Results from the flooded Stekenjokk tailings

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Based on papers by


Holmström, H. and Öhlander, B. 1999.


Weathering of the embankment

In flowing surface water

Diffusion from the tailings

Resuspension of tailings sand

Tailings

Water
Short facts about Stekenjokk

* Stekenjokk was mined between 1976 and 1988.

* The ore was a stratabound volcanogenic Zn - Cu deposit.

* Main sulfides were pyrite, sphalerite and chalcopyrite.

* Gangue minerals were quartz, feldspar, sericite, chlorite and carbonates.

* Mining left minor waste rocks dumps and 4.4 million tons taillings containing c. 20% sulphur, mainly as pyrite.

* The tailings were flooded in 1991 by raising the existing dykes.

* Water depth in the dam varies between 0.7-7 m.
MINERALOGICAL COMPOSITION OF TAILINGS

<table>
<thead>
<tr>
<th>Gangue minerals</th>
<th>Sulphide minerals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quartz</td>
<td>Pyrite</td>
</tr>
<tr>
<td>Muscovite</td>
<td>Pyrrholite</td>
</tr>
<tr>
<td>Chlorite</td>
<td>Sphalerite</td>
</tr>
<tr>
<td>Calcite</td>
<td>Chalcopyrite</td>
</tr>
<tr>
<td></td>
<td>Galena</td>
</tr>
<tr>
<td></td>
<td>Arsenopyrite</td>
</tr>
</tbody>
</table>
### Average chemical composition of tailings

<table>
<thead>
<tr>
<th>Element</th>
<th>%</th>
<th>Element</th>
<th>ppm</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO$_2$</td>
<td>34.8</td>
<td>As</td>
<td>1280</td>
</tr>
<tr>
<td>Al$_2$O$_3$</td>
<td>5.8</td>
<td>Ba</td>
<td>300</td>
</tr>
<tr>
<td>CaO</td>
<td>6.5</td>
<td>Cd</td>
<td>30</td>
</tr>
<tr>
<td>Fe$_2$O$_3$</td>
<td>27.6</td>
<td>Co</td>
<td>60</td>
</tr>
<tr>
<td>K$_2$O</td>
<td>0.8</td>
<td>Cr</td>
<td>26</td>
</tr>
<tr>
<td>MgO</td>
<td>4.8</td>
<td>Cu</td>
<td>1900</td>
</tr>
<tr>
<td>MnO</td>
<td>0.09</td>
<td>Mo</td>
<td>48</td>
</tr>
<tr>
<td>Na$_2$O</td>
<td>0.04</td>
<td>Ni</td>
<td>22</td>
</tr>
<tr>
<td>P$_2$O$_5$</td>
<td>0.2</td>
<td>Pb</td>
<td>1600</td>
</tr>
<tr>
<td>TiO$_2$</td>
<td>0.15</td>
<td>Sr</td>
<td>92</td>
</tr>
<tr>
<td>S</td>
<td>17.5</td>
<td>V</td>
<td>160</td>
</tr>
<tr>
<td>LOI</td>
<td>17.7</td>
<td>W</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Zn</td>
<td>6600</td>
</tr>
</tbody>
</table>
Average composition of the water column (dissolved phase) during a year (1995). The background has been sampled in the stream Stekenjokken upstream from the pond.

<table>
<thead>
<tr>
<th>Element</th>
<th>Winter/Spring (May) 38 samples</th>
<th>Summer (July/August) 107 samples</th>
<th>Autumn (September) 50 samples</th>
<th>Background (September) 1 sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ca</td>
<td>32.0±1.2</td>
<td>19.7±1.0</td>
<td>21.8±0.8</td>
<td>6.9</td>
</tr>
<tr>
<td>Fe</td>
<td>0.009±0.005</td>
<td>0.042±0.013</td>
<td>0.011±0.004</td>
<td>0.028</td>
</tr>
<tr>
<td>K</td>
<td>0.5±0.13</td>
<td>0.58±0.34</td>
<td>0.35±0.09</td>
<td>b.d</td>
</tr>
<tr>
<td>Mg</td>
<td>1.12±0.04</td>
<td>0.68±0.06</td>
<td>0.78±0.03</td>
<td>0.46</td>
</tr>
<tr>
<td>Na</td>
<td>1.30±0.18</td>
<td>1.00±0.24</td>
<td>0.85±0.10</td>
<td>0.75</td>
</tr>
<tr>
<td>S</td>
<td>18.1±0.5</td>
<td>10.9±0.5</td>
<td>12.2±0.4</td>
<td>1.7</td>
</tr>
<tr>
<td>Si</td>
<td>0.33±0.14</td>
<td>0.96±3.40</td>
<td>0.26±0.19</td>
<td>0.61</td>
</tr>
<tr>
<td>Al</td>
<td>1.04±0.73</td>
<td>3.97±0.68</td>
<td>2.01±0.71</td>
<td>10.30</td>
</tr>
<tr>
<td>As</td>
<td>0.44±0.11</td>
<td>0.34±0.09</td>
<td>0.34±0.11</td>
<td>b.d</td>
</tr>
<tr>
<td>Ba</td>
<td>2.85±0.13</td>
<td>1.89±0.27</td>
<td>1.99±0.16</td>
<td>1.34</td>
</tr>
<tr>
<td>Cd</td>
<td>1.07±0.20</td>
<td>0.69±0.06</td>
<td>0.65±0.06</td>
<td>0.06</td>
</tr>
<tr>
<td>Co</td>
<td>0.07±0.03</td>
<td>0.16±0.05</td>
<td>0.13±0.02</td>
<td>0.17</td>
</tr>
<tr>
<td>Cu</td>
<td>2.03±0.44</td>
<td>1.71±0.18</td>
<td>1.57±0.20</td>
<td>1.18</td>
</tr>
<tr>
<td>Hg</td>
<td>0.25±0.03</td>
<td>b.d</td>
<td>b.d</td>
<td>b.d</td>
</tr>
<tr>
<td>Mn</td>
<td>7.9±7.8</td>
<td>24.5±8.9</td>
<td>8.0±1.2</td>
<td>30.4</td>
</tr>
<tr>
<td>Ni</td>
<td>2.22±0.24</td>
<td>1.38±0.35</td>
<td>2.17±0.22</td>
<td>0.37</td>
</tr>
<tr>
<td>Pb</td>
<td>0.23±0.16</td>
<td>0.18±0.06</td>
<td>0.16±0.06</td>
<td>0.11</td>
</tr>
<tr>
<td>Sr</td>
<td>66.6±2.8</td>
<td>43.7±2.3</td>
<td>47.7±1.4</td>
<td>22.0</td>
</tr>
<tr>
<td>Zn</td>
<td>268±53</td>
<td>142±15</td>
<td>150±8</td>
<td>13</td>
</tr>
</tbody>
</table>

b.d = below the detection limit.
Distribution range of analysed elements between the dissolved and suspended phase. A high value indicates that the major part of the element is dissolved and vice versa.

<table>
<thead>
<tr>
<th>Element</th>
<th>Winter/Spring (May)</th>
<th>Summer (August)</th>
<th>Autumn (September)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[Diss./Diss.+Susp.]%</td>
<td>[Diss./Diss.+Susp.]%</td>
<td>[Diss./Diss.+Susp.]%</td>
</tr>
<tr>
<td>Si</td>
<td>92.9±0.0</td>
<td>87.1±0.1</td>
<td>88.1±0.0</td>
</tr>
<tr>
<td>Al</td>
<td>24.7±0.1</td>
<td>21.1±0.1</td>
<td>12.2±0.0</td>
</tr>
<tr>
<td>Ca</td>
<td>~100</td>
<td>~100</td>
<td>~100</td>
</tr>
<tr>
<td>Fe</td>
<td>b.d</td>
<td>40.4±0.1</td>
<td>16.8±0.1</td>
</tr>
<tr>
<td>K</td>
<td>99.8±0.0</td>
<td>99.1±0.0</td>
<td>99.5±0.0</td>
</tr>
<tr>
<td>Mg</td>
<td>99.9±0.0</td>
<td>99.5±0.0</td>
<td>99.5±0.0</td>
</tr>
<tr>
<td>Mn</td>
<td>26.8±0.1</td>
<td>92.7±0.0</td>
<td>79.4±0.0</td>
</tr>
<tr>
<td>Na</td>
<td>99.9±0.0</td>
<td>99.6±0.0</td>
<td>99.8±0.0</td>
</tr>
<tr>
<td>As</td>
<td>78.5±0.0</td>
<td>70.4±0.1</td>
<td>79.6±0.0</td>
</tr>
<tr>
<td>Ba</td>
<td>95.5±0.1</td>
<td>92.4±0.0</td>
<td>95.4±0.0</td>
</tr>
<tr>
<td>Cd</td>
<td>92.4±0.0</td>
<td>95.7±0.0</td>
<td>95.7±0.0</td>
</tr>
<tr>
<td>Co</td>
<td>64.1±0.1</td>
<td>93.5±0.0</td>
<td>90.1±0.0</td>
</tr>
<tr>
<td>Cu</td>
<td>72.7±0.1</td>
<td>69.9±0.0</td>
<td>57.5±0.2</td>
</tr>
<tr>
<td>Hg</td>
<td>99.7±0.0</td>
<td>b.d</td>
<td>b.d</td>
</tr>
<tr>
<td>Ni</td>
<td>97.3±0.0</td>
<td>96.7±0.0</td>
<td>97.8±0.0</td>
</tr>
<tr>
<td>Pb</td>
<td>b.d</td>
<td>35.8±0.04</td>
<td>b.d</td>
</tr>
<tr>
<td>Sr</td>
<td>~100</td>
<td>99.9±0.0</td>
<td>99.9±0.0</td>
</tr>
<tr>
<td>Zn</td>
<td>97.7±0.0</td>
<td>95.1±0.0</td>
<td>96.5±0.0</td>
</tr>
<tr>
<td>S</td>
<td>~100</td>
<td>~100</td>
<td>~100</td>
</tr>
</tbody>
</table>

b.d = The analysis of the dissolved phase was below the detection limit.

1 = Only one value.

2 = The standard deviation is very small for most elements and has been rounded off.
## Average composition of the suspended phase in the pond during a year (1995).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Winter/Spring (May)</th>
<th>Summer (August)</th>
<th>Autumn (September)</th>
<th>Average composition (15 samples)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5 samples</td>
<td>7 samples</td>
<td>3 samples</td>
<td></td>
</tr>
<tr>
<td>[mg/l±s.d] Suspended load</td>
<td>0.17±0.08</td>
<td>0.28±0.11</td>
<td>0.27±0.10</td>
<td>0.23±0.50</td>
</tr>
<tr>
<td>[weight%±s.d] Si</td>
<td>9.9±1.6</td>
<td>18.4±2.6</td>
<td>19.1±3.1</td>
<td>15.0±6.1</td>
</tr>
<tr>
<td>Al</td>
<td>2.0±0.34</td>
<td>5.06±0.66</td>
<td>6.96±3.04</td>
<td>4.27±2.48</td>
</tr>
<tr>
<td>Ca</td>
<td>5.68±0.50</td>
<td>4.5±0.69</td>
<td>4.14±0.97</td>
<td>4.52±1.43</td>
</tr>
<tr>
<td>Fe</td>
<td>21.0±3.8</td>
<td>20.5±4.5</td>
<td>17.8±5.1</td>
<td>19.3±6.3</td>
</tr>
<tr>
<td>K</td>
<td>0.55±0.47</td>
<td>1.26±0.33</td>
<td>1.35±0.25</td>
<td>1.05±0.50</td>
</tr>
<tr>
<td>Mg</td>
<td>0.84±0.15</td>
<td>1.28±0.14</td>
<td>1.59±0.28</td>
<td>1.13±0.43</td>
</tr>
<tr>
<td>Mn</td>
<td>8.91±1.63</td>
<td>0.51±0.14</td>
<td>0.80±0.24</td>
<td>2.92±4.04</td>
</tr>
<tr>
<td>Na</td>
<td>0.64±0.63</td>
<td>1.34±0.35</td>
<td>0.82±0.25</td>
<td>0.90±0.53</td>
</tr>
<tr>
<td>P</td>
<td>0.89±0.14</td>
<td>0.59±0.13</td>
<td>0.63±0.18</td>
<td>0.63±0.21</td>
</tr>
<tr>
<td>Ti</td>
<td>0.09±0.03</td>
<td>0.33±0.07</td>
<td>0.40±0.11</td>
<td>0.26±0.16</td>
</tr>
<tr>
<td>[ppm±s.d] As</td>
<td>724±157</td>
<td>485±120</td>
<td>380±133</td>
<td>545±186</td>
</tr>
<tr>
<td>Cd</td>
<td>534±127</td>
<td>122±30</td>
<td>121±40</td>
<td>26±215</td>
</tr>
<tr>
<td>Co</td>
<td>173±35</td>
<td>36±10</td>
<td>61±29</td>
<td>87±68</td>
</tr>
<tr>
<td>Cu</td>
<td>4682±1014</td>
<td>2895±696</td>
<td>6179±5720</td>
<td>4157±2635</td>
</tr>
<tr>
<td>Hg</td>
<td>4.28±1.27</td>
<td>3.46±1.18</td>
<td>3.06±1.30</td>
<td>3.66±1.23</td>
</tr>
<tr>
<td>Ni</td>
<td>395±82</td>
<td>170±43</td>
<td>211±110</td>
<td>254±124</td>
</tr>
<tr>
<td>Pb</td>
<td>1940±432</td>
<td>1215±338</td>
<td>1330±607</td>
<td>1483±518</td>
</tr>
<tr>
<td>Sr</td>
<td>153±28</td>
<td>220±22</td>
<td>170±20</td>
<td>18±57</td>
</tr>
<tr>
<td>V</td>
<td>91±39</td>
<td>125±51</td>
<td>120±26</td>
<td>108±51</td>
</tr>
<tr>
<td>Y</td>
<td>36±9</td>
<td>52±6</td>
<td>56±14</td>
<td>46±15</td>
</tr>
<tr>
<td>Zn</td>
<td>39627±8256</td>
<td>27032±6775</td>
<td>23185±8293</td>
<td>3055±9804</td>
</tr>
<tr>
<td>S</td>
<td>39938±7086</td>
<td>3706±8970</td>
<td>34618±11534</td>
<td>37616±8377</td>
</tr>
</tbody>
</table>

1 The amount of non-organic material (calculated with the ashweight), i.e. the actual load including organic material may be several times higher.
Based on mass-balance calculations of sulphate flux in the Stekenjokk tailings pond for the years 1992-2000,

Eriksson et al. (2001) estimated that the oxygen flux from the water cover to the tailings is less than $1 \times 10^{-10}$ kg O$_2$/m$^2$/s
Conclusions

The flooding at Stekenjokk works well. Only minor sulphide oxidation occur in the uppermost parts of the tailings.

The pond water is well mixed and oxic during the ice-free season.

Slightly higher metal concentrations occur below the ice during the winter, just above the sediment surface.

Diffusion from pore water is the major source of metals and other elements in the pond water. Previously weathered tailings release metals at a higher rate than unweathered tailings.

Resuspension is minor, and oxidation of resuspended sulphides is not an important metal source to the pond water.

There is oxygen available to 16-17 mm depth in the tailings.

During the years after the flooding, thin layers rich in Fe- and Mn-oxyhydroxides have formed in the uppermost part of the tailings, and a thin sediment layer rich in organic matter has been developed on top of the tailings.
In the uppermost part of the tailings, 33-42 % of the As, 73-83 % of the Cd, 59-76 % of the Co, 60-72 % of the Cu, 55-66 % of the Mo, 81-91 % of the Ni, 44-69 % of the Pb and 76-81 % of the Zn are bound to other phases than sulphides, presumably Fe- and Mn-oxyhydroxides and organic material.

The layers rich in Fe- and Mn-oxyhydroxides and organic material retain upwards diffusing metals, thereby lowering the amounts reaching the pond water.

The results show that it is possible that a flooded tailings pond may reach a state where the uppermost part of the tailings starts to function as a natural lake where sediments rich in organic matter and Fe- and Mn-oxyhydroxides control the diffusion of metals into the overlying water column, only a few years after remediation. However, it must be emphasised that the Stekenjokk tailings were flooded almost unoxidised and that the carbonate content of the tailings is relatively high.

The flooding at Stekenjokk works well, but if the flooding should be a walk-away solution, then dam stability is probably the weak point.