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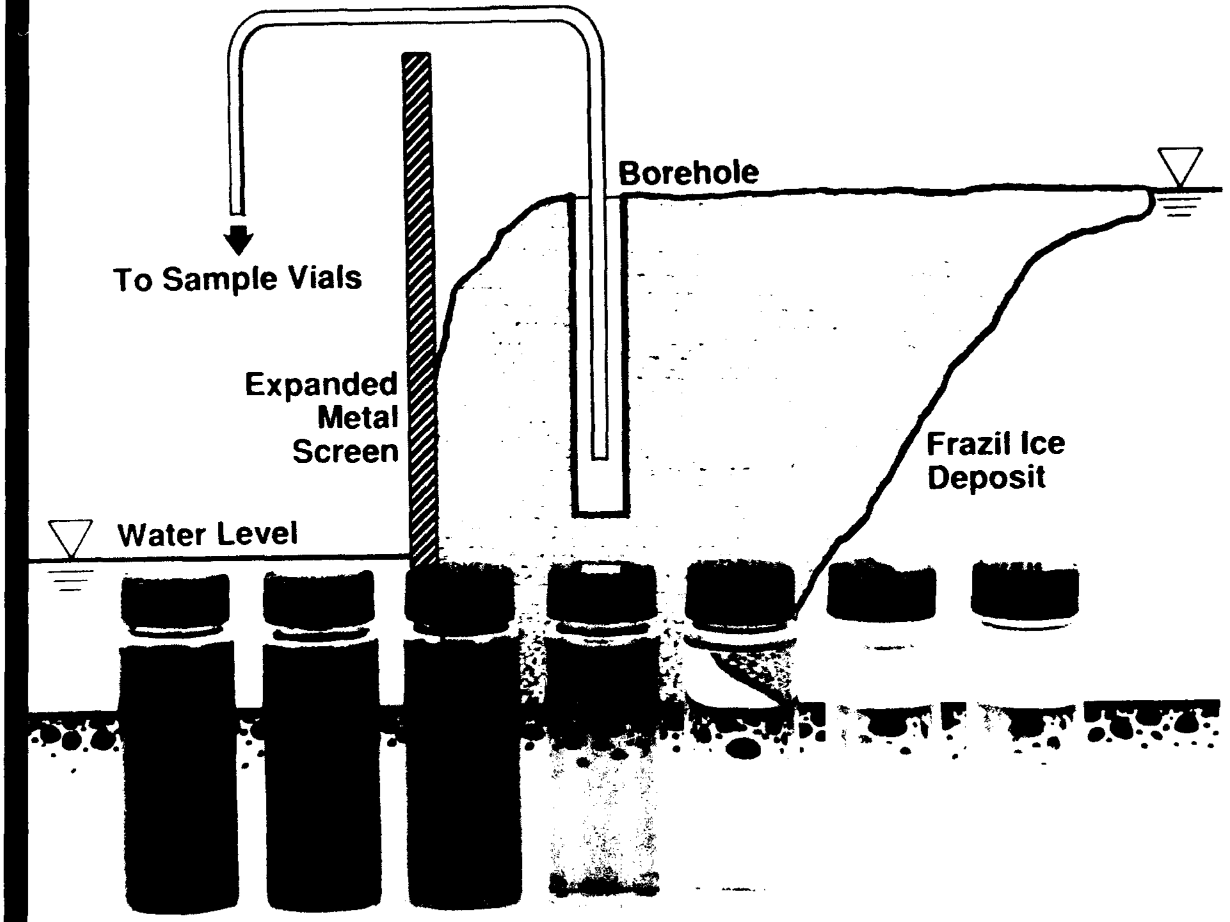
Determining the Intrinsic Permeability of Frazil Ice

Part 1. Laboratory Investigations

Kathleen D. White

December 1991



For conversion of SI metric units to U.S./British customary units of measurement consult ASTM Standard E380, Metric Practice Guide*, published by the American Society for Testing and Materials, 1916 Race St., Philadelphia, Pa. 19103.*

Cover: Sample vials of rhodamine dye used in borehole dilution tests for determining the intrinsic permeability of frazil ice.

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U.S. Army Corps of Engineers
Cold Regions Research &
Engineering Laboratory

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Part 1. Laboratory Investigations

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PREFACE

This report was prepared by Kathleen D. White, Research Hydraulic Engineer, Ice Engineering Research Branch, Experimental Engineering Division, U.S. Army Cold Regions Research and Engineering Laboratory. Funding was provided by In-house Laboratory Independent Research under the work unit *In-Situ Measurement of the Permeability of Frazil Ice.*

The author is indebted to John J. Gagnon for his assistance in conducting the laboratory experiments. Dr. Thomas P. Ballestero and Dr. J.-C. Tatinclaux also provided helpful advice. Steven F. Daly and Dr. George D. Ashton provided technical review and advice.

CONTENTS

ILLUSTRATIONS

TABLES

Determining the Intrinsic Permeability of Frazil Ice

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KATHLEEN D. WHITE

INTRODUCTION

Frazil ice causes problems in many northern rivers. Frazil ice deposits can block intakes and hinder navigation and can result in ice jam flooding. Knowledge of the characteristics of a frazil ice deposit can aid in the design of ice control methods for that particular site. Unlike sheet ice, many of the physical characteristics of frazil ice deposits are not well known. Among these are hydraulic conductivity, intrinsic permeability and porosity.

The intrinsic permeability is a property that describes the capacity for flow through the solid matrix, while the hydraulic conductivity relates the properties of the fluid and the intrinsic permeability of the solid matrix. The porosity of the deposit, which can also be approximated from the intrinsic permeability, is often used in estimating the volume of ice in the deposit.

In-situ methods for determining intrinsic permeability are desirable because frazil ice is a difficult material to sample and remove for testing without considerable disruption to the structure of the material. These disturbances include temperature effects and physical effects, such as vibration, which may change the packing characteristics. The ambient air temperature is often different from the temperature within a deposit, resulting in melting or freezing of the frazil sample after removal. There are no existing in-situ methods for determining the intrinsic permeability of frazil ice. In the past this property has been estimated using a permeameter test, which cannot be performed in-situ.

The borehole dilution method, developed as a nondestructive test to measure groundwater velocities, has been used to determine hydraulic conductivity in soils. Since a frazil ice deposit is a heterogeneous medium similar to water-bearing soil, this test method appears to hold some promise for determining frazil ice permeability. This report describes the borehole dilution method as modified for laboratory testing of frazil ice deposits. This technique shows promise as a relatively simple field method for the in-situ determination of the intrinsic permeability of a frazil ice deposit.

BACKGROUND

The intrinsic permeability of a material is an overall measure of the characteristics of the solid matrix that affect permeability. These include the size, shape and size distribution of the grains making up the material; the packing characteristics of the grains; the porosity of the deposit; and the tortuosity of the pores. The intrinsic permeability of frazil ice also reflects its morphology, which is characterized by layers of homogeneous material, either isotropic or anisotropic. The intrinsic permeability in the horizontal direction can be up to several orders of magnitude larger than in the vertical direction. Differences in intrinsic permeability between layers exist as well. The structure of frazil ice deposits is often a system of homogeneous, isotropic layers, since frazil ice deposits are generally made up of horizontal layers deposited during discrete events. These layers are often separated by a thin layer of less permeable material resulting from smoothing of the deposit during warm periods.

In a saturated material the coefficient of intrinsic permeability describes the ability of the material to transmit fluids. Some knowledge of this property is necessary to accurately model the response of the system to loading. For example, one might wish to estimate the force necessary to push an indenter through a frazil ice deposit. As the indenter moves into the deposit, resistance is provided by the structure of the ice matrix as well as the water contained in that matrix. The displacement of the water is controlled by the intrinsic permeability of the matrix.

The hydraulic conductivity K of a material, also called the coefficient of permeability, is the characteristic used to describe flow through a porous media. The hydraulic conductivity and the intrinsic permeability are related through the Nutting equation:

$$K = \frac{k\rho g}{\mu} \tag{1}$$

where k = intrinsic permeability of the solid matrix
g = acceleration due to gravity
μ = dynamic viscosity of the fluid
ρ = mass density of the fluid.

Determining intrinsic permeability

Neither intrinsic permeability nor hydraulic conductivity can be measured directly. They may be calculated from the seepage velocity v and the slope of the water surface using Darcy's Law:

$$k = \frac{v\mu}{\rho g \frac{dh}{d\ell}} \tag{2}$$

where dh is the change in head over distance $d\ell$. Darcy's law assumes that flow is laminar. Flow regimes are generally described by the Reynolds number:

$$Re = \frac{vd}{\upsilon} \tag{3}$$

where υ is the kinematic viscosity of the fluid and d is a representative length scale parameter, taken here to be the mean particle diameter. Laminar flow occurs in the region where the Reynolds number is less than 10. The assumption of laminar flow through soils has been validated through measurements. No Reynolds numbers have been reported for flow through a frazil ice deposit, although Wong et al. (1985) suggested that such flow might be turbulent. Based on the particle size and morphology of frazil ice deposits, I believe that the flow will be primarily laminar.

Several methods exist for in-situ measurement of the hydraulic conductivity in soils, including piezometer and borehole dilution tests. Piezometer tests involve monitoring the water levels in a single piezometer following the instantaneous removal or addition of a known volume of water. The hydraulic conductivity of the soil is proportional to the rate of inflow to or outflow from the piezometer and the difference between the initial head and the head at a given time. Hvorslev (1951) discussed the analysis of piezometer tests involving a variety of piezometer shapes and deposit conditions. The time period of these tests is on the order of hours to days or longer. The unsteady flow conditions in a laboratory flume or natural river, combined with difficulties in measuring small changes in head over a short time period, present obstacles in applying this test to a frazil ice deposit.

Dean (1976) first proposed measuring the intrinsic permeability of a frazil ice deposit in the field to support hypotheses regarding the amount of flow through the ice deposit. He chose to use the constant-head permeameter test, with 10W motor oil as the permeameter fluid.

In Dean's tests, frazil ice samples were obtained from three field sites by pushing a sample cylinder (30.5 cm high by 8.9 cm in diameter) horizontally through the frazil deposits. The samples were then held vertically and allowed to drain. During cold weather the samples were spun to speed the draining and decrease freezing within the sample. Once drained, the samples were placed within the test apparatus. The average intrinsic permeability obtained from two tests was 1.53×10^{-5} cm^2, which is comparable to that of an unconsolidated gravel deposit (Freeze and Cherry 1979). The range of average frazil particle sizes was reported to be 2–5 mm.

Beltaos and Dean (1981) conducted field investigations of a frazil ice deposit, which included measuring the intrinsic permeability using the permeameter method described above. They reported values of 1.63×10^{-5}, 1.56×10^{-5} and 1.50×10^{-5} cm^2 at depths of 2, 7.6 and 12.2 m below the frazil surface. Frazil particle sizes were between 1 and 6 mm.

Another type of in-situ test is the borehole dilution test. In borehole dilution tests the dilution of a tracer material in a borehole is monitored over time. A variety of tracer materials have been used in soils, including ionized substances such as salt, radioactive materials and fluorescent dyes (Davis et al. 1980). For frazil ice, tracer dilution tests involving salt would affect the structure of the ice deposit measured, and the use of radioactive tracers may be environmentally unacceptable in the field. Fluorescent dye tracers have been used in measuring stream discharge as well as groundwater flow, with little environmental effect (Wilson et al. 1986).

The borehole dilution technique using fluorescent dye is a well-established technique in groundwater investigations, and its application to frazil ice deposits is straightforward. However, some knowledge of the difference between the physical characteristics of the frazil ice deposit and those of soils is important in applying the borehole dilution test to frazil ice.

Applying the borehole dilution test to frazil ice

The borehole dilution test has been used to measure seepage velocity in a variety of materials. Intrinsic permeability and hydraulic conductivity can then be calculated once the seepage velocity is known. Lewis et al. (1966) suggested this expression for determining seepage velocity from borehole dilution tests:

$$C/C_0 = \exp(-8vt/\pi d) \qquad (4)$$

where C = concentration of the tracer at time t
C_0 = initial concentration of the tracer in the borehole
v = groundwater velocity
d = diameter of the borehole.

This relation assumes that tracer dilution is a result of the horizontal movement of water through the borehole. Uniform concentration of the tracer throughout the borehole and steady uniform flow through the deposit are also assumed. In practice the groundwater seepage velocity is found by plotting the log of the ratio of concentration at time t to the initial concentration versus time.

The manner in which the test borehole is formed can affect the borehole dilution test results. Packing or smoothing of the borehole walls during drilling causes the walls to be less permeable than the surrounding deposit. The calculated seepage velocity would also be lower than that actually occurring in the deposit, resulting in an underprediction of the intrinsic permeability. After extensive study of piezometers in soils, Hvorslev (1951) recommended that the walls of a piezometer, borehole or well (or the filter if one is necessary) be more permeable than the surrounding soils to avoid wall effects. It is unknown to what extent drilling using the CRREL ice auger will affect the walls of a borehole made in a frazil ice deposit.

The rapid development of frazil ice deposits in the laboratory is conducive to the formation of a homogeneous, isotropic medium. Andersson and Daly (in prep.) present thin sections taken from core samples of frazil ice deposits formed in the laboratory. These samples show a uniform deposit with depth, supporting the assumption that the laboratory frazil ice deposits are homogeneous and isotropic. However, irregularities such as caverns or channels can be present within the frazil ice deposit. Channels would dominate the flow regime, violating the uniform flow criterion and adversely affecting the test results. Full-depth boreholes could allow for vertical flow and mixing. Therefore, since the dilution test assumes horizontal flow, boreholes should be drilled only partially into a frazil ice deposit. For good results, boreholes should be located in a representative section of the deposit, and the walls and bottom of each borehole should be checked for competence.

Fluorescence measurements

Rhodamine WT, a fluorescent dye, was chosen as the tracer because of its lack of adverse environmental effects and because it is easily measured using a filter-type fluorometer. This dye is commonly used in borehole tests in soils and has been used to measure the discharge in rivers. Wilson et al. (1986) reviewed the operation of several filter fluorometers for several fluorescent dyes, including rhodamine WT. Basically, filter fluorometers measure the light emitted by a fluorescent material in a particular spectrum. The light source and the primary and secondary filters are chosen to enhance the measurement of the particular dye chosen and to decrease potential interferences. The measurement of fluorescence can be affected by environmental conditions, the most important of which are concentration and temperature.

Fluorescence is inversely proportional to temperature, and differences in temperature between samples and between the samples and the calibration standards have been adjusted by other researchers using a temperature correction factor (Wilson et al. 1986). Since the present series of tests was conducted at water temperatures lower than normal, the potential for temperature-associated error was significant. Possible temperature effects were minimized by warming the samples to room temperature so that they would be tested at the same temperature as the calibration standards. This procedure also prevented the formation of condensation on the sample cuvettes, which can adversely affect the fluorometer reading.

Fluorescence generally varies linearly with concentration at concentrations less than about 1 ppm and nonlinearly above this point. When the concentration of fluorescent material in a sample is so high that it affects the excitation as well as emitted light, the measured fluorescence may result in an artificially low reading (the sample has been "quenched"). Concentration quenching and nonlinearity can be avoided by targeting a range of concentrations between 100 ppt (parts per trillion) and 1 ppm or by diluting highly concentrated samples to fall within this range.

Quenching can also occur for reasons other than high concentration. True quenching, as opposed to concentration quenching, occurs when the measured fluorescence is less than the actual fluorescence because substances in the sample interfere with light excitation or emission by absorption or degradation, or because the fluorescent dye is affected chemically by a substance in the sample. In some cases, true quenching is reversible, and in others the effect is irreversible. Strong sunlight may cause irreversible quenching as it degrades the fluorescent material over time. Chlorine is another example of a substance known to cause irreversible quenching of rhodamine dyes because it can change the chemical composition of the dye (Wilson et al. 1986). Since the water source used in this study is untreated well water, it was assumed that chlorine concentrations were negligible.

Wilson et al. (1986) noted that high levels of dissolved oxygen may cause reversible quenching of rhodamine dyes. The solubility of oxygen in water is a function of the water temperature, and increased concentrations of dissolved oxygen are possible as the water temperature decreases. The amount of dissolved oxygen also depends on the turbulence and mixing of the river. Rivers that contain large deposits of frazil ice are generally characterized by water temperatures near 0°C and by turbulent conditions and are therefore likely to contain high levels of dissolved oxygen. This is also true of the laboratory flume, in which the turbulence and temperature of natural river water are simulated to produce frazil ice. Warming the samples to room temperature under quiescent conditions before measurement will minimize the temperature-induced effects of dissolved oxygen.

Mixing effects

In addition to affecting fluorescence measurements, temperature can also exacerbate density gradient differences. At room temperature, rhodamine dye is heavier than water and exhibits density stratification. For this reason the initial slug discharge of rhodamine should be as close to the water temperature as possible and must be well mixed in the borehole. In our tests the rhodamine was placed in the flume room before the tests for a sufficient time to cool to near water temperature but before freezing (identified by slush formation). Because of the short duration of the tests in the flume, the initial mixing was assumed to be adequate, but for long-term tests the water in the borehole should be mixed at intervals to prevent density gradients and stratification of the water due to temperature effects.

Diffusion effects

In typical borehole dilution tests a very rapid decrease in measured dye concentration occurs immediately, followed by a more steady decline. This initial rapid dilution is generally attributed to Fickian diffusion or density stratification. The initial response period is followed by a longer phase characterized by linear dilution over time. It is this linear portion of the dilution curve that is of interest in the borehole dilution test. To be sure that the fluorescent dye is in the measurable range during the linear portion of tests, a large initial concentration is desirable. Assuming an average borehole volume of 300 cm^3, the average expected initial concentration resulting from the addition of 2 mL of 2280-ppm rhodamine WT would be 15 ppm of rhodamine. This concentration is an order of magnitude higher than the highest sample measured.

METHODS AND MATERIALS

The laboratory testing took place in the CRREL refrigerated flume facility and used frazil ice produced in the flume. The flume, described in detail by Daly et al. (1985), is 36 m long, 1.2 m wide and 0.6 m deep. A frazil ice deposit was formed in the flume using the methods reported in Axelson (1990) for a full-height expanded metal screen. The flume bed slope was set at 0.005 and the discharge was about 0.02 m/s. The frazil seeder was used in all tests. One or two tests were performed on each frazil ice deposit. In some cases the same borehole was used for two tests. The experimental set-up is shown in Figure 1.

Once the frazil ice deposit had formed and stabilized (i.e. small increases in upstream head with time), a borehole was made in the ice using a 5.1-cm-diameter CRREL ice auger with the bit removed. The borehole was a partial-depth hole, extending to a point above the estimated bottom of the deposit. The walls of each borehole were checked to be sure that the ice deposit was competent and that no large voids were present. A 40-mL water sample was obtained for determining the background concentration of rhodamine WT in the flume.

The rhodamine WT was placed in the flume room and allowed to come to nearly the same temperature as the water. Approximately 2 mL of 2280-ppm rhodamine WT was then introduced into the borehole at middepth and surged to mix thoroughly. An initial water sample was taken from the borehole, followed by sampling at intervals over the next 10–60 minutes. Borehole water samples were taken using a peristaltic pump with a nominal flow of 400 mL/minute. The inlet tubing was placed about middepth in the borehole, and the water samples were discharged into two 20-mL scintillation vials wrapped in black tape and identified by cap number.

When samples were not being taken, the discharge line was placed in the borehole at about middepth. Middepth upstream water samples were obtained manually at the approximate centerline of the flume at convenient intervals to determine the effect of recirculation on the rhodamine concentration in the flume. The samples were stored in the flume facility for only a short period before being moved to a warmer room. All samples and standards were stored together in covered boxes at least overnight to be sure that they were at the same temperature during analysis and to minimize condensation.

Water samples were analyzed with a Turner Model 10 field fluorometer (Turner Designs 1981). A standard curve was developed for each day of testing using standard solutions containing 10, 20, 50, 100 and 500 ppt (parts per trillion); 1, 5, 10 and 100 ppb (parts per

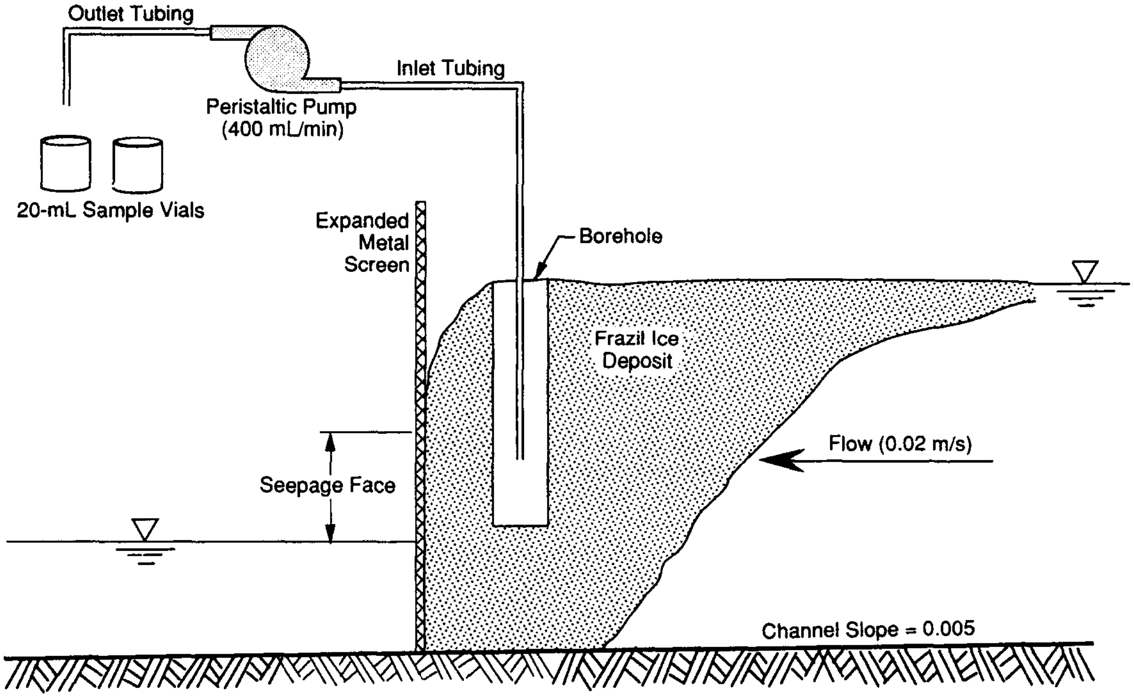

Figure 1. Borehole dilution test set-up.

billion); and 1 ppm (part per million) rhodamine WT. The standard solutions were prepared by the method described in Wilson et al. (1986). The 10-ppt standard solution was used to set the zero reading of the machine, while the full scale reading was set by the 1-ppm standard solution. A standard solution within the sample range was read occasionally to check for drift. Water samples were analyzed in order of expected increasing concentration, beginning from the latest sample taken and ending with the initial sample. The entire sample from each pair of scintillation vials was poured into the cuvette and mixed before being placed in the fluorometer. After the fluorometer reading, the cuvette was emptied and rinsed twice with distilled water before being refilled with the next sample. Distilled water was used to avoid any chlorine contamination from the chlorinated tap water. Carry-over of the 1-ppm standard was checked and found to be less than 10 ppt when no rinse was used. Following a test run the sample vials and caps were rinsed with tap water and then distilled water.

RESULTS

Seventeen tests were conducted. Using the method described in Lewis et al. (1966), a plot of the logarithm of the ratio of concentration at time t to maximum concentration vs time was developed for each test (App. A). In several tests, concentrations were seen to increase and then decrease again during the course of the test (see the data for tests 1, 2B, 6C and 8A, for example). The recirculation time in the flume at the average flow of 0.01 m^3/s was on the order of 6.5 minutes, assuming short-circuiting in the flume sump. This may explain the increases in rhodamine concentration that occurred around 6 minutes during tests 3B, 4A, 5B, 7A and 7B and later in other tests. However, the cause of earlier increases or repeated increases at shorter time intervals is unknown. The rhodamine dye solution in the borehole may have been incompletely mixed, or the samples could have been contaminated during handling. The increases could be the residue of earlier tests, although the mixing in the flume sump and headbox, combined with the turbulence of the flume, should prevent the formation of such "pockets" of increased rhodamine recirculating through the flume.

Samples were taken upstream from the frazil deposit during the tests to check for recirculation effects. These samples were obtained by making a hole in the ice sheet and dipping the vials into the water. Rhodamine is heavier than water and would tend to sink, so a surface sample would be expected to have a lower concentration than a sample taken from the middle or bottom of the water column. However, after analysis the recirculation

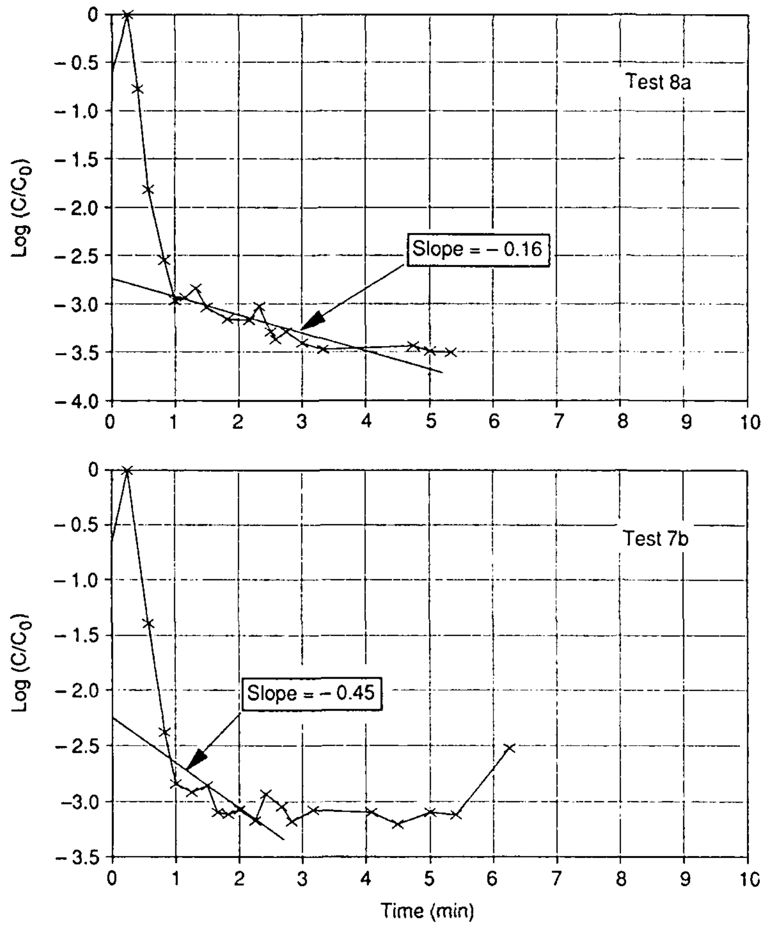

Figure 2. Examples of choice of values for regression analysis to determine seepage velocity.

samples were almost uniformly higher in concentration than the samples taken from the borehole. It is surmised that the samples were contaminated by dye on the sampler's skin, which was rewetted in the proximity of the sample vial. Because of this contamination the occurrence of recirculation could not be verified. As a result recirculation of the dye tracer was not taken into account in calculating seepage velocity.

Regression analyses were performed on the linear portion of the plots as shown in Figure 2. The data points chosen to develop the slope ($-8vt/\pi d$) were chosen by eye and did not include the rapid initial dilution that was attributed primarily to diffusion. The seepage velocity through the frazil ice deposit was calculated from

$$v = \frac{-\pi d}{8t}\,[\log\,(C/C_0)] \tag{5}$$

where C_0 was taken to be the highest level of fluorescence measured in each test. Of the 17 tests, three (1, 6a and 6b) did not yield usable slopes for calculating seepage velocity. The results for the remaining tests are given in Table 1.

The average of the correlation coefficients (r^2) between the 15 slopes analyzed was 0.7556, and the average seepage velocity was $9.27 \times 10^{-3} \pm 2.97 \times 10^{-3}$ cm/s. The coefficient of variation is 32%. In 60% of the tests the average velocity was within one standard deviation of the mean value, and all of the values were within two standard deviations of the mean. In some cases, multiple tests were run in one borehole in an effort to determine whether one borehole would yield repeatable results or whether the results would change over time. The results of first-run tests are listed in Table 2 and of later tests in Table 3. The seepage velocity in 86% of the first-run tests is within one standard deviation of the mean.

The results for second or third tests in the same borehole are given in Table 3. The variability between initial and subsequent tests in one borehole is much greater than between initial tests in boreholes in different ice deposits, or between subsequent tests.

The laboratory test involves a rather large change in head over a short distance as compared to the usual case in groundwater studies. The physical model can be considered analogous to the groundwater flow between two reservoirs with different water surface elevations (Fig. 3). Bear (1979) presented a solution to this case using the Dupuit–Forchheimer discharge formula:

$$k = \frac{2\mu v h_0 L b}{\rho g\,(h_0^2 - h_L^2)} \tag{6}$$

where L = length between the open water surfaces of the two reservoirs
b = width (generally taken as unit width)
h_0 = head on the upstream reservoir
h_L = head on the downstream reservoir.

The Dupuit–Forchheimer assumption is particularly sensitive to the choice of L (length between upper and lower water surface elevations) and Δh. Since data were not available for all parameters (h_0, h_L, L) for all tests, the intrinsic permeability was based on an average measured upstream water depth of 45 cm, downstream depth of 12 cm and length of 75 cm. The results, shown in Table 4, correspond to those for a silty to clean sand deposit (Freeze and Cherry 1979, Todd 1980).

Table 1. Borehole dilution test results.

Test	*Depth of borehole (cm)*	*No. of points in slope*	*Slope*	*Seepage velocity (10^{-3} cm/s)*	*Comments*
2A	20	7	–0.27	8.98	
2B	16	6	–0.19	6.32	
3A	12	8	–0.25	8.31	
3B	12	6	–0.18	5.98	Same borehole as 3A
4A	17	6	–0.39	12.97	
4B	17	8	–0.22	7.32	Same borehole as 4A
5A	8	7	–0.36	11.97	
5B	8	4	–0.39	12.97	Same borehole as 5A
5B	8	5	–0.18	5.98	Same test as above at later time
6C	15	5	–0.21	6.98	
7A	15	7	–0.25	8.32	
7B	15	8	–0.45	14.96	Same borehole as 7A
7C	15	5	–0.33	10.97	Same borehole as 7A
8A	17	16	–0.16	5.32	
8B	17	7	–0.35	11.64	Same borehole as 8A

Table 2. First-run tests.

Test	*Seepage velocity (10^{-3} cm/s)*
2A	8.98
2B	6.32
3A	8.31
4A	12.97
5A	11.97
7A	8.32
8A	5.32
Mean	8.88
Standard deviation	2.57
Coefficient of variation	29%

Table 3. Later tests in one borehole.

Test	*Position*	*Seepage velocity (10^{-3} cm/s)*	*Change between tests (%)*
3B	2	5.98	–28.0
4B	2	7.32	–43.6
5B	2	12.97	+8.3
5B	2	5.98	–50.0
6C	3	6.98	NA
7B	2	14.96	+80.0
7C	3	10.97	–26.7
8B	2	11.64	+118.8
Mean		9.31	+8.4
Standard deviation		3.37	60.9
Coefficient of variation		36%	>100

NA—not available.

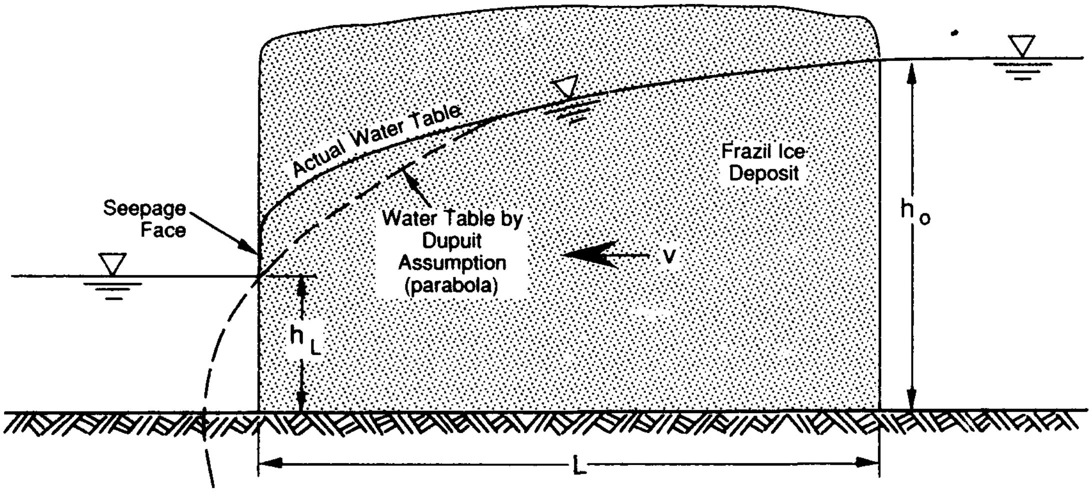

Figure 3. Definition sketch for Dupuit–Forchheimer discharge formula. (After Bear 1979.)

Table 4. Frazil ice deposit properties estimated using test results.

Test no.	*Intrinsic permeability (10^{-7} cm^2)*	*Hydraulic conductivity (10^{-2} cm/s)*
2A	5.87	3.22
2B	4.13	2.27
3A	5.43	2.98
3B	3.91	2.15
4A	8.48	4.65
4B	4.78	2.62
5A	7.83	4.30
5B	8.48	4.65
5B	3.91	2.15
6C	4.56	2.51
7A	5.43	2.98
7B	9.78	5.37
7C	7.17	3.94
8A	3.48	1.91
8B	7.61	4.18
Mean	6.06	3.32
Minimum	3.48	1.91
Maximum	9.78	5.37
Standard deviation	1.94	1.07
Coefficient of variation	32%	32%

The porosity of the frazil ice deposit may be roughly estimated using the Kozeny–Carman equation:

$$k = \frac{n^3 d_m^2}{180(1-n)^2} \qquad (7)$$

in which n is porosity and d_m is a representative grain size, often taken as d_{10} in soils. This equation is sensitive to the choice of the representative grain size. For example, if d_m were 0.1 mm, the porosity would be 58%, and if d_m were 0.3 mm, the porosity would be 37%, given the same value of intrinsic permeability. Using a mean frazil particle diameter of 0.2 mm, the average porosity of the test deposits calculated by the Kozeny–Carman equation was 43.6%.

DISCUSSION

The purpose of conducting the laboratory tests was to evaluate the feasibility of applying the borehole dilution technique to frazil ice for determining seepage velocity, intrinsic permeability and hydraulic conductivity. Use of the test results in making rough estimates of porosity using the Kozeny–Carman equation was also examined. Although the depth of the statistical analysis of the test results is limited by the number of tests, the data collected were sufficient to meet the purpose of the tests.

The average seepage velocity for 15 tests was $9.27 \times 10^{-3} \pm 2.97 \times 10^{-3}$ cm/s. While all of the test values were within two standard deviations of the mean value, only 60% of the tests were within one standard deviation of the mean, indicating some scatter. Upon separating the test results into two categories (initial and subsequent tests), the coefficient of variation for the initial tests is lower, indicating that there is less scatter in the initial tests than in subsequent tests (Tables 2 and 3). While the mean seepage velocity is higher in subsequent tests than in initial tests, the percentage change between tests in a particular borehole exhibits wide scatter and no general trend can be seen.

There are a number of possible causes for the variability of the test results. A larger number of samples used to determine the seepage velocity in each test would be desirable but difficult to achieve in the laboratory situation due to the rapid dilution of the dye. Continuous measurement of fluorescence would also be desirable, but under the present test conditions, a flow-through system, which would provide continuous fluorescence measurements, would be subject to a variety of interferences due to low temperatures (e.g. condensation, high dissolved oxygen). Non-uniform concentration in the borehole, unsteady flow and non-uniform flow are all possible sources of variation.

Based on an average particle diameter of 0.2 mm (Daly and Colbeck 1986), the Reynolds number associated with the average seepage velocity is less than 0.1, well within the laminar flow range. The Dupuit–Forchheimer approximation, which assumes laminar flow, was used to determine intrinsic permeability. The resulting average intrinsic permeability calculated was similar to that of fine sand. This result is consistent with estimates of intrinsic permeability using particle size; the mean diameter of fine sand is on the order of 0.5 mm, close to that of the frazil particles (0.2 mm) in the flume.

The coefficient of variation for the intrinsic permeability and hydraulic conductivity depends on that for seepage velocity. Although the value for all tests (32%) is at the low end of the high range (Harr 1987), it is still lower than that reported by Nielsen et al. (1973) for soils (85%). It is therefore reasonable to conclude that the coefficient of variation, while high, is in the normal range for the variables tested (seepage velocity, intrinsic permeability, hydraulic conductivity) and that the borehole dilution test results show an acceptable degree of scatter.

Measurements of the porosity of frazil ice deposits are difficult to obtain. Andersson and Daly (in prep.) calculated porosity from the measured weight of a known volume of saturated frazil ice. They tested a number of samples of frazil ice produced in the CRREL refrigerated hydraulic flume as well as several field samples

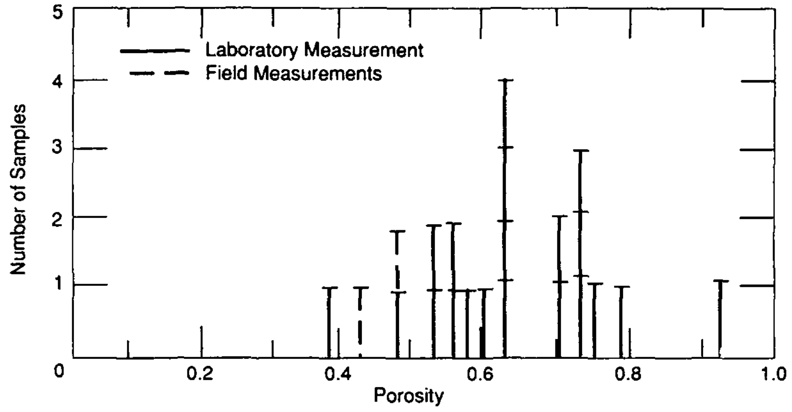

Figure 4. Porosity by weight of a frazil ice deposit. (From Andersson and Daly, in prep.)

Table 5. Comparison of intrinsic permeability.

	Borehole dilution k (*cm^2*)	*Dean (1976)* k^* (*cm^2*)	*Beltaos and Dean (1981)* $k^\dagger$ (*cm^2*)
Average value	6.06×10^{-7}	1.53×10^{-5}	1.56×10^{-5}
Minimum	3.48×10^{-7}	—	1.50×10^{-5}
Maximum	9.78×10^{-7}	—	1.63×10^{-5}
Standard deviation	1.94×10^{-7}	—	9.19×10^{-7}

* Two tests.
† Three tests.

(Fig. 4) and reported an average porosity of 67 ± 13% for twenty 0.3-dm^3 laboratory samples.

The average porosity resulting from the borehole dilution tests (43.6 ± 3.2%) is lower than the average value for laboratory samples obtained by weight measurements. These results may reflect disturbance to the frazil ice deposit during drilling, which could have caused the walls of the borehole to be less porous than the surrounding deposit. The porosity values computed using the borehole dilution test results were within the range reported by Andersson and Daly and compared favorably with their measurements on natural frazil ice (43% and 48%).

The constant-head permeameter test results reported by Dean (1976) and Beltaos and Dean (1981) are the only known measurements of the intrinsic permeability of frazil ice. However, there are some aspects of the test that may decrease its reliability in predicting the intrinsic permeability of the actual frazil ice deposit. Primary among these is the destructive nature of the test: as the sample is drained, particularly under centrifugal forces, the characteristics of the solid matrix are changed. Due to the low ambient air temperatures, some refreezing of the drained samples probably occurred. The packing, grain shape, tortuosity and porosity of the deposit will be affected by this procedure. Vertical (rather than horizontal) samples are generally used in permeameter tests on soils. In a homogeneous, isotropic medium, no difference would be perceived between the vertical and horizontal samples. However, the nature of the frazil ice deposition process appears to favor nonhomogeneity; thus the permeability may be affected by the orientation of the sample. These factors may have contributed to the two-orders-of-magnitude difference between the laboratory borehole dilution results and the field permeameter results (Table 5). The differences in the frazil deposits themselves (e.g. particle size, morphology) may have also contributed to the difference in the results.

The combination of these factors makes it difficult to draw any meaningful comparisons between the intrinsic permeability of laboratory and field deposits found using the different test methods. Field tests of the borehole dilution method are necessary before a more detailed comparison with the earlier measurements can be made.

CONCLUSIONS

The borehole dilution test was modified for use in determining the seepage velocity through a frazil ice deposit grown in the hydraulic flume. This relatively simple test consists of monitoring the dilution, over time, of a fluorescent dye introduced to a borehole in frazil ice. The Reynolds number associated with the average seepage velocity of 9.27×10^{-3} cm/s satisfied the laminar flow assumption of the Dupuit–Forchheimer approximation, which was used to model the flow in the laboratory tests. The average intrinsic permeability of the frazil ice deposits calculated from the seepage velocity (6.06×10^{-7} cm^2) and corresponding hydraulic conductivity (3.32×10^{-2} cm/s) were on the order of those for fine sand. The coefficient of variation (32%) for these properties is within an acceptable range.

The average intrinsic permeability found using the borehole dilution test in a laboratory deposit was about two orders of magnitude less than the values reported using a permeameter test on samples taken from natural frazil ice deposits. Because the frazil deposits and the test methods differed in many ways, field tests of the borehole dilution method are necessary before a more detailed comparison with the earlier measurements can be made.

The average porosity during the borehole dilution tests was roughly estimated from the Kozeny–Carman equation to be 43.6%. This value, while low, is within the range of values reported by Andersson and Daly (in prep.).

The borehole dilution test is an in-situ, nondestructive test that is fairly simple to perform in the laboratory and could be modified for use in the field. The borehole dilution method should be tested in the field to compare the results of this test with those of the permeameter test in natural ice. In soils the test can indicate the presence and characteristics of layered systems. If this test can be used successfully in the field, it will provide a method for determining the seepage velocity, intrinsic permeability, hydraulic conductivity and morphology of natural frazil ice deposits, as well as rough estimates of porosity.

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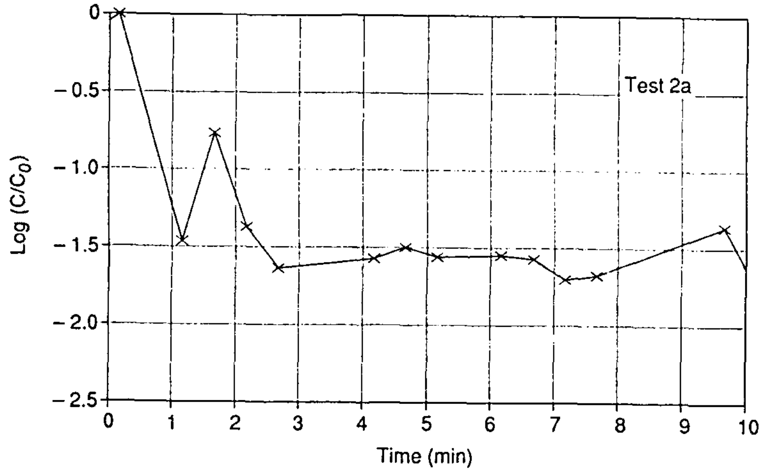
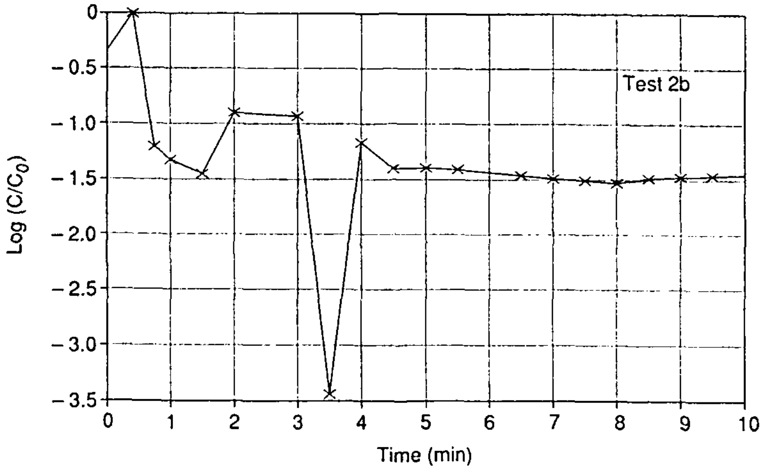
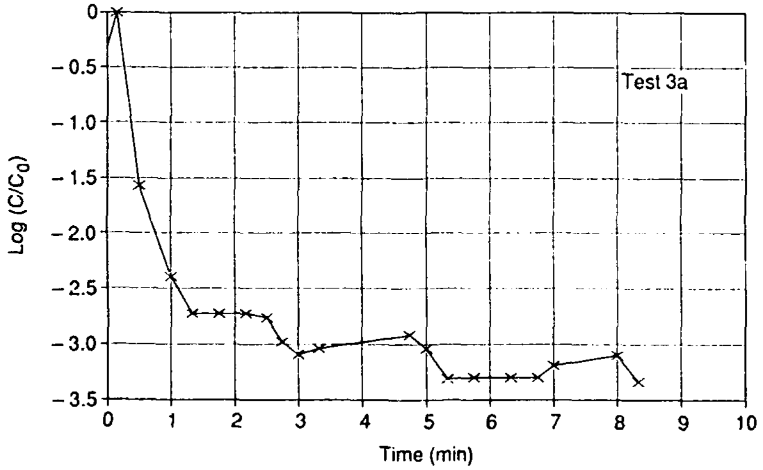
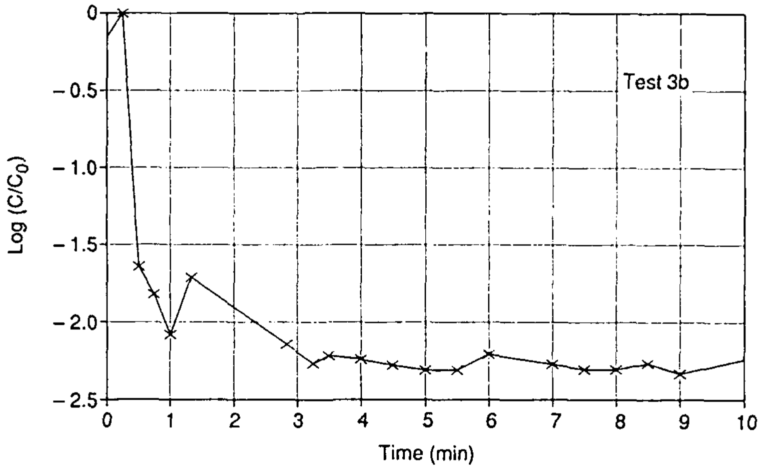
APPENDIX A. TEST RESULTS.








Test 3b
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-1.5
-2.0
-2.5
0
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2
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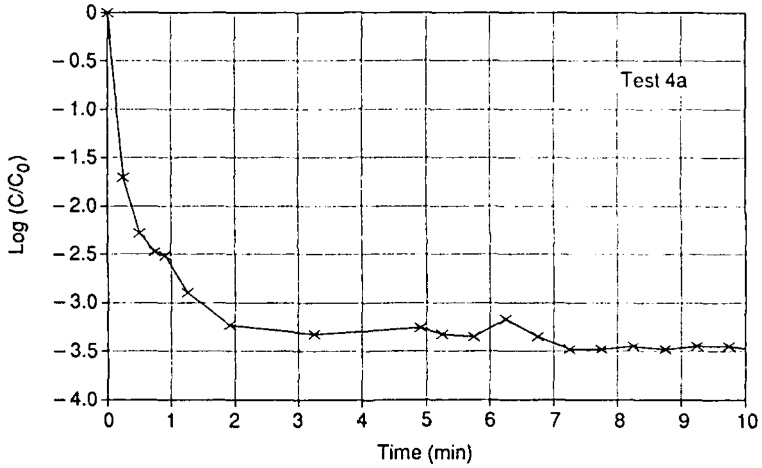
4
5
6
7
8
9
10
Time (min)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Log (C/C0)
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-1.5
-2.0
-2.5
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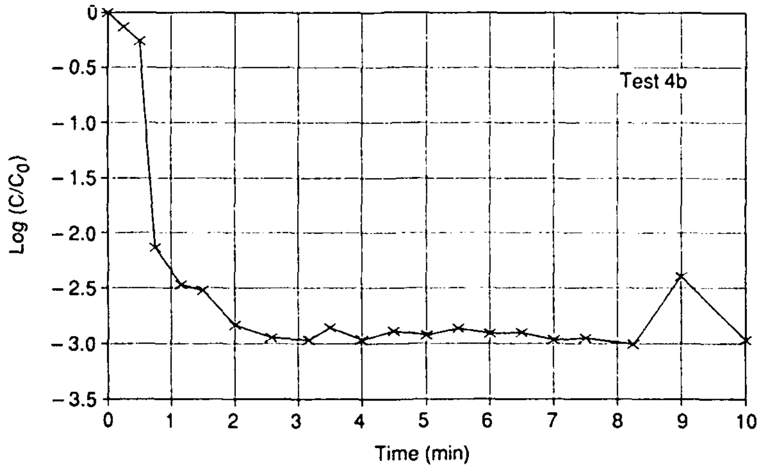
-3.5
-4.0
0
1
2
3
4
5
6
7
8
9
10
Time (min)


Test 4b
Log (C/C0)
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-0.5
-1.0
-1.5
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-2.5
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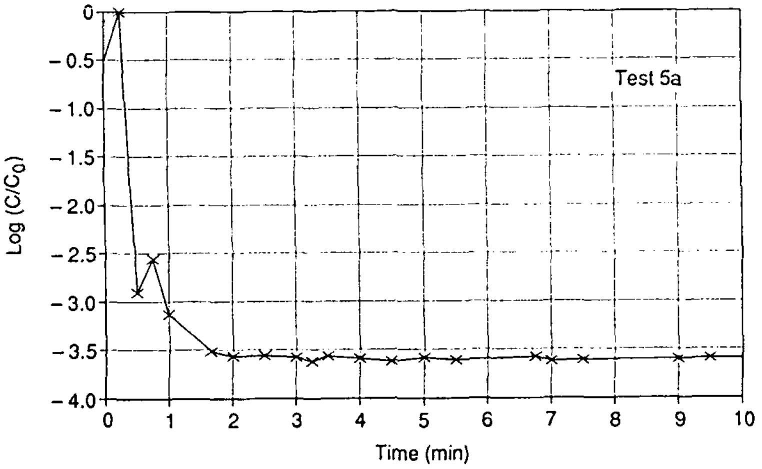
-3.5
0
1
2
3
4
5
6
7
8
9
10
Time (min)


Test 5a
Log (C/C$_0$)
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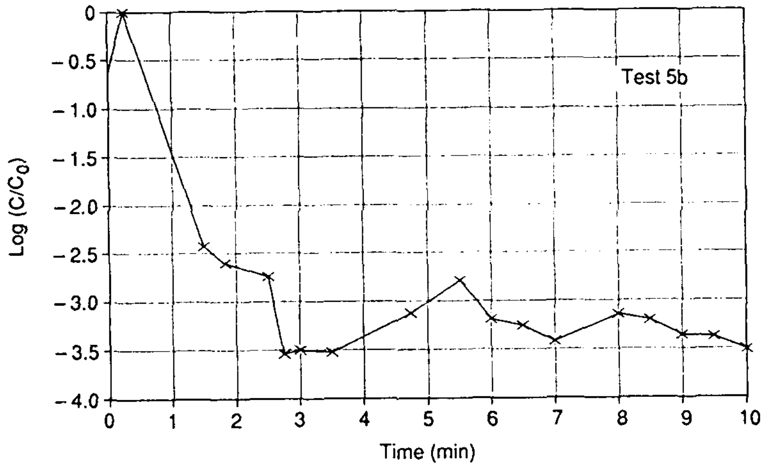
- 1.0
- 1.5
- 2.0
- 2.5
- 3.0
- 3.5
- 4.0
0
1
2
3
4
5
6
7
8
9
10
Time (min)


Test 5b
Log (C/C$_0$)
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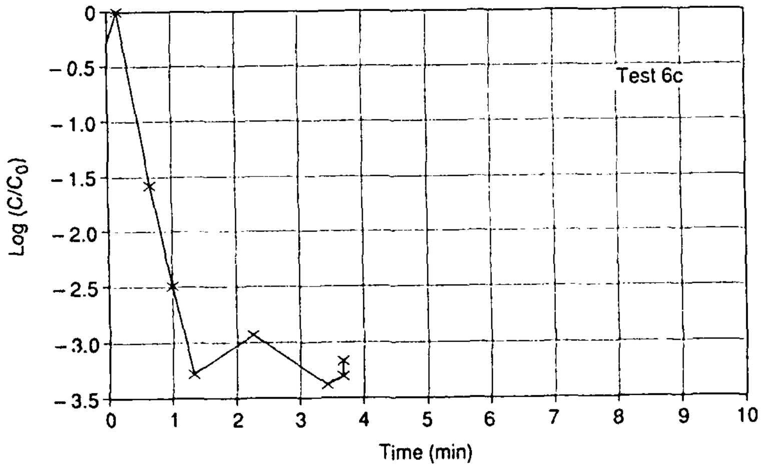
- 0.5
- 1.0
- 1.5
- 2.0
- 2.5
- 3.0
- 3.5
- 4.0
0
1
2
3
4
5
6
7
8
9
10
Time (min)


Test 6c
Log (C/C$_0$)
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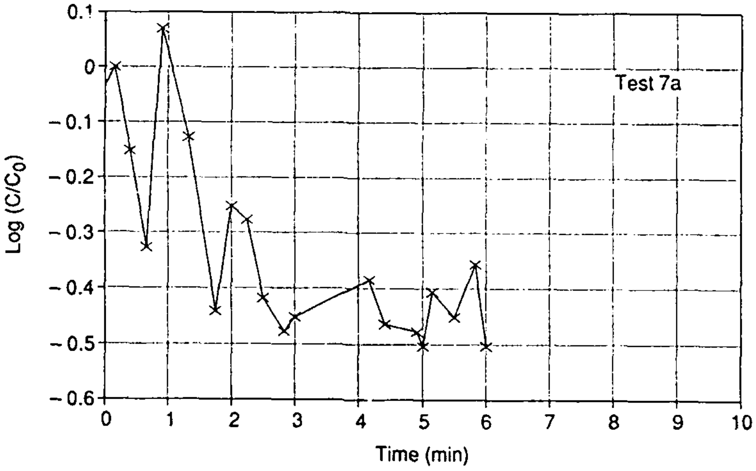
- 1.0
- 1.5
- 2.0
- 2.5
- 3.0
- 3.5
0
1
2
3
4
5
6
7
8
9
10
Time (min)


Test 7a
Log (C/C$_0$)
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0
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-0.3
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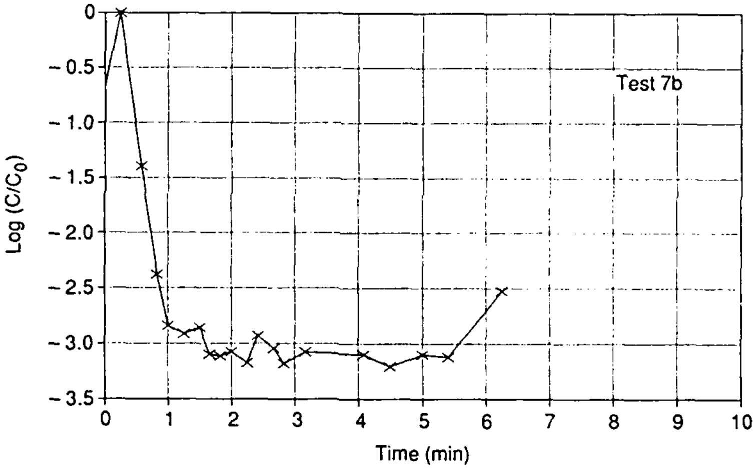
-0.5
-0.6
0
1
2
3
4
5
6
7
8
9
10
Time (min)


Test 7b
Log (C/C$_0$)
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-0.5
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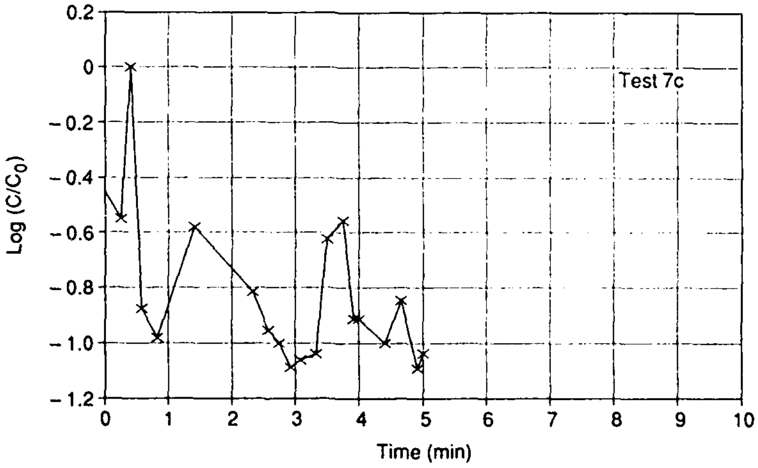
-1.5
-2.0
-2.5
-3.0
-3.5
0
1
2
3
4
5
6
7
8
9
10
Time (min)


Test 7c
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-0.4
-0.6
-0.8
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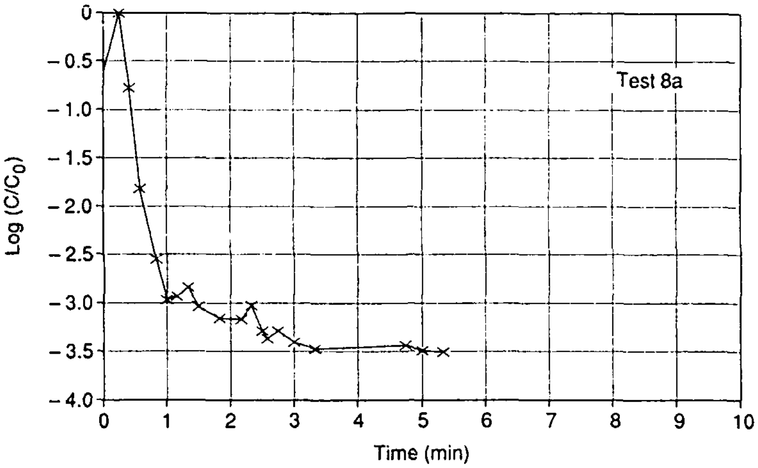
2
3
4
5
6
7
8
9
10
Time (min)


Test 8a
Log (C/C$_0$)
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−1.5
−2.0
−2.5
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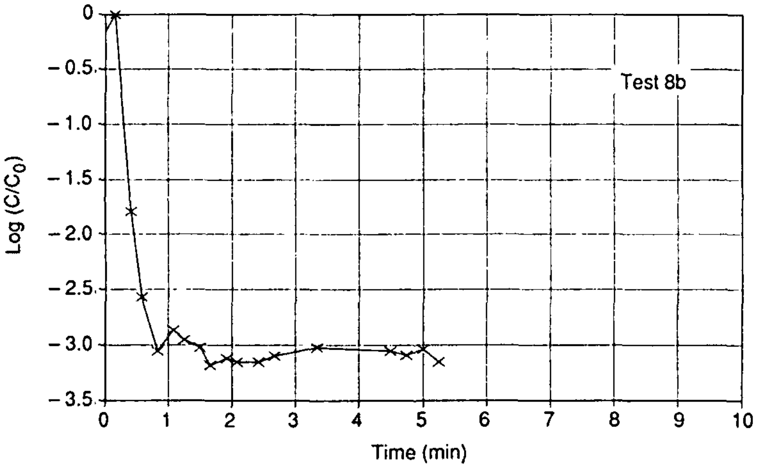
−3.5
−4.0
0
1
2
3
4
5
6
7
8
9
10
Time (min)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−1.5
−2.0
−2.5
−3.0
−3.5
0
1
2
3
4
5
6
7
8
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Time (min)

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The intrinsic permeability of frazil ice describes the capacity for flow through the ice matrix and can be used to estimate the porosity of the deposit. There are no existing in-situ tests for determining the intrinsic permeabiliy of a frazil ice deposit. The borehole dilution test, an in-situ, relatively nondestructive test often used in soils testing, was modified for use in frazil ice. In this test the dilution of a dye tracer introduced into a borehole made in a laboratory frazil ice deposit was measured over time. The test results were used to find the seepage velocity through the frazil deposit, from which the intrinsic permeability is calculated using the Dupuit–Forchheimer approximation to flow between two reservoirs. The results from the laboratory experiments indicate that the test may be modified for use as an in-situ method to determine intrinsic permeability in frazil ice deposits.

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River ice

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