A large scale laboratory swell test to establish the susceptibility to expansion of crushed rock containing pyrite

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ABSTRACT
Certain rock types, particularly mudstones and shales, are susceptible to destructive progressive expansion, when they contain sufficient oxidisable sulphides and other minerals that allow the growth of gypsum. The most widely documented cases of damage from pyrite-induced expansion are in Quebec, but the most recent cases have come to light in Ireland and it is now estimated that thousands of houses, as well as some industrial and institutional buildings are undergoing progressive damage. This paper describes a series of large scale laboratory swell tests conducted over a period of almost two years. The results confirmed that crushed mudstone aggregate continues to swell at a rate of 0.6% of fill thickness per year even after being removed from a 5-year old building where it had caused severe structural damage. The swell tests also confirmed that all size components in a well graded aggregate contribute to the rate and magnitude of heave.

RÉSUMÉ
Certains types de roches, particulièrement les schistes argileux et les shales, peuvent être affectées par un gonflement destructif progressif, lorsqu'elles contiennent suffisamment de sulfures oxydables et autres minéraux qui permettent la croissance de gypse. Les cas les mieux documentés de dommages causés par le gonflement relié à la pyrite se trouvent au Québec, mais les cas les plus récents sont apparus en Irlande, et on estime que des milliers de résidences, en plus de certains bâtiments industriels et institutionnels, subissent actuellement des dommages progressifs. Cet article décrit une série d'essais de gonflement à grande échelle réalisés en laboratoire sur une période près de deux ans. Les résultats confirment que l'agrégat de schiste argileux continue de gonfler à un taux de 0,6 % de l'épaisseur du remblai par année, même après avoir été retiré d'un bâtiment âgé de 5 ans, où il avait engendré des dommages structuraux importants. Les essais de gonflement confirment également que toutes les fractions granulométriques d'un agrégat à granulométrie étalée contribuent à la vitesse et à l'ampleur du soulèvement.

1 INTRODUCTION

For over forty years the problems associated with heave in compacted rock fill containing pyrite, most commonly black shales and mudstones, have been recognized (Nixon 1978; Penner et al 1972; Wilson 1987). While the occurrences of these problems have been to some degree isolated, when they occur they can have devastating affect, particularly where family homes are involved. In Quebec, it took almost 20 years to fully understand the problems and address them in terms of new standards and protocols (ACQC 1999). Slab heaving due to the swelling of pyritic fill was reported in the Teesside area of the UK in the late 1970s (Nixon, 1978) and in the Iwaki City area (Fukushima Prefecture) of Japan, about 1,000 wooden houses built directly on exposed mudstone sediments were damaged by heaving of their foundations (Yamanaka et al. 2002). Warren Anderson of the Kentucky Geological Survey has reported three case studies of pyritic fill and foundation heave problems involving a middle school, a factory building and a hospital located in Estill County, Kentucky, USA (Anderson 2008). The most recent outbreak of widespread pyrite-induced heave problems is in Ireland where problems began to be identified in late 2006 in the midst of the Celtic Tiger construction boom. The extent of the problems is still not fully known, but to date over a thousand houses have experienced structural damage, as well as schools, institutional buildings, and warehouses giving rise to damages of greater than a hundred million Euros.

The fact that severe pyrite-related heave continues to occur confirms that the problem is still not fully recognized or understood. This paper describes a series of large scale laboratory swell tests that were performed to study the development of heave over time in a compacted crushed rock fill. The tests were performed on an aggregate fill material that was removed from a 5-year old building that had experienced structural damage due to floor slab heave.

2 PYRITE-INDUCED HEAVE IN COMPACTED FILLS

2.1 Mechanism of Heave

Iron sulphides such as pyrite (FeS_2) can oxidize in some sedimentary rocks such as argillaceous limestone, mudstone and shale. The pyrite occurs in various crystalline forms, including well-crystallized cubic, euhedral pyrite (grains 0.5mm to 3mm or larger in size) and very fine-grained pyrite (grains 1 µm to 5µm in size) that forms framboidal masses that are highly reactive. These finer grained forms of pyrite tend to be associated with fine grained sedimentary rocks, such as mudstones that formed in anaerobic marine environments, and occur in a widely dispersed form.

Pyrite oxidation releases ferrous sulphates or iron hydroxides and sulphuric acid. Where calcite ($CaCO_3$) is present it is dissolved by the sulphuric acid and goes into solution. When the solution becomes oversaturated, gypsum (calcium sulphate) crystallizes both on the surface of particles and more critically within clay-rich laminations in the aggregate particles. As the crystals grow and the solution infiltrates between the natural laminations in the rock, this latter process prises the laminations apart. The resulting change in volume introduces vertical stresses that cause heaving and cracking in the concrete slabs. Estimates of pressures induced by gypsum crystal growth in these situations varies widely, and values ranging from 60 kPa to as high as 1,000 kPa have been quoted in the literature (Bryant 2003). Swelling has been detected to be still active after 40 years (Ballivy et al. 2002) based on monitoring of affected houses in Quebec.

2.2 Typical Testing Protocols

In the context of pyrite-induced heave, there are two main aspects of the problem that require appropriate testing. One relates to assessment of aggregates prior to use and the other to establishing whether or not underfloor fill has caused, or has the potential to cause, heave. The former testing application is an easier one to address since a highly conservative approach can be adopted. One such approach is that developed in Quebec (BNQ 2003) based on a determination of a Swelling Potential Petrographic Index (SPPI).This rates aggregates on a scale from 0 to 100 based largely on the clay content and only aggregates with SPPI values less than 10 are recommended for use under floors. The SPPI approach is not universally applicable as it was based specifically on the experience and rock lithologies in Quebec and it does not represent a sole basis to determine whether an aggregate *in situ* is fit for purpose or whether it must be removed. Further, the SPPI excludes the very fine fraction from evaluation. A reliable approach is needed since it can take up to 10 years for heave to occur and the cost implications to remove compacted fill beneath a building in use are significant.

The most practical approach is to recognise that aggregate susceptibility to pyrite-induced heave is a function of aggregate quality, the form and prevalence of the pyrite present and presence of calcite. These factors can be explored by way of a testing suite comprising water absorption, Micro-Deval, Magnesium Sulphate Soundness, Total Sulphur, Acid Soluble Sulphate and petrographic examination. However, the outcome requires interpretation based on prior experience and represents no more than a risk assessment.

2.3 Need for a Laboratory Swell Test

Despite numerous recorded occurrences around the world of widespread structural damage as a result of pyrite-induced heave, the problem is still not fully understood and continues to occur as evidenced by the damage being dealt with in Ireland. While the main factors that give rise to the problem are generally known, the secondary factors, such as the influence of bacteria, climate, *in situ* density, and aggregate gradation, have not been quantified. Despite extensive use of petrography and scanning electron microscopy (SEM) to examine the phenomenon of gypsum growth at the microscopic level, even basic aspects such as the relationship of the rate of pyrite oxidation to the extent of induced heave, have not been determined. The absence of a reliable and representative laboratory-scale swell test to allow the heave process to be studied with various variables isolated, has hampered the development of quantitative answers to this problem. A further challenge in dealing with the pyrite heave problem is the difficulty of predicting the future rates of pyrite oxidation. Depending on the form of pyrite and other factors, the time for the onset of physical building damage can vary from 2 to 10 years. This issue can only be solved with the assistance of the controlled simulation achieved with a laboratory swell test.

3 DEVELOPMENT OF LABORATORY SWELL TEST

3.1 Criteria

The need to have a reliable laboratory swell test was recognized in Quebec and development work began at Sherbrooke University in about 1995 (Ballivy and Bellaloui 1997). The results of trials using a small scale laboratory swell test were presented in detail at the 2002 AEG Seminar in Laval (Bérubé et al. 2002). The devised test was considered for use in Ireland but was found inappropriate for a number of reasons. Firstly it is performed in a 150 mm diameter CBR mould and thus the sample particle size is limited to a maximum size of about 20 mm. The crushed rock fills being investigated in our work were up to 63 mm in size and it was suspected that the mechanism of heave would not be uniform within different particle size ranges. In addition the Sherbrooke University protocol requires the introduction of bacteria (*thiobacillus ferrooxidans*) into the specimen and it was not known how relevant this was to the swelling problems in Ireland. A further concern related to the problems reported with respect to differentiating the component of the overall measured heave attributed to hydration of the sample versus that attributed to gypsum growth. It was believed that a larger sample size would allow a better differentiation of these contributions to volume change. For these reasons, a larger scale swell test was deemed essential.

3.2 Initial Experimental Set-Up

The initial experiment with a large scale laboratory swell test began in December 2007. The test was performed in a 1.2 m internal diameter concrete manhole ring with a compacted sample height of 1.02 m. The concrete pipe section (1.2 m high) was placed vertically within a heavy duty steel trough and the aggregate, with a maximum particle size of 75 mm, was compacted within the cylinder. There was no base installed in the pipe as it was assumed that the mass of the concrete pipe and fill would be adequate to force the heave to occur at the top of the fill. This assumption proved wrong. Within seven weeks of commencement of the test it was noted that the entire test cylinder had tilted slightly on the base, due to the expansion of the fill in combination with the friction acting on the inside of the concrete pipe. After 17 weeks, a vertical hairline crack developed in the side of the concrete pipe. After 50 weeks, the vertical crack had opened to 12 mm. Using analytical and numerical techniques, the pressure produced inside the pipe at rupture was back-calculated and established to be about 600 kPa. Based on this initial experience, it was decided to use a smaller pipe section with a rigid base attached.

3.3 Improved Experimental Set-Up

In light of the outcomes of the initial laboratory swell test trial, an improved experimental arrangement was devised. The main differences were (a) use of a smaller sample size, (b) a rigid base in the pipe to force all the expansion in one direction only, and (c) inclusion of a control sample for comparison. The modified swell tests commenced in July 2009 and involved a calcareous mudstone with a maximum aggregate size of 63 mm. A sample size 300 mm high by 600 mm in diameter was considered appropriate to allow the full unprocessed sample to be used and to allow the development of sufficient magnitudes of heave within a reasonable time frame.

A cylindrical segment of non-reinforced concrete pipe 500 mm long and with a 60 mm wall thickness, was used as the test container. A fixed, rigid steel plate was installed in the base of the cylinder. The cylinder was placed in a HDPE trough, approximately 970 mm by 870 mm in area and 250 mm high. This was to allow the lower portions of the sample to be fully immersed in water. Given the relatively high water table in the Dublin area (sometimes within 1.5 m of the ground surface) and the fluctuating levels year round, it was decided that the water in the trough would be removed and replaced on a two-week cycle. Alternating wetting and drying was also likely to accelerate the pyrite oxidation. In typical residential construction 500 mm of underfloor fill is common and even thicknesses of over 1.0 m have been observed. Thus, the occasional saturation of the lower portion of underfloor fills *in situ* is not uncommon. The test set-up is shown in Figure 1.

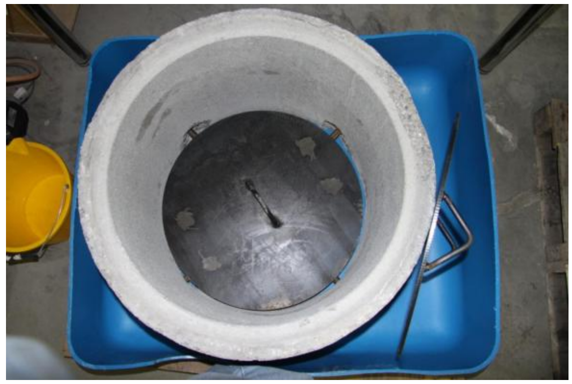

Figure 1. Concrete test cylinder prior to installation of sample

4 TEST MATERIALS AND PROCEDURES

4.1 Materials

Five swell tests were undertaken: four using a problematic calcareous mudstone that was removed from a 5-year old institutional building during remedial works and one containing a high quality crushed limestone that was used as a control.

The mineral composition of the calcareous mudstone was determined by X-ray diffraction and interpreted using the Rietveld technique. The typical mineral composition is summarized in Table 1. Based on extensive bulk chemistry testing on recovered samples, the pyrite content of the mudstone was estimated to average 2.7% and to range from 1.1% to 3.9%.

Table 1. Mineral composition of calcareous mudstone.

Quartz	Calcite	Clay Minerals	Dolomite	Gypsum	Pyrite
33%	32%	25%	5%	3%*	2%

*This is secondary gypsum as it is not present in the source quarry

The recovered aggregate samples were geologically examined and were found to be elongated and platy. Two lithologies were identified – a calcareous mudstone/siltstone and a medium to fine grained limestone. The calcareous mudstone/siltstone made up approximately 95% of the sample with the remaining 5% consisting of the limestone. Secondary mineralisation had occurred on the outer surfaces of some particles. This was identified as gypsum and calcite crystals (subsequently confirmed by SEM analysis). Some particles showed extensive partings along lamination boundaries. Gypsum was also seen to have formed within the laminations (Figure 2).

Figure 2. Visible gypsum crystal clusters on faces of freshly opened lamination

An extensive program of physical testing was undertaken on the aggregate for characterization purposes. Figure 3 presents particle size distribution curves for the test materials. The 'All in' material was well graded with 31% and 8%, respectively, passing the 5 mm and 63 µm sieves. In addition, a wide range of physical testing was undertaken using both European and North American standards. These results are summarized in Table 2.

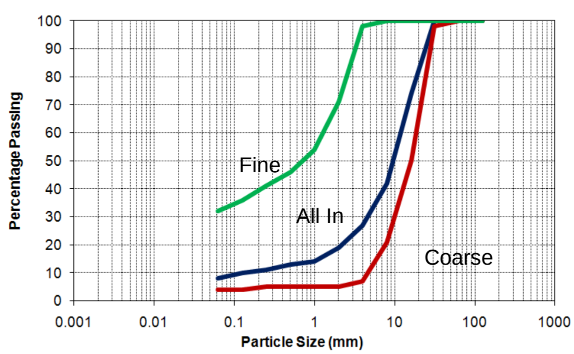

Figure 3. Particle size grading curves for test samples

The results summarized in Table 2 reflect a poor quality construction aggregate. The Micro-Deval testing confirmed breakdown of more than 40% of the material during the test. Similarly, the Magnesium Sulphate Soundness testing registered breakdown of approximately half of the material during the test. While the fines were determined to be non plastic, the liquid limits were high, over 30%. In Ireland, road base aggregates must have liquid limit values less than 21% to avoid the inclusion of problematic fines. The coarse aggregate absorption values were well above the 2% maximum typically required for construction aggregates. The Petrographic Number was determined to be about 300, also well above the allowable limits for even use as aggregate subbase.

Table 2. Summary of physical test results.

Test	Standard	Range	Average
Coarse Aggregate Absorption (%)	BS 812:Part 2 1995	2.6-3.9	3.1
Plastic Limit	BS 1377-2:1990		Non-plastic
Liquid Limit (%)	BS 1377-2: 1990	30-37	34
Ten Percent Fines Value (kN)	BS 812-111:1990	47-50	49
Micro-Deval – Coarse (%)	ASTM D6928	40-64	52
Micro-Deval – Coarse (%)	BS EN 1097-1:1996	41-59	47
Micro-Deval – Fine (%)	ASTM D7428	58-60	59
Magnesium Sulphate Soundness – Coarse (%)	ASTM C88	44-54	49
Magnesium Sulphate Soundness – Coarse (%)	BS EN 1367-2:1997	38-67	54
Sand Equivalent	ASTM D2419	24-25	24
Methylene Blue (g/kg)	BS EN 933-9:1999	1.4-2.5	1.8
Flakiness Index (%)	BS EN 933-3:1997	23-35	32
Petrographic Number	CSA A23.2-15A	280-320	300
Grainsize – passing 5 mm (%)	BS EN 933-1:1997	N/A	31
Grainsize – passing 63 µm (%)	BS EN 933-1:1997	N/A	8

4.2 Test Set-up

The materials used in the five swell tests are summarized in Table 3.

Table 3. Summary of swell test materials.

Test Number	Sample Description
BY-B	High quality crushed limestone granular road base (50 mm max. particle size) - Control Sample
BY-C	Recovered fill (63 mm max. particle size)
BY-D	Fine component of recovered fill (5 mm max. particle size)
BY-E	Coarse component of recovered fill (5 to 63 mm size range)
BY-F	Recovered fill (63 mm max. particle size). Duplicate of BY-C.

The grading curves for the material used in Tests BY-D (Fine) and BY-E (Coarse) are shown along with the original as-sampled fill material (All-In) in Figure 3. The fill was compacted into each test cylinder in three equal lifts to achieve a final sample thickness of 300 mm using a pneumatic drill with plate tamper attachment. The surface was levelled and a heavy steel top plate installed. Two sets of measuring gauges were used to monitor any movement of the top plate. Initially two Avongard© corner tell-tale gauges were installed between the inside wall of the concrete pipe and the steel top plate. As these gauges can only be read to an accuracy of about 0.5 mm, they were used as back-up to the more accurate dial gauges. Three dial gauges, reading to an accuracy of 0.005 mm, were rigidly mounted on the concrete test cylinder wall with the point resting on the top plate. Table 4 summarizes the condition of the test materials at the start of the test. A photograph of the gauges in place at the start of test is shown in Figure 4.

Table 4. Condition of material at start of test

Test	Total Sulphur (%)	Equivalent Pyrite Content at Start of test (%)	Water Content (%)	Bulk Density (Mg/m^3)
BY-B	0.03	0.04	3.4	2.005
BY-C	Not determined		6.9	1.945
BY-D	1.6	1.62	8.3	1.332
BY-E	1.5	2.24	3.4	1.825
BY-F	1.3	1.91	6.4	1.832

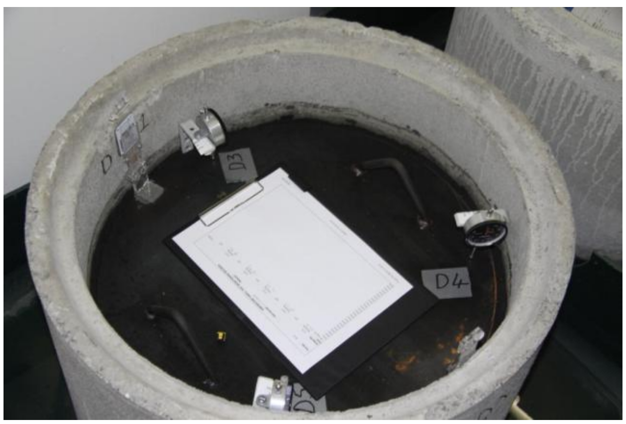

Figure 4. Monitoring gauges in place at start of test

The moisture density relationship for the mudstone was determined in accordance with BS 1377: Part 4:1990: 3.7 and a maximum dry density of 2.18 Mg/m^3 was obtained at an optimum water content of 9.0%.

The three dial gauges were not installed until two weeks after the start of the test to allow sufficient time for hydration affects to take place.

4.3 Results

To date the tests have been running for over 100 weeks (23 months) with dial gauge readings taken on a weekly basis. Ambient temperatures have also been recorded and indicated typical temperatures between 18 and 24°C. The base of the sample was subjected to alternating wetting and drying as described in Section 3.3.

The plots for the measured dial gauge movement for Test BY-C are shown in Figure 5. The results show some minor tilting of the top plate and suggest some non-uniformity in heave over the area of the sample. The plot also confirms some changes in rate of heave between the three gauges. It is not surprising that the heave is non-uniform and this explains the extensive cracking patterns observed in ground-supported floor slabs due to pyrite-induced heave.

The results of the monitoring of the upward movement of the top plate in all five tests are shown in Figure 6. The line plotted for each test is the average movement for the three dial gauges on that test.

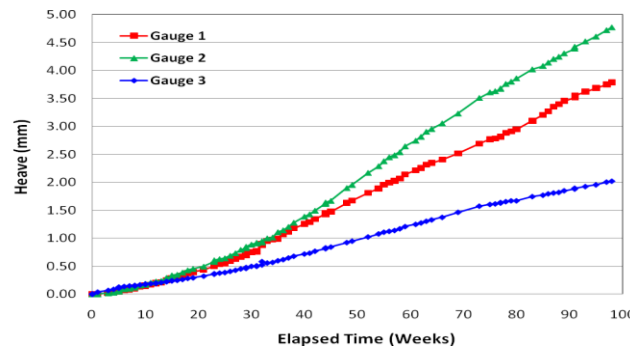

Figure 5. Heave plots for Test BY-C

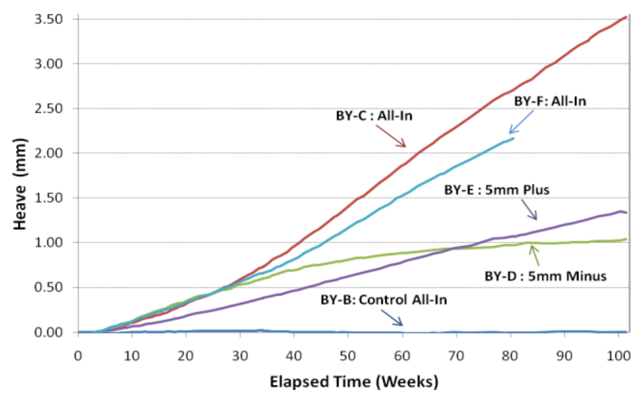

Figure 6. Average heave for all five tests

The heave plots in Figure 6 demonstrate that the changes in average rate of heave are quite smooth. The two-week cycling of the water in the trough had no noticeable impact on the shape of the trendlines.

Table 5. Summary of total heave after 52 and 100 weeks

Test	Material	Movement in mm	
		After 52 weeks	After 100 weeks
BY-B	Control	0.00	0.00
BY-C	Mudstone All-In	1.53	3.49
BY-D	Mudstone Fines	0.83	1.03
BY-E	Mudstone Coarse	0.67	1.34
BY-F	Mudstone All-In (Duplicate)	1.27	Terminated

Table 5 summarizes the total cumulative upward movement after 52 and 100 weeks for the tests. Test BY-F was terminated after 80 weeks. No measurable movement was detected for the limestone control test sample. The two duplicate tests on the all-in mudstone material show generally similar heave results. The higher magnitude of heave in BY-C compared to BY-F may be as a result of the higher bulk density in the fill in that test. Both the fines and coarse fractions show significantly lower total heave when compared to the all-in samples. In the case of the fines (Test BY-D) the initial rate of heave was quite fast but by about Week 50 the rate of heave decreased and by Week 100 heave had almost ceased. This is consistent with the expectation that pyrite contained in fine-grained aggregate is more readily accessible and so oxidizes faster. Thus the fines component is the fast reactor in terms of the time for initial damage to occur. By contrast the coarse component (BY-E) had a slower initial rate of heave. By about Week 70 it had surpassed the heave of the fines. This is also consistent with the expectation that more time is needed for the pyrite to oxidize within the coarse fraction. In addition, the coarse fraction would have a higher voids content which would accommodate some of the gypsum that forms on exterior particle surfaces. In considering the magnitude of heave summarized in Table 5, it should be borne in mind that when the tests were initiated, the aggregate was already five years old and had already caused significant structural damage to a building prior to removal. In other words, a considerable amount of the original pyrite had already oxidized.

At Week 80 the BY-F test was discontinued and the test dismantled. Initially, a segment of the concrete pipe wall was cut out to reveal the profile of the compacted fill. A clear change in the appearance of the fill was noted in the form of a higher fines content and visible reduction in the middle sized particles, as shown in Figure 7. Gypsum was observed on freshly opened laminations of the coarser particles. Much of the samples comprised wet fine material, which crumbled easily between the fingers and left a sticky black clayey residue. Some minor amounts of coarser more competent calcite-rich particles were present.

Samples of the aggregate material were removed for physical and chemical testing. Three pairs of small samples were taken from the top, middle and bottom of the aggregate for chemical testing. Then two bulk samples were taken, one from the top 150 mm and one from the lower 150 mm for physical testing. The results of the chemical testing are summarized in Table 6.

Figure 7. Exposed condition of aggregate after removal of section of test cylinder

Table 6. Results of chemical tests after 80 Weeks for BY-F

	Total Sulphur (%)	Sulphur present as Sulphate (SO_4)	Equivalent Pyrite Present (%)	% of Pyrite Already Oxidized
Start of Test	1.30	0.84	1.91	22
After 80 Weeks - Top	1.25	0.96	1.74	26
After 80 Weeks - Middle	1.55	1.45	1.99	31
After 80 Weeks - Bottom	1.40	2.05	1.34	49

Note: Results are the average of two determinations

From Table 6 there is a clear trend that the inferred degree of oxidation of the mudstone increased significantly during the 80 weeks test duration. Furthermore, there is a trend of increasing oxidation with depth within the sample. At the bottom of the sample, the area exposed to repeated wetting and drying, close to 50% of the pyrite was oxidized at the end of the test. Knowing that 22% of the pyrite was already oxidized at the start of the test, the pyrite oxidized during the test is 49-22 = 27%. In other words, the oxidation achieved under the accelerated laboratory condition in 1.5 years is similar to, or slightly higher, than that achieved under site conditions in 5 years.

The results of limited physical testing on the two bulk samples recovered from the test after 80 weeks are summarized in Table 7. They are compared to the average test results for the testing on the material at the start of the test given in Table 2. The grading curves for the two recovered bulk samples are shown in Figure 8 along with the grading curve for the material at the start of the test.

Table 7. Summary of physical test results after 80 weeks

Test	Standard	At Start (Average)	After 80 Weeks - Top	After 80 Weeks - Bottom
Coarse Aggregate Absorption (%)	BS 812:Part 2 1995	3.1	3.3	3.0
Liquid Limit (%)	BS 1377-2: 1990	34	35	33
Micro-Deval – Coarse (%)	BS EN 1097-1:1996	47	54	46
Grainsize – passing 5 mm (%)	BS EN 933-1:1997	31	56	50
Grainsize – passing 63 µm (%)	BS EN 933-1:1997	8	17	15

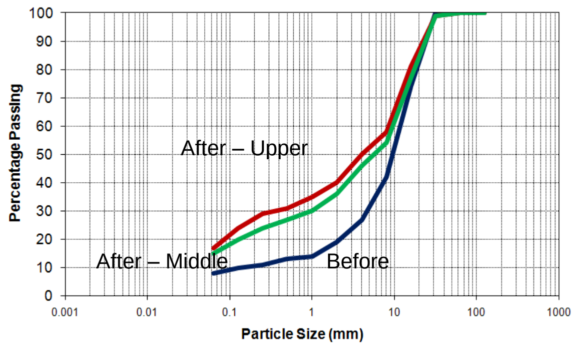

Figure 8. Comparison of All-in grading curves before and after swell test

Given the limited amount of testing it is difficult to confirm any definitive trends. However, there appears to be a dramatic increase in the liquid limit for the lower sample which would be consistent with the degradation of the clay components in the mudstone. The grading analyses also suggest some differences before and after with a significant increase in the particles finer than about 10 mm. The extent of the change in grading was similar for both the upper and lower samples despite the variation in the extent of pyrite oxidation with depth.

5 DISCUSSION OF TEST RESULTS

5.1 Characteristics of Heave

Monitoring of the behaviour of a compacted calcareous mudstone aggregate in a rigid concrete container over a 100 week period confirms that progressive heave occurs. The magnitude of the heave is significant considering that the aggregate was already 5 years old when the test commenced and the test sample was only 300 mm thick. For the well graded or All-in sample BY-C the measured vertical heave was 3.5 mm over 100 weeks, equivalent to 1.8 mm per year. After almost two years of monitoring the rate of heave was showing no signs of slowing down. The rates of actual pyrite-induced floor heave in buildings in Canada is extremely variable as reported by Ballivy et al. (2002). Monitoring of floor heave rates in affected buildings in Ireland where the subject material was used have suggested heave rates of 3 to 6 mm per year for 4 to 6 year old buildings. As noted, in practice aggregate fill thicknesses of greater than 500 mm are not uncommon and this may account for the higher heave rates observed when compared to the laboratory swell test findings.

The widespread presence of gypsum crystal growth within laminations and on particle surfaces provided visible evidence within the aggregate of heave. The natural laminations within the mudstone, in combination with the high absorptive properties of the rock fabric, readily allow ingress of sulphate saturated solution into the aggregate particles and the precipitation of gypsum. As the gypsum grows, these laminations are prised open and results in an overall degradation of the aggregate. We believe this chemical weathering process explains the generation of additional fines within the aggregate as the oxidation proceeds.

From an investigation of a large number of affected buildings where calcareous mudstone containing over 2% pyrite has been used as under slab fill, it has been confirmed that structural damage has initiated within 2 to 5 years of construction and that this condition only requires oxidation of 10 to 25% of the pyrite present. The magnitude of heave at even low levels of oxidation is not explained simply by the volume increase that occurs with the conversion of pyrite to calcium sulphate. An examination of freshly opened laminations, confirms that only a small proportion of the fracture face is occupied by gypsum, typically less than 10% of the area. Thus as the gypsum crystals grow and open the lamination further, extensive additional void space is created within the aggregate particles giving rise to significant bulk volume increase in the compacted fill.

The current laboratory swell tests confirm that accelerated rates of oxidation can be induced by the repeated wetting and drying of the compacted aggregate. In this process which accompanies degradation of the aggregate, it is possible that some of the gypsum is re-dissolved and removed thus mitigating the full extent of heave that could occur in more benign conditions.

The difference in heave response for the fines and coarse fractions of the mudstone aggregate is consistent with what would be expected, i.e. the finer fraction oxidizes more readily. While both the fine and the coarse components contribute to the heave, they do so at different rates. Thus any laboratory swell testing that does not include all particle size ranges present *in situ*, could yield misleading results. Further confirmation of the aggressive nature of fines containing pyrite is provided in a case study by Carr et al. (2006). He describes a school in upstate New York that sustained structural damage within four years of construction as a result of the use of finely crushed granite containing pyrite.

From a heave susceptibility perspective, a well graded aggregate that is well compacted will maximize the magnitude and duration of heave in a susceptible aggregate.

5.2 Evaluation of the Laboratory Swell Test

These results confirm the value of this swell test set-up in investigating the characteristics of aggregates suspected of having the potential to cause heave. While these tests were run for close to two years, consistent heave trends were established within 6 months. An accelerated response could probably be achieved if the test was conducted at temperatures above 30°C. The sample size, 300 mm high by 600 mm in diameter, is considered appropriate for the testing of material with particle sizes up to about 75 mm. The absence of any movement in the crushed limestone control sample readily provides a basis for assessment of problematic aggregates.

The system of heave measurement worked well and dial gauge accuracy of 0.005 mm is necessary to confirm trends early. The tests conducted registered in the order of 0.02 mm of movement per week. The use of concrete instead of steel test containers facilitated the dismantling of the test as well as examination and sampling of the test material on completion of the test.

The test arrangement described in this paper is ideally suited to further investigate the factors that influence the occurrence of heave in pyritic aggregates. For example, other factors that need to be further explored include temperature, sample thickness, access to moisture, presence of bacteria and grading characteristics. It would also be possible to embed stress cells within the fill and provide a fixed top plate to permit a study of the rate and magnitude of heave pressures generated in confined spaces.

Given the huge costs involved in replacing underfloor fill in existing buildings, *in situ* treatments need to be developed and the proof of such concepts would also benefit from laboratory simulation.

6 CONCLUSIONS

This paper describes a series of laboratory swell tests to investigate the development of pyrite-induced heave in compacted calcareous mudstone aggregate. The material tested had been removed during remedial works to a five-year old building where the aggregate had caused significant structural damage. The main conclusions from this test program are as follows:

- Pyrite-induced heave in compacted aggregates can be induced in laboratory conditions.
- Test specimens 300 mm high by 600 mm in diameter are considered appropriate to test aggregates with particle sizes up to 75 mm.
- Aggregates that are well graded have higher rates of heave and achieve a greater magnitude of heave when compared to either fines or coarse components of the same rock material.
- Measured rates of heave were in the order of 1.8 mm per year for 300 mm of compacted crushed rock fill, equivalent to a heave rate of 0.6%/year.
- A significant increase in the level of pyrite oxidation during the course of the test was confirmed, with higher rates of oxidation being associated with greater access to moisture.
- There appears to be a link between progressive heave, increased oxidation and degradation of the aggregate particles. This was noted in the form of an increase in fines as well as in liquid limit following the test.
- The laboratory swell test approach as described in this paper should facilitate the development of more reliable predictive methods for the susceptibility to heave of aggregates made from fine grained sedimentary rocks containing pyrite.

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