PERFORMANCE OF CONCRETE BARRIERS IN RADIOACTIVE WASTE DISPOSAL IN THE UNSATURATED ZONE

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ABSTRACT

Concrete barriers are an important component of many designs for disposal of radioactive waste in the unsaturated zone. In order to evaluate the effectiveness of the concrete barriers performance assessment models representing the material degradation rates and transport properties must be developed. Models for evaluation of fluid flow and mass transport through partially failed concrete barriers located in the unsaturated zone are presented. Implications of the use of impermeable barriers design are discussed. Concrete of highest quality may not always be desirable for use in all components of waste disposal vaults.

INTRODUCTION

In the US and other countries low level radioactive waste disposal facilities will take the form of earth covered concrete bunkers (Figure 1). In order to evaluate the performance of these disposal systems an evaluation must be made of the role of the concrete barriers. The concrete can serve several functions in the disposal system including structural support, limiting of water percolation, geochemical conditioning of water contacting the waste and waste containers, and slowing of radionuclide release rates.

Because high quality concrete is relatively impermeable, most of the flow through a concrete system is likely to be through cracks. The permeability of intact concrete with low water/cement ratio is very low [1]. For this reason, cracks, particularly microcracks, are thought to actually control concrete permeability in service environments. Microcracks are caused by a variety of phenomena including response of concrete and reinforcement bars to physical loading, drying shrinkage, and expansion/contraction from temperature changes. Methodologies for estimation of crack width and spacing in concrete slabs have been developed by Bazant and others [2]. Crack like openings can also be present at joints in the concrete. Rather than attempt to determine the extent of cracking, we instead look at the performance implications of cracks.

FLUID FLOW THROUGH CRACKS

The first analysis assumes saturated flow through the concrete layer. Although the concrete vaults will typically be located in the unsaturated zone, areas of saturation may be expected in and above portions of the concrete as illustrated in Figure 2. A phenomenon called capillary perching also leads to near saturation in very fine grained barrier materials which are underlain by more coarse grained material. Because of the very small size of the pores in the barrier material and the large pore sizes in the coarse grained material, the barrier material will not drain into the large underlying pores until saturation is reached.

If an infinitely long, parallel-sided crack through the concrete is assumed, the flow through the crack is:
Figure 1. Schematic of below ground concrete vault.

\[ K = \frac{\rho g b^2}{12 \mu} \]  

(1)

Studies of flow through cracks in concrete slabs have shown that actual flow is typically 1/3 to 2/3 of the theoretical value [3]. This is presumably due to variation in thickness and roughness along the walls. A value of 1/2 is used herein giving:

\[ K = \frac{\rho g b^2}{24 \mu} \]  

(2)

The above equations consider only the head loss involved in passing through the crack. In some situations the resistance to water entering (and/or exiting) the crack may also be significant. The governing equation for steady state percolation through cracks is:

\[ K \nabla^2 H = 0 \]  

(3)

Boundary conditions are a fixed head at the crack mouth and fixed head at distance, and no flow at intact concrete portions.

Total flow through the crack at steady state is obtained by integration over the opening surface.

\[ Q = \int S \int (-K \nabla H) \cdot \vec{n} \, dA \]  

(4)

In the Cartesian coordinate system the flow is calculated for a \( \Psi \) length segment of an infinitely long slit. Following Chambre et al. [4], the equations are put into dimensionless form by defining the following variables:

\[ h = \frac{H - H_*}{H_0 - H_*} \quad \quad z = \frac{Z}{\Psi} \quad \quad q = \frac{Q}{K \Psi (H_0 - H_*)} \]  

\[ x = \frac{X}{\Psi} \]
The flow rate in terms of dimensionless variables is:

$$q = -2 \int_{0}^{1} \frac{\partial h}{\partial z} dx$$

(5)

The percolation rate through the porous medium is given by the solution of the governing equations in terms of a dimensionless flow rate q. The dimensionless format assists with generalization of the results.

When examining flow through a cracked concrete layer, both resistance in passing through the crack and entrance/exit resistances can be important (Figure 3). The entrance resistance to flow through a series of parallel cracks was estimated with the finite difference flow and transport code PORFLO [5]. To facilitate generalization of the results they are cast in terms of dimensionless variables.

Figure 4 illustrates the impact of crack spacing and thickness of the porous medium on flow rate from a single crack when multiple equally spaced cracks are present. The results are given in terms of dimensionless crack spacing ($x_{c} = x_{c} / \psi$) and dimensionless distance to a fixed head boundary ($z_{c} = z_{c} / \psi$) where $\psi$ is the half width of the crack. The distance to a fixed head boundary ($z_{c}$) corresponds to the thickness of the porous layer above the concrete. Reduction of the crack spacing (i.e., larger number of cracks per unit area) reduces the flow rate from each crack.
Figure 3. Schematic of simulation geometry. \((H_3-H_2)\) is the head drop entering (or exiting) the crack while \((H_2-H_1)\) is the head drop in the stem of the crack. \(W\) is the concrete slab thickness and \(\psi\) is the crack half width.

The above calculations consider entrance and exit head losses separately from head loss in passing through the crack. By using a series of resistors analogy, expressions can be derived for combined head loss. With narrow cracks, the resistance to flow is dominated by passage through the crack itself. With relatively wide cracks, the entrance and exit resistances predominate. The overall analysis suggests that the permeability and thickness of the surrounding porous material may play an important role in limiting flow through partially failed concrete barriers.

Location of the facilities in the unsaturated zone greatly complicates the role of cracks in influencing performance. In unsaturated environments, water remains in a state of tension created by capillary action and adsorption. Because cracks are large relative to the pore size of the matrix, they have a limited ability to hold water in tension. In other words, under unsaturated conditions cracks will drain quickly. The drained cracks not only no longer contribute to flow but may also serve as barriers to flow [6]. Depending upon the degree of saturation, cracks may produce effects that range from orders of magnitude increases in flow rate to significant decreases in flow relative to an uncracked specimen. The ability of cracks to hold water (and thereby contribute to flow) is a function of pressure head (Figure 5).

The pressure head for drainage of a crack of width \(2\psi\) is:

\[
\phi = \frac{-2\gamma \cos(\alpha)}{\beta \rho g}
\]  

(6)

Thus the crack width giving permeability increase at any given pressure head is the greatest width which will not be drained or:

\[
\psi_{\text{max flow}} = \frac{-\gamma \cos(\alpha)}{\beta \rho g} = -0.074[\text{cm}^2]
\]  

(7)

Equations have been derived which estimate the maximum flow rate through the system as a function of concrete strain (total gap space) and pressure head of the water. This can be done by assuming that all the cracks are the largest size which will conduct water at the ambient pressure head. The maximum crack permeability under partially saturated conditions (i.e., \(\phi \leq 0\)) is:
velocities are more rapid in cracks. Cracks also contribute from matrix diffusion than external environment. Typically unimportant. In these situations cracking can be lowered by diffusion of contaminants from the aqueous solution inside the crack out into the surrounding concrete matrix (matrix diffusion).

**MASS TRANSPORT THROUGH CRACKED CONCRETE**

Radionuclides which become dissolved or entrained in the water which percolates through the vault will preferentially exit through cracks. Because the volume of cracks is typically much lower than the pore space in the matrix, for any fixed flow rate flow velocities are more rapid in cracks. Cracks also offer less surface area per volume of water for sorption of radionuclides than pore spaces. The rate of mass transport through cracks can be lowered by diffusion of contaminants from the aqueous solution inside the crack out into the surrounding concrete matrix (matrix diffusion).

The importance of matrix diffusion in limiting mass transport through cracks in concrete barriers is examined using the analytical solution of Tang [7]. The calculations assume different values of the diffusion coefficient of contaminants in the concrete matrix. The concrete is assumed to be 100 cm thick with a porosity of 10%. The results are graphed as dimensionless concentration at the crack exit \( C/C_0 \) and dimensionless time (time/water travel time). At the narrow crack widths and high diffusivities, matrix diffusion will be effective in slowing radionuclide transport through fractures in the concrete. At wider crack widths and with higher quality concrete, matrix diffusion will be relatively unimportant. In these situations the cracks serve as direct conduits to the external environment.

The high quality, dense concretes best suited to longevity, give much lower contributions from matrix diffusion than concretes with a higher water/cement ratio. High quality concretes are less likely to form cracks, since they are less subject to chemical attack. However the consequences of cracking may be greater in high quality

\[
K_{max} = \frac{S y^2 \cos^2(\alpha)}{6 \phi^2 \mu g} = \frac{S \gamma^2 \cos^2(\alpha)}{6 \mu g} = 900 \left[ \frac{\text{cm}^3}{\text{s}} \right] \frac{\text{S}}{\phi^2} \quad \Psi_{maxflow} < \frac{SW}{2}
\]
Figure 5. Pressure head at which cracks of different widths will hold water.

(low water/cement ratio) concrete than low quality concrete. The properties (low water/cement ratio) which are favorable for the roof and structural components of a below ground concrete vault may not be preferable for grouting and/or floor material.

CONCLUSIONS

Cracks and joints in concrete barriers are important for controlling water infiltration and mass transport of radionuclides in low level waste disposal facilities located in the unsaturated zone. Mathematical models have been applied as tools for evaluating the performance of cracked concrete slabs. Saturated conditions are comparatively easy to model with predictable increases in flow rate resulting from the presence of cracks. Unsaturated conditions are more complex and the effects of cracks are more difficult to model. In the unsaturated zone, cracks can result in large increases in flow rate but may, under some circumstances, actually decrease flow rates through concrete. In each case the flow rate through the cracked concrete is dependent upon crack spacing and the permeability + thickness of adjoining porous materials.

Mass transport through fractured concrete is a result of matrix diffusion and flow through cracks. The material properties of various concretes influence these two mechanisms differently. Further investigation of the effects of cracks is required to determine the optimum material properties of concrete for long term performance of disposal facilities.

NOMENCLATURE

\[
\begin{align*}
A &= \text{surface of crack (L}^2\text{)} \\
b &= \text{crack width} = 2V \\
g &= \text{acceleration of gravity (980 cm/s}^2) \\
H &= \text{hydraulic head (L)} \\
H_0 &= \text{hydraulic head at crack mouth (L)} \\
H_1 &= \text{hydraulic head at distance} \\
h &= \text{dimensionless head} = (H - H_1)/(H_0 - H_1) \\
K &= \text{hydraulic conductivity (L/T)} \\
\bar{n} &= \text{unit normal vector} \\
Q &= \text{total flow out crack (L}^3/T\text{)} \\
q &= \text{dimensionless flow rate through crack} \\
S &= \text{strain in concrete} \\
V &= \text{Darcy velocity (L/T)} \\
W &= \text{concrete layer thickness or width of concrete slab (L)} \\
w &= \text{dimensionless thickness} = W/V \\
X &= \text{lateral distance (L)} \\
X_0 &= \text{half of lateral distance between cracks (L)} \\
x &= X/V = \text{dimensionless lateral distance} \\
Z &= \text{distance normal to crack (L)} \\
Z_0 &= \text{thickness of porous media above concrete (L)} \\
z &= Z/A = \text{dimensionless normal distance} \\
\Psi &= \text{characteristic dimension (crack half width) (L)}
\end{align*}
\]
Figure 6. Dependence of matrix diffusion in concrete cracks upon effective diffusivity. Crack width is 0.02 mm, length 100 cm. Diffusivity is as shown in units of cm²/s.

\[ \rho = \text{density of water (g/cm}^3) \]
\[ \mu = \text{viscosity of water (0.01 g/cm s)} \]
\[ \phi = \text{pressure head (L)} \]
\[ \gamma = \text{surface tension of water (72.7 dyne/cm)} \]
\[ \alpha = \text{cement water contact angle (assumed = 0)} \]

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