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FLOOR HEAVE DUE TO BIOCHEMICAL WEATHERING OF SHALE

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BY

E. PENNER, W. J. EDEN AND J. E. GILLOTT

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SOULEVEMENT DU PLANCHER CAUSE PAR LA DECOMPOSITION
BIOCHIMIQUE DE SCHISTE

SOMMAIRE

On a récemment étudié le soulèvement d'un plancher du sous-sol d'un édifice à trois étages, à Ottawa. L'édifice est construit sur du schiste noir de la période silurienne, appelé formation de Billings. L'étude de la zone de soulèvement a révélé que le schiste avait été altéré physiquement et chimiquement jusqu'à une profondeur de 0.7 à 1 mètre. Le reste du schiste n'était pas altéré, ni endommagé, mais contenait plusieurs filons de sulfure naturel de fer et sa teneur générale en sulfure pyriteux était de plus de 1.6%. On a localisé les principaux facteurs d'altération, soient du jarosite et du gypse, entre les lamelles du schiste et dans les fissures de la zone altérée. Les mesures de l'acidité, variant de pH 2.8 à 4.4, indiquent que la décomposition biochimique est causée par des bactéries autotrophiques du groupe Thiobacillus-Ferrobacillus. On a pallié au soulèvement en créant des conditions défavorables à la croissance de bactéries. A cet effet, on a neutralisé la région soulevée en inondant le schiste d'une solution basique et en maintenant artificiellement le niveau hydrostatique élevé afin de réduire l'entrée de l'air et l'accumulation de l'acide.

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ANALYZED

FLOOR HEAVE DUE TO BIOCHEMICAL WEATHERING OF SHALE

SOULEVEMENT DU PLANCHER CAUSE PAR LA DECOMPOSITION BIO-CHIMIQUE DE SCHISTE
ПОДЪЕМ ПОЛА В РЕЗУЛЬТАТЕ БИОХИМИЧЕСКОГО ВЫВЕТРИВАНИЯ СЛАНЦА

E. PENNER, W.J. EDEN and J.E. GILLOTT, National Research Council of Canada and University of Calgary (Canada)

SYNOPSIS. Heave of a basement floor in a three-storey building in Ottawa was recently investigated. The building is founded on black shale of Ordovician age known as the Billings formation. Examination in the heaved zone revealed that the shale had been altered physically and chemically to a depth of 0.7 to 1 m. Below this the unaltered shale was sound but contained numerous pyrite veins and also had a general pyritic sulfur content as high as 1.6%. The main alteration products that were responsible for the heave, jarosite and gypsum, were located between shale laminae and in fissures in the altered zone. Acidity measurements ranged from pH 2.8 to 4.4, pointing to biochemical weathering by autotrophic bacteria belonging to the *Thiobacillus-Ferrobacillus* group. Heaving was arrested by creating conditions unfavourable for bacterial growth. This involved neutralizing the heaved area by flooding the shale with a basic solution and keeping the water table high artificially to reduce air entry and acid build-up.

Heave of the basement floor of a three-storey extension to the Bell Canada Building in Ottawa, founded on shale, was recently investigated. The study was initiated when the displacement of the basement floor interfered seriously with the alignment and operation of power and switching facilities located in this area. Problems of a similar nature have been described by R.M. Quigley and R.W. Vogan (1970) and M. Spanovich and R.B. Fewell (1969). A note on the heaving problem by the authors of this paper (E. Penner et al 1970) describes some aspects of the preliminary investigation carried out at the present site.

The original building was constructed in 1929 and although a small amount of heave has occurred in the ensuing years it has not interfered with the alignment of the equipment located on the basement floor. An extension was added to this building in 1961 with all the corresponding floors located at the same elevation. Heaving of the basement floor in the extension was noticed about 4 years after the addition was completed. The affected area is about 225 m², which represents about one-sixth of the total basement space. Heaving was thought to have started sometime in 1964 or 1965; the displacement of the floor was sufficiently serious by the end of 1966 to initiate an investigation. The heaved area appeared as two rounded domes as shown by the displacement contours in Fig. 1. The influence on equipment

alignment is shown in Fig. 2. The object of the investigation was to establish the cause of heave and to initiate remedial measures for controlling the heave until the equipment could be relocated.

GEOLOGY

The Bell Canada building is founded on the Billings formation, a black pyritiferous calcareous and fissile shale (A.E. Wilson 1946). The shale formation is about 6 m thick at this location and lies conformably on interbedded limestones and shales of the Eastview formation. These deposits belong to the Ordovician system and were formed some 450 million years ago. Palaeozoic rocks of this age are cut by two major sets of faults in the Ottawa area (A.E. Wilson 1946). The Bell Canada building is situated about 2.4 km northwest of the Gloucester fault, a major dislocation which trends NW-SE.

A minor fault which appeared to have a strike in the direction of the heaved areas was observed in an excavation immediately south of the Bell building. This fault was also uncovered during the excavation of examination pits below the floor slab of the Bell Canada building. As will be referred to later, the shattered nature of the shale near the fault is thought to have contributed to the severity of the weathering and heaving problem.

FIGURE 1 LOCATION OF INSTALLATIONS AND CONTOURS OF MAXIMUM HEAVE , CM

FIG. 2 LEVELLING OF GENERATORS NECESSITATED BY FLOOR HEAVE

FLOOR CONSTRUCTION AND INTERIOR COLUMN FOOTINGS

The 30-cm-thick reinforced concrete floor slab was placed on a 15-cm layer of crushed limestone. This levelling course, which also contained an underfloor drainage tile system, had been placed directly on the shale at about 1.5 m below the original shale level. The interior column footings were 2.4 by 2.4 by 1.2 m thick and placed at about 2.7 m below the original shale level, i.e. 1.2 m below floor level.

HEAVE AND HEAVING RATES

During the observed period of heaving beginning in April 1967 - the maximum measured floor displacement was 5.6 cm over a period of about 32 months, a heave rate of approximately 0.18 cm per month. Based on the estimated floor elevation immediately after construction, the maximum total movement is 10.7 cm. A plot of the floor movement at various locations is given in Fig. 3. The location of the points is noted in Fig. 1.

INVESTIGATION

Core recovery by drilling was poor in the heaved zones so examination pits were excavated at three locations within the problem area (Fig. 1). The top 40 to 50 cm of shale were extremely soft and crumbly and could be removed with a hand shovel; below this, excavation was carried out with the aid of a jack hammer. Layering of the shale was in the horizontal plane and the thickness of the laminae ranged from millimetres at the surface to several centimetres near the bottom of the 1.8-m excavation. In general the shale was cut by near-vertical joints throughout the section.

Joint surfaces and shale laminae in the altered zone (top 0.5 to 1 m) were covered with a yellowish-brown coating and numerous colourless crystals.

FIGURE 3 BELL BLDG FLOOR MOVEMENTS

The altered zone was found to be acidic and, based on numerous measurements, the range in pH was established as 2.8 to 4.4. Below about 1 m the shale appeared to be sound. Figure 4 shows the difference in the physical appearance between the altered and unaltered shale.

FIG. 4 PHYSICAL DIFFERENCES - SHALE IN HAND DUG PIT BETWEEN ALTERED AND UNALTERED SHALE

MINERALOGY

The mineralogical investigation was directed at determining the reaction products of the altered shale. The mineralogy of the unaltered components below the weathered crust was also studied.

Shale laminae - altered zone (30 to 60 cm). - The most intense lines in the X-ray diffractograms were attributed to quartz and gypsum. Peaks attributable to 10 Å mica (illite) and kaolinite or chlorite were also fairly strong. Jarosite and pyrite were present but not in dominant amounts.

Soft material between laminae - altered zone (30 to 60 cm depth). - Gypsum and jarosite were present in dominant quantities. Illite and kaolinite or chlorite were also present as well as quartz. Further X-ray studies suggested the presence of some mixed-layer swelling clay minerals.

Unaltered shale (120 to 180 cm; no visible pyrite). - Diffractograms of these samples differed from the altered zone in that lines attributable to gypsum or jarosite were absent. Pyrite, calcite, illite and quartz were all present.

Veins of pyrite - unaltered zone (120 to 180 cm). - The material located in joints and partings that was visually identified as pyrite was verified by X-ray analysis (Fig. 5). It was uncertain, however, whether other iron sulfides were also present.

Colourless crystals - altered zone (30 to 60 cm). - The major phase in the abundant colourless crystals visually identified as gypsum was verified by X-ray analysis.

Yellowish-brown coating on shale laminae - altered zone (30 to 60 cm). - The major phase of the yellowish-brown deposit was identified as jarosite, $\text{KFe}_3(\text{SO}_4)_2(\text{OH})_6$.

CHEMISTRY

Table I gives the chemical analysis of the shale

other shales. As would be expected, the unaltered shale has essentially no sulfate sulfur as might be expected (samples Nos. 2, 3 and 4).

BIOCHEMICAL CONSIDERATIONS

The existence of extensive pyrite intrusions and a general pyritic content in the unaltered zone, the type of alteration products identified in the altered zone and the acid conditions in the altered zone suggested that autotrophic bacteria were probably involved in the weathering and heaving process. Autotrophic bacterial oxidation is a common phenomenon in many coal mines (S.I. Kuznetsov et al 1963) and is sometimes used in extracting metal economically from low grade pyritiferous ores (V.F. Harrison et al 1966). The energy for growth and proliferation of autotrophes is obtained by the oxidation of inorganic compounds in the presence of atmospheric oxygen.

TABLE I. CHEMICAL ANALYSIS, PER CENT BY WEIGHT

SAMPLE NO.	1	2	3	4	5	6	7
DESCRIP- TION	Composite Sample, Altered Zone, 0-50 cm. No visible pyrite	Composite Sample, Non-heaved area, Unaltered, 0-15 cm. No visible pyrite	Composite Sample, Non-heaved area, Unaltered, 2.7 m. No visible pyrite	Composite Sample Heaved Area, Unaltered, 1.37 m. No visible pyrite.	Composite Sample, Altered layer, 0-45 cm.	Composite Sample, Heaved Area, Unaltered, 1.8 m.	Composite Sample, Surface of Altered Zone
Sulphate Sulfur	0.46	0.0	Trace	0.01	0.64	Not Determined	Not Determined
Pyritic Sulfur	1.45	1.61	1.3	1.41	1.45	Not Determined	Not Determined
Carbonate (inorganic as CO_2)	Not Determined	Not Determined	Not Determined	Not Determined	Not Determined	6.1	2.6

Samples 1, 2, 3, 4, 6 and 7 analyzed by Division of Chemistry, National Research Council of Canada.

Sample 5 analyzed by Mines Branch, Department of Energy, Mines and Resources of Canada.

samples from both the altered and unaltered zone. These results show that some pyrite still persisted in the altered zone as shown by sample No. 1. The unaltered rock has a high content of carbonates (sample No. 6); a lower content of carbonates was found in the altered shale. In general, the shale has a high organic carbon content compared with

Proteinaceous body material is produced from atmospheric carbon dioxide and other nutrients such as nitrogen contained in the shale.

The main oxidation reactions are thought to be as follows (Harrison et al 1966, Kuznetsov et al 1963):

Reaction No. 1 is thought by some to be entirely chemical although others believe the oxidation of sulfide to be assisted by autotrophic bacteria. Reaction No. 2 is thought to be entirely due to the oxidation by bacteria of the *Ferrobacillus*-*Thiobacillus* group since this reaction does not proceed chemically in an acid environment. Oxidation of pyrite can proceed as given in reaction No. 3 by the reaction with ferric sulfate, a strong oxidizing agent produced in No. 2. One of the reaction products in No. 3 is ferrous sulfate which the autotrophes oxidize again according to No. 2. The medium becomes increasingly acidic as the oxidation reactions proceed since more acid is produced than is utilized.

As the shale is calcareous, the formation of gypsum is derived from the neutralization process between the excess sulfuric acid and calcite. Jarosite, $\text{KFe}_3(\text{SO}_4)_2(\text{OH})_6$, also a main reaction product in the altered zone, forms most readily under acid conditions as found in the altered zone. The potassium content of jarosite is thought to come from the degradation of clay minerals and/or by base exchange reactions in the highly acid environment.

FIG. 5 UNALTERED SHALE WITH PYRITE
VEINS IN JOINTS.

These reactions cause heaving because the molar volumes of the unaltered components are less than the reaction products. The volume increase from pyrite to jarosite is 115% and from calcite to gypsum 103%. It is also very apparent that the weathered products form between the shale laminae although in the rotted material gypsum and jarosite were found to exist inside the pores of the laminae.

All facets of the weathering reactions are not understood nor is the exact disposition of the mineral known before and after oxidation and how this affects volume change. The reactive components of the unaltered shale, the reaction products identified in the altered shale and the acidic condition were strong evidence, however, that the weathering process was associated with autotrophic bacterial oxidation and that it resulted in the heave observed.

Micro-organisms of the *Ferrobacillus*-*Thiobacillus* group were isolated from the altered shale materials by the Soil Research Institute, Canada Department of Agriculture and were subsequently photographed with a scanning electron microscope (Fig. 6). These bacteria were shown to have the ability to oxidize ferrous iron to the ferric form in culture solutions. It was also shown that the end product in an inorganic growth media was jarosite. These bacteria are known to require an acid environment, the optimum being around pH 2.2; above pH 4.5 dormancy is induced.

Air to aid bacterial growth is believed to have gained ready access to the shale via the empty tile drain system which had been placed in the crushed lime-stone layer below the floor. In the minor fault zone encountered in one of the examination pits, the open nature of the fractured shale further facilitated air entry and thus heaving and weathering were extremely severe.

FIG. 6 BACTERIA OF THE FERROBACILLUS-
THIOBACILLUS GROUP ISOLATED FROM
ALTERED SHALE ZONE.

The groundwater table was 4 m below floor level and the shale under the floor was relatively dry. It has been shown more recently that a relatively dry environment is preferred by these bacteria for rapid proliferation and the formation of the reaction products. The basement space was also exceptionally warm (30°C) due to the heat loss from the power equipment and this too would favour bacterial activity.

REMEDIAL TREATMENT

Modifications in the power equipment had been made to allow realignment as heaving progressed; by the summer of 1969, however, a critical stage had been reached. The choice was either to move the equipment located on the heaved area or arrest the heaving. The basis for the treatment selected was to create unfavourable conditions for the growth of the bacteria and if this could be achieved, heaving would be stopped.

The treatment technique was to neutralize with a base the acid conditions in the altered zone and to reduce air entry by saturation with water. The direct air supply to the shale was reduced by flooding the examination pits with water thereby raising the water table into the active zone. pH measurements had shown that extremely acid conditions (pH 2.8) existed in relatively localized pockets of activity. By keeping the shale saturated it was hoped that the acids in these pockets would diffuse out and be washed away.

Neutralization with sodium hydroxide was thought to be undesirable since the sodium ion might induce some swelling in the clay shales and potassium hydroxide was, therefore, considered preferable. Laboratory experiments were undertaken to ascertain if the neutralization process would induce any immediate and unforeseen dimensional changes in the shale. Duplicate samples of the shale from the altered zone, approximately 0.6 cm thick and 20 cm² in area, were immersed in three concentrations of KOH solution, (0.01, 0.1 and 1 N) under a load of 0.28 kg/cm². The solutions were changed daily during the entire period of the experiment.

The results are shown in Fig. 7. The 0.01 and 0.1N solutions induced small settlements of the order of 0.1 and 0.2%. The 1 N KOH solutions induced a swelling of nearly 6%. The decision was, therefore, to keep the treatment concentration below 0.1 N KOH although the exact nature of the dimensional changes resulting from treatment were not well understood.

X-ray diffractograms of these KOH-treated samples showed the disappearance of gypsum peaks. Separately prepared samples of gypsum and jarosite from the altered shale - the two main reaction products existing in the altered zone - gave results interpreted according to the following reactions:

These reactions suggest that if KOH were added to the altered shale some of the soluble components produced would be washed away in the flooding process. The result might be that some settlement would be induced.

NEUTRALIZATION AND FLOODING

Three 5 cm observation wells, 5 cm in diameter, were drilled in the heaved area to a depth of 2.4 m to monitor the depth to the water table as treatment proceeded (Figure 1) and to permit sampling of the groundwater for pH measurements.

Examination pit No. 1 (Fig. 1) was fitted with an automatic float to keep the pit continuously full of water. Treatment started on 21 January 1970. The potassium hydroxide solution was automatically dispensed into the pit to give a concentration less than 0.1 N based on water consumption. In early April 1970 the two other examination pits in the heaved zone were also fitted with an automatic float and brought into operation for treatment and flooding with water. The KOH solution was maintained in the same way. During the period from 21 January 1970 to 13 May 1971 over 12 tonnes of KOH were dispensed into the shale of the heaved zone. During this time the pH of the groundwater and the depth of

FIGURE 7 DIMENSIONAL CHANGE OF ALTERED SHALE AT THREE CONCENTRATIONS OF KOH

the water table was monitored. These results are given in Figs. 8 and 9 respectively. The consumption of water was about 16000 litres per day.

In June 1970, after about 3 months of treatment, an examination trench was excavated between pits Nos. 2 and 3 to measure the pH in the shale itself at various depths. The results are shown in Figs. 10a and 10b. The results were encouraging since the acid conditions in the shale had been greatly reduced and the fissures were well impregnated with KOH solution although low pH's still persisted near the surface. Observation wells Nos. 1 and 2 also showed that acid conditions persisted and treatment was continued. During September, October and November 1970 there was a great improvement in the pH in the observation wells and the decision was made to discontinue the KOH treatment but continue the water supply to keep the water table as high as possible and create wet conditions beneath the slab.

The pH has continued to increase and at present (December 1971) it ranges from pH 6.4 to 7.1.

Elevation surveys have been continued throughout the investigation. As shown in Fig. 3 for the period following the start of treatment, floor movements have been controlled satisfactorily. Some settlement has occurred in the centre of the heaved zone but this has not been sufficiently serious to interfere with the operation of the equipment in this area. The settlement is thought to be the result of washing the more soluble components out of the heaved shale as mentioned in relation to reactions 4 and 5.

Although heaving has been arrested, it is expected that in time the owners may wish to replace the heaved floor portion with a structural floor. Flooding may have to be continued to limit air entry and prevent acid conditions from being re-established.

FIGURE 8 THE pH IN THE OBSERVATION WELLS

FIGURE 9 DEPTH TO WATER TABLE AT VARIOUS LOCATIONS IN THE HEAVED ZONE

FIGURE 10a pH MEASUREMENTS OF SHALE IN INSPECTION TRENCH

FIGURE 10b
PLAN VIEW OF POSITION OF INSPECTION TRENCH, PITS NO. 2
AND 3 AND CONCRETE FOOTING (SEE FIGURE 1 FOR LOCATION OF
TRENCH)

The authors have been able to demonstrate the preference for dry conditions by the autotrophes for rapid deterioration of pyritic shale. Figure 11 shows a photograph of a shale sample of low pyrite content (0.1%) that was taken a month after it was inoculated with these bacteria. The sample was kept at 30°C in a container above, but not in contact with, water. The light areas in Fig. 11 are a yellowish-brown mineral identified as jarosite. Samples of unaltered pyritic shale have been infected in this way from several shale formations in the Ottawa region and all have been shown to support bacterial growth under the environmental conditions described.

CONCLUDING REMARKS

1. The biogenic alteration of pyrite in shale causes an expansion within the altered zone and results in heave of structures founded on it.
2. The preferred environment for the process seems to be warm, relatively dry and with a plentiful supply of air.
3. The process can be arrested by changing the environment by saturation with water. The water is believed to restrict the supply of air and to prevent pockets of high acidity from developing.
4. Laboratory experiments indicate that very small quantities of pyrite can support this process.

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FIG. 11 DEVELOPMENT OF ALTERATION ZONES CONTAINING JAROSITE ON LOW PYRITE CONTENT SHALE (0.1%) ONE MONTH AFTER INOCULATION WITH SHALE INFECTED WITH FERRO-BACILLUS-THIOBACILLUS BACTERIA.

with tests and generous advice concerning the microbiological aspects. Mr. V.F. Harrison, Mines Branch, Department of Energy, Mines and Resources, and Mr. D.S. Russell, Division of Chemistry, National Research Council of Canada, assisted with chemical analyses.

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