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Waste Isolation Pilot Plant Project: Disposal Room Processes

Development and Testing of Waste Surrogate Materials for Critical Shear Stress

Progress Report
September, 1998

Prepared by:
Rich Jepsen
Jesse Roberts
Wilbert Lick
Department of Mechanical and Environmental Engineering
University of California
Santa Barbara, CA 93106

Prepared for:
Sandia National Laboratories
Waste Isolation Pilot Plant Project
Albuquerque, NM 87185

Supporting:
Sandia Contract AX-9022
WBS# 1.1.01.2.7

SWCF-A:1.1.01.2.7:DRPR1:NF:TD:QA: Progress Report, September, 1998, AX-9022 (UCSB)

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1. Introduction

In this study, the erosion rates of waste surrogate materials have been determined as a function of depth, shear stress, and salinity by means of a unique flume (Sedflume) previously developed and tested at the University of California at Santa Barbara (McNeil *et. al.*, 1996; Jepsen *et. al.*, 1997). Three types of waste materials and a total of 15 samples were tested.

The purpose of the study was to determine the critical shear stress for waste surrogate materials and compile data records of the test activities. The Department of Energy (DOE), Carlsbad Area Office (CAO) has determined that inadvertent drilling intrusions into the WIPP could cause a direct release of contaminants to the surface. This would be caused as drilling fluids circulate through the wellbore creating shear stresses that may erode waste from the borehole walls.

In the following section, brief descriptions of Sedflume and experimental procedures are given. The results of the tests for each sample are summarized in the third section. A summary and concluding remarks are given in the final section.

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2. Experimental Procedures

The information in this section is partially based on the articles by McNeil *et. al.* (1996) and Jepsen *et. al.* (1997).

2.1 Description of Sedflume

Sedflume is shown in Figure 1 and is essentially a straight flume that has a test section with an open bottom through which a rectangular cross-section tube containing the sample can be inserted. The main components of the flume are the sample tube; the test section; an inlet section for uniform, fully-developed, turbulent flow; a flow exit section; a water storage tank; and a pump to force water through the system. The sample tube, test section, inlet section, and exit section are made of clear acrylic so that the sample-water interactions can be observed. The sample tube has a rectangular cross-section, 10 cm by 15 cm, and can be up to 1 m in length.

Water is pumped through the system from a 120 gallon storage tank, through a 5 cm diameter pipe, and then through a flow converter into the rectangular duct shown. This duct is 2 cm in height, 10 cm in width, and 120 cm in length; it connects to the test section which has the same cross-sectional area and is 15 cm long. The flow converter changes the shape of the cross-section from circular to the rectangular duct shape while maintaining a constant cross-sectional area. The flow is regulated by a three-way valve so that part of the flow goes into the duct while the remainder returns to the tank. Also, there is a small valve in the duct immediately downstream from the test section which is

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opened at higher flow rates to keep the pressure in the duct and over the test section at atmospheric conditions.

At the start of each test, the sample tube is filled with the waste surrogate material. The material had been previously compacted by RE/SPEC Inc. into a brick shaped form which fits snugly into the sample tube. The tube and the material it contains are then inserted into the bottom of the test section. An operator moves the sample upward using a piston which is inside the tube and is connected to a hydraulic jack with a 1 m drive. The jack is driven by the release of pressure which is regulated with a switch and valve system. By this means, the sample can be raised and made level with the bottom of the test section. The speed of the jack movement can be controlled at a variable rate in measurable increments less than 0.5 mm.

Water is forced through the duct and the test section over the surface of the sample. The shear produced by this flow causes the sample to erode. As the sample in the tube erodes, it is continually moved upwards by the operator so that the sample-water interface remains level with the bottom of the test and inlet sections. The erosion rate is recorded as the upward movement of the sample in the tube over time.

2.2 Hydrodynamics

For the flow rates of interest, it can be observed that fully developed turbulent flow exists in the test section. Turbulent flow through pipes has been studied extensively, and empirical functions have been developed which relate the mean flow rate to the wall shear stress. In general, flow in circular cross-section pipes has been investigated (Schlichting, 1979). However, the relations developed for flow through circular pipes

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can be extended to non-circular cross-sections by means of a shape factor. An implicit formula relating the wall shear stress to the mean flow in a pipe of arbitrary cross-section can be obtained from Prandtl's Universal Law of Friction (Schlichting, 1979). For a pipe with a smooth surface, this formula is

$$\frac{1}{\sqrt{\lambda}} = 2.0 \log\left[\frac{UD\sqrt{\lambda}}{\nu}\right] - 0.8 \qquad (2.1)$$

where U is the mean flow speed, ν is the kinematic viscosity, λ is the friction factor, and D is the hydraulic diameter defined as the ratio of four times the cross-sectional area to the wetted perimeter. For a pipe with a rectangular cross-section, or duct, the hydraulic diameter is

$$D = 2hw/(h + w) \qquad (2.2)$$

where w is the duct width and h is the duct height. The friction factor is defined by

$$\lambda = \frac{8\tau}{\rho U^2} \qquad (2.3)$$

where ρ is the density of water and τ is the wall shear stress. Inserting Eqs. (2.2) and (2.3) into Eq. (2.1) then gives the wall shear stress τ as an implicit function of the mean flow speed U.

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For shear stresses in the range of 1 to 100 dyne/cm^2, the Reynolds numbers, UD/v, are on the order of 10^4 to 10^5. These values for Reynolds numbers are sufficient for turbulent flow to exist for the stresses of interest in this study. For flow in a circular pipe, turbulent flow theory suggests that the transition from laminar to turbulent flow occurs within 25 to 40 diameters from the entrance to the pipe. Since the diameter of the circular pipe is 5 cm, this suggests an entry length of 125 to 200 cm. The length of the duct leading to the test section is 120 cm and is preceded by a 30 cm flow converter and several meters of inlet pipe. In addition, since the duct is rectangular with an aspect ratio of five and a hydraulic diameter of 3.3 cm, the transition to turbulence is more rapid than for a circular pipe. These arguments along with direct observations indicate that the flow is fully turbulent in the test section.

2.3 Sample Collection and Preparation

Samples tested in Sedflume were obtained from RE/SPEC Inc. where they had been prepared and compacted into bricks with a 10 cm by 15 cm cross-section. Each sample was sealed in plastic wrap, aluminum foil and finally by a wax shell prior to shipping. The protective covering was carefully removed and the samples were inspected and placed into the tube. Each sample remained sealed until the day of the erosion test. Some samples were allowed to soak in water for a day or more after the original test was run in order to investigate any differences that might occur after they had been saturated in water.

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2.4 Measurements of Sediment Erosion Rates

The procedure for measuring the erosion rates of the samples as a function of shear stress and depth was as follows. The samples were obtained as described above and then moved upward into the test section until the sample surface was even with the bottom of the test section. A measurement was made of the depth to the bottom of the sample in the tube. The flume was then run at a specific flow rate corresponding to a particular shear stress. Erosion rates were obtained by measuring the remaining sample depth at different time intervals, taking the difference between each successive measurement, and dividing by the time interval.

In order to measure erosion rates at several different shear stresses using only one sample, the following procedure was generally used. Starting at a low shear stress, the flume was run sequentially at higher shear stresses with each succeeding shear stress being twice the previous one. Generally about three shear stresses were run sequentially. Each shear stress was run until at least 0.5 mm but no more than 5 mm were eroded. The time interval was recorded for each run with a stop watch. The flow was then increased to the next shear stress, and so on until the highest shear stress was run.

2.5 Measurements of Critical Shear Stress for Erosion

A critical shear stress can be quantitatively defined as the shear stress at which a very small, but accurately measurable, rate of erosion occurs. In the present study, this rate of erosion was chosen to be 10^{-4} cm/s; this represents 1 mm of erosion in approximately 15 minutes. Since it would be difficult to measure all critical shear

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stresses at exactly 10^{-4} cm/s, erosion rates were generally measured above and below 10^{-4} cm/s at shear stresses which differ by a factor of two. The critical shear stress was then linearly interpolated to an erosion rate of 10^{-4} cm/s. This gave results with a 20% accuracy for the critical shear stress. Some of the samples could not be eroded at rates greater than 10^{-4} cm/s within the range of shear stresses possible. For these samples, the test was run at a particular shear stress for several hours in order to obtain a measurable amount of erosion.

2.6 Measurements of Sample Density

A device, known as the Density Profiler (Gotthard, 1998), was used to measure the bulk density of the samples prepared in the laboratory and is described here. The Density Profiler is similar to the X-Ray device described by Been (1981) but uses a gamma radiation emitter as a source. The main components of the Density Profiler are a ^{137}Cs gamma radiation source, a NaI crystal scintillation counter, a flat plate containing the source and the counter, a housing that retains the rectangular box core containing the sample, a vertical and horizontal lead screw, and two step motors. One motor is connected to each lead screw; the vertical lead screw drives the plate up or down; the horizontal lead screw drives the rectangular box core side to side. By this means, bulk density measurements can be taken anywhere throughout the core in measurable increments as small as 1 mm.

The bulk density is related to the absorption of the gamma radiation from the ^{137}Cs source. The amount of radiation absorbed by the sediment core is measured and the density of the core material can be calculated using the following equation

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$$N = N_o e^{-\mu \rho x} \qquad (2.4)$$

where N is the number of counts which pass through the core sample, N_o is the number of counts with no sample, μ is the mass absorption coefficient, ρ is the bulk density, and x is the sample width (10 cm). By solving for ρ, one obtains

$$\rho = \frac{-1}{\mu x} \ln \frac{N}{N_o} \qquad (2.5)$$

For ^{137}Cs, the gamma radiation energy is 660 keV and the mass absorption coefficient is 0.076 cm^2/g.

In order to determine the bulk density of the samples with the Density Profiler, the following procedure was generally used. A measurement of the number of counts passing through an empty Plexiglas tube was measured. In all cases, the counter was allowed to count for ten minutes to assure density measurements with an accuracy of 0.01 g/cm^3 or better. Measurements of the number of counts passing through the sample were made at different locations along the length of the core. The number of density measurements taken and hence the resolution of the density profile were limited by time requirements.

2.7 Measurements of Erosion with Salinity as a Parameter

Erosion rates were measured for some samples with saline water. The erosion measurements were done as described above. The saline water was obtained by adding

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Cargill Inc. Diamond Crystal Solar Salt to the 120 gallon tank. The amount of salt added to the tank was such that the mixture would be 3.5% salts. The effects of salt water and fresh water were observed for the same sample by alternating the type of water used between each shear stress run on the sample.

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3. Results

A total of 15 samples were received from RE/SPEC, Inc. The samples were labeled B1 through B15. Sample B1 was too large to fit into the tube, and sample B10 was broken when received. Therefore, these two samples were not tested. There were three material types that were tested. The first type was represented by samples B1 through B6, the second by samples B7 through B9, and the third by samples B10 through B15. Densities were not measured for samples B1 through B6. Samples B13, 14, and 15 were tested with both salt water and fresh water. For all samples, erosion rates and density were independent of depth. The following describes the results for each sample. Table 1 gives the average erosion rate for each shear stress tested, Table 2 gives the critical shear stress, and Table 3 shows the average density found for each sample measured.

Sample B1 was used as a practice sample to determine the appropriate compacted sample size that would fit into the tube. The sample was too large to fit and could not be forced in the tube by any means without destroying it. This information was given to RE/SPEC, Inc. and all subsequent samples were fabricated to fit into the tube.

Sample B2 fit into the tube well, and the erosion test was run. The surface of the sample was smooth and dark brown in color. At low shear stresses of 4 to 8 dyne/cm^2 there was a very small amount of material eroded. This material was lost during the initial period of these tests. It was observed that some of the material on the surface was loose and easily eroded, but the majority was left intact and the sample did not need to be raised in the test section. Therefore, there was no measurable erosion below 8 dyne/cm^2.

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For shear stresses at and above 12 dyne/cm^2, the erosion consisted of periodic bursts of material from the sample surface. The surface became very uneven after the 24 dyne/cm^2 shear stresses had been run and the test was stopped.

The test for sample B3 was qualitatively similar to B2. The initial low shear stresses eroded some of the loose material on the surface of the sample, but the majority of the material remained intact. Although some loose material came off the surface at shear stresses between 2 and 20 dyne/cm^2, there was not enough eroded to raise the entire surface until a shear stress of 24 dyne/cm^2 was reached. It was observed that there was much fibrous material that did not erode even though the surrounding material was removed. This fibrous material projected from the surface of the sample into the flow, yet it still remained intact. At higher shear stresses of 32 and 40 dyne/cm^2, the erosion consisted of both small pieces of material and larger chunks which were greater than 1 cm in size. The shear stresses of 20 and 24 dyne/cm^2 were repeated at depth and gave similar results to that measured near the surface of the sample.

Sample B4 had measurable erosion at a shear stress of 10 dyne/cm^2. Below this shear stress there was erosion; however, as seen in previous samples, the erosion was negligible. Erosion rates were repeated at different depths for 12 and 16 dyne/cm^2, and the results were similar.

Sample B5 showed measurable erosion at 8 dyne/cm^2. The only shear stress run on this sample was the 8 dyne/cm^2 test because the flow meter's paddle wheel was destroyed from the recirculating debris which became caught in the apparatus. Therefore, the test was stopped and a screen was introduced to keep large debris from recirculating through the flow meter for subsequent tests.

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The test for sample B6 showed measurable erosion occurring at shear stresses of 16 dyne/cm^2 and higher. A test was run for a shear stress of 14 dyne/cm^2. In ten minutes, 0.5 mm of material was eroded. This is very close to an erosion rate of 10^{-4} cm/s which is defined as the erosion rate for the critical shear stress. The erosion test was repeated for 16 dyne/cm^2 and showed similar erosion rates with depth.

Samples B7 through B9 were very different in appearance compared to the first six samples. These samples were dark brown and rust colored with much more uniform fine-grained material. The previous samples were more varied in color and in size.

Sample B7 had an average density of 2.06 g/cm^3, and the variation with depth was within $\pm$ .01 g/cm^3. This sample was much easier to erode than previous samples. There was measurable erosion at 2 dyne/cm^2, and the critical shear stress was between 2 and 3 dyne/cm^2. The erosion was mostly bedload at shear stresses lower than 4 dyne/cm^2 and was approximately 50% bedload at 6 and 8 dyne/cm^2. The erosion of the material was observed to be particle by particle. All erosion rates varied little with depth at the same shear stress.

Sample B8 had an average density of 2.10 g/cm^3 and also did not vary with depth. This sample was more difficult to erode than B7. The critical shear stress for erosion was 3.0 dyne/cm^2, and higher shear stresses gave lower erosion rates than observed with B7. Some of the eroded material seemed larger than what was observed in B7. Also, sample B8 eroded more in aggregate chunks of material of 1 to 3 mm in size rather than individual particles as observed in B7. The erosion at all shear stresses was subsequently observed to be mostly bedload because of the larger size of the eroded material. There was no difference in erosion as a function of depth.

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The test for sample B9 showed it to be the most dense and compact of the group. The average density was 2.16 g/cm^3, and the density varied from 2.14 g/cm^3 at the surface of the sample to 2.17 g/cm^3 at the bottom. This variation is almost within the error of the measurement. The erosion tests for B9 showed similar results to that observed in B8 with B9 being slightly more difficult to erode than B8.

The group of samples B10 through B15 all consisted of similar material. They were white or light gray in color and made up of uniform size grains. Sample B10 was received in an unusable condition and was not tested. Samples B13, 14, and 15 were tested with both fresh and saline water.

Sample B11 had a density of 2.10 g/cm^3 and was very difficult to erode. Some loose material came off the surface at shear stresses of 50 dyne/cm^2 or less but this material was observed to be loose from prior handling of the sample. For shear stresses between 64 and 120 dyne/cm^2, it was very difficult to distinguish any difference in the erosion rates. This was due to the erosion rates being much less than 10^{-4} cm/s with test periods of 20 minutes. The amount of erosion was less than 0.5 mm in the 20 minute time period, and therefore accurate measurements could not be made. However, there was visually observed erosion at each shear stress at and above 64 dyne/cm^2. Therefore, the tests were run for longer periods between 2 and 4 hours at one shear stress of 64 dyne/cm^2 in order to obtain an accurate measurement for the erosion rate. The erosion rates measured were between 2.1 x 10^{-5} and 2.8 x10^{-5} cm/s with an average of 2.6 x 10^{-5} cm/s. Also, the sample was allowed to soak in water for one day and the erosion was tested again at 64 dyne/cm^2. This gave an erosion rate of 2.8 x10^{-5} cm/s which was similar to the results of the initial tests.

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Sample B12 had a density of 2.11 g/cm^3 and was very difficult to erode. Additional care was taken in handling of this sample to avoid creating any loose grains: This sample was tested at 64 dyne/cm^2 while continuously soaking in water with time steps starting at 0, 1, 3, and 7 days. Each test was run for at least two hours. The first test gave an erosion rate of 4.6 x 10^{-6} cm/s which represented 0.5 mm of erosion in 3 hours. Since only 0.5 mm was measured, this value may not be as accurate as other erosion rates in which a larger and more easily measured amount of erosion was observed. After the initial test, the 1, 3, and 7 day tests showed no erosion at 64 dyne/cm^2.

Sample B13 had a density of 2.09 g/cm^3 and was eroded with fresh water as well as salt water. Erosion was very difficult to measure at shear stresses less than 64 dyne/cm^2. One measurement was obtained at 16 dyne/cm^2 at the surface, but this measurement is not very reliable because some of the material was observed to be already loose and the amount eroded was 0.5 mm. More consistent erosion was observed at 64 dyne/cm^2 where erosion tests were done between 1 and 2 hours in both fresh and salt water. The average erosion rates were very similar for both fresh and salt water.

The density for sample B14 was 2.0 g/cm^3 and was significantly lower than the previous samples of this group. The erosion rates were also larger for this sample, and erosion rates were measurable at shear stresses of 16 and 32 dyne/cm^2. There was no distinguishable difference between erosion with fresh and salt water.

Sample B15 was the least dense of the group with a density of 1.95 g/cm^2. The sample was also noticeably softer during handling. This sample was very easy to erode compared to the other samples of the group. The erosion rates were measured at 4 and 8 dyne/cm^2 and there was no difference between erosion with fresh and salt water. This

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was the only sample of the group in which an erosion rate greater than 10^{-4} cm/s could be measured. It was also the only sample in which erosion as a function of depth could be adequately observed. There was no distinguishable difference in erosion rates with depth.

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4. Summary and Concluding Remarks

In the present study, erosion rates and critical shear stresses were determined for waste surrogate materials by means of testing with Sedflume. These parameters were determined for three types of waste materials as a function of depth, salinity, and density. The exceptions are samples B1 through B6 for which density was not measured.

Several conclusions can be made which are universal for all samples. These are summarized in the following:

1) Erosion rates were constant with depth.
2) Samples B7 through B15 had constant densities with depth.
3) Erosion rates decreased with increasing sample density.
4) Erosion rates of fresh and salt water for samples B13, B14, and B15 were essentially the same.
5) Samples which were allowed to soak in water for several days had the same erosion properties as was measured initially.

The three materials tested were very different when compared to each other. Samples B1 through B6 had critical shear stresses between 7 and 22 dyne/cm^2, samples B7 through B9 had critical shear stresses between 2.2 and 3.4 dyne/cm^2, and samples B10 through B14 had critical shear stresses greater than 64, while B15 had a critical shear stress of 2 dyne/cm^2. Also, the data showed that when the density of the material used in samples B10 through B15 was below 2.0 g/cm^3, the material was significantly easier to erode.

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Tables

Table 1. Average Erosion Rate (cm/s) for each Shear Stress (dyne/cm^2)

Sample	2	3	4	6	8	12	16	20	24	32	40	64
B1*	-	-	-	-	-	-	-	-	-	-	-	-
B2	-	-	-	-	-	5.5E-5	8.5E-5	1.7E-4	1.4E-3	-	-	-
B3	-	-	-	-	-	-	-	-	2.0E-4	1.7E-3	2.2E-3	-
B4	-	-	-	-	-	1.4E-4	2.3E-3	8.3E-3	-	-	-	-
B5	-	-	-	-	1.7E-4	-	-	-	-	-	-	-
B6	-	-	-	-	-	-	8.1E-3	8.3E-3	-	-	-	-
B7	5.6E-5	3.3E-4	6.6E-4	5.0E-3	7.6E-3	-	-	-	-	-	-	-
B8	-	1.0E-4	3.1E-4	8.3E-4	1.5E-3	4.4E-3	-	-	-	-	-	-
B9	-	5.6E-5	2.1E-4	5.7E-4	1.8E-3	-	-	-	-	-	-	-
B10*	-	-	-	-	-	-	-	-	-	-	-	-
B11	-	-	-	-	-	-	-	-	-	-	-	2.6E-5
B12	-	-	-	-	-	-	-	-	-	-	-	4.6E-6
B13S	-	-	-	-	-	-	-	-	-	-	-	2.3E-5
B13F	-	-	-	-	-	-	-	-	-	-	-	1.8E-5
B14S	-	-	-	-	-	-	2.8E-5	-	-	3.7E-5	-	4.3E-5
B14F	-	-	-	-	-	-	5.9E-5	-	-	5.5E-5	-	4.0E-5
B15S	-	-	2.0E-4	-	4.3E-3	-	-	-	-	-	-	-
B15F	-	-	1.7E-4	-	3.3E-3	-	-	-	-	-	-	-

* Sample B1 was too large to fit in tube and sample B10 was received destroyed.

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Table 2. Critical Shear Stress (dyne/cm^2) for each Sample

Sample	Critical Shear Stress (dyne/cm^2)
B1*	-
B2	16.7
B3	22.0
B4	10.6
B5	7.2
B6	14.0
B7	2.2
B8	3.0
B9	3.4
B10*	-
B11	64<
B12	64<
B13	64<
B14	64<
B15	2.0

*Sample B1 was too large to fit in tube and sample B10 was broken when received.

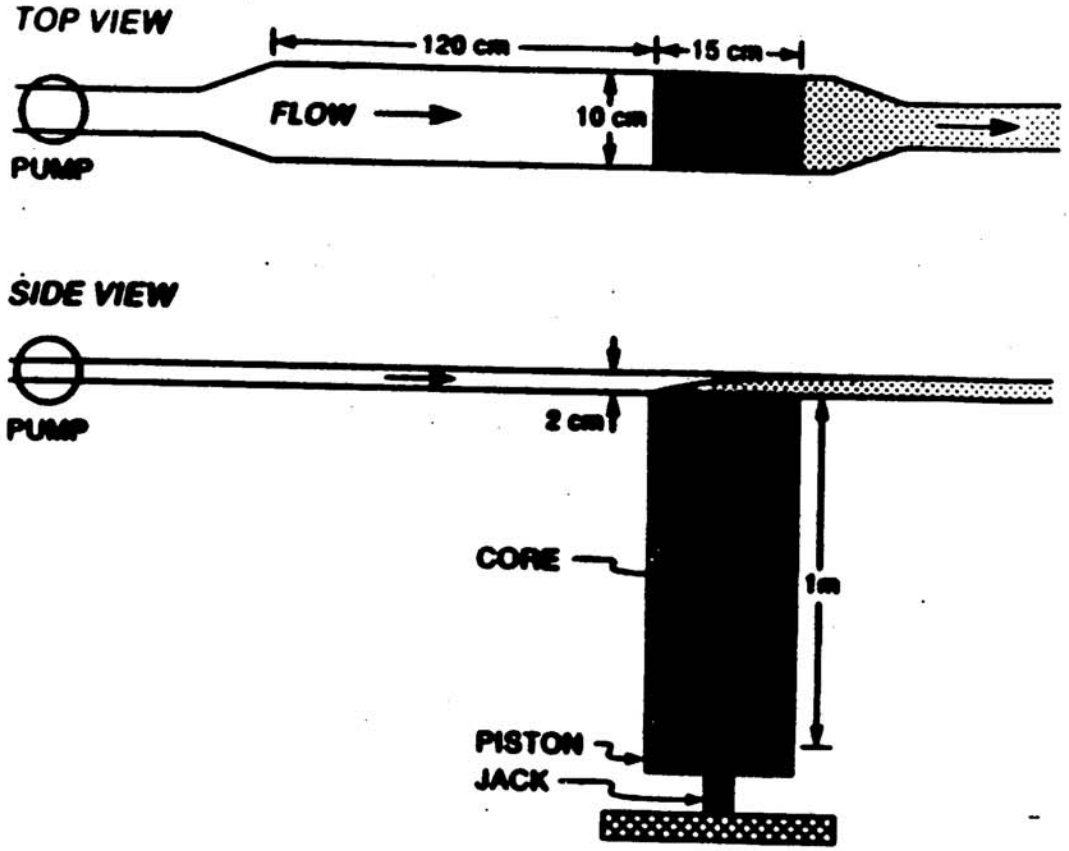
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Table 3. Sample Densities

Sample	Density (g/cm^3)
B7	2.06
B8	2.10
B9	2.16
B10*	- -
B11	2.10
B12	2.11
B13	2.09
B14	2.0
B15	1.95

*Sample B10 was broken when received.

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