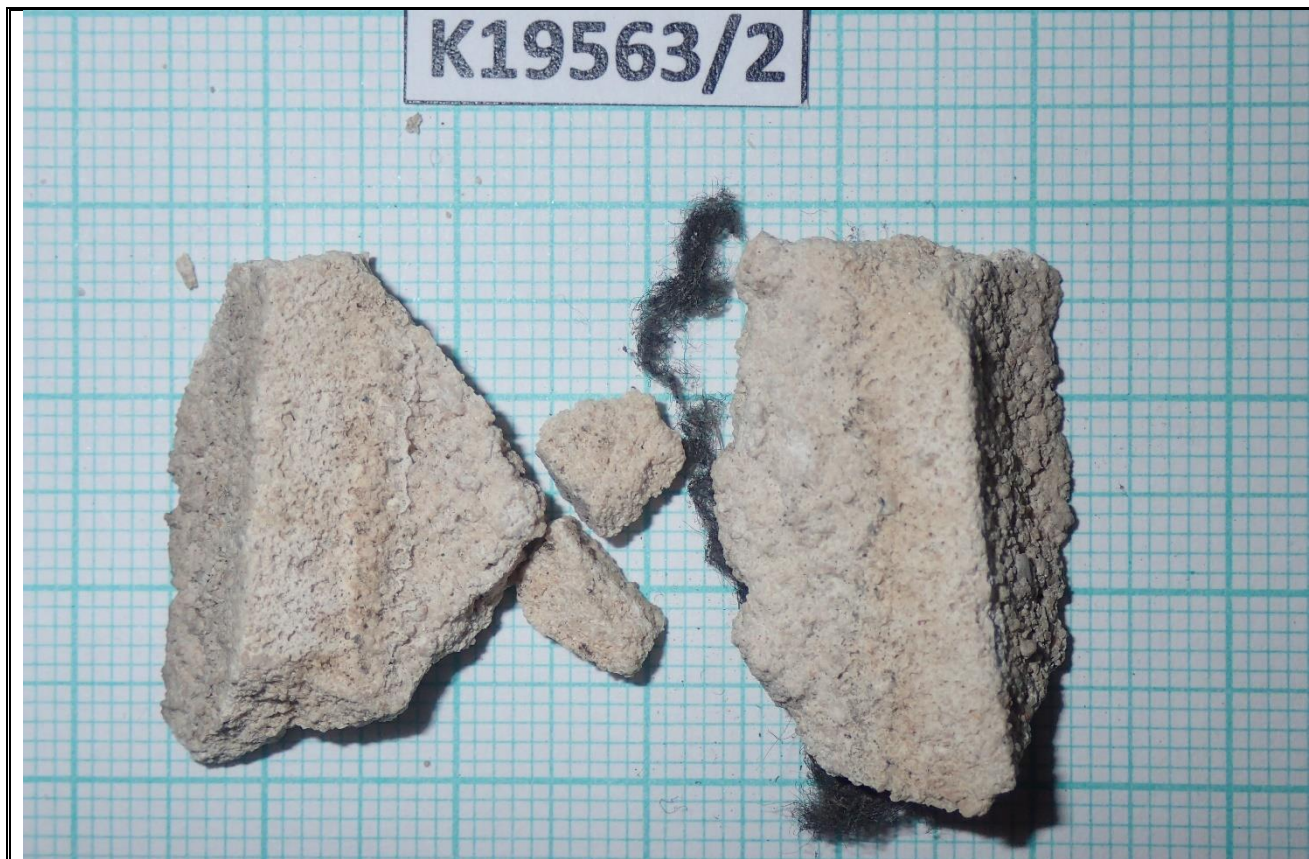


Figure B2

Sample K19563/2

Little Quay Street - Sample 2



View 1 (the scale bar is divided into millimetres and centimetres)



View 2 (the scale bar is divided into millimetres and centimetres)

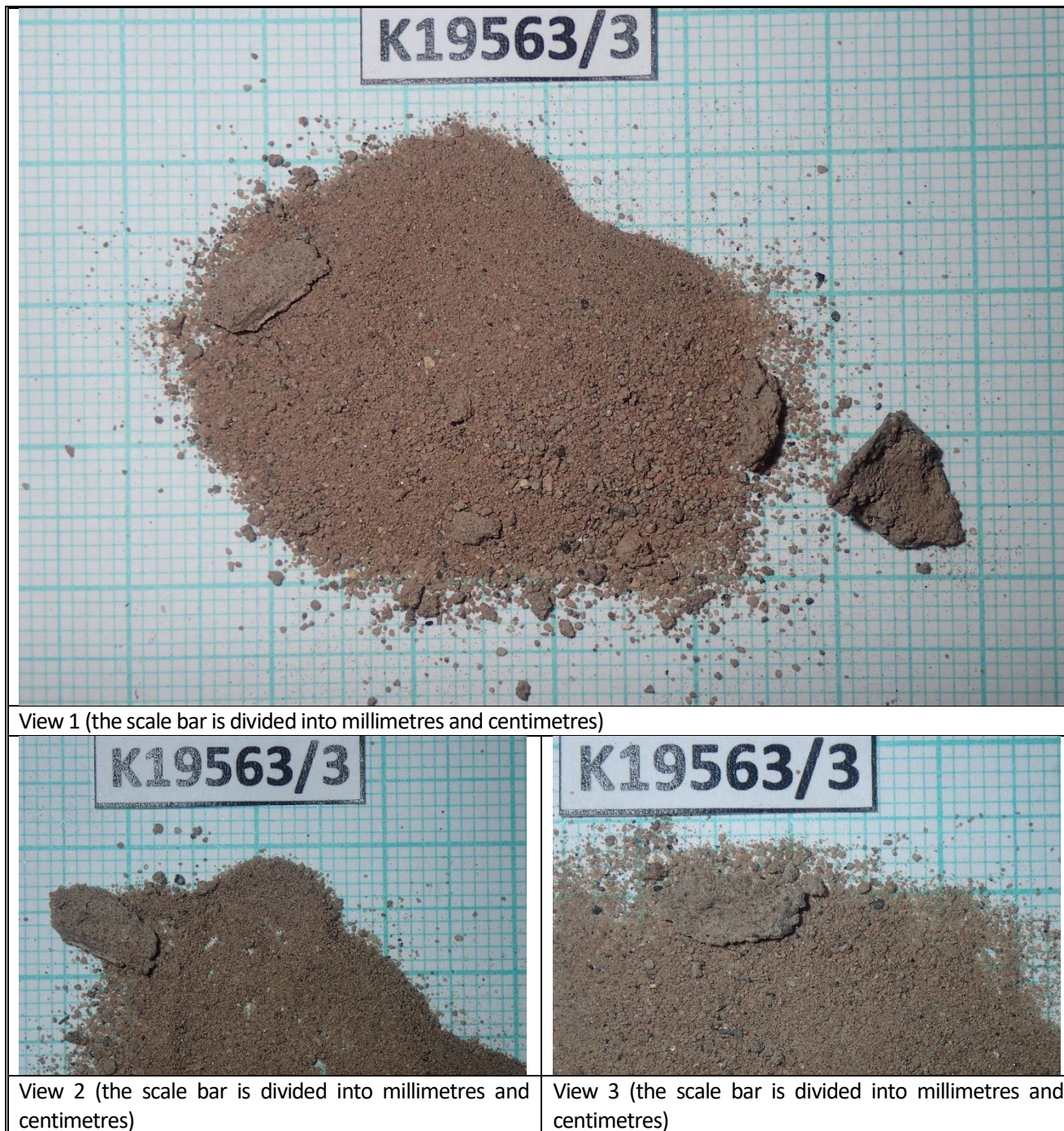


View 3 (the scale bar is divided into millimetres and centimetres)

Figure B3

Sample K19563/3

Courtyard - Sample 3



APPENDIX C – PHOTOMICROGRAPHS ILLUSTRATING THE THIN SECTIONS

Figure C1

Sample K19563/1 Atkinson Street - Sample 1

Thin section, oblique polars: View showing the contact between the Type 1 lime mortar on the left and the Portland cement-based mortar on the right. The contact between the two mortar types is highlighted by the yellow dashed line. Unhydrated Portland cement grains (PC) and quartz (Qtz) sand particles are present in the Portland cement mortar. The Type 1 lime mortar is overwhelmingly dominated by carbonated lime matrix, visible for example in F2/3. The lime mortar contains rare calcium silicate (CS) particles.

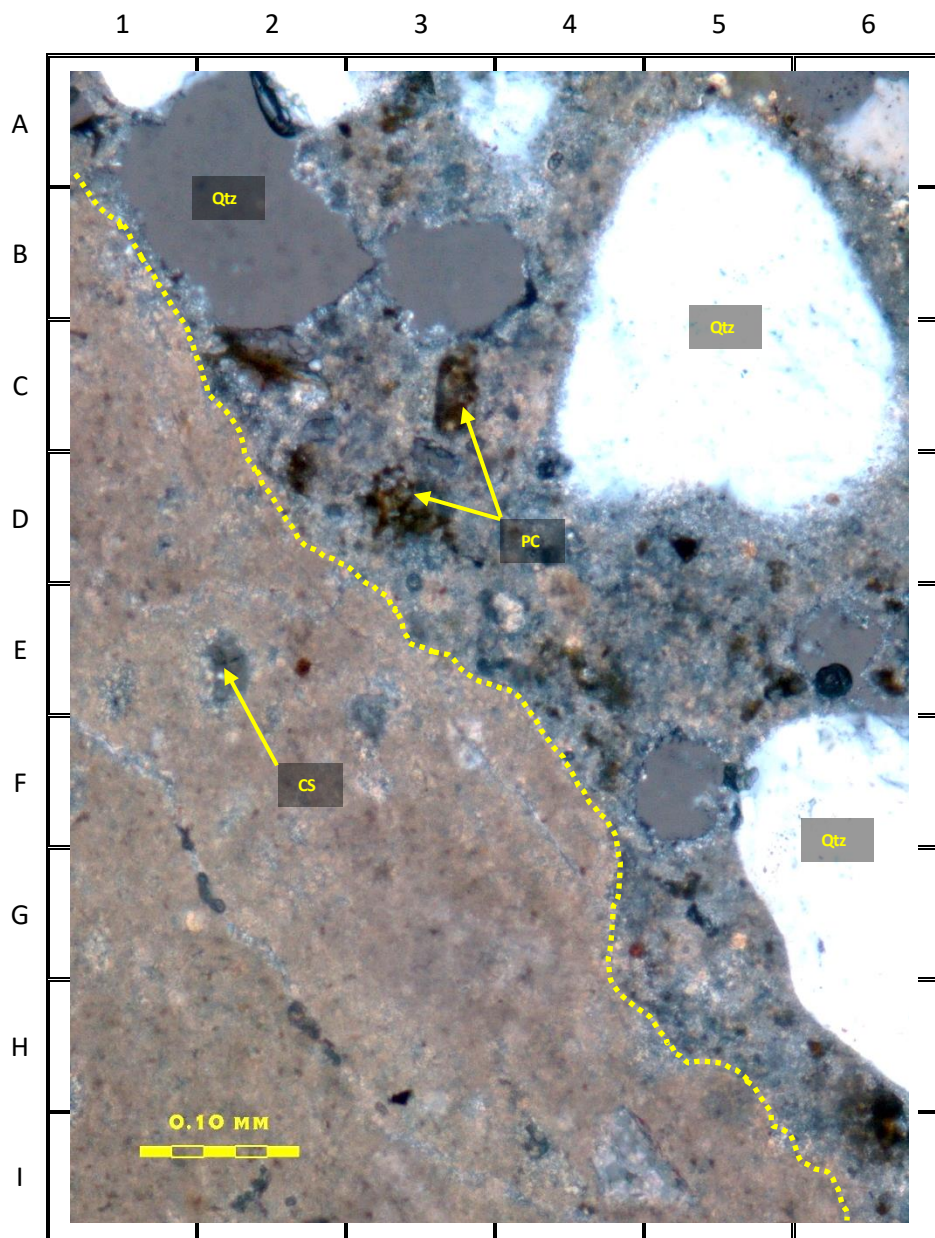


Figure C2

Sample K19563/1 Atkinson Street - Sample 1

Thin section, oblique polars: View showing the typical appearance of the Type 2 lime mortar. The field of view includes abundant quartz (Qtz) sand particles appearing various shades of grey that are surrounded by small amounts of hydraulic lime (HL) binder. Abundant voids are present throughout the field of view and can be seen for example in C2 and G3.

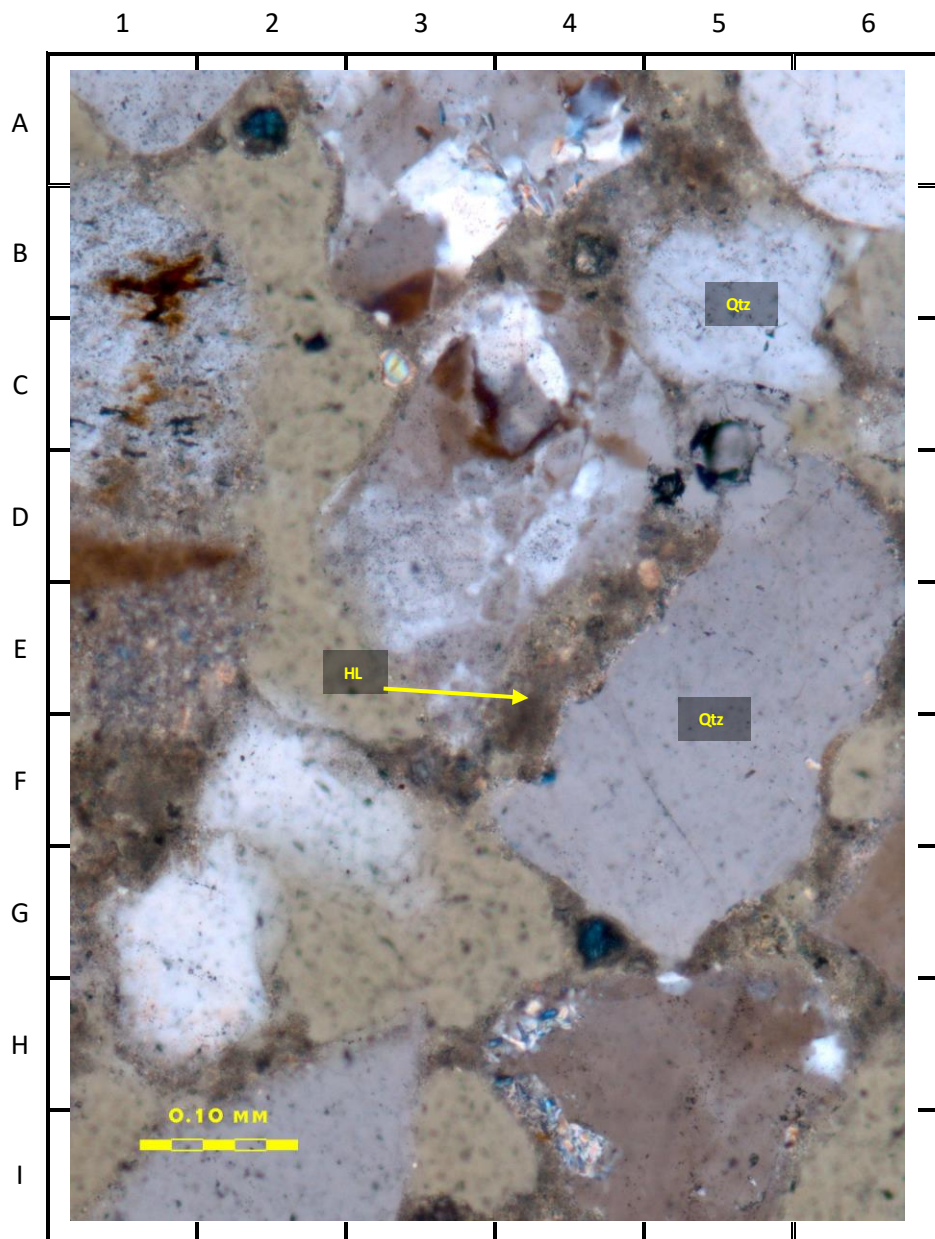


Figure C3

Sample K19563/1 Atkinson Street - Sample 1

Thin section, oblique polars: View showing an area of matrix in the Type 2 lime mortar. Note the partially hydrated calcium silicate (CS) particle that is surrounded by carbonated lime matrix, visible for example in F4. Several quartz (Qtz) sand particles are present.

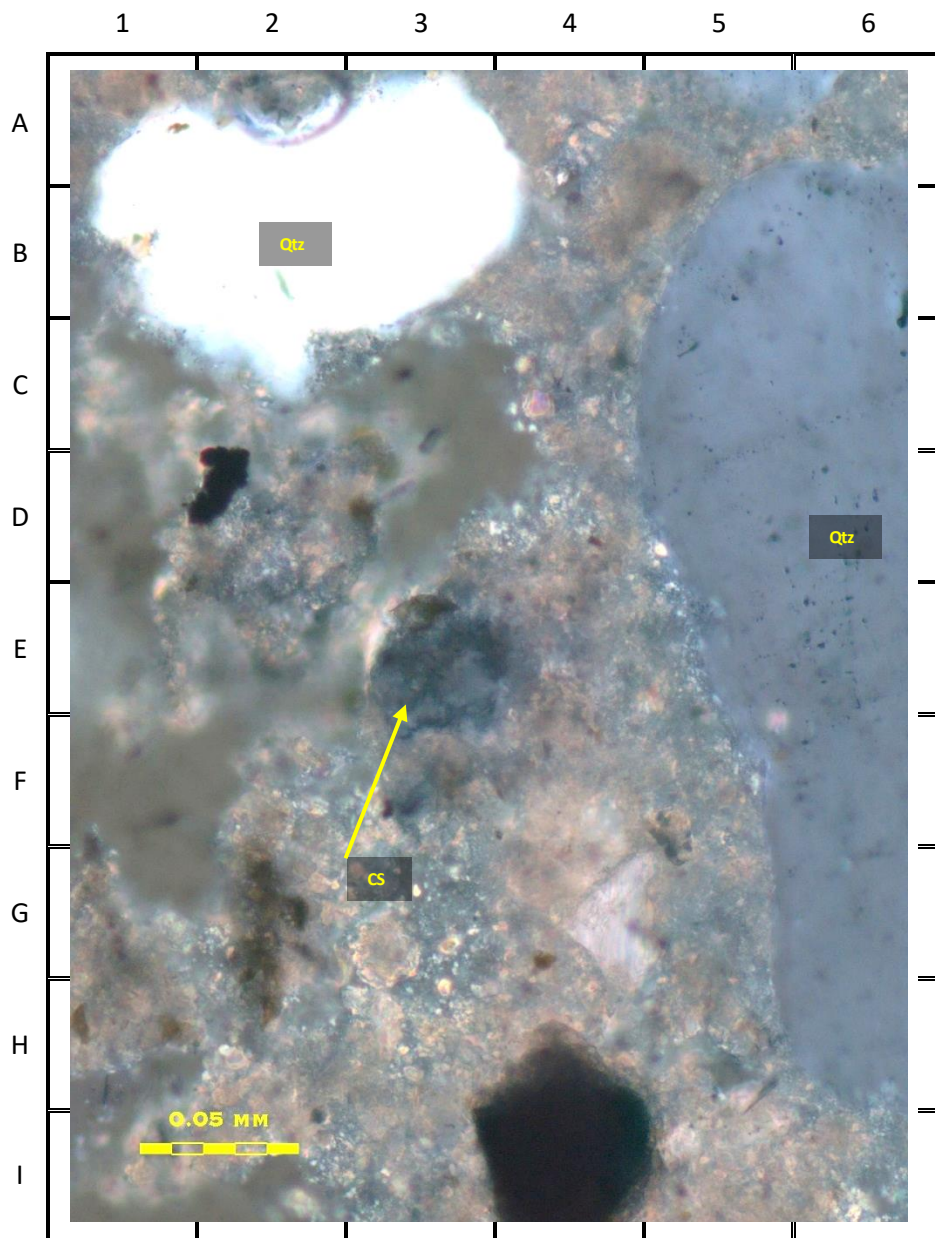


Figure C4

Sample K19563/2 Little Quay Street - Sample 2

Thin section, oblique polars: Low magnification view of the thin section showing abundant quartz sand particles appearing various shades of grey to white and crushed limestone particles, visible for example in F4 and C2 that are surrounded by an abundant carbonated hydraulic lime matrix.

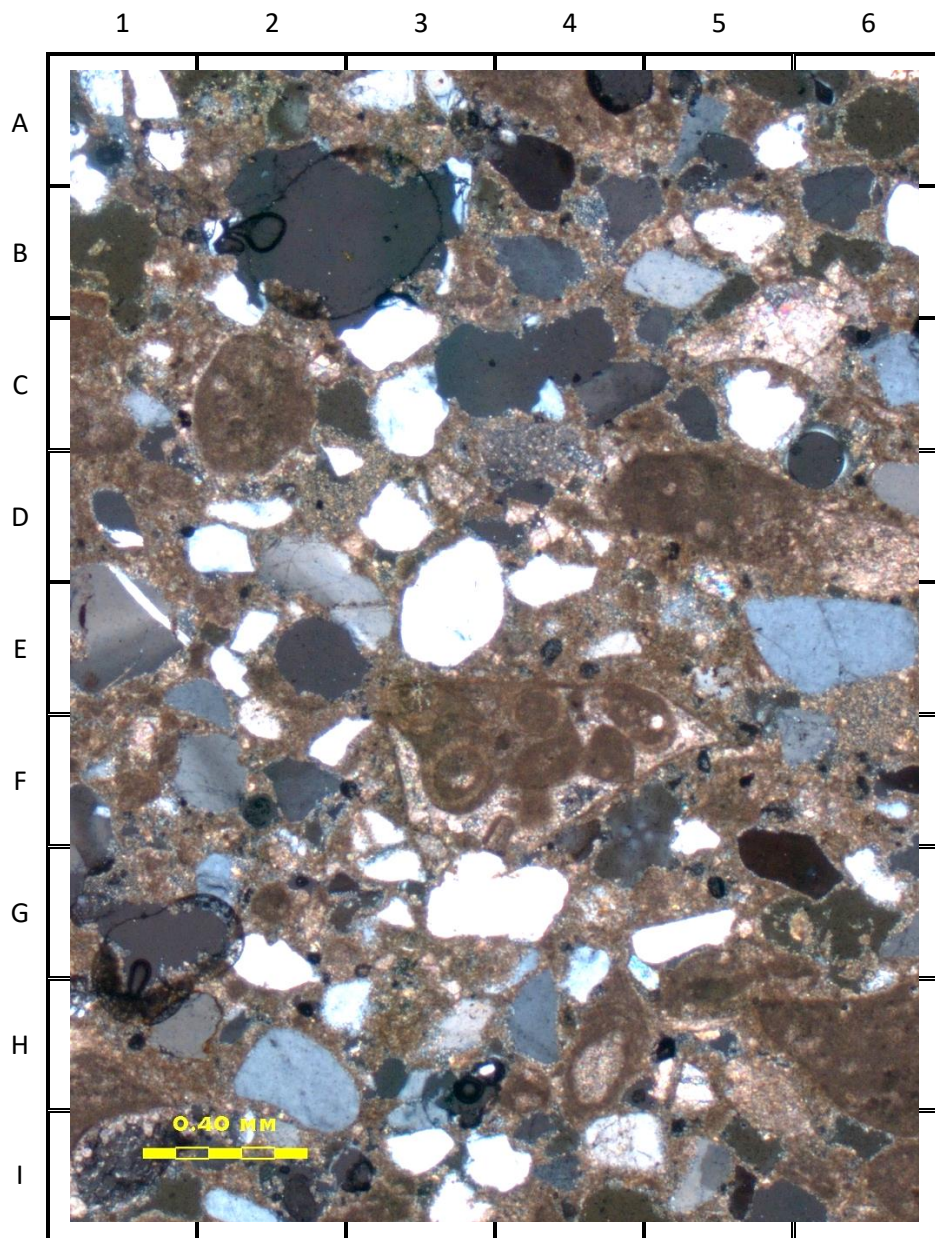


Figure C5

Sample K19563/2 Little Quay Street - Sample 2

Thin section, oblique polars: View showing an area of matrix with an unhydrated calcium silicate (CS) particle occurring in carbonated lime matrix and partially surrounds quartz sand particles appearing various shades of grey. An ironstone particle occurs in H6.

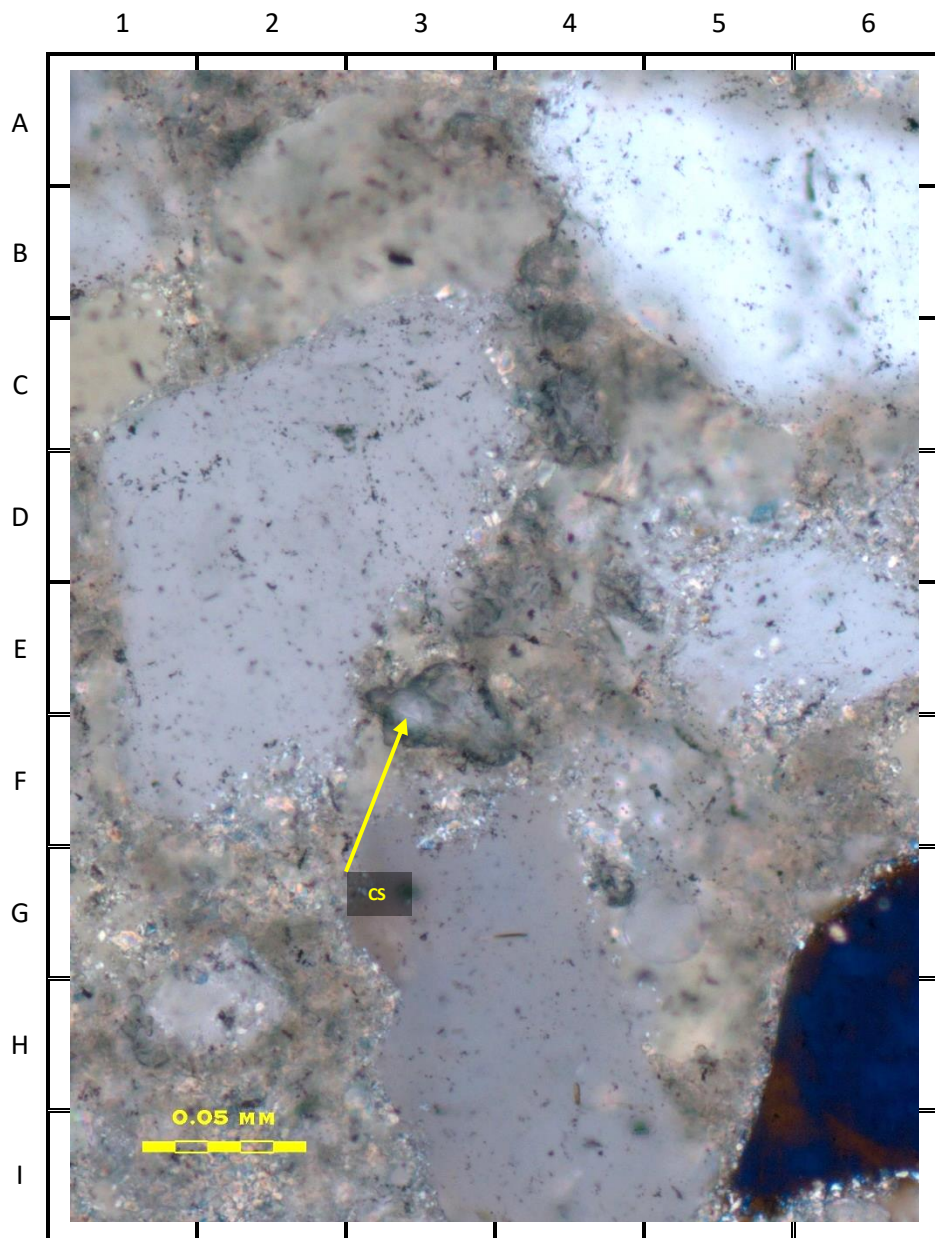


Figure C6

Sample K19563/3 Courtyard - Sample 3

Thin section, oblique polars: View showing an area of matrix with black coal ash particles visible for example around C4/5, and quartz sand particles visible for example in B/C2 and H3. Calcite crystals are growing within the matrix around F4 and I4/5.

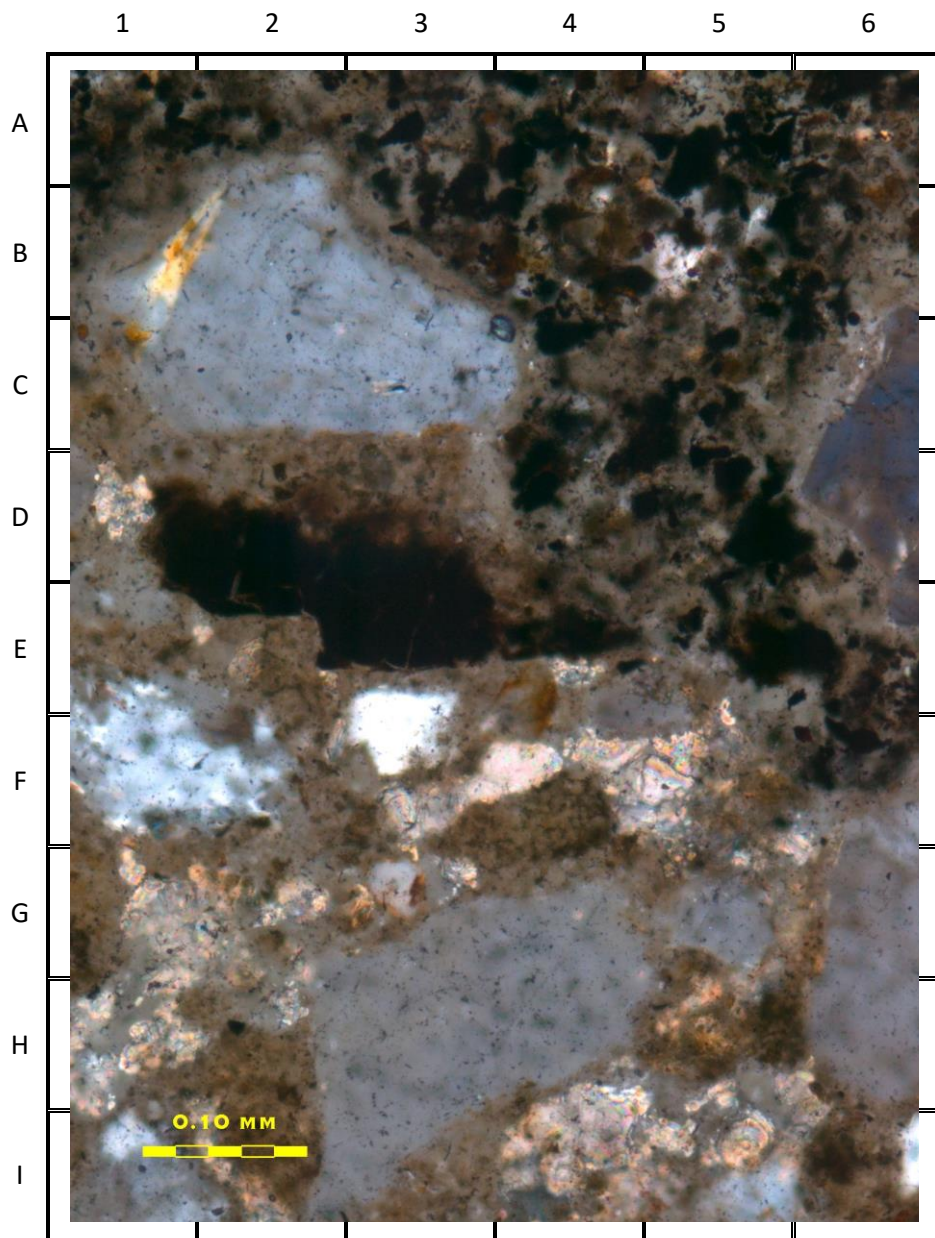


Figure C7

Sample K19563/3 Courtyard - Sample 3

Thin section, oblique polars: View showing an area of matrix that is composed of microcrystalline gypsum in E/F3. Quartz sand particles occur for example in B3/4 and F6.

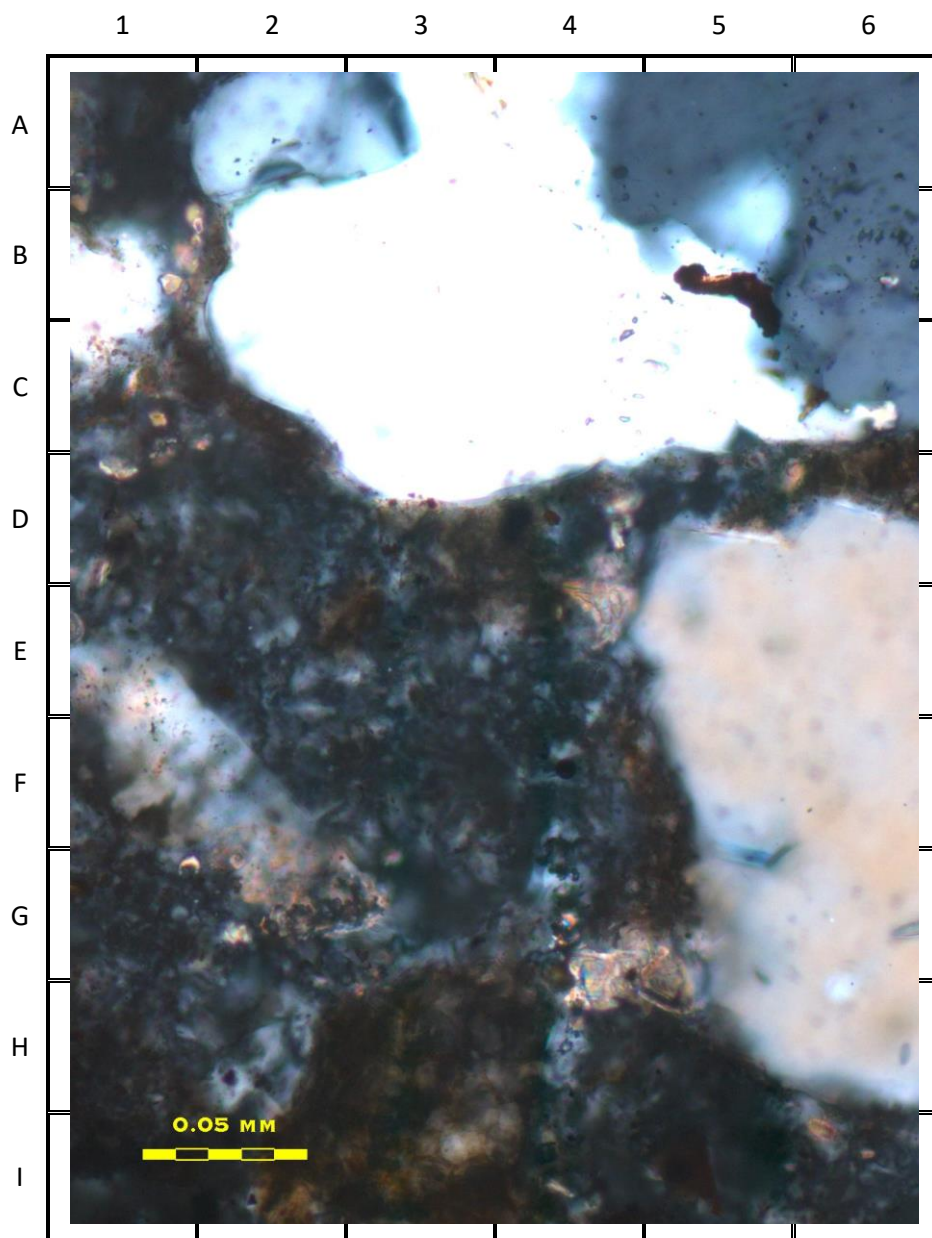
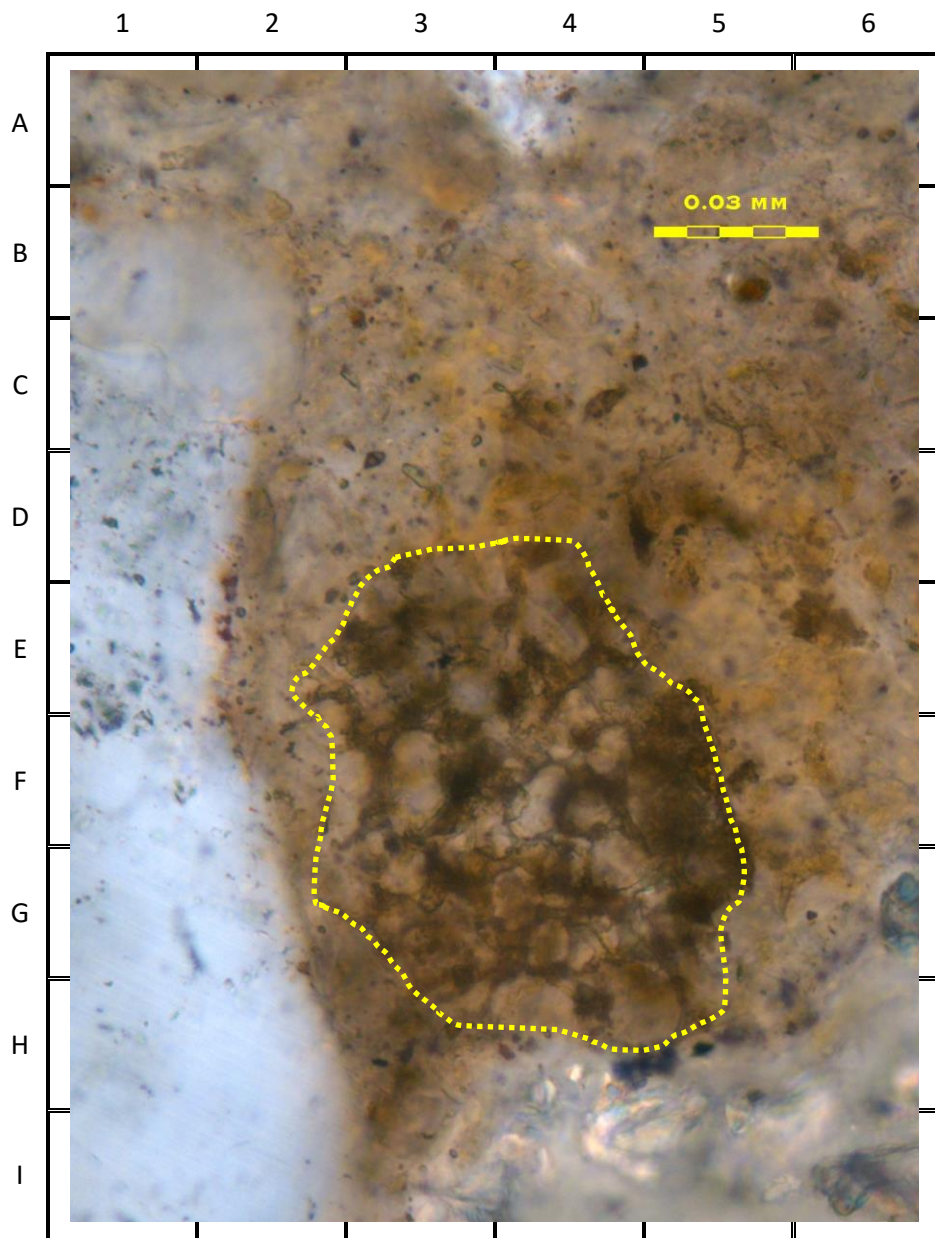


Figure C8

Sample K19563/3 Courtyard - Sample 3

Thin section, oblique polars: View showing an area of substantially hydrated matrix with a Portland cement grain-like structure outlined in yellow. Leached matrix with iron staining dominates the field of view and can be seen for example in C4/5. A quartz particle occurs in F1.



APPENDIX D – PETROGRAPHIC PROCEDURES AND GLOSSARY

1. Preliminary examination:

The samples are examined with the binocular microscope as received and their dimensions and main features are recorded. The features observed include the following.

- (a) The presence and position of reinforcement.
- (b) The extent to which reinforcement is corroded.
- (c) The nature of the external surfaces of the concrete.
- (d) The features and distribution of macro and fine cracks.
- (e) The distribution and size range and type of the aggregate.
- (f) The type and condition of the cement paste.
- (g) Any superficial evidence of deleterious processes affecting the concrete.

2. Polished surfaces:

A plate is cut, where possible, from each sample. This is typically about 20 mm thick and usually provides as large a section of the sample as is possible and typically has a polished surface area of $>100\text{cm}^2$. The plate is polished to give a high quality surface that can be examined with a high quality binocular microscope or even with the petrological microscope if necessary. The polished plate is used to assess the following.

- (a) The size, shape and distribution of coarse and fine aggregate.
- (b) The coherence, colour, and porosity of the cement paste.
- (c) The distribution, size, shape, and content of voids.
- (d) The composition of the concrete in terms of the volume proportions of coarse aggregate, fine aggregate, paste and void.
- (e) The distribution of fine cracks and microcracks. Often the surface is stained with a penetrative dye, so that these cracks can be seen. Microcrack frequency is measured along lines of traverse across the surface.
- (f) The relative abundance of rock types in the coarse aggregate is assessed.

3. Thin sections:

A thin section is prepared for each sample as appropriate. The section is usually made from a plate cut at right angles to the external surface of the concrete, so that the outer 70 mm or so of the concrete are included in the section. Sometimes it is more appropriate to make the section from inner parts of the concrete. This might be appropriate where specific problems are being investigated for example. The section normally measures about 50 x 70 mm.

In manufacturing the thin section a plate some 10 mm thick is cut from the sample. This is impregnated with a penetrative resin containing a yellow fluorescent dye. The resin penetrates into cracks, microcracks, and capillary pores in the sample. One side of the impregnated plate is then polished and the plate is mounted on to a glass slide. The surplus sample is then removed and the plate is ground and polished to give a final thickness of between 20 and 30 micrometres. At all stages the cutting and grinding is carried out using an oil based coolant in order to prevent further hydration of the cement and excessive heating of the section. The thin section is covered and then examined with a high quality Zeiss petrological photomicroscope.

The thin section supplies the following types of information:

- (a) Details of the rock types present in the coarse and fine aggregate and in particular structures seen within those rocks.
- (b) Details of the aggregate properties are measured such as the degree of strain in quartz.
- (c) The size, distribution and abundance of phases in the cement paste are assessed including, for example, the occurrence of calcium hydroxide and the amount of residual unhydrated clinker.
- (d) The presence of cement replacement phases such as slag or PFA can usually be recognised (though the amount of these phases cannot be judged accurately). The presence of high alumina cement can be detected and the type of cement clinker can often be assessed.
- (e) Any products of processes of deterioration of either the cement paste or the aggregate can be recognised.

4. Broken surfaces:

After the specially prepared surfaces and sections are completed, the remainder of the core is examined with the binocular microscope. In particular, the pieces are broken to produce fresh surfaces. These surfaces allow the contents of voids to be studied and the nature of aggregate surfaces or crack surfaces to be investigated.

5. Composition:

Where the size of the sample is appropriate the composition of the sample can be measured using either the polished slice or the thin section, depending on the size of the sample and on details of the aggregate type and paste. The thin section is preferable, for example where large quantities of dust are present. The volume proportions are found by the method of point counting using a mechanical stage. The amount of coarse aggregate can also be assessed by this method if a distinction can be made between coarse and fine aggregate. The results obtained usually represent the sample reasonably, but may not represent the concrete.

6. Water/cement ratio:

The hydration processes of cement paste vary significantly with the original water/cement ratio. Concretes with a low water/cement ratio tend to leave substantial quantities of unhydrated cement clinker and to develop only limited amounts of coarsely crystalline calcium hydroxide. In particular, the extent to which calcium hydroxide is separated into layers on aggregate surfaces and occurs in voids and on void surfaces varies with the original water/cement ratio. The number and proportion of unhydrated cement clinker particles varies inversely with the original water/cement ratio. Comparison with standard concretes made with known water/cement ratios visually, and by measurement allows the water/cement ratio of the cement paste to be assessed directly. The standard error attached to the estimation of water/cement ratio by this means is considered to be approximately +/- 0.1 for unaltered concrete of similar type that in the Sandberg Reference Concrete Collection. It should be noted that aggregate dust, the presence of admixtures and additives all contribute to uncertainty in the petrographic measurement of the water/cement ratio of the concrete.

7. Glossary:

The following is a short list of technical terms in common use in the petrographic examination of concrete².

Alkali-aggregate reaction (AAR): This is a broad term encompassing both alkali carbonate reaction (ACR) and alkali silicate reaction and alkali-silica reaction (ASR). It refers to reactions between alkalies in usually derived from the cement in the cement paste and aggregate particles. Some forms of alkali-aggregate reaction such as ASR result in the formation of an alkali-silicate gel that is readily detectable in thin sections. Other forms of alkali-carbonate reaction such as ACR may not result gel formation.

Alkali carbonate reaction (ACR): This form of reaction is very rare in the UK and there is some debate over the precise mechanism of this reaction. Most documented cases of ACR involve argillaceous, dolomitic limestone. The reaction which is expansive is rarely associated with the formation of obvious gel deposits.

Alkali-silicate/silica reaction (ASR): This is by far the most common form of AAR and generally results from reactions between either microcrystalline, cryptocrystalline, or substantially strained quartz and associated microcrystalline quartz at grain margins and alkalies in cement paste. On rare occasions, ASR may result from the presence of highly reactive opaline silica in aggregate. Petrographic examination is the definitive method for the detection of this form of concrete deterioration. The reaction commonly results in the development of cracking that originates within reactive aggregate particles and continues into the surrounding paste and gel deposits are commonly associated with the occurrence of ASR.

Calcium aluminate cement (CAC): This is a general term that encompasses high alumina cement (HAC) as well as some of the more modern aluminate cements used in rapid setting concrete repair materials or some types of sprayed concretes and grouts.

Carbonation: Carbonation most commonly results from the exposure of concrete to atmospheric carbon dioxide and results in the conversion of portlandite to calcium carbonate and also affects some of the cement hydrate phases forming complex calcium silicate hydrate carbonate compounds. In damp conditions or in concrete exposed to moisture containing dissolved carbon dioxide, coarse-textured carbonation may develop and coarse crystals of calcium carbonate may develop within the cement paste. "Popcorn" calcite deposition (PCD) is one form of this type of carbonation.

Cracking: Cracks are classified using the following terms:

- **Macroscopic cracks:** These cracks are visible in the hand specimen or with the aid of a stereo binocular microscope and are typically >0.01mm wide.
- **Macrocrack:** These are cracks that are readily visible to the naked eye without the aid of a stereo binocular microscope and are typically >0.1mm wide.
- **Fine crack:** These are cracks that are only readily visible with a stereo binocular microscope or in thin section. Cracks of this type are typically between 0.01 and 0.10mm wide.
- **Microcracking:** These cracks cannot be detected with a stereo binocular microscope. They are typically <0.01mm wide and are most easily seen in petrographic thin sections containing fluorescent dye and by using fluorescent illumination.

Delayed ettringite formation (DEF): This term describes deleterious ettringite formation in concrete that has been cured at elevated temperatures, typically >65°C. Ettringite formation resulting from this process can be readily detected using thin sections and the ettringite tends to form in peripheral cracks around aggregate surfaces and sometimes within microcracks in the paste.

² Applied Petrography Group. A code of practice for the petrographic examination of concrete (Author M A Eden), SR2, The Geological Society of London, London, 2010 (Available for download from <http://www.appliedpetrographygroup.com>).

Drying shrinkage cracking: Drying shrinkage microcracks tend to develop radially around the surfaces of fine aggregate particles in concrete. Fine cracks and macrocracks caused by drying shrinkage tend to be parallel-sided cracks and orientated perpendicular to concrete surfaces.

Ettringite: This is a very common calcium-alumino-sulphate mineral. It occurs in most concretes where moisture ingress has occurred. Ettringite formation may be deleterious in the case of DEF or sulphate attack where it can give rise to a deleterious expansion and distinctive forms of cracking but in most cases secondary ettringite formation is non-deleterious.

Fly ash (also known as PFA / pulverised fly ash): This material is a by-product of coal burning power stations and can be readily recognised in thin sections, where it is visible as spherical glass particles, some of which may be hollow. Hollow PFA particles may be referred to as cenospheres. PFA is also commonly associated with small quantities of graphite particles that appear black in thin section.

Fine crack: See section on cracking.

GGBS: Ground, granulated blast furnace slag. This material is commonly employed as a cement replacement material in concrete and can be easily recognised in thin section. The GGBS particles are typically angular and are composed almost entirely of glass.

High alumina cement (HAC): This is a form of cement manufactured from the fusion of limestone and bauxite. It is readily distinguishable in thin section from most other types of cement. Petrographic examination is the definitive method for the detection of carbonation in concrete containing HAC.

Macrocrack: See section on cracking.

Macroscopic: This is a general term referring to features that are visible to the naked eye or with the aid of a stereo microscope.

Microcrack: See section on cracking.

Microsilica: Well dispersed microsilica cannot be directly observed in thin sections. However, distinctive clots of undispersed microsilica are commonly present in concrete containing microsilica – even where most of the microsilica is well dispersed. Microsilica clots are isotropic, and tend to be spherical and are sometimes concentrically layered. They are typically <100µm in diameter.

PFA: See section on fly ash

Plastic shrinkage cracking: This form of cracking occurs in concrete prior to its hardening. It can be distinguished from many other forms of cracking in that it results in cracks that are generally restricted to the cement paste and are non-parallel sided. Cracks of this type typically appear on the concrete surface and commonly diminish in width rapidly with depth and the paste surrounding cracks of this type is commonly of locally high porosity reflecting the migration of moisture towards the cracks during the drying out of the concrete surfaces.

Porosity: This term is distinct from void content. It refers to microscopic pores within cement hydrates. Porosity is directly related to water/cement ratio, but is also strongly influenced by curing and many forms of concrete deterioration. Porosity is sometimes used as an indicator of water/cement ratio in hardened concrete.

Portland cement: Portland cement is the most common form of binder used in concrete and is manufactured from the burning of limestone and an alumino-silicate rock (clay or shale) at temperatures of up to 1500°C. There are many forms of Portland cement and it is commonly possible to distinguish sulphate-resisting and white Portland cement and ordinary Portland cement using petrographic thin sections.

Portlandite: Portlandite is calcium hydroxide and is one of the products formed during cement hydration. Portlandite is readily recognisable in thin sections and has a distinctively high birefringence that contrasts with the much lower birefringence of the hydrated cement phases.

Sulphate attack: This is a general term encompassing both conventional sulphate attack resulting in gypsum and ettringite formation, but also includes sulphate attack associated with thaumasite formation. Sulphate attack can be readily recognised in thin sections and commonly results in the development of surface-parallel cracks infilled with ettringite or thaumasite.

Thaumasite: This is a carbonate-sulphate calcium hydrate mineral with a complex composition. It is a common reaction product in concrete exposed to moisture containing both carbonate and sulphate ions. Thaumasite is most commonly encountered in concrete exposed to temperatures of $<4^{\circ}\text{C}$. Some forms of thaumasite can be readily distinguished from ettringite and have a high birefringence. However, some forms of thaumasite have a much lower birefringence and can be difficult to distinguish from ettringite without recourse to SEM micro-analysis.

Void: This describes empty spaces present in concrete that are typically greater than about 5 micrometres in diameter. It encompasses both entrained air voids (spherical voids typically $<1\text{mm}$ in diameter) as well as much larger entrapped air voids. It should be noted that it is possible for concrete to have a low porosity, but a high void content.

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