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ABSTRACT

The Evangelical Hospital located in Lewisburg, Pennsylvania has experienced distress in the form of cracked floor slabs and displaced structural steel due to swelling of the underlying fill material and natural bedrock formation. The bedrock consisted of black, pyritic, calcareous shale from the Marcellus Formation of the Hamilton Group (Devonian Age). The fill materials beneath the cracked concrete floor slabs consisted of the weathered shale fragments from this formation. Although mitigating the structural distress has been attempted, the building continued to experience problems relating to the swelling of the underlying bedrock materials. The expansion of the shale could be attributed to the oxidation of the pyrite, which produced sulfuric acid. The sulfuric acid, in turn, reacted with the calcium carbonate (calcite) in the shale partings producing the mineral gypsum. Since gypsum has approximately twice the molar volume of calcite, the result is an expansion or swelling of the shale. Various laboratory tests were conducted on the shale in an attempt to simulate the swelling processes. The failures and successes of the laboratory testing have given new directions for additional research to further educate Geotechnical Engineers unfamiliar with the expansive nature of pyritic shale.

INTRODUCTION

The existing Evangelical Hospital, located in Lewisburg, Pennsylvania, experienced concrete floor slab problems within three months of construction of an addition. Specifically, the concrete floor slabs, in areas underlain by fill materials containing pyritic shale from the foundation excavations, underwent as much as six inches of vertical upward movement or heaving. This heaving resulted in cracked concrete slabs and disruption of certain hospital functions. Upon visual inspection of the shale fill materials, a white/translucent crystal growth was noted on the shale partings. These crystals were identified as gypsum by x-ray diffraction analysis. Also, a total sulfur analysis revealed that the majority of the sulfur consisted of sulfate and that very little sulfide materials were available. The remedial measures taken were removal of the fill materials and the cracked concrete floor. Meanwhile, a structural reinforced concrete floor slab was installed in place of the damaged concrete floor. The structural reinforced concrete slab was 12 in. (30.5 cm) above the top of the fill and was supported by the walls. The void space would allow for future expansion of the pyritic shale without affecting the structural reinforced concrete slab (Hoover and Thornton, 1998).

Several other areas within the Evangelical Hospital also experienced structural distress due to swelling of the underlying pyritic shale bedrock and fill materials. Meanwhile, similar structural distress problems were encountered at the buildings on Juniata College campus located in Huntingdon. Both Huntingdon and Lewisburg are located in Central Pennsylvania, which is situated above the Marcellus Formation of the Hamilton Group (Devonian Age). Due to its nature of deposition together with the environmental conditions, abundant pyritic shale that contains sulfide minerals is present throughout the rock sequence in the Marcellus Formation. According to Dougherty & Barsotti, (1972), the swelling behavior of pyritic shale has caused considerable structural damage in many areas of the United States. However, standards on how to prevent or mitigate the detrimental effects on the engineering structures due to swelling of the underlying pyritic shale are not yet established. This paper investigated both the swelling behavior of a pyritic shale obtained from the project site under various environmental conditions and various mitigation measures to minimize potential destruction to the overlying structures.

BACKGROUND KNOWLEDGE

The middle Devonian Marcellus Formation is commonly considered to have been deposited in deep anoxic waters. The calcite in the fractures and joints of the pyritic shale is the result of the deposition of calcium carbonate from the groundwater, which fluctuates through the adjacent limestone strata. Most of the variation in sulfur content varies with the amount of pyrite. Pyrite accumulates syngenetically and diagenetically throughout the coalification process and later as secondary mineralization (Shultz, 1999). It is this variation in pyrite content that leads to the designation of the shale as "potentially" expansive. This is consistent with the heterogeneous nature of the pyrite in the rock core samples utilized in the laboratory testing.

The mechanism behind the expansion of the calcium carbonate or calcite due to the formation of gypsum can be seen in the molar volume differences. Szymanski (1989) presents the following molar volumes of pyrite, calcite and gypsum:

Pyrite (FeS_2):	23.9 mm^3/mol ($1.46x10^{-3}$ in^3/mol)
Calcite ($CaCO_3$):	36.9 mm^3/mol ($2.25x10^{-3}$ in^3/mol)
Gypsum ($CaSO_4 \bullet 2H_2O$):	74.7 mm^3/mol ($4.56x10^{-3}$ in^3/mol)

As can be seen in the volume differences, gypsum has approximately twice the molar volume of calcite. The expansion will occur in all directions; however, given the confined nature of structural fill and natural bedrock in conventional construction, the floor slabs and foundations resulting from expansion of the pyritic shale will, in most cases, be forced upward.

Pyrite oxidation takes place when the mineral is exposed to air and water. The process is complex because it involves chemical, biological and electrochemical reactions and varies with environmental conditions. Factors, such as pH, partial pressure of oxygen (pO_2), specific presence or absence of bacteria and/or clay minerals, as well as hydrological factors, determine the rate of oxidation. There is, therefore, no single rate law available to describe the overall kinetics of pyrite oxidation for all cases (Evangelou, 1975).

Pyrite containing rocks that have caused heave problems usually contain calcite as an integral part of the rock, as in calcareous shales and limestone, or as fracture fillings cutting through noncalcareous shales. When calcite is present, it reacts with sulfuric acid produced by oxidation of pyrite to form gypsum (Penner and Eden, 1972).

Bell (2000) presented an example of this process and is shown as follows:

$$\underset{\text{(pyrite)}}{2FeS_2} + 7O_2 + 2H_2O \rightarrow \underset{\text{(ferrous sulfate)}}{2FeSO_4} + \underset{\text{(sulfuric acid)}}{2H_2SO_4} \quad \text{(A)}$$

$$4FeSO_4 + O_2 + 2H_2SO_4 \rightarrow \underset{\text{(ferric sulfate)}}{2Fe_2(SO_4)_3} + 2H_2O \quad \text{(B)}$$

$$7Fe_2(SO_4)_3 + FeS_2 + H_2O \rightarrow 15FeSO_4 + 8H_2SO_4 \quad \text{(C)}$$

$$Fe_2(SO_4)_3 + 6H_2O \rightarrow 2Fe(OH)_3 + 3H_2SO_4 \quad \text{(D)}$$

Reaction A involves the initiation of pyrite oxidation and leads to the formation of sulfuric acid. Once the pH falls below 4, conditions become more favorable for the biotic oxidation of pyrite by Thiobacillus ferrooxidans (Reaction B) converting the ferrous sulfate to ferric sulfate. The biotic reaction of pyrite is four times faster than the abiotic reaction at pH 3. Reaction C can be important at low pH, when dissolved Fe(III) is present. If the pH is above 3, then acidity is also generated by reaction D.

Sulfuric acid may react with calcite to produce gypsum, which involves an expansion in volume:

$$\underset{\text{(calcite)}}{CaCO_3} + H_2SO_4 + H^+ \rightarrow \underset{\text{(gypsum)}}{CaSO_4 \bullet 2H_2O} + CO_2 \quad \text{(E)}$$

If carbon dioxide (CO_2) can escape, the pH can rise and the dissolution of calcite will slow down. In a closed system, however, CO_2 will not be released and the pH will stay lower, resulting in continued rapid dissolution of calcite until the acidity has been consumed.

LABORATORY TESTING

In the laboratory, swelling tests and swelling pressure tests were conducted. In addition, chemical analyses of sulfur and carbonate carbon contents were performed to provide chemical compositions necessary for understanding the swelling behavior of the test shale samples. The test pyritic shale samples were obtained from the Evangelical Hospital property. Two types of samples were tested – rock cores and crushed shale (bulk fill). The rock cores had a diameter of 2 in., and the bulk fill had a maximum particle size of 3/8 in. which was chosen in consideration of the 4 in. compaction mold diameter. The bulk fill had two different gradations – well- and poorly-graded. The test bulk fill specimens were compacted in CBR molds to two different densities. The swelling tests were conducted in three phases in an attempt to simulate the environmental conditions that cause pyritic shale swelling in the field.

Swelling Tests

Of the three phases of testing, phase one simulates the oxidation process. The other two phases were performed in an attempt to enhance the amount of swelling by adding independently the calcium carbonate and sulfuric acid concentrations into test specimens.

Phase one – Oxidation

In this phase of swell testing, two shale fill samples were compacted to 100% of the maximum dry density into 6 in. diameter CBR (California Bearing Ratio) molds, which were fastened on the porous base plates. The samples were initially soaked in a tap water bath for a period of approximately 1 month, and the swelling during that period was measured using a conventional dial gage with 0.001 in. (.0254 mm) graduation. The amount of swelling was less than 0.05 in. (1.27 mm). The samples were then taken out of the water baths and placed in a room with 100% humidity (concrete curing room) for a period of another month. The samples actually experienced a slight decrease in volume during this time. The samples were then taken out of the curing room and placed at room temperature for another month and allowed to dry out. Continued shrinkage of the samples occurred during this period. The samples were further subjected to two-week cycles of wetting and drying during the next three months. The amount of swelling during that period was only typical of "normal" soils subjected to the same procedure without significant swelling. The test samples were removed from the molds after six months for a visual inspection. Details of test procedures and test results are available elsewhere (Hoover, 2002). After the tests, no crystal growth was seen. Thus, the insignificant swelling observed in this phase of testing can be attributed to the failure of the pyrite to oxidize. The lack of insignificant oxidation might be due to either that the shale samples have already oxidized or that there was insufficient calcium carbonate in the samples or both. This led to the second phase of testing.

Phase two – Increasing calcium carbonate concentration

It has been found that water samples obtained from the Hamilton Group contained an average calcium carbonate concentration of 135 mg/L and an average pH of 7.26 (Reese and Lee, 1998). Thus, it was hypothesized that a supply of calcium in the water should enhance the expansive behavior of the pyritic shale.

Bulk fill samples --
For this phase of swelling tests, six compacted shale samples were tested. Of these six samples, two samples were well-graded with two densities, and four samples were poorly-graded also with two densities. The test shale samples contained in the CBR compaction molds with porous plates were soaked in water containing different concentrations of dissolved calcite for a period of one month. Three concentrations of calcite were tested; they were 75, 150, and 300 mg/L. The maximum amount of swelling for the well-graded samples was about 0.05 in. (1.27 mm) compared with approximately 0.002 in. (0.0508 mm) for the poorly-graded samples. The less swelling with the poorly-graded specimens could be attributed to the larger void space inside the specimens to accommodate the volume expansion of shale particles than the well-graded specimens. After one month of soaking, the test samples were taken out of the calcium carbonate bath for a period of one month and allowed to dry. Each of the samples initially experienced a small amount of shrinkage but leveled out in the remainder of the month without exhibiting swelling. The samples were then subjected to alternating cycles of soaking and drying for the third month. No further appreciable swelling was noticed. As a result of the calcium carbonate bath, when the samples were removed and allowed to dry, a white deposit appeared on the CBR molds. However, no crystalline deposits were noticed in the shale fill when the samples were removed from the molds. The lack of visible crystalline deposits in the shale fill may be due to the settling of calcium carbonate into the static water environment. It should be noted that tap water was utilized for test samples preparations. Another possible explanation is that the oxidation process may have already completed due to handling and manipulation of the samples prior to testing. Furthermore, possible release of carbon dioxide, which formed from chemical reactions, into the open environment of the laboratory set-up may have caused the pH to increase. As the pH increased, the calcite would be difficult to dissolve and thus the transformation into gypsum could be retarded. A more detailed discussion on this effect has been given by Hoover (2002).

Core Samples --
For swelling test, the rock core specimen was set up in a triaxial testing apparatus, and the triaxial chamber was filled with distilled water containing a 300 mg/L concentration of $CaCO_3$. The water was removed and added in weekly cycles for the next two months. No significant swelling was recorded during this period. Calcite deposits were noted during the drying periods on the outside of the rock core sample. However, no crystal growth appeared in the shale partings.

Phase 3 – Addition of sulfuric acid
This phase was intended to simulate oxidation by supplying different concentrations of the catalyst involved in the oxidation process, i.e. sulfuric acid.

Bulk Fill Samples --
A total of four compacted bulk fill samples, two each for well-graded and poorly-graded samples, and each gradation with two different dry densities (99 pcf (1586 kg/m^3) and 114 pcf (1826 kg/m^3)) were soaked in a solution with 1.0% and 3.0% concentrations of sulfuric acid. The tests lasted for about 45 days. The test results showed that swelling took place abruptly during the first 4-5 days then became almost constant for the poorly-graded samples. For the well-graded samples, swelling increased gradually at a steady constant rate. At the end of 45 days of soaking, the maximum swelling were approximately 0.05 and 0.13 in. (1.27 and 3.3 mm) for the well-graded in 1.0% and 3.0% concentrations of sulfuric acid, respectively. For the poorly-graded samples, the maximum swellings were about 0.03 and 0.06 in. (0.6 and 1.52 mm) for 1.0% and 3.0% concentrations, respectively. The pH of the sulfuric acid was measured before and after each of the tests. The results showed that after the tests, the pH values increased dramatically from 0.46 and 0.33 to 2.46 and 4.57 for well-graded samples with 1.0% and 3.0%, and from 0.80 and 0.22 to 5.95 and 5.23 for poorly-graded with 1.0% and 3.0% concentrations, respectively.

Core Samples --
Four rock cores consisting of black carbonaceous pyritic shale, which reacted slightly with 10% HCI during a visual inspection, had natural and mechanically induced (rock coring process) fractures at varying dips. The maximum relative dip of the fractures was approximately 30^0 from the horizontal. These core specimens were soaked in a solution containing sulfuric acid; two cores were soaked in 1.5% concentration,

and the other two were individually soaked in 0.75% and 3.0% concentrations of sulfuric acid until the swelling leveled off at about 90 days. One of the cores in 1.5% concentration was removed earlier for carbonate carbon analysis. The maximum peak swellings were 0.112, 0.442, and 0.472 in. (2.84, 11.2 and 12.0 mm) for 0.75%, 1.5%, and 3.0% concentrations, respectively.

Swelling Pressure Tests

Bulk Fill Samples --
A total of four samples having the same gradations and densities of the swelling test samples were tested in a solution with 1.0% and 3.0% concentrations of sulfuric acid. The test set-up was similar to that used for swelling tests except that a proving ring was placed between the top of specimen and a loading yoke of a triaxial test apparatus. As would be expected, the pressure vs. time data mirrored the shape of pressure vs. time relation. The pressure increased abruptly during the first 4-5 days then leveled off. The test lasted for 45 days. The maximum swelling pressures were 331 and 518 psf for the well-graded samples with 1.0% and 3.0% concentrations of sulfuric acid, respectively; and 360 psf for both 1.0% and 3.0% concentrations with the poorly-graded samples. Also, the pH of the sulfuric acid before and after each test was recorded. As before, the pH values after the tests increased dramatically from 0.46 and 0.33 to 6.21 and 6.37 for the well-graded samples with 1.0% and 3.0%; and from 0.80 and 0.22 to 5.92 and 4.56 for the poorly-graded samples with 1.0% and 3.0%, respectively.

Core Samples --
Three rock core samples, one having 5 fractures and each of the other two with 3 fractures, were tested using the same test set-up described above. The core samples were soaked in a solution with 2.0% concentration of sulfuric acid for 45 days. The shape of pressure vs. time curves is quite different from that of the swelling vs. time curves in that the pressure gradually increased with time without an abrupt change at the onset. The maximum pressures at the end of 45 days were 13,176 6,077, and 4,651 psf (631, 291 and 223 kPa).

Carbonate Carbon Tests

As stated before, one core specimen tested for swelling was removed earlier than the other core specimens for carbonate carbon tests. The test results showed that the percent carbonate carbon contents were 2.9, 2.4, and 2.3 for the conditions of un-soaked, soaked for 4.4 hrs, and soaked for 119.8 hrs in the sulfuric acid, respectively. These data indicated that the amount of calcium carbonate available to react with sulfuric acid decreased during swelling as it converted into gypsum and carbon dioxide. According to the swelling mechanism reviewed earlier, this observation should be expected.

Total Sulfur Analysis

Total sulfur analysis was performed for the test bulk fill samples. The test results including total sulfur, sulfate, pyritic, and organic contents are summarized in Table 1. The data indicated that the pyritic sulfur content is much greater than 0.1%, which was suggested as a threshold value for potential expansion by Dougherty and Barsotti (1972). The 0.1% threshold basically postulated that the "potential" for expansion is based on the available amount of sulfide minerals that can be converted into sulfate.

Table 1. Total Sulfur and Forms of Sulfur Analysis

Sample Description	Total Sulfur (%)	Sulfate (%)	Pyritic (%)	Organic (%)*
#1 well graded shale	1.9	1.5	0.3	0.1
#2 poorly graded shale	4.1	1.0	2.2	0.9
#3 rock bulk shale	3.1	1.0	1.5	0.6

Results in weight percent on as-received basis.
* = total sulfur – (sulfate + pyritic)

ENGINEERING SIGNIFICANCE

The presence of pyritic shale at a potential building site should be a warning to the Geotechnical Engineer to be extremely cautious when providing engineering recommendations. If the pyritic shale layer is going to be uncovered during excavation for the floor slabs or foundations, there is the potential for inducing oxidation and subsequently expansion. Also, the material may be considered for use as structural fill in cut/fill scenarios, parking lots, backfill behind retaining structures, etc. where the potential for inducing oxidation of the pyrite is greatly increased. The following subsections outline some of the considerations necessary given the research conducted.

Spread Footing Design

Typically, Geotechnical Engineers assign net allowable bearing capacity values ranging between 4,000 and 8,000 psf (192 and 383 kPa) (BOCA, 1993) for a weathered shale stratum. This range of bearing capacity is below the swelling pressure values measured on the rock cores in the laboratory. Specifically, the swelling pressure measured in the laboratory ranged between 4,651 and 13,176 psf (223 and 631 kPa) due to the formation of gypsum in the shale partings. It should be noted that the swelling pressures were measured from test specimens that were restrained from swelling, and that the test specimens were approximately 6.0 in. (15.2cm) in height. When overlain by foundation systems, that possess some degrees of freedom for upward movement, the swelling pressure can be significantly less than the measured values.

Consideration should be given to the fact that although the potential swelling pressures can be well above a design bearing capacity, the resulting heave may not be enough to cause structural damage. Damage to a structure depends on its tolerance to absorb differential movement within and between load bearing members; therefore, some structures may move differentially without a noticeable effect on the function or aesthetics of the structure. It should be pointed out that the amount of swelling determined in the laboratory may not be representative of the field conditions, because the swelling tests were performed without surcharge loading on top of the test specimens. To obtain more realistic swelling as well as swelling pressure, the laboratory tests should be conducted on specimens subjected to the same state of stress as that in the field.

Until more comprehensive testing is accomplished to measure the expansion under surcharge loads, engineers may consider designing spread footings on potentially expansive shale based on higher than typical bearing capacities in order to counteract the opposing swelling forces which may result during the oxidation of the pyrite. Meanwhile, considerations should be given to the possibility of elastic deformation or to the presence of clay seams or other weak layers making the footing susceptible to punching shear failure. Additional laboratory and field testing would be warranted before providing recommended bearing capacities for expansive bedrock.

The weathered and fractured nature of bedrock should be considered in the determination of bearing capacity. It should be noted that a weathered pyritic shale layer will be more susceptible to oxidation and will swell more than an intact or fresh bedrock stratum. If remedial measures, such as spray-on sealants, are not taken to prevent the exposure of the material to atmospheric oxygen, it may be advisable to design the spread or continuous wall footings based on the bearing capacities typically given for fresh or unweathered bedrock. Also, it may be advisable to over-excavate the weathered shale to a more sound and less fractured stratum in order to prevent oxidation and swelling.

Floor Slab Considerations

The test simulating the expansion of structural fill containing the expansive shale fragments reveals that significant swelling potential is a possibility. This swelling becomes greater as the depth of the structural fill increases, which could present problems to lightly loaded floor slabs. For example, the well-graded sample with 3.0% sulfuric acid expanded approximately 0.13 in. (3.30 mm) or 2.6 percent in terms of specimen height. Given that the sample was approximately 5.0 inches in height, for example, if 10.0 ft (3.0 m) of this material was used as structural fill, then an expansion of approximately 2.6 in. (166.0 mm) could possibly be achieved without considering possible effect of surcharge pressures.

Given the relatively light loading conditions for typical on-grade concrete slabs and the possibility of expansive pressures exceeding the floor slab loads, there is a potential for structural damage, such as slab heaving and cracking. Data from the Evangelical Hospital project revealed that cracking to floor slabs occurred in areas where 4.0 ft. (1.2 m) to 10.0 ft. (3.0 m) of pyritic shale fill was utilized as structural fill. The pressures necessary to displace and crack these floor slabs could be greater than those measured in the laboratory. Not only could the floor slab crack causing tripping hazards and destroying tiling, the heaving of the floor slab could also disrupt doorways function.

By understanding the pressures induced by expansion of the shale materials, it would be possible for engineers to design floor slabs to tie into structural members. Also, the use of more steel reinforcement and possibly post-tensioned slabs may be options to limit the potential for structural damage.

If confidence can be placed in predicting the upper limit of expansion, then it would be possible to design structural floor slabs to avoid contact between the expansive fill and bottom of the floor slab. The data of swelling potential could also be utilized in retrofit projects where the expansion has caused structural damage to the floor slab and a structural slab is considered as a replacement in lieu of complete removal of a large amount of expansive shale fill.

Swelling Restraint

It would be possible to minimize the destructive effects of swelling by designing rock bolts in combination with a reinforced “mud slab”. The rock bolting system could be designed based on the results of laboratory or field expansion tests in which a surcharge pressure was utilized. The surcharge pressure should be equal to the expected field conditions. The bonding zone of the bolts would have to extend below the expansive layers; however, due to the nature of the expansive process, which requires oxidation to induce swelling, the bolts may not have to be extended deep into the stratum. Thus, the use of shallow rock bolts may be an attractive method. Specific design details would have to be applied to individual projects.

Swelling Prevention

Attempts can be made to limit or prevent the oxidation process by limiting the exposure of shale surfaces beneath proposed floor slab areas. Remediation measures include the use of bituminous spay sealants, thin mud slabs, limiting the use of calcareous subbase materials and constructing structural slabs and others. The use of spray sealants is limited to dry work environments and is often impractical due to the amount of construction traffic and utility line excavations necessary over the course of a construction project. Thin concrete mud slabs have been used where there is a constant supply of groundwater and a spray on sealant is impractical. Also, the limited use of calcareous materials such as limestone or dolomite as subbase, backfill or aggregate in concrete has been suggested as a way to limit the presence of calcite in the expansion process.

Since the upper weathered areas of the shale bedrock are most susceptible to oxidation during construction, one recommendation would be to remove the loose, weathered shale to the depth of the hard and intact bedrock. Once the intact bedrock has been exposed, immediately apply the sealant as the excavation proceeds in order to limit the extent of exposure to atmospheric oxygen. Considerations should be given to the presence of groundwater and precipitation when planning the type and time of sealing operations. Also, it is conceivable that future utility trench excavations through the area may disrupt the seal and allow for oxidation of the weathered shale material.

The release of carbon dioxide in an open system may be responsible for increasing the pH and subsequently retarding the dissolution of calcite. By not allowing the calcite to dissolve, the formation of gypsum will not occur and swelling of the shale will be prevented. Given this hypothesis, it may be possible to install a ventilation system to allow for the carbon dioxide to escape into the atmosphere. This system would be similar in nature to a radon remediation system. There is the possibility that an open system would allow for more oxidation of the pyrite and subsequently more production of sulfuric acid.

The current state-of-practice for Geotechnical Engineers is to recommend that pyritic shale not be utilized as a structural fill beneath the floors or foundations or behind retaining structures. The data obtained in this study suggests that certain measures may be taken to minimize the detrimental effects of expansive pyritic shales.

Well-graded shale fragments which are compacted to typical project specifications, e.g. 100% of Standard Proctor compaction, contain a small amount of void space leaving little or no room for the expansion to be absorbed within the matrix of the material. However, there may be less chance for the material to undergo oxidation due to the limited amount of space available for the infiltration of oxygen.

Poorly graded shale fragments have more internal void space to absorb particle expansion within the material matrix. As a result, heaving of the overlying concrete floor slab may be smaller than that of well graded shale fill. However, the greater void space may result in an increased risk for oxidation. Normally, poorly graded fill materials are not accepted as structural fill due to the difficulties in providing adequate compaction.

When a need arises to mix the pyritic shale with other materials, every effort should be made not to mix the pyritic shale with a calcareous material such as limestone or dolomite. The main reason is that mixing with calcareous materials may result in an increased risk for expansion of the shale as well as the calcareous material if sulfuric acid is introduced from the oxidation process.

The moisture content of the material, as well as the presence of a fluctuating water table within the shale fill may be an important factor in the expansion process. Given that the production of sulfuric acid results from the oxidation process, water would be a necessary medium for the movement of the acid into the areas of the shale that contain calcium carbonate. A fluctuating water table would accelerate the oxidation process and provide the necessary transportation of the sulfuric acid solution into the shale partings that contain calcium carbonate. Therefore, placing the fill at low moisture contents and protecting the materials from a fluctuating water table may aid in preventing the production of gypsum crystals within the shale.

CONCLUSIONS

The forms of sulfur analysis indicated that the pyritic shale at the test location could be classified as “potentially” expansive given the 0.1% pyritic sulfur threshold identified by previous researchers. The 0.1% threshold was established primarily from past experience with little theoretical analysis. As more data become available from further research, the threshold value could be refined

It is very difficult to simulate the oxidation process in the laboratory given the large numbers of variables required for investigation. Introducing sulfuric acid to the pyritic shale simulated the oxidation process and allowed an investigation into the conversion from calcium carbonate to gypsum. The data obtained during the laboratory experiments have yielded valuable information regarding the design of foundations and floor slabs. Specifically, the data can be utilized in providing design bearing capacities and in designing retaining systems, such as rock bolts.

RECOMMENDATIONS FOR FURTHER RESEARCH

Continued research on this subject problem is needed in order to fully understand the swelling mechanism as well as to develop a mathematical model to predict the amount of swelling and swelling pressure of pyritic shale. In the study, considerable effort should be directed toward chemical analyses to determine the forms of sulfur and calcite contents. Specifically, the sulfuric acid concentrations resulting from oxidation of pyrite should be determined from each test specimen during swelling.

The current practice of geotechnical engineering design and construction related with pyretic shale normally take the measures of preventing exposure of the pyritic shale to the atmosphere and to percolating water. The idea is to limit the exposure to oxygen thus potentially slowing down or limiting the oxidation process. It is worth investigating the effectiveness of preventing the dissolution of calcite and subsequent production of gypsum by venting the carbon dioxide released during the reaction between calcite and the sulfuric acid.

A field-testing program, consisting of monitoring large quantities of potentially expansive fill materials or exposed bedrock over time, would be an important addition to the advancement of the understanding of the potentially expansive nature of pyritic shale. Measuring the chemical compositions of groundwater and the resulting changes to the mineralogy of an expansive shale material would give valuable insight into the swelling mechanism of pyritic shale.

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