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Expansion of Pyritic Shales

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Please note

Weathering of rock formations containing pyrite--an oxidation process--results in a volume increase associated only recently with basement floor heave in Canada. It is now known that pyrite weathering was identified as early as 1950 as a major foundation problem in the U.S.A. in buildings dating back to 1920. For example, structural damage amounting to millions of dollars is reported to have occurred in the industrial-metropolitan region of Pittsburgh.

Weathering of pyrite is particularly destructive because of the attendant volume and stress increases that occur with oxidation and the chemical reactions that follow between the oxidation products and other components of pyrite bearing strata.

Pyrite oxidation reactions also produce sulphuric acid, reportedly a major pollutant of fresh water streams receiving drainage water from shale beds disturbed by coal mining operations. Pyrite weathering, however, can also be beneficial, as in the recovery of metals such as copper and uranium by the "dump" or "heap" leaching process. Indeed, much of the available information on pyrite weathering has been derived from studies initiated to improve metal recovery from low grade sulphide ores.

Pyrite Occurrence

Pyrite is the most common iron disulphide mineral in rock. It has been reported in rocks of all types and geologic ages, but is found most often in metamorphic and sedimentary rocks where it occurs as either a primary mineral or a fine, widespread impregnation of subsequent origin. Pyrite is frequently found in association with coal and shale deposits.

The minimum amount of pyrite that will cause heaving problems is not known with certainty. Some reports describe difficulties with contents as low as 0.1 per cent by weight. In the Ottawa area heaving problems have been encountered only in rock formations with much higher pyrite contents, although a systematic sampling program has not been carried out. At one location the fissures below part of a basement contained extensive lenses of pyrite several millimeters in thickness, with finely disseminated pyrite throughout the deposit.

Volume Increase and Floor Heave

Damage to structures from volume changes that accompany pyrite weathering is usually confined to slab-on-grade basement floors. Normally, heaving is not uniform and differentials of up to 12 inches have been reported, although in Canada the maximum measured differential floor heave is about 5 inches. These differentials are particularly destructive to partition walls, fittings and doors, and special precautions must be taken with partitions to avoid transmitting displacements to the floor above the basement. Equipment sensitive to misalignment has to be relevelled as illustrated in Figure 1.

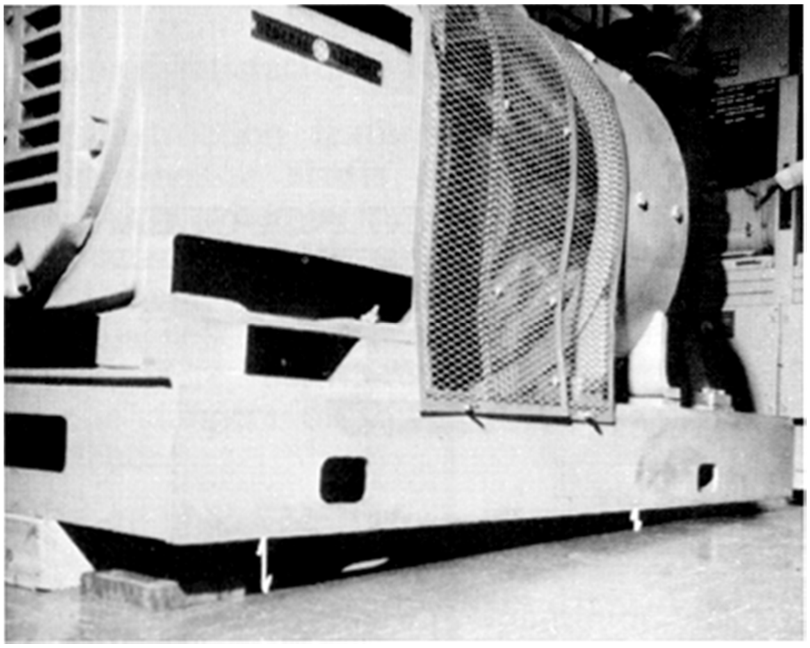

Figure 1. Levelling of generators necessitated by floor heave.

The weathering process starts at the surface of the shale and proceeds into the shale mass, causing almost complete disintegration of the affected zone. Vertical surfaces of shale exposed in trenches, disturbance by blasting, or fault zones that allow air penetration horizontally tend to enhance the rate of weathering and lead to very severe conditions. Fills of pyritic materials are particularly subject to accelerated weathering and heaving.

Alteration has been noted to a depth of 3 feet in originally sound pyritic shale over a 10-year period in Ottawa: and there are reports in the literature of weathering to a depth of 10 feet during the lifetime of a building. Heaving is not usually immediate, or not sufficiently severe to cause problems until six months to two years after construction. Older buildings may also be affected, but the heaving may go unnoticed because it is confined to the basement area, often the least used portion of the building.

Pyrite Weathering and Volume Increase

The weathering of pyrite is a chemical-micro-biological oxidation process; some of the oxidation reactions are believed to be solely chemical, others are attributed to autotrophic bacteria of the Ferrobacillus-Thiobacillus group (Figure 2), and still others are both chemical and micro-biological.

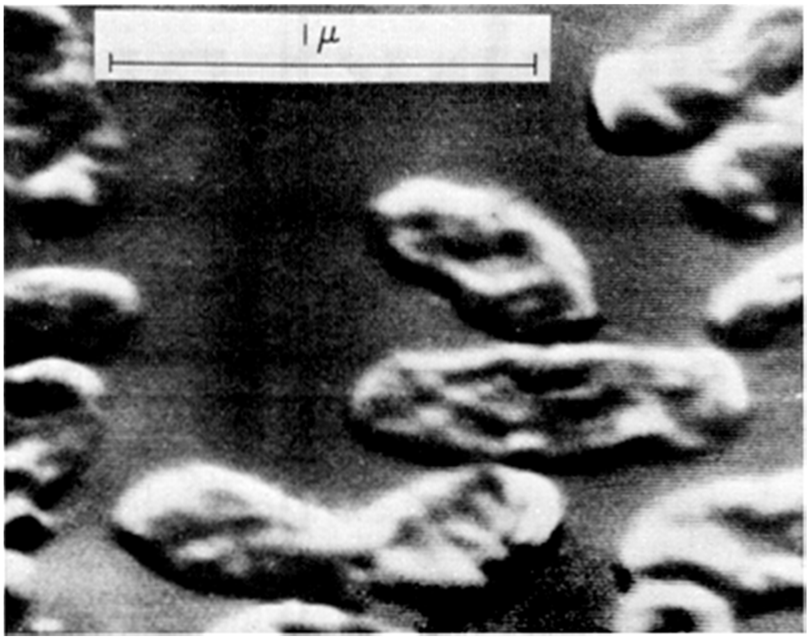

Figure 2. Bacteria of the Ferrobacillus-Thiobacillus group isolated from weathered shale under heaved floor.

The first reaction is the oxidation of iron sulphide to sulphate and is thought to be *assisted* by bacterial action.

$2FeS_2 + 2H_2O + 7O_2 \rightarrow 2FeSO_4 + 2H_2SO_4$ (1)

pyrite (iron sulphide) ferrous sulphate

Reaction (2) *cannot* proceed chemically in an acid environment and has been shown to be completely attributable to bacterial oxidation.

$4FeS_4 + O_2 + 2H_2SO_4 \rightarrow 2Fe_2(SO_4)_3 + 2H_2O$ (2)

ferrous sulphate ferric sulphate

In reaction (3) the ferric sulphate formed in (2) reacts with unreacted pyrite in the system, in the process reducing the ferric iron.

$7Fe_2(SO_4)_3 + FeS_2 + 8H_2O \rightarrow 15FeSO_4 + 8H_2SO_4$ (3)

All the iron is now in the ferrous state, which is again oxidized by bacteria. It is clear, therefore, once oxidation has been initiated it quickly accelerates because it is, in a sense, self perpetuating. The bacteria involved require an acid medium between pH 2 and 4.5 and go into dormancy outside this range. Pyrite bearing material always becomes acid, so that this is one way of identifying weathering of this type unless the material was originally highly calcareous.

Pyritic rocks that have caused heave problems usually contain calcite either as an integral part of the rock, as in calcareous shales and limestones, or as fracture fillings cutting through noncalcareous shale. Bacterial oxidation of pyrite is also known to occur in massive non-layered noncalcareous rocks. The likelihood of its causing severe heaving problems under buildings in these circumstances is less because the most severe expansion seems to occur when layers of the rock are forced apart by growth of gypsum (Figure 3). When calcite is present it reacts with the sulphuric acid produced by oxidation of pyrite to form gypsum according to Equation 4.

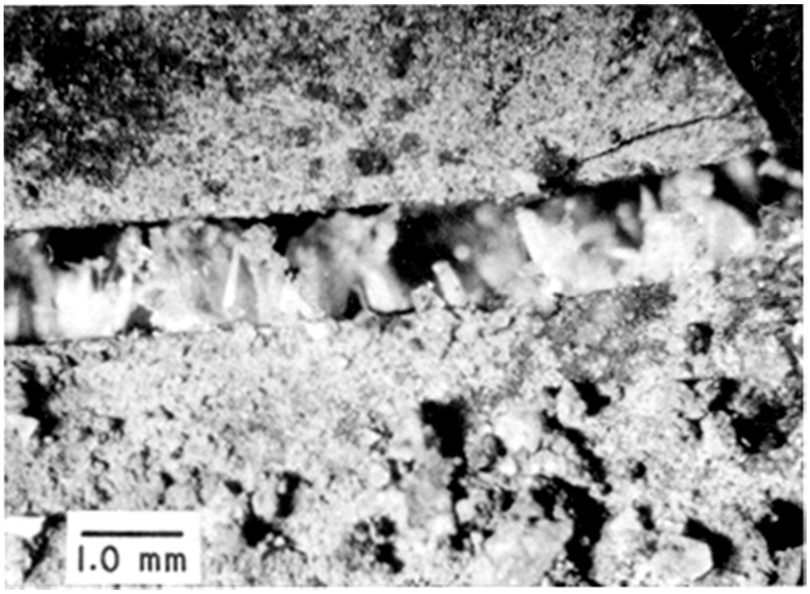

Figure 3. Growth of gypsum forces shale platelets to separate. This process is similar to ice lensing in soils.

$$H_2SO_4+CaO_3+2H_2O \rightarrow CaSO_42H_2O+H_2O+CO_2 \quad (4)$$

calcite gypsum

Heaving of columns has not been observed even in situations where the adjacent floor showed marked distortion. This may be due to two factors:

1. the footings may have been positioned lower than the floor and hence below the weathered zone, or
2. the effect of differential pressure on the solubility of gypsum may have prevented it. It is known that increased pressure causes increased solubility of gypsum. The pressure under load-bearing footings will be many times greater than that under the floor and consequently will prevent crystallization under the footings. Any heave will take place in zones of least pressure. This hypothesis seems to be borne out by observations: for example, no gypsum was found under an observed footing although it was plentiful under the adjacent floor area.

The formation of gypsum which tends to crystallize between the layers in rock (Figure 3) is thought to be an important factor in floor heave. When calcite converts to gypsum (equation 4), the volume increases by a factor of two, but of greater importance is the force associated with the growth of gypsum crystals. Under ideal circumstances this force can be extremely high. When gypsum grows in rock under buildings it tends to form needle-like crystals that force the layers apart, resulting in much greater heave than would occur with simple volume expansion during formation.

Another chemical component found in all weathered pyritic materials is jarosite, $KFe_3(SO_4)_2(OH)_6$, easily recognized by its bright yellow-brown colour. The calculated volume increase from pyrite to jarosite is 115 per cent. There is also a volume increase from pyrite, in equation 1, to ferric sulphate, in equation 2, amounting to 170 per cent, but it is believed that because jarosite and gypsum are "end" products these are the minerals to which volume increases can be assigned with confidence and are thought to be the main contributors to volume increase and heaving.

Weathering leaves the remaining material in a soft mushy condition not unlike the consistency of soil, although the original material may have been a hard competent shale. There is usually an imperceptible gradation in the severity of shale degradation, being most severe at the surface and blending into unweathered material at some distance from the surface.

Factors that Enhance Pyrite Weathering and Heaving

Documented experiences are so meagre that all the factors or combinations of factors that contribute to pyrite weathering and destructive heaving and bulging of basement floors are still not known with certainty. Some factors, however, are common to the damaged structures already investigated or are self evident from a knowledge of the pyrite oxidation process.

Autotrophic bacteria obtain their energy from the oxidation of inorganic compounds and atmospheric oxygen is consumed in the process. Proteinaceous body materials are produced from atmospheric CO_2 and nutrients such as nitrogen are usually available in pyritic shales to support bacterial growth and reproduction. Restricting the air supply should minimize both the chemical and microbiological oxidation reactions and hence reduce heaving rate. It is important therefore to consider the design features of basement floors that facilitate air entry.

Basement floor slabs of large buildings are normally underlain with a drainage layer of crushed rock or gravel and a drainage tile system. Both features allow air to enter the underlying pyritic rock if the water table is well below this zone. Fissures in the rock and fault zones of crushed material also facilitate air entry deep into rock that is drained; and vertical cuts or trenches for plumbing or other services below the main level of the excavation further permit lateral air entry. All are undesirable if pyrite is present in the rock formation and the groundwater table is some depth below the floor slab.

In considering such features, therefore, it must be remembered that groundwater levels may be lowered even after construction by the placing of deep sewers and water mains in adjacent streets. This lowering of the water table might well initiate oxidation and heaving of foundation materials containing pyrite after a building has performed satisfactorily for many years.

Construction features such as deep wells below elevator shafts are most undesirable, particularly when a number of elevator shafts are located on both sides of a passageway in the basement, because the section isolated between the wells will be particularly well drained and aerated. Here, heaving can be really excessive and the dangers of this are well known from experience.

Optimum temperatures for the autotrophic bacteria are thought to range between 30 and 35°C. Hot basements, as might exist in machine rooms located in basement areas, raise the temperature of the underlying materials and this increases bacterial multiplication and proliferation and hence increased oxidation and heave rates result. Experiences reported in the literature have shown that when a part of the basement was kept artificially colder than the remaining space this area showed much less distress from bulging and heaving.

Pyritiferous rock fill or waste from coal mines, because of its fragmental nature, weathers rapidly when in a drained condition and should never be used as fill under basement floors.

Design Recommendations for Basement Floor Slabs on Pyrite-Bearing Rock with Known History of Heaving

As the weathering process described in the foregoing paragraphs can only proceed in the presence of oxygen. efforts should be made to minimize the exposure of the rock to air. The following points are of prime importance where the groundwater table is well below the excavation level:

1. Excavate with the least possible disturbance of the shale below the grade line of the basement. Shattering of the bedrock provides easy entry of air to the shale.
2. Protect exposed surfaces of shale by a coating of concrete grout or asphalt in all areas where shale will be exposed to the air for more than 24 hours. This includes service trenches and exposed areas that will receive backfill to bring to grade.
3. Completely fill footing trenches with concrete.

4. Insulate the basement floor under spaces where temperatures are above normal. The rate of the oxidation process and bacterial activity are increased as the temperature rises.
5. Avoid placing buildings over badly shattered shale. When it cannot be avoided, give consideration to a structural floor system. Such floor systems will relieve the undesirable effects of heave, but the consequences of the acid produced by the weathering process should be considered in choosing the system.
6. Avoid the use of pyritic or other unstable material as fill under basement floors or in service trenches either from neighbouring excavations or from fill sources such as waste dumps from coal mines.

Remedial Treatment of Older Buildings

Where basement floors of existing buildings have been damaged by weathering and heaving, remedial measures may be taken by (a) the artificial raising of the groundwater table in the weathered zone, or (b) removal of the heaved floor slab and altered shale and its replacement by a structural floor leaving a crawl space between the fresh shale surface and the floor.

Option (a) is least costly, but it can only be used at sites where the natural drainage conditions will permit reasonable control of groundwater levels. Grout curtains may assist in this process and should be considered as an alternative to option (b). A system of observation wells will be required to monitor the groundwater level achieved.

Option (b) is costly and will require removal of the heaved portion of the floor slab and all the altered shale. The sound shale exposed should be protected from deterioration. Some attempts have been made to apply a dense concrete coat directly to a fresh shale surface to reduce air entry and heaving.