AGGREGATES PRONE TO CAUSING PYRITE-INDUCED HEAVE: HOW THEY CAN BE AVOIDED

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Abstract

Beginning in 2007, a large number of recently constructed houses in the Greater Dublin Area developed severe floor and wall cracking. Following investigation, it was confirmed that the damage was as a result of the use of calcareous mudstone aggregates containing reactive pyrite as hardcore fill. The oxidation of the pyrite resulted in the growth of gypsum within the hardcore which caused heave of the slab and associated structural damage. Since then, thousands of houses and apartments, as well as commercial, retail and institutional buildings have been confirmed to have the same problem. It has been determined that the problematic hardcore was supplied from at least five different quarries in the eastern part of Ireland. Similar problems with expanding under floor aggregate fill had been experienced in the Montréal area of Canada between 1984 and 2000 where it is estimated that up to 20,000 houses were affected. The problem there was eliminated in 2003 with the introduction of a new certification protocol for unbound aggregates used under floors. The characteristics of these problematic swelling aggregates have been established using data from both Ireland and Canada. They are characterized by having poor physical-mechanical properties, high content of fine grained pyrite and high clay contents. From a review of floor slab monitoring in affected buildings it has been demonstrated that the heave rates can be as high as 20 mm per year, but more typically are less than 10 mm per year. The heave pressures developed are substantial and can be as high as 600 KPa. The avoidance of these aggregates requires a full understanding of the source rock geology, as well as reliance on established laboratory physical testing, supplemented by chemical testing and petrographic examination.

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Introduction

The phenomenon of swelling shale bedrock affecting building performance was recognized in Canada in the late 1960s. The Rideau Health and Occupation Centre on Smyth Street in Ottawa experienced heave in one section of the building (Quigley and Vogan, 1969). The building was founded in the Lorraine shales that overlie the Billings shale in the area.

The first case of suspected pyrite-induced floor heave identified in Ireland was in late 2006. The second recorded case was a house in a housing estate in north Dublin which was constructed in 2003. In March 2007 it was confirmed that the cause of the cracked and heaved floors and cracked partition walls experienced in the house was swelling of the underlying crushed rock fill beneath the floor slabs. The damage was confined to the floors and internal partition walls with no visible damage on the exterior of the house. The fill material was tested and confirmed to be crushed calcareous mudstone, with estimated original pyrite concentrations of approximately 2.6%. The Petrographic Number (as defined by the Canadian Standards Association (CSA), 1994) for a sample of the under floor aggregate was found to be 250, confirming very low physical-mechanical quality.

Recent Problems In Ireland Related To Pyrite In Unbound Aggregates

History of problem

Between about 1995 and 2007, an economic and real-estate boom in Ireland caused a huge increase in demand for building materials, particularly aggregates. In addition to an increase in commercial and residential construction, there was also an unprecedented boom in road construction with an aggressive motorway construction program also underway. The National Roads Authority (NRA) updated aggregate specifications for road works in 2000 and again in 2004 to conform to the new European Standard. They subsequently mandated that all quality control and quality assurance testing on road works be undertaken in laboratories accredited to ISO 17025. No similar response to ensuring quality of construction materials occurred in the building sector. While the Building Regulations had some basic requirements for hardcore fill in buildings, there was no tradition of third party testing and builders relied on the quarries to supply material suitable for use.

With aggregate supply in the country increasing by over 40% between 2001 and 2006, lower quality aggregate sources were exploited to meet the growing demand. These lower quality aggregates were mainly supplied to the residential construction sector. By early 2007, widespread reports of unusual patterns of cracking began to emerge with houses that were 3 to 5 years old. It soon became clear that this damage was directly attributable to pyrite-induced swelling of the compacted under floor hardcore.

Geology and rock types

The main source quarries for the problematic aggregates are in the eastern part of Ireland and generally comprise fine grained argillaceous sedimentary rocks. These are described as muddy limestones, calcareous mudstones/siltstones and shales.

While these quarries stated at the time that they could supply aggregates conforming to Clause 804 (NRA, 2000), i.e. the National Roads Authority granular road base material, no contemporary independent sampling and testing was undertaken to confirm this. Extensive testing carried out on samples of the hardcore recovered from buildings during remedial works demonstrate that the aggregates fail to meet the Liquid Limit, Coarse Aggregate Water Absorption, Magnesium Sulphate Soundness and Ten Percent Fines Value for Clause 804. This is not surprising given the geological formations that were being exploited. One such quarry, near Dublin Airport, is located within the Tober Colleen Formation that is described as "dark grey, calcareous, commonly biorturbated mudstones and subordinate thin micritic limestones" (Geological Survey of Ireland (GSI), 2001). The Tober Colleen Formation is of Lower Carboniferous age and is the lowest unit within the Calp Limestone. Another problematic quarry was located further north within the Loughshinny Formation. This rock is described as "argillaceous, pyritic, locally cherty micrites and graded calcarenites, interbedded with dark grey to black shale" (GSI, 2001). Two further Co. Meath quarries that have supplied problematic pyritic aggregates are from the Lucan Formation and are described as "dark grey, well bedded, cherty, graded limestones and calcareous shales" (GSI, 2001). The geological succession of these various formations is illustrated in Figure 1 and aggregate appearance is shown in Figures 2 and 3.

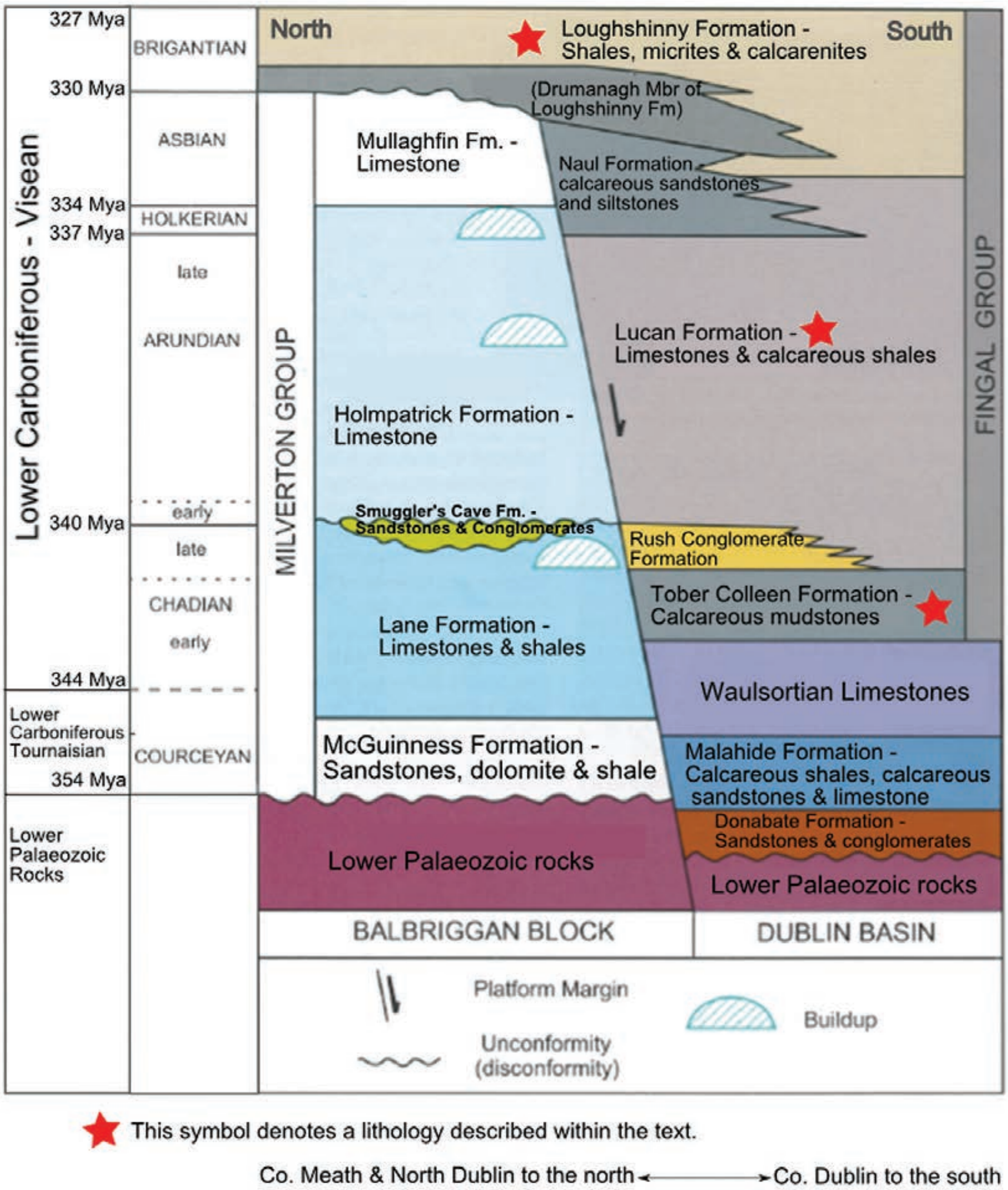

Figure 1. *The Dinantian successions in north Co. Dublin (from GSI, 2001)*

Figure 2. *Aggregate particle from a quarry in the Tober Colleen Formation opened on a lamination revealing gypsum clusters (white flecks).*

Figure 3. *Aggregate particle from five-year old hardcore with laminations propped open with gypsum.*

How damage occurs

These fine grained argillaceous sedimentary rocks, comprising mainly calcareous mudstones, siltstones and shales, were formed in an anoxic marine environment. They frequently contain disseminated fine grained pyrite in framboidal form. This form of pyrite, due to the small grain size, reacts easily with moisture and oxygen present in a damp under floor setting. The oxidation process produces ferrous hydroxide, sulphuric acid (H_2SO_4) and carbon dioxide. The problematic pyritic mudstones and siltstones typically contain 15 to 30% calcite. The sulphuric acid dissolves the calcite present and this releases calcium ions into solution. The solution becomes super saturated over time, which results in the crystallisation of gypsum ($CaSO_4 \cdot 2H_2O$). The gypsum tends to nucleate predominantly along the laminations of the rock particles, as these allow moisture and air to penetrate the rock more easily. This production of gypsum then results in an increase in bulk volume within the fill material, giving rise to expansion.

Pyrite oxidation is significantly enhanced by bacterial action including Thiobacilli and related genera, which are neutral pH bacteria. Bacteria tend to multiply in acidic environments with high temperature and humidity conditions. Most of the expansion from this bulk increase in volume is upwards, since it is perpendicular to the main orientation of the laminations which align horizontally with compaction. The floor slabs of the building are pushed upwards, which pushes the internal partition walls upwards. Some lateral expansion also occurs, causing the rising walls to be pushed outwards. This has resulted in cracks in the concrete floor slabs, cracks above door frames, cracking in plinths from lateral expansion, and doors sticking on heaving floors.

The only current remedial option for these buildings in Ireland is to remove the problematic hardcore completely and replace it with an inert fill. Less costly options are being developed with a view to preventing further oxidation of the infill in situ, which would be much cheaper and a less disruptive option for homeowners.

Extent of hardcore problems in Ireland

In June 2012, the Irish Minister for the Environment, Community and Local Government released a report prepared by the 'Pyrite Panel' (Department of Environment, Community and Local Government, 2012) that he had set up to investigate the problem. The study confirmed that pyrite-related damage was occurring in a significant number of houses in the area of north County Dublin, and the surrounding counties of Kildare, Offaly and Meath.

The Pyrite Panel report stated that a total of 74 housing estates were identified as being affected, comprising approximately 12,250 housing units. It further stated that, to date, approximately 1,100 private dwellings on 12 different estates had been remediated by way of total removal and replacement of the problematic hardcore. Houses that were constructed between 2002 and 2006 represented the vast majority of all suspected cases. The elapsed time from construction to presentation of damage ranged from 2 to 9 years. It was noted that this was much earlier than in the cases reported in Canada, where, in general, it took 8 to 20 years to manifest as a problem. This faster rate is in all likelihood influenced by such factors as the nature of the particular form of pyrite in Ireland, as well as temperature and exposure conditions of the hardcore.

With an average repair cost per house of about €45,000, the total repair bill for houses with potentially problematic hardcore could be close to half a billion Euro. The report concluded that the problematic hardcore was mainly supplied by five quarries. In a submission from the Irish Concrete Federation (ICF) it was noted that their members operate 300 quarries in Ireland, but that during the construction boom, some 1,200 quarries were operating. It appears that many of these quarries were operated on an ad hoc basis and it was reported that some aggregate suppliers did not operate their own quarries, but simply operated gravel trucks and procured aggregate from wherever was convenient.

Recommendations from Pyrite Report

The Pyrite Panel report contained a series of recommendations on how to proceed to best correct the pyrite problem in Ireland. The main focus of these recommendations was the need to develop a standardised sampling and testing protocol to identify and characterise the extent of a pyrite problem in a building as well as the need for a standard for undertaking remedial works. However, the Panel also had some recommendations for the quarry industry. These are summarized briefly below:

- More rigorous testing and certification of hardcore products, including factory production control;
- Suppliers should be able to provide proof of compliance with quality standards;
- Materials should be traceable to source quarry;
- Quarries should carry adequate insurance for the scale and type of work they are supplying; and
- Data related to products should be available on request.

Moves to implement the key recommendations of the Pyrite Panel commenced in late 2012. The National Standards Authority of Ireland (NSAI) moved quickly to prepare new national standards for the testing and characterisation of hardcore in houses and to define how remedial works should be undertaken. These new standards, I.S. 398, Parts 1 and 2, are to be released in early 2013. There is also work underway to revise the Standard Recommendation, S.R. 21, that accompanies I.S. EN 13242 (NSAI, 2003), the European standard for unbound aggregates used in construction.

Past Pyrite Problems In Canada

The hardcore performance problems in Ireland are reminiscent of similar widespread problems experienced in Canada from the 1960s. Initially, these problems related to building foundations supported on shallow shale bedrock, but throughout the 80s and 90s some 20,000 houses in Quebec developed floor slab damage due to pyritic heave. It is useful, in better understanding the pyrite problems in Ireland to review the experience gained in Canada.

Locations and geology

The first identification of pyrite-related problems in buildings in Canada was in the Ottawa area in the 1960s. Subsequently, in the 1970s similar problems were recorded in Sainte-Foy near Québec (Bérubé et al, 1986). By the mid-1980s, widespread pyrite-related problems, on the scale of an epidemic, were reported in the Montréal area. As can be seen from Figure 4, these areas trend in a north-easterly direction parallel to the St. Lawrence River.

When the geological mapping for these areas is examined (Figure 5), it is seen that the affected areas are characterized by shale deposits. This is consistent with the published literature on pyrite-related problems around the world where they are associated with areas of

Figure 4. *Map showing Ottawa, Montréal and Québec City indicating the north-easterly trend of these locations along the St. Lawrence River.*

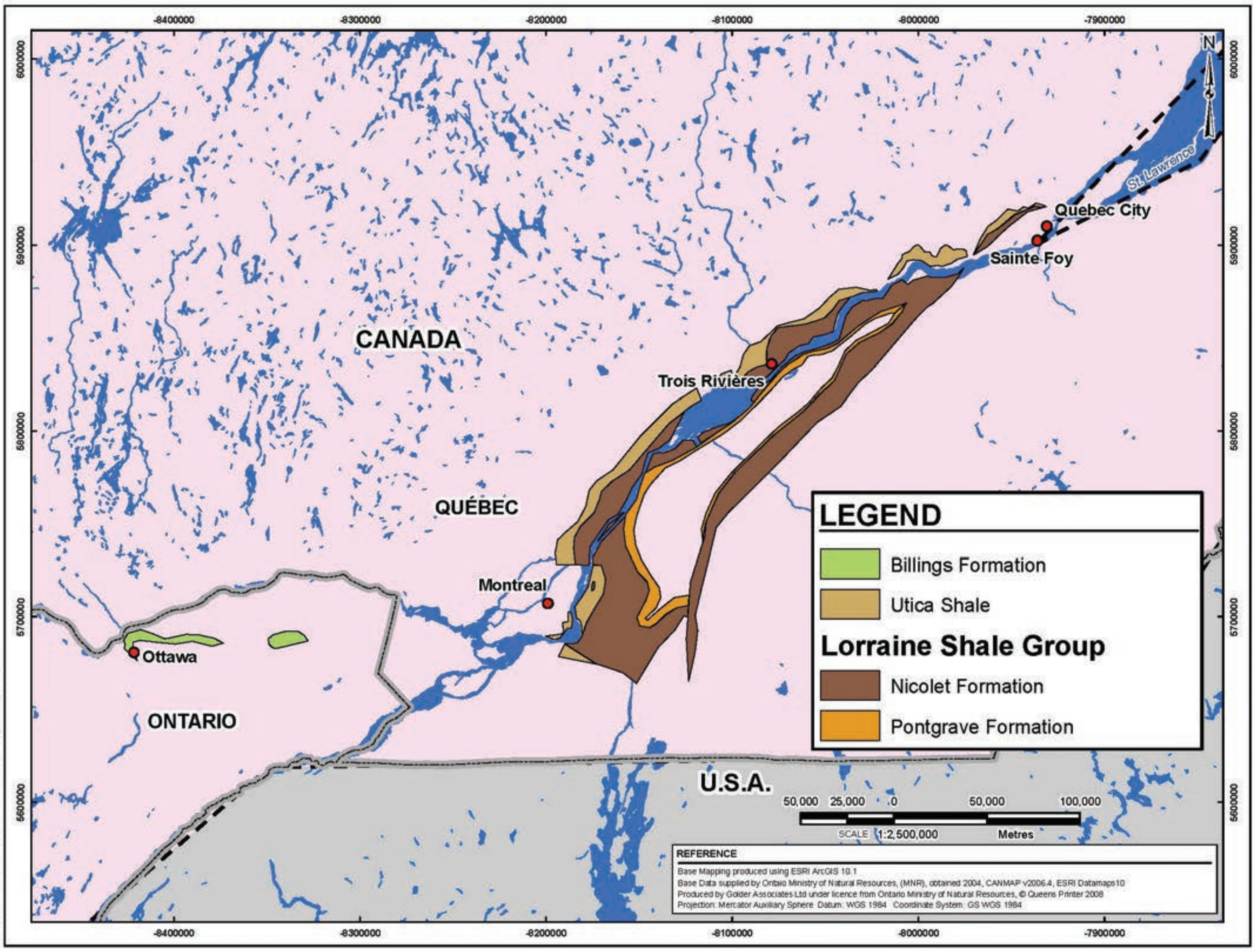

Figure 5. *Extent of shale bedrock in areas reporting pyrite-related problems (from Ontario Ministry of Natural Resources, 2008).*

shale and mudstone, i.e., fine grained sedimentary rocks with significant clay contents.

It should be noted that pyrite-related problems in buildings have come about in two different ways. The first is due to heave of building foundations and floor slabs supported on shale bedrock, and the second is where crushed shale or mudstone has been used as compacted under floor fill (i.e. hardcore) or backfill against foundation walls.

In the Ottawa area, the heave-related problems have been mainly associated with the Billings Formation of Ordovician age. As seen from the schematic in Figure 6, the Billings Formation is associated with the Carlsbad and Queenston Formations which are also shales. The Billings Shales are typically described as dark grey, black and brown shales, interbedded with calcareous siltstone and silty limestone of the Carlsbad Formation (HPVM, 1996). They are also frequently interbedded with the red to greenish gray siltstone and shale of the Queenston Formation. These shales were formed in an anoxic marine environment some 450 million years ago. Typical of rocks formed from fine marine muds, they generally contain widely disseminated fine-grained pyrite.

Along the St. Lawrence River, between Montréal and Québec City, are a series of shale deposits comprising Utica Shales and Nicolet and Pontgrave Formation shales of the Lorraine Shale Group. These formations are Ordovician Age, i.e. about 450 million years old. The Utica Shales are 50 to 300m thick and were deposited during a period of rapid sea level rise in a poorly oxygenated environment. They comprise siliciclastic and carbonate muds with moderate to high calcite contents. Because of this calcite content, many of these rocks could be classified as silty limestones and so were frequently used in the 70s, 80s and 90s as processed crushed rock in residential and commercial construction.

PERIOD	GROUP	FORMATION
ORDOVICIAN	QUEENSTON	QUEENSTON
	CARLSBAD	CARLSBAD
	BILLINGS	BILLINGS
	OTTAWA	Lindsay
		Verulam
		Bobcaygeon
		Gulf River
		Shadow Lake
	ROCKLIFFE	ROCKLIFFE
	BEEKMANTOWN	Oxford
		March
CAMBRIAN	POTSDAM	Nepean
PRECAMBRIAN		

Figure 6. *Ordovician sequence in the Ottawa area.*

The overlying Lorraine Shales were more argillaceous, had lower calcite contents, and comprised mudstones and siltstones as well as true shales. They also have high concentrations of disseminated pyrite.

Typical case study

To illustrate the similarities of pyrite-induced building damage between Ireland and Canada, we can consider the case of a two-storey warehouse building in the City of Ottawa. The building was constructed in the 1960s and damage in the form of floor cracking and unevenness was first noted in the 1980s. There was a relatively high water table at the site so a sump and pump had been installed some 3.6 m below the floor slab. In addition, there was an elevator shaft that extended approximately 2.0 m below the floor slab. Damage was first noted in the form of cracking in the floor slab in the area of the building near the sump (Figure 7).

Figure 7. *Intersecting floor cracks indicative of upward heave of the floor slab in a warehouse building in the City of Ottawa.*

Over the intervening years, the floor heave continued to progress and was estimated to be approaching 100mm in total heave displacement. Some temporary repairs were undertaken but eventually more extensive rehabilitation was deemed necessary as the operations of the fork lift trucks were being affected.

An investigation confirmed that only a thin layer (<100mm) of compacted aggregate fill separated the underside of the floor slab from the underlying bedrock surface. The lowering of the local water table in the vicinity of the sump had allowed the pyrite in the upper portions of the shale bedrock to oxidize and for gypsum to develop between laminations (Figure 8). It could be clearly seen from visual examination that the laminations within the shale were being prised apart by the growth of gypsum.

Figure 8. *Close-up view of the brown Billings shale (approx.150 mm across) with clusters of gypsum crystals on lamination surfaces.*

Solution to pyrite problems in Quebec

As a result of the extent of the problem in Québec, a technical committee (*Comité Technique Québécois D'étude Des Problèmes De Gonflement Associés à La Pyrite*) was created in 1997 to examine the problems caused by the swelling of granular backfill under concrete floor slabs. It was established that the swelling occurs as a result of chemical reactions involving some of the minerals present in the aggregates used in that area of Québec. Due to the extent of the problem, the committee developed standard procedures for investigating and evaluating the problem. These procedures are known as Procedure CTQ-M200, and entitled, "Appraisal procedure for existing residential buildings" (Comité Technique, 2001).

One of the key aspects of CTQ-M200 is the performance of a Swelling Index Test. This petrographically-based test procedure was developed in 1999 by the Québec Technical Committee and was referred to as CTQ-M100/2000. This was subsequently adopted as a Québec Standard (Bureau de normalization due Québec (BNQ), 2003) and designated as BNQ 2560-500. The laboratory test procedures are divided into two stages. Stage 1 comprises:

- Sieve analysis
- IPPG (indice pétrographique du potential de gonflement) – Swelling Index Test
- Absorption test
- Micro-Deval testing

Essentially, the Stage 1 evaluation focuses on establishing the clay content of the crushed rock material (i.e., Swelling Index Test) and two key physical quality parameters. What is interesting is that it does not involve the determination of pyrite contents. In the Swelling Index Test, also referred to as the SPPI test (Swelling Potential Petrographic Index), the sample is divided into 20, 14, 10 and 5mm size fractions. These are then examined by the petrographer who evaluates the clay content within each of the sample particles. Depending on the clay content, a weighting factor ranging from 0 to 1 is applied. If no clay is present in the particle, a granite or basalt, for example, it is scored as 0. If it is a pure shale it is scored as a 1. On this scale a clayey limestone would be assigned a score of 0.5 and a limestone with some clay veneer would be assigned 0.1. A final weighted score is then determined, taking into account the original grading of the sample. This final score, or Swelling Index, will fall between 0 and 100. An Index of 0 would indicate a crushed rock product containing no clay and thus with no likelihood of causing pyrite-induced heave. Crushed rock products with Swelling

Index values of 10 or less are considered suitable for use in construction.

The Stage 2 of the BNQ testing protocol is generally undertaken when the results of the Stage 1 testing are not conclusive. Stage 2 involves:

- Total sulphur content (S)
- Sulphate content (SO_4)
- Alumina contents (clay content)
- Carbon dioxide contents (carbonate content)

BNQ 2560-500 has been adopted as the basis for certifying aggregates for use in building construction. Since about 2000, most of the aggregate producers observed this certification requirement and purchasers look for it. The process is referred to as "DB" (dalle de béton or concrete slab) certification. The process for certification requires the sampling and testing to be performed by an approved laboratory and must be performed for every 10,000 tonnes of material for which the Swelling Index must be 10 or less. Each approved stockpile is then assigned a certification number to ensure future traceability.

Susceptible Aggregates

The types of lithologies that give rise to pyrite-induced heave are those that would be rated as poor quality rock for construction aggregates (i.e. high clay content, high water absorption, and highly anisotropic) and with high fine-grained pyrite content, in association with some calcite. The common rock types include calcareous mudstones and siltstones, shales, and muddy limestones.

The low quality of the aggregates prone to pyrite-induced heave can be confirmed from conventional aggregate suitability testing. The most indicative tests are coarse aggregate absorption, Micro-Deval and Magnesium Sulphate Soundness. Results for these tests from typical Irish and Québec problematic mudstones and shales are shown in Figure 9. The red line on the charts indicates typical industry upper limits of acceptability for good quality construction aggregates. Test results for good quality crushed limestone aggregate are shown for comparison.

It is not possible to establish a pyrite threshold level above which heave problems can be anticipated. This is because there are too many other variables related to the physical characteristics of the compacted hardcore as well as to the environmental conditions under which it is used. There have been cases where equivalent pyrite contents as low as 0.5% by mass have caused structural damage. This would be equivalent to 0.3 % total sulphur, which is well below the maximum concentration allowed in unbound aggregates according to European Standard EN 13242 (NSAI, 2003). Hawkins and Pinches (1992), who studied this problem in the UK, suggested that if the difference between the total sulphur content and the potential sulphur in sulphate, was above 0.5% then the material may be susceptible to ground heave. The problematic aggregates in Ireland exceed this oxidisable sulphide limit and have pyrite contents by mass of greater than 1% and more typically greater than 2% as shown in Figure 10.

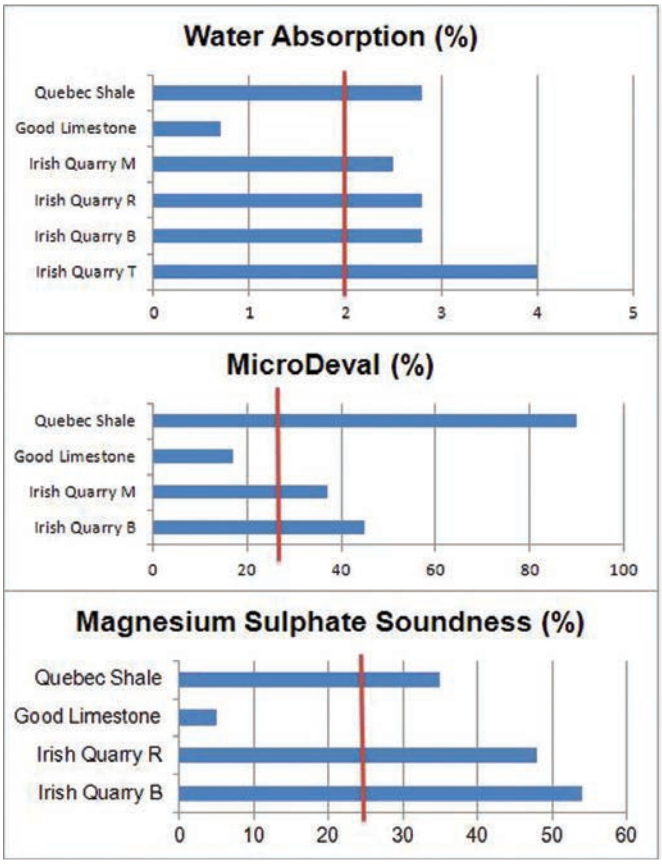

Figure 9. *Typical results for Water Absorption, Micro-Deval and Magnesium Sulphate Soundness for problematic shales and mudstones from Ireland and Québec.*

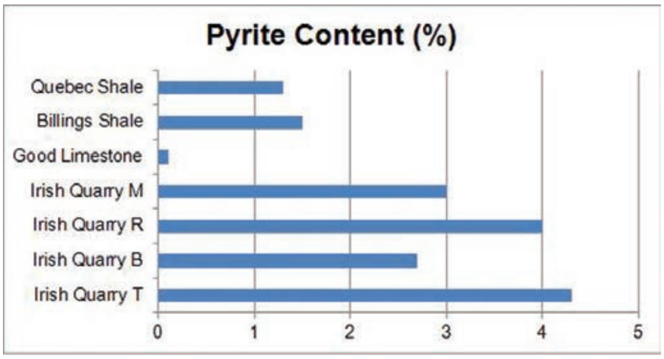

Figure 10. *Comparison of estimated pyrite contents in problematic mudstones and shales.*

The equivalent pyrite content can best be determined by bulk analytical chemistry methods. However, it needs to be done in conjunction with thin section petrography to confirm the form of pyrite and to establish that no sulphides other than pyrite, are present.

The growth of expansive gypsum requires the availability of calcite. Most of the Irish calcareous mudstones/siltstones have calcite contents in the range of 15 to 30%. However, as little as 1% calcite is sufficient to feed the reactions. Many problematic shales have calcite contents of less than 5% (Figure 11).

Clay content is also an important component, as demonstrated by the basis of the Québec Swelling Index Test. A simplified tri-linear plot can be used to compare the relative proportions, of clay, calcite and other minerals in these aggregates. From Figure 12 it can be seen that the mudstone aggregates from three problematic quarries in Ireland and those from the Québec Lorraine shales all have calcite contents less than about 40% and generally high clay contents. The Québec Utica shales are much more variable and those with higher calcite contents and low clay contents being inert and suitable for use.

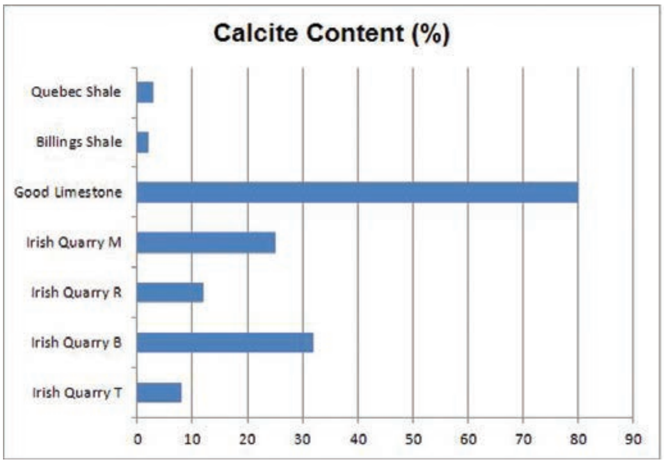

Figure 11. *Comparison of calcite contents in problematic mudstones and shales.*

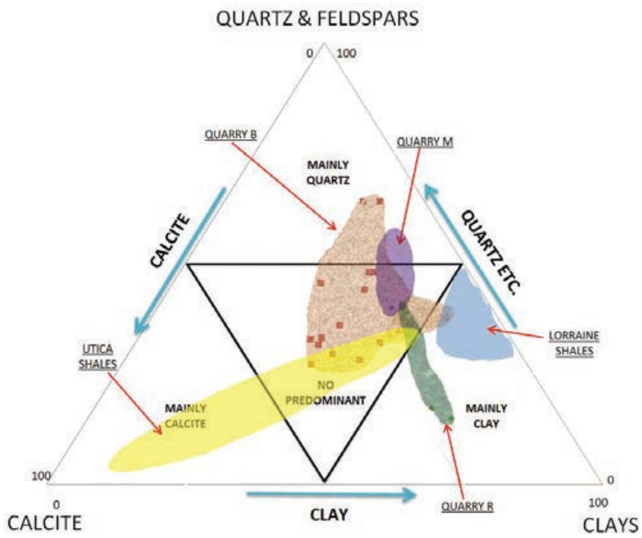

Figure 12. *Comparison between Utica and Lorraine shales and Irish mudstones that cause pyrite-induced heave. Quarries B, M and R are Irish quarries.*

Pyritic Heave Rates And Pressures

The rates of pyrite-induced expansion within buildings will vary significantly depending on a wide range of influence factors. These include the following:

- Whether it is a foundation on shale bedrock or a floor slab placed on a compacted shale or mudstone fill;
- Quality of the source rock and proportion of mudstone/shale vs limestone;
- The distribution and form of pyrite within the aggregate;
- The *in situ* density of the infill (based on the degree of compaction and applied loads);
- The extent of moisture within the infill and access to capillary water;
- Ambient temperature and pH;
- The particle size distribution of the infill (the fine fraction will oxidize faster than the coarse fraction);
- Trace element concentrations;
- The thickness of the infill; and
- The presence of bacteria.

Despite these variables, some orders of magnitude for rates of heave can be established from a review of monitoring in buildings that has been reported in the literature and from the results of forensic engineering investigations. Some recorded heave data is plotted in Figure 13. For North America the reported heave ranges are from 10 to 22 mm per year.

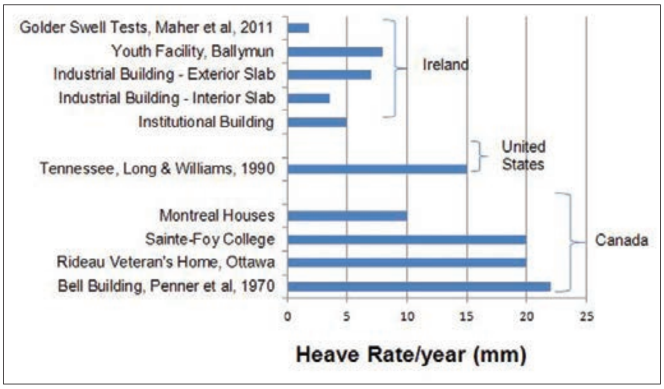

Figure 13. *Recorded heave rates in buildings due to pyrite-induced heave.*

From a number of buildings in the Dublin area where monitoring has been undertaken for periods of up to three years, the heave rates are lower and generally in the range of 4 to 8 mm per year. From laboratory swell tests undertaken using crushed mudstone from the Dublin area, heave rates were measured at about 2mm per year in a 300mm thick layer of compacted fill (Maher et al, 2011).

Expansion pressures

In connection with a legal proceeding in Ireland, Golder Associates developed a large scale laboratory swell test to study pyrite-induced heave in a controlled laboratory environment. The initial experiment with a large scale laboratory swell test began in December 2007 (Maher et al, 2011). The test was performed in a 1.2m internal diameter concrete manhole ring with a compacted sample height of 1.02 m.

After 17 weeks of monitoring, a vertical hairline crack developed in the side of the concrete pipe. After 50 weeks, the vertical crack had expanded to 12mm. Using analytical and numerical techniques, the pressure produced inside the pipe at rupture was back-calculated and established to be about 600kPa.

Figure 14 illustrates various estimates of pressures generated from pyrite expansion. It can be seen that the back analysed value from the Golder Laboratory Swell

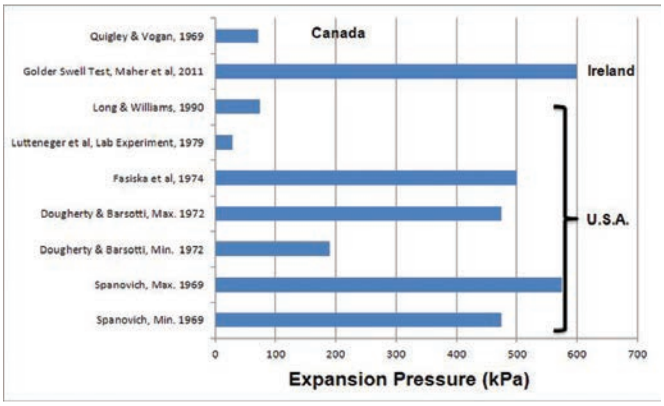

Figure 14. *Comparison of estimated pyrite heave pressures from a literature review.*

Test (Maher et al, 2011) of 600kPa is in line with estimates made by Spanovich in 1969 (Spanovich, 1969).

Conclusions

Shales and mudstones, in general, have always been acknowledged as not suited for the production of good quality construction aggregates. Due to their high clay contents, low strength and laminated structure, they tend to have high water absorption characteristics and low resistance to abrasion and impact. With these characteristics, these rock types are very vulnerable to chemical weathering. The easy access to moisture and the low internal bonds between laminations allow the very fine disseminated pyrite to readily oxidize. Since many of these shales may also contain small amounts of calcite, all the ingredients for the formation of calcium sulphate dehydrate, or gypsum, are present. It is generally accepted that the higher the clay contents in shales and mudstones, the poorer the quality of the rock in terms of durability and mechanical properties. It is for these reasons that the test standard developed in Québec (BNQ 2560-500, 2003) to assess susceptibility of an aggregate to pyrite-induced heave, is the Swelling Index Test which is based on establishing the clay content of the sample.

From extensive testing of the problematic calcareous mudstones in Ireland, the following are the characteristics of those that have caused structural damage in buildings:

- Equivalent pyrite contents above about 1%. Thus the 1.0% Total Sulphur limit in the European standard does not screen out problematic aggregates;
- Oxidisable sulphides >0.5%;
- The pyrite is in very fine grained form and is widely disseminated as determined by petrographic examination;
- The aggregates contain high clay contents, generally above about 20%;
- The aggregates have poor physical-mechanical test properties with water absorption values greater than 2%, and with MicroDeval and Magnesium Sulphate Soundness losses greater than 25%.

Adherence to normal good practice for assessing source rock for suitability for the production of construction aggregates and reliance on the accepted laboratory test suites, including chemical and petrographic testing, should prevent these problematic aggregates from making their way into the built environment.

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