Laboratory investigation of matrix imbibition from a flowing fracture

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Abstract. Predicting fluid flow and transport behavior in unsaturated, fractured rock is greatly simplified where matrix imbibition can be modeled as a linear function of the square root of time ($t^{1/2}$); however, such treatment implicitly assumes homogenous matrix properties. To investigate matrix heterogeneity effects, we perform a simple experiment in which x-ray imaging is used to measure the imbibition of water from a flowing fracture into a slab of volcanic tuff. Experimental results show matrix imbibition to follow a linear $t^{1/2}$ relationship even though the saturated hydraulic conductivity of the tuff varies by over four orders of magnitude.

Introduction

A key element in predicting groundwater and contaminant travel time through unsaturated, fractured rock is a thorough understanding of the interaction between the fracture system and porous matrix. In such systems, permeable, well-connected fractures are capable of yielding very rapid transport. However, where strong capillary gradients are present, matrix imbibition may impede or even preclude intermittent fracture flow (Nitao and Buscheck, 1991; Zimmerman and Bodvarsson, 1989), potentially increasing travel times by several orders of magnitude.

To predict transport behavior in unsaturated, fractured rock, a variety of conceptual models have been developed. These models differ primarily in the way fracture-matrix interaction is represented. For example, in quasi steady-state systems, composite-continua models are employed that assume equilibrium between the fractures and matrix. In these models, fracture-matrix interaction is not explicitly modeled but incorporated via effective media properties (Peters and Klavetter, 1988). Where transient behavior is important, dual-porosity models are commonly used. In this approach the fracture system forms the continuum for fluid flow while fracture-matrix interaction is modeled as a source/sink term to the fractures (Gilman, 1986). These calculations are simplified where the source/sink term can be reduced to a simple algebraic or integral expression. A number of methods have been employed to model matrix imbibition in an infinite medium where flow is capillary dominated and one-dimensional. Among these are similarity transform methods (Philip, 1955), boundary layer or integral methods (Zimmerman and Bodvarsson, 1989), and empirical methods (Rossen, 1977). Each of these approaches are in general agreement that the imbibition flux and wetting front penetration are linearly related to $t^{1/2}$. The more realistic case of imbibition into three-dimensional porous blocks (i.e., converging matrix flow) has been investigated by Zimmerman et al. (1990). They found strict linear imbibition to occur only at very early times (i.e., where penetration depth is small relative to the curvature of the block); however, significant deviation from linear behavior did not occur until the wetting front reached the mid-point of the block.

The advantage of modeling matrix imbibition as a linear function of $t^{1/2}$ is apparent. Where linear behavior is exhibited, a constitutive parameter termed the sorptivity is used to quantify the time dependence of matrix imbibition. In this paper we explore, by means of a physical experiment, the influence of matrix heterogeneity on imbibition. X-ray imaging methods are used to measure the imbibition of water from a single slot fracture into slabs of volcanic tuff. In this way, the linearity of the imbibition process is studied and the matrix sorptivity calculated as a function of spatial resolution.

Physical Experiment

A fracture-matrix experiment was performed in a simple two-dimensional, thin slab system oriented normal to the plane of the fracture. The system consisted of two air-dried rock slabs (Topopah Spring Tuff from Busted Butte, Nevada Test Site), each measuring roughly 50 by 15 by 2.5 cm thick. The slabs were mated along the 50 cm (sawn) edge to form a single 0.1 mm slot fracture. The test system was wrapped in mylar to minimize evaporation; however, a 1 cm gap was maintained between the tuff slabs and mylar to allow unrestricted movement of air from the slabs. A constant flux boundary condition was applied at the top of the vertically oriented fracture (5 ml/min.) and a constant suction boundary (10 cm water) was applied at the bottom of the fracture with a hanging water column (Figure 1).

At the onset of infiltration, water moved rapidly through the fracture and began to drip from the bottom of the hanging column. Water did not fully span the width of the fracture but instead fingered within the 2.5 cm fracture thickness. As time progressed, fluid moved from the fracture into the matrix (initially at near zero saturation) until the wetting fronts neared the outside edges of the tuff slabs, at which time the experiment was stopped. During this period, x-ray imaging was performed using a 60 kV potential and exposure time of 3 minutes (Tidwell and Glass, 1994). Two-dimensional x-ray images, integrated over the thickness of the slab, were acquired at

Paper number 95GL01097
0094-8534/95/95GL-01097$03.00

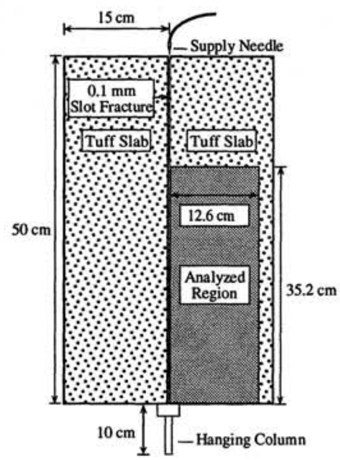

Figure 1. Schematic of the fracture-matrix experiment. Boxed region delineates area analyzed.

5, 15, 30, 60, 120 and 180 minutes. Potassium iodide (KI) was dissolved in the water (10% by weight) to enhance the x-ray adsorption contrast between air and water. Following the experiment, the slabs were rinsed for several weeks to remove all KI, oven dried, vacuum saturated with fresh KI solution, and finally re-imaged to yield the fully saturated field (necessary in quantifying matrix saturation and porosity).

Using a digital camera, the x-ray images recorded on film were digitized into arrays of 1024 by 1024 pixels (0.44 mm by 0.44 mm) each with a dynamic gray-scale range of 4096 levels. A subsection of the experiment, 800 pixels tall and 288 pixels wide (352 mm tall, 126.7 mm wide), was chosen for analysis (Figure 1). Saturation fields as a function of time were then calculated for this region from the digitized images using the method of Tidwell and Glass (1994). The porosity field was also determined. This involves subtracting the log (natural) transformed background (dry) image from the log (natural) transformed vacuum saturated image, normalizing the difference image by its mean intensity, then multiplying by the average porosity for the slab (determined independently by gravimetric methods to be 0.20 ±0.005). Figure 2 presents the saturation fields at 5, 15, 60, and 180 minutes along with the porosity field.

Matrix Sorptivity

Richards equation for one-dimensional, capillary-dominated flow may be written in the non-linear diffusion form:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}\left(D(\theta)\frac{\partial \theta}{\partial x} \right) \tag{1}$$

subject to the boundary and initial conditions:

$$\begin{aligned} \theta(x, t=0) &= \theta_i \\ \theta(x=0, t>0) &= \theta_o \\ \theta(x \to \infty, t \geq 0) &= \theta_i \end{aligned} \tag{2}$$

where θ is the liquid saturation, and $D(\theta)$ is the water diffusivity of the medium. Equation (1) with (2) admit a similarity transform to the non-linear ordinary differential equation:

$$\frac{\eta}{2}\frac{\partial \theta}{\partial \eta} = \frac{\partial}{\partial \eta}\left(D(\theta)\frac{\partial \theta}{\partial \eta} \right) \tag{3}$$

with boundary conditions:

$$\begin{aligned} \theta(\eta=0) &= \theta_o \\ \theta(\eta \to \infty) &= \theta_i \end{aligned} \tag{4}$$

where η is the similarity variable given by $x/t^{1/2}$. Although Equation 3 is non-linear, its solution, subject to the boundary conditions given in (4), is dependent only on η regardless of the functional form of $D(\theta)$. If the analysis and assumptions given above adequately model system behavior and the hydraulic properties of the medium are homogeneous, any given saturation level (θ) must propagate through the medium with a $t^{1/2}$ dependence. Similarly, the total volume of water imbibed per cross-sectional area of medium I (or fracture) must be linearly related to $t^{1/2}$. The constant of proportionality relating I

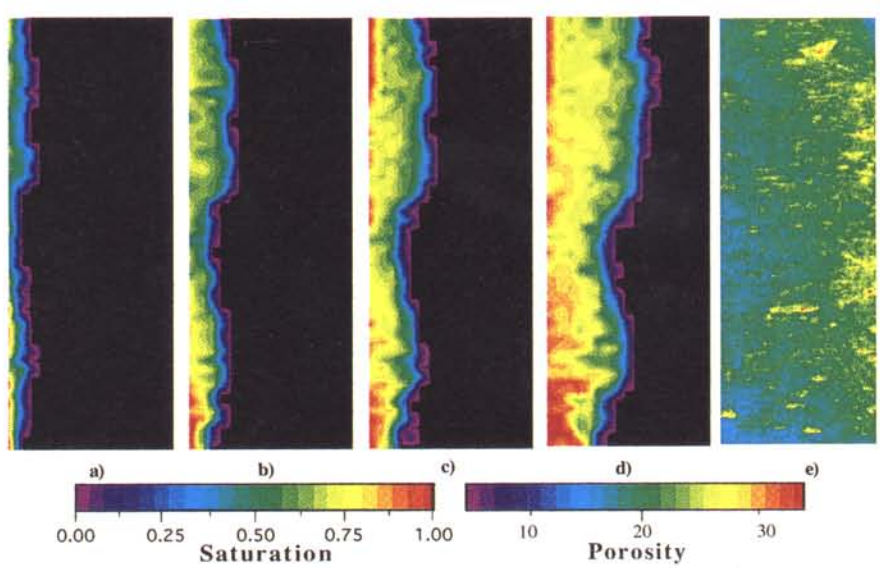

Figure 2. Measured saturation fields for the right hand tuff slab at a) 5, b) 15, c) 60, and d) 180 minutes. The corresponding porosity field (e) is also presented. Resolution of the images has been decreased via spatial averaging to 50 by 18 pixels to improve image reproduction.

and $t^{1/2}$ is called the sorptivity (Philip, 1955), denoted by S:

$$I(t) = S(\theta_o, \theta_i)t^{1/2} \tag{5}$$

The sorptivity, which embodies capillarity and has dimensions of $[L/T^{1/2}]$, is dependent on the supply saturation θ_o, and the initial saturation of the medium θ_i. Given the relative ease of measuring the sorptivity, it has found common use in solutions to unsaturated flow problems and estimation of other more difficult to measure hydraulic properties (Zimmerman et al., 1993).

In applying this conceptual model, I(t) was calculated from the measured saturation and porosity images (Figure 2) at t = 5, 15, 30, 60, 120, and 180 minutes. These calculations were made at four different resolutions corresponding to fracture lengths of 0.44, 7.0, 28.2, and 112.6 mm. In each case, I(t) was calculated at 0.44 mm intervals along the fracture (a moving average was used in the later three cases). Sorptivity was then calculated at each resolution according to Equation 5 via simple linear regression. In this way, S is a measure of matrix imbibition integrated over the thickness of the slab and corresponding fracture length. Results are plotted versus fracture position in Figure 3. The effective sorptivity at the scale of the analyzed region (352 mm fracture length) was calculated to be 0.058 mm/min$^{1/2}$.

Discussion

The appropriateness of using Equation 5 to model matrix imbibition from our flowing fracture can be evaluated by investigating the linearity of the *I* vs. $t^{1/2}$ relationship as quantified by the correlation coefficient ρ. For the 800 measurements of S made on the tuff slab at the 0.44 mm resolution, ρ ranged from 0.958 to 0.999 with mean of 0.995 and standard deviation 0.005. As measurement resolution decreased (i.e., fracture length increased) these statistics were noted to consistently improve. Based on these data, it is evident that *I* and $t^{1/2}$ exhibit a strong linear relationship.

Linearity of the *I* vs. $t^{1/2}$ relation would be jeopardized in any system for which Richards equation is an inappropriate governing equation or when any of the assumptions upon which the similarity transform of Richards equation is based are violated. That is, the medium is assumed homogeneous, and matrix imbibition is 1-D and capillary dominated (with negligible gravitational forces). In addition, a uniform initial condition is assumed with prescribed uniform saturation along one boundary while the other boundary must be at sufficient distance to be unaffected by the imbibing wetting front. Of these conditions, two were not met by this experiment: the fracture was not uniformly saturated and the matrix was heterogeneous.

Non-uniform saturation in the fracture had its greatest influence on matrix imbibition at early times in the experiment. At early times there was a component of matrix flow transverse (from the finger edges toward the slab faces) to the wetting front. This behavior is evidenced in our data by the intercept of the *I* vs. $t^{1/2}$ relationship that is generally different than zero (mean of -0.08 mm and standard deviation of 0.05 mm). However, in our experiment the slab is thin, hence transverse flow is limited and linear imbibition is quickly attained.

The tuff slabs used in this experiment are characterized by thin pumice inclusions (visible in Figure 2e) dispersed within a dense matrix. The pumice inclusions are oriented normal to the fracture but rarely span the full thickness of the tuff slab (~one every 20 cm). As these pumice inclusions are very porous, they form the primary heterogeneity relative to matrix imbibition. The intensity of this matrix heterogeneity is demonstrated by constant-head permeameter measurements made on 10 core samples trimmed from the tuff slabs. These tests produced conductivity measurements ranging from 3.6 E-8 to 2.3 E-4 cm/sec (Glass et al., 1994). Matrix heterogeneity is expected to influence imbibition in one of two ways. First, heterogeneity dispersed along the path of the wetting front may induce variations in the imbibition rate and thus non-linearity in the *I* vs. $t^{1/2}$ relationship. The strong linearity of the data presented above argues against such behavior. Second, matrix heterogeneity transverse to flow may promote violation of simple 1-D imbibition. Where strong spatial variation in hydraulic properties occurs, transverse diffusion (within the plane of the tuff slab) of the wetting front will be promoted. If this indeed occurs, then linearity and hence ρ will decrease where S changes quickly (e.g., in the vicinity of fracture heights 45, 130, and 190 mm). However, inspection of Figure 4 suggests that this is not the case.

The data can also be used to address questions concerning characterization of matrix sorptivity. For instance, what is the

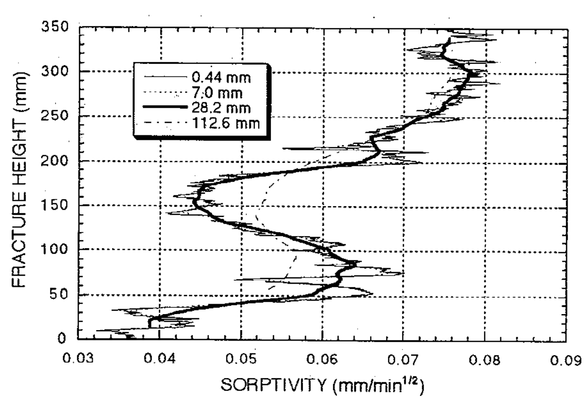

Figure 3. Sorptivity as measured along the height of the fracture. Traces are presented for four different measurement resolutions corresponding to fracture lengths of 0.44 , 7.0, 28.2, and 112.6 mm.

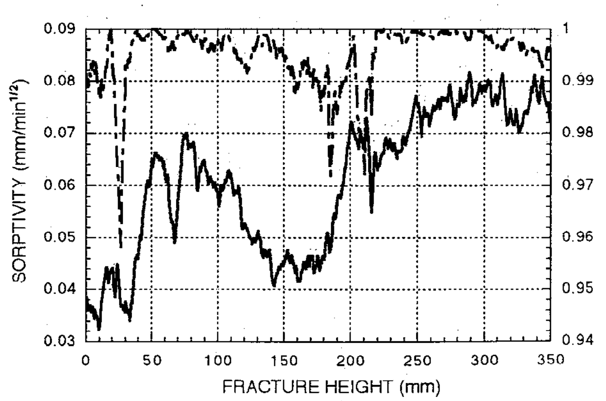

Figure 4. Sorptivity (measured at a resolution of 0.44 mm) and associated correlation coefficient vs. fracture height. The solid line traces the sorptivity profile, while the broken line traces the correlation coefficient.

appropriate sampling size for measuring the sorptivity? Consider the sorptivity traces given in Figure 3. At the highest sampling resolution, a low frequency trend is apparent with a higher frequency "noise" superimposed. As such, an appropriate sampling strategy would preserve the low frequency information while filtering out the high frequency component. In Figure 3, the 28.2 mm resolution data are seen to best meet this criteria and hence represents the preferred sampling size (assuming there is need to preserve the heterogeneity in S). In a similar manner, the descriptive statistics of S associated with the different measurement resolutions were compared. The mean sorptivity was found to remain constant while a minimal decrease in the variance was noted (coefficient of variation of 0.23, 0.22, 0.20, and 0.14, respectively) with decreasing measurement resolution. In other words, measurement resolution had little influence on the primary descriptive statistics of S. Also of interest is the small coefficient of variation exhibited by the sorptivity. Both of these findings are contrary to that commonly experienced with other hydraulic properties such as permeability. If these findings prove to be the norm rather than an exception, they demonstrate important advantages for using sorptivity in the modeling of matrix imbibition.

Conclusion

The work presented here serves as a basis for additional experimentation necessary in understanding the influence of matrix imbibition on fracture flow. For the highly simplified fracture-matrix system tested, matrix imbibition was found to follow a linear $t^{1/2}$ relationship, even in light of considerable matrix heterogeneity. However, in cases where the heterogeneity is not so favorably oriented with respect to the imbibition process (i.e., pumice inclusions were of limited size, rarely spanning the thickness of the slab, and oriented parallel to the direction of flow), non-linear imbibition behavior may be encountered. As such, additional experiments are needed to fully quantify heterogeneity effects (i.e., orientation and characteristic length) on matrix imbibition. In our experiment we also found non-uniform saturation within the fracture to have little influence on linear imbibition behavior. However, where the characteristic length of the fracture wetted structure is small with respect to the matrix block surface area (unlike our experiment), significant deviation from linear imbibition behavior is expected. Potential mechanisms responsible for non-uniform fracture saturation include air entrapment (Glass and Norton, 1992) and gravity driven fingering (Nicholl et al., 1994). Although not explored here, other mechanisms/system characteristics which may bound the applicability of Equation 5 for modeling matrix imbibition include: the presence of fracture coatings (Chekuri et al., 1994), non-uniform initial matrix saturation, matrix blocks bound by flowing and non-flowing fractures, and convergent flow resulting from imbibition into 3-D matrix blocks (Zimmerman et al., 1990).

Acknowledgments. The authors would like to acknowledge Kerim Martinez and Yvette Castro who played key roles in collecting the x-ray data. This work was supported by the U.S. Department of Energy, Office of Civilian Radioactive Waste Management, Yucca Mountain Site Characterization Project Office, under contract DE-AC04-94AL85000, WBS 1.2.5.4.6, WA-0040, and QAGR 1.2.5.4.6 Revision 0.

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(Received December 16, 1994; Accepted January 26, 1995.)