COLUMN TESTS INVESTIGATION OF MILLING WASTES PROPERTIES USED TO BUILD COVER SYSTEMS[1]

Mostafa Aachib, Michel Aubertin, and Robert P. Chapuis[2]

Abstract: Among the alternatives that can be used to control the production of acid mine drainage generated by reactive tailings (milling wastes), the use of so-called dry covers appears to be one of the most practical. The purpose of such covers is to limit the flow of water and/or oxygen to the tailings, so that reactions leading to acid generation can be stopped. Various types of materials have been considered to build such covers, including geomembranes and fine-grained soils. Because these materials are not always economically available, the authors have proposed the use of fine tailings that do not contain sulfide as a capillary material in a multilayer cover system. To investigate the potential efficiency of milling wastes, a research project is presently underway. It includes different types of tests on homogenized tailings to determine some of their hydrogeological properties, such as hydraulic conductivity, capillary curves, and effective diffusion coefficient. In this paper, the authors briefly review the basic principles behind the design of multilayer cover systems to control acid production. Then some of the main components of an ongoing laboratory investigation are presented. The emphasis is placed upon column tests procedures used to evaluate various cover configurations. Some analytical and numerical solutions to specific problems related to cover design are finally given.

Introduction

Canada is one of the largest mineral producers in the world. This activity provides an important input to the country's economy, but it is also a source of concern regarding environmental protection. Among the various potential problems linked to the mining industry, it is usually acknowledged that acid mine drainage (AMD), resulting from the oxidation of sulfide minerals, represents the most serious threat to the ecological balance of natural habitats. In Canada, over 12,000 ha of tailings (milling wastes) and about 350 million mt of waste mine rock have been identified as acid-generating material, resulting mainly from the last four or five decades of base metal mining (Itzkovitch and Feasby 1993). A preliminary estimate of the reclaiming cost amounts to more than Can$ 5 billion, considering the presently available technology.

When one considers the various alternatives for stabilizing reactive wastes and reclaiming the land, the installation of covers (or caps) appears to be one of the most practical solutions, albeit often very expensive. The goal of such covers is to limit the flow of water and/or oxygen to the sulfidic wastes, which are the essential elements for the production of AMD. Various types of materials can be used to build such covers. Water cover to submerge tailings is certainly one of the most promising ways to control the production of AMD, as oxygen diffusion is considerably reduced (e.g., SRK 1989). The construction of an artificial water basin over an existing tailings pond can cause some difficulties, however, because of topography limitations, possible long-term stability problems, and of uncertainties regarding the actual effectiveness of water covers to stop an ongoing reaction of acid production and metal solubilization (e.g., Ritcey 1991).

Different types of processed materials can also be used in covers, such as geomembranes, bitumen, cement, etc., but it now appears that one of the most appealing techniques relies on the use of natural soils and other particulate media. In this case, it is generally considered that the main objective of the cover design is to ensure

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that it will be an efficient barrier to oxygen transport. To do so, it is essential that at least part of the cover remains close to saturation. This can be accomplished by using a capillary barrier system (e.g., Nicholson et al. 1989, Collin and Rasmuson 1990, Aubertin and Chapuis 1991a).

Traditionally, fine-grained soils have been used to build the capillary layer in a complex cover made of different superimposed materials. Recently, it has been suggested that tailings themselves, that ideally would not produce AMD, could be used for that purpose (Aubertin and Chapuis 1990, 1991a). There are various advantages in using tailings which are often located close to (if not on) the site. For instance, existing mills could treat sulfide-free ores in order to produce part of the cover system for an existing tailings pond generating AMD.

In this paper, the authors present the core of an ongoing research project aimed at investigating the behavior of tailings used as a capillary barrier in a multilayer cover system. The general approach of the project is described. It makes use of various laboratory experiments that provide the main hydrogeological properties of the material, such as hydraulic conductivity, capillary characteristic curves, and effective diffusion coefficients for oxygen, together with physical models and numerical modeling calculations. The main elements of the research program and some preliminary findings are presented and briefly discussed. Because the basic geotechnical properties of tailings have been presented elsewhere (Aubertin and Chapuis 1991b, Aubertin et al. 1993a, Chapuis et al. 1993), they are not presented in this paper.

Capillary Barrier Concept

A capillary barrier can be generated when a porous material located above the water table maintains a water content close to saturation. This phenomenon can be advantageously controlled when a fine-grained material layer is placed between two coarser grained material layers. In this case, the middle layer will tend to maintain a high water content while the coarser materials will dry more easily.

Capillary Characteristics

To quantify the actual behavior of a layered system, one has to investigate the ψ-θ_w relationship of the different materials, where ψ represents the negative water pressure (or suction) and θ_w is the volumetric water content. This relationship is given by the capillary characteristic curve, which provides very important information for the cover design because θ_w largely influences the hydraulic conductivity K and the effective diffusion coefficient for oxygen D_e. Various methods have been used to measure the capillary characteristic curves of particulate media (e.g., Kovács 1981, Fredlund and Rahardjo 1993), and ensuing curves obtained from these tests have been described by different models (e.g., Bear 1972, Arya and Paris 1981).

On figure 1, one can see schematical ψ-θ_w relationships for a sand and a silt. When the elevation above the water table (or equivalent negative pressure) is below ψ_a (often called "Air Entry value - AEV"), the material remains close to saturation; in this case, the capillary forces acting in the largest pores are sufficient to resist the effect of the potential energy. As elevation is increased above ψ_a, the suction pressure increases (in absolute value), and water content decreases gradually as smaller pores are progressively drained until the residual water content θ_r is reached at an elevation corresponding to ψ_r (Kovács 1981).

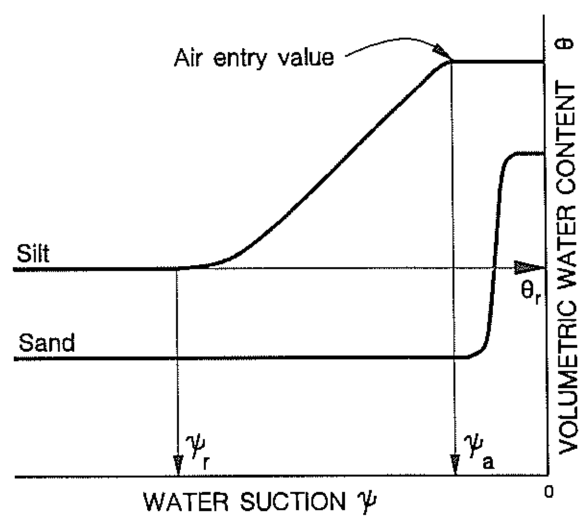

Figure 1. Typical moisture characteristic curves.

The AEV (or ψ_a) value is a very important parameter for capillary barriers because it indicates the height above the water table associated with nearly full saturation for a porous medium. It has been found experimentally that this value is about 10 to 50 cm for sands, between 100 to 300 cm for most silts, and above 5 to 10 m for clays (e.g., Lambe and Whitman 1979, Todd 1980).

The value of the main parameters of the suction curve (ψ-θ_w), that is, ψ_a, ψ_r, and θ_r, appears to be controlled by some of the basic properties of the material, such as grain size and porosity. A few relationships have been proposed to express the effect of these influence factors. A general formulation for that purpose, which would encompass most of the existing equations, could be expressed as follows:

$$\psi = f\ (D_x,\ n,\ Y\ ), \tag{1}$$

where D_x is the grain size, n is the porosity, and Y represents a complementary function (usually omitted in most formulations) introduced to take into account specific effects that could be expressed from other basic properties such as specific surface area S, viscosity of water μ, plasticity index I_p, and so on. In actual expressions proposed in the literature for ψ_a, equation 1 is generally given as a linear (Bear 1972) or nonlinear (Yanful 1991) function of the effective diameter D_{10}, while the porosity function is often expressed as (1-n)/n (e.g., Bear 1972, Kovács 1981). After investigating existing models, wide disparities have been found between the obtained results (Aubertin et al. 1993a, Aachib et al. 1993). Thus, one of the goals of this ongoing project is to develop a more appropriate expression (Ricard, in preparation).

By using the ability of different types of materials to maintain different water content as a function of height, it is possible to conceive a layered system in which a capillary layer (made of a fine-grained material that has a high ψ_a value) remains close to saturation. In a well-designed system, the thickness L of the capillary layer that could be maintained close to full saturation is given by (Nicholson et al. 1989):

$$L = |(\psi_a)_f| - |(\psi_r)_c|, \tag{2}$$

where $(\psi_r)_c$ represents the equivalent suction pressure corresponding to the residual water content of the coarse material, and $(\psi_a)_f$ is the AEV of the fine material layer placed above. As an example, using $|(\psi_r)_c| = 80$ cm for a sand (which is often about twice the value of $(\psi_a)_c$ according to Kovács 1981) and $(\psi_a)_f = 180$ cm for fine tailings, one obtains L=1 m. Interestingly, preliminary calculations on the efficiency of a layered system to decrease the oxygen flow show that there is not much gain to be made in increasing thickness L above 1 m (Nicholson et al. 1989, Aachib et al. 1993); this aspect will be discussed further later on.

The concept of a multilayer cover system placed well above the water table and in which the fine layer can maintain a high degree of saturation has been confirmed by some laboratory tests (Yanful 1991) and by numerical modeling calculations (Akindunni et al. 1991, Yanful and Aubé 1993).

Unsaturated flow

During and after a water inflow from the top, coarse material layers placed above and below the fine material layer serve to drain the cover. However, when these coarse materials themselves have been drained and their volumetric water content reaches θ_r, then they help to maintain a high θ_w value in the in-between layer because their hydraulic conductivity is considerably reduced. Thus the water will not tend to flow downward, nor will it move upward because the coarse material placed above the fine material also serves as a non-capillary barrier preventing capillary rise.

To better understand the behavior of a layered cover, one has to study different properties of the materials used in the system. As the hydraulic conditions play a key role, it is worth discussing the matter further.

The well-known Darcy's law is generally used to describe the flow of water in a porous medium under saturated conditions. However, when the degree of saturation S_r is less than 100%, one has to express the water flow equation as a function of ψ and θ_w. One popular approach in this instance is to use a modified version of Darcy's law in which the hydraulic conductivity is given as a function of the water content. Following numerous experimental investigations, different models have been proposed to describe the relationship between the unsaturated hydraulic conductivity $K(S_e)$ and θ_w (e.g., Mualem 1986). One of the most popular was proposed by Van Genuchten (1980); it can be written as follows:

$$K(S_e) = K_s \; S_e^{0.5} \left(1 - (1 - S_e^{1/\gamma})^{\gamma}\right)^2 \tag{3}$$

with

$$S_e = \frac{\theta_w - \theta_r}{\theta_s - \theta_r}, \tag{4}$$

where S_e = effective degree of saturation ($0 \le S_e \le 1$),
K_s = saturated hydraulic conductivity,
θ_s = volumetric water content at saturation,
and γ = constant parameter for curve adjustment.

According to this model, $K(S_e)$ becomes zero when θ_w reaches θ_r, and it tends toward K_s when θ_w approaches θ_s; such limiting values are in accordance with most experimental measurements.

Experimental Program

The behavior of tailings used in cover systems as a capillary barrier is studied using various experimental devices. Consolidation behavior is investigated with standard oedometer tests on homogenized tailings, while hydraulic conductivity is studied by performing constant-head and falling-head permeability tests in oedometric cells and in rigid-wall permeameters (Aubertin et al. 1993a). Capillary characteristic curves, on the other hand, are established by using various techniques, including the pressure plate vessel (Aubertin et al. 1993b), while the transport of oxygen in a humid porous material is presently studied with different approaches including one device used previously by Yanful (1993). All these basic experiments provide inputs into a numerical model that will be used to predict the actual behavior of a cover system.

The numerical model is calibrated and validated by performing two types of column tests (Aachib et al. 1993). The first type of column, called the drainage column (fig. 2), is used to estimate the water conditions existing in the cover. It is a plexiglass column having an internal diameter of 15.5 cm and a height of 110 cm . The column is instrumented with tensiometers and TDR (time domain reflectometry) probes to measure, respectively, suction pressure and volumetric water content along its length. The column design was adapted from Yanful (1991).

This column is used to investigate the behavior of various layered systems under different water boundary conditions. Although upward flow is sometimes considered, most experiments are performed under downward flow. Results of the drainage column tests are compared with those obtained on individual materials in capillary tests and with numerical calculations.

The other type of column test is performed in the control columns used to evaluate the performance of cover systems placed over sulfide tailings (fig. 3, B). These columns serve to evaluate the reduction in oxygen flow through the cover and toward the reactive tailings. Ten columns have been built for long-term tests, which started in October 1993 and will last until November 1994. These columns are also made from plexiglass, and eight of them have a height of 1.7 m. Two identical columns are made for each system, one being instrumented with TDR probes and thermocouples and the other one free of any instrument perturbation. The cover layers, which are placed over a layer of tailings containing about 20% iron sulfide, include a layer of sand (30 cm in thickness), a non-reactive tailings layer (50 cm in thickness), and a final layer of sand (20 cm in thickness). The sand used in the covers is a concrete sand, and the capillary barriers are made from three different tailings free of sulfide minerals. Another tailing containing a small amount of pyrite is also investigated in the last two columns. Two smaller columns have also been built with reactive tailings without any cover in order to evaluate the effect of the cover (fig. 3, A). In all the columns, water is added from the top periodically, and the percolating water reaching the bottom of the column is analyzed; electric conductivity, pH, sulfate, and metal contents are determined. These provide indication of the possible reactions happening in the system. Temperature measurements in the column also serve as indirect evidence of chemical reactions in the column.

The RETC program (Van Genuchten et al. 1991) is used to evaluate the conditions in the cover system. Numerical calculations are compared with measured performance in the control columns to validate the basic calculation approach.

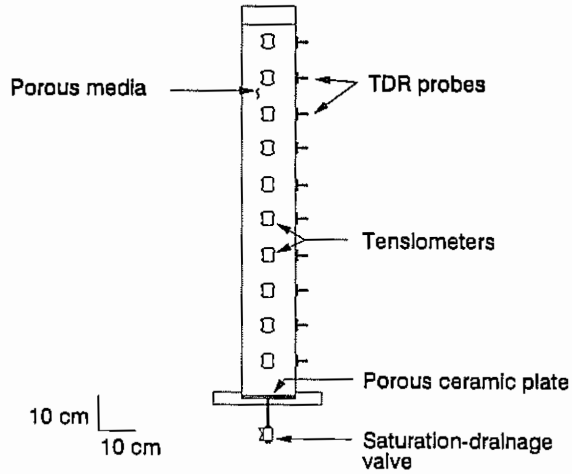

Figure 2. Schematical representation of the drainage column.

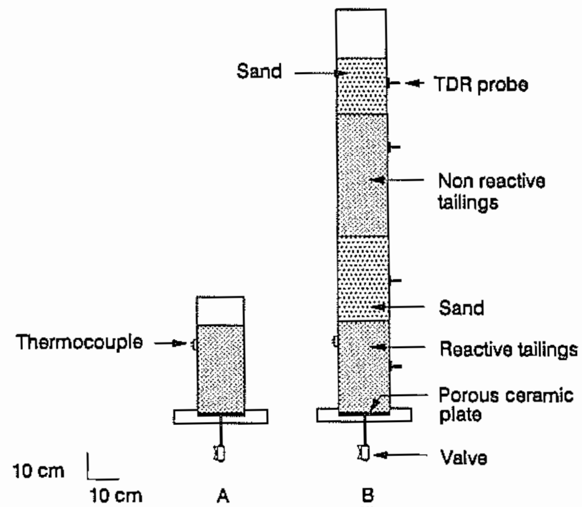

Figure 3. Schematical representation of the control columns;
A: reference column for reactive tailings without covers;
B: reactive tailings covered by a layered system.

Preliminary Calculations for Two Cover Systems

In covers made from partly saturated materials, it is often considered, at least for preliminary calculations, that oxygen transport is controlled by molecular diffusion in the gaseous or liquid phases, as temperature and pressure gradient effects are neglected (Collin 1987, Nicholson et al. 1989). Such oxygen diffusion is associated with concentration gradients between conditions found in the atmosphere and those of the porous media.

Using the presently available information, the authors have performed some simple calculations in order to compare the efficiency of two cover scenarios; more details are given in Aachib et al. (1993). The first case is that of a single layer cover having a thickness L. The starting points of the calculations are Fick's laws given by Bear (1972) and Shackelford (1991):

$$F(t) = \theta_g D_e \frac{\partial C(t)}{\partial z} \tag{5}$$

and

$$\frac{\partial C(t)}{\partial t} = \frac{\partial}{\partial z}\left(D_e \frac{\partial C(t)}{\partial z}\right) - k_r C(t) \ , \tag{6}$$

with

$$\theta_g = \frac{V_g}{V} \ , \tag{7}$$

where $F(t)$ = diffusive flux of oxygen (kg/m²/s),
D_e = effective diffusion coefficient of oxygen (m²/s),
$C(t)$ = oxygen concentration in the gaseous phase at time t (kg/m³),
z = depth (m),
t = time (s),
θ_g = volumetric gas content of the porous media, also called gas-filled porosity (m³/m³),
V_g = gas volume (m³),
V = total volume (m³),
and k_r = reaction rate constant (for sulfide oxidation).

In this equation θ_g is related to the degree of saturation S_r and porosity n :

$$\theta_g = n(1 - S_r) \ . \tag{8}$$

Analytical solutions to these equations have been given by Crank (1975), for $k_r = 0$ (non-reactive cover system):

$$F(t) = 2C_o\theta_g \sqrt{\frac{D_e}{\pi t}} \sum_{m=o}^{\infty} \exp\left[-\frac{(2m+1)^2 L^2}{4D_e t}\right] \tag{9}$$

and

$$C(z,t) = C_o \ \mathrm{erfc}\left(\frac{z}{2\sqrt{D_e t}}\right), \tag{10}$$

where

$$\mathrm{erfc}\ (u) = 1 - \frac{2}{\sqrt{\pi}} \int_o^u \exp(-v^2)\ dv \ , \tag{11}$$

and m is an integer variable. These are obtained for the following limiting conditions:

$C = 0$ for $t = 0$ and $z \geq 0$,
$C = C_0$ for $t \geq 0$ and $z \leq 0$,
and $C = 0$ for $t \geq 0$ and $z \geq L$,

where C_0 is the atmospheric oxygen concentration. These conditions imply a decreasing oxygen concentration in the cover until it is reduced to zero at the top of the reactive tailings, where the oxygen consumption is very rapid. In these equations, D_e is calculated from the modified Millington-Shearer model given by Collin (1987) and Aubertin et al. (1993a):

$$D_e = (1 - S_r)^2\ [a(1-S_r)]^{2x}\ D_o + S_r^2\ (a\ S_r)^{2y}\ H\ D_w \ , \tag{12}$$

where D_o = diffusion coefficient of oxygen in air (m²/s),

D_w = diffusion coefficient of oxygen in water (m^2/s),
H = solubility constant of gas in water,
and a,x,y = material parameters, expressed as function of n and S_r.

To estimate the value of D_e, results of Reardon and Moddle (1985) were used to calibrate the above model. Typical parameters values for the sand and tailings are thus obtained. Calculation results are shown in figure 4. As one can see, $D_e \approx D_w$ when $S_r \approx 90\%$. Having a D_e value for the humid porous system practically equal to that of water is very advantageous because water covers have often been considered the most efficient way to control production of AMD (e.g., SRK 1989). In the case of dry covers, however, one is somewhat less concerned with stability problems of the retaining structures.

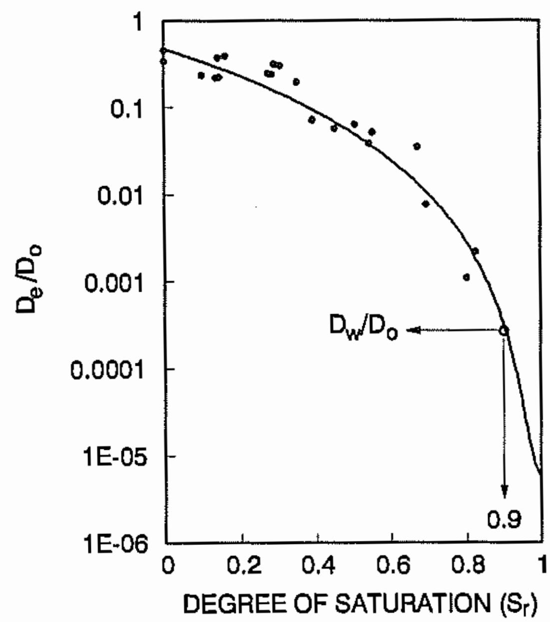

Figure 4. Effective diffusion coefficient expressed as a function of the degree of saturation (see equation 12); data taken from Reardon and Moddle (1985).

Using these equations, a first calculation is made for steady state flow in a simple layer using typical parameters for the cover material (i.e., C_o=21%, n=0.41, S_r=0.87, L=1.1 m, D_e=4.61x10^{-9} m^2/s); this calculation gives F(t)=0.036 $kg/m^2/yr$ O_2.

Using the same set of equations, one could also calculate the efficiency of the cover layer, as defined by Nicholson et al. (1989):

$$E_c = \frac{F_r}{F_c} = \frac{\sqrt{k_r (D_e)_r}}{(D_e)_c} L + 1 , \qquad (13)$$

where F_r = oxygen flux through the reactive tailings without a cover,
F_c = oxygen flux through the cover,
and $(D_e)_{r,c}$ = effective diffusion coefficient in the reactive tailings (r) and cover material (c).

Figure 5 shows some calculated E_c values as a function of L and S_r, for $k_r = 300\ yr^{-1}$. These results compare well with those of Nicholson et al. (1989) obtained for slightly different conditions. These show that increasing the thickness of the cover above about 0.5 to 1 m does not much change its efficiency. Also, these show that a cover 1 m thick with S_r = 90% is more efficient than one of 4 m having an S_r = 80%. As expected, the degree of saturation is thus found to be a critical parameter for cover design.

For a complex cover made from different horizontal layers, one can also calculate the oxygen flux with the first Fick's law for steady-state flow, equating the flux at each interface, which gives the following equation (Yanful 1991):

$$\left(\frac{D_i}{L_i}\right) C_{i-1} + \left(\frac{D_{i+1}}{L_{i+1}} - \frac{D_i}{L_i}\right) C_i + \left(\frac{D_{i+1}}{L_{i+1}}\right) C_{i+1} = 0 , \qquad (14)$$

where index i is given for layer i. Again, assuming atmospheric oxygen concentration at the surface and a zero concentration at the top of the reactive tailings, one calculates that the same flux of oxygen is obtained for the single layer cover with L = 1.1 m, and for a three-layer system in which the capillary barrier (n = 0.41, S_r = 90%) is only 0.5 m thick. Table 1 compares the two scenarios. This result is possible because the layered system helps to maintain a high degree of saturation in the capillary barrier, which in turn reduces the value of the effective diffusion coefficient that largely controls the oxygen flux.

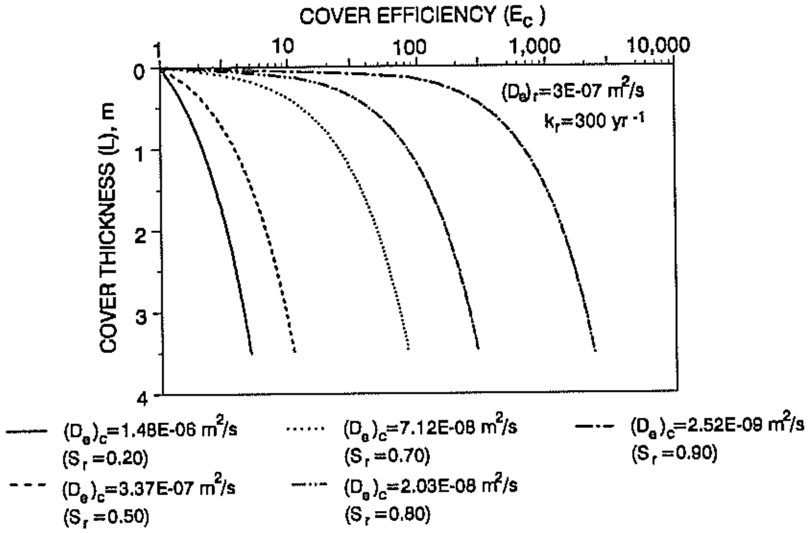

Figure 5. Relationship between the cover thickness and its efficiency to reduce the oxygen flux (after Aachib et al. 1993).

Table 1. Oxygen flux calculations for two cover systems.

Cover	Material	n	S_r	L, m	D_e, m²/s	Oxygen flux, kg/m²/yr O_2
One layer	Tailings	0.41	0.87	1.10	4.61×10^{-9}	0.036
Three layers	Sand Tailings Sand	0.39 0.41 0.39	0.10 0.90 0.10	0.30 0.50 0.30	1.87×10^{-6} 2.52×10^{-9} 1.87×10^{-6}	0.036

Conclusion

After briefly reviewing the basic principles behind the use of covers made from particulate media to control the production of acid mine drainage (AMD), the authors have presented the core of a laboratory research effort to investigate the properties of milling wastes used in a multilayer cover system. The emphasis is placed upon the two types of column tests used to calibrate and validate a model in which the input parameters are obtained from basic laboratory tests, such as hydraulic conductivity, capillary characteristic curves, and effective diffusion coefficients of oxygen. The description of the experimental devices is followed by some preliminary calculations on the efficiency of a layered cover system to reduce oxygen flow, based on analytical solutions of Fick's laws. Using these, it is infered that the critical parameter in the design of a cover system is the volumetric water content, which (as may be expected) should be maintained as high as possible in the capillary layer in order to reduce the flow of oxygen. A degree of saturation of 90% in a porous material produces a layer that has about the same effective diffusion coefficient as that of water. So far, this fairly broad research project has shown that tailings present some very interesting properties as a constitutive material in a multilayered system, considering their relatively low hydraulic conductivity, high water retention characteristics and capacity to reduce the flow of oxygen.

Acknowledgements

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