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### **A Simple Laboratory Experiment for the Measurement of Single Phase Permeability**

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#### **Abstract**

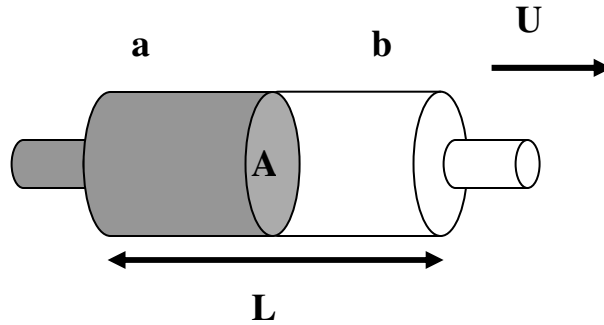
A simple experiment for measuring single-phase permeability of fully saturated porous medium is introduced. The experiment utilizes radial flow of a non-volatile wetting fluid through a porous medium such as ceramic tile, concrete or sand. The radial position of flow front is measured as a function of time and the collected data are analyzed using Darcy's Law to determine the permeability. In addition, the phenomenon of the multiphase flow through the medium with a broad pore size distribution is demonstrated.

#### **Introduction**

The study of soil and groundwater contamination and their remediation have become increasingly important in recent years as the environmental impact of various activities on human health have come into focus (Appelo & Postma, 2005; Canter & Knox, 1996; Goelitz, Troutman, Godsy, & Franks, 1985; Libra, Hallberg, & Hoyer, 1987; Parker, Katyal, Kaluarachchi, & Lenard, 1991; Sparks, 2003). The release of chemicals, such as hydrocarbons, pesticides, and chemical warfare agents, etc. into soil and subsurface poses a great threat to the biosphere environment (Carson, 1962; Weimaster & Ellzy, 1995). The quantification and extent of spread of these chemicals has primary importance for carrying out the remediation work and is considered a first step in the remediation hierarchy. The extent of spread of a chemical can be estimated if information regarding the transport parameters through the medium of interest (substrate) is available (Abdul & Gibson, 1991; Ball & Roberts, 1991; Dube, Zbytniewski, Kowalkowski, Cukrowska, & Buszewski, 2001; Loaque, Corwin, & Ellsworth, 1998, Kay, Blackwell, & Boxall, 2004). If the substrate is a porous medium, which often is the case, one of the transport parameters is permeability. This paper describes a simple experiment that allows measurement of single phase permeability of a liquid through a porous medium such as ceramic tile, concrete, asphalt, brick, sand, or topsoil. This method can also be easily expended for measuring other properties of porous media.

#### **Background Information**

Darcy's Law is a constitutive equation describing the flow of a fluid through a porous media (Bear, 1972; Darcy, 1856; Whitaker, 1986). It is a simple proportional relationship between the flow rate through the porous medium, the viscosity of the fluid and the pressure difference over a given distance (Figure 1). The permeability is a measure of the ability of a porous medium to transmit fluids measured in the units of length square or darcies ( $1 D = 0.98692 \times 10^{-12} m^2$ ). The transportability can differ for distinct principal directions, and for such media all three principal direction values have to be determined. However, for an isotropic medium, the permeability is equal in all three directions and is defined as a scalar value.



$$U = \frac{-(KA)}{\mu} \left[ \frac{P_b - P_a}{L} \right]$$

$K$  = Medium Permeability  
 $A$  = Surface Area of the Flow  
 $\mu$  = Viscosity

$L$  = Length of the Pressure Drop  
 $P_b - P_a$  = Pressure Drop

Figure 1. Darcy's Law

The initial definition of the permeability is established for the fluid flow where the porous medium is fully saturated by one fluid phase only. This is single-phase permeability or simply permeability. In the more complicated cases where two or more fluid phases are present, Darcy's law is generalized by defining the phase permeability for each phase. It is obvious that the phase permeability depends on the phase content (phase saturation). Furthermore, the relative permeability is defined as a ratio of the phase permeability of a particular phase to the permeability of the porous medium in fully saturated condition. Calculation of relative permeability allows for comparison of the different abilities of fluids to flow in the presence of each other, i.e., the presence of more than one fluid generally inhibits flow of the other phases.

### Radial spread under constant pressure

For the single-phase permeability measurement, the experiments are designed to obtain the simple flow patterns. One-, two- and three-dimensional geometry can be used for permeability prediction (Adams, Miller, & Rebenfeld, 1988; Cai, 1992; Nedanov & Advani, 2002). The position of the fluid front is recorded as a function of time, regardless of the flow dimensionality. In the two-dimensional geometry, if the fluid spreads in the radial direction from a circular inlet of radius ( $r_0$ ), the fluid front is approximately circular and due to the radial symmetry, the flow can be considered one-dimensional. From Darcy's law, the radial fluid velocity of the fluid of molecular viscosity ( $\mu$ ) through the isotropic porous medium of permeability ( $K$ ) is defined as:

$$u_r = -\frac{K}{\mu} \frac{dp}{dr} \quad (1)$$

Where the radial velocity is defined as  $u_r = \phi \, dr/dt$ , and  $\phi$  is porosity of the porous medium. The experiments are carried out under either constant pressure or constant flow rate. For the constant pressure difference ( $\Delta p$ ) condition, the radial flow front ( $r_f$ ) progresses with the time ( $t$ ) as given in the following form (Adams, Miller, & Rebenfeld, 1988):

$$r_f^2 \left( 2 \ln \left( \frac{r_f}{r_0} \right) - 1 \right) + r_0^2 = 4 \frac{K \Delta p}{\mu \phi} t \quad (2)$$

The left hand side of Equation (2) is a function of ( $r_0$ ) and ( $r_f$ ) only, where the first parameter is known ( $r_0$ ) and the second one ( $r_f$ ) is measured in the experiment. Therefore, the linear form of

Equation (2) can be written as  $Y(r_o, r_i) = \kappa t$ . Finally, from the slope of the linearized data ( $\kappa$ ), the permeability can be calculated:

$$K = \frac{\mu\phi}{4\Delta p} \kappa \quad (3)$$

The constant pressure difference between the inlet and outlet ( $\Delta p = p_{inl} - p_{out}$ ) can be provided using the pressurized vessel at the inlet ( $r_o$ ), or vacuum at the outlet ( $r_i$ ). Such setup requires sealing of the porous medium. However, the capillary force can also be used to produce constant pressure difference ( $\Delta p$ ) equal to the capillary pressure ( $p_c$ ) for the fluid per porous medium system specified (Dane, Oostrom, & Missildine, 1992; Katz & Thompson, 1986). Here, the system does not need to be sealed, and only the fluid has to be provided continuously at the inlet ( $r_o$ ). This is applicable to the porous media with narrow pore size distribution, where the fluid front is narrow and can be considered as an interface. If the porous medium has a broad pore size distribution, the advancing fluid front is not uniform and spreads, leading to a medium that is not fully saturated with fluid; this is an example of a multiphase flow. In this region (flow front), the permeability is different from the permeability in the portion of the porous medium that is fully saturated. This permeability is referred to as the phase permeability that applies to multiphase flows and depends on fluid content (saturation). The solution given in Equation (2) cannot be used for phase permeability determination.

### Experimental Set-up and Procedures

The experimental setup will consist of a porous substrate, with a “blind” cylindrical hole (not a hole which is through the entire thickness of the substrate) in the middle (for hard media) or with a tubular mesh insert (for soft media), Pasteur Pipette for liquid delivery, stop watch, ruler, precision balance, graduated cylinder and a digital camera for recording images (optional). The blind cylindrical hole extends through the thickness of the tile and stops two millimeters from the glossy surface of the tile which is impermeable to liquid. This is to ensure two dimensional behavior of the spread. A similar approach was taken for the tubular mesh insert used for soft media. The experiment can be performed with any non-volatile liquid including water. Various porous substrates, such as ceramic tile, brick, a concrete slab, a box with sand, glass beads or topsoil, etc. can be used.

In order to measure the permeability, the porosity of the substrate material should initially be measured. For the case of hard substrates, such as ceramic tile, concrete or brick the following procedure was used. The large sized substrates (for example intact ceramic tiles) were broken into multiple smaller pieces such that they fit inside a graduated cylinder. Those pieces were dried in the oven for five hours at a temperature of 110°C and weighted on a precision balance. Then, the samples were soaked in the water for five hours with mechanical agitation and were reweighed. After removing the samples from water, they were gently blotted to remove any surface water prior to being weighed. The total volume of each sample also needs to be measured since the porosity is the ratio of the empty volume of the sample to its total volume. This was accomplished by dropping each sample into a graduated cylinder containing 5 mL of water and measuring the volume of displaced water.

For the case of soft substrates, such as, sand or topsoil the previous procedure was modified. After drying the material in the oven, the substrate was poured into a graduated cylinder and a large volume of water (at least three to five times greater than the volume of the substrate material) was added. The container was mechanically agitated for one hour to let the water diffuse into the substrate material. The volume of water above the substrate was then measured. Porosity of the substrate material is calculated by taking the ratio of water volume inside the substrate material to the volume of the substrate material.

Before starting the permeability measurements, the substrates were dried in the oven for five hours at temperature of  $110^{\circ}\text{C}$ . The blind cylindrical hole, or the tubular mesh insert, in the substrate can be 5 – 15 mm in diameter and at least three quarters of the sample thickness deep in order to insure fluid radial flow. It should be emphasized that the dimensions of the hole/insert are not critical, but the geometry is. If the hole/insert is not circular or if large cracks are present in the vicinity of the edge, the diffusion patterns will not be circular. The Pasteur Pipette was used to fill the hole/insert with the liquid. The hole has to be filled continuously during the experiment. Keeping the hole/insert full without overfilling is important. If the hole/insert is overfilled, liquid will flow on the surface of the substrate and data obtained will be invalid. At specific time intervals, usually every 15-30 seconds, the diameter of the diffusion circle was measured with the ruler. A digital camera was also used to take images for additional image analysis after the experiments. Figure 2 shows the schematic of the experimental setup.

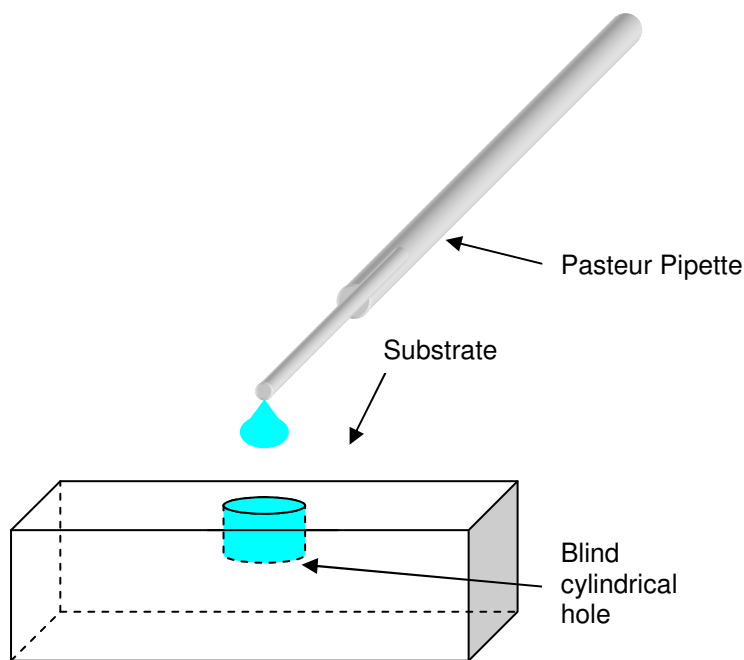


Figure 2. Schematic of experimental setup

## Results, Calculations and Discussion

Four porous substrates were used: 1) commercially available six by eight inch ceramic tiles made by United States Ceramic Tile Company, 2) a piece of concrete prepared from the commercially available Quikrete mix, 3) commercially available play sand (two varieties) and 4) 0.2 mm diameter glass beads purchased from Aldrich Chemical company, Milwaukee, Wisconsin. One reason for using the concrete is to show the principle of multiphase flow front. The spread of water and a NaOH (0.2 M) solution (NaOH solution was used during the initial experiments to better visualize the flow front using phenolphthalein detection) through porous media were investigated. The experiments were usually completed after 20 minutes minimizing any side reactions that may take place between NaOH and sand or concrete. Figure 3 shows the setup and flow pattern of water in ceramic tile, concrete, glass beads and sand.

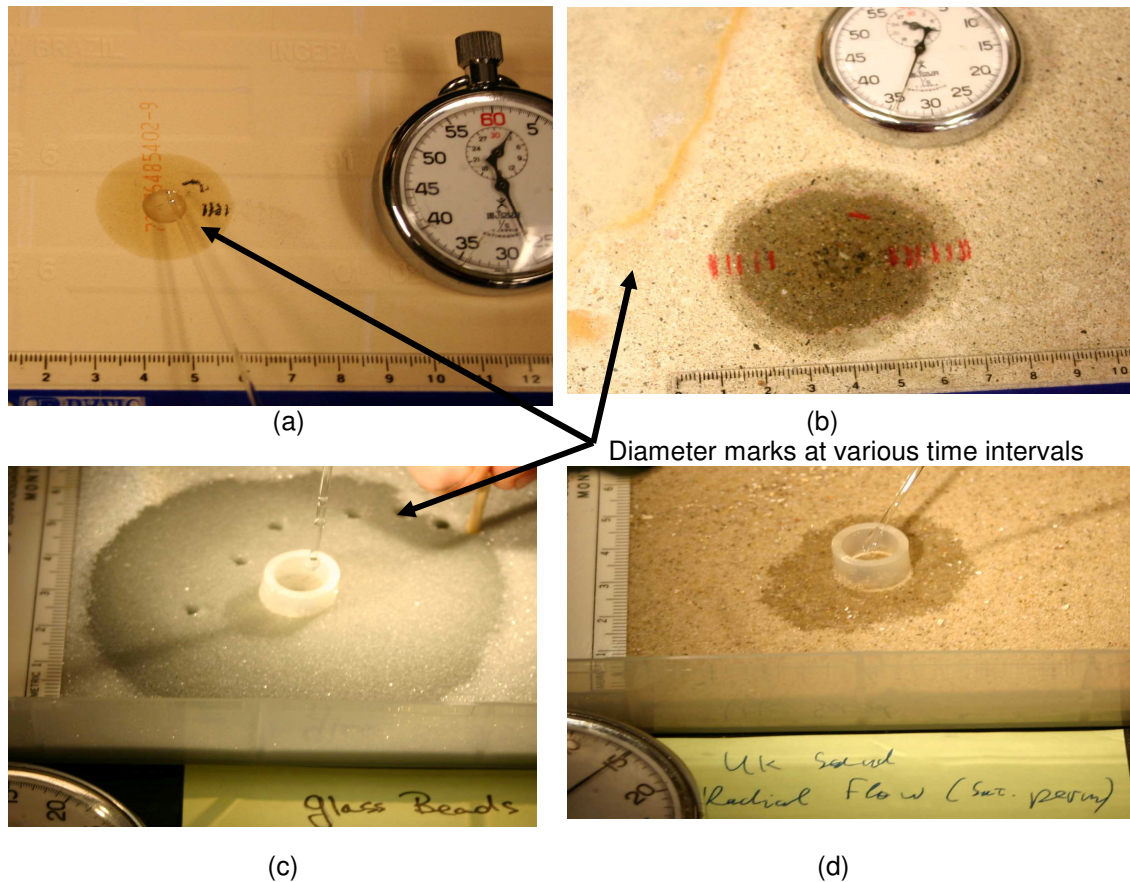


Figure 3. Fluid spread into ceramic tile (a), concrete (b), glass beads (c), and sand (d)

Two distinct features of the flow should be distinguished in Figure 3: medium isotropy, and flow nature that can be either single- or multiphase flow. As shown in Figure 3(a) (c) and (d), the flow fronts for ceramic tile, glass beads and sand are indeed very well defined and are known as “interface.” Generally, this is true for media with small local variation in the structure, and has narrow pore size distributions. Therefore, the fluid flow into the ceramic tile, glass beads and sand can be considered single-phase spreads. The interface shape remained circular or approximately circular (the flow front in sand is not completely circular due to its heterogeneity) throughout the experiment. Hence, the ceramic tile, glass beads and sand behave as isotropic materials. On the other hand, the concrete behaves in a different manner. Figure 3(b) shows two regions: the fluid front that consists of faster low saturated region (light shade) followed by higher saturated region (dark shade), and therefore, in the fluid front region multiphase flow occurs. The form of the fluid front implies that the concrete has large variations in the local structure, and a broad pore size distribution. However, the observation that the fluid front remains circular in time implies that the concrete is also an isotropic material. Equation (2) applies for isotropic media with single-phase flow. Therefore only ceramic tile, glass beads and sand satisfy these conditions. Capillary force was the driving force for the spread of liquid in all experiments.

Equation (2) suggests that the reduced results, regardless of the value of ( $r_0$ ), follow the same linear dependency  $Y(r_0, r_f) = \kappa t$ , providing that the same fluid and porous medium are used. This is used to check the repeatability of the experiment. For this study, two ceramic tiles with the inlets of two different radii,  $r_0 = 3$  mm and  $r_0 = 5$  mm were used. The spread of NaOH (0.2M) solution under the influence of the capillary force was monitored. The results are shown in Figure 4, where it can be observed that the results collapse onto the same dependency, as expected.

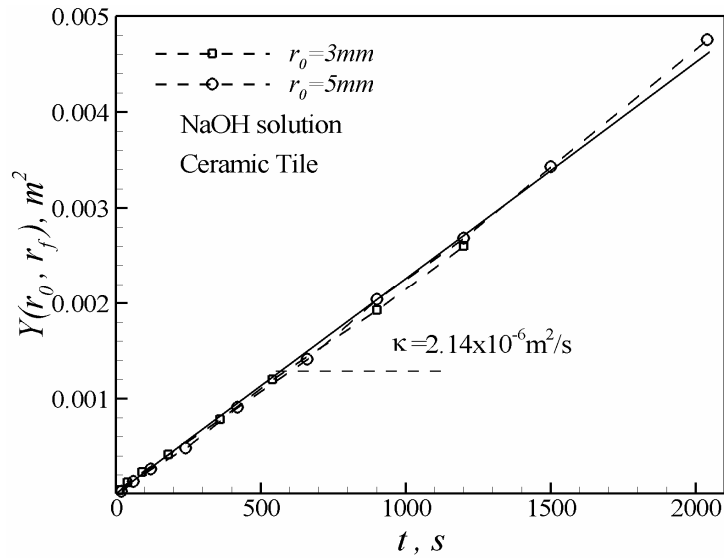


Figure 4. Repeatability of the experimental results for two different inlet radii,  $r_0=3$  mm and  $r_0=5$  mm.

Once the fluid or the substrate is changed, the  $Y(r_0, r_f) = \kappa t$  is still a valid correlation, but the slope ( $\kappa$ ) changes due to the different fluid viscosity, substrate porosity and the capillary pressure. Figure 5 depicts the experimental results for water and NaOH (0.2 M) solution spreads in ceramic tile while Figure 6 depicts the results for water spread in sand and glass beads.

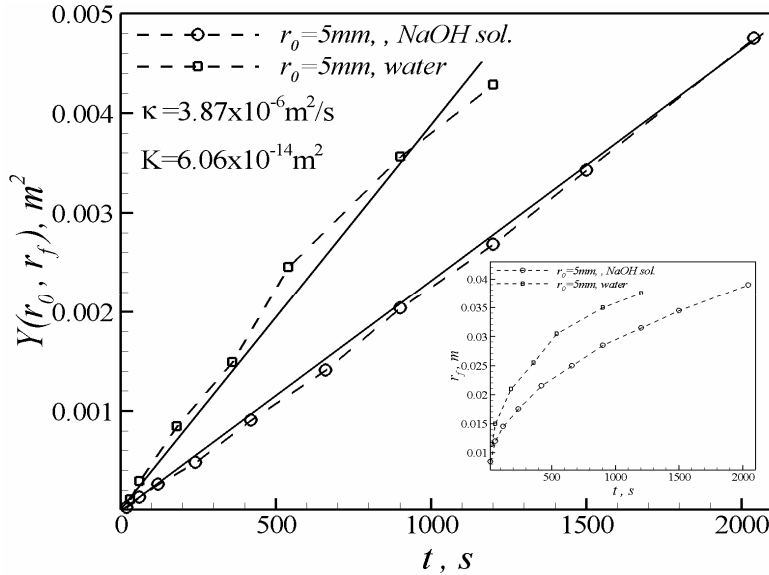


Figure 5. The data reduction of the radial flow experiments and linear fit for the permeability prediction in ceramic tile. Inset figure contains the data as obtained from experiment.

For Figures 4, 5 and 6; the time is given on the horizontal axis, and on the vertical axis, reduced radial position is used. In the inset figure,  $(r_f, t)$  data are shown.

The numerical results for these experiments are listed in Table 1, which shows the radial interface position ( $r_f$ ) vs. time. The same radius ( $r_0$ ) of inlet is used for water and NaOH spread



in tile. The radial position ( $r_f$ ) differs for these two experiments due to fluid viscosity and capillary pressure.

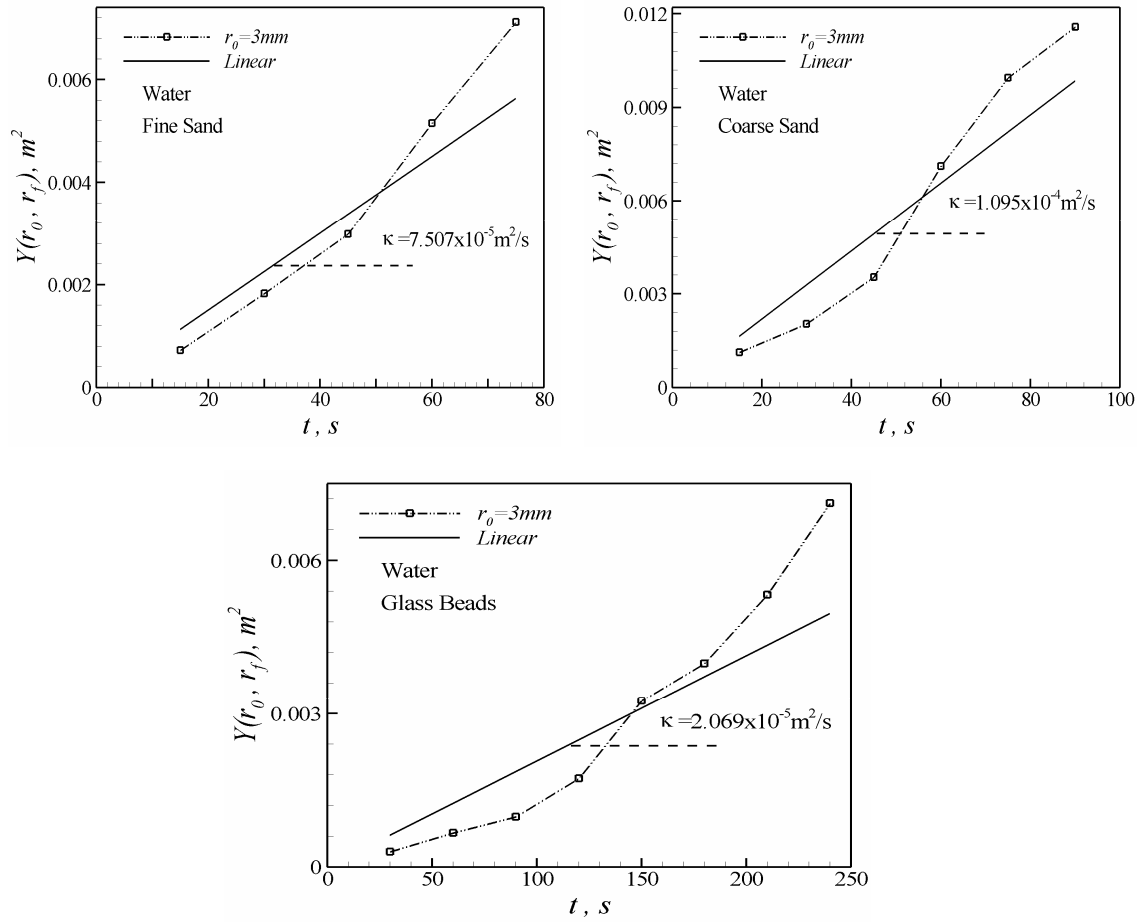


Figure 6. The data reduction of the radial flow experiments and linear fit for the permeability prediction. Fine and coarse sands and glass beads

Table I. Radial Flow of Low-Volatile Fluids

Tile/Low-Volatile Fluids				Fine Sand		Glass Beads		Coarse Sand	
Water		NaOH		Water		Water		Water	
t, s	r <sub>f</sub> , mm	t, s	r <sub>f</sub> , mm	t, s	r <sub>f</sub> , mm	t, s	r <sub>f</sub> , mm	t, s	r <sub>f</sub> , mm
0	0	0	0	0	0	0	0	0	0
30	11.5	20	8.5	15	17	30	12.5	15	20
60	15	60	12	30	24	60	16.5	30	25
180	21	120	14.5	45	29	90	19	45	31
360	25.5	240	17.5	60	36	120	23.5	60	41
540	30.5	420	21.5	75	41	150	30	75	47
900	35	660	25			180	32.5		
1200	37.5	900	28.5			210	36.5		
		1200	31.5			240	41		
		1500	34.5						
		2040	39						

For the water and NaOH (0.2 M) solution spread in ceramic tile, two distinct values for the slope were calculated as:

- (i)  $\kappa_1 = 3.867 \times 10^{-6} \text{ m}^2/\text{s}$
- (ii)  $\kappa_2 = 2.136 \times 10^{-6} \text{ m}^2/\text{s}$

Furthermore, the following slopes were calculated for the spread of water in sand and glass beads:

- (iii)  $\kappa_3 = 7.507 \times 10^{-5} \text{ m}^2/\text{s}$  Fine Sand
- (iv)  $\kappa_4 = 1.095 \times 10^{-4} \text{ m}^2/\text{s}$  Coarse Sand
- (v)  $\kappa_5 = 1.095 \times 10^{-4} \text{ m}^2/\text{s}$  Glass Beads

The porosities of all substrates were measured according to the procedure described in the experimental section and are tabulated in Table 2.

Table II. Substrate Porosities

Ceramic Tile	Fine Sand	Glass Bids	Course Sand
24%	37%	31%	28%

For a large number of fluids, the fluid viscosity is available in a standard property tabulation, and for water, viscosity,  $\mu = 10^{-3} \text{ Pa}\cdot\text{s}$ . The capillary pressure was determined using static measurements. Since the capillary pressure is a function of saturation, the level of saturation of the substrates was experimentally verified by measuring the liquid content of a plug of the medium near the flow front and was found to be fully saturated. Here, using the capillary pressure of 3 KPa ( $\Delta p = p_c = 3 \text{ kPa}$ ), the following single phase permeabilities were calculated:

- $K = 5.0 \times 10^{-14} \text{ m}^2$  Tile
- $K = 2.3 \times 10^{-12} \text{ m}^2$  Fine Sand
- $K = 2.84 \times 10^{-12} \text{ m}^2$  Coarse Sand
- $K = 4.8 \times 10^{-13} \text{ m}^2$  Glass Beads

## Conclusion

This experiment provides a simple and inexpensive method by which single-phase permeability of a non-volatile liquid through a uniform porous medium with a narrow pore size distribution can be measured. This experiment provides a small introduction to the field that encompasses areas of environmental and geotechnical engineering and chemistry. As the environmental impact of the spread of various chemicals gains more importance and receives more attention, the remediation and containment of such spreads become increasingly crucial to the health of society and natural ecosystems. In order to effectively address remediation and contamination issues, various parameters associated with the chemicals and the medium need to be known and/or measured. This paper serves to introduce an easy method to measure one of these parameters, namely single phase permeability of a porous medium. It is our hope that by introducing these topics; we can shed light into how normal human activity may have lasting effects on health and viability of the natural environment.

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