

Core 20511/C8 – Pyrrhotite in foundation concrete of 7 Mulroy View, after expansion testing

Department of Housing, Local Government and Heritage, and Geological Survey Ireland

Pyrrhotite-bearing concrete investigation, Co. Donegal

Laboratory Analysis Services in support of Geological Survey Ireland’s “Irish Construction Materials” Project.

Phases 2 and 3 Report: Assessment of Foundation Concrete From 4 Houses

1283831-03 (01)

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Date: 14 March 2025

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Samples are retained for ONE month from the issue of the final report. Should you wish us to retain the samples for a longer period, or should you wish to collect the samples please could you advise us at your earliest convenience.

EXECUTIVE SUMMARY

RSK has been undertaking a laboratory investigation on behalf of the Irish Government and Geological Society of Ireland on the long term durability behaviour of concrete in relation to apparently defective housing built in NW Ireland in the period between late 1990s to early 2010s. Earlier investigation works attributed the concrete defects to the presence of excessive amounts of 'free' muscovite mica in the concrete and to the presence of reactive sulfide minerals, especially pyrite, leading to internal sulfate attack (a problem identified elsewhere in Ireland). Subsequently certain aggregates from the affected area, in particular one phyllite aggregate, has been identified as containing the particularly reactive iron sulfide pyrrhotite. RSK has been undertaking investigations into the durability of supplied concrete samples relating to 4no properties (including one control property, exhibiting no superstructural damage). The investigation has mainly focussed on precast concrete blocks used both for superstructure and immediately below-ground construction, however a total of 10no core samples have been provided from the cast *in situ* foundation concrete of these 4no selected properties.

Core samples have been subject variously to petrographic examination, instrumental microanalysis by SEM/EDX and XRD, compressive strength and density determination and chemical analysis of cement and sulfate content, total sulfur and sulfide content by a variety of methods. The suite of testing was undertaken on 'as received' concrete and following accelerated durability tests based on the RICS Mundic Stage 3 Expansion test method or the Accelerated Oxidisation test published in Canadian Standard CSA A23.1:19 / A23.2:19 Attachment P3, with the objective of providing information on the susceptibility to progressive damage to these concrete foundations by internal sulfate attack.

Generally, the foundation concrete from the three damaged test properties was similar in terms of aggregate and cement type and water cement ratio, and was generally reasonably dense and well compacted. Sporadic pyrrhotite and pyrite (and sometimes traces of chalcopyrite) were present in the phyllite aggregate. As received concrete showed slight evidence of secondary sulfate development consistent with sulfide oxidisation and the early stages of internal sulfate attack processed, but these had not progressed significantly with regards to presenting a risk of damage to the concrete.

Both accelerated durability tests promoted a small amount of further sulfide oxidisation, shown by an increase in sulfate concentration in the concrete samples after these tests. However, none of the tested concrete showed significant expansion, which suggests that while some pyrrhotite oxidisation may be ongoing, this is insufficient oxidisation to cause significant damage to the concrete.

Overall, it is concluded that, whilst some of the processes of internal sulfate attack are happening and will continue to occur, provided there is no change of the environment around the foundation concrete, the rate of progression is very slow and therefore there is a low risk that this will be sufficient to cause significant damage to the foundation concrete within the intended design life of the buildings.

The information given in this summary is necessarily incomplete and is provided for initial briefing purposes only. The summary must not be used as a substitute for the full text of the report

1 INTRODUCTION

1.1 Background

Irish Standard IS 465¹ was initially published in 2018 to provide guidance on site investigations, sampling and laboratory testing of concrete, especially blockwork concrete, used for house building between the mid/late 1990s to early 2010s; many houses built during this age exhibited significant superstructural cracking to rendered masonry. In much of Ireland, especially southern counties, this was attributed to the presence of pyrite, and in particular the relatively reactive framboidal form, being present in aggregate in the concrete, and sometimes causing damage by internal sulfate attack (ISA) with the oxidisation of the pyrite. Apparently similar damage to buildings in the County Donegal area of northwest Ireland was attributed to an excessive concentration of ‘free’ muscovite mica within the concrete²; excessive mica can be problematic by affecting the flow and compaction properties of a fresh concrete mix, and therefore may lead to the production of poor-quality concrete.

Later investigation has indicated that the affected concrete in County Donegal typically contains a phyllite aggregate that includes a minor amount of the highly reactive iron sulfide mineral pyrrhotite, and that the deterioration is likely to be caused by pyrrhotite oxidisation, the release of sulfate (and H⁺) ions and consequently internal sulfate attack on the hardened cement phases in concrete.

While the majority of cases investigated in Ireland have related to precast concrete blocks, the same deterioration mechanism, via the use of pyrrhotite-bearing aggregate in concrete, has been identified in cast *in situ* concrete in both the Trois Rivières area of Quebec³ and in Connecticut⁴. There are therefore doubts as to the durability of cast *in situ* concrete containing pyrrhotite-bearing aggregate used in cast *in situ* concrete foundations to affected properties in County Donegal, and consequently whether the cast *in situ* foundation concrete should be included in remediation schemes on affected properties.

Concrete blocks affected by ISA typically experience a primary deterioration mechanism triggered by the expansive oxidisation (rusting) of iron sulfides, resultant release of sulfuric acid and subsequent dissolution, alteration and weakening of the cement matrix eventually leading to conversion or failure of the concrete, with the formation of secondary ettringite and/or thaumasite as the products of sulfate attack. These reactions are in part represented by the following equations well documented in the literature⁵.

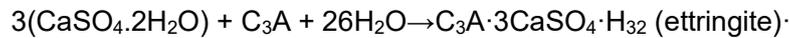
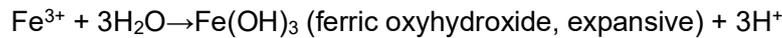
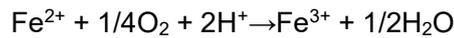
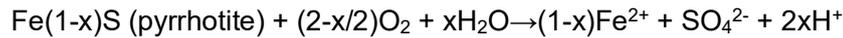
¹ IS 465:2018+ A1: 2020. Assessment, testing and categorisation of damaged buildings incorporating concrete blocks containing certain deleterious materials and Amendment 1: National Standards Authority of Ireland, 2020.

² McCarthy, D. Kane, N. Lee, F. Blaney, D. Report of the Expert Panel on Concrete Blocks, 2017, <https://www.gov.ie/en/publication/0218f-report-of-the-expert-panel-on-concrete-blocks/>.

³ A. Rodrigues, J. Duchesne, B. Fournier, B. Durand, P. Rivard, M. Shehata, Mineralogical and chemical assessment of concrete damaged by the oxidation of sulfide-bearing aggregates: Importance of thaumasite formation on reaction mechanisms, Cement and Concrete Research, Volume 42, Issue 10, 2012, Pages 1336-1347, ISSN 0008-8846,

⁴ 6 R. Zhong, K. Wille, Deterioration of residential concrete foundations: the role of pyrrhotite-bearing aggregate, Cem. Concr. Compos. 94 (2018) Pages 53–61.

⁵ Jana, D, Concrete Deterioration from the Oxidation of Pyrrhotite: A State-of-the-Art Review, Chapter 5, Maher, M.L.J, Pyrite and Pyrrhotite, 2023, Pages 139-221, ISBN 979-8-88697-329-7, Nova Science Publishers, Inc.



1.2 Objective

Samples were obtained from 3no houses identified as showing evidence of damage to superstructural rendered concrete blocks, and one from earlier construction utilising aggregate from a different source, to provide a control property. RSK was provided with samples variously of concrete blocks taken from the outer leaf and inner leaf superstructural walls and below ground rising wall, along with core samples taken from the concrete footing (foundation concrete); it is understood that the cast *in situ* concrete utilised generally the same aggregates as used in the precast blocks (subject to some variation in the quality of the material produced at different times).

RSK's investigation programme was to include an initial assessment of the concrete materials as received (Phase 1), accelerated durability test methods following the Mundic guidance⁶ from the UK and a protocol developed for Canadian Standard guidance⁷ (Phase 2), and subsequent reassessment of the concrete (Phase 3).

This report details only the findings of Phase 2 and Phase 3 work undertaken on the foundation concrete, including interpretation of the results in terms of the durability of the concrete and its likelihood to provide acceptable in-service performance based on a 50-year design life of the houses. The investigated houses are typically between circa 15- and 20-year-old with the exception of the control sample from a house of approximately 30 years age.

1.3 Previous and Future Work

RSK has undertaken extensive laboratory testing on all provided samples. The results of the Phase 1 investigation (prior to accelerated durability tests) have been provided to the clients in Report 1283831-01.

A separate full report (1283831-04) covers Phase 2 and Phase 3 results for the other elements investigated.

⁶ RICS Guidance Note. (2015). The Mundic Problem, RICS Professional Guidance Note, UK. 3rd edition. London: Royal Institution of Chartered Surveyors (RICS). ISBN 978 1 78321 094 7

⁷ CSA A23.1:19/CSA A23.2:19 Concrete materials and methods of concrete construction/Test methods and standard practices for concrete, P3, Pages 370-381, CSA, Canada, ISBN 978-1-4883-0744-7

2 SAMPLES

2.1 Sampled Properties

The properties were selected by Donegal County Council and advised to have been taken from four vacated houses in Co. Donegal. Three of the houses were considered test properties, these were 15-25 years old and were known to have experienced structural damage/defects typical of the area identified in accordance with I.S. 465. The other 'control' property was known to have been constructed in the 1980's and be in good condition. The properties are listed below.

Test Properties

- 7 Mulroy View, Co. Donegal, (7MV)
- 21 Glendale Drive, Co. Donegal, (21GD)
- 28 Abbots Wood, Co. Donegal, (28AW)

Control Property

- Carrowmore, Co. Donegal, (C)

The properties all include mass concrete strip foundations, with the test properties exhibiting blockwork rising walls up to DPC and rendered cavity wall concrete block masonry construction above. The control property reportedly does not include separate rising wall and DPC details, with the blockwork constructed with both leaves of the cavity wall direct from the concrete foundations.

2.2 Sampling

Sampling was undertaken by Crana Cranes Limited (approved sub-contractor to Donegal County Council) under the supervision of IGSL, acting on behalf of GSI. Sampling was undertaken between 9 and 12 January 2023, in generally damp or wet conditions and with saturated ground conditions. Provided photographs of the site sampling are included in Report 1283831-01 **Appendix B**.

2.3 Samples

Selected samples were provided to RSK and other research partners by IGSL. Initially, 42 samples were provided to RSK, with these being received at RSK's UKAS-accredited materials testing laboratory in Hemel Hempstead on 28 March 2023, with these being assigned the unique batch identification number 20511. Of these 46 samples, nine were cores from foundation concrete.

Following a request for some additional sample materials from 28 Abbots Wood, a further six samples were provided and assigned the batch identification number 20954. This batch included one further core of foundation concrete.

Table 2.1 Foundation Samples received by RSK

Location	RSK Ref	Client sample ref	Sample type	Element	Client Area Location	Date Sampled	As received condition
7MV	20511/C7	4B	Core	Foundation	E, FF, W	10/01/2023	F/C
	20511/C8	4E	Core	Foundation	E, FF, W	10/01/2023	In
	20511/C9	4G	Core	Foundation	E, FF, W	10/01/2023	In
21GD	20511/C27	5B	Core	Foundation	E, GE	9/01/2023	In
	20511/C28	5E	Core	Foundation	E, GE	9/01/2023	In
28AW	20511/C20	4A	Core	Foundation	E, GE	11/01/2023	In
	20511/C21	4D	Core	Foundation	E, GE	11/01/2023	In
	20954/C5	4C	Core	Foundation	E, GE	11/01/2023	In
C	20511/C14	4A	Core	Foundation	E, GE	12/01/2023	In
	20511/C15	4C	Core	Foundation	E, GE	12/01/2023	F

Notes: Locations – E: Exterior, GE: Gable End, FF: Front Facing, W: West

Conditions – In: Intact, F: Fragmented, C: Crumbly

3 LABORATORY METHODS

3.1 RICS - The Mundic Problem, Stage 3 expansion testing

Expansion testing was conducted in accordance with RICS guidance note 'The mundic problem, 3rd edition'. The Stage 3 test is primarily applicable to concrete blocks from a specific area of the Southwest region of the UK where spoil from metalliferous mining activities have been used locally as aggregate. Therefore, any criteria should not be thought to apply outside of that regional use nor be directly applicable for cast *in situ* concrete as with these foundation samples. The method involves measuring the unconstrained linear expansion of concrete cores that have been exposed to a water-saturated atmosphere at a constant temperature of 38°C for at least 250 days. The testing period can be expanded to at least 350 days if the expansion shown is progressing at a slow rate when 250 days of exposure is reached. During this investigation, all foundation cores apart from one (250 days) were kept in exposure conditions for 350 days to provide further time for any reactions to occur. This is particularly relevant given that the test is designed for less dense concrete blockwork samples rather than dense mass concrete samples.

3.2 CSA A23,1:19/A23.2:19 Attachment P3 (informative) oxidisation testing

To determine residual oxidisation potential and the possibility of thaumasite formation, an adaption of the test method developed by Andrea Rodrigues at Université Laval and incorporated in CSA A23, 1:19/CSA A23, 2:19, P3. The methodology describes a procedure for determining the potential deleterious character of sulfide-bearing⁸ aggregates through a two-phase accelerated mortar bar test. In this study, the methodology was adapted to test the concrete core samples with similar sample sizes and stud arrangements specified within RICS guidance note 'The mundic problem, 3rd edition'.

To prepare the sub-samples three pairs of bespoke titanium DEMEC Gauge studs spaced at 50 mm separation were fixed at equal intervals (120°) around the circumference of a set of up to four 75 mm diameter cores taken from the investigated elements (dependent on sample availability).

Cores undergo immersion in 6% sodium hypochlorite solution for 3hrs±15min and are then removed, weighed and measured as a zero reading then left to dry for 3hrs±15min. After drying samples are stored above a saturated sodium chloride solution (75 %RH) at 80 °C. The bleach utilised was Ki-Chem UK Limited t/a Cleaning supplies 2U, 6% Bleach, which had an advertised NaOCl content of 6 % and determined pH of 12.3 and a NaOH 0.07 wt % (internal testing and calculation).

Every week, the cores undergo two immersion periods in the 6% sodium hypochlorite (as specified above) and once a week, after an immersion period, the length, mass and condition of each core are taken and recorded.

⁸ The method has been specifically developed following the construction of defective buildings incorporating concrete with pyrrhotite-bearing aggregates in the Trois Rivières / Shawinigan areas of Quebec.

After 13 weeks of storage at 80 °C and 75 %RH (P3 Phase 1) between immersions samples transition to storage above water at 4°C (P3 Phase 2) and continue the twice-weekly immersions in sodium hypochlorite and once-a-week measurements.

Samples were taken off test if they had disintegrated, lost structural integrity or had lost measuring studs repeatedly in P3 Phase 1. In P3 Phase 2 the same sample deterioration required measurements were stopped but disintegrated samples continued to go through the cycling but in a perforated holding container to permit the possibility of thaumasite formation to occur and allow an equal comparison (where possible).

3.3 Petrographic examination – ASTM C856-20⁹ and I.S. 465 7.3

For investigated samples, one polished and one cover slipped thin section and a polished slice (approximately up to 100×100×20 mm sized, Phase 1 only) were produced using either the minimum of water required or alternative grinding media. Examination of the concrete was conducted using a polarising Zeiss Axioscope A1 petrographic microscope, utilising reflected, transmitted and reflected UV light sources.

3.4 SEM/EDX analysis

SEM/EDX analysis was conducted at an RSK-approved sub-contractor with on-instrument consultation given as needed by RSK personnel. Various sizes of concrete samples ranging from 25×25×25mm to 50×30×25 mm were vacuum impregnated with epoxy resin, polished to a 3-micron finish, and carbon-coated on a single face for analysis.

A JEOL 6480 LV SEM equipped with an Oxford Instruments X-MAX80 SD X-ray detector and INCA x-ray analysis system was used to image the samples and perform the EDX analysis. EDX analyses the characteristic X-rays produced by the interaction between the primary electron beam and the sample. The technique identifies all elements present with atomic numbers of 5 (boron) and greater with a detection limit of approximately 0.1 weight % with all measurements semi-quantitative. The SEM was operated at an accelerating voltage of 15 kV.

3.5 XRD analysis (semi-quantitative)

XRD analysis was conducted at an RSK-approved sub-contract using a fully automated Bruker D8 powder diffractometer employing copper α radiation ($\lambda=0.15406\text{nm}$) and an energy dispersive Si detector. The samples were continuously spun during data collection and were scanned using a step size of $0.02^\circ 2\theta$ between the range of $5^\circ\text{-}80^\circ 2\theta$. Phase identification using XRD is achieved by comparing the diffraction pattern obtained from the unknown, to a standard database that is compiled by the International Centre for Diffraction Data (ICDD).

⁹ ASTM C856-20, Standard practice for petrographic examination of hardened concrete, ASTM, 2020

3.6 Compressive strength of cores samples – BS EN 12504-1:2019

A set of 1:1 length-to-diameter ratio concrete core samples were sub-sampled, prepared (ground) and tested in accordance with BS EN 12504-1¹⁰. Compressive strengths were compared to cube strength specifications.

3.7 Density – BS EN 12390-7:2019+AC:2020

As-received dry densities were measured in accordance with BS EN 12390-7:2019¹¹+AC:2020 on 1:1 cored concrete samples to provide a check on sample compaction.

3.8 Cement content – BS 1881-124:2015+A1:2021

Analysis was performed on 1 kg of material either previously tested for compressive strength or the remnants of the sample after sub-sampling. The analyses for insoluble residue, soluble silica and calcium oxide were carried out in accordance with BS 1881-124:2015+A1:2021¹², Clause 6. Note, that the cement content calculated as kg/m³ used the determined densities for some samples, whereas other samples used the determined densities from the same or near similar element (See Appendix C).

3.9 Total sulfur – BS EN 1744-1: 2009+A1:2012

The total sulfur content was determined in accordance with BS EN 1744-1¹³, Clause 11 acid digestion method. The extraction was conducted using hydrogen peroxide and dilute hydrochloric acid, and the sulfur was precipitated as barium sulfate. The result is reported to the nearest 0.1% by mass of dry aggregate. Note, that the test method describes testing aggregate samples. In this case, the concrete samples were additionally prepared to pass a 2 mm sieve before the specified sieving was conducted. Concerns have been raised about the reliability of the results obtained by this technique, which appears to significantly under-estimate the total sulfur of samples where petrographic examination confirms the presence of sulfide minerals.

Subsequently, additional testing was undertaken wherein powdered samples were directly tested for total sulfur content utilising high-temperature combustion and infra-red analysis (LECO). This method is provided as an option in BS EN 1744-1 Clause 11.2, although the acid digestion method is the reference method. A similar method is described in the Canadian standard CSA A23.1 as the preferred method for determining total sulfur in aggregate.

¹⁰ BS EN 12504-1:2019. Testing concrete in structures. Part 1 – Cored specimens. Taking, examining and testing in compression. BSI, London, 2019.

¹¹ BS EN 772-1:2011+A1:2015 Methods of test for masonry units Determination of compressive strength, BSI, London, 2015

¹² BS 1881-124:2015+A1:2021, Testing Concrete - Methods for analysis of hardened concrete, BSI, London

¹³ BS EN 1744-1:2009+A1:2012, Tests for chemical properties of aggregates - Chemical analysis, BSI, London

3.10 Acid soluble sulfate content – BS EN 1744-1:2009+A1:2012

The acid soluble sulfate content was determined in accordance with BS EN 1744-1, Clause 12. The extraction was conducted using dilute hydrochloric acid and the sulfate was precipitated as barium sulfate. The sulfate content is reported to the nearest 0.1% by mass of dry aggregate (sample). Note, that the test method describes testing aggregate samples. In this case, the concrete samples were additionally prepared to pass a 2 mm sieve before the specified preparation procedure was conducted. It has been suggested that the test method may cause some dissolution of pyrrhotite, and therefore the results obtained represent more sulfur than consistent with the total sulfate content of the sample¹⁴.

3.11 Water soluble sulfate content – BS EN 1744-1:2009+A1:2012

The water-soluble sulfate content was determined in accordance with BS EN 1744-1, Clause 10. The 2:1 water extract was treated with an excess of barium chloride to precipitate the sulfate as barium sulfate, which was determined gravimetrically. The result was expressed as SO₃ to the nearest 0.01% by mass of dry aggregate (sample). Note The test method describes testing aggregate samples. In this case, the concrete samples were additionally prepared to pass a 2 mm sieve before the specified preparation procedure was conducted. The resulting material was tested to determine the water-soluble sulfate content in accordance with BS EN 1744-1 for fine aggregate.

3.12 Determination of sulfate – BS EN 196-2:2013

The sulfate content was determined in accordance with BS EN 196-2:2013¹⁵. The acid extract was treated with an excess of barium chloride to precipitate the sulfate as barium sulfate, which was determined gravimetrically. The result is expressed as sulfur trioxide, SO₃ by weight of sample and of cement. Note that the method is for testing cement while the samples are mass concrete. The standard details the calculation for reporting the sulfate content by mass of sample. A further calculation was performed to report the sulfate by mass of cement. This was performed following BS 1881-124:2015+A1:2021 and using the determined cement content. This calculation is not included in BS EN 196-2:2013.

3.13 Determination of sulfide – BS EN 196-2:2013

The sulfide content of the sample was determined in accordance with BS EN 196-2:2013, clause 4.4.5. Note that the method is for testing cement while the samples tested comprised mass concrete.

¹⁴ Personal communication of Mike Eden (Sandberg) based on commentary on pyrrhotite solubility in textbooks such as Deer, Howie and Zussman.

¹⁵ BS EN 196-2:2013 Method of testing cement - Chemical analysis of cement, BSI, London

3.14 BRE SD1 Suite D Brownfield Testing

Representative portions of concrete samples previously submitted for oxidisation/expansion testing were submitted to Envirolab (an RSK Group company) for further BRE SD1:2005¹⁶ Suite D brownfield testing consisting of pH (probe), water soluble sulfate (colorimetry), acid soluble sulfate (inductively coupled plasma, optical emission spectroscopy, ICP-OES) and total sulfur analyses (ICP-OES) using in-house standards.

Leachate samples from the bottom of containers used during the RICS Stage 3 testing were also sub-sampled and submitted for the same BRE SD1 Suite D brownfield testing for water samples. This comprised of pH (probe), water soluble sulfate (colorimetry) and magnesium content (ICPOES, when specified by results).

¹⁶ BRE Special Digest 1: 2005. Third Edition. Concrete in aggressive ground. BRE, Garston, UK. ISBN 1 86081 754 8

4 TEST ASSIGNMENT

The tests undertaken on each sample are detailed in **Table 4.1**. Note that Phase 3 testing was subject to testing restrictions due to the sample masses and geometries available.

Table 4.1 Test Assignment

Location	RSK Reference	Phase 1 - As received testing											Phase 2 - Durability testing		Phase 3 - Post durability testing													
		Petrography	SEM/EDX	XRD	Compressive Strength	Density	Cement content	Total sulfur	Acid soluble sulfate	Water soluble sulfate	Pyrite/pyrrhotite content	Determination of sulfate	Determination of sulfide	CSA A23.1 P3 Oxidisation	RICS Stage 3 expansion	Petrography	SEM/EDX	XRD	XRF	Compressive Strength	Density	Cement content	Total sulfur	Acid soluble sulfate	Water soluble sulfate	Determination of sulfate	Determination of sulfide	BRE Suite D Brownfield
7MV	20511/C7	X	X	X	X	X	X	X	X	X	X	X		X					X	X	X	X	X	X	X	X	X	X
	20511/C8 [†]												X		X	X	X	X				X ^H						
	20511/C9												X	X	X ^R	X ^R	X ^R	X ^R	X ^C	X ^C	X ^C	X	X ^C	X ^C	X ^C	X ^C	X ^C	X ^C
21GD	20511/C27	X	X	X										X	X	X	X	X			X	X	X	X	X	X	X	X
	20511/C28			X	X		X	X	X	X	X	X	X		X	X	X	X			X	X	X	X	X	X	X	X
28AW	20511/C20	X	X	X										X	X	X	X	X				X ^H						
	20511/C21				X		X	X	X	X	X	X	X		X	X	X	X				X ^H						
	20954/C5												X	X					X	X	X	X	X	X	X	X	X	X ^R
C	20511/C14	X	X	X			X	X ^A	X	X	X	X																
	20511/C15						X	X ^A	X	X	X	X																

^H HTC Only, [†] Double suite of Phase 3 tests to investigate the difference between CSA A23.1 P3 Phase 1 and CSA A23.1 P3 Phase 2, ^A Acid digestion only, ^R RICS Stage 3 only, ^C CSA A23.1 P3 Only

5 LABORATORY TEST RESULTS

Some test results and certificates have previously been provided to the client as part of report 1283831-01. For the physical and chemical testing undertaken on 'as received' samples, as the testing was carried out *en masse* with the concrete blockwork samples, results from all samples are included on the certificates (appendices C, D and E). For materials tested following the accelerated durability testing, the certificates only report the results for foundation concrete samples apart from a few exceptions (see all appendices).

5.1 Phase 2 – Durability Testing

Detailed results of the RICS Mundic Stage 3 expansion testing and CSA A23.1-19 oxidation testing are given in **Appendix A** (Certificates of Test), and summarised in **Table 5.1**.

Table 5.1 Summary of Foundation Durability Test Results

Property	RICS Mundic Stage 3 expansion testing			CSA A23.1: 19 Accelerated Expansion testing			
	Mean Expansion %	Mean Mass change %	Length of test, days	Mean Expansion, %	Mean Mass Change, %	Length of test, weeks	Observations
7MV	0.014	1.7	350	0.03	2.9	26	Intact, rusty, some pitting of phyllite
21GD	0.010	3.1	350	0.04	2.4	26	Intact, rusty, some pitting of phyllite
28AW	0.021	3.7	350	0.12	2.0	26	Intact, rusty, some pitting of phyllite
	0.014	3.7	250				

5.2 Phase 3 – Petrographic Examinations

Detailed results of the petrographic examinations are provided in **Appendix B** (Certificates of Examination), and are summarised in **Table 5.2**.

Note that the term *in situ* refers to within the concrete, in Phase 1 this refers to when the concrete was in place within the properties. For Phase 3, *in situ* refers to a combination of when the concrete was in place within the properties and during Phase 2 durability testing.

Table 5.2 Summary of Petrographic Examinations - Foundations

Property	RSK Sample reference	Phase 1 Observations – As Received	Phase 2 Durability Test	Phase 3 Observations – After durability test
7MV	20511/C7	14 mm crushed all in phyllite-quartzite (PHY) aggregate bound by a Portland-type cement. 0.5 % excess voidage. Concrete visually sound but evidence of leaching, potential for sulfate attack, and splitting of phyllite. Common partial <i>in situ</i> oxidisation of sulfides. Rare to frequent secondary sulfates including an isolated occurrence of thaumasite replacing cement matrix Sporadic to common pyrrhotite and pyrite Rare microcracking and fine cracking.	-	-
	20511/C8 (2 exams)	-	CSA A23.1 P3 Oxidisation	14 mm crushed all in phyllite-quartzite (PHY) aggregate bound by a Portland-type cement. 0.5 % excess voidage. Concrete intact but evidence of leaching, rare weakened cement matrix, splitting of phyllite particles, sporadic to common pitting and oxidisation of sulfides (more common toward the outer surfaces and after 26 weeks of exposure), and some unidentified secondary deposits. Secondary portlandite and secondary carbonation in section (26 weeks exposure). No confirmed secondary sulfates Sporadic to common pyrrhotite and pyrite and rare to sporadic partial to minor (outer surfaces, 13 weeks exposure) and sporadic to common partial to severe (26 weeks exposure) <i>in situ</i> sulfide oxidisation Rare microcracking Rare to sporadic degradation and leaching.
	20511/C9	-	RICS Stage 3 expansion	20 mm crushed all in phyllite-quartzite (PHY) aggregate bound by a Portland-type cement. 0.5 % excess voidage. Concrete intact but evidence of leaching, secondary portlandite, possible gypsum and secondary ettringite, with rare trace <i>in situ</i> sulfide oxidisation (typically towards the exposed surfaces). Some secondary carbonation was observed towards an end surface. Rare secondary sulfates (gypsum and ettringite) Sporadic to common pyrrhotite and pyrite Rare microcracking Rare to sporadic degradation and leaching.
21GD	20511/C27	14 mm crushed all in phyllite-quartzite (PHY) aggregate bound by a Portland-type cement. 1.5 % excess voidage. Visually low cement content, leaching, and splitting of phyllite aggregate. Traces of oxidisation of limited opaque minerals (rarely <i>in situ</i>). Limited secondary carbonation and alteration at the upper surface. Rare to sporadic secondary sulfates Frequent pyrrhotite and pyrite Rare microcracking Common degradation and leaching	RICS Stage 3 expansion	20 mm crushed all in phyllite-quartzite (PHY) aggregate bound by a Portland-type cement. 1.0 % excess voidage. Concrete intact but has sporadic areas of low cement, weakened matrix, limited leaching, and secondary portlandite. Isolated patches of secondary carbonation. Sporadic partial to trace <i>in situ</i> sulfide oxidisation. Common staining adjacent to sulfide reaction sites. Secondary sulfates absent Sporadic to common pyrrhotite and pyrite Rare microcracking Rare to sporadic degradation and leaching.
	20511/C28		CSA A23.1 P3 Oxidisation	20 mm crushed all in phyllite-quartzite (PHY) aggregate bound by a Portland-type cement. 1.5 % excess voidage. Concrete intact but sporadic areas of low cement, weakened cement matrix, limited leaching and secondary portlandite. Rare secondary carbonation. Sporadic to common partial <i>in situ</i> sulfide oxidisation (outer surfaces). Rare secondary ettringite. Sporadic to common pyrrhotite and pyrite Rare microcracking Sporadic degradation and leaching.

Table 5.2 Summary of Petrographic Observations (Continued)

Property	RSK Sample reference	Phase 1 Observations – As Received	Phase 2 Durability Test	Phase 3 Observations – After durability test
28AW	20511/C20	14 mm crushed all in phyllite-quartzite (PHY) aggregate bound by a Portland-type cement. 2-3 % excess voidage. Sporadic partial <i>in situ</i> oxidation of opaque minerals, splitting of phyllite particles, trace evidence of sulfate mobilisation and leaching Sporadic secondary gypsum Frequent pyrrhotite and pyrite Sporadic microcracking Rare degradation and leaching	RICS Stage 3 expansion-	20 mm crushed all in phyllite-quartzite (PHY) aggregate bound by a Portland-type cement. 1.5 % excess voidage. Concrete intact but with rare to sporadic partial to entire <i>in situ</i> sulfide oxidation, splitting of phyllite particles, frequent leaching with secondary portlandite and sulfate mobilisation Rare secondary ettringite and possible gypsum Common pyrrhotite and pyrite Rare to sporadic microcracking Rare to sporadic degradation and leaching
	20511/C21	-	CSA A23.1 P3 Oxidisation	14 mm crushed all in phyllite-quartzite (PHY) aggregate bound by a Portland-type cement. 2.0 % excess voidage. Concrete intact but with sporadic partial to entire, <i>in situ</i> sulfide oxidation. Limited matrix alteration and secondary deposits. Splitting of phyllite particles Secondary sulfates absent (at resolution of optical microscopy) Sporadic to common pyrrhotite and pyrite Rare to sporadic microcracking Rare to sporadic degradation and leaching
C	20511/C14	14 mm partially crushed all-in sandstone (SST) aggregate bound by Portland-type cement. 5-8 % excess voidage Concrete was strong with traces of <i>in situ</i> oxidation of discrete sulfides and rare splitting of aggregate particles. Common secondary ettringite Sporadic pyrrhotite and pyrite Rare microcracking Rare degradation and leaching	-	-

5.3 Instrumental Microanalysis

Detailed results of the petrographic examinations are provided in **Appendix C** (Certificates of Examination), and are summarised in **Table 5.3** (SEM examinations) and **Tables 5.4** and **5.5** (XRD analysis).

Table 5.3 Summary of SEM Results - Foundations

Property	RSK Sample reference	Phase 1 Observations – As Received	Phase 2 Durability Test	Phase 3 Observations – After durability test
7MV	20511/C7	13% 'free' muscovite in binder Pyrrhotite and pyrite with are chalcopyrite both discrete and within aggregate. Limited pyrrhotite oxidisation. Secondary ettringite and possible thaumasite in voids and replacing binder around isolated 'free' mica. Evidence of the initial stages of internal sulfate attack processes, not presently causing damage	-	-
	20511/C8	-	CSA A23.1 P3 Oxidisation	Limited pyrrhotite and pyrite with rare chalcopyrite and possible ilmenite. Variable levels of oxidisation, including locally complete oxidisation of sulfides. Calcium depletion and carbonation of the cement matrix, rare secondary calcite and iron oxides. Accumulation of calcium alumina-chloride (Friedel's Salt) at edges of sulfides.
	20511/C9	-	RICS Stage 3 expansion	Limited pyrrhotite and pyrite and rare chalcopyrite. Variable levels of oxidisation, mostly sporadic but including rare locally complete oxidisation of sulfides. Calcium depletion, carbonation, rust staining and rare formation of secondary ettringite and calcite. Elevated sulfur concentrations associated with carbon in the cement matrix.
21GD	20511/C27	18% 'free' muscovite in binder. Limited amounts of pyrrhotite, pyrite and chalcopyrite both discrete and within aggregate. Pyrrhotite rarely partially oxidised. Limited secondary calcite in voids. No evidence of internal sulfate attack	RICS Stage 3 expansion	Limited pyrrhotite and pyrite and rare chalcopyrite. Variable levels of oxidisation (typically sporadic), including rare locally complete oxidisation of sulfides Chemical analysis suggested an elevated sulfur level in the cement matrix Calcium depletion, carbonation, secondary calcite formation, iron oxide development and plucking out of quartz grains
	20511/C28		CSA A23.1 P3 Oxidisation	Limited pyrrhotite and pyrite and rare chalcopyrite. Variable levels of oxidisation, (typically sporadic) including locally complete oxidisation of sulfides Calcium depletion, secondary carbonation, rare formation of secondary calcite replacing portlandite, and iron oxides. Accumulation of calcium alumina-chloride (Friedel's Salt) at edges of sulfides, possibly as ettringite pseudomorphs. Chemical analysis suggested an elevated sulfur level in the matrix. Rare replacement of the cement surface with sodium chloride.

Table 5.3 Summary of SEM Results - Foundations (Continued)

Property	RSK Sample reference	Phase 1 Observations – As Received	Phase 2 Durability Test	Phase 3 Observations – After durability test
28AW	20511/C20	18% 'free' muscovite in binder. Pyrrhotite, pyrite and rare chalcopyrite both discrete and within aggregate. Sporadic oxidation of pyrrhotite and rarely of pyrite. Secondary ettringite and gypsum including bridging areas of cement matrix depletion or alteration. Evidence of sulfate replacement of the cement matrix	RICS Stage 3 expansion-	Limited pyrrhotite and pyrite and rare chalcopyrite. Variable levels of oxidation (typically sporadic), including rare locally complete oxidation of sulfides to iron oxides or iron carbonate Calcium depletion, carbonation, rare formation of secondary calcite replacing portlandite. Chemical analysis suggested an elevated sulfur level in the matrix.
	20511/C21	-	CSA A23.1 P3 Oxidation	Limited pyrrhotite and pyrite and rare chalcopyrite. Variable levels of oxidation, including locally complete oxidation of sulfides. Calcium depletion, carbonation, rare formation of secondary calcite replacing portlandite, and iron oxides. Accumulation of calcium alumina-chloride (Friedel's Salt) at edges of sulfides. Chemical analysis suggested an elevated sulfur level in the cement matrix
C	20511/C14	6% free muscovite in binder. Already-oxidised pyrrhotite and pyrite, including rare framboidal pyrite present both as discrete particles and in aggregate. Rare secondary calcite and no sulfates	-	-

Table 5.4: Compositional analysis by XRD – Foundation – As Received

Property	RSK Sample reference	Chlorite	Muscovite ¹⁷	Quartz	Albite	Calcite	Paragonite	Gypsum	Pyrite	Pyrrhotite	Ettringite	Rutile	Pargasite	Anorthoclase	Dolomite	Portlandite	Quintinite
7MV	20511/C7	36.3	42.0	12.5	4.5	0.3	0.7	0.3	0.1	0.1	0.5	0.1	0.3	0.7	0.3	0.5	0.3
21GD	20511/C27	45.5	37.4	11.8	2.4	0.2	0.6	0.1	0.1	0.1	0.3			0.6	0.5	0.2	0.3
	20511/C28	42.0	37.5	14.2	3.1	0.3	0.7	0.1		0.1	0.4	0.1		0.8	0.1	0.2	0.3
28AW	20511/C20	41.6	44.1	9.6	1.7	0.3	0.7	0.1		0.1	0.2			0.7	0.2	0.3	0.3
C	20511/C14	38.6	22.3	26.6	6.2	2.0	1.1	0.3		0.1	0.3		0.3	1.8	0.1		0.4

¹⁷ Formerly reported as illite/muscovite

Table 5.5 Compositional analysis by XRD – Foundations – After durability tests

Property	RSK Sample reference	Phase 2 Durability Test	Chlorite	Muscovite ¹⁷	Quartz	Albite	Calcite	Ettringite	Rutile	CaMgCO ₃	Hydrocalumite	Dolomite	Portlandite	CaAlOOC ₃ .H ₂ O
7MV	20511/C8	Ox(13)	36.2	26.4	24.1	3.7	1.2	0.4	0.3	6.6	0.9	0.2		
		Ox(26)	34.9	28.6	27.1	4.7	1.3	0.4	0.2	1.4	1.0	0.4		
	20511/C9	Mu	34.8	30.2	26.5	3.2	0.4	0.6	0.2	1.7		1.0	0.4	1.0
21GD	20511/C27	Mu	37.3	26.8	22.8	5.9	1.0	0.7	0.3	3.7			0.3	1.1
	20511/C28	Ox	36.1	32.6	23.2	3.2	2.7	0.5	0.4		1.3			
28AW	20511/C20	Mu	35.5	46.2	11.5	3.3	0.9	0.6	0.3				0.7	1.0
	20511/C21	Ox	33.5	38.4	18.3	5.3	1.1	0.4	0.3	1.6	1.1			

Ox () – CSA A23.1 P3 Oxidisation (number of weeks on test), Mu – RICS Mundic Stage 3 expansion

5.4 Physical Testing

Detailed results of physical testing for compressive strength and density are provided in **Appendix D** (Certificates of Test) and are summarised in **Table 5.6**.

Table 5.6 Summary of physical test results – Foundations

Property	RSK Sample Reference	As received		Phase 2 Durability Test	After durability tests	
		Compressive Strength MPa	Density kg/m ³		Compressive Strength MPa	Density kg/m ³
7MV	20511/C7	29.9	2240	Mu	17.8	2280
	20511/C9	-	-	Ox	11.9	2380
21GD	20511/C28	14.2	2260	Ox	-	-
28AW	20511/C21	22.2	2260	Ox	-	-
	20954/C5			Ox	16.7	2060
					Mu	13.4

Ox () – CSA A23.1 P3 Oxidisation (number of weeks on test), Mu – RICS Mundic Stage 3 expansion

5.5 Chemical Testing

Detailed results of chemical testing are provided in **Appendix E** (Certificates of Analysis) and summarised in **Table 5.7** and **Table 5.8**.

Table 5.7 Summary of chemical test results – Foundations

Property	RSK Sample Reference	Phase 1 - As received							Phase 2 Durability Test	Phase 3 - After durability testing						
		Cement content kg/m ³	Total sulfur % S (sample) ¹⁸	Total sulfur % S (aggregate) ¹⁸	Acid soluble sulfate % SO ₄	Water soluble sulfate %SO ₃	Sulfate %SO ₄ (BS EN 196)	Sulfide % S ²⁻ (sample, BS EN 196)		Cement content kg/m ³	Total sulfur % S (sample) ¹⁸	Total sulfur % S (aggregate) ¹⁸	Acid soluble sulfate % SO ₄	Water soluble sulfate %SO ₃	Sulfate % SO ₄ (BS EN 196)	Sulfide % S ²⁻ (sample, BS EN 196)
7MV	20511/C7	310	0.2 0.72	0.0 0.52	0.5	<0.01	0.28	0.32	Mu	360	0.2 0.61	0.0 0.41	0.5	<0.01	0.49	0.05
	20511/C9	-	-	-	-	-	-	-	Ox	360	0.2 0.55	0.0 0.35	0.6	0.03	0.59	0.03
21GD	20511/C27	-	-	-	-	-	-	-	Mu	290	0.2 0.54	0.0 0.34	0.5	<0.01	0.47	0.02
	20511/C28	270	0.2 0.70	0.0 0.50	0.4	<0.01	0.26	0.43	Ox	290	0.2 0.62	0.0 0.42	0.4	0.07	0.54	0.01
28AW	20511/C20	250	0.2	0.0	0.4	<0.01	0.43	0.25	-	-	-	-	-	-	-	-
	20511/C21	-	0.87	0.67	-	-	-	-	-	-	-	-	-	-	-	-
	20954/C5	-	-	-	-	-	-	-	Mu	270	0.2 0.54	0.0 0.34	0.3	<0.01	0.32	0.55
		-	-	-	-	-	-	-	Ox	270	0.2 0.50	0.0 0.30	0.4	0.04	0.43	0.18
C	20511/C14	160	0.1	0.0	0.2	<0.01	0.12	0.08	-	-	-	-	-	-	-	-
	20511/C15					-			-	-	-	-	-	-		

Ox – CSA A23.1 P3 Oxidisation (number of weeks on test), Mu – RICS Mundic Stage 3 expansion.

Table 5.8 BRE Suite D Brownfield testing

Property	RSK Sample reference	Durability test	Concrete				Leachate		
			pH	Water soluble sulfate SO ₄ mg/l	Acid soluble sulfate SO ₄ wt %	Total sulfur S wt %	pH	Sulfate mg/l SO ₄	Mg mg/l
7MV	20511/C7F	RICS	12.47	132	1.65	0.53	9.27	1770	-
	20511/C9D	CSA	11.85	1040	0.71	0.54			
28AW	20511/C20E	RICS					7.01	1910	-
	20954/C5A	RICS	12.44	58	<0.02	0.50			
21GD	20511/C27E	RICS	12.30	37	0.68	0.57	10.33	483	-
	20511/C28B	CSA	11.80	675	0.47	0.61			

¹⁸ First reported result is by the reference acid digestion method in BS EN 1744-1. The second reported result is a repeat test using the high temperature decomposition method (LECO analysis) on the same material.

6 DISCUSSION

6.1 Phase 1 – As received concrete

As noted, the foundation concrete samples were taken by coring vertically down from the top surface of strip concrete footings below the external masonry walls of the selected buildings. No sampling was undertaken from footings to internal partition walls.

The three test properties that exhibited evidence of damage to the superstructural blockwork walls are understood to all have been constructed between circa 1998 and 2008, with the 'control' property 'Carrowmore' being constructed during the 1980s. It is understood that the design life of a residential dwelling in the Republic of Ireland is specified to be 50 years, although clearly many houses will comfortably exceed this; structural concrete would be required to perform acceptably for this duration (under normal circumstances and subject to no significant changes in the local environment) with no maintenance for this duration. As such, the Carrowmore property, at approximately 40 years from construction is beyond the mid-point of its service life; the visual examination suggests this is a relatively poor-quality concrete, however it does not exhibit evidence of significant deterioration. By comparison, the defective houses are between about 1/4 and 1/3 of the way through their design life.

The foundation concrete for the three 'defective' test properties was generally relatively similar in composition and characteristics, with similar aggregate and binder types. Each of the examined samples was seen to include pyrrhotite and crystalline pyrite, plus traces of chalcopyrite, with there being some varied evidence of *in situ* oxidisation of the pyrrhotite. Secondary mineralisation was variable in both nature (ettringite, gypsum, calcite, in one examined sample, tentatively thaumasite) and frequency (rare to frequent), however any deterioration of the concrete in the as received samples did not appear to be the cause of any significant damage to date. As such, while the concrete composition appeared to present a risk from damaging internal sulfate attack (ISA) reactions, the condition of the investigated concrete itself indicates minimal or very slow progression of the ISA processes in service.

The foundation cores from 21 Glendale Drive exhibited relatively common degradation and leaching, however this may have been associated with in service exposure to mobile water, and did not appear to be associated with damage consistent with ISA.

In other instances of internal sulfate attack on concrete associated with pyrrhotite oxidisation in aggregate, the affected concrete has typically been in a setting with the construction that is subject to wetting and drying cycles and the presence of atmospheric oxygen. For both the cases in Quebec and Connecticut, the most vulnerable concrete elements have been in a zone from immediately below ground level up to approximately 0.5 m above ground level. In Quebec, the concrete in this zone, when constructed using the most reactive aggregates, generally exhibited damage by cracking visible as the concrete surface within the first 3 to 5 years after construction (and there have been very few cases where significant damage has started to manifest after more than about 5 years¹⁹).

¹⁹ The author has acted as an Expert Witness in relation to the major pyrrhotite-concrete case in Trois Rivieres, and has undertaken extensive reviews of documentation in support of various of the legal claims.

However, in the cases in Connecticut, the rate of development of damage was significantly more variable and in many cases slower, with obvious cracking to the concrete occurring for anything between about 5 and 35 years after construction.

In this case, the foundation concrete is mostly in an environment likely to remain wet or at least damp, and be exposed to less atmospheric oxygen than the superstructure concrete. As such, the rate of progression of the reaction has been slow, and is likely to remain that way.

The Mundic guidance followed here is predominantly for precast concrete blocks, and only provides a density test for concrete footings that contain potentially reactive aggregates, as a test to verify that the concrete can resist the possible deterioration.

It should also be noted that, other than the potential issues caused by the sulfides and the potential weakness of the concrete because of the relatively high abundance of muscovite mica (which may be a contributor to the observed splitting of some of the phyllite aggregates), the foundation concrete from the three defective test properties appears to be a reasonably good quality material, with low excess voidage and a reasonable (high end of normal) water/cement ratio. By comparison, the 'Carrowmore' foundation concrete is a significantly poorer quality material, with higher voidage (5 to 8 %) and a low cement content.

6.2 Phase 2 – Accelerated Durability Tests

It should be noted that the RICS Mundic test was designed principally for assessing precast concrete masonry blocks, which are much weaker and more porous and permeable than these foundation concretes, and therefore care is needed in interpreting the results. Similarly, the Canadian Standard test method was developed as a means of assessing the potential expansive properties of newly quarried aggregate rather than being applied to concrete after a period in service, and as such should be considered as informative only.

The Mundic Stage 3 expansion testing includes a cut off of 0.025% expansion over the period between 7 days and 250 days (or 350 days as in the case), with concrete falling below this being classed as Class A₃ (stable group 2 aggregate). All the samples subject to this test complied with this criterion, suggesting that while the concrete includes aggregates with composition that could cause expansion, the actual expansion was limited and sufficiently low to suggest the aggregates produce a non-swelling and therefore adequately stable concrete (although noting the caveat that dense cast in situ concrete may behave somewhat differently to precast blocks because of the physical properties of the concrete rather than any inherent better performance of a potentially reactive aggregate).

The Canadian Standard mortar bar test is run over two phases, with the first phase intended to promote accelerated oxidation of any potentially reactive iron sulfide minerals, and the second phase to promote expansion if the concrete is susceptible to damaging thaumasite attack. The results obtained herein suggest that the concrete from the foundations is at least somewhat susceptible to further iron sulfide oxidation (demonstrated by the development of rust staining and surface pitting), however there was chiefly minimal expansion of the concrete, which had stayed intact (even when some expansion was recorded), suggesting that the cores are of low susceptibility to damage by internal sulfate attack. This may be because of the relatively good physical

characteristics of the concrete (strength, density and low voidage) when compared with the concrete blockwork, or may be because there is insufficient iron sulfide oxidising to lead to significantly damaging levels of sulfate attack reactions within the cement.

The inspections and petrographic examinations following these tests showed only relatively small-scale changes, with some additional oxidisation of sulfides, in particular pyrrhotite, but limited additional development of secondary sulfates, and did not demonstrate any development of additional microcracking. The majority of the deterioration occurred at the outer surfaces of the cored concrete sub-samples with less occurring toward the centre. This suggests that the higher density and the associated lower permeability of the mass concrete within the foundations may inhibit the ingress of oxidising agents, to some degree helping to restrict the conditions for sulfide oxidisation and related ISA to occur.

It should be noted that the test was originally designed for mortar bars with a greater surface area both within the samples and the utilised aggregate (crushed to a fine aggregate). The lower surface-to-volume ratio of the 75 mm diameter cores and depth to the centre of the sample volume may have reduced the effectiveness of the oxidising agents. However, as discussed above the samples of mass concrete can be directly compared with the blockwork samples from the same property for relative performance due to similar sample geometry and aggregate content and type.

6.3 Phase 3 – Chemical Composition and Physical Properties

The chemical analysis of cement content suggested that the foundation concretes for the three defective test properties were of moderate cement content (250 to 310 kg/m³). The determined compressive strength for the as received concrete was between 14.2 MPa and 29.9MPa

IS EN 206-1 guidance (current at the time of construction) would classify the environment of the foundations as XC2: Wet, rarely dry and subject to long-term water contact. The National Annex NA5 to IS EN 206-1 provides guidance for the requirements for a C12/15 concrete to comply with the XC2 exposure requirements, and therefore be suitable for use as concrete foundations. This requires a maximum water/cement ratio of 0.55, a minimum cement content of 270 kg/m³ and a minimum strength of 12 MPa. The concrete from the three damaged properties is largely consistent with this, within the range of laboratory error.

Irish Building Regulations 2012 Technical Guidance Document A Clause 1.1.5 provides guidance for the design provisions for strip foundations of plain concrete. This includes the option of the concrete being C12/15 characteristic strength and with a minimum 200 kg/m³ cement content. Allowing for the reduced strength that may be obtained from cores from cast in situ concrete, when compared with specifically prepared test cubes, all the foundation concrete for the three test properties complied with both the strength requirement and minimum cement content.

By comparison, the foundation core from the Carrowmore property was cement poor, with a cement content of 160 kg/m³ being consistent only with ST1 concrete, which would not generally be considered adequate for the foundations of a residential building and falls below the requirements of the Building Regulations, although the evidence from site is that it has in fact performed adequately. Unfortunately, the provided samples were not suitable for testing for compressive strength.

The determined cement content on samples following the expansion tests did not show any decrease, indeed the two cores for which replicate tests were undertaken showed a slight increase in the apparent cement content, which was likely just a result of some variation within the sub-samples tested and the precision of the test method. It was noted though that the compressive strength of the samples (from Mulroy View) decreased significantly following the durability testing; this was not associated with a decrease in density (indeed, the density increased). This may therefore indicate alteration of the hardened cement paste (indeed, analysis of the leachate produced in the Mundic test showed the release of some soluble sulfates, which may have derived from the cement or from acidic byproducts of oxidation reactions) resulting in a weakening of the hardened cement paste itself or of the paste to aggregate bond. Petrographic examinations showed the presence of secondary minerals consistent with this.

The total sulfur determined both before and following the accelerated durability tests by the BS EN 1744-1 reference method (acid digestion) gave consistent results of either 0.1-0.2% S (by mass) for each sample analysed. As previously noted, these are unrealistically low values, as there should always be around 0.1-0.2 % total sulfur (by mass) solely derived from the cement, and the petrography identified both sulfide and sulfate minerals present in the hardened concrete, principally in the aggregate, at levels greater than these determined values. By comparison, the total sulfur determined by high temperature combustions (LECO) returned total sulfur in the range 0.7 to 0.9 % (by mass) for the bulk concrete, which can be considered approximately 0.15 to 0.20% above the total sulfur of the aggregates (owing to the sulfate present in the cement paste); as such, the total sulfur of the aggregate is likely to be in the range 0.50 to 0.75% S. These results are more consistent with the visual evidence from petrography and other analyses.

The acid soluble sulfate content of the as-received test property concrete (as tested by the BS EN 1744-1 method) was in the range 0.4 to 0.5 % SO₄, while the results after the accelerated durability testing were generally slightly higher between 0.3 and 0.6%, with both samples tested before and after showing a 0.0-0.1% increase in the acid soluble sulfate. This suggests that a small amount of further oxidation occurred during these accelerated durability tests, but of relatively limited extent and insufficient to cause any observable damage to the concrete, nor to significantly alter the observations of secondary sulfate mineralisation in the concrete.

Water soluble sulfate was negligible for the as received concrete, for the two samples subjected to the RICS Stage 3 expansion testing as the majority of water-soluble sulfates had leached into the bottom of the test containers, indicative of either sulfate generation or sulfate mobilisation. There was a slight increase in the water-soluble sulfate concentrations for the two samples subject to the Canadian Standard accelerated oxidation expansion test, which may have been derived from the chemicals used for exposure.

By comparison, the sulfate and sulfide testing undertaken in accordance with the BS EN 196-2 test methods suggested that the sulfate content of most of the samples increased significantly and the sulfide levels decreased. It should be noted that the sulfate levels determined for the 'as received' concrete were significantly lower than those determined as acid soluble sulfate by BS EN 1744-1, and that the levels determined after the accelerated durability tests were broadly similar with the acid soluble sulfate content of the same samples.

The chemically determined sulfide content, by the BS EN 196-2 test method, generally appears to be lower than suggested by petrography, in particular for the samples after the accelerated durability testing. However, the relative decrease in the determined sulfides may represent the influence of easily oxidisable sulfides being oxidised during the durability testing, or the digestion of some sulfides, particularly pyrrhotite, in the acid digestion process used for the determination of sulfate.

6.4 Overall Prognosis

While the concrete used in the investigated house foundations appears to be of a composition that includes risk factors for damaging internal sulfate attack, there is only very limited evidence that the internal sulfate attack processes have progressed within the concrete *in situ*, and there presently is no evidence that significant damage to the concrete has occurred; as the attack process is progressive, this indicates that (assuming no significant changes in conditions around the foundations) any damage is likely only to occur long into the future, beyond the intended design life of the foundations.

This slow progression is likely a consequence of the position of the foundations, being in a largely saturated condition and with relatively low free oxygen. As such, the environmental conditions to promote damaging internal sulfate attack are either never or only rarely present in these buried concrete elements.

The absence of carbonate-bearing aggregate in the concrete may also be significant, as this minimises the likelihood of the thaumasite form of sulfate attack (TSA) occurring. TSA is more significantly damaging than conventional sulfate attack, and is the favoured mechanism in wet / saturated conditions (compared with conventional sulfate attack, predominating in damp conditions), but requires the presence of a source of carbonate . While the carbonated cement could provide some of this, it is likely insufficient in volume to allow significant TSA progression.

It is also noted that all the foundation concrete tested via either accelerated durability test, while showing some evidence of on-going chemical reactions, did not show significant expansion or deterioration of the concrete indicative of a high risk of damage. It is likely that this is, at least in part, a consequence of these being reasonably dense and well compacted concrete. As noted earlier, the Mundic guidance (admittedly, principally for concrete likely to contain pyrite in the aggregate) only includes an assessment of the density of the cast in situ foundation concrete, with this being considered sufficient to mitigate the risk of damaging internal sulfate attack reactions.

Based on the above, it is considered that there is only a low risk that on-going pyrrhotite oxidation, and associated internal sulfate attack processes, will lead to the development of significant damage to the concrete elements sufficient to adversely affect their engineering performance within the remaining intended design life of these buildings.

7 CONCLUSIONS

- The foundation concrete from the three damaged test properties is largely similar in terms of composition. The same aggregate (PHY) and similar cement (CEM I) and water/cement ratio have been used. These generally appear to be in compliance with the requirements of Irish Building Regulations and Irish Standard requirements for XC2 exposure class concrete (within the accuracy of the laboratory testing).
- Phyllite aggregate, containing sporadic pyrrhotite and pyrite, is present in samples from all three properties, but is virtually absent from the concrete from the control property (although potentially reactive framboidal pyrite was observed).
- Other than the presence of the potentially reactive iron sulfide minerals, the foundation concrete from the three defective test properties is reasonably sound. The relatively high muscovite mica content does not appear to have had a significant adverse effect on the installation and compaction of the concrete.
- On examination, the 'as received' concrete cores generally showed some slight evidence of pyrrhotite oxidation and the development of secondary sulfate minerals (ettringite, gypsum and rarely thaumasite), consistent with the mechanisms that lead to damage to concrete by internal sulfate attack. However, at this time, this development is slight and is not associated with any notable damage to the concrete (unlike with some examples of the superstructural concrete).
- Core samples from the three damaged test properties were tested by either the RICS Stage 3 expansion test or the Canadian Standard accelerated oxidation adapted expansion test. While neither of these test methods was designed for the testing of in situ cast mass concrete, the results obtained suggested that, despite the presence of potentially reactive constituents in the aggregate, the concrete did not show signs of unusual expansion consistent with potentially damaging internal sulfate attack. The adapted Canadian Standard test did lead to a single moderate expansion result (not generally indicative of internal sulfate attack), and the development of some rust/pitting deposits on the concrete, particularly the outer surfaces.
- Chemical testing before and after the accelerated durability testing indicated there was some further oxidation of pyrrhotite, shown by the increase in the acid soluble sulfate concentration and associated decrease in the sulfide mineral concentration (as tested in accordance with BS EN 196-2), although noting that the post durability test sulfide concentrations determined appeared inconsistent with the levels of sulfide minerals observed petrographically.
- Total sulfur testing by the reference method in BS EN 1744-1 consistently returned values of 0.2 % S by mass of sample, which was lower than would be anticipated by petrographic examinations. Retesting by high temperature combustion technique (LECO) gave significantly higher values, consistent with total sulfur concentrations in the sample of around 0.70 to 0.90%.
- Based on the observed conditions and the performance through the accelerated durability testing, plus the exposure conditions on site (assuming these remain similar), it is considered that the risk of internal sulfate attack progressing sufficiently to cause significant damage and affect the engineering performance of these foundations within the intended 50-year design life is low.

8 REMARKS

These findings refer only to the samples tested and to any materials properly represented by those samples.

Any assessment of risk mentioned herein is based upon the findings of these specific investigations and any information provided to the investigation. Extension of this assessment of risk to any properties not included in this investigation should be with caution and ideally should include site-specific assessment of the existing foundation concrete.

Statements of uncertainty of test measurements are provided on test certificates only where these are specifically declared by the documented Test Method and are the result of a formal inter-laboratory precision trial.