

***In Situ* Treatment of Acid Mine Drainage in Groundwater Using Permeable Reactive Materials**

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Acid-mine drainage (AMD) can introduce elevated concentrations of sulfate, ferrous iron and other dissolved metals to groundwater and receiving surface water. Permeable reactive barriers (PRBs) offer an approach for the passive interception and in situ treatment of AMD-impacted groundwater. Three field-scale applications and supporting laboratory columns in the past six years have shown that several thousands of mg/L sulfate, more than 1,000 mg/L iron, and several tens of milligrams per liter of other metals can be removed from plume or tailings groundwater. The reactive materials, which incorporate various forms of organic carbon, promote microbially mediated sulfate reduction, the generation of hydrogen sulfide, and the subsequent precipitation of sparingly soluble iron and other metal, such as Cd, Ni, Co, Cu, Zn, As or Zn, sulfide minerals. The applications include PRBs for the treatment of a plume at full scale from a mine-tailings impoundment and at demonstration- and full-scale at a former metal processing facility. These PRBs have removed sulfate and metals from groundwater. Similar materials were also used to create reactive layers within test cells directly in a tailings impoundment to evaluate the potential removal iron and sulfate from pore water before it migrates from the tailings impoundment.

PRBs have been considered as an alternative for plume control and remediation at many contaminated sites (Powell et al. 1998). PRBs have two essential functions. The PRB must facilitate the interception or capture of a contaminant plume at some distance down-gradient of the source, and provide treatment or removal of contaminants to acceptable levels. Treatment is achieved within or down-gradient of the barrier by physical, chemical or biological processes.

AMD is caused by the oxidation of residual sulfide minerals in the vadose zone of mine tailings and waste rock. AMD effluent is acidic and contains elevated concentrations of sulfate, ferrous iron [Fe(II)] and dissolved trace metals. Although buffering of the pH to near-neutral conditions may occur in groundwater flow systems, the oxidation of Fe(II) to Fe(III) occurs upon discharge of AMD to receiving surface water. This generates additional acidity and results in the precipitation of ferric oxyhydroxides, and can have adverse impacts on aquatic ecosystems by lowering the pH and enhancing the mobility of trace metals in surface water.

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PRBs can be used for to the in situ interception and treatment of AMD in appropriate hydrogeological settings (Benner et al., 1997; 1999; Blowes et al., 2000; Smyth et al., 2001). Alternate remedial options may be difficult to implement and maintain at full scale. Examples include the conventional collection, lime treatment and settling of AMD effluent; the use of covers to control the introduction of water and oxygen to the wastes; or the use of wetlands to treat AMD effluent.

In 1995 Benner et al. (1997; 1999) installed a PRB system that was approximately 20 m long, 3.6 m deep and 4 m thick in the direction of groundwater flow across a bedrock-bounded shallow aquifer at the Nickel Rim Mine near Sudbury, Ontario. The PRB consisted of a mixture of municipal compost, leaf mulch, wood chips, limestone and gravel (50%). The PRB system was installed in a backhoe-excavated trench and, was capped by clay to minimize direct infiltration of surface water into the reactive materials. The horizontal component of groundwater velocity in the vicinity of the PRB is of the order of 15 meters per year. The pH of the groundwater entering the PRB has ranged between 4 and 6, and contained 1000 to 5000 mg/L sulfate and 200 to 2500 mg/L iron.

The quality and acid-generating potential of groundwater has been improved significantly within and down-gradient of the PRB. The concentrations of sulfate, iron and other metals have been decreased by the PRB, and alkalinity has been increased. A zone of higher flow in which the residence time of groundwater is approximately 60 days was identified within the central portion of the PRB. Throughout the remainder of the PRB, the residence time of groundwater has been as much as 165 days (Benner et al., 1997: 1999). The variation in flow is a consequence of variability in groundwater flow in the aquifer and heterogeneity of hydraulic conductivity within the PRB. Evidence for sulfate reduction has included the identification of sulfate-reducing bacteria, the detection of dissolved sulfide (17 mg/L), isotopic enrichment of ^{34}S in remnant sulfate (Benner et al. 1999), and the identification of iron mono-sulfide solids in cores from within the PRB (Herbert et al. 2000). Spatial and temporal variations in the extent of sulfate and metals removal may have been caused by heterogeneity of hydraulic conductivity, loss of reactivity with time, and fluctuations of temperature within the PRB.

In 1997 a demonstration-scale PRB was installed at a former ore-concentrate storage facility on an industrial property in Vancouver, British Columbia. The site is adjacent to a tidally influenced channel, and the surficial aquifer comprises heterogeneous fill and alluvial sand and gravel, containing some cobbles and boulders (McGregor et al., 2000). The test wall was constructed using guar-gum slurry-trenching techniques, and the reactive materials consisted of a mixture of leaf compost, limestone and pea gravel (approximately 84%). The PRB was approximately 10 m in length, 6 m in depth and 2.5 m in thickness in the direction of groundwater flow. McGregor et al. (2000) estimated the residence time of water within the PRB to be three days and excellent attenuation of the metals of concern was achieved within the PRB. Locally, the concentration of sulfate entering the PRB exceeded 1,500 mg/L, and as much as several hundred of milligrams per liter was removed by sulfate reduction. The attenuation of metals also occurred. For example, average concentrations in groundwater decreased from 4.510 to 0.0077 mg/L for copper and from 2.396 to 0.082 mg/L for zinc between multi-level wells up- and down-gradient of the test PRB (McGregor et al. 2000). The full-scale PRB was installed

at the site in late 2000 and early 2001, and it consisted of approximately 400 linear meters of reactive wall consisting of compost, gravel and limestone. In zones of higher contamination, a second reactive wall that included zero-valent iron in the reactive mixture to enhance reactivity was also installed.

Smyth et al. (2001) described a promising test application of PRB technology directly in a mine-tailings impoundment. This approach to remediation is attractive because it can be initiated in conjunction with the disposal of tailings, and has the potential of immobilizing AMD contaminants within the tailings prior to off-site discharge. Tailings at the Kidd Creek Metallurgical Site near Timmins, Ontario have been deposited as a thickened tailings-slurry in a conical pile of approximately 15 m in depth and several thousand meters in diameter within the 1200-hectare impoundment. In September 1999 three treatment cells (3m x 3m) were installed within tens of meters of the perimeter drain where hydraulic gradients have an upward component. In two of the cells, different organic-rich waste materials from the forestry industry were incorporated in the upper meter of tailings (approximately 15% by volume). Core and monitoring well data suggest that active sulfate reduction is occurring in one of the test cells containing organic forestry wastes. Several thousands of milligrams per liter of sulfate and iron, and several hundreds of milligrams per liter of zinc, have been removed from pore water within one meter of ground surface in this cell.

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