Black shale heaving at Ottawa, Canada[1]

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Three inches (7.6 cm) of differential heave has caused severe structural deformation of a lightly loaded building founded directly on drained black shale bedrock in Ottawa, Canada. Portions of the building founded on shale below the water table have not heaved.

The heave is attributed to oxidation of disseminated iron sulfide in the shale by autotrophic bacteria to produce secondary hydrous sulfates of greater volume. Autotrophic bacteria of the *Ferrobacillus* and *Thiobacillus ferrooxidan* types, which cause this type of oxidation in warm, drained, humid environments, were confirmed by laboratory cultures to exist in the rock waters.

The potential importance of heave and sulfate attack on future underground concrete structures in areas of Ottawa underlain by black shale is discussed.

Un soulèvement différentiel de trois pouces (7.6 cm) a causé des déformations structurales sévères à un édifice légèrement chargé et directement appuyé sur un lit de schiste argileux noir drainé. Les parties de l'édifice reposant sur le schiste argileux au-dessous de la table d'eau n'ont subi aucun soulèvement.

Le soulèvement est attribué à l'oxidation du sulfure de fer disséminé dans le schiste argileux par des bactéries autotrophiques produisant des sulfates secondaires hydratés de plus grand volume. L'existence dans les eaux de la roche sous le bâtiment de bactéries autotrophiques de types ferrobacille et thiobacille ferrooxidant, qui causent ce genre d'oxidation dans des environnements chauds, drainés et humides, a été confirmée par des cultures en laboratoire.

L'importance potentielle du soulèvement et de l'attaque au sulfate sur de futures structures souterraines en béton construites dans les régions d'Ottawa où l'on trouve les schistes argileux noirs est discutée.

Introduction

Concern has developed recently in the city of Ottawa about heaving of structures founded directly on black shale bedrock. Although historically not a problem, two interesting cases of heave have recently come to the authors' attention. In one case, in downtown Ottawa, interior, vertical, electrical conduits have been buckled and a floor slab founded on drained black shale bedrock badly cracked by 4 in. (10.2 cm) of differential heave. Only the floor slab areas have been affected, so there has been no structural damage to date. In the second more serious case in southeast Ottawa, the interior columns of a lightly loaded structure have heaved up to 3 in. (7.6 cm) over a 20-y period while the exterior, load bearing walls do not appear to have moved. As a result, there has been considerable distortion of the structure and if movements continue, the structural integrity of the building will be affected.

Considerable preliminary mineralogical work has been done on the latter structure and the purpose of this report is to describe and explain the movements on the basis of this work and make tentative suggestions regarding construction procedures required to prevent similar heaving of other structures.

The work done has consisted of carefully logging core obtained at the site in November, 1965, followed by X-ray diffraction studies on the rock. Also, water samples taken from the old boreholes in March, 1968 have been subjected to chemical and bacterial analysis.

In view of the very complex chemical alterations that appear to have caused the heaving and the rather limited scope of the field investigations to date, it is suggested that this paper be considered preliminary in nature. It is the authors' hope that further field excavation and

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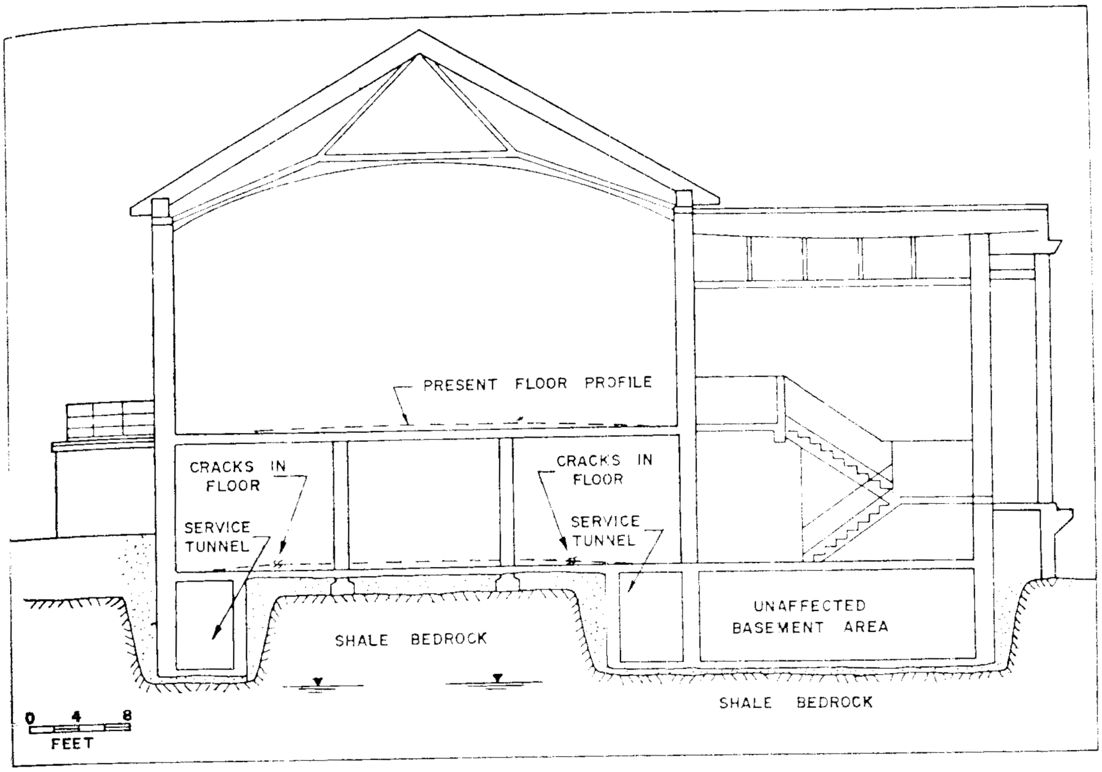

FIG. 1. Cross section showing heave of ground floor slab and uplift of second story floor.

sampling will be done below the heaved structure so that the hypotheses in this paper can be confirmed.

Site and Geology

The structure under discussion is the therapy treatment building of the Rideau Health and Occupation Centre which is located in southeast Ottawa about three miles (4.8 km) from the city center. The rock in this area is dark gray shale of the Lorraine Formation according to Canada Department of Mines and Resources map 413A (Wilson 1964). The Lorraine shales are somewhat lighter in color than the black-brown shales of the underlying Billing's Formation which extends into the center of the city. The rocks are of Ordovician age and are relatively flat lying.

Description of Structure and Movements

The structure is a small, two-story building in which there are basement areas, an area without basement and a deep swimming pool, all founded on shale bedrock. Figure 1 shows a cross-section through the building. The affected area is the two-story portion without basement founded directly on intact rock. The adjacent basement area and the deep swimming pool show no signs of heave.

A poured-concrete heating and service tunnel about 5 ft (1.5 m) wide and 7 ft (2.1 m) high was constructed in a trench dug into rock around the rectangular circumference of the building. The exterior brick walls, which show no cracking, are founded on the exterior walls of this service tunnel. The central mass of shale bedrock was not excavated and forms a horizontal plateau 6 to 7 ft (2.1 m) above the bottom of the service tunnel (Fig. 1). The interior columns of the building are founded on this rock plateau and are lightly loaded as they support only the floor weight of the second floor auditorium. The roof above the auditorium is apparently carried by an arch supported by the exterior walls. The ground floor slab consists of concrete, poured over about 18 in. (46 cm) of granular material above bedrock. This floor also forms the roof of the service tunnel.

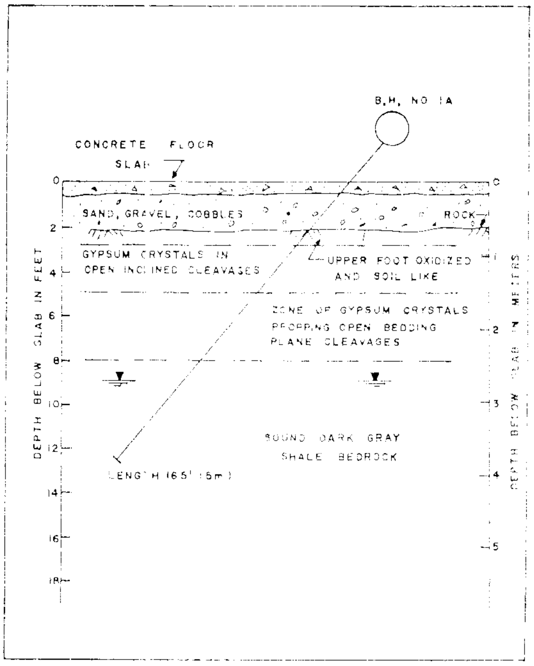

FIG. 2. Geologic section at borehole 1A, drilled into plug of shale bedrock shown in Fig. 1.

Footing drains located along the exterior walls of the service tunnel keep the water level at a depth of about 9.5 ft (2.9 m) below ground floor level as shown in Fig. 1.

During the winter the service tunnels are very hot. In February, 1968, hot air issuing from one of the old boreholes drilled through the concrete floor into the plug of rock was at an estimated temperature of 85 °F (29.4 °C). During the summer when the heat is not on, the rock is probably close to ambient rock temperature.

According to surveys carried out by the Department of Public Works Testing Laboratories between 1965 and 1969, the concrete floor slab has heaved up to 3 in. (7.6 cm) forming a long continuous crack more-or-less above the edge of the unexcavated plug of rock. The floor slopes markedly from this crack towards the exterior walls. The floor of the second story auditorium is markedly upwarped indicating that the interior columns have also heaved. Secondary cracks and distortions in the interior walls and partitions are of course very noticeable.

The rate of heave over the past 4 y is averaging about 0.1 in. (2.5 mm)/y and appears to be about constant.

Shale Bedrock

The rock is medium-to-dark gray shale which exhibits a distinct mica sheen on the bedding plane cleavages, and thus might be classified as a low grade slate. Although very prone to cleaving, the rock is not really fissile like most black shales.

Borehole 1A, drilled inside the building at a 50° angle, as part of an earlier investigation, was logged in detail. As shown in Fig. 2, the upper foot of rock contains bands of orange, oxidized silty shale and soil like material filling the bedding plane cleavages. Despite poor core recovery from 3 to 5 ft (0.9–1.5 m) depth, because of the jointed nature of the rock, soft white gypsum crystals were observed coating the inclined joint surfaces as shown in Fig. 3.

The core between 5 and 9 ft (1.5 and 2.7 m) was characterized by open, wavy, bedding plane cleavages occasionally propped apart by flat gypsum crystals about $\frac{1}{32}$ in. (0.7 mm) in thickness. Figure 4 is a photograph showing a close-up of these crystals. It is probable that more gypsum is present in the rock than shows in the core, which has been subjected to torque, grinding, and abundant wash water during the drilling operations.

Below 9 ft (2.7 m) the core was sound and no gypsum was observed. It should be noted again that the water level is also at a depth of about 9 ft.

X-ray Diffraction, Chemical and Bacterial Analyses

X-ray diffraction traces were obtained on preferred orientation specimens of the $-2\ \mu$ fraction of the gray shale, obtained by dispersion using an ultrasonic vibrator. The clay was X-rayed air dried and either wet or glycol saturated.

The clay fraction of the shale contains abundant illite or mica as evidenced by strong 10.2 Å peaks. A marked shoulder on this peak, which changes somewhat in both size and position on wetting, as shown in Fig. 5, indicates considerable interlayering with a swelling clay mineral phase. Changes in the 5.03 Å illite peak on wetting also indicate interlayering.

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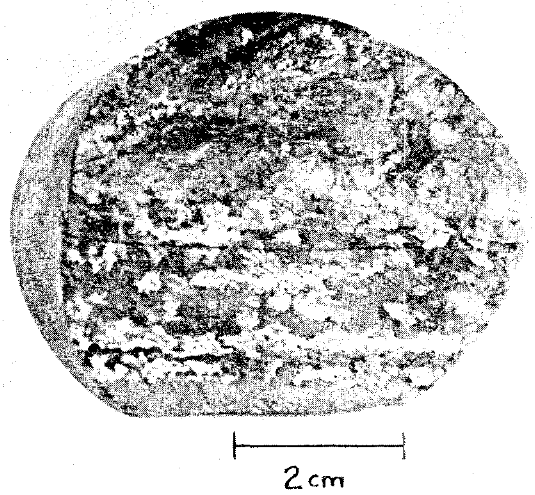

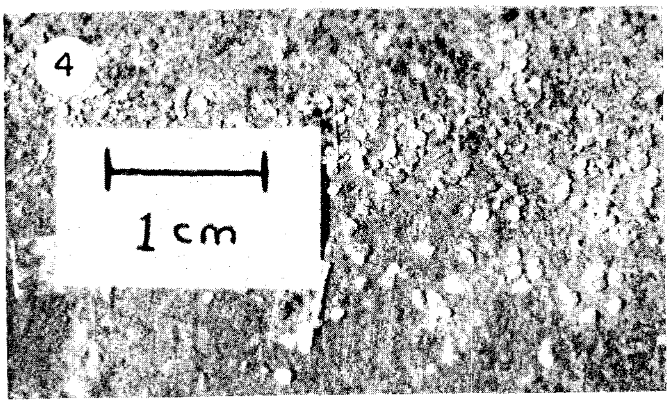

FIG. 3. Gypsum crystals coating inclined cleavage planes. 3 to 5 ft (1 to 1.5 m) depth
FIG. 4. Close up of gypsum crystals in bedding plane cleavages, 5 to 9 ft (1.5 to 2.7 m) depth.

A strong 7.2 Å peak relative to a weaker 14.7 Å peak indicates the presence of abundant iron chlorite. Moderate to minor collapse of the 14.7 Å peak relative to the 10 Å peak on potassium saturation indicates the presence of a variable amount of vermiculite.

Powder patterns run on the shale showed that quartz was also very abundant and suggested that a trace to 3 or 4% of carbonate is also present in the shale. The ochre-like silt and an orange silt from the upper foot of the bedrock gave X-ray peaks for quartz and clay minerals only. The iron oxides were apparently amorphous to X-rays. The white crystals propping open bedding plane cleavages at 7.5 (2.3 m) and 8.5 ft (2.6 m) were confirmed to be gypsum.

Two shale samples from 6 ft (1.8 m) and 10 ft (3.0 m) depth were analyzed by a commercial test laboratory for their sulfur content expressed as percent FeS_2 (pyrite). The lighter color sample from above the water table contained 0.70% FeS_2 compared to 3.92% for the unaltered, blacker, sample from just below the water table at 10 ft depth.

Water samples were taken from one of the old boreholes for chemical analyses even though it was known that the water was probably highly contaminated by fresh water used for the core drilling. About 170 p.p.m. of

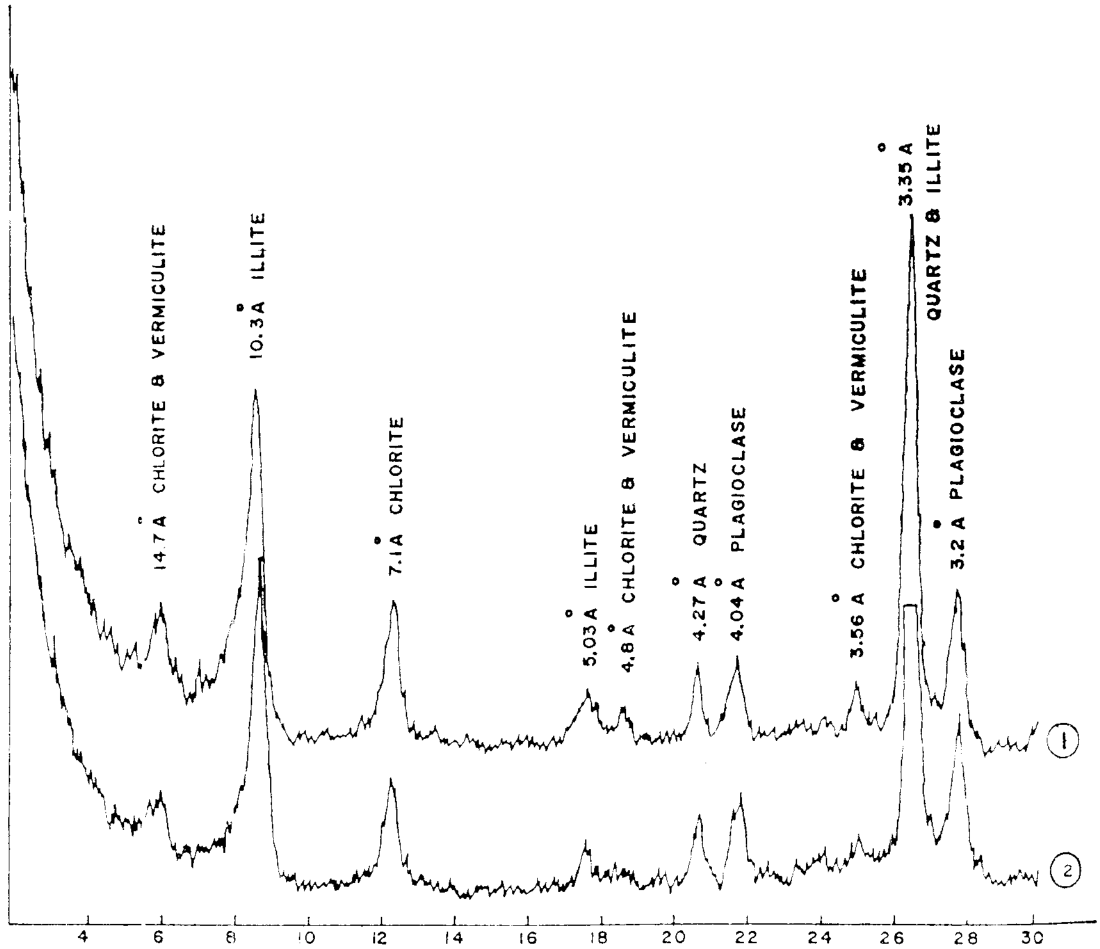

FIG. 5. X-ray diffraction traces, −2 μ fraction of Lorraine shale. 1—air dried preferred orientation, 2—glycol preferred orientation.

calcium, 12 p.p.m. of magnesium, and 340 p.p.m. of sulfate as SO_4 were present in the water. The samples were neutral, having pH values of 7.

Extracts of the water samples were incubated in a ferrous sulfate medium at pH 2.6 for two weeks on a rotary shaker. Microscopic examination showed the presence of abundant autotrophic bacteria of the *Thiobacillus ferrooxidans* and *Ferrobacillus ferrooxidans* types.

Discussion

There seem to be two possible heave mechanisms at the site: 1) hydration and expansion of swelling clay complexes observed in the X-ray studies, and 2) geochemical alteration of sulfides to produce secondary sulfates and heave resulting from pressures of crystallization.

Because the adjacent, lightly loaded basement floors founded directly on submerged shale have not heaved and because the plug of shale in question is above the water table, heave because of hydration seems very improbable. Nevertheless, a swell test was run on an air-dry piece of shale core from 9 ft (2.7 m) depth as shown in Fig. 6. Initial hydration with distilled water produced about 0.9% swelling followed by an additional 0.3% swelling as the load was reduced from 2000 to 100 lb./ft² (1.0 to 0.05 kg/cm²). Assuming a 1% heave by hydration over the rock plug

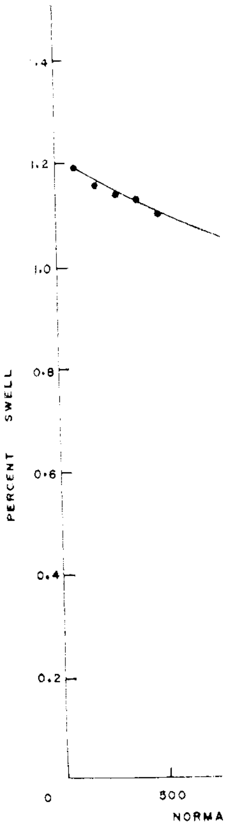

FIG. 6. Swell test
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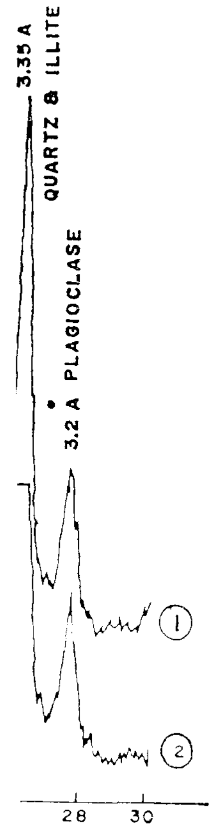

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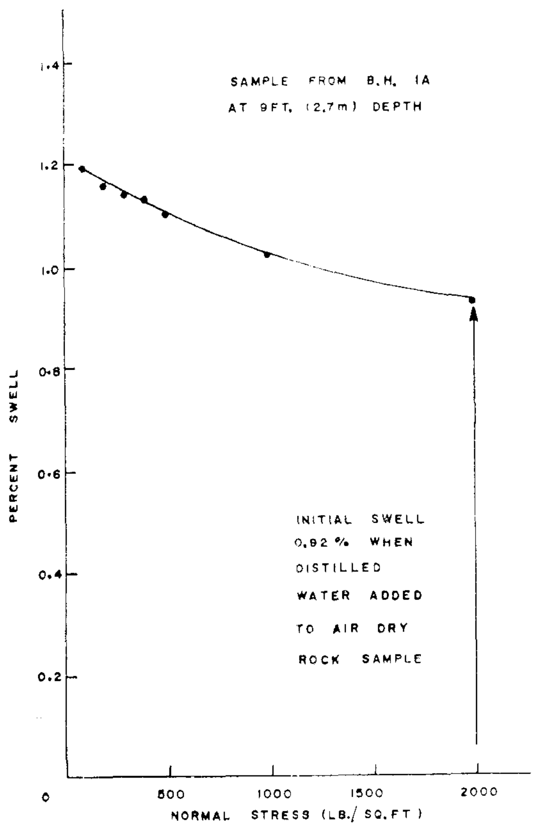

FIG. 6. Swell test on Lorraine shale from 9 ft (2.7 m) depth.

thickness of 8 ft (2.4 m) yields a calculated heave of only 1 in. (2.5 cm) compared to the 3 in. (7.6 cm) present. At the present time, it is believed that heave by clay mineral hydration is negligible. More work is proposed, however, on the effects of hot–cold cycling of the shale in a humid environment. Conceivably various types of fatigue and expansion might occur from the annual winter-heating–summer-cooling cycle.

The important heave mechanism at the site is believed to be geochemical alteration of sulfides in the rock to produce secondary sulfates having a much greater volume. Expansion of the black, bituminous shales in Oslo, Norway has been attributed to sulfide oxidation by Bastiansen *et al.* (1957). Pyrrhotite in the Oslo shales is the reactive component, oxidizing so rapidly on exposure to air that its presence was difficult to establish. In addition to the effects of its own oxidation, the pyrrhotite apparently catalyzes the oxidation of normally, non-reactive pyrite.

Severe black shale expansion problems also occur along the south shore of Lake Erie and are typified by conditions in Cleveland, Ohio. In a general editorial in the Engineering News Record (1960), heaves of up to 1 ft were described. Again, oxidation of iron sulfide to hydrous iron sulfates of much greater volume is the cause.

At the Ottawa site under discussion, the amount of secondary gypsum which props apart the bedding plane cleavages in the core is believed to correspond roughly to the amount of heave, which is about 3 in. (7.6 cm). The reasons for the growth of this secondary gypsum involve some complex chemical alterations which seem to be controlled by the environmental condition of the shale plug.

The following argument is presented as the most plausible explanation at the present time:

1) Secondary gypsum occurs only above the water table in a zone which is probably partially saturated by capillary rise. The environment is a warm, humid one, especially during the winter when the service tunnel is hot from heating operations. Such an environment is ideal for the growth of aerobic, oxidizing bacteria which were confirmed to exist from the cultures grown in the laboratory.

2) The dark shales around Ottawa normally contain pyrite (FeS_2) in thin laminae, patches, and in disseminated very fine-grained form. In fact, pyrite normally contributes, along with organic matter, to the black color of the shales. The presence of sulfur disseminated in the black shale (probably as pyrite) was confirmed by chemical analyses as mentioned.

3) Autotrophic bacteria of the *Thiobacillus* and *Ferrobacillus ferrooxidan* types, which were found in the groundwater at the site, derive their energy from oxidizing pyrite or ferrous sulfate (Zajic 1969). It is hypothesized, therefore, that these bacteria have oxidized or catalyzed the oxidation of pyrite in the shale producing sulfuric acid. This sulfuric acid has slowly dissolved calcite disseminated in the shale and in the rock cleavages, altering it to gypsum. The gypsum has migrated in solution, eventually precipitating out as the flat crystals observed in the horizontal and inclined cleavage openings. For this mechanism to cause heaving

it is necessary for the gypsum to have crystallization pressures equivalent to the weight of about 10 ft (3 m) of rock or about 1500 lb/ft^2 (0.75 kg/cm^2).

It is possible that other water soluble sulfates may be contributing to the heave at the site but were washed out by the diamond drilling operations. Such sulfates are discussed in detail by Moum and Rosenqvist (1959) for the Norwegian black shales.

At the present stage of the black shale expansion studies, it appears as though oxidizing conditions are necessary to activate heaving. If entry of oxygen can be prevented then the probability of oxidation, even by bacteria, is greatly reduced. If the ground water level at a site is high, one way of excluding oxygen is to keep the rock submerged by careful design of foundation drainage systems. In Oslo, Norway and in Cleveland, Ohio, newly excavated shale is immediately coated with either an asphaltic or cement coating to prevent entry of air and oxygen bearing water. These techniques appear to be reasonably successful.

Because there is virtually no long-term history of heave in the Ottawa area, it seems that the recent cases are related to different environmental conditions created under a few new buildings. The two significant heave problems mentioned, and several other minor ones which have not been investigated, are all located on black shale of either the Billings or Lorraine Formations. These rocks form the bedrock surface in the east and southeast areas of the city and extend into the center of the city in a very shallow syncline or basin. The environmental conditions which catalyze the heaving reactions in these shales can only be established by a continuing study of new heave problems in the city.

A potentially more widespread and serious problem than the rock heaving described above is sulfate attack on future underground concrete structures. These include sewers, heating and other service tunnels, and future transportation systems. Downward percolation of oxygen bearing groundwater will oxidize the reactive shales producing soluble sulfates which on percolation through concrete could cause rapid deterioration. Experiences with these types of problems in Oslo are described in some detail by Moum and Rosenqvist (1959). Apparently subsurface waters in some sections of Oslo are so aggressive that underground concrete structures have had to be abandoned after just a few months. Highly mineralized fault zones typical of Ottawa may prove to be quite troublesome. Accurate surface and subsurface location of these faults by taking advantage of present and future civil engineering projects might prove to be an extremely worthwhile urban geology project.

Summary

Differential heave of a structure founded on black shale within the city of Ottawa has been described in detail. Long term oxidation of iron sulfides in the shale bedrock to produce hydrous sulfates of much greater volume is believed to have caused the movements. Oxidizing bacteria have probably catalyzed the reactions which have occurred in a plug of drained rock which is kept warm by a circumferential heating tunnel.

The long term ramifications of sulfate attack on underground structures is given consideration.

Acknowledgments

Special thanks are extended to Mr. J. E. Wilkins, A/Director of Design and Construction, Capital Region, Department of Public Works and to the Department of Veterans' Affairs, for permission to publish this work. The original work was done under the auspices of H. Q. Golder and Associates Limited grant 1319-GO2 to R. M. Quigley at The University of Western Ontario. Special thanks are also extended to Dr. J. E. Zajic of Western's bioengineering laboratory for culturing and identifying the bacteria in the rock waters.

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Black shale heaving at Ottawa, Canada: Discussion

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The authors (Quigley and Vogan, this issue) have presented a very interesting case which could be indexed under keywords such as: foundation problems, weathering, sulfate attack, and bacterial leaching. This list of keywords indicates the complexity of the problem. I would like to discuss especially two factors mentioned by the authors: the effects of bacteria and of the temperature gradient in the soil.

The Effects of Bacteria on Pyrite

Bacteria are used experimentally in ore dressing to recuperate metals from very low grade sulfide ores, especially from the more stable minerals like chalcopyrite and sphalerite. In the case of unstable minerals like pyrite and pyrrhotite the bacterial action is not necessary to produce rapid oxidation: pyrite dust in a well ventilated mining drift can oxidize fast enough to catch fire. Given the right oxidation potential, which is normally obtained in soils above the water table, these two sulfides will transform into lower free energy minerals. It is probable that the bacteria accelerate the reactions, but destroying them by the use of fungicides would not stop the oxidation of iron sulfides.

The Effects of a Temperature Gradient

It is the author's opinion that the critical factor causing pyrite oxidation is the temperature gradient, especially in winter when a 30 °F to 40 °F temperature differential can be obtained. This temperature gradient is responsible for upward migration of water and dissolved oxygen which in turn cause the oxidation of the pyrite and the resulting sulfatation of the calcite.

The author would like to illustrate the importance of the temperature gradient by presenting a case which has certain points in common with the one described by Quigley and Vogan. A concrete floor slab, where exposed to radiant heat from above, was completely disintegrated after one year whereas unheated portions of the same slab, a few feet away, do not show deterioration. The coarse concrete aggregate is composed of limestone and granular dolomite, the latter containing very finely disseminated pyrite. The heated and disintegrated concrete contains a very rusty dolomite which crumbles readily when pressed between the fingers, whereas the same dolomite remains pale gray and very sound in the nearby concrete floor.

It seems that the temperature gradient is responsible for the upward movement of water and oxygen which migrate through the concrete to oxidize the pyrite. Pyrite oxidation produces sulfate ions which are then available to form ettringite. Limonite, calcite, aragonite, and portlandite are some of the minerals which were detected in the numerous fractures of the altered dolomite.

This example is somewhat similar to that of the black shales and it seems to indicate a highly accelerated rate of reaction due to a temperature differential. A laboratory experiment was performed to test this hypothesis. A core of the unaltered concrete, the sides of which were sealed with epoxy, was placed upright with its lower end in a shallow water bath. The upper end of the core was heated with an infrared lamp. After three months the cylinder was broken open and the preexisting fractures appeared coated with calcite and aragonite. This shows that highly soluble minerals like gypsum can be deposited in fractures above the water table provided a permanent capillary rise is induced by a thermal gradient.

As the authors have pointed out, there are various ways to prevent oxidation. A watertight coating, like asphalt, sprayed immediately after excavation seems to be a good solution because it would prevent the upward escape of water from the material underlying the foundation and thus prevent the capillary rise of this water across the concrete. On the other hand, a gunnite or concrete coating, if not thermally insulated, might not be efficient, especially if there is a thermal gradient which would cause a capillary rise.

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Black shale heaving at Ottawa, Canada: Discussion

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Many troublesome features of soil and rock behavior can be attributed to the development of gypsum *in situ* and Quigley and Vogan (this issue) have made a valuable contribution by their exposition of a fascinating example. Much of their explanation is entirely convincing and it is now of interest to know what measures they favor to avoid this type of problem in heated basements in the future.

In my general report to the Oslo Geotechnical Conference (Morgenstern 1968), I drew attention to the role of diagenesis of secondary gypsum in progressive failure and I would like to take this opportunity to discuss this further. The process is related directly to the example of heave just described by the authors. Pyrite (FeS_2) is a very common constituent in many stiff clays and mudstones. For example, it is found in the London Clay, the Bearpaw Shale, the Pierre Shale, and many other Cretaceous and Tertiary deposits of geotechnical significance. Its reaction with oxygen bearing water in the zone of weathering is well-known (e.g. Fairbridge 1967) and is as follows:

$$2\ FeS_2 + 2\ H_2O + 7\ O_2 \rightarrow 2\ FeSO_4 + H_2SO_4$$

Ferrous sulfate and sulfuric acid are formed. The ferrous sulfate may often combine further with water to yield limonite and more sulfuric acid. The characteristic greenish-yellow stain of limonite is common in the face of fissures toward the bottom of the weathered zone. The dehydration of limonite to hematite accounts for the more commonly found reddish stain on fissures. The reaction which generates the limonite is:

$$FeSO_4 + 2\ H_2O \rightarrow Fe(OH)_2 + H_2SO_4$$

Calcium carbonate is generally available in many materials in the form of foraminifera or dispersed lime salts. Lime combines with sulfuric acid to produce gypsum which crystallizes out. The reaction is:

$$H_2SO_4 + CaCO_3 + 2\ H_2O \rightarrow Ca \cdot SO_4 \cdot 2\ H_2O + H_2CO_3$$

The formation of gypsum in place creates a local volume increase which disrupts the clay. This leads to a mechanical weakening and enhanced swelling characteristics. Differential strains associated with non-uniform swelling increase the propensity for progressive failure.

The presence of gypsum may also be significant in explaining the heave of subgrade in road-cuts. Hepworth (1965) described in detail three sections in the Upper Cretaceous Mancos Shale where heave of the ground surface occurred at the base of cuttings. In each case gypsum was present. A plausible relationship here is that both the chemical and mechanical weathering effects which result from the formation of gypsum weaken the mudstone and increase its capacity to swell during slaking.

Another type of problem associated with gypsum occurs when anhydrite is hydrated to form gypsum. This is accompanied by a substantial increase in volume and a considerable pressure if confined. Brune (1965) has described several dramatic examples of this phenomenon. For example, a loud boom was heard one night in the town of Paint Rock, Texas and it was discovered that a rock uplift had occurred on a near-by ranch. The uplift extended for 1000 ft (304 m) along a stream channel whose bed had been raised by as much as 10 ft (3.0 m). Water had stood in the channel previously. Nearly all the cases cited by Brune occurred beneath pools of standing water. The implications for the impounding of reservoirs are obvious.

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