COMPATIBILITY OF A SAND-BENTONITE MIXTURE WITH ACID ROCK DRAINAGE

Ernest K. Yanful and Keith S. Shikatani

Abstract: An important consideration in the design of hydraulic barriers for containing acidic seepage at mine sites is the long term interaction of the acid water with the barrier material. A sand-bentonite mixture may be used in the construction of slurry wall backfills and as core material for dams in cases where natural clays are not available. This paper discusses the results of permeability and chemical tests performed on a compacted sand-bentonite mixture permeated with acid rock drainage (ARD). The hydraulic conductivity, $k$, of the sand-bentonite mixture averaged $\sim 1.6 \times 10^{-4} \text{ cm/s}$ with distilled water and $2.4 \times 10^{-4} \text{ cm/s}$ with ARD. The slight increase in $k$ was probably due to transformation of some montmorillonite and illite to kaolinite during the interaction of the sand-bentonite mixture with ARD. The results indicate that although ARD did not adversely alter the hydraulic conductivity during 800 days of permeation, it consumed enough buffering capacity to produce acidic effluents and promote the mobility of metals such as zinc. Thus the long term integrity of the sand-bentonite barrier may be undermined.

Key words: hydraulic barriers, hydraulic conductivity, leaching, buffering capacity, metal mobility.

Introduction

Acid rock drainage (ARD) is formed when reactive iron-bearing sulphide minerals (principally, pyrite and pyrrhotite), contained in mine residues such as tailings, are exposed to oxygen and water. The oxidation of pyrite [FeS$_2$] can be represented by the reaction:

$$2\text{FeS}_2(s) + 7\text{O}_2(g) + 2\text{H}_2\text{O}(l) = 2\text{Fe}^2+(aq) + 4\text{SO}_4^{2-}(aq) + 4\text{H}^+(aq)$$ (1)

The ferrous iron [Fe $^{2+}$] may further oxidize to ferric iron (Fe$^{3+}$) which may, in turn, either oxidize more pyrite and other sulphide minerals [CuS, ZnS, PbS] present or hydrolyze to form ferric hydroxide [Fe(OH)$_3$]. The resulting leachate, in the absence of sufficient buffering minerals such as carbonates and alumino-silicates, is the ARD and is characterized by low pH and high concentrations of sulphate, iron and other heavy metals. In the case of sulphide oxidation associated with mine waste rock, the resulting leachate is known as acid rock drainage (ARD).

In the design of hydraulic barriers (for example, slurry-trench walls and upgraded dams) for

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containing potential ARD flows at mine sites, the compatibility of sand-bentonite mixtures with acidic drainage becomes an important consideration. Structural changes resulting from leaching of the mixture constituents by acidic drainage could lead to increases in hydraulic conductivity. The study of long-term integrity of the sand-bentonite structures as acidic pore waters migrate through them should be part of the tailings management scheme.

This paper presents the results of a laboratory study initiated to examine the interaction of a sand-bentonite mixture with ARD. The compatibility of sand-bentonite mixtures with ARD was assessed by determining the hydraulic conductivity, k, in a flexible-wall permeameter. Information on the interaction of ARD with the sand-bentonite would be useful to mining operations faced with predicting the integrity of hydraulic barriers such as a compacted soil on exposed, acid-producing tailings beaches and slurry walls constructed to reduce seepage from upstream acid-producing tailings. At mine sites where natural clays and low-permeability tills are not available, a sand-bentonite would be a reliable alternative. In addition, compacted sand-bentonite mixtures, unlike clays and tills, have been found in laboratory studies to maintain their hydraulic conductivities, k, after several freeze-thaw cycles (Wong and Haug, 1991). This suggests that hydraulic barriers constructed from sand-bentonite mixtures are likely to maintain their integrity in temperate climates in the long term, provided chemical compatibility with the intended holding fluids or leachates can be assured.

The samples were first permeated with distilled water for a minimum of one pore volume to establish a baseline k. The permeant was then switched to ARD and the tests continued for several additional pore volumes. The mineralogy and chemistry of the soils were examined before and after k testing to identify any changes which would explain the k data.

Materials and Methods

Materials

During the study, an 8% sodium bentonite/92% sand mixture was used. The medium-coarse sand was obtained from a sand pit located near the decommissioned Waite Amulet tailings site near Rouyn-Noranda, north-central Quebec, while the sodium bentonite was acquired from a local retailer and was of a commercial variety.

The grain size distributions of the test materials are summarized in Table I.

Table I - Grain size Distributions of Materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Clay Size</th>
<th>Silt Size</th>
<th>Fine Sand Size</th>
<th>Medium to Coarse Size</th>
<th>Gravel Size</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&lt; 0.002 mm</td>
<td>0.002 to 0.075 mm</td>
<td>0.075 to 0.42 mm</td>
<td>0.42 to 4.75 mm</td>
<td>&gt; 4.75 mm</td>
</tr>
<tr>
<td>WA Coarse</td>
<td>74.3 %</td>
<td>25.7 %</td>
<td>9.01 %</td>
<td>83.97 %</td>
<td>6.36 %</td>
</tr>
<tr>
<td>Bentonite</td>
<td>74.3 %</td>
<td>25.7 %</td>
<td>9.01 %</td>
<td>83.97 %</td>
<td>6.36 %</td>
</tr>
</tbody>
</table>

Permeants

Two permeants were used in the k tests: deionized, distilled water and ARD. The ARD was obtained from leached, oxidized mine tailings in column experiments at the Noranda Technology
Centre and was analyzed and found to be similar in chemical composition to ARD produced at base metal mine sites. The chemical characteristics of the permeants used are presented in Table II. As indicated, the ARD is characterized by acidic pH and high concentrations of sulphate, iron and other heavy metals.

Table II - Chemical Characteristics of the ARD

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calcium</td>
<td>332.0</td>
</tr>
<tr>
<td>Magnesium</td>
<td>181.0</td>
</tr>
<tr>
<td>Sodium</td>
<td>20.0</td>
</tr>
<tr>
<td>Potassium</td>
<td>0.05</td>
</tr>
<tr>
<td>Iron</td>
<td>4,600.0</td>
</tr>
<tr>
<td>Manganese</td>
<td>462.8</td>
</tr>
<tr>
<td>Aluminum</td>
<td>183.0</td>
</tr>
<tr>
<td>Silicon</td>
<td>23.4</td>
</tr>
<tr>
<td>Zinc</td>
<td>1,050.0</td>
</tr>
<tr>
<td>Copper</td>
<td>596.0</td>
</tr>
<tr>
<td>Cadmium</td>
<td>112</td>
</tr>
<tr>
<td>Arsenic</td>
<td>7.2</td>
</tr>
<tr>
<td>Sulphate</td>
<td>16,000.0</td>
</tr>
<tr>
<td>Chloride</td>
<td>-</td>
</tr>
<tr>
<td>pH</td>
<td>2.40</td>
</tr>
</tbody>
</table>

Notes: (1) All values except pH are in mg/L
(2) Blanks mean not detected.

Hydraulic Conductivity Testing

Equipment description

A schematic representation of the triaxial permeameter system used in the k tests is shown in Fig. 1. The system consists of a Geostore Brainard-Kilman Model S-511 triaxial cell, a pneumatic triaxial/permeability control panel, and bladder accumulator. The machined aluminum and plexiglas triaxial cell is capable of testing samples to a maximum diameter of 100 mm with a maximum working pressure of 1200 kPa. To resist corrosion, all control valves on the triaxial cell were 316 stainless steel "zero volume change" ball valves.
Air pressures for the testing were supplied from a single source and managed through the control panel. The permeant (inflow) was supplied to the base of the sample and the outflow exited at the top of the sample. Hydraulic gradient was controlled by the difference between the inflow and outflow pressures. Side wall leakage was minimized by the application of heavy vacuum grease to the sample before the sample was covered with the rubber membrane. The cell confining pressure also minimized leakage as well as simulated overburden pressure on the sample.

The accuracy of the system was verified by a calibration technique involving the substitution of the soil sample with a 100 mm diameter by 100 mm length, solid PVC (polyvinyl chloride) cylinder. The PVC cylinder was tested at inflow, outflow and cell pressures identical to those applied in an actual test. An accuracy -1% to +2% was obtained for hydraulic conductivities of $1 \times 10^{-8}$ cm/s.

Sample preparation and compaction

The bulk sample of sand was oven dried for a period of 24 hours and sieved through a #4 size as per ASTM Standard D698-78 to remove any large pebbles. All material retained on the #4 sieve was discarded. The sample of sand was then thoroughly mixed with 8% sodium bentonite (by weight). The mixture was brought to approximately 3% water content by the addition of de-ionized water. The sample was mixed thoroughly and left to equilibrate, double bagged in a sealed
plastic pail for a period of forty-eight hours. Sufficient material was mixed to provide two samples for duplicate testing. A moisture density test was then performed to determine the optimum moisture content (OMC) and the maximum dry density (MDD). This was performed in accordance with ASTM Standard D698-78: 25 blows per layer, 3 layers in a 10 cm (4 in.) diameter compaction mold.

Two samples were compacted and used for k-testing. The first sample was designated PSB4 and the second PSB5. Prior to compaction, the sand-bentonite mixture was checked for its water content using the ASTM microwave oven method. Once the proper water content was established, the samples were compacted in accordance with the ASTM standard. The compacted sample was extruded and a 5.13 cm test specimen was obtained for k-testing. A second sample was similarly compacted and a 5.10 cm sample was cut for the PSB5 test. The diameters and heights were measured in three locations on each sample, and the averages recorded. The weights were also measured, and the volumes and wet and dry densities were calculated based on the water content data established from the trimmings from the samples.

Each sample was covered with high vacuum grease along its length and circumference, then sandwiched between filter papers and porous stones and finally set on the pedestals of the triaxial permeameter for testing. A back pressure of 10.5 kPa and cell pressure of 14 kPa were applied to keep the rubber membranes in contact with the samples.

Sample saturation and permeation

Initially, the samples were saturated by setting the cell pressures to 68.9 kPa and the back pressures to 65.5 kPa and allowing water to flow into the samples. The water levels in the saturation burets were monitored until the flows had either slowed or stopped. Porewater pressure reaction tests were then conducted on each sample to verify the degree of saturation, using the B-value (pore pressure coefficient). For both of the samples, B-values of ≥ 95% were obtained and were considered adequate for k-testing. A detailed description of the saturation and permeation procedure is presented by Yanful et al (1995).

The saturated samples were then consolidated at predetermined effective stresses and permeated with the appropriate permeants (Table III). Hydraulic conductivity, k, was calculated from the difference between the inflow and outflow pressures and the pertinent sample dimensions using Darcy's law. The sand-bentonite sample designated PSB4 was initially permeated with 1.79 pore volumes of distilled water, followed by 4.22 pore volumes of ARD. The hydraulic gradients recorded during the test ranged from 42.23 to 65.15. This test was terminated at a total 6.01 pore volumes. The duplicate sample PSB5 was tested in a similar manner. It was initially permeated with 2.36 pore volumes of distilled water, followed by 7.13 pore volumes of ARD. This test is still in progress. The hydraulic gradients recorded (to date) ranged from 46.03 to 56.17.

Effluent collection and analysis

The k test equipment was adapted to incorporate burets for measuring the outflow volumes and sampling effluents obtained from permeation. Collected effluent samples were analyzed for pH, sulphate, chloride, major cations and heavy metals. Measurement of pH was by a combination electrode calibrated in appropriate buffers, sulphate by ion chromatography and cations and metals by inductively-coupled plasma emission spectroscopy.
Table III - Sample Dimensions and Gradients Used in k-Testing

<table>
<thead>
<tr>
<th>Sample</th>
<th>Length (cm)</th>
<th>Permeant</th>
<th>Pore Volumes</th>
<th>Gradient</th>
</tr>
</thead>
<tbody>
<tr>
<td>PSB4</td>
<td>5.13</td>
<td>Distilled Water</td>
<td>1.79</td>
<td>65.17</td>
</tr>
<tr>
<td></td>
<td></td>
<td>AMD</td>
<td>4.22</td>
<td>42.23</td>
</tr>
<tr>
<td>PSB5</td>
<td>5.10</td>
<td>Distilled Water</td>
<td>2.36</td>
<td>56.17</td>
</tr>
<tr>
<td></td>
<td></td>
<td>AMD</td>
<td>7.13</td>
<td>46.03</td>
</tr>
</tbody>
</table>

Results and Analysis

Hydraulic Conductivity, k

Sample PSB4

The results of hydraulic conductivity, k tests conducted on sand-bentonite mixture PSB4 at an average hydraulic gradient of 52.9 are presented in Fig. 2. As shown, a final k of $1.5 \times 10^{-9}$ cm/s was obtained at the end of 1.79 pore volumes of permeation with distilled water. The sample was then permeated with ARD for 4.22 pore volumes at an average gradient of 42.2 during which period the k appeared to have increased slightly to $2.1 \times 10^{-9}$ cm/s. The average hydraulic gradients observed are presented in Table III. The gradient measured during part of the ARD permeation was low because of iron precipitating from the ARD and blocking the small opening in the tubes, thus causing erroneous readings at the differential pressure transducer. The tubes were subsequently cleaned and the tests resumed. This temporary clogging was responsible for the slight drop in k around 2 to 2.5 pore volumes, shown in Fig. 2.

Sample PSB5

The results of hydraulic conductivity, k tests conducted on the duplicate sample had an average hydraulic gradient of 56.2 and are presented in Figure 3. As shown, a final k of $1.8 \times 10^{-9}$ cm/s was obtained at the end of 2.36 pore volumes of permeation with distilled water. The permeant was subsequently switched to ARD and the sample permeated to 9.41 pore volumes at an average gradient of 46.0. The k increased slightly to $2.6 \times 10^{-9}$ cm/s. As noted before, temporary decreases in hydraulic gradient during ARD permeation are responsible for the slight dip in the k versus pore volume graph in Fig. 3.

Effluent Chemistry

Figure 4 shows pH values versus pore volumes measured for test PSB4. The data for test PSB5 were very similar and are, therefore, not presented here. The pH of the permeant was 3.18. The data indicate gradual decrease in the pH of the effluent (soil pore water displaced by the permeant) a circum-neutral value at 2.5 pore volumes to a steady value of approximately 3.0 at 4.5 pore volumes. It is clear that the buffering capacity of the sand-bentonite mixture was depleted after two pore volumes of ARD permeation.
Figure 2 - Hydraulic Conductivity vs Pore volumes for PSB4 Test

Figure 3 - Hydraulic Conductivity vs Pore Volumes for PSB5 Test
Relative concentrations (ratio of influent to effluent or C/C₀) of sulphate (SO₄²⁻) observed during the k-tests are presented in Fig. 5. Again, only data for test PSB4 are presented here because of the similarity to the data for PSB5. The results indicate that after one pore volume of ARD permeation, only ~ 10% of the sulphate in the ARD was passing through the sample. This sulphate attenuation could be attributed to geochemical processes such as bacteria-mediated reduction to sulphide and gypsum precipitation, as reported by Yanful et al. (1995). The effluent sulphate concentration eventually equalized that of the influent (ARD), after almost 4.0 pore volumes of ARD permeation.

Observed relative concentrations for zinc are presented in Fig. 6. The data suggest that nearly 60% of the zinc in the ARD was passing through the sample after ~ 3.0 pore volumes of ARD permeation. It is obvious that continued permeation of the sample with ARD beyond the 6.0 pore volumes would have resulted in zinc equilibrium.

Soil Mineralogy and Chemistry

A comparison of the soil mineralogy before and after ARD permeation indicated only slight changes in mineralogy occurred. The total carbonate (dolomite plus calcite) content was reduced by ARD permeation from 1.3 to 0.3%; this reduction provided some of the initial buffering of the effluent. The dominant clay mineral present (montmorillonite) was attacked by the ARD but illite was only slightly attacked. Both x-ray diffraction and geochemical analysis indicated that some transformation of montmorillonite and illite to kaolinite occurred as a result of the ARD permeation.
Figure 5 - Relative Concentration of $\text{SO}_4^{2-}$ vs Pore Volume During k-Testing

Figure 6 - Relative Concentration of Zinc vs Pore Volume During k-Testing
Plagioclase feldspar was also found to have been slightly weathered due to the ARD permeation. Acid leaching of plagioclase (NaAlSi₃O₈, for example) to form kaolinite (Al₂Si₂O₅(OH)₄) can be represented by the well known reaction (Drever, 1982):

\[ 2\text{NaAlSi}_3\text{O}_8 + 2\text{H}^+ + 9\text{H}_2\text{O} = \text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4 + 2\text{Na}^+ + 4\text{H}_2\text{SiO}_4 \]

Altschuler et al (1963) provided evidence of direct transformation of montmorillonite to kaolinite during low temperature weathering of Florida soils. Kaolinite formation is enhanced in an acidic (pH < 7) environment where the concentration of Al³⁺ is high relative to that of Si⁴⁺ and divalent and univalent cations such as Fe²⁺, Ca²⁺, Mg²⁺, Na⁺ and K⁺ are continuously removed or leached away. These conditions were present in the k-tests with ARD.

The alteration of primary minerals such as montmorillonite and feldspar to form secondary minerals such as kaolinite essentially preserved the soil void ratio and the hydraulic conductivity, k. Although the k did not change during the > 800 days of ARD permeation, the buffering capacity of the soil was significantly reduced, as indicated by the drop in pH from near neutral values to < 3.0. An immediate consequence of the depletion of buffering capacity is the mobility of metals.

**Conclusions**

For the compacted sand-bentonite mixture (92% sand and 8% bentonite) and the hydraulic gradients used (42 - 65), acid rock drainage (ARD) did not significantly alter the hydraulic conductivity, k. The value of k, measured in a flexible wall permeameter on two duplicate samples, averaged ~ 1.65 x 10⁻⁹ cm/s with de-ionized distilled water and 2.35 x 10⁻⁹ cm/s with ARD. The slight increase in k could be attributed to transformation of some montmorillonite to kaolinite due to ARD interaction. The buffering capacity was significantly reduced by ARD permeation, as indicated by the drop in effluent pH from near neutral values to < 3.0. The effluent data also indicate that the depletion of buffering capacity would lead to increased mobility of metals such as zinc.

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**References**


