2nd International Conference on Iron-Sulfide Reactions in Concrete
Hilton Mystic | Connecticut | USA | May 13th & May 14th 2026

Influences of Aggregate, Concrete Quality and Exposure Condition on Pyrrhotite Oxidation and ISA-Related Damage in the County Donegal, Ireland – Case Studies from Damaged to Undamaged Homes and Crumbled Blocks to Strip Concrete Foundations

Dipayan Jana (1)

Construction Materials Consultants, Inc. and Applied Petrographic Services, Inc.

(1) *Construction Materials Consultants, Inc.*

Abstract

Oxidation of pyrrhotite present predominantly in phyllite aggregates, and the resultant internal sulfate attacks (ISA) in paste from sulfates released from pyrrhotite oxidation are the mechanisms responsible for cracking and crumbling of concrete blocks across thousands of homes in County Donegal, Ireland. Comparing case studies of samples from (a) crumbled blocks of five damaged homes, (b) blocks from an undamaged home, and (c) strip concrete foundations of three homes all located in the County Donegal showed that the reasons for preferential distress in the blocks from outer leaf of damaged homes are directly related to the following factors: (1) abundance of reactive pyrrhotite in phyllite compared to the other aggregates (e.g., micaceous quartzite, metagreywacke, and quartzite), (2) availability of oxygen and moisture in the blocks during service for pyrrhotite oxidation, especially for easy migration through the (3) porous skeletal microstructure of low cement content blocks having 15-25% voids, (4) extensive contamination of paste with mica (muscovite-chlorite) from easily abradable phyllite (as high as 50% of the paste volume), (5) extensive alteration of paste by lime leaching leaving a Si-Al-rich gelatinous residue in the crumbled paste, and (6) formation of various products of ISA (e.g., ettringite in non-carbonated to thaumasite or gypsum in carbonated paste) especially in the outer leaf from where samples of damaged homes were received. Extensive oxidation of pyrrhotite grains not only in the mortar fractions but also in grains encashed within phyllite are seen in all distressed blocks resulting in the characteristic stripped patterns of iron oxide bands in iron sulphide matrix.

By contrast, sound conditions of blocks in the undamaged home despite having similar open microstructure as the damaged blocks are due to (a) the use of dominant denser and coarser-than-phyllite, less abradable pyrrhotite-free metagreywacke and micaceous quartzite crushed stone coarse aggregates, which have left (b) a significantly lesser (7-10%) abraded mica in paste, and (c) includes mostly non-reactive pyrite with only minor pyrrhotite found in rare phyllite gravel, which is usually unoxidized or oxidized before being added to the block.

Samples of strip foundations in two of the three homes showed crushed stone coarse aggregates of the same dominant pyrrhotite-bearing phyllite followed by mica schist or micaceous quartzite as in the distressed blocks. However, pyrrhotite oxidation is slow in the foundations with no detectable ISA in the non-carbonated interior paste. This is due to: (1) the overall denser microstructure of lower *w/c*, higher-cement-content dense, well-consolidated foundations than the open microstructure of blocks containing (2) a significantly lesser (7-10%) abraded mica in the paste and, most importantly, (3) high water saturation in foundations during service, which have restricted diffusion of oxygen needed for pyrrhotite oxidation. Typical stripped patterns of oxidized bands in pyrrhotite so common in the distressed blocks are rare in the foundations, only seen in a few poorly developed oxidized grains in the mortar fractions. Foundation of the third home has more crushed micaceous quartzite and mica schist in coarse aggregate than pyrrhotite-bearing phyllite where phyllite was added as alluvial gravel and hence showed pyrrhotite oxidation and cracking along foliation planes prior to the incorporation in concrete. As a result, although the potential for distress was higher in the two phyllite-bearing foundations (at least for oxidative expansion and cracking in aggregates than ISA in paste) than in the third but high humidity during service has restricted oxygen diffusion and, thereby, favoured those two underground foundations from development of any reported visible cracking despite 15-20 years in service.

Total sulfur contents (S_T) of blocks are 0.27 to 0.39 in the damaged home, 0.07 in the undamaged home, and 0.22 to 0.28 in the strip foundations, which are well-correlated with the abundance of pyrrhotite-bearing phyllites in aggregates. S_T values of distressed blocks and strip foundations even before conversions to aggregate S_T are all well in excess of 0.1% limit for pyrrhotite-bearing aggregates as stated in EN 12620. Despite the absence of visible distress, high S_Ts from positive detection of pyrrhotite in all three foundations have prompted the homeowners to replace those foundations.

Severe distress of the outer leaf compared to the strip foundation is directly related to the concrete quality and exposure conditions of blocks versus foundations, whereas slow progress of distress in the strip foundations compared to severely cracked and crumbled residential foundations in the eastern USA indicate a rather complicated interplay of factors that are responsible for pyrrhotite oxidation and subsequent ISA. Pyrrhotite oxidation leading to paste disintegration from ISA, and lime leaching are the dominant mechanisms of distress in the blocks of damaged homes but limited pyrrhotite oxidation and perhaps limited ettringite-form of ISA in the confined spaces in non-carbonated interiors would be the early stages of distress in foundations if foundations were undersaturated for effective oxygen diffusion.

Irrespective of the exposure, use of *pyrrhotite-free* dense, coarse-grained quartzite, micaceous quartzite, or metagreywacke would have been a better aggregate choice for sound performance of blocks, as seen in the blocks of the undamaged home than *pyrrhotite-bearing metapelites* (phyllite, mica schist). This reinforces the importance of petrographic examinations of quarried stones and gravels for risk factor assessments of damaged dwellings, not for mica but for iron sulfide minerals (e.g., in a 'modified' version of I.S. 465 to include iron sulfide testing), and evaluate the potential dangers of these minerals in aggregates prior to incorporation in new concrete blocks or foundations.

Keywords: *aggregate, blocks, oxidation, pyrrhotite, sulfate.*

1. INTRODUCTION

Contrary to the hypothesis of excessive mica leading to freezing-related distress of concrete masonry blocks [1], oxidation of pyrrhotite in metapelite aggregates (phyllite, mica schist) causing decomposition of paste by internal sulfate attack (ISA) from sulfates released from pyrrhotite oxidation has been well-documented [2, 3, 4, 5] to be the primary mechanisms for cracking and crumbling of thousands of homes in County Donegal, Ireland. Furthermore, a holistic approach is being proposed [3, 5] to include influences of various factors that have aggravated the distress, e.g., (i) open microstructure of blocks to accelerate migration of moisture and oxygen for oxidation, (ii) preferential location of pyrrhotite in the easily abradable phyllite, which has facilitated easy release of sulfates to paste in moist condition, (iii) influences of aggregate types and mineralogies (relative abundances of metapelites vs metagreywacke/metaquartzite in aggregates), and (v) exposure conditions of blocks during service from moist to intermittent dry conditions influencing various modes of paste decomposition from ettringite-related ISA in non-carbonated paste to thaumasite or gypsum-related ISA in the carbonated paste to extreme decomposition by extensive lime leaching leaving crumbled Si-Al-rich residues.

The present study encompasses samples from: (a) five damaged homes (DM, SM, PD, ShM, and D) all showing extensive map cracking of renders to crumbling of the outer leaf, (b) one undamaged home (MM) without any cracking or crumbling, and (c) underground strip foundations of three homes (PD, JB, and MB) all of which have been replaced from the 'pyrrhotite fear' around the area despite no reported visible distress after 15-20 years of service. This offers an ideal opportunity for investigation of the above-mentioned influences on damage from open microstructure of distressed blocks to denser microstructure of strip foundations, which were exposed to different environmental conditions (above versus underground) during service.

1.1 Dalradian Metasediments

Damaged homes in the County Donegal, Ireland contain pyrrhotite-bearing aggregates quarried from 700-million-year-old Dalradian metasediments, e.g., (a) phyllite and mica schist, which were metamorphosed from fine-grained pelitic sedimentary rocks (mudstone, shale), or (b) quartzite, micaceous quartzite, or metagreywacke, respectively metamorphosed from coarser-grained sedimentary rocks, e.g., quartz sandstone, quartz-feldspar (arkosic) sandstone, or greywacke (having a higher micaceous matrix and a denser, darker-grey tone than arkose). Amongst these two broad classes, it is the metapelites from the finest grain phyllite to relatively coarser pelitic mica schists that are the deadliest of all with phyllite been the primary candidate for distress for hosting abundant finely disseminated pyrrhotite grains that were readily oxidized for easy penetration of moisture and oxygen first through the open porous microstructures of low-paste-content blocks and then through the weak folded foliation planes (crenulation cleavages) of phyllites.

1.2 Damaged versus Undamaged Homes

The primary difference between the five damaged home and one undamaged home is the abundance of pyrrhotite-bearing phyllite followed by mica schist in the damaged homes whereas the presence of non-pyrrhotite-bearing metagreywacke and micaceous quartzite, mainly the absence of pyrrhotite in the undamaged home.

1.3 Damaged Blocks versus Strip Concrete Foundations

Dominant pyrrhotite-bearing phyllite was found in all five damages homes and in at least two of three strip foundations. Overall denser microstructures of foundations (from the use of mixes having higher paste contents and lower water-cement ratios) than the porous skeletal microstructures of blocks (from lower interstitial paste contents and higher void contents between aggregates) and high humidity during service have slowed down the distress in the foundations mainly from slowing down pyrrhotite oxidation by restricting gas diffusion and resultant ISA-part of distress after pyrrhotite oxidation.

2. METHODS

Samples were examined by: (1) optical microscopy (reflected-light microscopy of polished thin and solid sections, and transmitted-light microscopy of polished thin sections) for iron sulfide minerals, oxidation products, aggregate mineralogy/texture, paste composition/microstructure/alteration, and secondary deposits; (2) SEM-EDS studies of polished thin/solid sections for further characterization of pyrrhotite and compositions of paste; (3) XRD studies of bulk samples for detection of iron sulfide minerals, aggregate mineralogies, and ISA products, and (4) combustion IR for total sulfur content (S_T).

3. RESULTS & DISCUSSION

3.1 Total Sulfur

Total sulfur, S_T (from pyrrhotite, pyrite and other sulfides in aggregates and cement sulfate) of the five damages homes are (in mass%) 0.342% for DM, 0.389% for SM, 0.269% for PD, 0.369% for ShM and 0.266% for DM all exceeding the limit value of <0.1% for aggregates that contain pyrrhotite stated in EN 12620 [7]. By contrast, S_T of the undamaged home is 0.066%, which is directly related to the absence of pyrrhotite. Two concrete foundations containing pyrrhotite-bearing phyllite showed S_T of 0.282% for PD and 0.268% for JB but the third foundation MB with lesser pyrrhotite (only in phyllite gravel) and more mica schist and quartzite/metagreywacke than other two foundations showed a S_T of 0.217%. Samples were tested according to I.S. 465 [6] and BS E.N. 1744-1 from high temperature combustion in an atmosphere of pure oxygen, followed by quantification by infrared detectors. When corrections were made to the bulk S_T for contributions from aggregates, the corrected values are increased by 8% for low-paste content blocks and 20% for high-paste content foundations [3], i.e., 0.287-0.420 for distressed blocks and 0.322-0.338 for foundations, which are all noticeably higher than the maximum 0.1% limit for pyrrhotite-bearing aggregates as stated in EN 12620 [7].

3.2 Petrographic Examinations

In all five damaged homes, (1) crushed phyllite followed by subordinate (2) mica schist are the dominant coarse aggregates (Fig. 1) where pyrrhotite is preferentially concentrated in phyllite whereas coarser grained non-pyrrhotite-bearing (3) micaceous quartzite and (4) metasandstone/metagreywacke are present only in minor amounts. Opposite is true for the undamaged home (MM) where pyrrhotite-free crushed metasandstone/metagreywacke is the most abundant coarse aggregate with minor micaceous quartzite and quartzite, where only one pyrrhotite-bearing phyllite gravel of an alluvial source was detected, which was probably an acidental inclusion in the dominant crushed sandstone/greywacke aggregate. Like the distressed blocks, two strip foundations (PD, JB) contained dominant crushed phylite and subordinate mica schist in coarse aggregate with the former being the common host for pyrrhotite; the third foundation (MB) has crushed mica schist and metagreywacke, and subordinate phyllite as gravel having finely disseiminated pyrrhotite in phyllite mostly pre-oxidized in alluvial source.

Phyllite in all distressed blocks contains major amounts of interlayered muscovite, chlorite and subordinate amounts of very fine-grained silty quartz and alkali feldspar all in parallel layered arrangements to form the typical foliation or sheet-like flakes and characteristic crenulation cleavages of deformed foliations. Weak zones along foliation planes and crenulation cleavages provided pathways for migration of moisture and oxygen to oxidize finely desseminated grains of pyrrhotite in phyllite.

Muscovite and chlorite are nonswellable sheet silicates but their presence as easily breakable foliated sheets in phyllite along with their inherent finer grain size than schist have contaminated the mortar fractions of blocks with abraded phyllite flakes (>10% to as high as 50%, by paste volume) to increase the water demand at a given workability and reduce the compressive strength. Mica schist is relatively coarser grained than phyllite, consisting of muscovite mica, biotite, chlorite, deformed quartz, and alkali feldspar all in parallel arrangements to define the schistose texture. Micaeous quartzite is noticeably denser and coarser than mica schist but still showing parallel alignments of mica flakes in the coarse-grained granoblastic quartz. Metasandstone and metagreywacke are coarser grained than phyllite or schist, but show typical clastic texture of sandstone or greywacke of detrital quartz and feldspar and more calcite and micaceous grains (wacke) in the matrix of the latter. Quartzite is monomineralic of all types, coarsest, of interlocking granoblastic quartz. Phyllite and mica schist are the metamorphosed derivatives (metapelites) of mudstone, shale, or micaceous stilstone, which are the common hosts for pyrrhotite, whereas micaceous quartzite, greywacke and quartzite are the coarser-grained metamorphosed derivatives of arkosic sandstone/greywacke of the Dalradian supergroup.

Abundant pyrrhotite grains in phyllite (sizes from <1 mm at long to <0.5 mm at short directions) have acted as the effective sites for expansion from oxidation during service especially at the moist and alkaline (pH >10, less to non-carbonated) conditions of blocks. Some prior oxidations (especially for gravels), however, may have occurred in geologic formation and during storage in the aggregate stockpile. Mode of occurrence of pyrrhotite varied from fine-grained isolated disseminated irregular-shaped to subhedral equant grains to mostly elongated grains aligned along the dominant foliation planes, which shows extensive reddish-brown oxidation products (e.g., goethite, ferrihydrite) causing further cracking, splitting, and disintegration of phyllite. In situ oxidation of pyrrhotite has caused further splitting and crumbling of phyllite especially since most pyrrhotite grains have crystallized along the prevailing foliation planes where the inherent phyllitic texture of foliation and deformed (crenulation) cleavage planes provided pathways for ready migration of moisture to facilitate oxidation. Additionally, spectacular radial cracks are often seen from oxidized pyrrhotite grains in phyllite as a testament of *in situ* expansion from pyrrhotite oxidation. Reddish-brown oxidized pyrrhotite products are preferentially noticed between the greenish sheened (from chlorite) foliated sheets where expansive oxidation reactions have further disintegrated the phyllite. Pyrrhotite contents in phyllite varied from 0.75 to 1.5 percent by volume. Pyrrhotite is sometimes associated with pyrite and chalcopyrite. No evidence of oxidation of pyrite or its subsequent sulfate attack (as found in the Counties Mayo, Clare and Limerick from framboidal pyrite within calcareous mudrock) was found in the present study.

After phylite and mica schist, non-pyrrhotite-bearing metagreywacke, micaceous quartzite, and metaquartzite are three less common types in the damaged homes, but they become the dominant rock types with only negligible pyrrhotite-bearing phyllite (only one gravel) in the undamaged home (MM). Quartz-feldspar-bearing arkosic quartzite and metagreywacke (both showing clastic texture but latter with higher micaceous and calcitic matrix than the former) and micaceous quartzite (with parallelism of mica in coarse-grained granoblastic quartz matrix) are the main rock types in umdamaged home.

Paste in the blocks of all damaged homes showed (i) severe carbonation, which is best depicted from its characterstically high birefringence in polarized light microscope along with (2) near-isotropic porous paste from severe lime leaching leaving only sílica-alumina rich gelatenous residues of no strength or cementitious properties. By contrast, paste in the undamaged home (MM) shows (3) 'patchy' carbonation to (4) non-carbonated calcium silicate hydrate (CSH) and portlandite (CH) rich areas; both carbonated and non-carbonated paste are notiecably denser than severely cabronated and leached paste in damaged homes. Abaded phyllite is abundant in all damaged blocks but more restrictred in the undamaged block for the lack of phyllite, or in the strip foundations for noticeably denser paste enclosures around coarse aggregates.

Two strip foundations (PD and JB) showed the same abundant pyrrhotite-bearing phyllite followed by subordinate mica schist (PD, JB) or micaceous quartzite (JB) as in the blocks of damaged homes except the interstitial spaces between aggregates are completely filled with noticeably denser (from use of lower *w/c*) paste from adequate consolidation with noticeably less abraded phyllite or mica in paste than in the paste of damaged blocks. For the third foundation (MB) pyrrhotite-bearing phyllite was the least abundant only in a minor gravel where most of the oxidation of pyrrhotite in phillite has occurred prior to the incorporation in concrete. The dominant rocks in foundaiton MB are mica schist, metagreywacke, micaceous quartzite, and quartzite, none with any detectable pyrrhotite to cause a threat as the other two foundations. Other than typical siliceous particles (quartz, quartzite, feldspar, chert, siltstone, and mica from abraded coarse aggregate) found in all three foundations, MB also contained a minor fraction of crushed seashell fragments in sand. Concrete in all three foundations are non air-entrained (estimated <3% air). Paste is portland cement-based in all three foundations except fly ash at <5% and 10-15% of total cementitious materials detected in PD and JB, respectively (which may have provided an aided densification of paste from pozzolanic reactions). Estimated water-cement ratios are 0.50-0.55 in PD and MB to 0.45-0.50 in JB. Carbonation of paste is limited to the exposed surface ends (to depths of 10-20 mm) with mostly non-carbonated interiors in PD and JB (unlike pervasive leaching and carbonation of paste in the damaged blocks) but shows more pervasive carbonation in MB.

3.3 SEM-EDS Studies

SEM-EDS studies of distressed blocks from damaged homes showed (a) oxidized pyrrhotite grains in phyllite and in mortar fractions having well-developed parallel Fe-O oxidized bands in Fe-S matrix where (b) the O/Fe atomic ratios of oxidized bands are noticeably higher than the ratios found in similar oxide bands in pyrrhotite from crumbled foundations of eastern US, (c) S/Fe atomic ratios of alternate sulphide matrix in pyrrhotite are close to pyrite stoichiometry than pyrrhotite, (d) extensive microcracking in the oxidized pyrrhotite grains, often extending into the aggregate and even to the neighbouring paste, (e) thaumasite precipitation in cracks and voids in one damaged home (DM), but (e) no elevated sulfate levels (S/Ca atomic ratios are mostly within 0.0 and 0.05) in the interstitial paste fractions in four out of five damaged homes due to extreme lime leaching and alterations to form the dominant silica-alumina gel of no cementitious property sometimes with occasional islands of secondary calcite precipitates. By contrast, similar absence of sulfate enrichment in otherwise dense, non-carbonated (PD, JB) to carbonated (MB) paste in strip foundations is due to the absence of advance pyrrhotite oxidation to release sulfate in paste, which is confirmed by the absence of the typical stripped patterns of oxidized pyrrhotite grains in phyllite (except only crude Fe-O bands in some grains in the mortar fraction). Abraded phyllite contents (calculated from clustered phase maps of muscovite and chlorite from corresponding elemental maps of K and Mg) is found to be noticeably higher in the mortar fractions of distressed blocks (as high as 50%) than in the mortar fraction of undamaged home, MM (10%), or in the mortar fractions of strip foundations (< 5% in MB to 5-10% in JB and PD).

3.4 XRD

Results of XRD for pyrrhotite-bearing phyllite and mica schist in the distressed blocks and two strip foundations (PD and JB) are similar with quartz, chlorite, and muscovite as main minerals, and feldspar (albite, orthoclase) and calcite as the minor minerals. Both pyrrhotite and the oxidized form, ferrihydrite, are detected in damaged blocks but were undetected in bulk samples of undamaged blocks. Only two foundations (PD and JB) showed trace pyrrhotite in bulk concrete but no oxidized forms.

4. CONCLUSIONS

The main difference between the blocks of damaged and undamaged homes is the absence of pyrrhotite or pyrrhotite-bearing phyllite in the coarse aggregate of the latter. As a result, S_T of damaged homes are noticeably higher, i.e., in excess of the 0.1 mass% limit of pyrrhotite-bearing aggregates in EN 12620 as opposed to well within that limit in the undamaged home. Additionally, the change in rock types from crushed friable phyllite-dominant coarse aggregate in the damaged homes to crushed but non/less-friable metagreywacke/micaceus quartzite aggregate in the undamaged home has resulted in a noticeably lower abraded mica in the paste of undamaged home (<5 volume %). Severe carbonation and lime leaching of paste in damaged homes compared to less carbonated to non-carbonated, non-leached paste in undamaged home indicates more restricted access of moisture and atmospheric carbon dioxide through the uncracked painted renders of the undamaged home compared to the easy access of elements through the severely cracked to crumbled renders of the damaged homes.

Inherent higher porosity of blocks from abundant interstitial voids and low paste (cement) contents compared to lower porosity of strip foundations from lower interstitial voids, higher paste (cement) contents to well-coat the aggregates, and dense well-consolidated natures of concrete foundations as opposed to blocks have offer many benefits to the strip foundations, especially when two of the three foundations contained the exact same pyrrhotite-bearing phyllite as the dominant coarse aggregate as in the damaged blocks. First benefit is the protection of pyrrhotite from advance oxidation during service in the foundations by restricting the oxygen access through the dense foundation, especially if the foundations were water saturated during service to prevent oxygen diffusion, which was impossible in blocks of outer leaf for easy access of moisture and oxygen first through the interconnected interstitial voids to reach phyllite and then through the foliation planes of phyllite to reach pyrrhotite. As a result, well-developed stripped patterns of oxidized bands in pyrrhotite that are so common in the distressed blocks were difficult to find in the strip foundations (found mostly in the mortar fractions of foundations than within phyllite). High humidity (water saturation) during service in the underground foundations prevented diffusion of oxygen needed for pyrrhotite oxidation since oxygen diffusion in water-saturated concrete is negligible compared to dry or unsaturated concrete, often reduced by a factor of 10^4. Second, limited moisture migration through dense concrete has also restricted the possibility of leaching and decalcification of paste in the strip foundations, which are so pervasive in the damaged blocks. Third, restricted pyrrhotite oxidation has also restricted ISA in the paste of strip foundations (only secondary ettringite crystallization in voids and relatively porous areas of paste from prolonged presence of moisture was found in one strip foundation, PD). Extensive SEM-EDS analyses of paste in all three strip foundations showed no sign of elevated S/Ca atomic ratios to indicate sulfate release from pyrrhotite oxidation, which is the primary prerequisite for ISA. Despite pervasive carbonation of paste in MB, there was no sign of thaumasite form of ISA. Higher abraded mica in the paste (from higher phyllite aggregate) of damaged blocks has facilitated moisture ingress, access of oxygen, and diffusion of sulfate ions to paste to promote ISA in the damaged blocks.

In the damaged blocks it is suggested [2,3] that (1) ettringite-form of ISA occurs in the non-carbonated paste from conversion of monocarbonate to ettringite by the released sulfate leading to expansion, (2) partial dissolution of abraded muscovite and chlorite in the alkaline environment of cement paste can provide additional monocarbonate to raise the expansion potential by additional ettringite formation, (3) carbonation of CSH and CH to calcite promotes thaumasite-form of ISA and eventually to (4) gypsum (more common in the drier inner than the moist outer leaf for faster carbonation and slower pyrrhotite oxidation in the inner leaf) leading to crumbling and loss of strength of paste from decomposition of CSH. Extensive lime leaching leading to formation of Si-Al-rich gelatinous mass in all the damaged homes in this study caused the ultimate loss in integrity of paste and large-scale crumbling of blocks.

Compared to the damaged blocks, higher quality of concrete in the strip foundations has only slowed down pyrrhotite oxidation and restricted ISA but not necessarily eliminated that potential since as long as there is pyrrhotite to be oxidized (as seen in all three foundations from the abundance in crushed phyllite in two foundations to subordinate phyllite gravel in the third) there is always potential for in situ expansion from oxidation and subsequent ISA in paste from the released sulfate. The evidence is spectacularly clear in many other foundations, e.g., from eastern US to Canada [8].

5. REFERENCES

[1] McCarthy, D., Kane, N., Lee, D, Blaney, D (2017). Report of the Expert Panel on Concrete Blocks, Department of Housing, Local Government and Heritage, 2017. https://www.gov.ie/en/publication/0218f-report-of-the-expert-panel-on-concrete-blocks.

[2] Leemann, A., Lothenbach, B., Münch, B., Campbell, T. and Dunlop, P (2023). The “mica crisis” in Donegal, Ireland–A case of internal sulfate attack? Cement and Concrete Research, 168, p.107149. https://doi.org/10.1016/j.cemconres.2023.107149.

[3] Leemann, A., Münch, B., Lothenbach, B., Winnefeld, F. and Dunlop, P (2024). Defective homes in Donegal, Ireland: effect of exposure conditions and concrete quality on pyrrhotite oxidation and internal sulfate attack. Cement and Concrete Research, 186, p.107684. https://doi.org/10.1016/j.cemconres.2024.107684.

[4] Brough C., Staniforth B., Garner C., Garside R., Colville R., Strongman J., Fletcher J (2023) High risk concrete blocks from County Donegal: The geology of defective aggregate and the wider implications. Construction and Building Materials 408:133404. https://doi.org/10.1016/j.conbuildmat.2023.133404.

[5] Jana, D. (2024) Cracking and crumbling of concrete blocks in County Donegal, Ireland: A holistic approach from case studies on deleterious effects of open microstructure of blocks, phyllite aggregate, pyrrhotite oxidation, paste carbonation, lime leaching, and internal sulfate attacks, 1st International Conference on Iron-Sulfide Reactions in Concete, Quebec City, Universite Laval Campus, Canada, May 14-17, pp. 34-38.

[6] I.S. 465:2018+A1:2020 Assessment, testing and categorisation of damaged buildings incorporating concrete blocks containing certain deleterious materials. National Standards Authority of Ireland, Dublin.

[7] EN12620, Aggregates for Concrete, European Committee for Standardization, Brussels, 2002 + A1:2008.

[8] Jana D (2023) Concrete Deterioration from the Oxidation of Pyrrhotite: A State-of-the-Art Review. In: Maher MLJ (ed) Pyrite and Pyrrhotite, Nova Science Publishers, Inc, pp. 137-221.

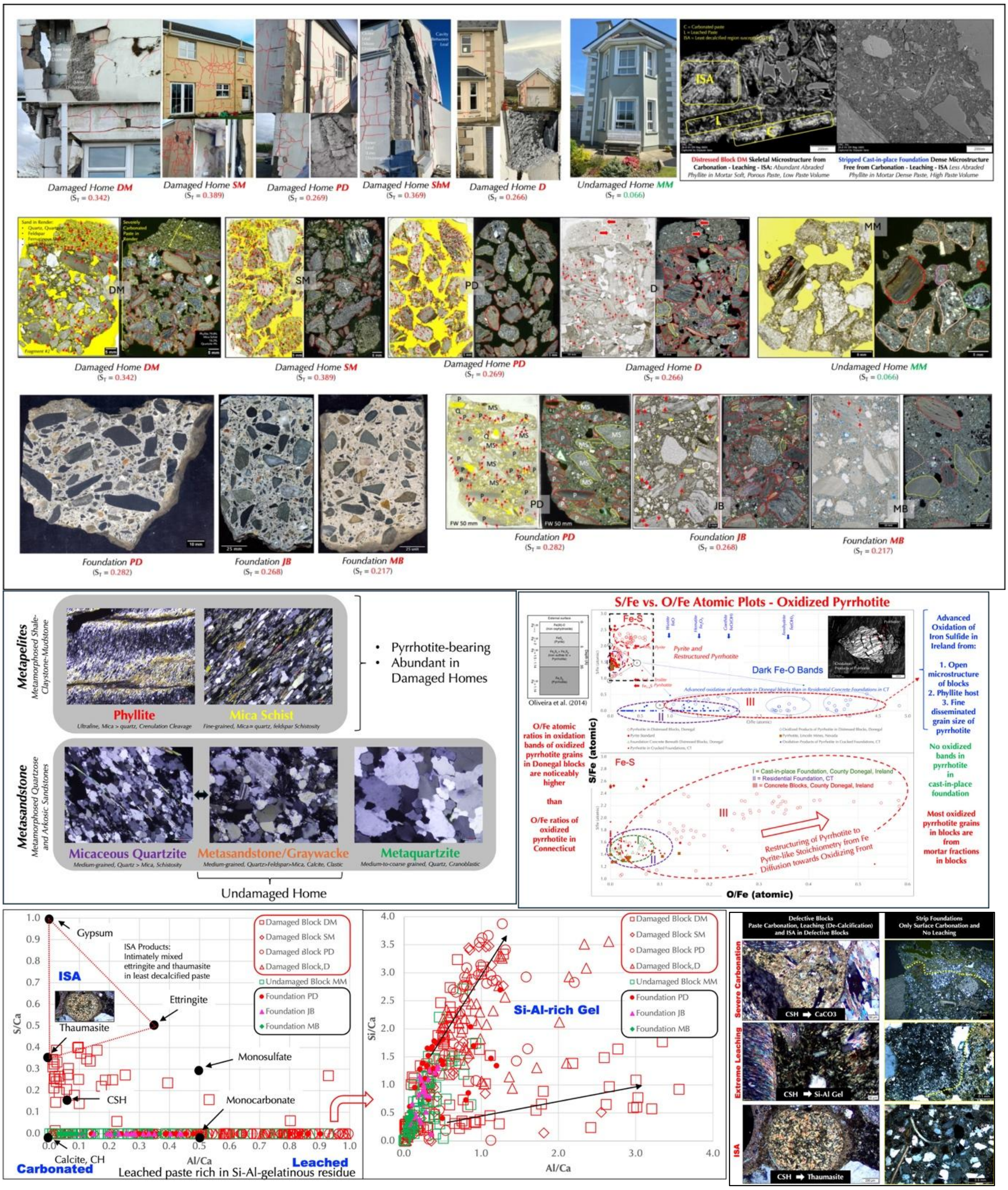

Figure 1: Row 1 left: Five damaged homes and one undamaged home and associated total sulfur (S_T). Row 1 right: BSE images of porous, leached, carbonated, ISA-affected skeletal microstructure of paste in a damaged block compared to dense microstructure of a strip foundation. Row 2: Fluorescent dye-mixed epoxy-impregnated 50 x 75 mm size thin sections of four damaged homes and one undamaged home (right most) in PPL and XPL showing dominant pyrrhotite (red arrows in PPL)-bearing phyllite (marked in red lines in XPL) in the damaged homes versus pyrrhotite-free metagreywacke (marked in beige lines in XPL) in the undamaged home. Row 3 left: Lapped cross sections of samples from three dense, well-consolidated concrete in strip foundations. Row 3 right: Scanned whole-slide thin section images in PPL and XPL of strip foundations showing the same dominant pyrrhotite-bearing phyllite as in the damaged blocks in two foundations (PD, JB) and in the third foundation (MB) having crushed mica schist/metagreywacke, and phyllite as gravel aggregate. Row 4 left: Micrographs of five dominant rock types where metapelites are the host of pyrrhotite and common in damaged homes, whereas quartzite/metagreywacke are pyrrhotite-free and found in the undamaged home. Row 4 right: SEM-EDS plots (S/Fe versus O/Fe atomic ratios) of oxidized pyrrhotite in damaged blocks versus foundations from Ireland and superposed on the data from the eastern US. Row 5 left: SEM-EDS plots (S/Ca versus Al/Ca and Si/Ca versus Al/Ca atomic ratios) of paste from damaged homes and foundations showing elevated S/Ca ratios in one damaged home from thaumasite ISA but mostly non-elevated S/Ca ratios from extensive carbonation and lime leaching in other damaged homes, and lack of sulfate contamination in the paste of three strip foundations. Row 5 right: Severe carbonation, leaching, and thaumasite formation in the paste of a damaged home (DM) compared to dense non-carbonated CSH-CH interior (in PD and JB) to carbonated paste (in MB, which also has some seashells in sand) in the strip foundations.