The Influence of Geochemical Processes on Mine Waste Material Structure and Physical Stability

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• Geochemical Processes or Mechanisms that Affect Large Scale Structures of Mine Waste Facilities
• Physical Implications from these Processes, Materials and Systems:
  – Changes in porosity and permeability (increase or decrease) resulting in a change in design parameters
  – Changes in strength and structure resulting in a change in physical stability
• Case Examples
• Summary
Geochemical processes change the structure, strength and chemical stability of geologic materials (minerals) and by extension affect the stability of large scale mine waste engineered structures:

- Metallurgical Waste Disposal (slag and other process waste)
- Waste Rock and Heap Leach Piles
- Tailings Storage Facilities
- Earthen and Tailings Dams
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- Degradation and mass loss
- Changes in material parameters, porosity and permeability
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Two main geochemical processes or mechanisms effect the physical and hydrologic properties of mine waste materials:

1. Primary Mineral Alteration (weathering): hydrolysis and dissolution of minerals within waste materials; and/or,
Weathering Affects Physical Properties of Mine Waste

- Weathering is the breakdown of rocks and minerals, by physical, chemical or biological processes.

- Chemical weathering = mineralogical alteration.
  - Hydrolysis, Dissolution / Desorption
  - Oxidation and Neutralization

Sulphide dissolution and oxidation + carbonate and silicate dissolution and neutralization → mineralogical changes over time in Mine Waste Facilities
### Mineral Alteration Changes Physical Properties

<table>
<thead>
<tr>
<th>Primary Mineral</th>
<th>Sym</th>
<th>Chemical Formula</th>
<th>Molecular Weight (g/mol)</th>
<th>Specific Gravity</th>
<th>Hardness</th>
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</thead>
<tbody>
<tr>
<td>Pyrrhotite</td>
<td>Po</td>
<td>Fe₇₋ₓSₓ</td>
<td>85.12</td>
<td>4.61 (avg)</td>
<td>3.5-4.5</td>
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<tr>
<td>Pyrite</td>
<td>Py</td>
<td>FeS²</td>
<td>119.98</td>
<td>5.01</td>
<td>6.5</td>
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<td>Galena</td>
<td>Gl</td>
<td>PbS</td>
<td>239.27</td>
<td>7.4</td>
<td>2.5</td>
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<tr>
<td>Chalcopryte</td>
<td>Cpy</td>
<td>CuFeS₃</td>
<td>183.33</td>
<td>4.1-4.3</td>
<td>3.5-4.5</td>
</tr>
<tr>
<td>Alkali Feldspar</td>
<td>Fp</td>
<td>(K,Na)[Al₂O₃]</td>
<td>278.33</td>
<td>2.55-2.63</td>
<td>6</td>
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<tr>
<td>Plagioclase</td>
<td>Pg</td>
<td>Na[Al₂Si₂O₈][OH]₂</td>
<td>270.77</td>
<td>2.62-2.76</td>
<td>6-6.5</td>
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<tr>
<td>Muscovite</td>
<td>Mv</td>
<td>K₆<a href="OH">Al₂Si₄O₁₀</a>₄</td>
<td>398.71</td>
<td>2.77-2.88</td>
<td>2-2.5</td>
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<table>
<thead>
<tr>
<th>Secondary Mineral</th>
<th>Sym</th>
<th>Chemical Formula</th>
<th>Molecular Weight (g/mol)</th>
<th>Specific Gravity</th>
<th>Hardness</th>
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</thead>
<tbody>
<tr>
<td>Jarosite</td>
<td>Jar</td>
<td>KFe₃(SO₄)₂(OH)₆</td>
<td>500.81</td>
<td>2.9-3.3</td>
<td>2.5-3.5</td>
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<tr>
<td>Schwertmannite</td>
<td>Sch</td>
<td>Fe₉O₁₈(OH)₁₂(SO₄)₂</td>
<td>1345.76</td>
<td>3.77-3.99</td>
<td>2.5-3.5</td>
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<tr>
<td>Ferricyanide</td>
<td>Fhy</td>
<td>Fe₆O₇·0.5(H₂O)</td>
<td>168.70</td>
<td>3.8</td>
<td></td>
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<tr>
<td>Melaterite</td>
<td>Mel</td>
<td>Fe₆(SO₄)·7(H₂O)</td>
<td>278.02</td>
<td>1.89-1.9</td>
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<tr>
<td>Rozelite</td>
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<td>Fe₆(SO₄)·4(H₂O)</td>
<td>223.97</td>
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<td>2.3</td>
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<tr>
<td>Copiapite</td>
<td>Cop</td>
<td>Fe₆⁺Fe₆⁺(SO₄)₂(OS)₂·20(H₂O)</td>
<td>1249.94</td>
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<td>2.5</td>
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<td>Halotrichite</td>
<td>Hal</td>
<td>Fe₆⁺Al₆(SO₄)₂·22(H₂O)</td>
<td>890.40</td>
<td>1.78-1.9</td>
<td>1.5-2</td>
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<td>Goethite</td>
<td>Gt</td>
<td>FeOOH</td>
<td>88.85</td>
<td>4.3</td>
<td>5-5.5</td>
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<tr>
<td>Anhydrite</td>
<td>Ah</td>
<td>CaSO₄</td>
<td>136.1</td>
<td>2.97</td>
<td>3.5</td>
</tr>
<tr>
<td>Gypsum</td>
<td>Gp</td>
<td>Ca(SO₄)₂·2H₂O</td>
<td>172.2</td>
<td>2.3</td>
<td>2</td>
</tr>
<tr>
<td>Cerrusite</td>
<td>Cer</td>
<td>PbSO₄</td>
<td>267.21</td>
<td>6.58</td>
<td>3.5-3.5</td>
</tr>
<tr>
<td>Kaolinite</td>
<td>Kln</td>
<td>Al₂<a href="OH">Si₂O₅</a>₆</td>
<td>258.16</td>
<td>2.61-2.68</td>
<td>2-2.5</td>
</tr>
<tr>
<td>Smectite</td>
<td>Smc</td>
<td>(1/2Ca,Na)<a href="OH">Al₂Si₄O₁₀</a>₄·nH₂O</td>
<td>2.2-7</td>
<td>2.7</td>
<td>1.5-2</td>
</tr>
</tbody>
</table>

**Weathering and Alteration**

![Image of weathering and alteration process]
Mineral Alteration Affects Porosity and Permeability

Weathered silicate primary minerals and secondary Fe products can reduce porosity and permeability.

Higher Hydraulic conductivity
Lower Hydraulic conductivity

Iron
Silicon

Secondary Mineral Precipitation
Accumulation of Amorphous Fe
Dehydration Crystallization
Key issues for consideration in geotechnical stability from geochemical changes include:

1. Degradation of structural fill resulting in a loss of physical stability;
2. Degradation of fill and filter materials resulting in a change in material permeability (increase or decrease) altering the original design parameters;
3. Accumulation of secondary mineral precipitates resulting in a change in material properties (i.e. permeability or strength).

Particle changes leading to changes in:
- Compressibility,
- Consolidation,
- Cohesion (increase or decrease)
- Porosity (increase or decrease)
- Permeability (increase or decrease)

In some cases, the development of amorphous secondary minerals could lead to changes in key material behaviours (i.e. change from a frictional material where strength comes from grain to grain contact or to a frictionless material where the contact between grains is reduced).
Case 1: Sulphidic Base Metal TSF

- Flooded base-metal TSF:
  - >100 km$^2$;
  - Deposition >50 yrs in several individual areas.
  - Geochemical assessments predicted PAG tailings.
  - Impacted surface and pore water quality:
    - Seepage from older areas well exceeded regulatory guidelines prior to treatment.
    - Seepage from younger areas was getting worse.

- Secondary minerals were observed as a product of changing geochemical conditions.
- Evolution of tailings mineralogy as it relates to physical stability in the ageing TSF was largely unknown/unrecognized.
Case 1: Mineral Alteration Changes Physical Properties

TSF Stratigraphy

- Oxidized Zone
- Transition Zone
- Unoxidized Zone

Graphs showing:
- Depth vs. Paste pH
- Depth vs. Total Ni (ug/g)
Case 1: TSF Mineral Alteration Changes Physical Properties
Case 1: TSF Mineral Alteration Changes Physical Properties

ML/ARD Progression

Weathering and Alteration

Deposited 1940’s
Deposited 1960’s
Deposited 1980’s
Deposited 1990’s
Case 1: TSF Mineral Alteration and Permeability Changes

Precipitate formation rates are variable across the CTA. The rates are dependent upon many factors including:

- Fe concentration
- Physiochemical conditions at the seep/toe (pH, ORP, temp)
- Oxidant availability
- Age of the dam
- Degree of precipitate accumulation in surrounding area
  - i.e. can a new seep develop when the primary seep blinds?
- Drains vs Seeps
- Residence Home
  - i.e. how long has the porewater had home to react with tailings
Case 2: Saline Seepage Water and Construction Fill Degradation

Au TSF:
- Slurry deposited tailings,
- Net Negative water balance,
- Reclaimed water – progressively more saline,
- Geochemical assessments predicted NPAG tailings.

No problem-right?

- Waste rock used to construct dams
  - Weathered and non-weathered BIF
  - Geotechnical testing used DI water showed competent material properties
Case 3: Highly Altered WR + Sulphide Oxidation

- Porphyry Cu-Au Mine:
  - Highly altered deposit type,
  - Carbonates present but high sulphide content,
  - PAG tailings and PAG + NPAG waste rock.

- Sulphide oxidation produced acidity,
- Acidity neutralized by available carbonates. Decades later, acidity is promoting silicate mineral alteration and neutralization by the dissolution of alteration products (clays).
Case 4: Precipitates Reduce Seepage Flow in Waste Rock

Low flow, saturated. Migrating seepage emergence (1m/4yrs), Porewater contains elevated Fe and fill materials filled with amorphous and crystalline precipitates

Flow ~0.1 L/sec

Flow ~1 L/sec

Fe-precipitates flushed, increased porosity, increased flow

Order of magnitude change in flow
Case 5: Cements from Seepage through Slag

- Slag draped over starter dam (toe road)
- Where seepage emerges through slag, the fill is heavily oxidized, coated with crystalline precipitates and cemented
- Seepage is rising up the dam as seepage pathways are blinded by precipitate accumulation and cementation
What Have We Learned from Case Examples?

- Weathering primary minerals and the formation of secondary minerals is common in mine waste environments.
  - Can be accelerated in wet, saline, already highly altered deposits, high sulphide materials, acidic seepage, etc.);
  - Reactions are controlled by the surrounding physiochemical conditions and depend on the composition of the solids and liquids in the system
  - Results in physical and chemical changes to the materials

- However, the influence of geochemical change on physical material properties is not well understood in our current state of practice.
How Do We Improve Our State of Practice?

Conceptual Model

Chemical Weathering

Chemical Testing

Physical Testing

Specialized Testing

Geochemical

Geotechnical

Hydro(geo)logical
Changes to the physical and chemical nature of tailings, dam fill, waste materials and process/pore and seepage waters are important factors that should be considered in mine waste management (environmental + geotechnical)

- Regular physical monitoring will help identify problems associated mineral alteration and/or precipitate formation before physical changes are observed (e.g. rise in phreatic surface)
- Specialized field monitoring and laboratory testing is often needed to determine site specific geochemical processes
- Understanding reaction pathways can help predict outcomes and even mitigate issues early (and reduce risk)

The importance of geochemical processes as a function of mineral alteration and understanding its relation to dam stability will likely become increasingly important as greater scrutiny is placed on waste management now and in the future.
Thank You!

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Precipitates in Seismic Stabilizing Buttresses

Free Flowing Non-Flooded

Flooded Non-Covered

Flooded Covered

Constructed 2014

Constructed 2010

Constructed 1998
Problem:

- Observed changes in facility performance (e.g. phreatic surface, seepage emergence, porosity and permeability, pore or seepage water quality)
- Observed physical changes in tailings, dam fills, or waste materials

Physical

- Subsurface investigations (test pitting, drilling, core extraction, geotechnical testing)
- Solid material characterization (rock, tailings)
- Chemical and mineralogical composition

Chemical

- Seepage and porewater quality
- Geochemical testing of solids + seepage or porewater
- Hydrological and hydrogeological modelling and prediction
- Geochemical modelling and prediction

Specialized

- Customized laboratory testing and field trials
- Risk reduction and remediation