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Experimental Investigation of Transport of Finite Solids in A 76 mm-Diameter Partially-Filled Pipe

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U.S. DEPARTMENT OF COMMERCE, Malcolm Baldrige, *Secretary*
NATIONAL BUREAU OF STANDARDS, Ernest Ambler, *Director*

PREFACE

This report is one of a group documenting National Bureau of Standards (NBS) research and analysis efforts in developing water conservation test methods, models for technical and economic analysis, and strategies for implementation and acceptance of practices. This work is sponsored by the Department of Housing and Urban Development/Office of Policy Development and Research, Division of Energy Building Technology and Standards, under HUD Interagency Agreement H-48-78.

ABSTRACT

An exploratory experimental investigation of the hydro-transport mechanisms of finite solids with non-uniform, unsteady and transient water flow introduced into a pitched-horizontal drain (p-h drain) pipe by discharging a plumbing fixture was carried out. The purpose of the investigation was to examine the effects of relevant variables on the velocity attained and the distance traversed by the solid in the p-h drain. The variables selected for the study include: the water volume used (i.e., the volume of water discharged from the plumbing fixture into the drain), diameter and length of cylindrical solid, and diameter and slope of the p-h drain.

This report contains a description of the experimental equipment and procedures, and a summary of the data acquired during the solid transport experiment in 7.6 cm diameter drain pipe at a pipe slope of 0.02, 0.04, and 0.06.

The solid dragged on a thin film of water between the solid and drain wall when relatively small water volumes ($V_w \leq 1.9$ liters or 0.5 gallons) were used; and the solid moved like a waterborne object when relatively large water volumes ($V_w \geq 3.8$ liters or 1.0 gallons) were used. The solid velocity and the distance traversed by the solid increased with an increase in the water volume used, an increase in the drain slope, a decrease in the solid diameter, and a decrease in the solid length.

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1. INTRODUCTION

1.1 BACKGROUND

Water shortages experienced during the past several years have brought increased attention to the need for water conservation. This concern for water conservation has drawn attention to the large quantities of water used in water closet (WC) operations and to a variety of means that can curtail this use. It has been estimated that about forty percent of the water used in the home is used for WC operation, about 95 liters (50 gallons) per person per day. [1,4] It has also been estimated that a reduction of thirty percent or more in this usage can be realized by replacing the conventional WC's (19 to 26 liters/flush) with the currently available water-saving units (11-13 liters/flush)[3-5], and a reduction of up to 90 percent of this water usage is possible if the conventional syphonic-flush water closets are replaced with innovative systems.[3]

Some researchers and plumbing professionals [5,9], however, have reported concern about the use of very low-volume WC's, indicating that such a usage may reduce the wastewater flow in the horizontal drains below that needed for the transportation of waterborne solid waste, and thus impair the effectiveness of the drainage system. Relatively little has been done in the United States to study the waste transport phenomena within the horizontal drains or to examine the effects of reduced water flows on the transportation of solid waste.

Cole [5], and Konen and DeYoung [10] studied the effects of low volume [11-13] liters/flush) water closets on sanitary drainage systems. They reported that the flow reduction in the drainage system resulting from the use of these units is not likely to produce any adverse effects. The reported results are not conclusive, however, because the investigators did not include the waterborne solids as a part of the wastewater flow through the drainage system. Cole [5] also determined the flow velocity and flow depth in horizontal drains for different flush volumes. He reported that flush volumes less than 13 liters (3.5 gallons) per flush would substantially reduce the flow depths in the horizontal drains, which may cause problems for the transportation of solid waste.

Studies to investigate the transportation of solids, flushed from low-volume water closets, through horizontal drains are under way in some European countries and in Japan. Some of these studies are cited below.

Swaffield et al. have been studying the transportation of relatively large solids (maternity pads) at Brunel University, U.K. [9,11]. In their studies, water closet contents (9 to 10.2 liters of water and a maternity pad) were flushed into a relatively long ($\geq$ 14 meters) pitched horizontal drain to investigate the solid transport. From this experimental work, they report that the transient partially filled pipe flow has three zones. These are: (1) initial zone, adjacent to the elbow at the horizontal drain entrance where turning of the flow and the wall impact reduce the solid velocity. The solid is then accelerated by the momentum of water flowing behind the solid; (2) a second zone, where the fluid friction predominates and the solid decelerates;

(3) a final zone, where the solid stops in the pipe as the water leaks past the solid. The results of their experiments indicate that the velocity of the solid as well as the distance traveled by the solid increase with an increase in the flush volume, and an increase in the drain slope. The velocity of the solid during deceleration correlates with the square root of the ratio $L/_S$, where L is distance along the pipe and S is the pipe slope. Governing momentum equations have also been developed but without a mathematical formulation of all the force terms.

Kamata et al. [12] at the University of Tokyo, Japan, have conducted experiments to measure the distance traveled by solid waste simulants, flushed with different water volumes (5, 8, 10 and 12 liters) from water closets within a horizontal drain. Their experiments were conducted with drain having circular and oval cross-sections. They used the following waste simulants: (1) four pieces of cylindrical polyvinyl chloride (PVC) sponges (22 mm diameter, 80 mm length); (2) four pieces of toilet paper; (3) both (1) and (2) together; and (4) single pieces of larger solids such as sanitary napkins and cloth and paper diapers. Their results indicate that the distance traveled by the solids in the horizontal drain is increased when: (1) flush volume is increased; (2) slope of the drain pipe is increased; and (3) cross-sectional area of the drain is reduced either by using a smaller diameter circular pipe or by using an oval cross-sectional pipe. They concluded that: (1) the increase in the distance traveled by solids with increased pipe slope is mainly due to the increase in flow velocity; and (2) the increase in distance travelled by solids with a change in pipe cross-section is mainly due to the increase in flow depth.

Nielsen and Nielsen [13] reported preliminary data acquired for a 3- to 4-year research program (1979 to 1982) under way at the Danish Building Research Institute, Horsholm, Denmark. The objective of this research program is to acquire necessary data to design drainage systems for buildings with water closets which use only 3 liters (0.8 gallons) of water per flush. The experimental apparatus simulates a 110 mm (4.3 in.) building drain receiving solid waste from water closets situated on different floors via two soil stacks. One of the soil stacks carries wastes from three 8-liter water closets situated on three different floors, and the other one from three 3-liter units situated on three different floors. Natural sponges having cylinderical shapes, 30 mm diameter by 100 mm length, are being used as solid waste simulants. The preliminary data on the distance traveled in the building drain by the solids indicate that: solids from 8-liter units traveled farther than those from 3-liter units and solids from units located at higher levels traveled farther than those of units located at lower levels. When the solid discharged from a unit did not clear the simulated building drain, the unit was flushed again and again, but without any solids in the bowl, until the solids cleared the building drain. Three-liter units had to be flushed several times before the drain was cleared.

1.2 WATERBORNE WASTE TRANSPORT

The primary function of the water utilized for water closet operations is to remove and transport the solid as well as liquid waste through the drainage network without clogging. The waste is transported by the water in two distinctly separate operations. First, the waste is carried out from the closet bowl, moved through the trap and fittings, and transferred to the horizontal drain. Second, the waste is transported through the horizonal drain into the soil stack and through the building drain into the sewer or on-site treatment facility. This study deals only with the second operation, that is, the transport of solid waste deposited in the horizontal drain.

Impact with the wall of the turning elbow decelerates the solid flushed from a WC, and the solid enters the horizontal drain with a speed nearly equal to zero. The solid is then accelerated and transported by the action of the water entering the drain behind the solid. Therefore only a portion of the total water consumed per flush (that is, the quantity of water which leaves the closet bowl behind the solids) is available for transporting the solid through the horizontal drain. Because, as Swaffield et al. [9] reported, almost all of the water present in the bowl for the trap seal leaves the bowl ahead of the solid, and there is a certain minimum quantity of water necessary for transferring the solid from the closet bowl into the drain. Both of these quantities of water are dependent upon the geometry of the closet bowl and bowl-to-drain connections. It follows, therefore, that any reduction in the total flush volume without changing the closet bowl or bowl-to-drain connections would reduce the amount of water available for transporting the solid through the horizontal drain.

Horizontal drain is only partially filled; the flow is usually non-uniform and unsteady. The transportation of solid waste within the horizontal drain is also dependent upon the rate of flow, that is, both the depth and velocity of water flowing through the partially filled drain. The flow rates required for the transportation of solids through the horizontal drain are dependent upon many other variables, and the information on such flow rates is not readily available. No information exists concerning the depth of flow, and the generally accepted velocity of about 0.6 m/s (2 ft/s) may not be applicable. This is so because this value of flow velocity was derived for the transportation of sediments, such as gravel, through the sewers [14,15]. Most of the solid waste leaving a water closet has a specific gravity close to one, (0.95 to 1.05).

The flow rate (depth & velocity) in the drain pipe serving a water closet is dependent upon the discharge rate from the closet bowl, bowl-to-drain connections, horizontal drainpipe variables (i.e., diameter, length, roughness and slope), and horizontal drain exit conditions. Water discharge rate data, for a typical conventional water closet, available in the literature [2] show that the discharge rate gradually rises from zero to peak, may remain constant for a few seconds, and then gradually falls off to zero. These data suggest that the flow rate of water behind the solid decrease, with increasing time or distance traversed by the solid. Data reportd by Konen [2] indicate that the discharge rate from a water-saving water closet (12-13 liter/flush) falls to zero after reaching a peak sooner than a conventional unit (19-20 liter/flush). Konen's data suggest that a reduction in the total flush volume would reduce both the amount and flow rate of water discharged behind the solid, thus increasing the likelihood of solid deposition in the horizontal drain causing drain blockage. Bishop [16] reported this type of adverse experience when tanks of conventional water closets were modified to reduce water usage in the Cabin John area, a suburb of Washington, D.C. Reducing the water used for water closet operations by modifying the closet tank caused blockage problems in some of the horizontal drains.

1.3 SCOPE

To minimize the likelihood of drain clogging with a reduced flow, the pitched horizontal drain should be properly designed. That is, the selected drain pipe variables (diameter, length, and slope or pitch) should be such that the water volume discharged behind the solid can adequately transport the solid waste through the drain. Theoretical and/or empirical relationships relating the variables of the drain pipe, water volume used, and the solid waste transport parameters, however, are almost nonexistent. The hydrodynamics of solid waste transport through the p-h drain is not completely understood and the exact formulation of the water flow induced forces responsible for motion of the solid in the drain pipe has not been established. Development of mathematical models for solid waste transport in p-h drains requires a good understanding of the transport mechanism.

The objectives of the study program are: (1) to determine the parameters controlling the transport of solids within the pitched-horizontal drain by examining the effects of relevant variables on the transportation of solids; (2) to develop mathematical model (or models) for analyzing the hydraulics of solid transport within the drain; and (3) to establish design recommendations for drain pipe diameter, length and slope for the satisfactory transportation of waste with reduced water usage.

The study program has been divided into four subtasks as follows: (1) Experimental Investigation. The purposes are to investigate experimentally the transportation of finite solids through a p-h drain with flows introduced into the drain by a simulated water closet discharge and to examine the effects of relevant variables on the transportation of solids; (2) Preliminary Model Development. The purpose of this subtask is to develop preliminary mathematical models based upon the equations governing the solid motion within the drain employing principles of fluid dynamics such as force balance, momentum and energy exchange; (3) Experimental Study Under Simulated Service Conditions and Refinement of Math Models. Purposes are to conduct experimental investigation under simulated service conditions to compare the information acquired in subtasks 1 and 2, and validate and refine the mathematical models; and (4) Establishment of p-h Design Recommendations. The purpose is to utilize the information acquired in subtasks 1, 2, and 3 and the available information from literature and establish design recommendations for pipe diameter, length, and slope for an effective waste removal from low-volume water closets. The study reported herein deals only with the first subtask, i.e., the experimental investigation.

1.4 PURPOSE OF SCOPE OF THE EXPERIMENT

The significant solid transport parameters include the velocity (U_s) attained by the solid, and distance (L_s) through which the solid is transported in the drain by the water volume used. [9,11,12] It was pointed out earlier the solid from a WC enters the horizontal drain with a speed nearly equal to zero, and is transported by the action of the water entering the drain afterwards. Hence, the experiment has been designed to place solid waste simulants in an empty p-h drain connected to a simulated water closet which permits control of water discharged behind the solid, introduce flow into the drain behind the solid, measure U_s and L_s, and examine the effects of relevant variables on U_s and L_s.

Variables that may influence U_s and L_s include the following: solid variables (shape, size, specific gravity, surface roughness, amount and distribution); drain pipe variables (diameter, length, roughness, slope); volume of water discharged behind the solid, and water discharge rate-time history; fixture-to-drain connection variables (type and size of trap, size of down pipe, size and type of elbows); draine exit conditions (type of drain-to-stack connection, stack load conditions); and lateral bends in the drain, if any. It was decided, however, to consider only some of the more important variables in the initial experimental study. Total water volume discharged behind the solid, and solid and drain pipe variables, appearing relatively more important than the others, were selected. Flat ended right circular cylinders with specific gravity equal to one were selected as solid waste simulants. The solid transport experiments were conducted with only one solid at a time in a 3-inch (76.2 mm) diameter drain having a pitch equal to 0.02, 0.04, and 0.06. Thus, the independent variables selected for the initial experimental work include the following: volume of water discharged behind the solid; diameter and length of the solid, coefficient of friction between the solid and pipe; and diameter and slope of the drain pipe.

This report contains a discussion of the data compiled in the first exploratory experimental investigations. The report contains a description of the experimental equipment and solids, and a summary of the data on the transport of cylindrical solids in a 3-inch diameter pitched horizontal drain with different volumes of water. These data include visual observations and the velocities attained and distances traversed by solids in the drain at three different pitches.

2. EXPERIMENTAL EQUIPMENT AND PROCEDURE

2.1 EXPERIMENTAL EQUIPMENT

The apparatus used in the experiment is shown schematically in figure 1. A right circular cylindrical tank containing a flush valve and down pipe is utilized to simulate a water closet. The flush valve is operated by a solenoid switch. The down pipe is connected to the pitched horizontal drain via a 90 degree elbow followed by a tee. The tee permits insertion of the experimental solid into the drain. The pipe is transparent to permit visual observation of the transport phenomenon. The drain pipe is mounted on several stands which are evenly spaced along the length of the drain. The height of the stands is adjustable to allow for changes in the pitch of the drain. The exit end of the drain is open to the atmosphere and the efflux from the drain is caught in a container for proper disposal. All pipes and fittings used to construct the apparatus are of standard plumbing sizes.

Photocell detectors were utilized to measure velocity of the solids transported through the p-h drain. A photocell and a light source placed on opposite sides of the circumference at a cross-section of the pipe constitute a photo detector. When a solid passes through the pipe cross-section containing the detector, light to the photocell is interrupted and an electric signal is generated. The signal from the photocell is fed to an electronic counter (or clock). This signal can be employed to start a counter, to stop a counter, or to stop one and start another. The velocity of the solid is computed from the time interval for the passage of the solid between two photodetectors located at a known distance apart along the length of the pipe. A photograph of two such light sources-photocell detectors is shown in figure 2.

Four photodetectors, numbered 1 through 4, are located at specific distances apart, as indicated in figure 1. The signal from detector 1 starts the first counter, the signal from detector 2 stops the first counter and starts the second, the signal from detector 3 stops the second counter and starts the third, and the signal from detector 4 stops the third counter. The logic circuit is shown schematically in figure 3. This detector-counter system provides the time period required to determine the solid velocity within the three sections, i.e., the sections between detectors 1 and 2, 2 and 3, and 3 and 4. As indicated in figure 1, the first section (i.e., section between detectors 1 and 2) is adjacent to the drain entrance; it begins at a distance of 0.45 m downstream from the starting position of the solid and is 0.30 m in length. The second section (i.e., section between detectors 2 and 3) starts where the first section ends; it is 3.60 m in length and extends over most of the central part of the p-h drain. The third and last section (i.e., the section between detectors 3 and 4) preceds the drain exit; it starts where the second section ends and ends at a distance of 0.45 m upstream of the drain exit; it is 0.30 m in length.

2.2 SOLID WASTE SIMULANTS

Flat ended right circular cylinders were used as test solids in the experiments. These cylinders were constructed from opaque and rigid plastic tubings. A typical experimental cylinderical solid is shown schematically in figure 4. One end of the hollow cylinder is completely plugged, and the other end is only partially plugged with the plug containing a concentric threaded hole. The partially plugged end of the cylinder is closed with a threaded cap. The end plugs and threaded cap were made from the same plastic material and were so constructed that the center of gravity of the closed cylinder concided with its geometric center. The hollow cylinder with threaded cap allows for desired changes in the specific gravity of the solids, since the cylinders can be filled with different materials. The specific gravity of the solid used was adjusted to be equal to 1.0. The coefficient of wet friction between the solid and the pipe, measured in the laboratory, was equal to 0.6. The aspect ratios (length/diameter) of the twenty solids used in the experiment are given in table 1.

Table 1

Aspect Ratio (Length/Diameter) of the Twenty Cylindrical Solids

		Length (cm)				
		2.5	3.8	5.1	6.4	7.6
Diameter (cm)	1.9	1.33	2.00	2.67	3.33	4.00
	2.5	1.00	1.50	2.00	2.50	3.00
	3.2	0.80	1.20	1.60	2.00	2.40
	3.8	0.67	1.00	1.33	1.67	2.00

2.3 EXPERIMENTAL PROCEDURES

The pitch of the drain pipe was adjusted to the desired value. A solid was inserted through the tee opening and placed on the lower wall of the p-h drain. The end of the solid facing the elbow was aligned with an indicator line marked on the outside lower wall of the drain opposite to the tee opening; the indicator line is approximately at the center of the tee (see figure 1). With the solid at rest in the drain, the light source-photocell detectors were energized and three gallons (11.35 liters) of water was flushed behind the solid from the tank. Visual observations and photographs of the solid transport phenomenon were made.

The passage of the moving solid through the drain cross-section containing the photo detectors was detected and timed by the detector-counter system. The experiments were run with the following water volumes 3.0, 2.0, 1.0, 0.5, 0.4, 0.3 and 0.2 gallons (11.35, 7.56, 3.78, 1.90, 1.51, 1.13 and 0.76 liters). Three test runs were carried with each of the water volumes. When the solid did not clear the p-h drain, the distance traversed by the solid within the pipe was measured and recorded. The times recorded by the counters were utilized to calculate the average speed of the solid within each section of the drain (i.e., the drain sections between photo detectors 1 and 2, 2 and 3, and 3 and 4).

Each of the twenty solids, listed in table 1, were tested with the seven different water volumes mentioned above.

Six of the solids were covered with tight fitting rubber sleeves to change the coefficient of friction between the solid and the drain pipe wall. The coefficient of wet friction between the sleeved solids and the pipe wall, measured in the laboratory, was equal to 1.0. The six solids included one 2.5 cm diameter cylinder which was 6.4 cm long, and all five of 1.9 cm diameter cylinders. The full length rubber sleeves were fabricated of 0.3 cm thick flexible tubing. Hence, in addition to chainging the coefficient of friction, the sleeves also changed the diameter of the solid. These sleeved solids were also transported through the drain with various volumes of water with pipe pitch set at 0.02.

The forgoing experiments were reported with the p-h-drain positioned at two other pitches (0.04 and 0.06). The experiments with sleeved solids, however, were conducted only with drain pipe pitch set at 0.02 because the results of the earlier experiments had indicated that once the solid was waterborne and cleared the drain the friction coefficient between the solid and pipe was not very important.

3. EXPERIMENTAL RESULTS AND DISCUSSION

The results obtained for the transport of simulated solids are summarized in this section.

3.1 VISUAL OBSERVATIONS

Before discussing the visual observations of the solid transport phenomenon, it is instructive to describe the flow that ensues when a plumbing fixture, such as the experimental water-closet simulator, is discharged into an empty p-h drain. The drain pipe is only partially filled, and the flow is both non-uniform, unsteady and lasts only for a short duration (15 to 60 seconds). Both the flow rate (i.e., depth and velocity of flow) and flow duration through any cross-section are primarily dependent upon the volume of water discharged and the rate at which water leaves the fixture or enters the drain. In general the flow rate rises rapidly to a peak value and then gradually falls off to zero.

When water was discharged into the drain containing a simulated solid at rest on its lower wall, the flow through the drain pipe basically displayed the above-mentioned pattern with the following modification. The solid at rest, initially, obstructs the water flowing from the upstream direction. The water is forced to dam up upstream of (behind) the solid, and to leak past the stationary solid streaming through the crescent-shaped space between the solid and the pipe wall. As a result of this restriction, a "wave" traveling in the upstream direction of the solid was observed. The depth of water stream behind (upstream of) the solid rises at a faster rate than that in front (downstream) of it which causes hydrostatic head difference across the solid. Hence, the solid at rest in addition to its weight is also subjected to the following forces in the downstream direction: a pressure force equal to a hydrostatic head difference across the solid due to unequal stream depth at the opposite ends of the solid, and a velocity head difference due to unequal water velocities on the two ends of the solid; and a drag force due to the water streaming past the solid. The flow-induced forces acting on the solid increase with an increase in water influx.

The solid remains stationary until the sum of forces acting in the downstream direction overcome the force due to static friction between the solid and the pipe wall. When this friction force is exceeded, the solid starts to move. This initial interaction between the stationary solid and the water influx to set the solid into motion was observed for all of the experiments, and it appeared to be independent of the experimental variables. Once the solid was set in motion, the phenomenon that followed, however, was greatly dependent upon the volumes of water discharged and the other experimental variables. Observations of this phenomenon suggested that the various volumes of water used in the experiment may be grouped into three ranges. These are: small volumes (0.10, 0.20, and 0.30 gallons or 0.38, 0.76, and 1.13 liters); intermediate volumes (0.40 and 0.5 gallons or 1.51 and 1.90 liters); and large volumes (1.00, 2.00, and 3.00 or 3.78, 7,57, and 11.35 liters). Each volume range revealed the effects of experimental variables on the solid movement to a different extent. The patterns of solid movement in each volume range were quite similar, but the patterns of the water stream adjacent to the solid were somewhat different in each range. These observations for the three water volume ranges are discussed below.

Small Volumes. When small volumes (0.10 to 0.30 gallons or 0.38 to 1.13 liters) of water were discharged into the drain, the effects of the experimental variables on the motion of the solid were very pronounced and visible. The stationary solid accelerated very slowly, and the acceleration of the larger diameter solids was slower than that of smaller diameter solids. The depth of the water stream behind the solid remained below the lower half of the solid, and the solid apparently dragged on a very thin film of water on the lower wall of the drain pipe throughout the course of its motion within the drain. During the motion of the solid, water continued to flow around the solid, since the speed of water was larger than the speed of the solid.

The solid accelerated to a maximum speed, and apparently continued moving with this maximum velocity as long as the forces acting on the solid in the downstream direction were sufficient to balance the force due to sliding friction. The magnitude of the maximum speed attained by the solid with these small water volumes was less than that of the local water speed, and the water kept leaking past the solid. When the water influx behind the solid declined, the forces acting on the solid in the downstream direction became smaller than the force due to sliding friction, the solid started to decelerate and slowly came to a stop within the drain pipe with some water still present in the drain behind the solid. The remaining water then flowed around the stationary solid and exited the drain. Smaller solids traveled farther than larger solids when equal volumes of water were discharged, all of the 1.9 cm diameter solids cleared the drain pipe with 0.30 gallons (1.13 liters) of water, while the 3.8 cm diameter solid traveled only a few centimeters. The solids clearing the drain exited the pipe while decelerating with a portion of the total water used exiting the pipe after the solid.

When sleeved solids were transported through the drain having a pitch equal to 0.02, the effects of the coefficient of friction between the solid and the pipe wall on solid transport were also observed. The sleeved solids were slower to be set in motion, and traveled a shorter distance in the drain than the sleeved solids having an equivalent diameter.

Intermediate Volumes. When intermediate volumes (0.40 and 0.50 gallons or 1.51 and 1.90 liters) of water were used, the effects of the experimental variables on the motion of the solid, although less pronounced, were very similar to those observed for the small water volume tests. That is, the acceleration of larger solids was less than that of smaller solids.

The solid accelerated from rest to a maximum speed, traveled at this maximum speed for a while, and then decelerated. The acceleration of the solids from rest to maximum speed was faster than in the previous case with small water volumes. Also, in this case, most of the solids cleared the drain, while in the previous case only a few of the solids cleared the drain. The solids which stopped within the drain in this case included: all of the sleeved solids and some 1.5 inch (38.1 mm) diameter solids with 0.40 gallons (1.51 liters) of water; and some sleeved solids with 0.50 gallons (1.90 liters) of water. As before, the solid which cleared the drain pipe exited the drain while decelerating with a portion of the total water used exiting the pipe after the solid. In situations where the solid stopped within the drain pipe, the portion of the water remaining in the pipe flowed around the stationary solid and exited the drain.

The depth of the water stream behind the solid, in some situations, reached up to about the lower half of the solid for a short while when the solid was accelerating, but for most of the solid's motion within the drain, it stayed below the lower half of the solid. The solid mostly dragged on a thin film of water on the lower wall of the drain pipe, as water continued to flow around the solid.

Figure 5 and 6 show the photographs of a 2.5-cm diameter and 5.1-cm long cylinder being transported with 0.50 gallons (1.90 liters) of water. In figure 5, the solid is just leaving photo detector No. 1 and all of the solid is not visible. A close examination of this photograph reveals that the depth of water stream upstream of the solid is larger than that in front of it, and that the depth of the water stream upstream of the solid is almost as deep as the lower half of the solid. In figure 6, the solid is in between photo detector Nos. 3 and 4, and the depth of water stream adjacent to the solid is much below the lower half of the solid. Also, the depth of the water stream upstream of the solid is larger than that downstream of the solid.

<u>Large Volumes</u>. When large volumes (1.00, 2.00 and 3.00 gallons or 3.78, 7.57 and 11.35 liters) of water were used, the effects of the experimental variables on the motion of the solid were not apparent. The solid accelerated quickly to a maximum speed, and apparently exited the drain with the maximum speed. There were some exceptions, however; the 1.50-inch (38.1 mm)-diameter solids and all of the sleeved solids when transported with 1.00 gallons (3.78 liters) of water exited the drain while decelerating. In all of the tests with large volumes of water, the solid cleared the drain and a major portion of the water used exited the pipe after the solid.

The depth of the water stream adjacent to the solid was higher than the lower half of the solid for most of the solid's motion within the drain. Throughout the length of the drain pipe stream depth upstream of the solid was larger than that downstream of the solid. The solid was mostly riding on a thick film of water, and it was apparently moving with the local velocity of the water stream as a waterborne object.

Figure 7 shows a photograph of a 2.5-cm-diameter and 5.1-cm-long solid being transported with 1.00 gallon (3.78 liters) of water. In the photograph, the solid is between photo detectors 1 and 2. A close examination of the photograph shows that the depth of the water stream adjacent to the solid is slightly higher than the mid height of the solid, and that the depth of water stream upstream of the solid is larger than that downstream of the solid. The increased depth of the water stream a short distance upstream of the solid is the "moving wave" which was traveling in the upstream direction during the experiment.

The visual observations indicate that the solid has three phases of motion, and these three phases of solid motion occur in three different zones of the drain. The first or initial zone where the solid accelerates from rest to a maximum speed; the second zone, where the solid continues to move at the maximum speed; and the third or final zone, where the solid decelerates from the maximum attained speed to a stop. The length of each zone as well as the magnitudes of respective accelerations and velocities are dependent upon the water volume used and the other experimental parameters.

Also, depending upon the water volume available for transporting the solid and solid variables, the length of a drain may be either longer or shorter than the combined length of the three zones. For example, with small water volumes most experimental solids failed to clear the drain, indicating that the length of the experimental drain was longer than the combined length of the three zones. While with larger water volumes all of the experimental solids cleared the drain, indicating that the length of the experimental drain was shorter than the combined length of the three zones, a desired condition for the proper transport of solids through a p-h drain.

3.2 SOLID VELOCITIES

The velocity of the solids was measured in three different sections of the p-h drain namely the pipe sections between photodetectors No. 1 and 2, 2 and 3, 3 and 4. The positions of the three sections with respect to the drain entrance and exit are as indicated in figure 1. The average values of the solid velocities within each of the respective sections are denoted by U_1, U_2, and U_3. The velocity U_1 represents the solid velocity during the initial stage of its motion following the acceleration from a state of rest. The velocity U_2 and U_3 represent the solid velocity where the solid may be accelerating, moving with a constant velocity or decelerating.

The velocities attained by various solids with different water volumes are presented in figures 8 through 14. The data presented in these figures represent the average of three repeated experimental values under the same conditions.

Figures 8 (8-1 through 8-10), 9 (9-1 through 9-15), and 10 (10-1 through 10-15) show the solid velocity versus water volume discharged into the drain for various solid lengths and diameters with the pipe slopes equal to 0.02, 0.04, and 0.06 respectively. Each figure is for one of the velocities (U_1, U_2 or U_3) for one drain slope, one solid length and all four solid diameters. For example, figures 8-1, 8-2, 8-3, 8-4, and 8-5 show solid velocity U_1 respectively for 2.5, 3.8, 5.1, 6.4 and 7.6 cm long solids and a drain slope of 0.02. Figures 8-6 through 8-10 show the solid velocity U_3 in a similar manner (the solid velocity U_2 was not measured for the drain slope of 0.02). Figures 9-1 through 9-5, 9-6 through 9-10, and 9-11 through 9-15, respectively, show velocity U_1, U_2 and U_3 at a drain slope of 0.04. Figures 10-1 through 10-5, 10-6 through 10-10, and 10-11 through 10-15 respectively show velocity U_1, U_2 and U_3 at a drain slope of 0.06.

An examination of figures 8, 9, and 10 indicates that: (1) the solid velocity increases with an increase in the water volume used; and (2) the solid velocity decreases as the solid diameter is increased. The data presented in these figures also suggest that the incremental increase in the solid velocity with an incremental increase in the water volume used is larger for small water volumes ($V_w \leq 0.5$ gallons or 1.9 liters) than that for large water volumes ($V_w \geq 1.0$ gallons or 3.78 liters). This pattern of the effect of incremental change in the water volume on the solid velocity may be interpretted as follows: when the depth of the water stream in the drain is relatively small and the solid is dragging on a very thin film of water between the solid and the pipe wall, a small increase in the amount of water volume used substantially increases the depth of water stream in the drain and the thickness of the water film between the solid and the pipe wall and reduces the friction; this pattern of solid-water movements was observed when small water volumes ($V_w \leq 0.5$ gallons or 1.9 liters) were used. With large water volumes ($V_w \geq 1.0$ gallons or 3.78 liters) the depth of the water stream in the drain is relatively large and the solid is not dragging on a thin film of water but moving as a waterborne object, an increase in the stream depth due to further increase in water volume used has little or no effect on the friction; and any increase in solid speed is primarily due to an increase in the water speed. This pattern of solidwater movement was observed when large water volumes were used. This pattern of the solid velocities dependence upon the water volume used suggests that the depth of the waterstream in the p-h drain is a significant parameter for solid transport.

Figure 11 shows the velocities U_1, U_2 and U_3 of a 2.5 by 5.1 cm (diameter by length) solid in the drain having a slope of 0.04. An examination of figure 11 indicates that: (1) the magnitude of velocity U_1, in general, is larger than that of velocity U_3; and (2) the magnitude of velocity U_2 is larger than that of velocity U_1 except when very small water volumes are used. These observations indicate that the solid accelerates to a maximum velocity and then starts to decelerate.

Figure 12-1, 12-2 and 12-3, respectively, show solid velocity U_1, U_2 and U_3 for 2.5 cm diameter solids and a drain slope of 0.04. An examination of the figures indicates that: (1) the solid velocity U_1, in general, decreases as the solid length is increased; and (2) the effect of the solid length on the solid velocity U_2 and U_3 does not show a definite trend. It appears that: (1) the solid length is an important parameter during the initial phase of the solid motion, when the solid is starting from rest, and (2) the solid length becomes less important as a parameter when the solid is moving with a constant speed or accelerating (or decelerating) slowly

Figures 13-1, 13-2 and 13-3, respectively, show velocity U_1, U_2 and U_3 for a 2.5 by 5.1 cm solid for all three p-h drain slopes. An examination of these figures indicates that the solid velocity increases with an increase in the slope of the p-h drain, particularly when small water volumes ($V_w \leq 0.5$ gallons or 1.9 liters) are used. It also indicates that the solid velocity U_1 at a slope of 0.06 is higher than that at a slope of 0.02 and lower than that at a slope of 0.04. The solid velocity U_2 at a slope of 0.06 is lower than that at a slope of 0.04, particularly when larger water volumes ($\geq$ 1.0 gallons or 3.78 liters) are used. The indication of the existence of an optimum value of the drain slope requires further examination. The effect of the p-h drain slope on the velocity of the solids with relatively large water volumes indicates that the depth of water stream in the partially filled p-h drain is an important parameter for solid transport. For a constant (steady) flow rate through the drain the flow velocity would increase as the drain slope is increased thereby causing a decrease in the stream depth. However, the effect of the change of slope on the flow is very complex, depending on whether the initial flow was supercritical or subcritical, which may lead to a hydraulic jump [17].

Figures 14-1 and 14-2 respectively show velocities U_1 and U_2 of two 2.5 by 3.8 cm solids with different surface roughness characteristics and figures 14-3 and 14-4 show similar data for two 2.5 by 6.4 cm solids. One of the two solids represented in each of these figures is the unsleeved solid, and the coefficient of friction between the solid and the drain pipe wall is approximately equal to 0.6; the other solid is the sleeved solid, and the coefficient of friction between this solid and drain pipe wall is approximately equal to 1. An examination of these figures reveal that the solid surface roughness characteristic does not have a significant effect on the solid velocity. This is so because the velocity of the sleeved solid is lower than that of the unsleeved solids during some experiments and higher in others. Also, the difference in the velocities of the sleeved and the unsleeved solids, during most experiments, was within the normal experimental scatter. Thus, the velocity data confirm the conclusion reached earlier, that the surface roughness of the solid becomes insignificant as a parameter once the solid is waterborne and moving.

The effects of the water volume used and the p-h drain slope on the solid velocity indicated by these data are similar to those indicated by the data of Swaffield et al. [9], although the two experiments were conducted under different conditions. As reported earlier in the Introduction, Swaffield et al. [9] used relatively larger solids (maternity pad), and flushed the solid from a water closet along with the water into a relatively long ($\geq$ 14 m) p-h drain; and in their experiment, the velocity of the solid increased with an increase in the water volume and an increase in the drain slope. However, the solid velocities in the experiments reported in this report varied from 0.0 to 8.0 ft/sec (0 to 2.4 m/s), while in the experiment of reference 9 it varied from 0.0 to 4.0 ft/sec (0 to 1.2 m/s).

3.3 DISTANCES TRAVERSED BY THE SOLIDS WITHIN THE P-H DRAIN

It was noted previously in the discussion of visual observations that all but some sleeved solids cleared the 5 meter long p-h drain with 0.5 gallons (1.9 liters) of water, and all of the solids cleared the p-h drain with water volumes in excess of 0.5 gallons. Hence, the data on the distance traversed by the solid within the p-h drain (L_s) are limited. These data are summarized in figures 15 to 19.

Figures 15-1, 15-2 and 15-3 show L_s versus water volumes (V_w) for 5.1 cm long solids for a slope of 0.02, 0.04 and 0.06 respectively. Figure 16-1 shows L_s versus V_w for 2.5 by 3.8 cm sleeved and unsleeved solids for a drain slope of 0.02, and figure 17-2 shows L_s versus V_w for 2.5 by 6.4 cm sleeved and unsleeved solids for a p-h drain slope of 0.2.

Figures 17-1 and 17-2 show L_s versus solid diameter for 5.1 cm long solids for all three drain slopes, and for water volumes respectively equal to 0.2 and 0.3 gallons (0.76 and 1.13 liters); and figures 17-3 and 17-4 are similar to figure 17-1 and 17-2, respectively, for 7.6 cm long solids.

Figures 18-1 and 18-2 show L_s versus solid length for 2.5 cm diameter solids, for all three drain slopes, and for water volumes respectively equal to 0.2 and 0.3 gallons (0.76 and 1.36 liters); and figures 18-3 and 18-4 are similar to figures 18-1 and 18-2, respectively, for 3.8 cm diameter solids.

Figures 19-1 and 19-2 show L_s versus V_w for all three p-h drain slopes for 2.5 by 5.1 cm solids and a 3.8 by 5.1 cm solid, respectively.

An examination of figures 15 to 19 indicates that the distance traveled by the solids increases with: (a) an increase in the water volume used, (b) a decrease in the solid diameter, (c) a decrease in the solid length, (d) an increase in the p-h drain slope, and (e) a decrease in the coefficient of friction between the solid and the drain pipe wall.

The effects of the water volume used and the p-h drain slope on the distance travelled by the solids indicated by these data are similar to those indicated by the data of Swaffield et al. [9] and Kamata et al. [12], although the various experiments were conducted under different conditions. As reported earlier in the Introduction, the researchers of references 9 and 12 utilized different solids than used in this experiment, they also flushed the solid along the water from a water closet into a relatively long p-h drain (14 m or longer) while in this experiment the solid is placed in the empty p-h drain, which is relatively short (5 meters).

4. CONCLUSIONS

1. The water volumes used for transporting the solids through a 7.6 cm-diameter drain may be grouped into two volume ranges: small volumes, which are equal to or less than a 0.5 gallon (1.9 liters) of water; and large volumes, which are equal to or greater than 1.0 gallon (3.78 liters) of water. A solid drags on a thin film of water between the solid and the p-h drain wall when small water volumes are used to transport the solid, while the solid moves as a waterborne body when large water volumes are used.

2. The velocity attained by a solid increases with an increase in the water volume. The incremental increase in the solid speed with an incremental increase in the water volume is larger for small water volume than for larger water volumes.

3. The solid velocity decreases with an increase in the solid diameter. The solid velocity also decreases with an increase in the solid length. However, the effects of the solid length on its velocity are more significant during the initiation of the motion of the solid than during the remainder of its motion within the p-h drain.

4. The solid velocity increases with an increase in the p-h drain slope, particularly when small water volumes are used. When large water volumes are used, the solid velocity also increases with an increase in the p-h drain slope, but as the drain slope is further increased, the solid velocity decreases indicating the possible existence of an optimum value of the drain slope. The effects of drain slope on the solid velocity also suggest that the depth of water stream in the partially filled p-h drain is a significant parameter for the transportation of solids.

5. The distance traveled by the solid within the p-h drain increases with: (a) an increase in the water volume, (b) a decrease in the solid diameter, (c) a decrease in the solid length, (d) an increase in the drain slope, and (e) a decrease in the friction coefficient between the solid and the drain pipe wall.

Acknowledgement

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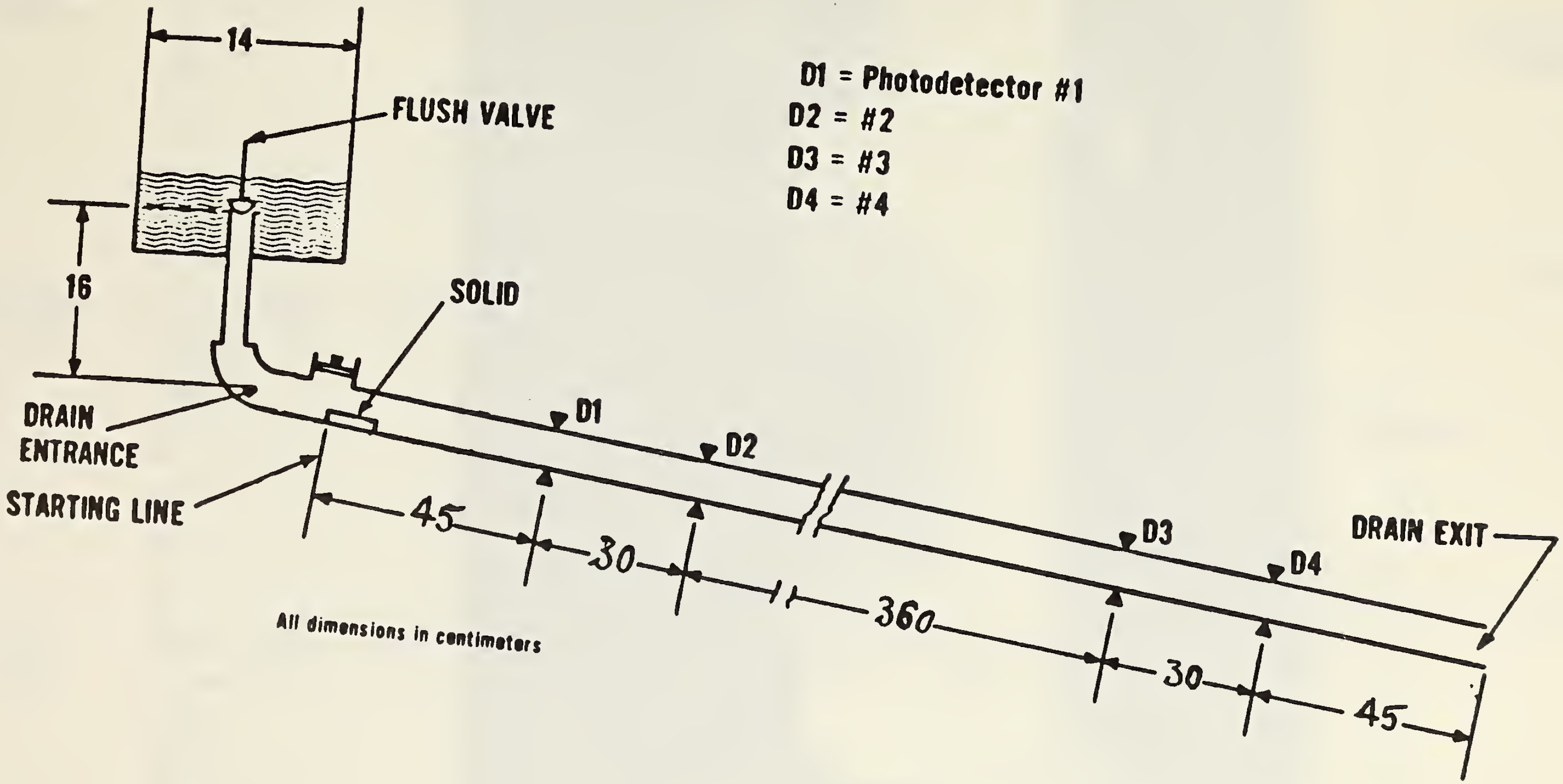


Figure 1. Schematic of experimental apparatus

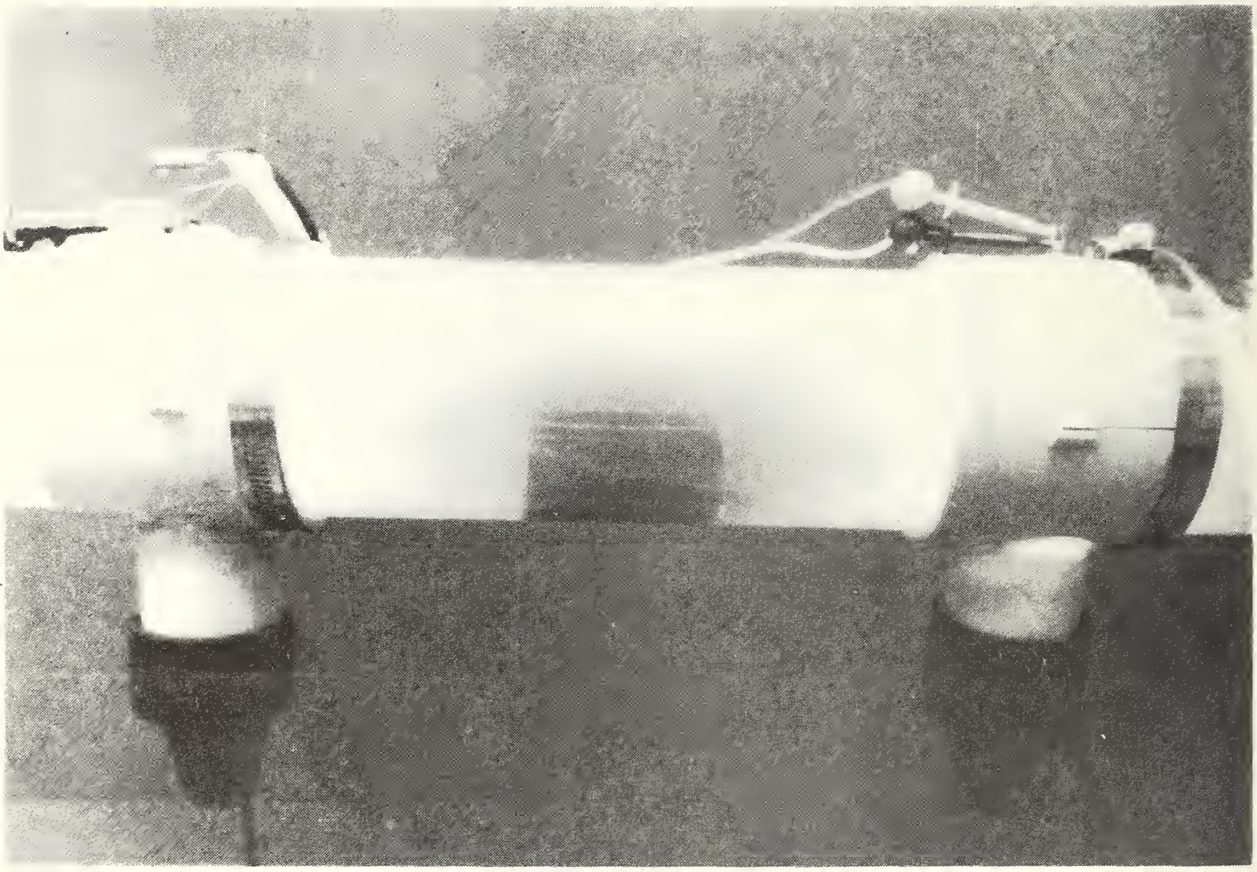


Figure 2. Close-up of photo-cell detectors

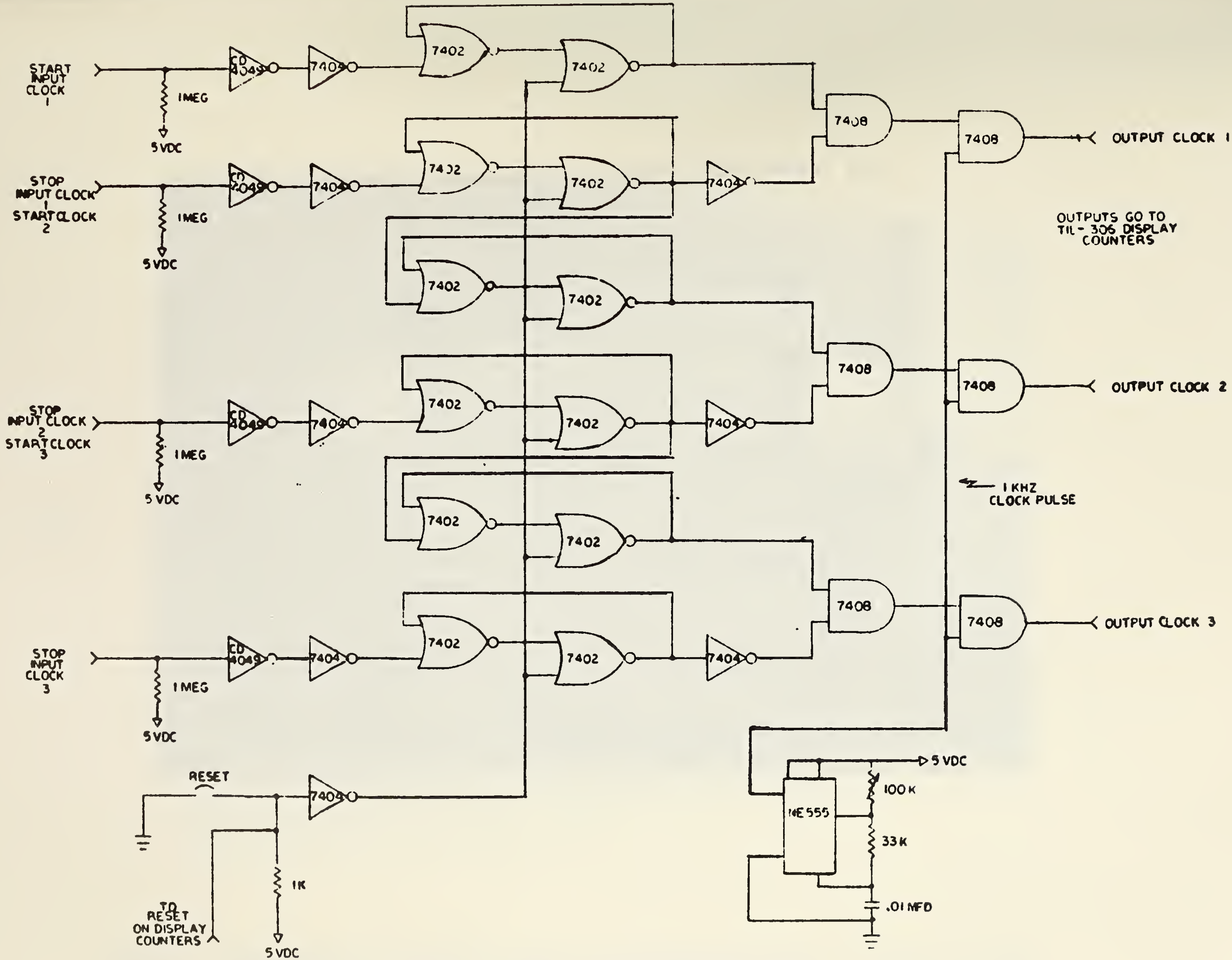


Figure 3. Logic circuit for photodetectors

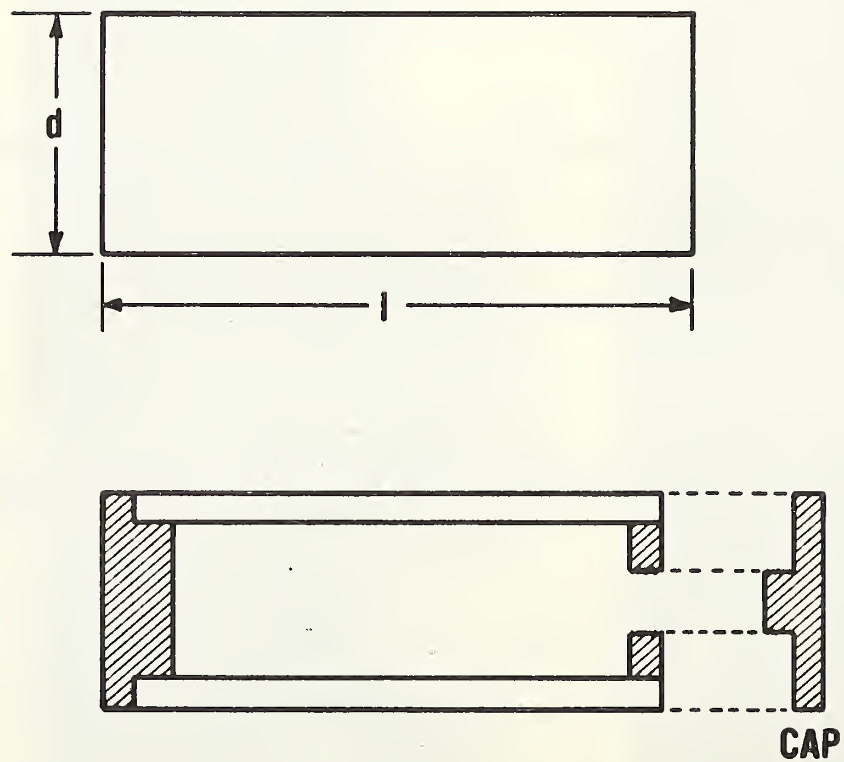


Figure 4. Schematic of a typical experimental solid

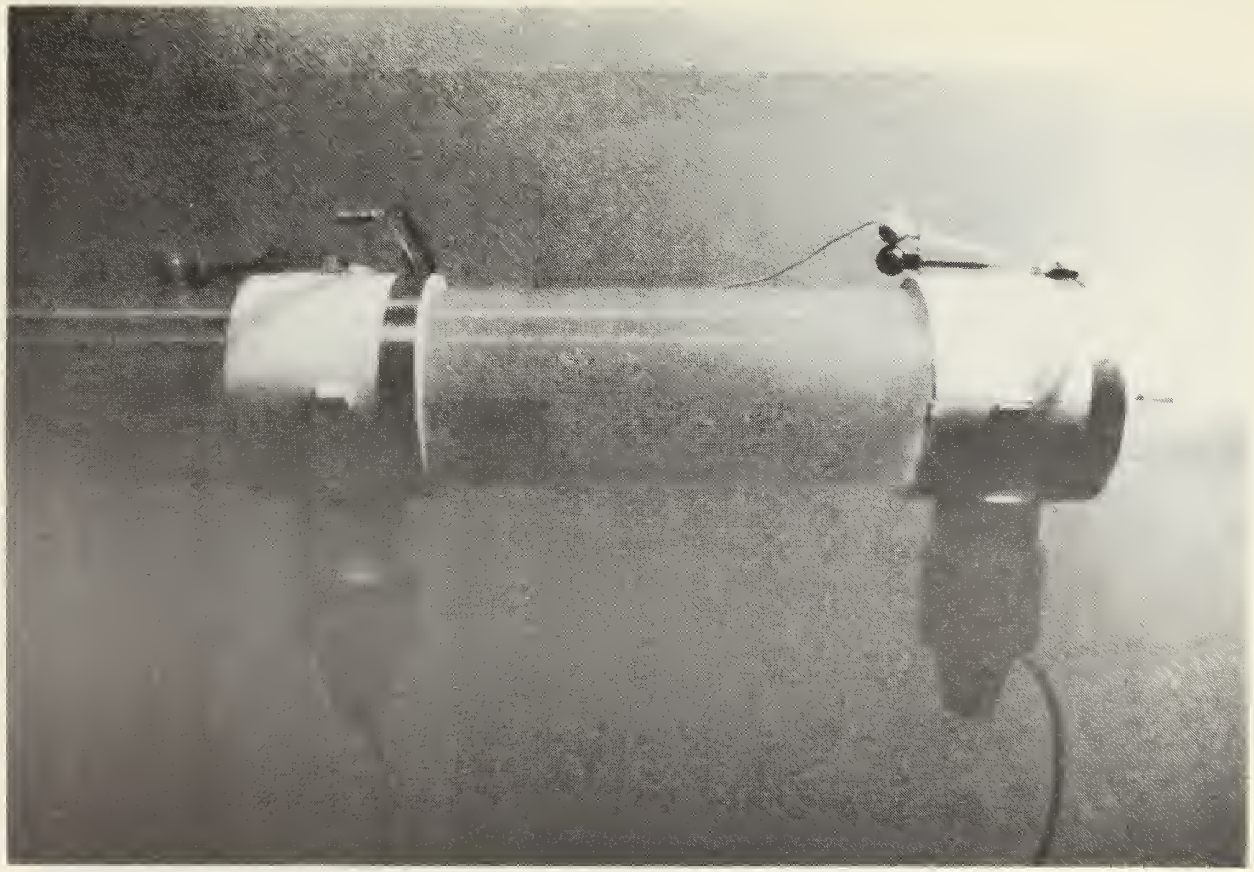


Figure 5. Photograph of a 2.5 by 5.1 cm solid transported with 1.9 liters of water

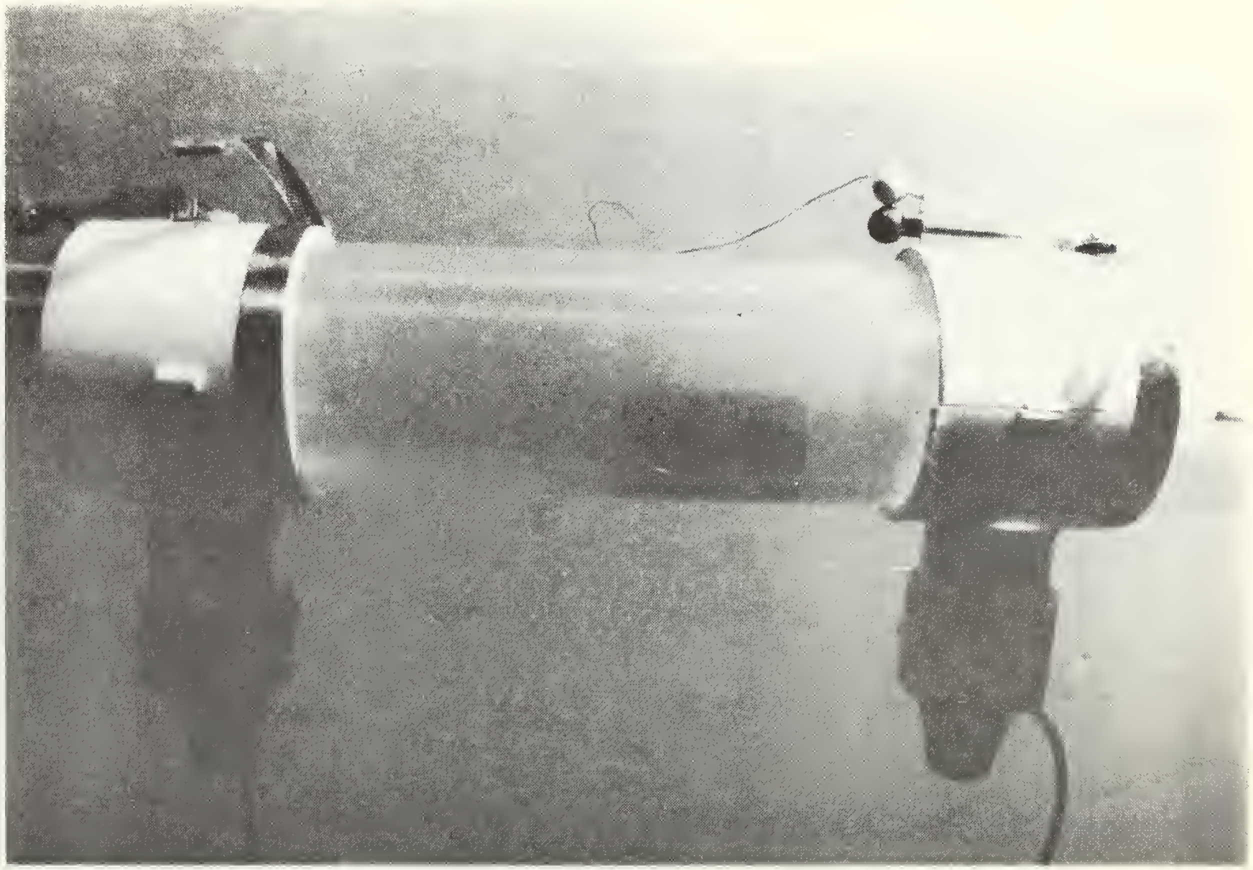


Figure 6. Photograph of a 2.5 by 5.1 cm solid transported with 1.9 liters of water

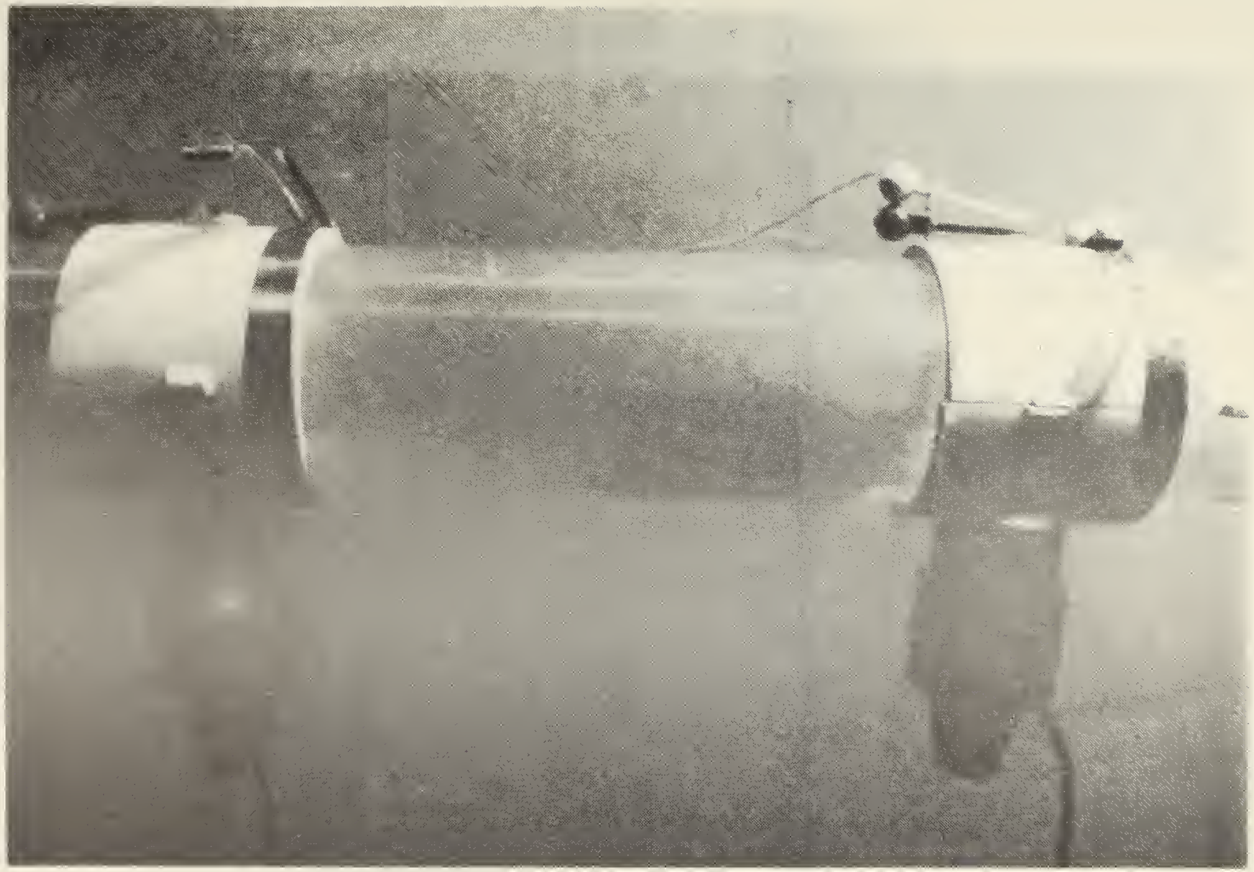


Figure 7. Photograph of a 2.5 by 5.1 cm solid transported with 3.78 liters of water

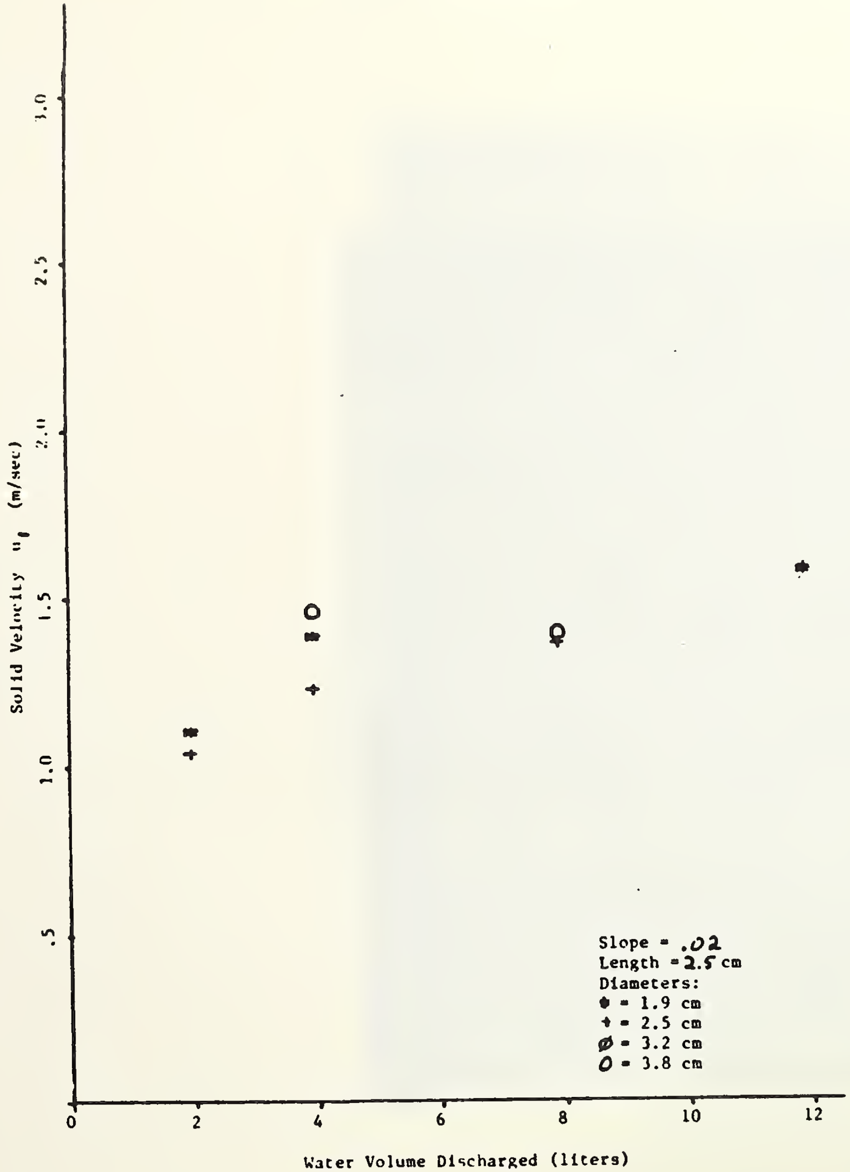


Figure 8-1. Solid velocity versus water volume used

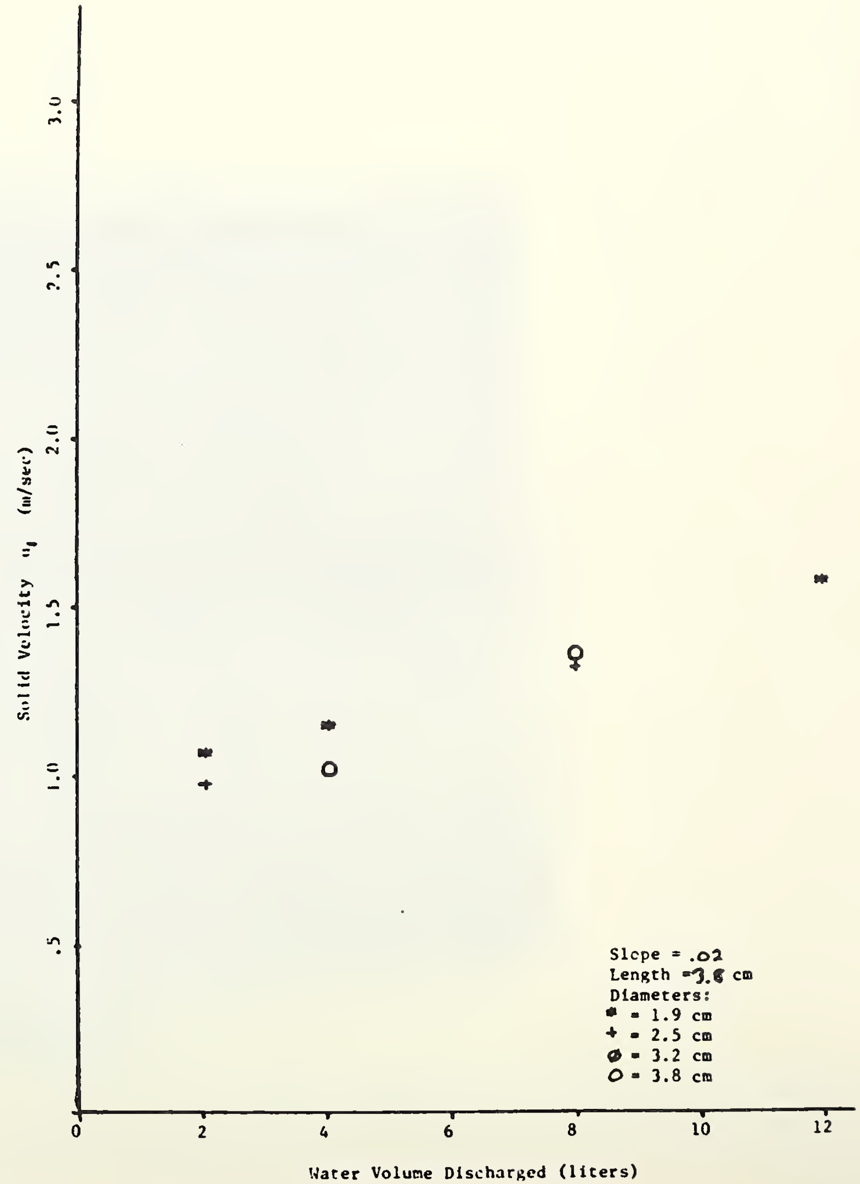


Figure 8-2. Solid velocity versus water volume used

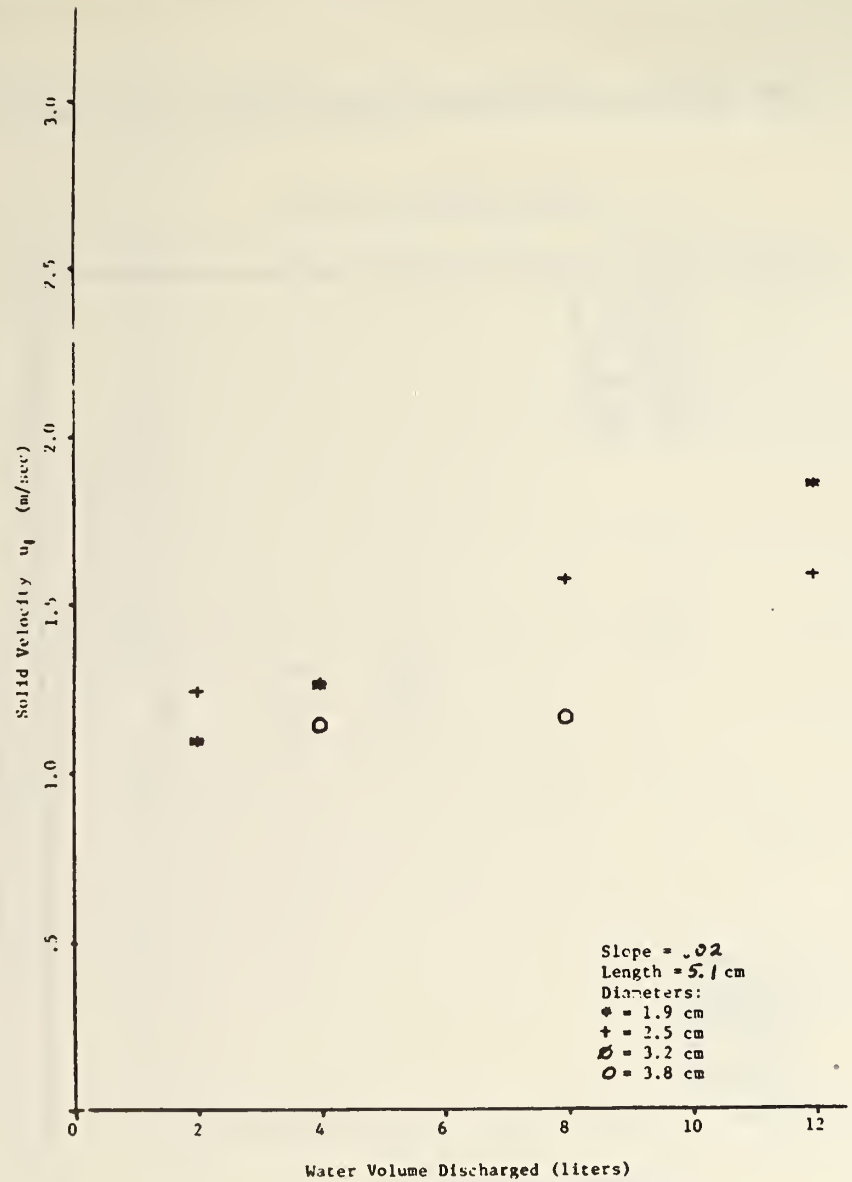


Figure 8-3. Solid velocity versus water volume used

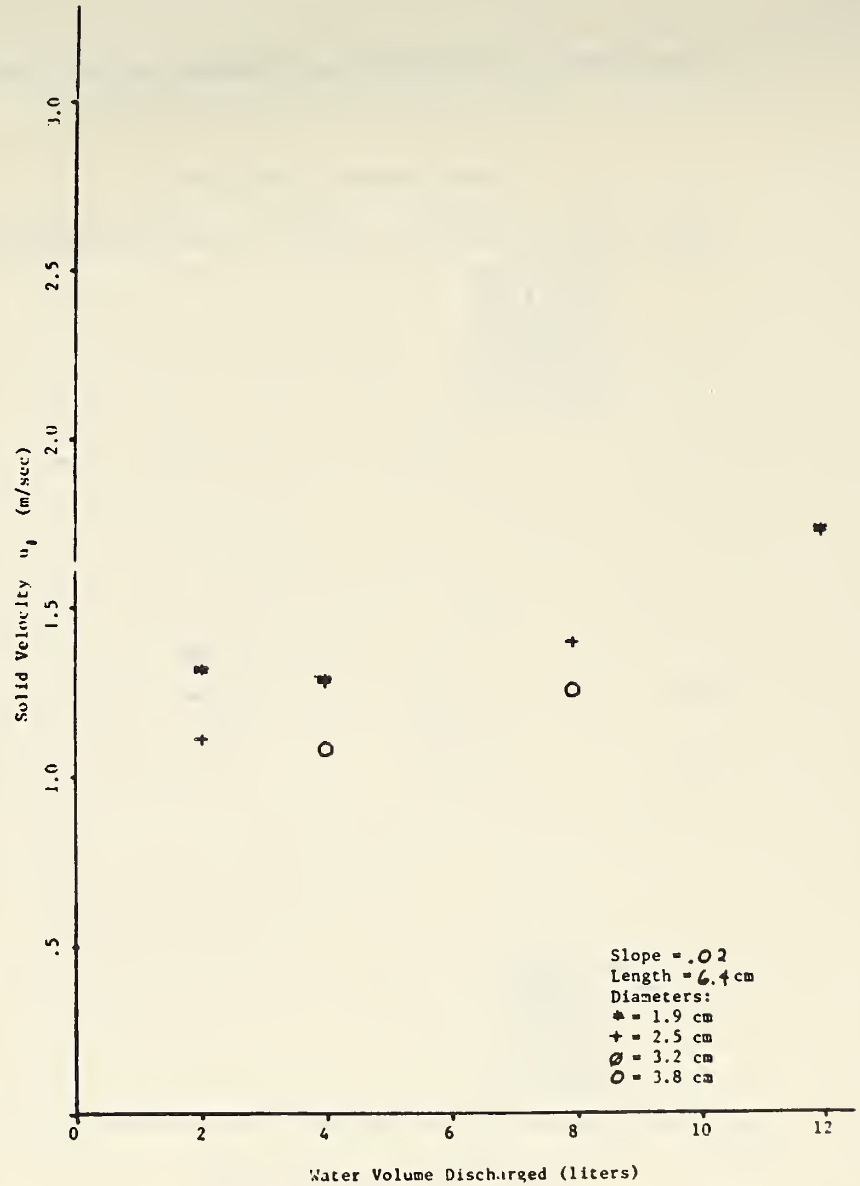


Figure 8-4. Solid velocity versus water volume used

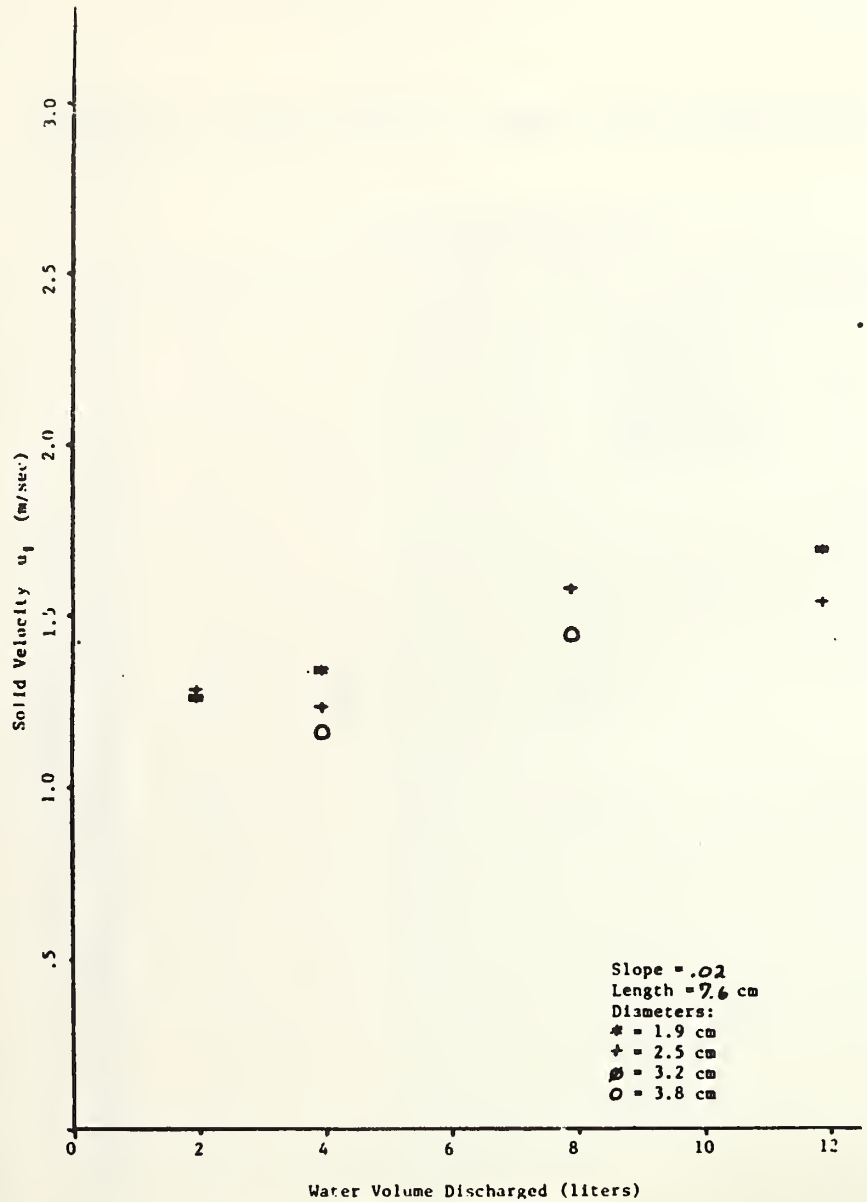


Figure 8-5. Solid velocity versus water volume used

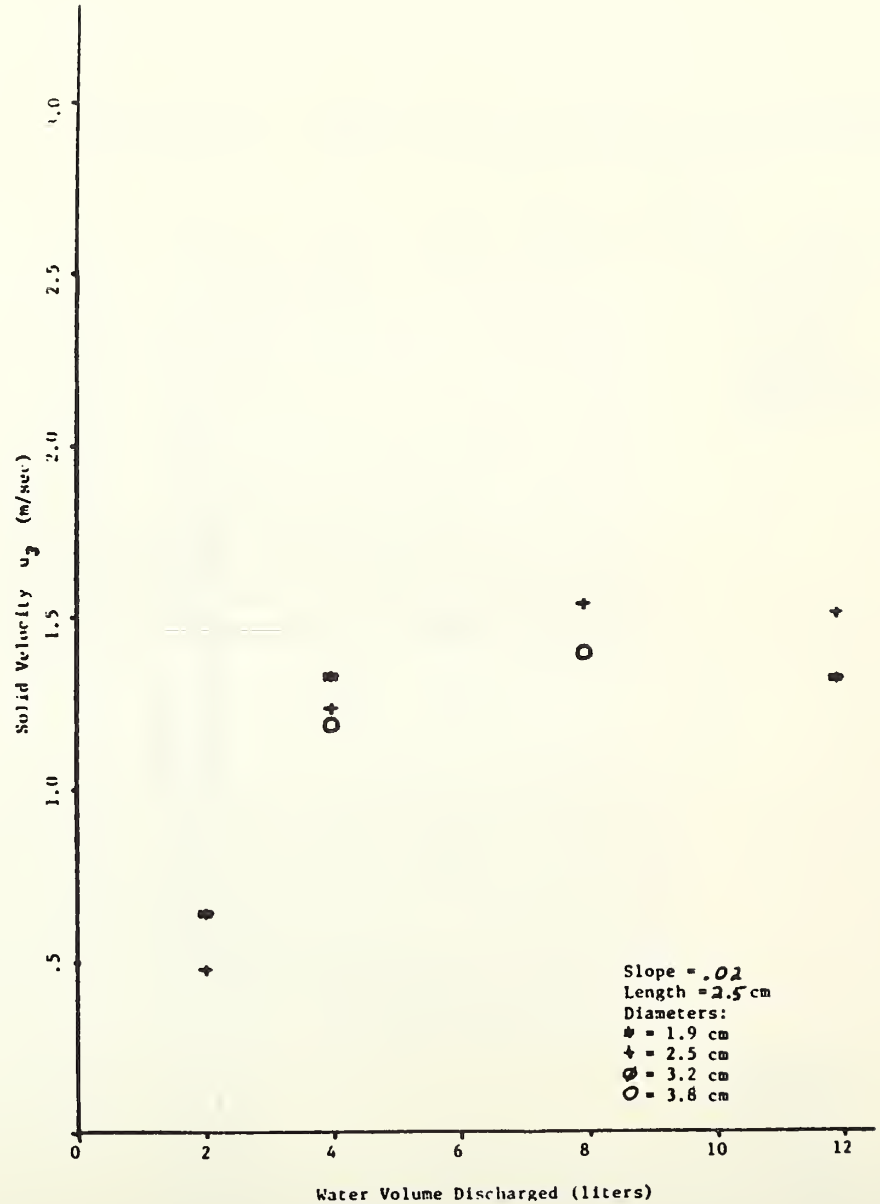


Figure 8-6. Solid velocity versus water volume used

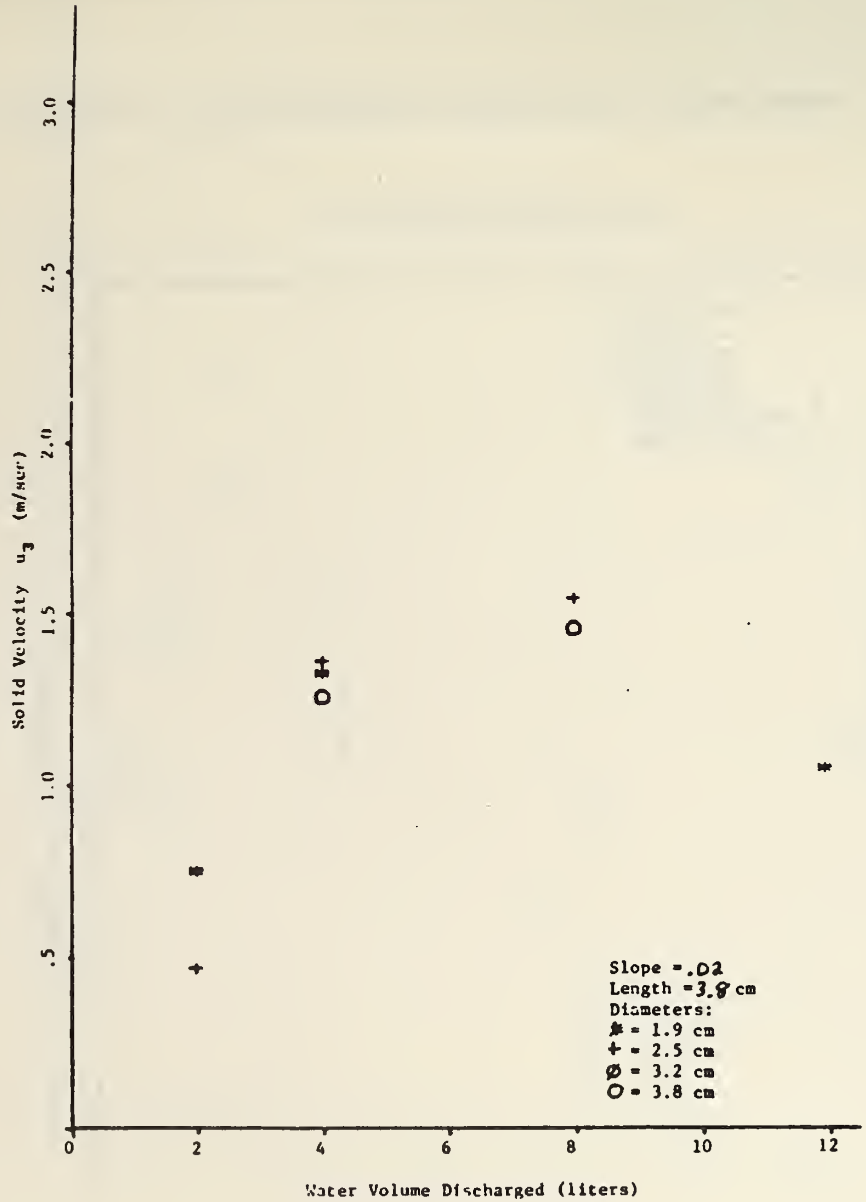


Figure 8-7. Solid velocity versus water volume used

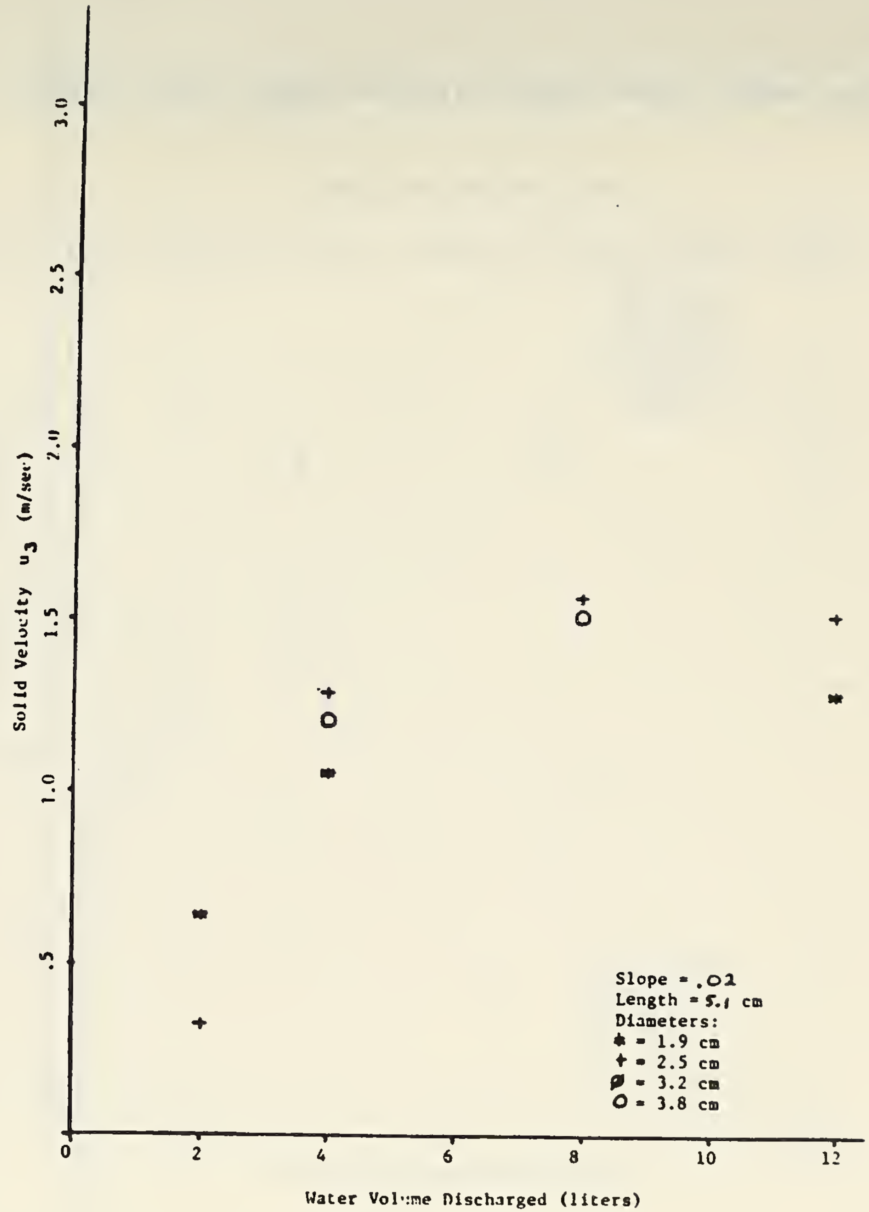


Figure 8-8. Solid velocity versus water volume used

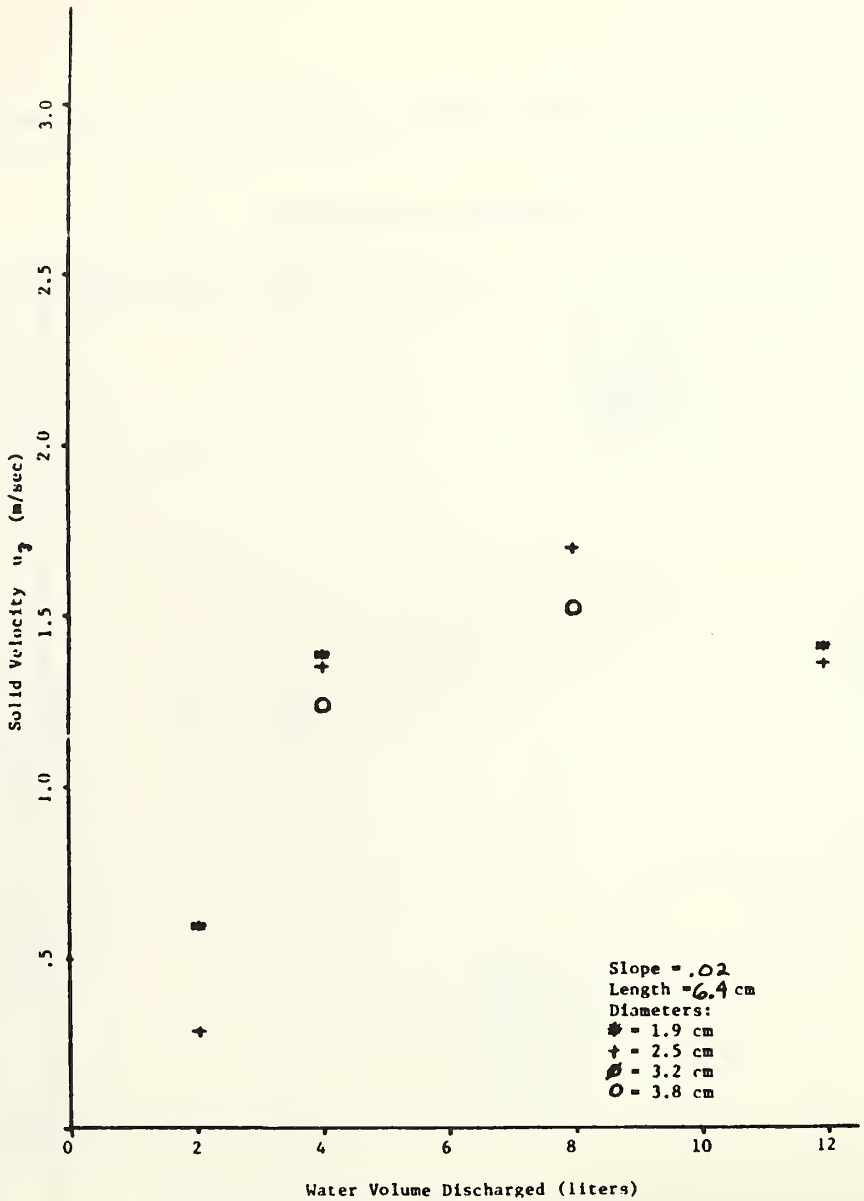
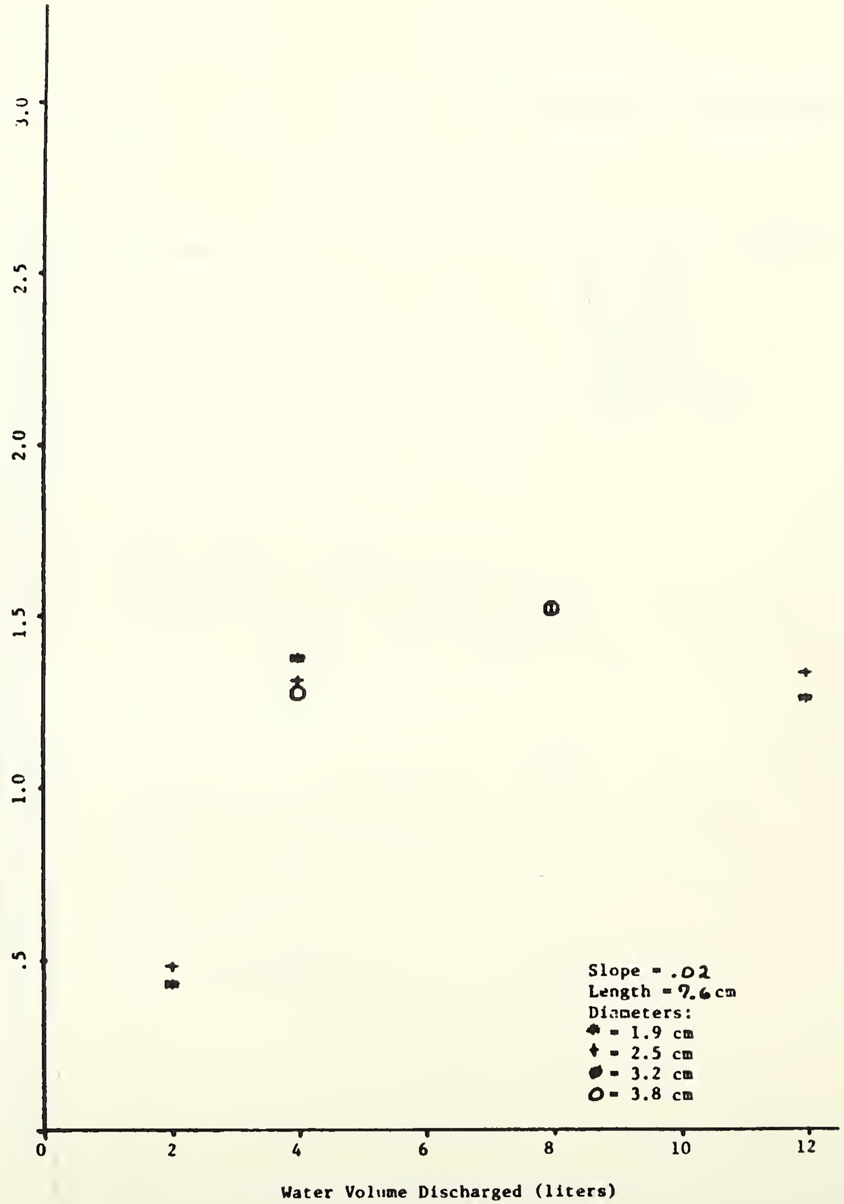


Figure 8-9. Solid velocity versus water volume used



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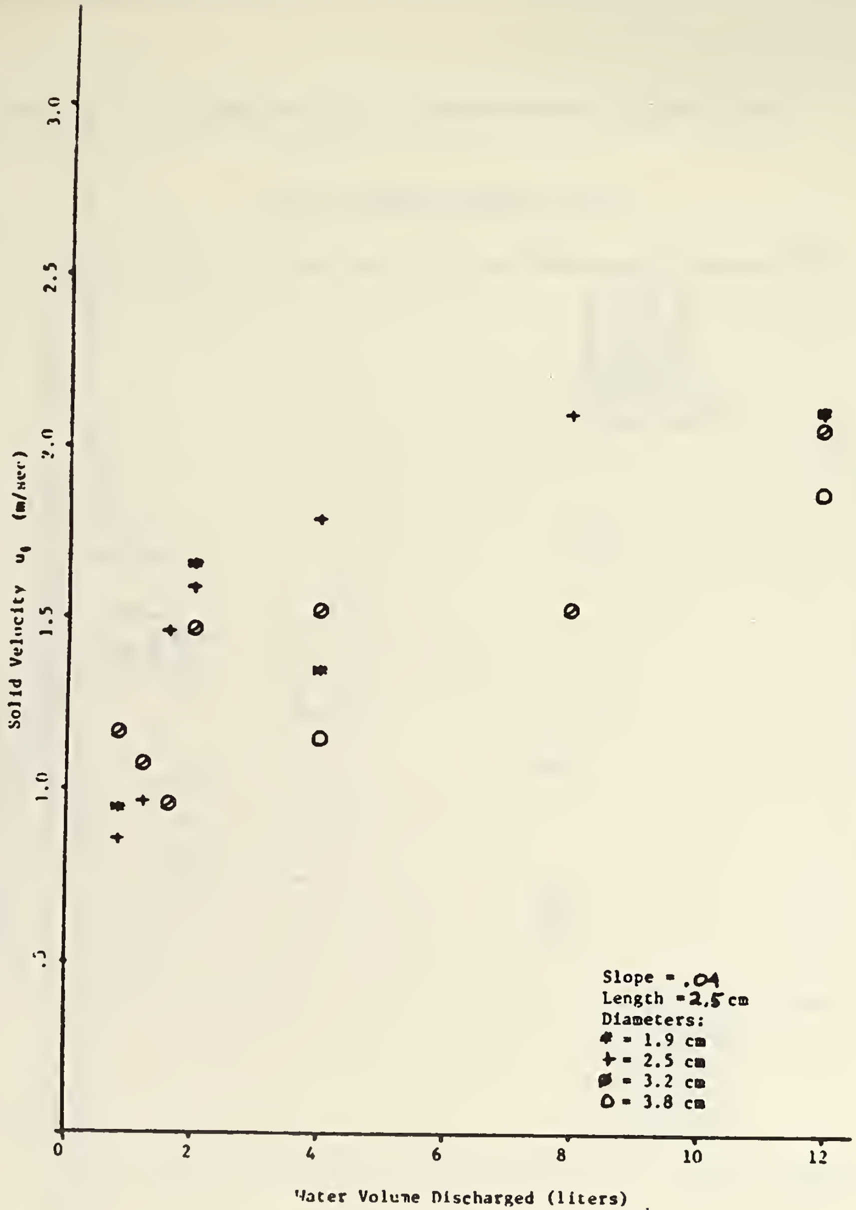
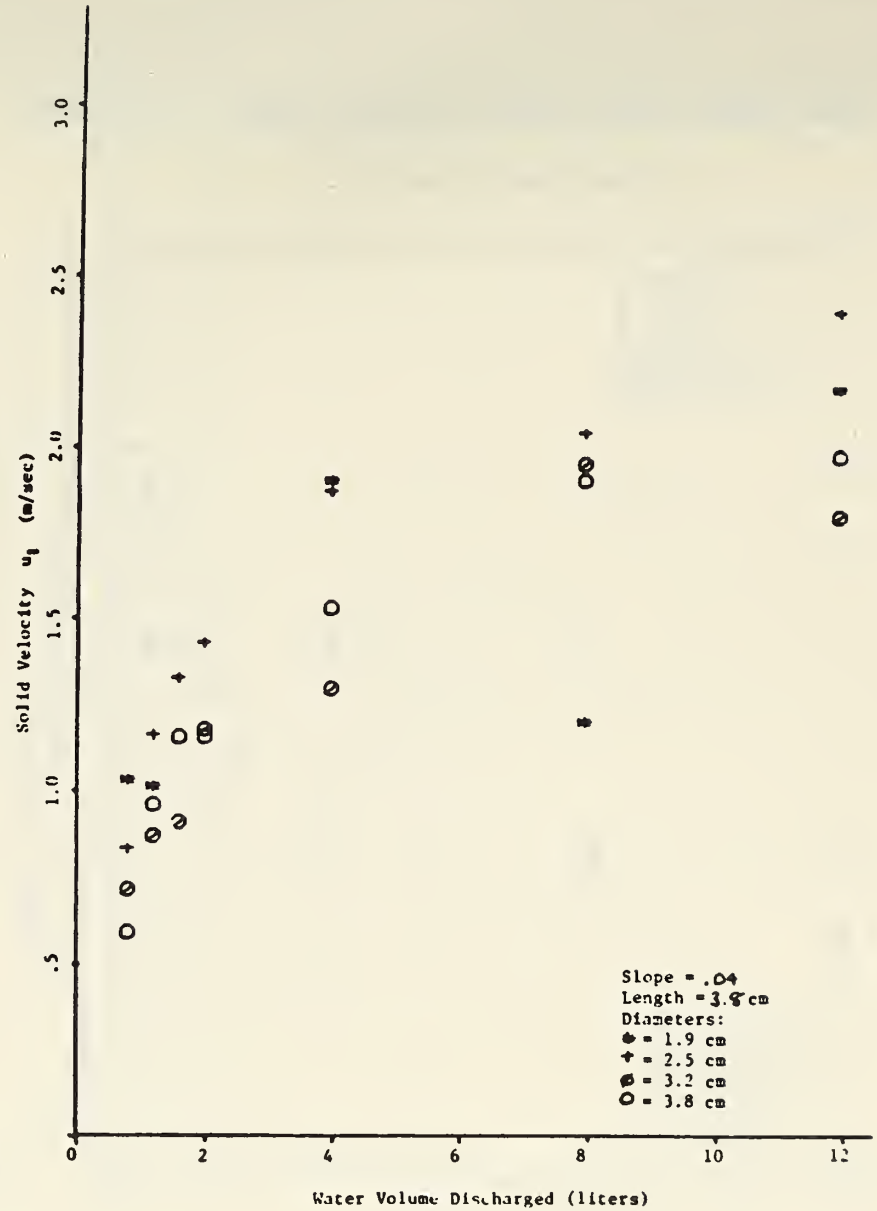


Figure 9-1. Solid velocity versus water volume used



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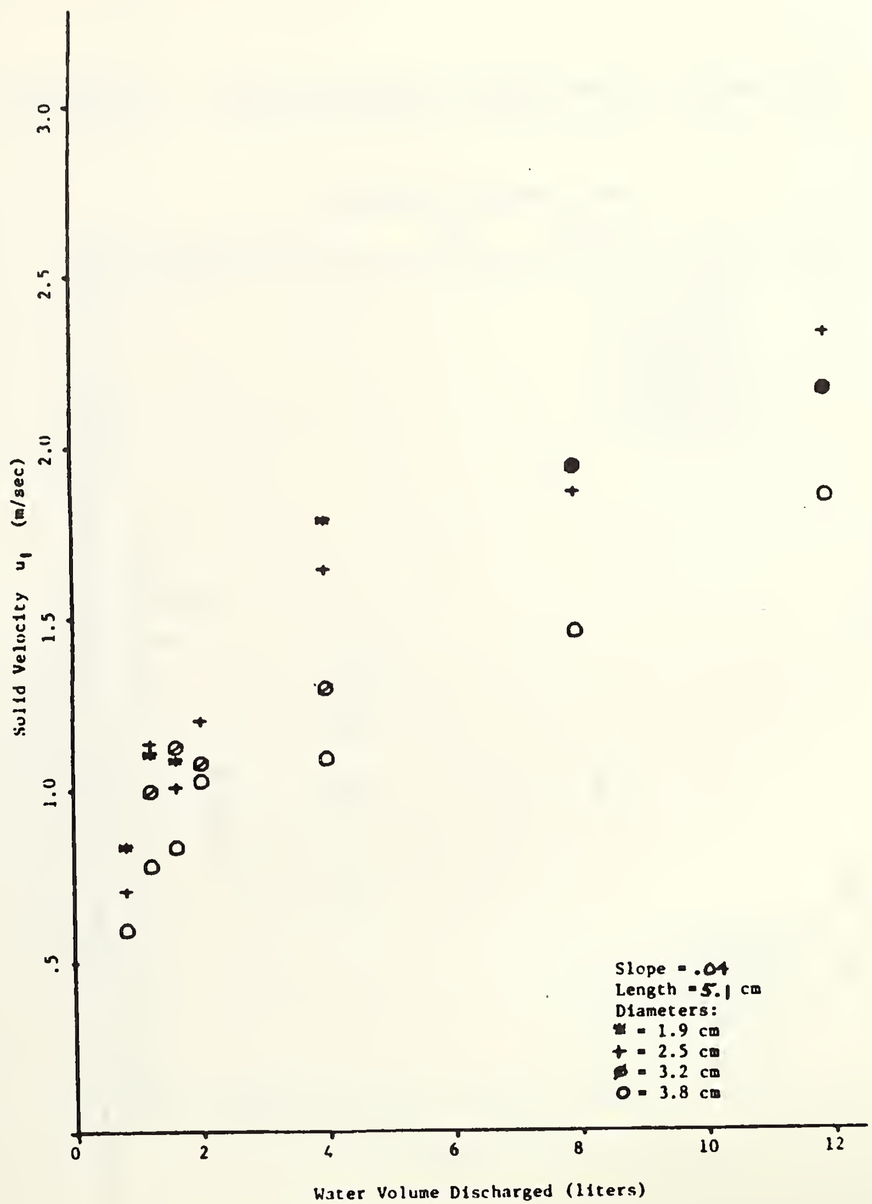
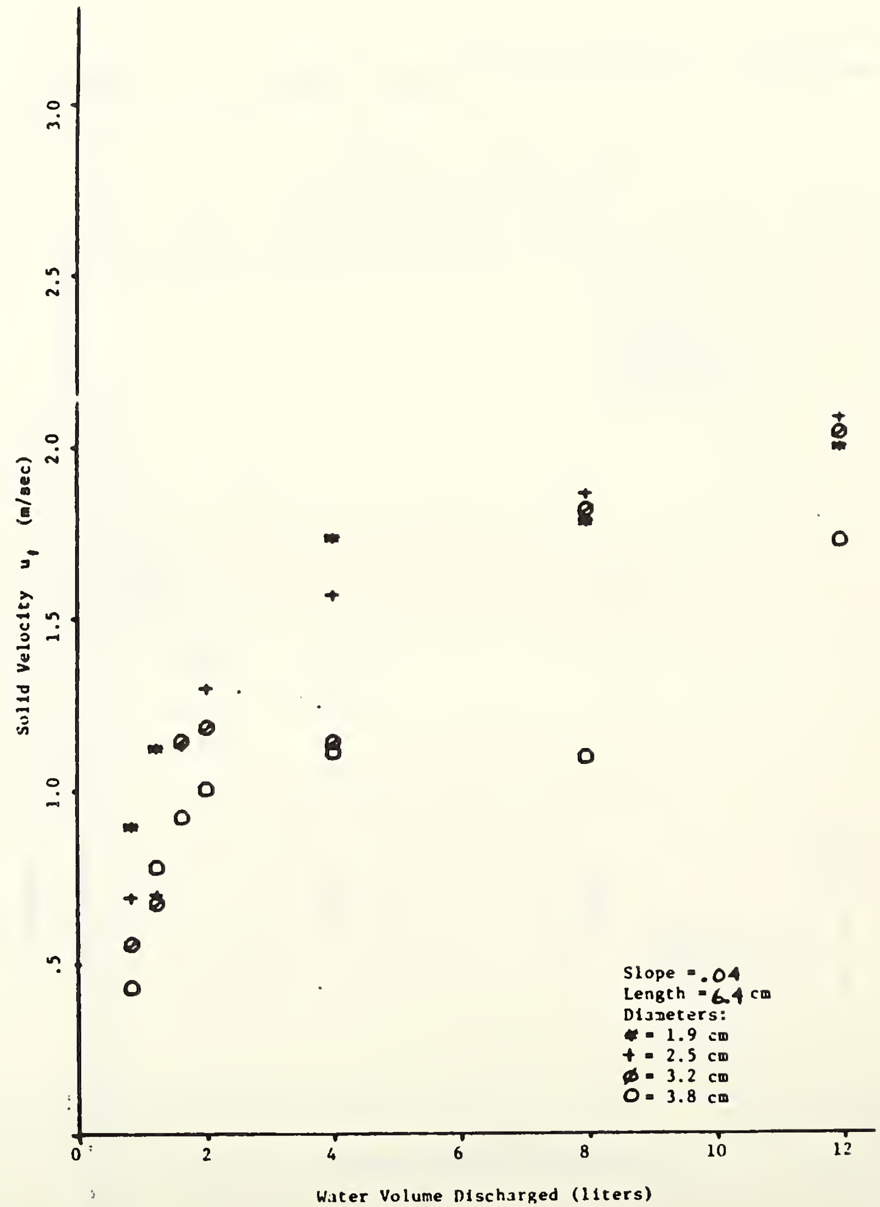


Figure 9-3. Solid velocity versus water volume used



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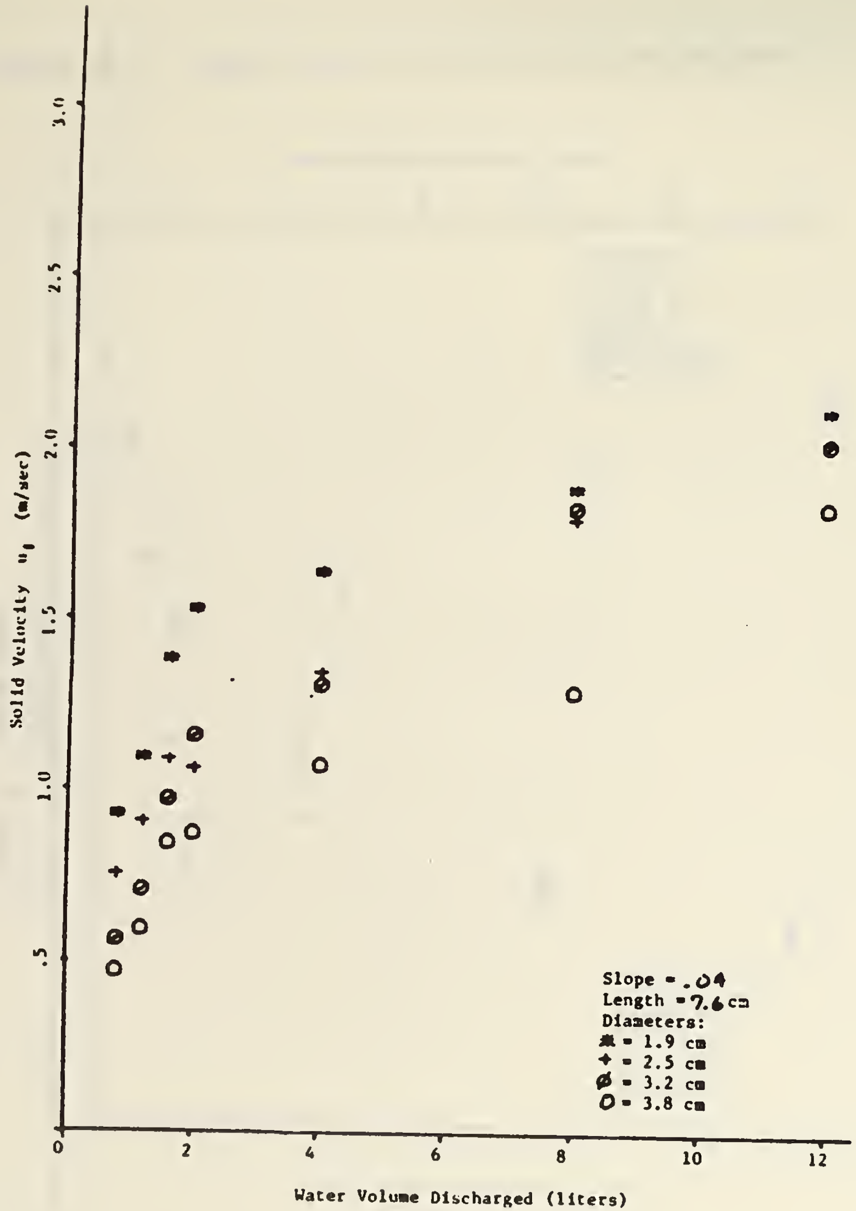


Figure 9-5. Solid velocity versus water volume used

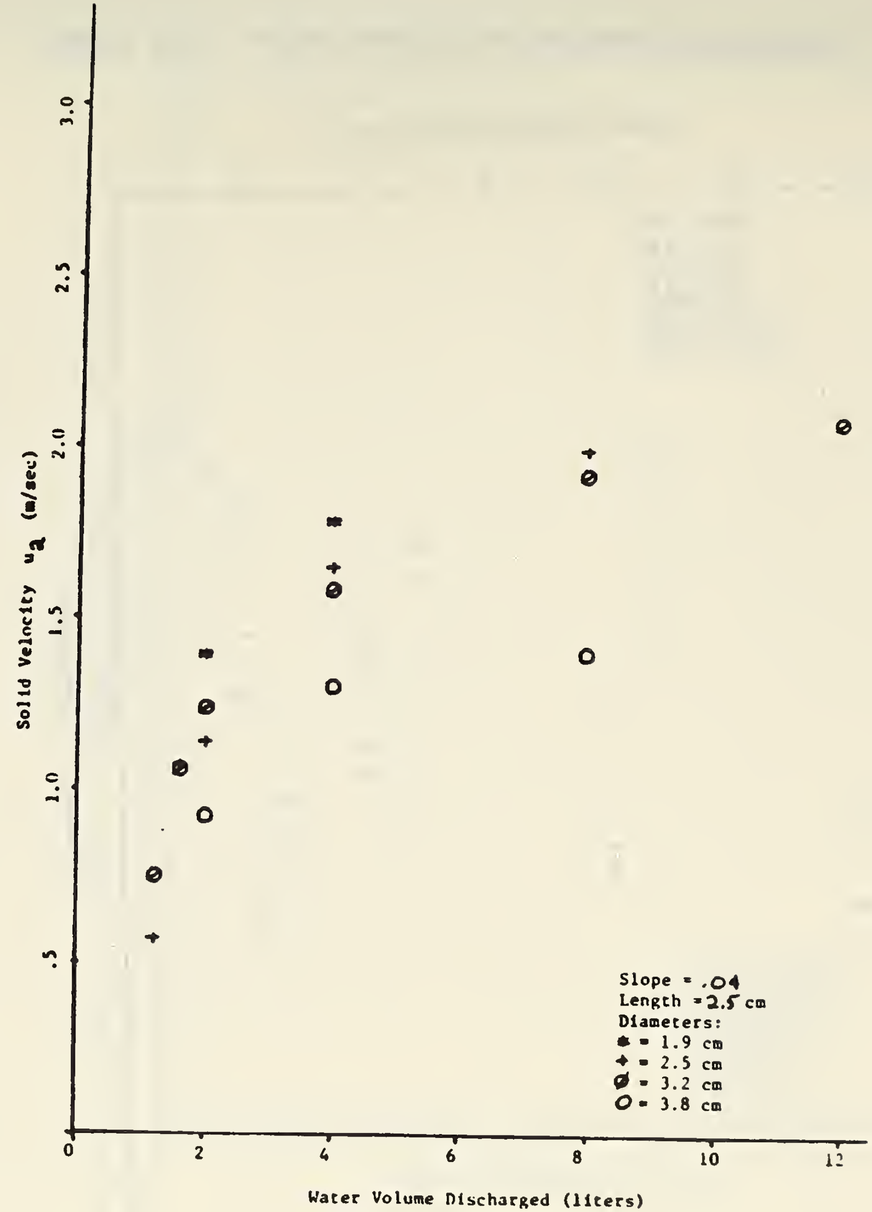


Figure 9-6. Solid velocity versus water volume used

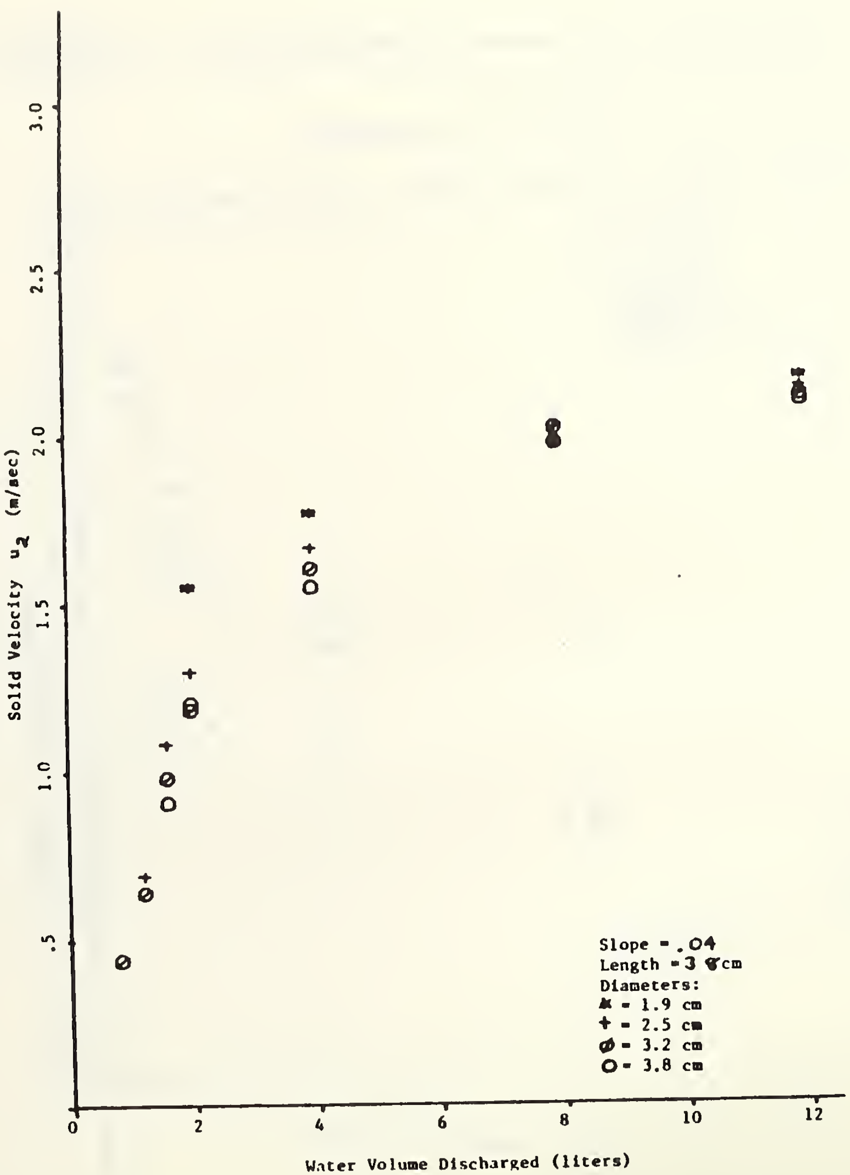
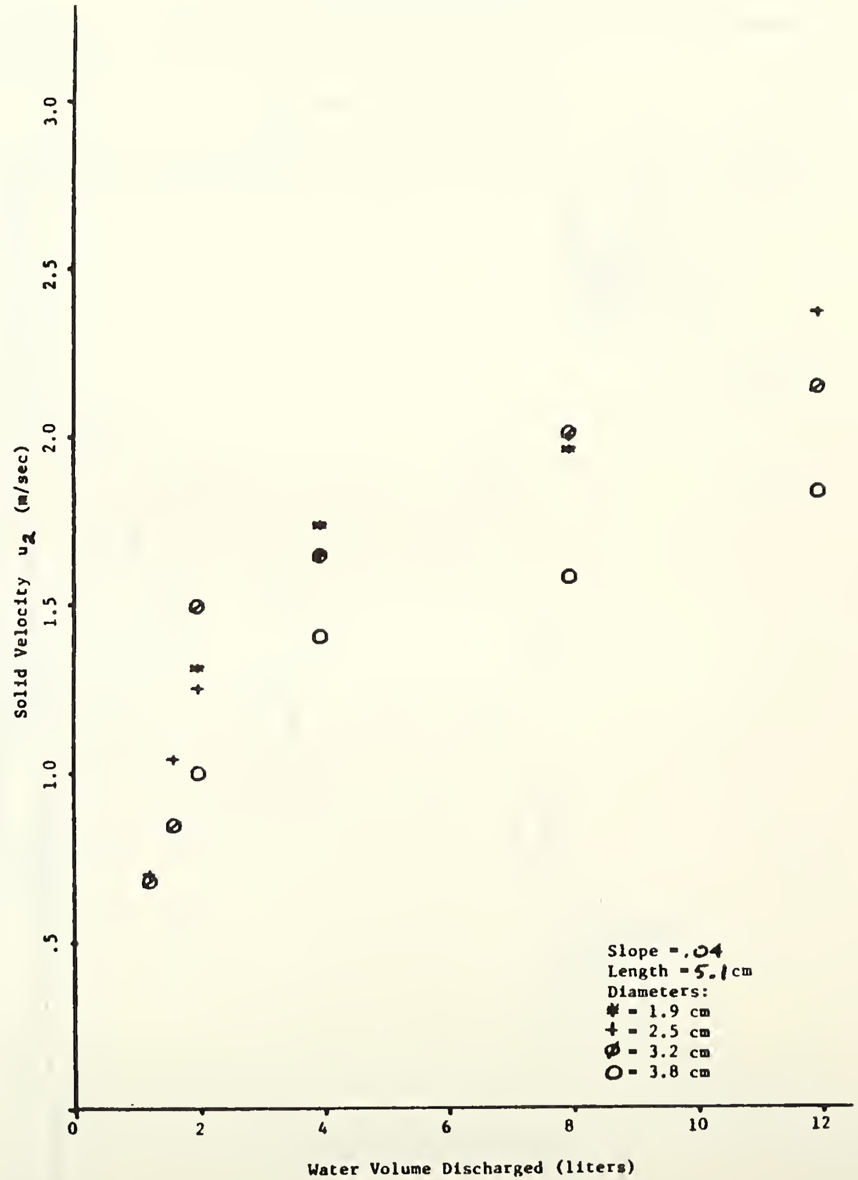


Figure 9-7. Solid velocity versus water volume used



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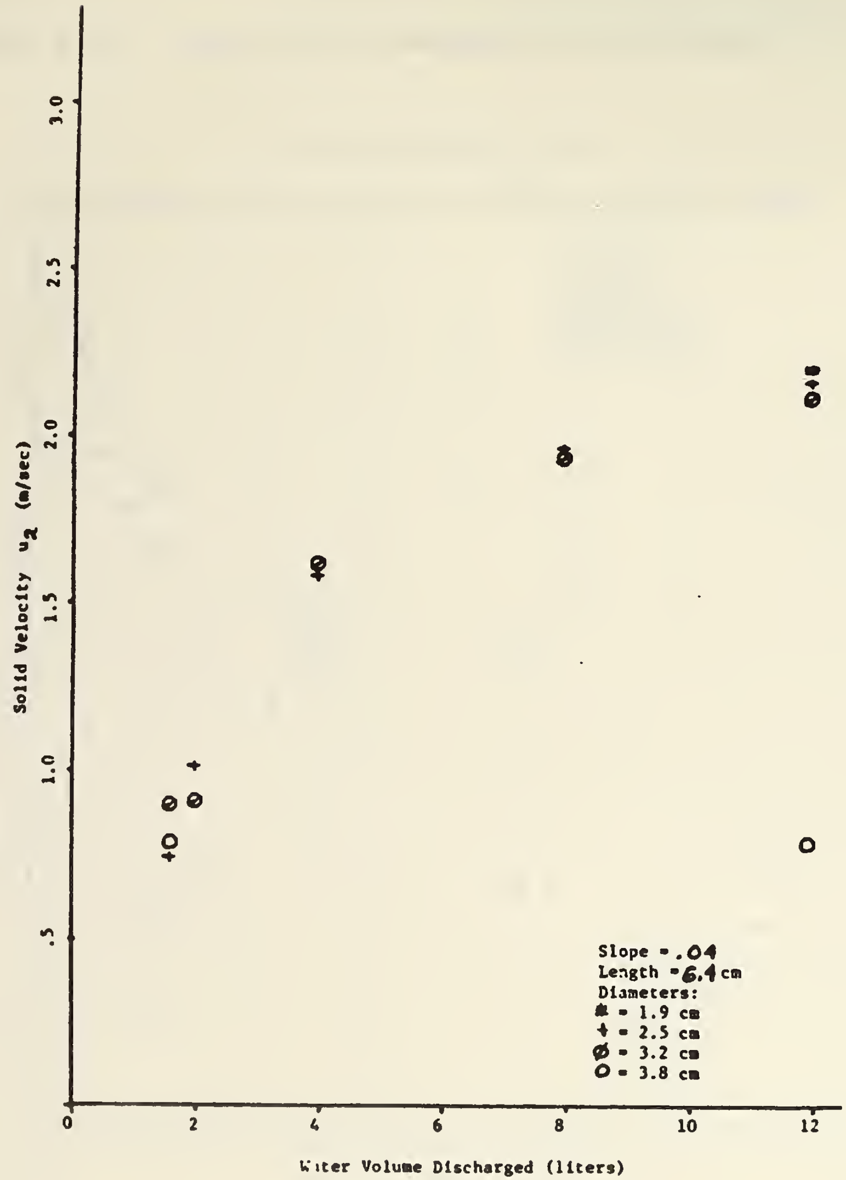

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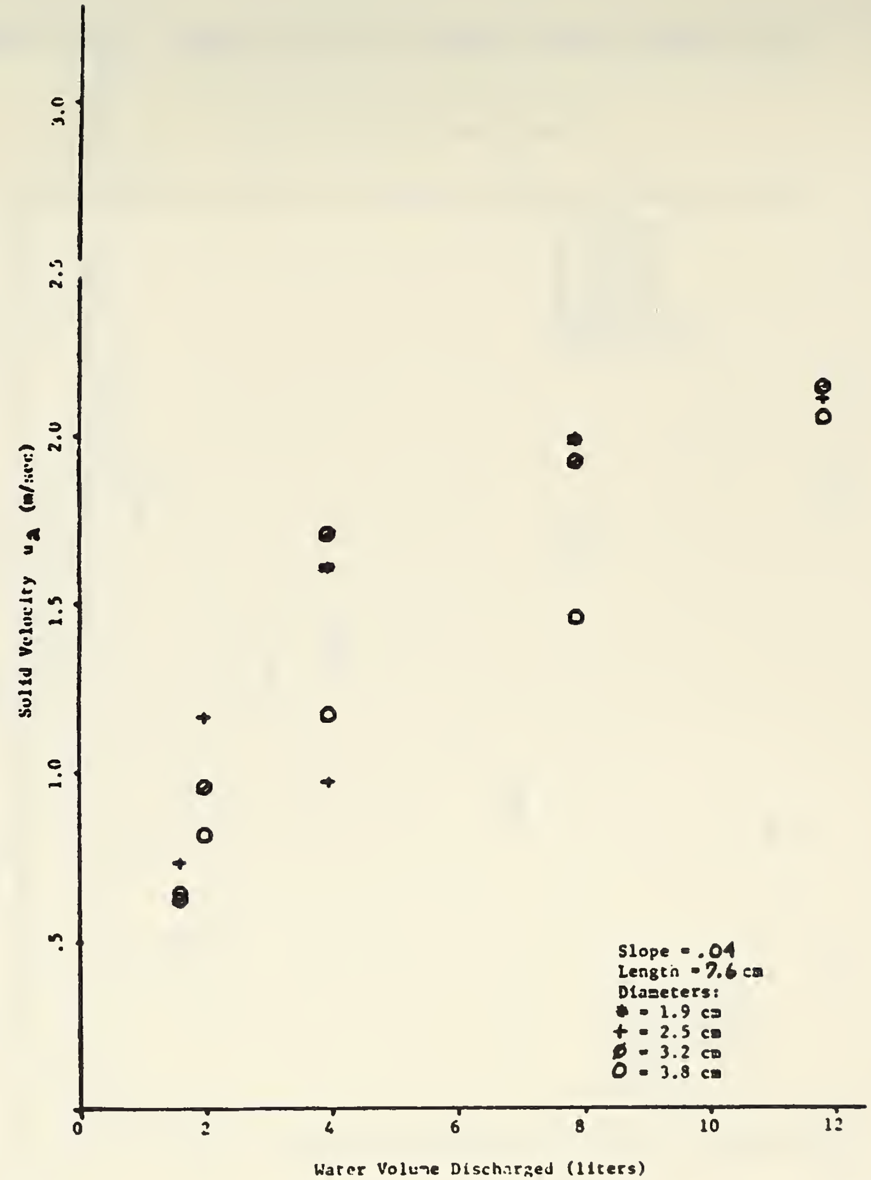

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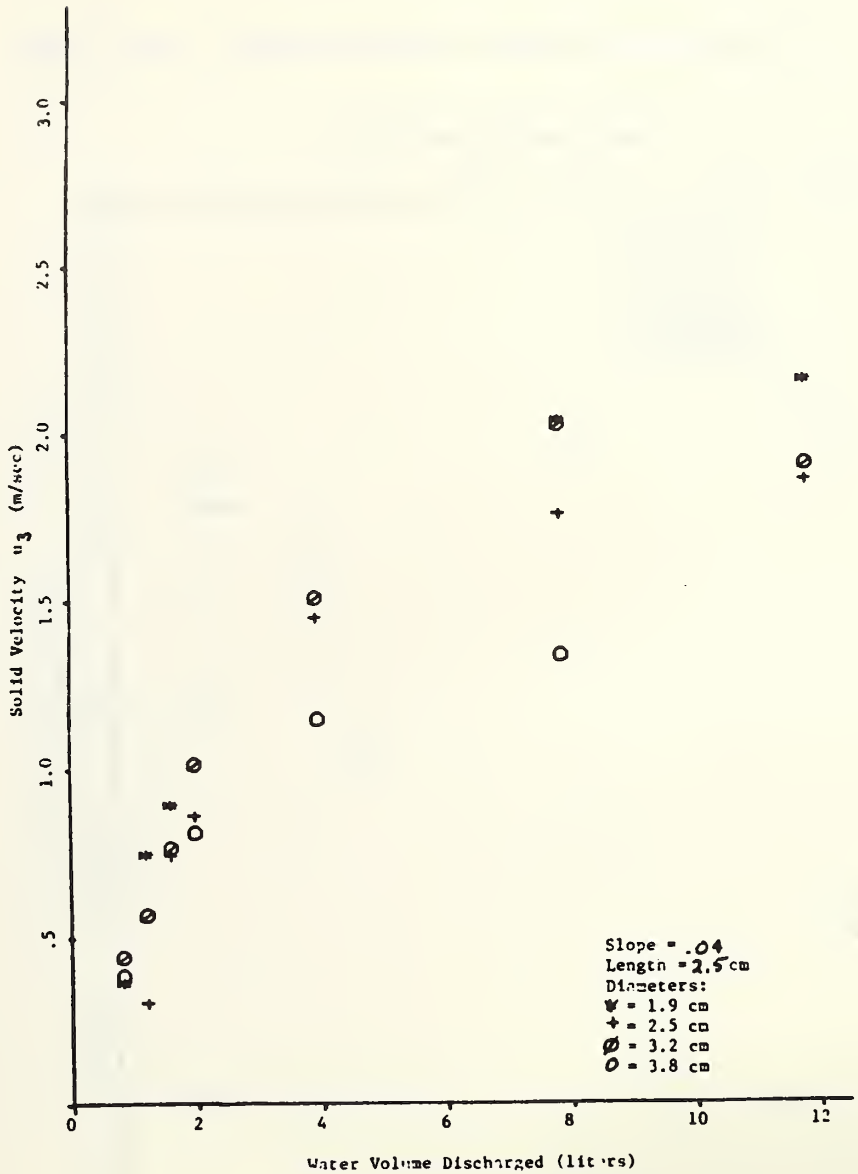


Figure 9-11. Solid velocity versus water volume used

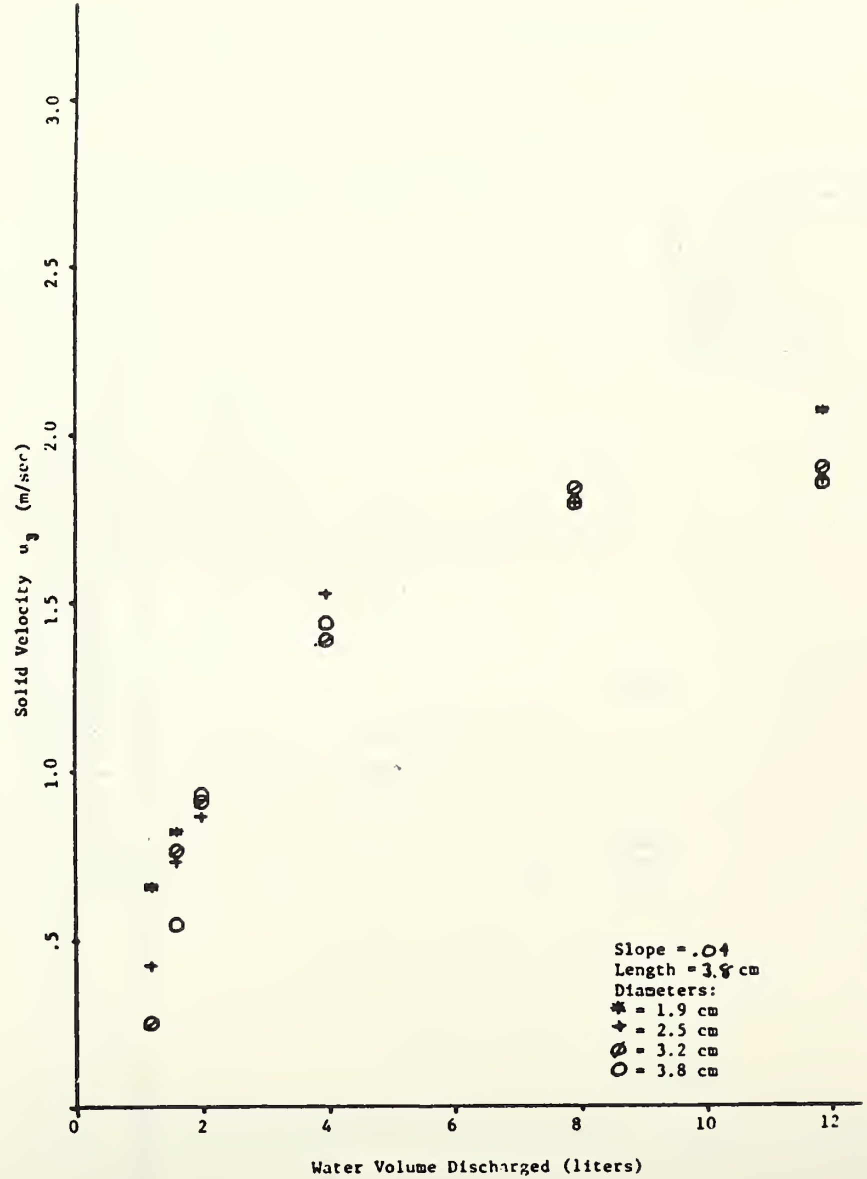
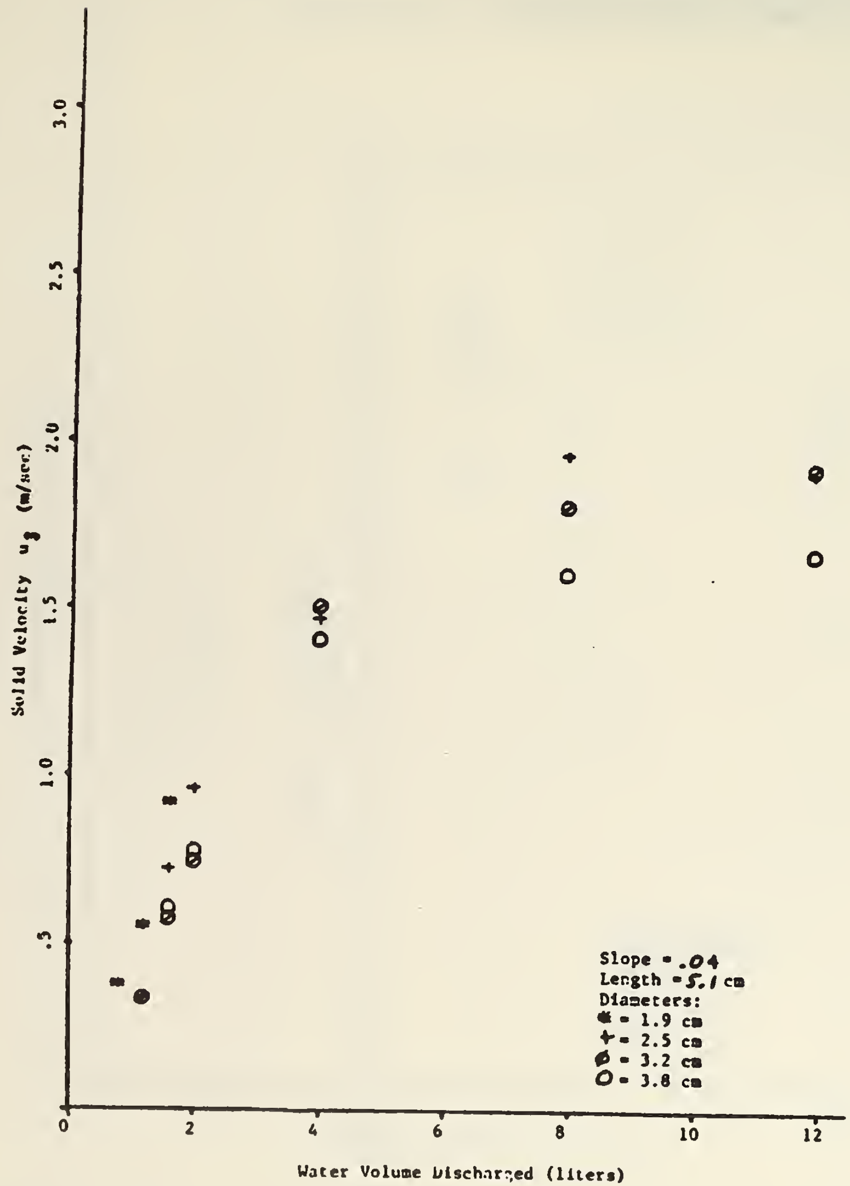


Figure 9-12. Solid velocity versus water volume used



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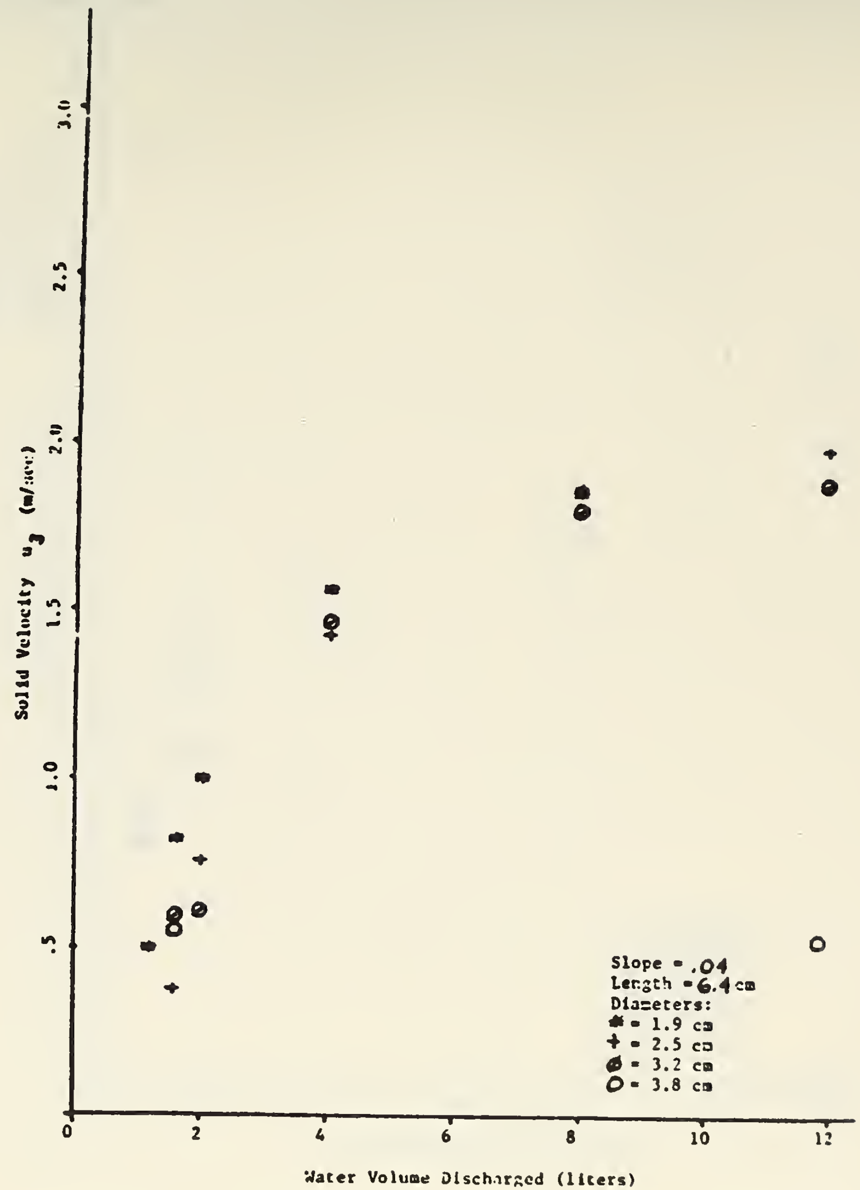
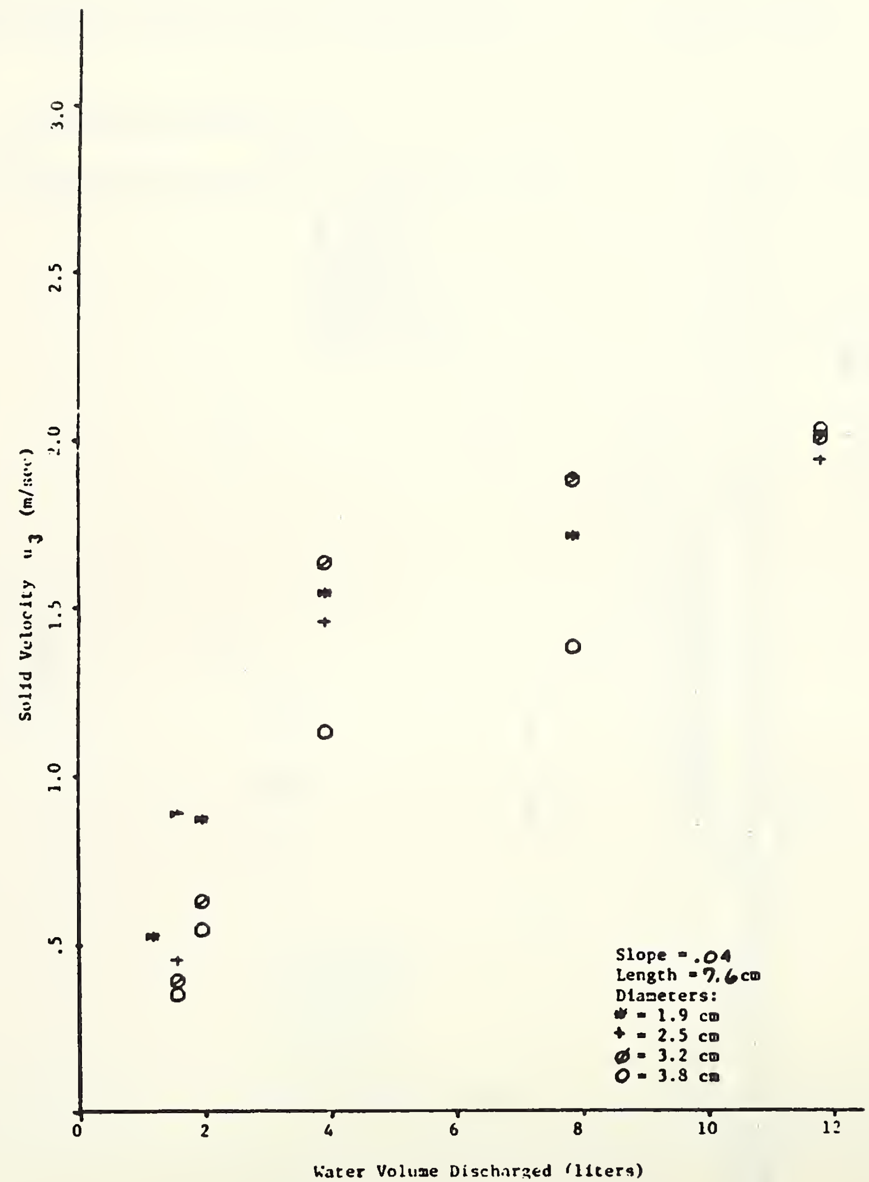


Figure 9-14. Solid velocity versus water volume used



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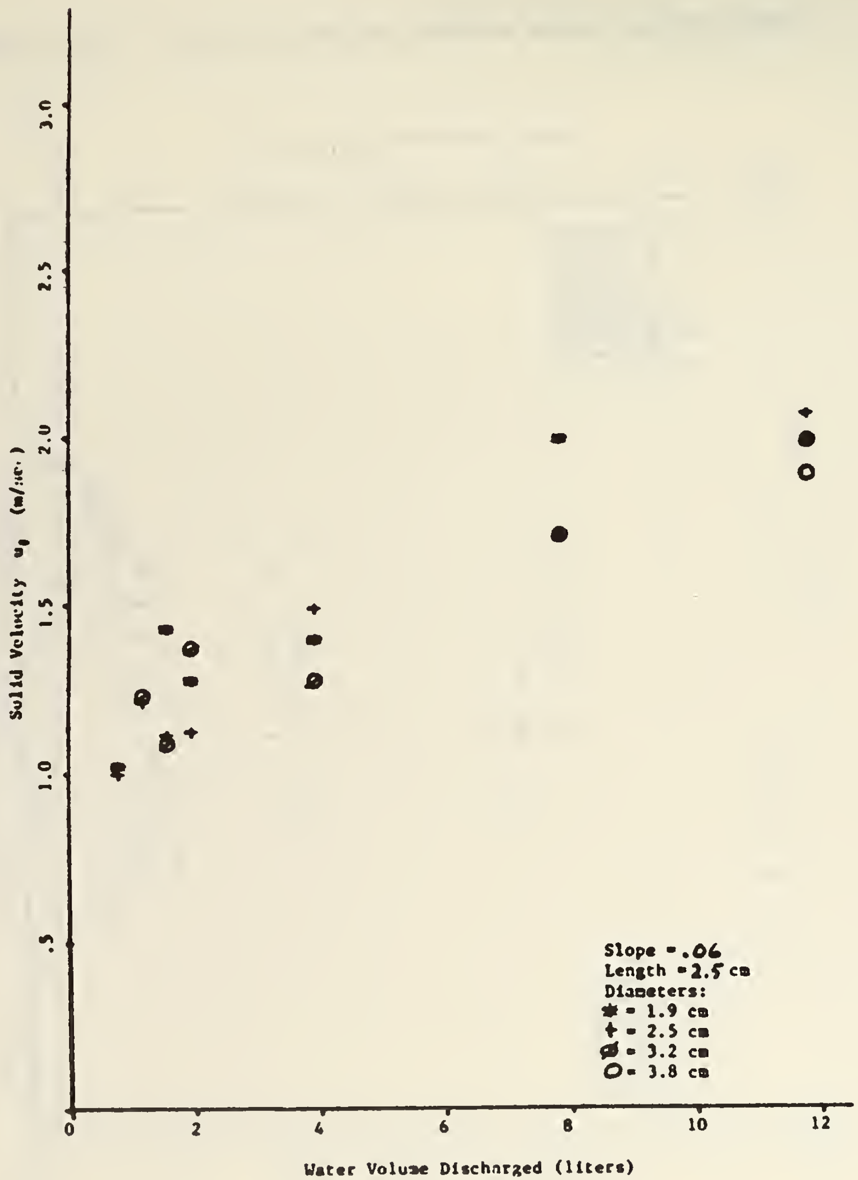


Figure 10-1. Solid velocity versus water volume used

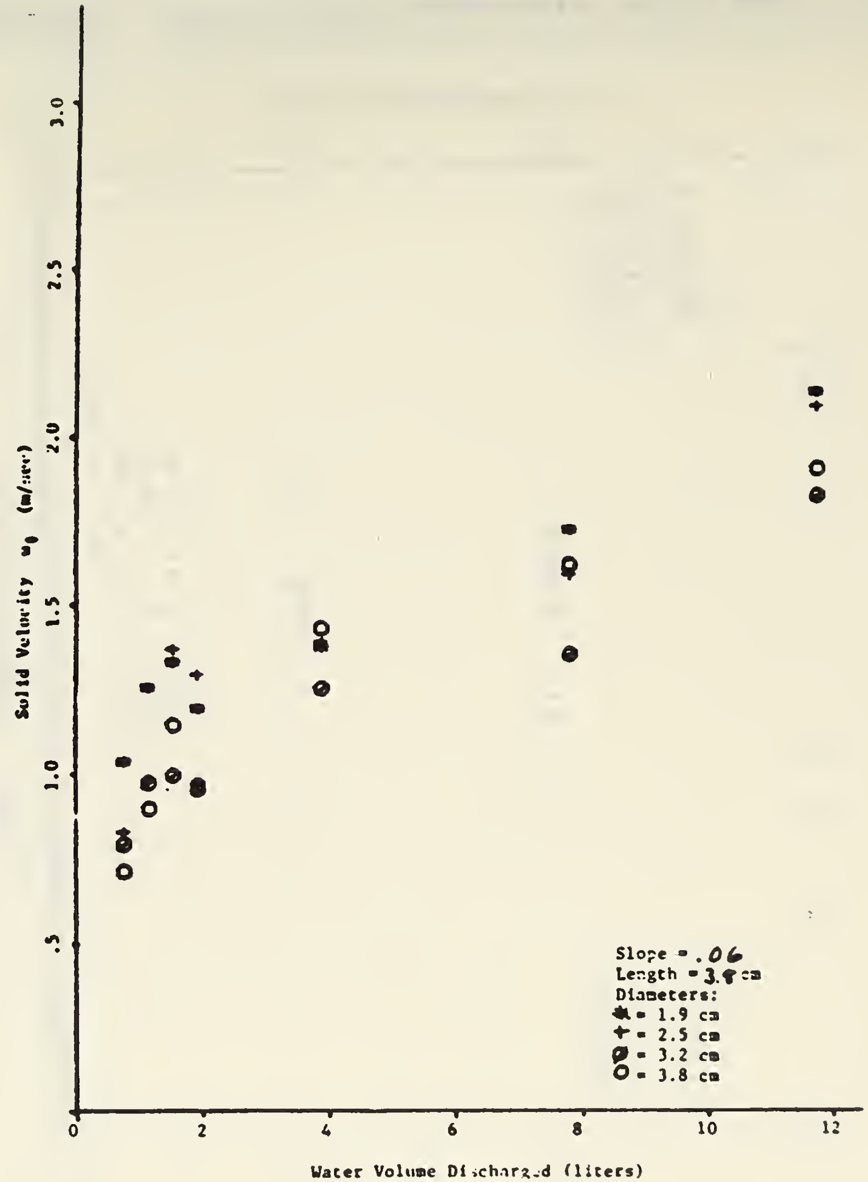
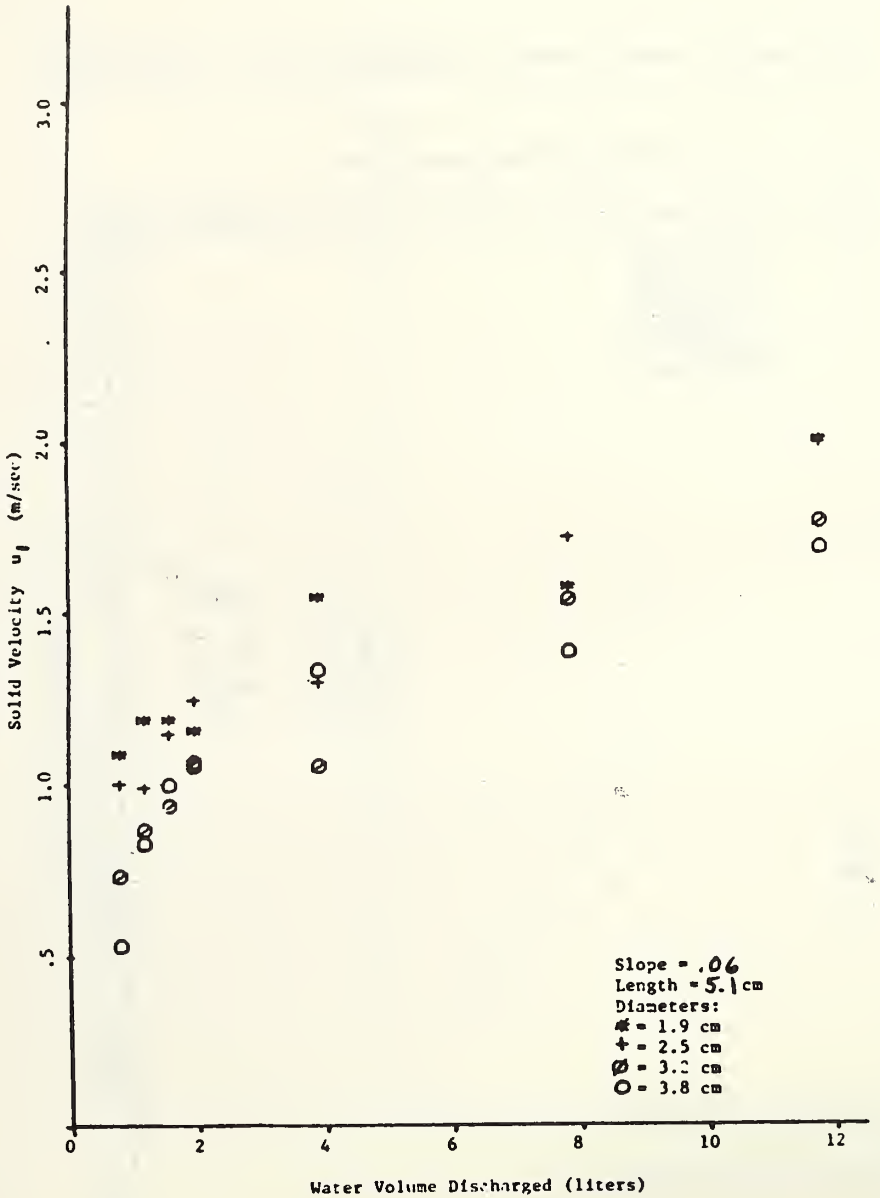


Figure 10-2. Solid velocity versus water volume used



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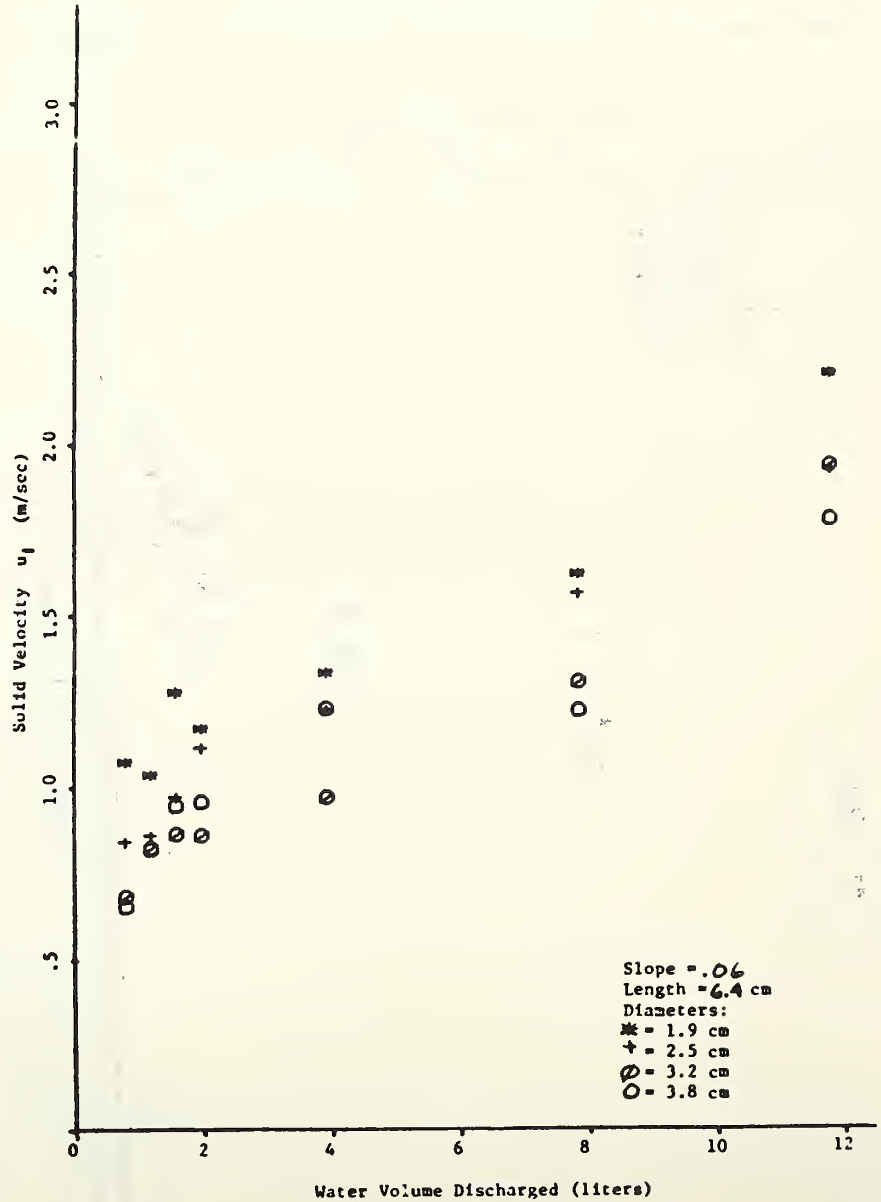

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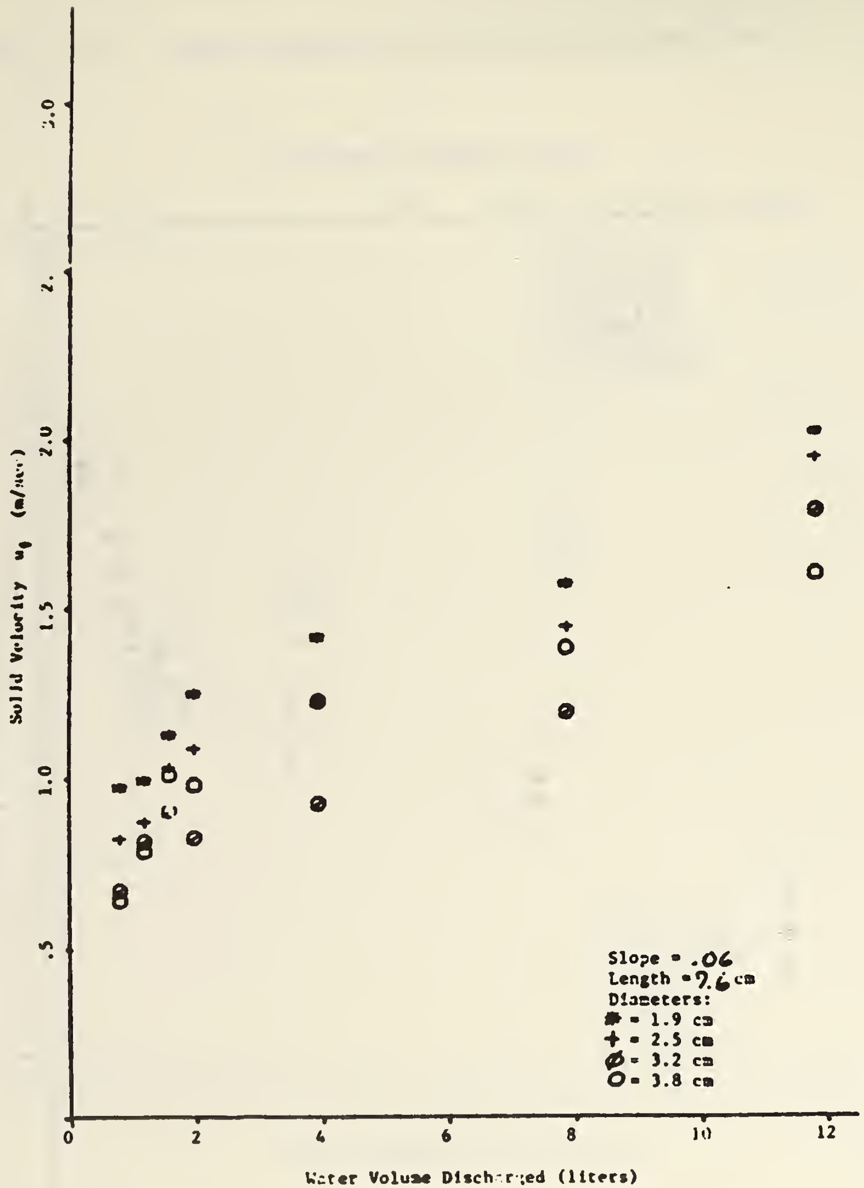

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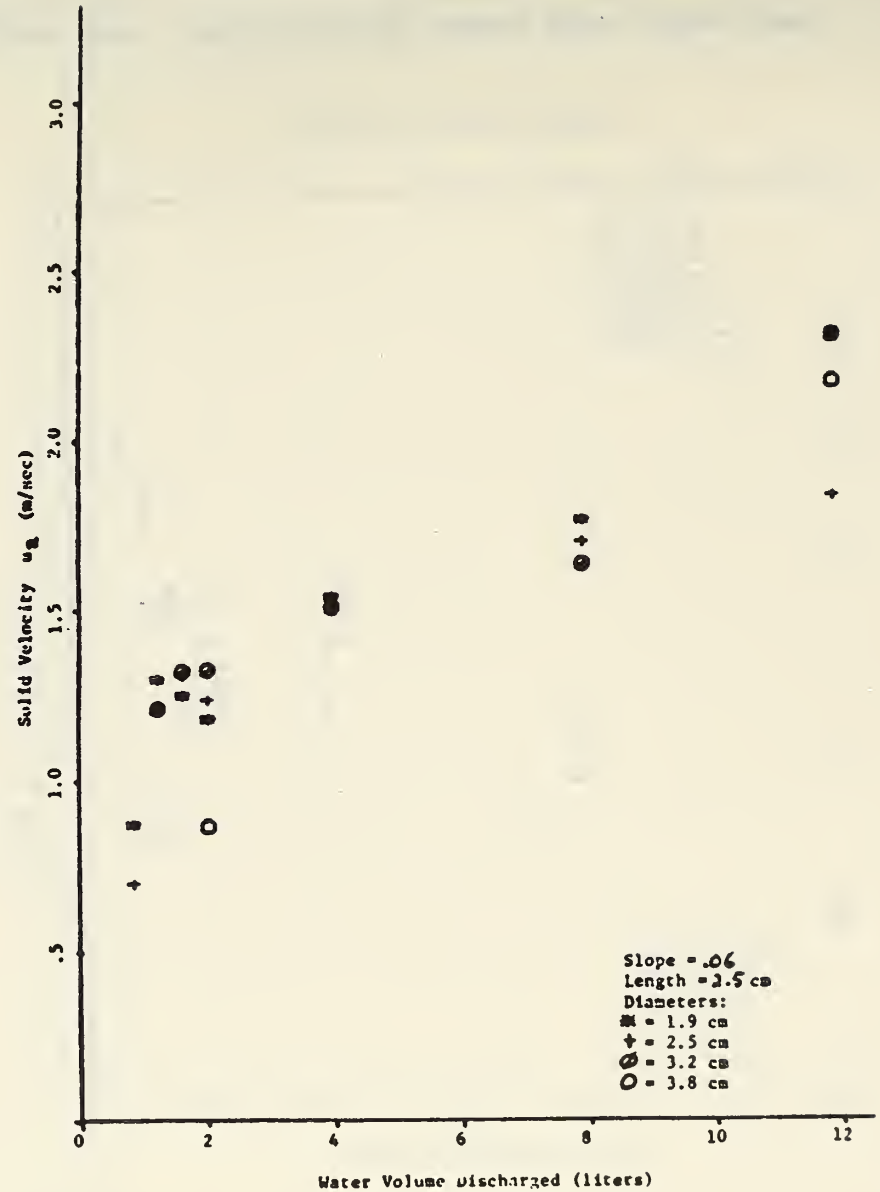

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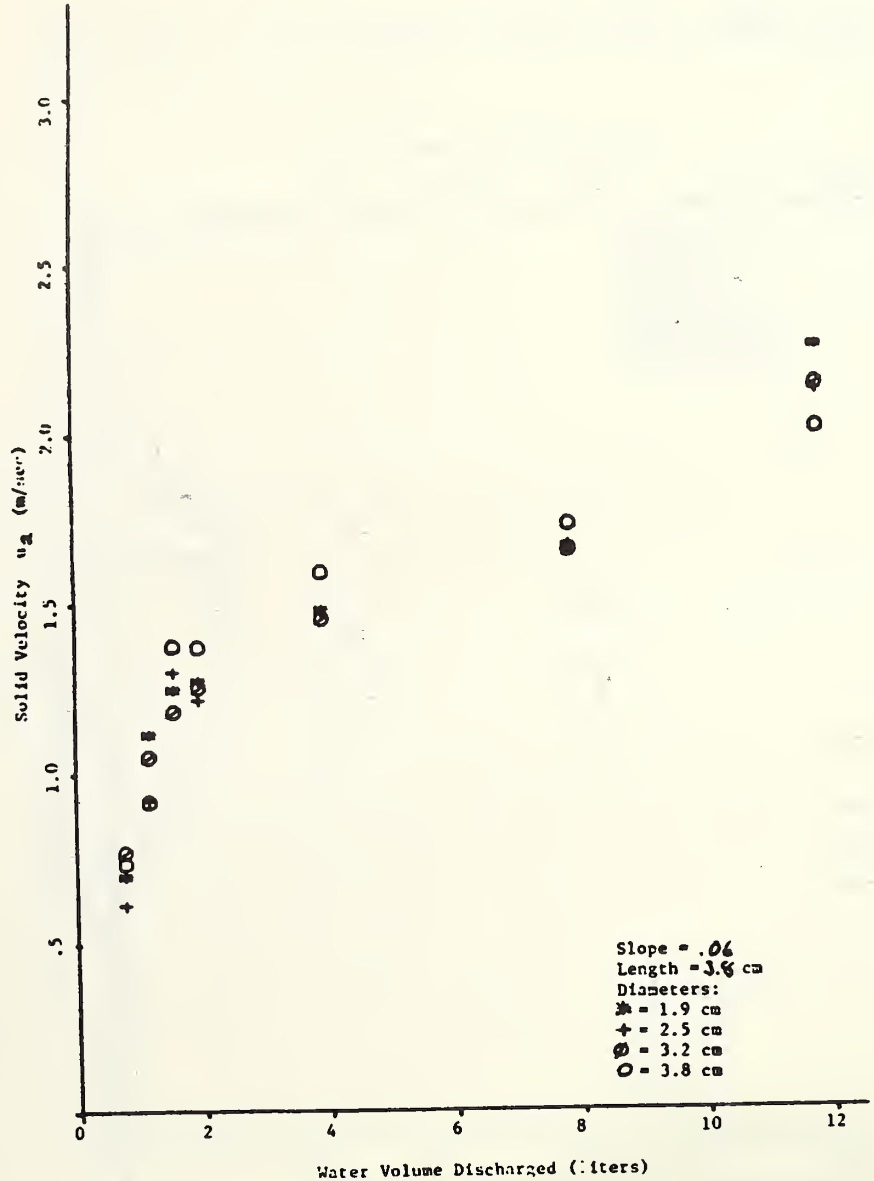

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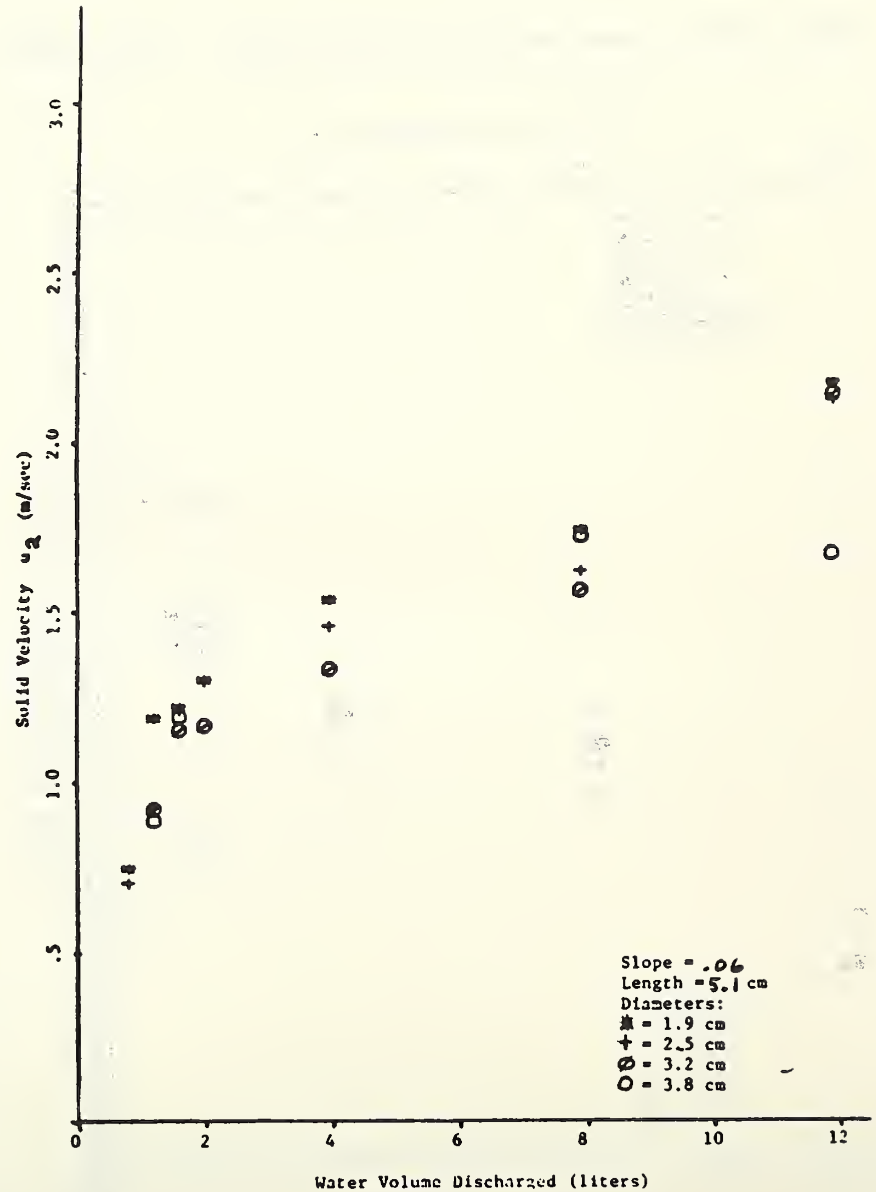

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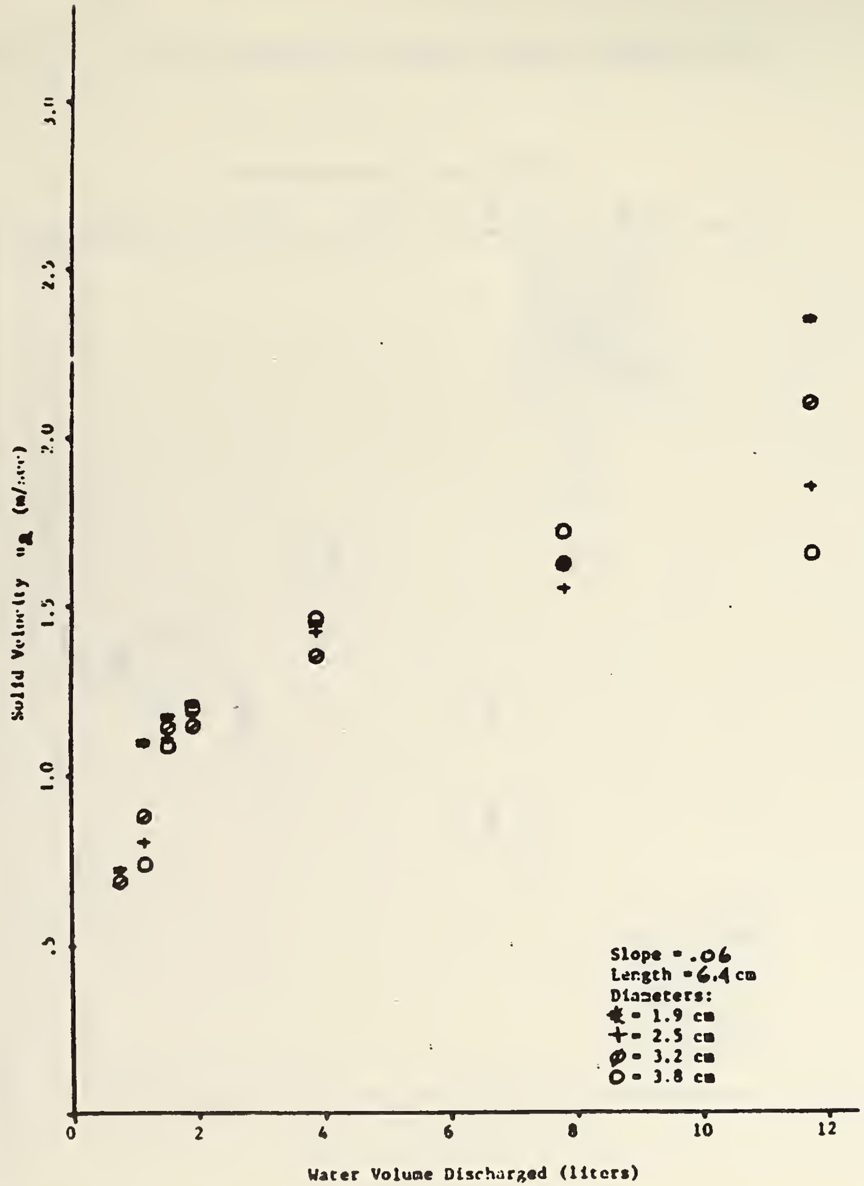

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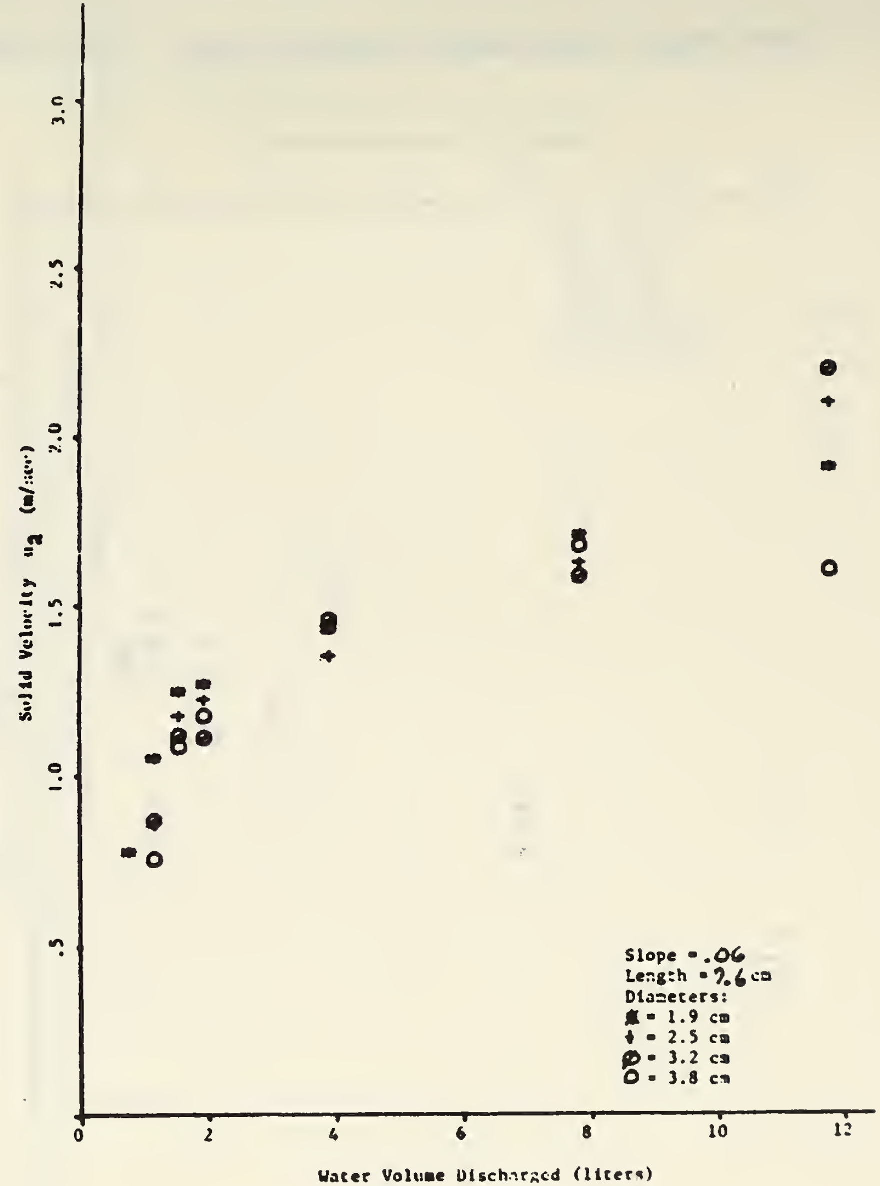

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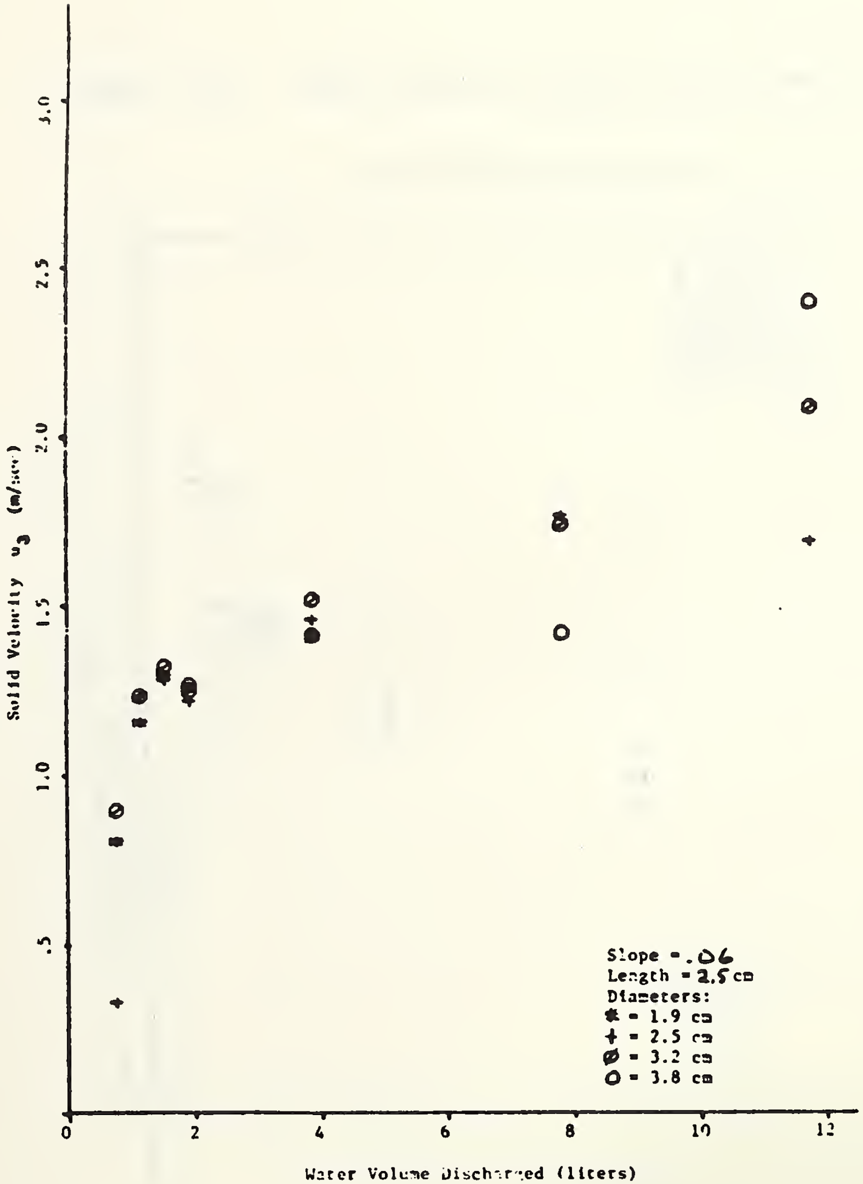

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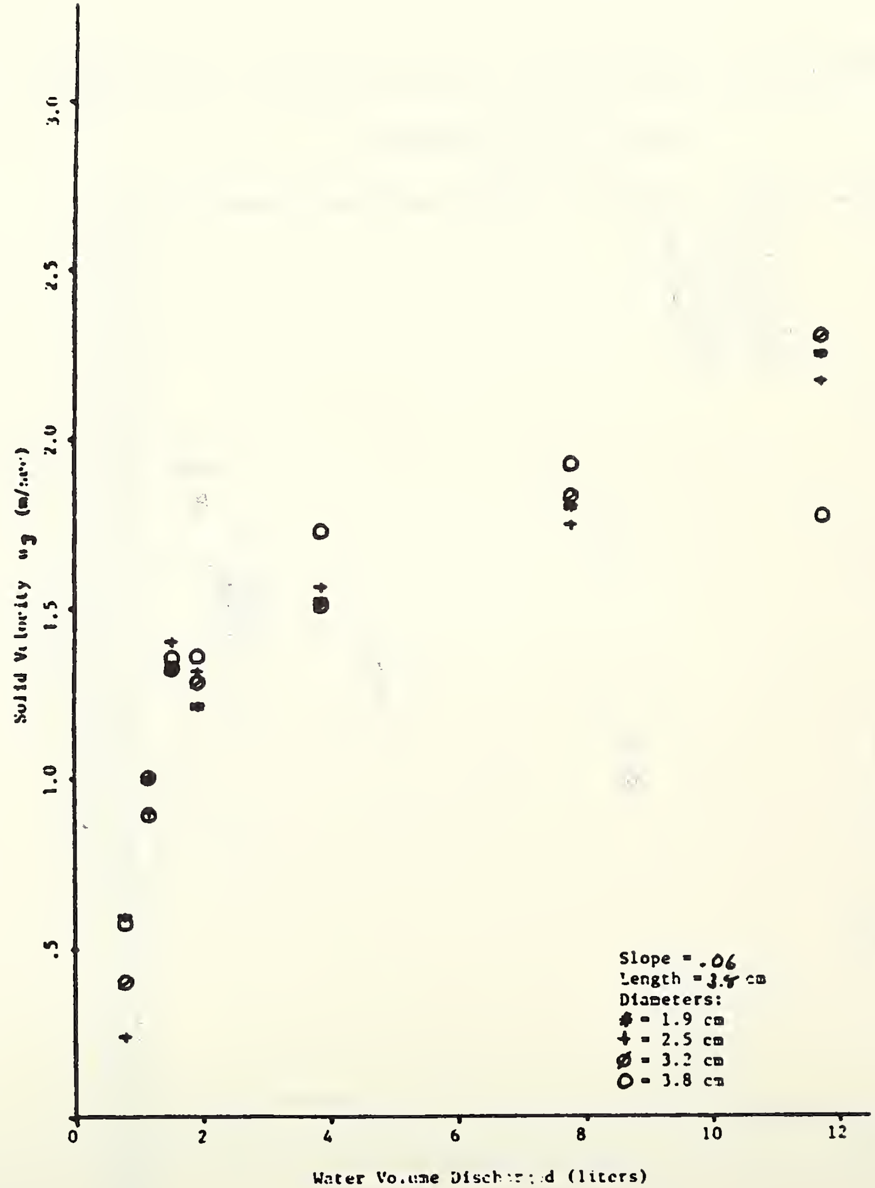

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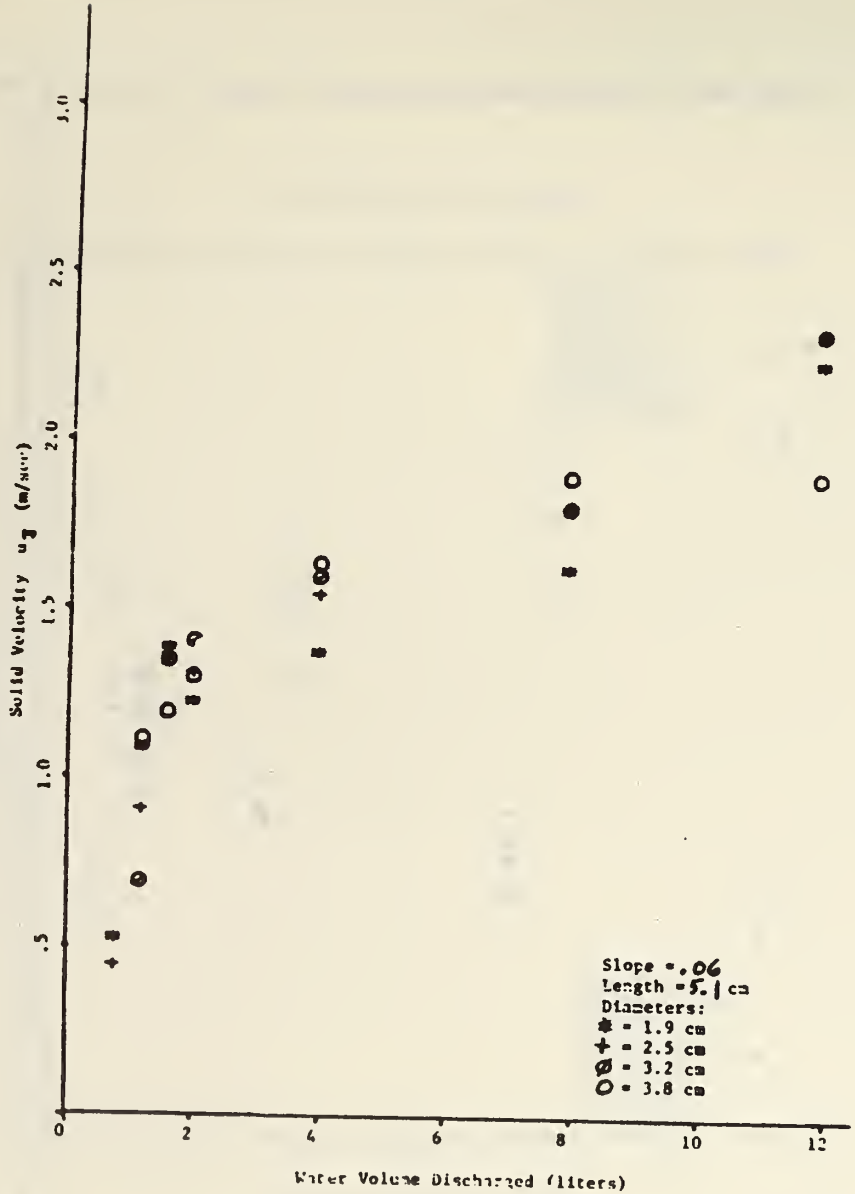

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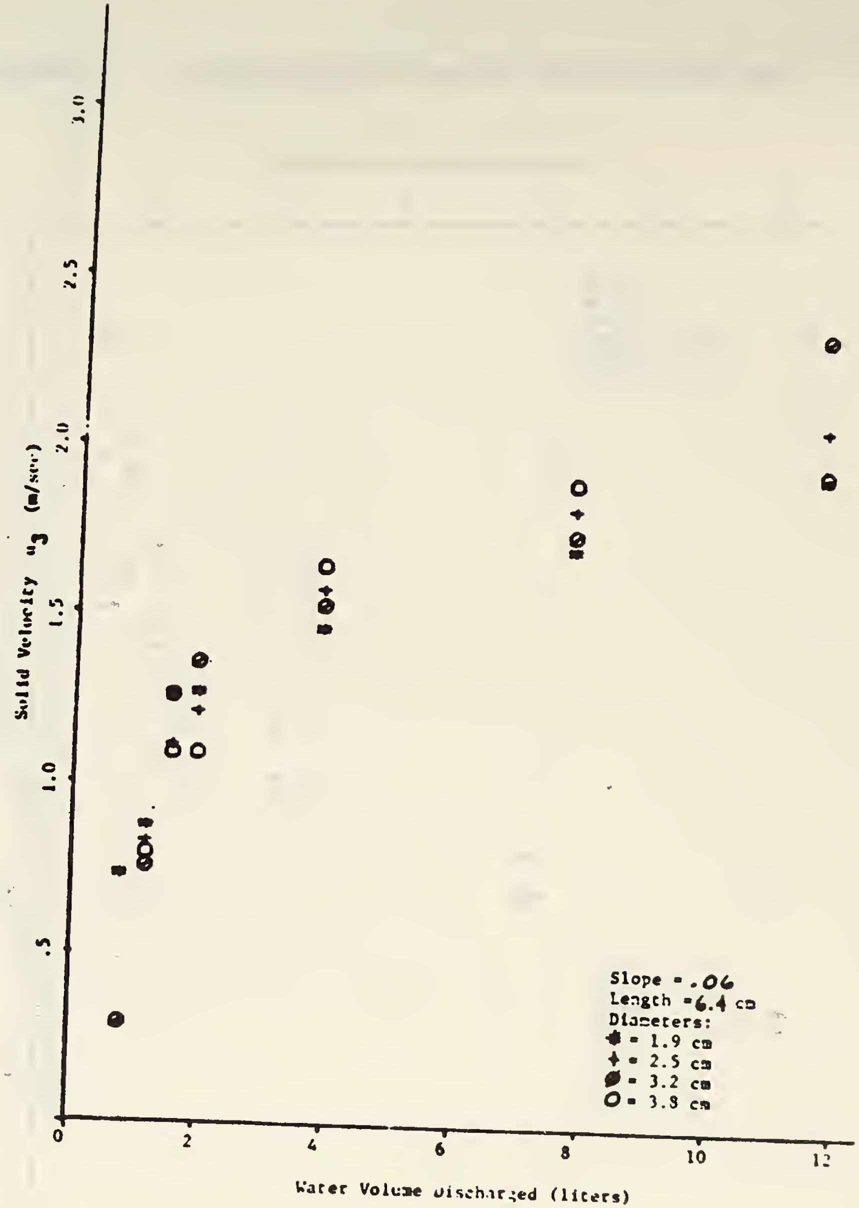

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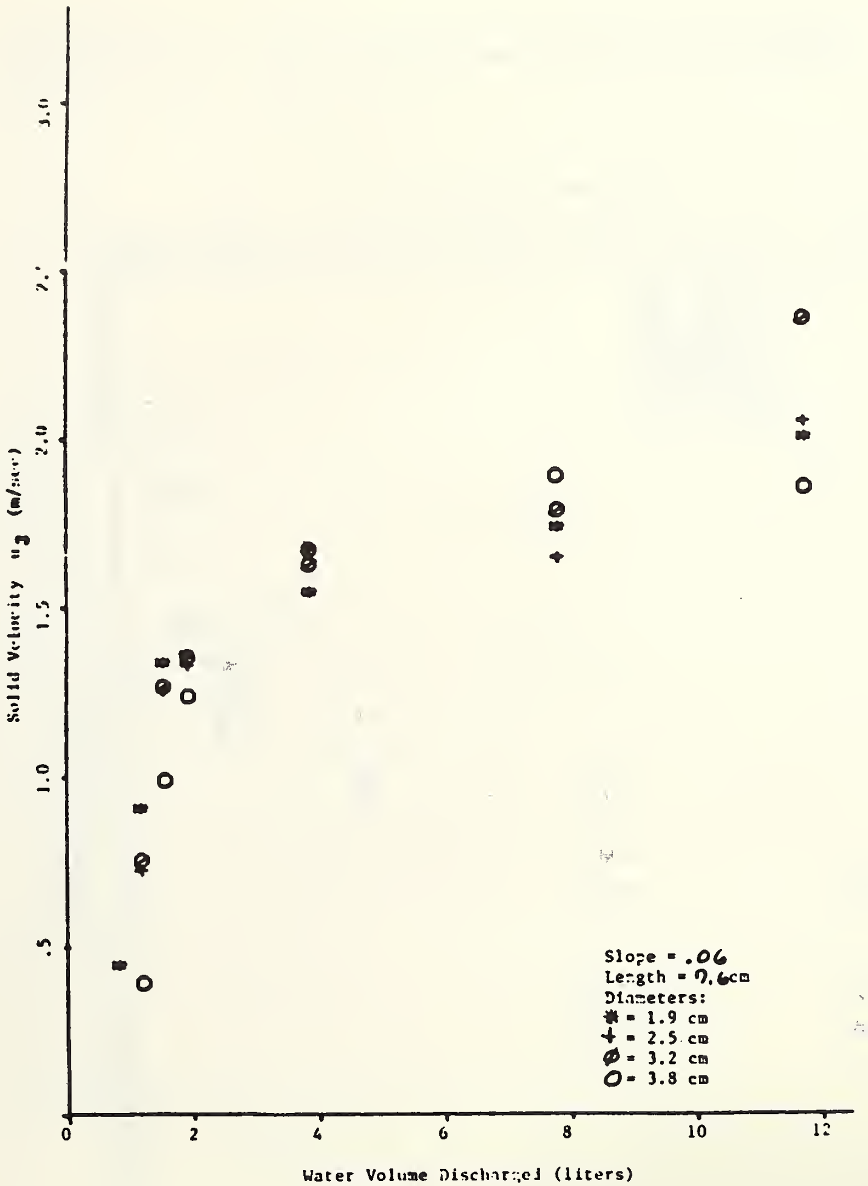

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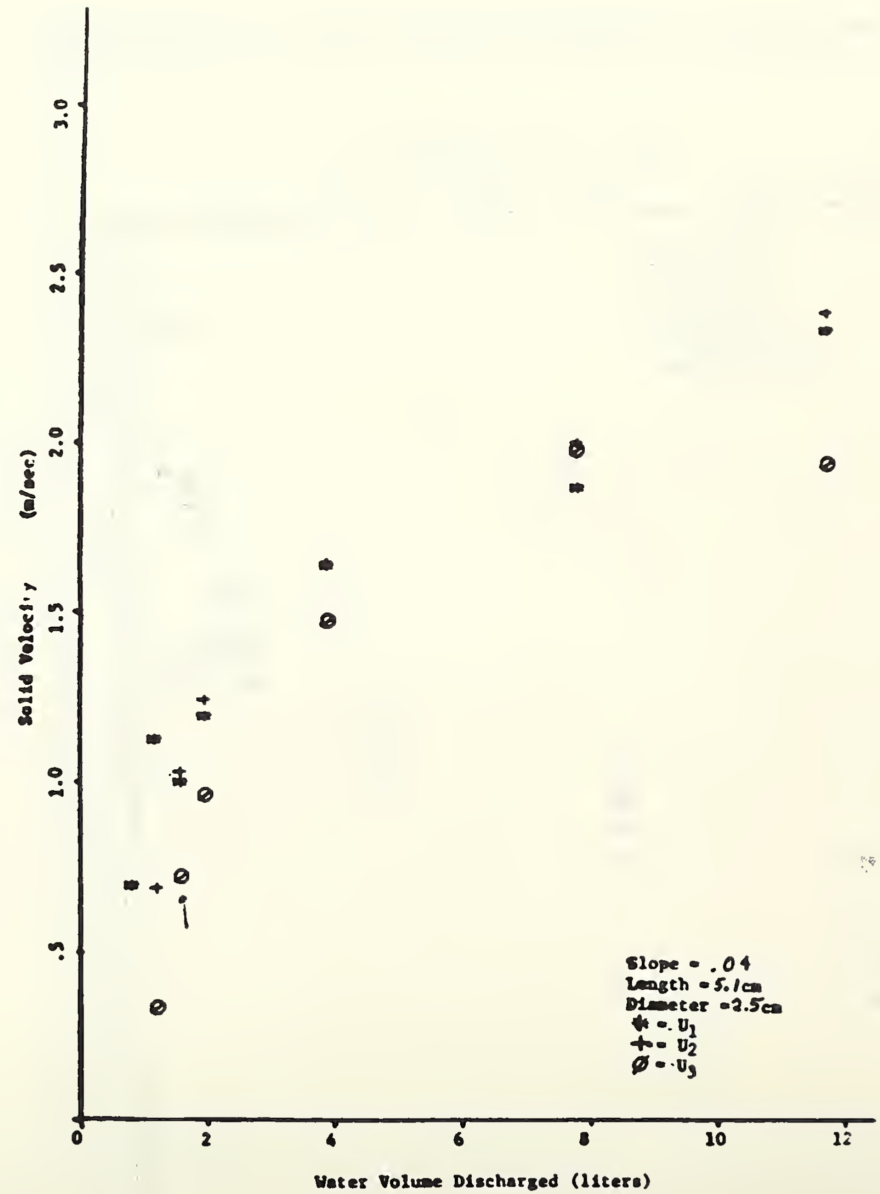

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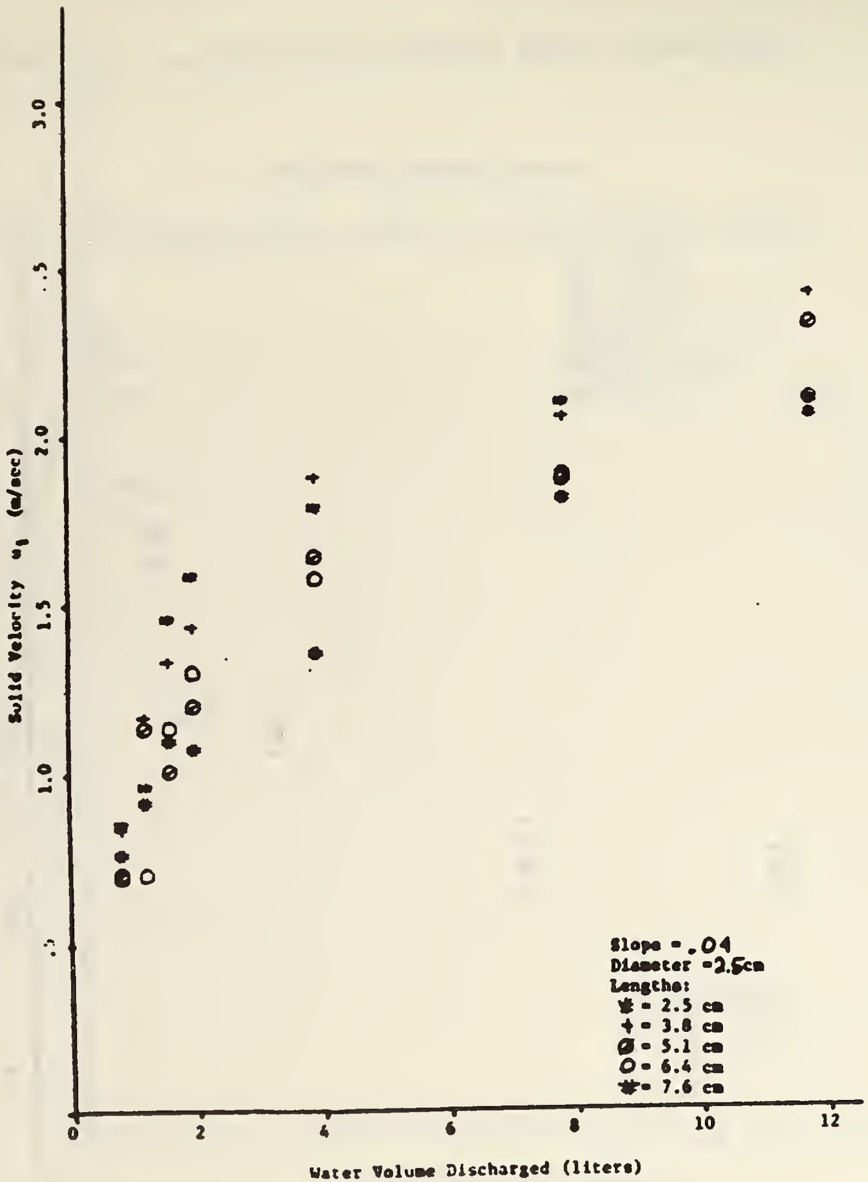
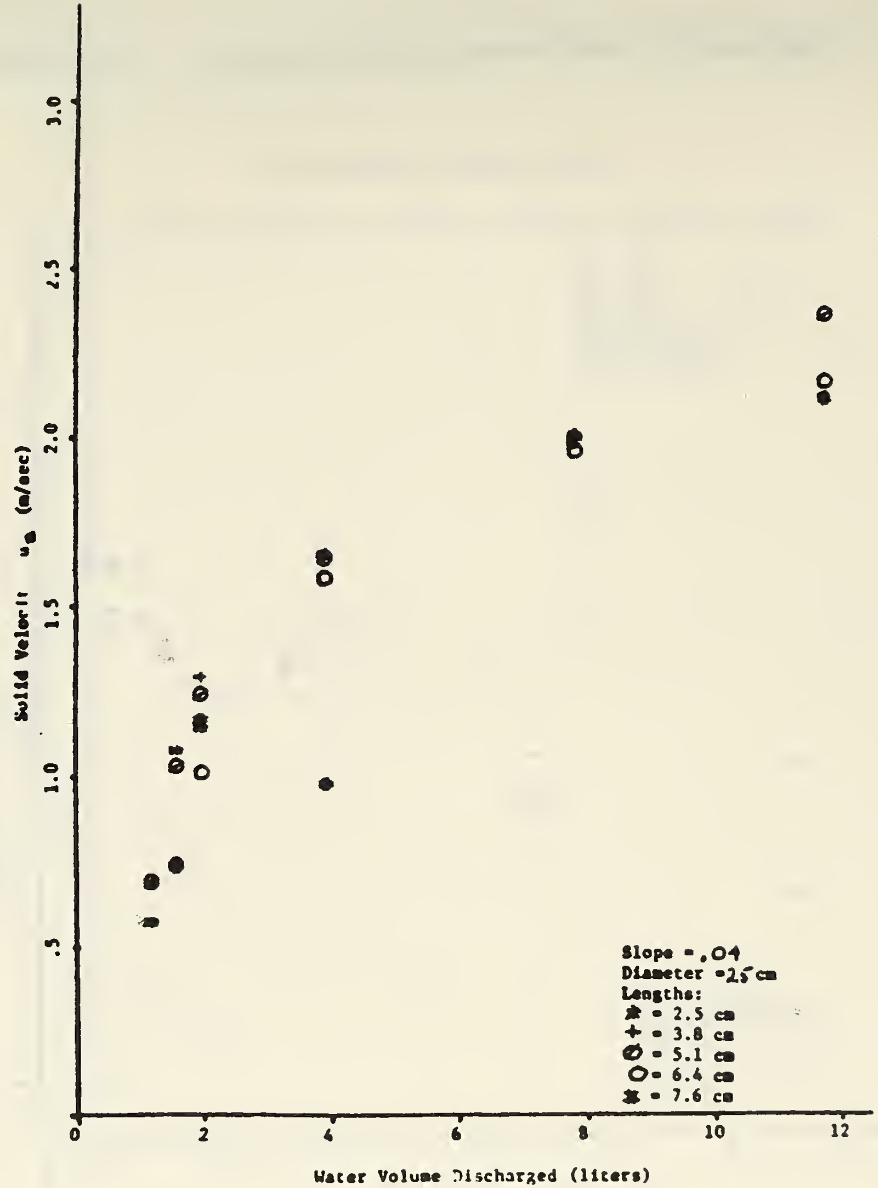


Figure 12-1. Solid velocity versus water volume used



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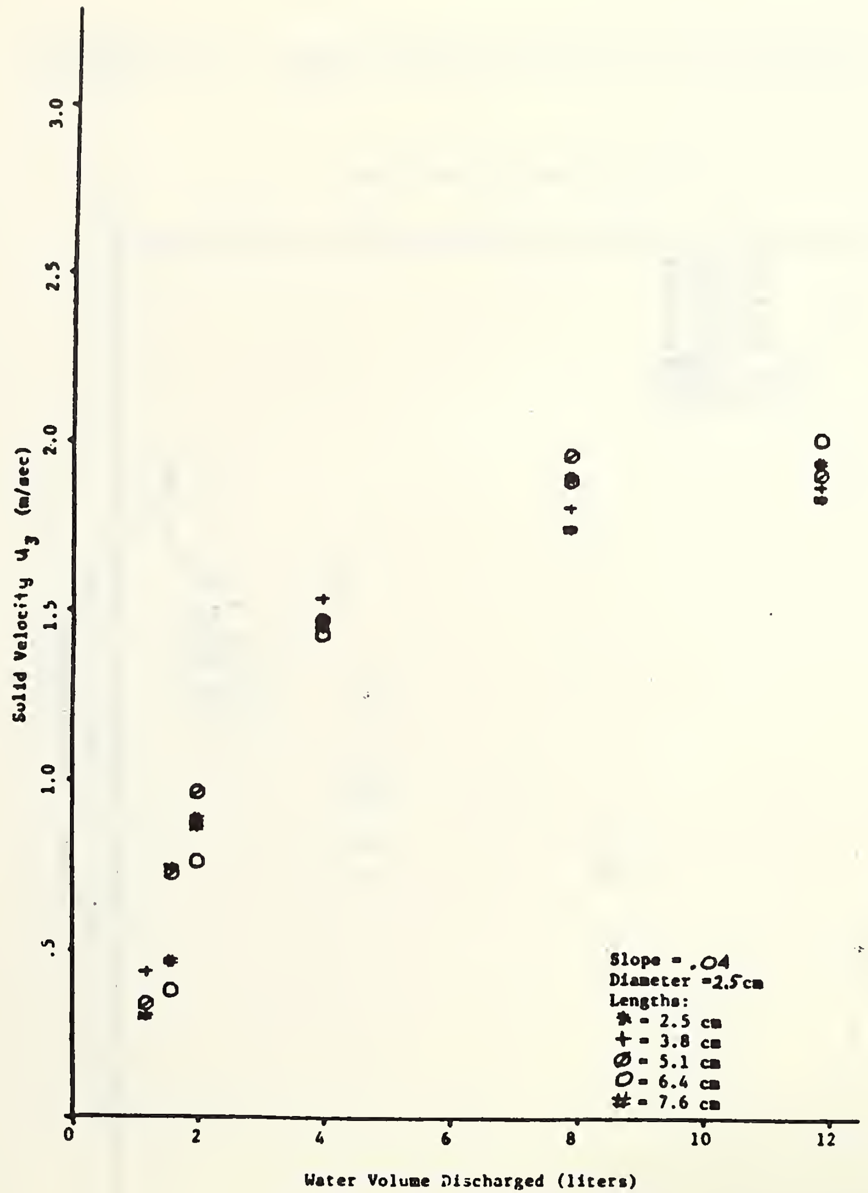

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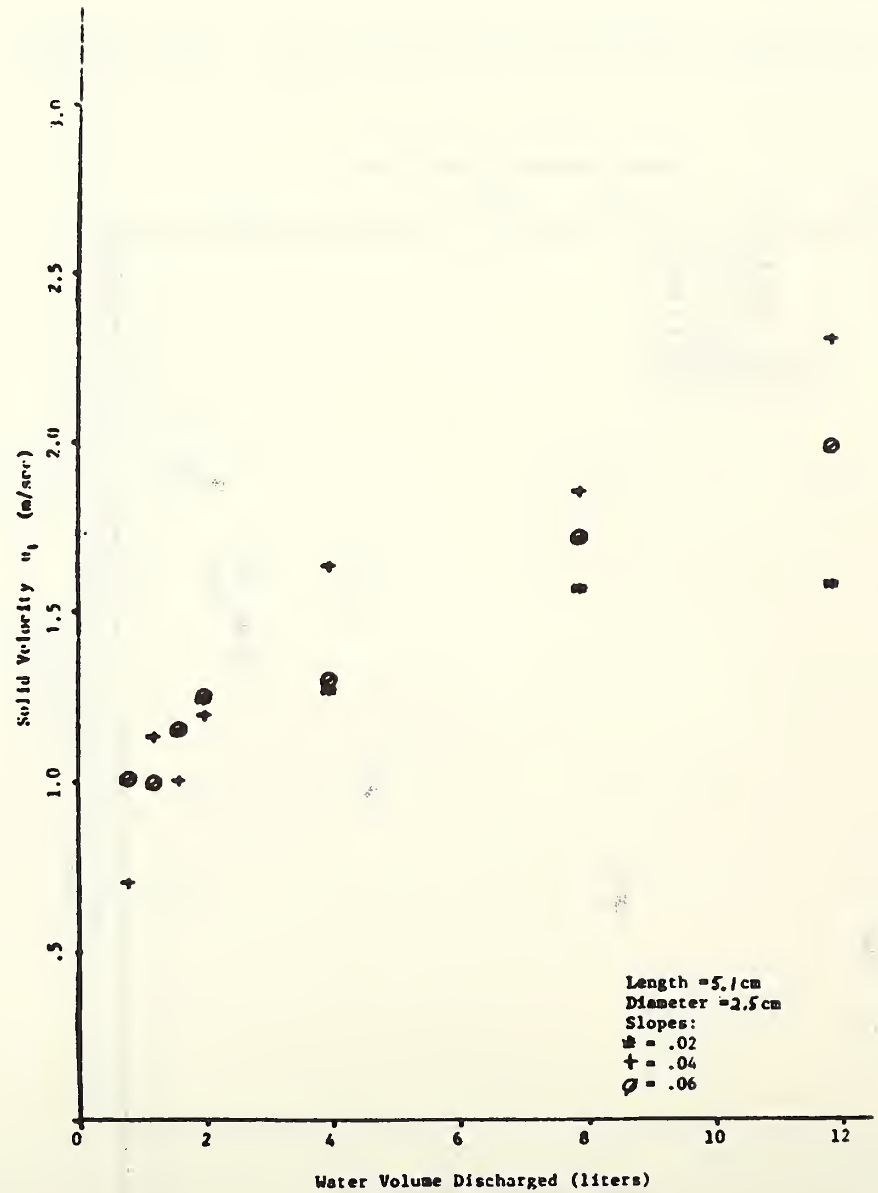

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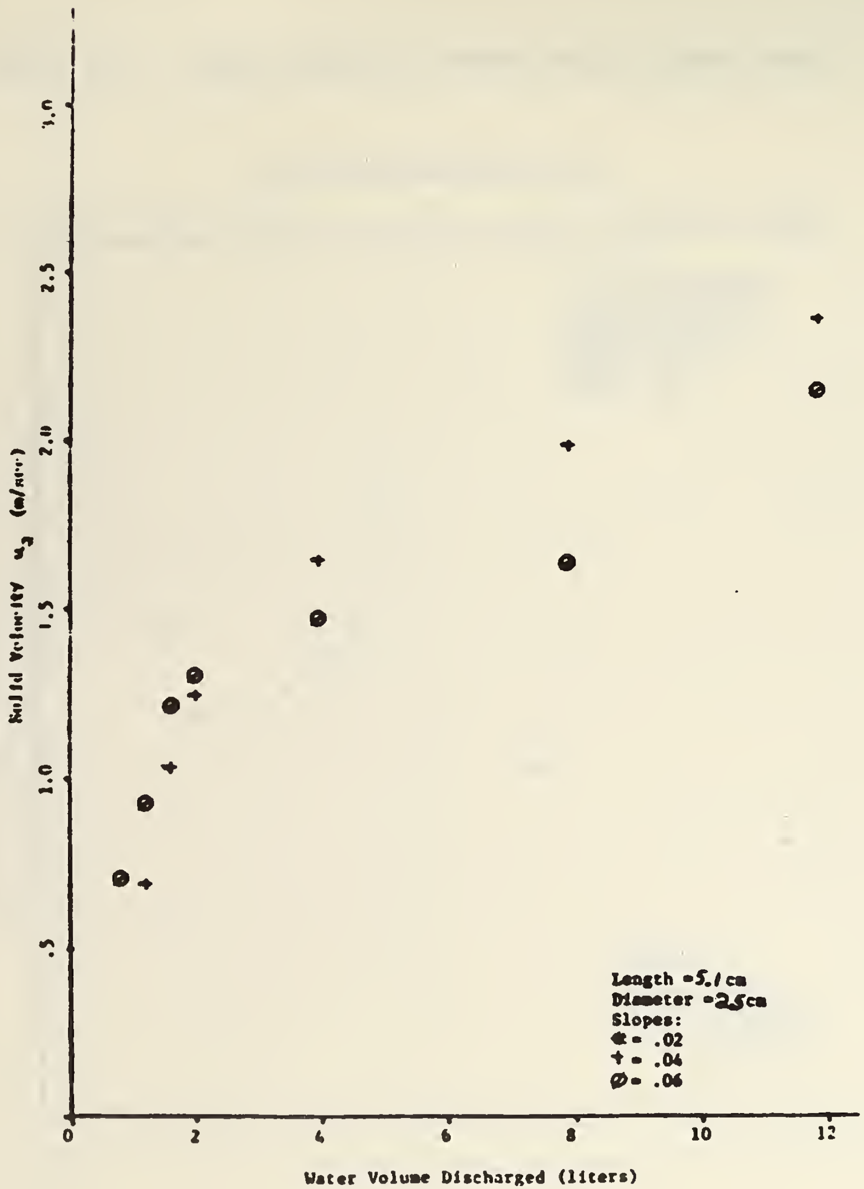

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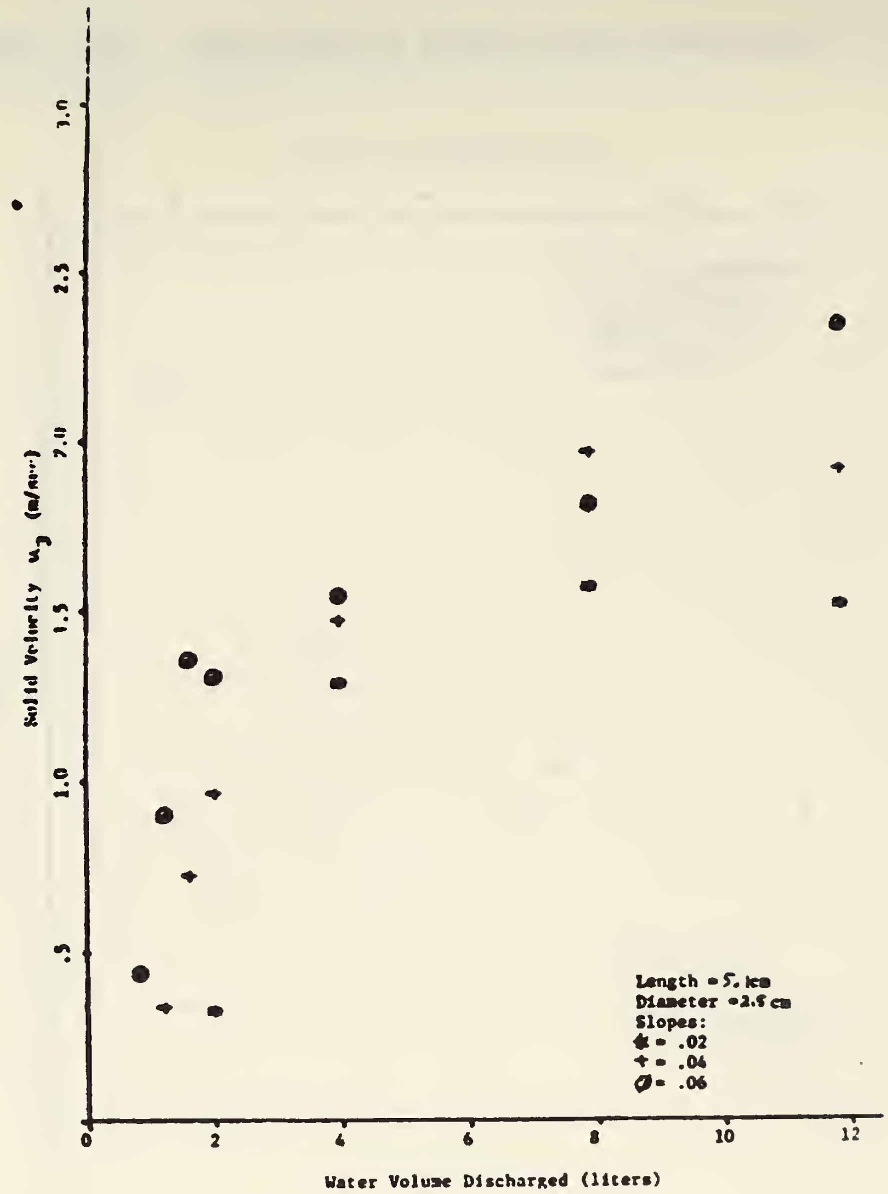

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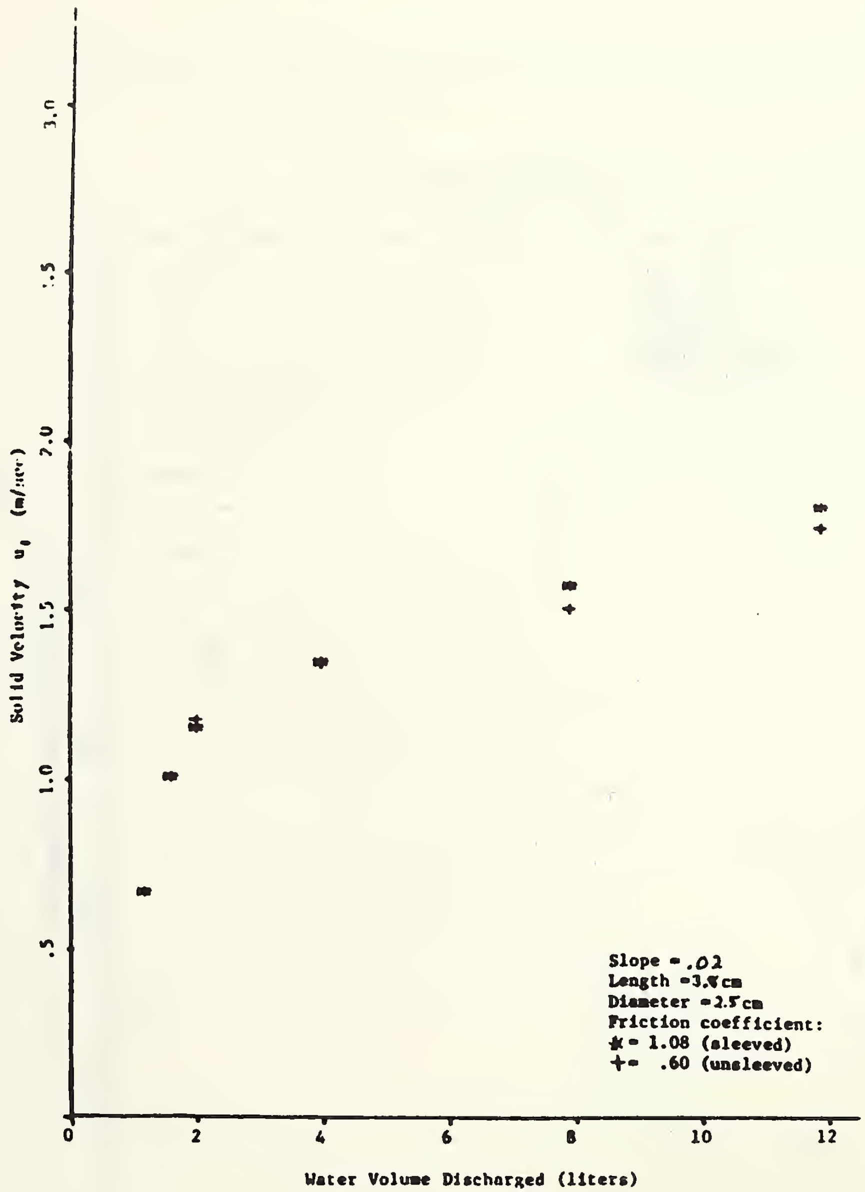

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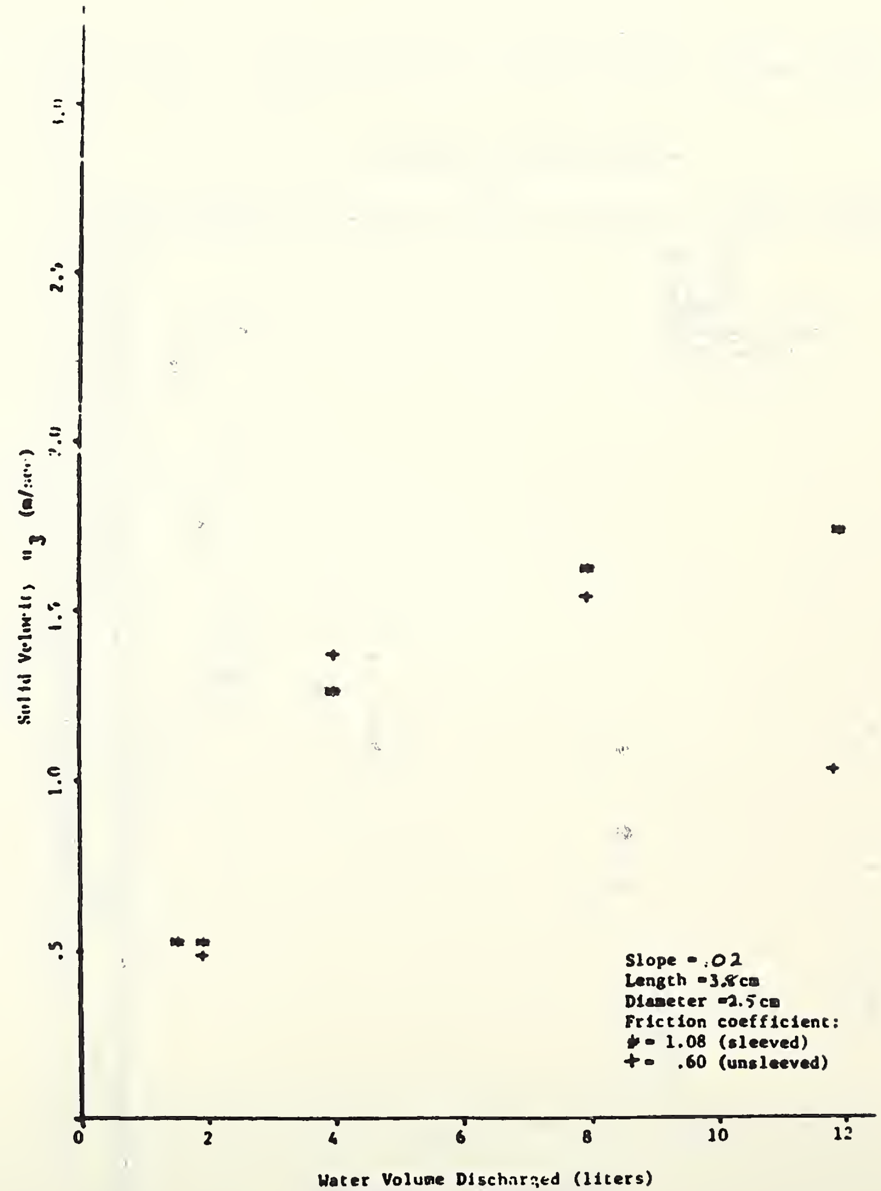

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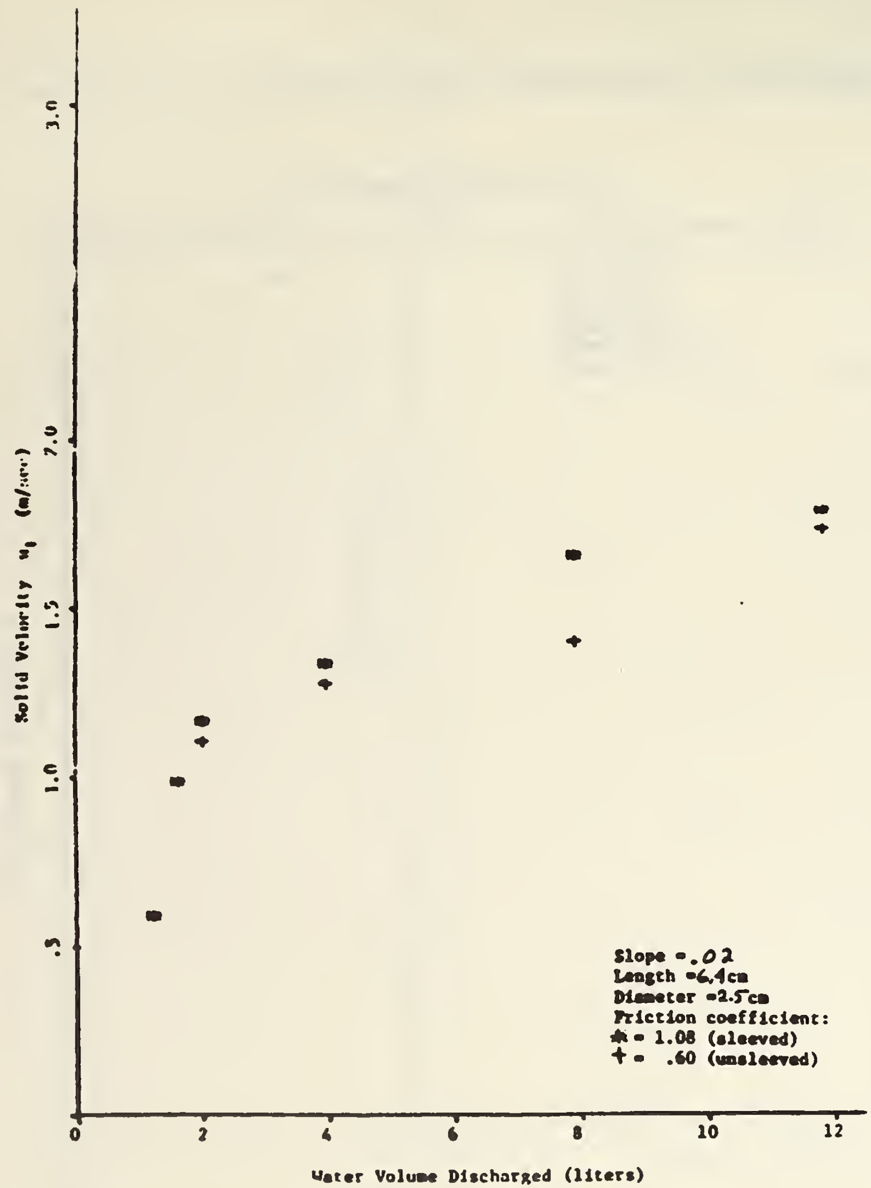


Figure 14-3. Solid velocity versus water volume used

Figure 14-4. Solid velocity versus water volume used

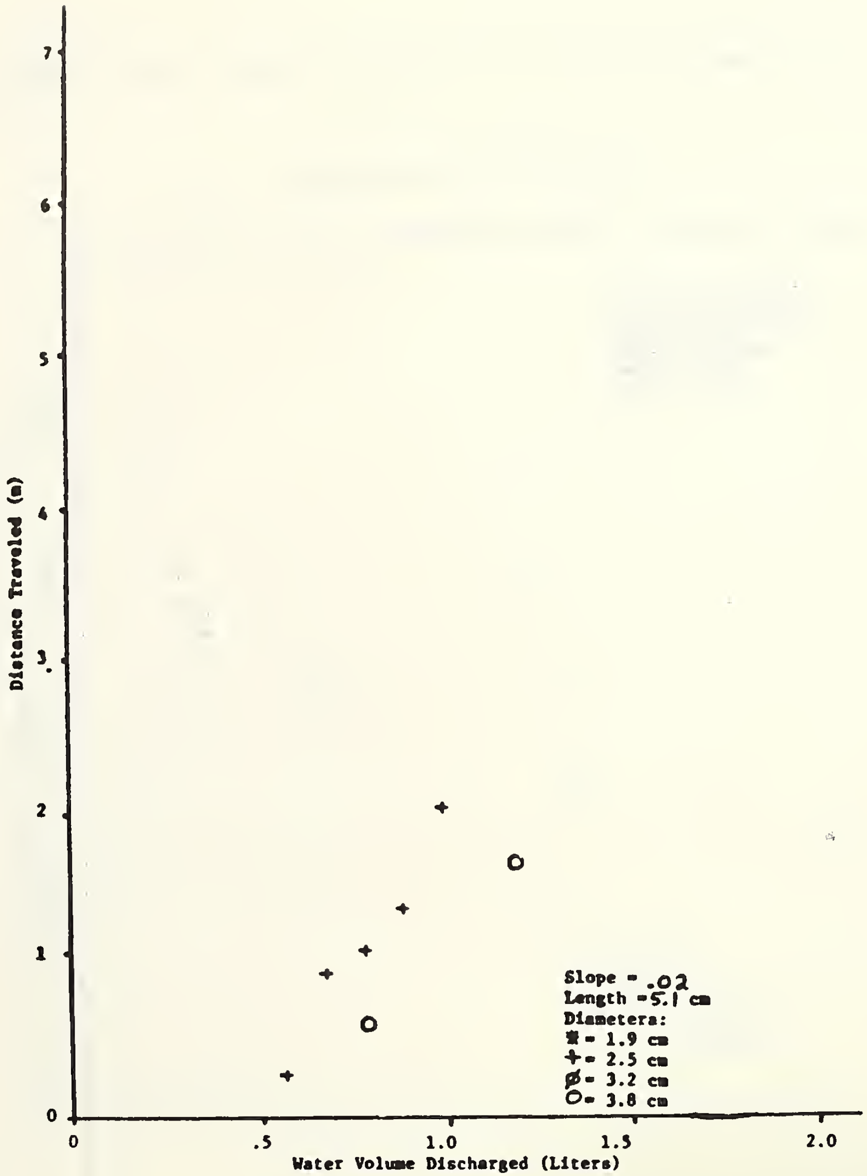
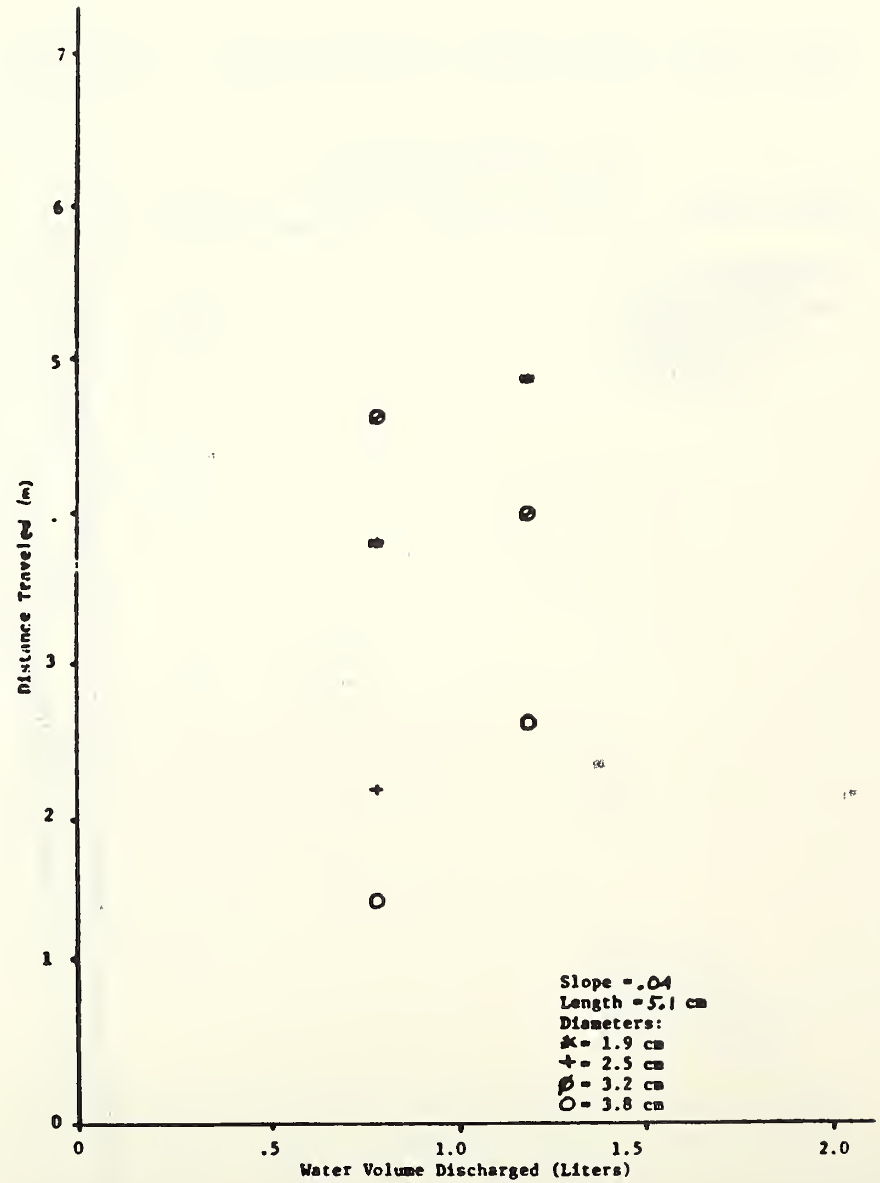


Figure 15-1. Distance traveled versus water volume used



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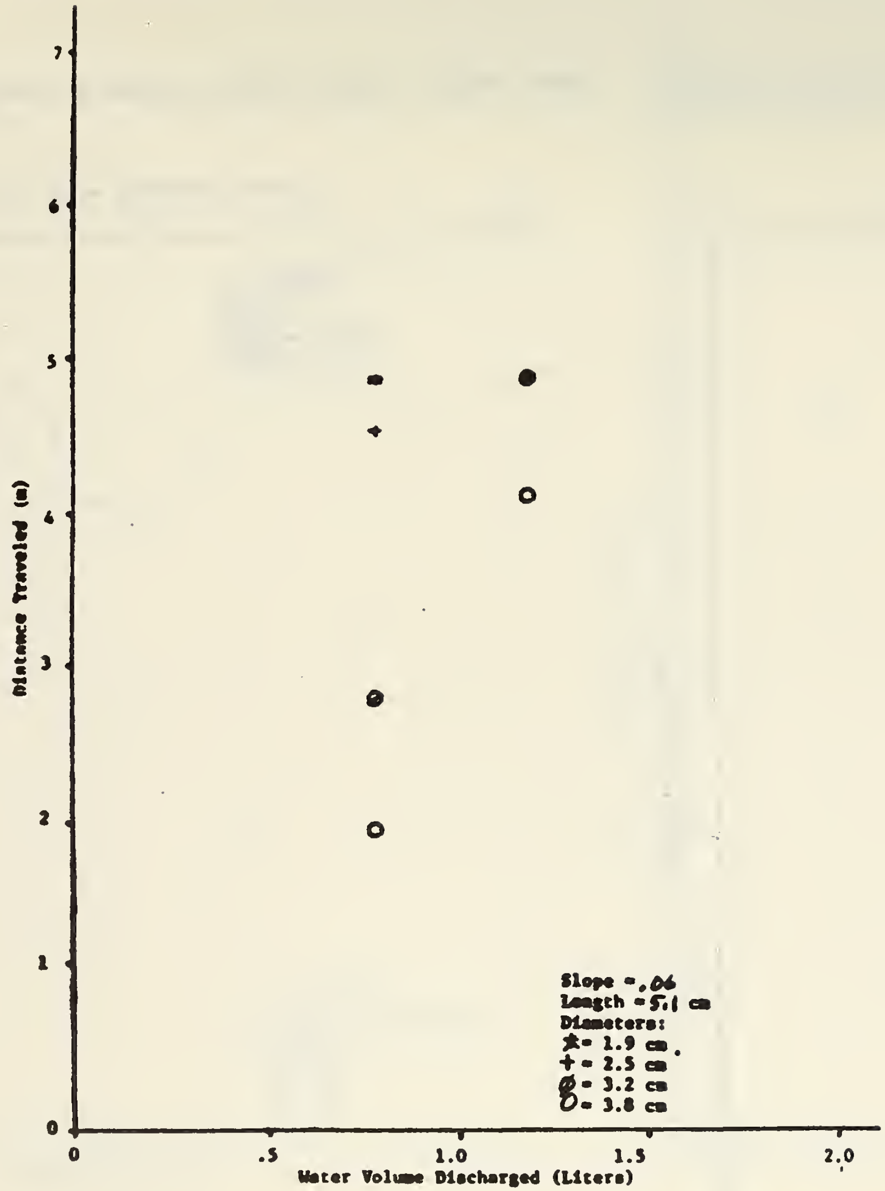


Figure 15-3. Distance traveled versus water volume used

Figure 16-1. Distance traveled versus water volume used

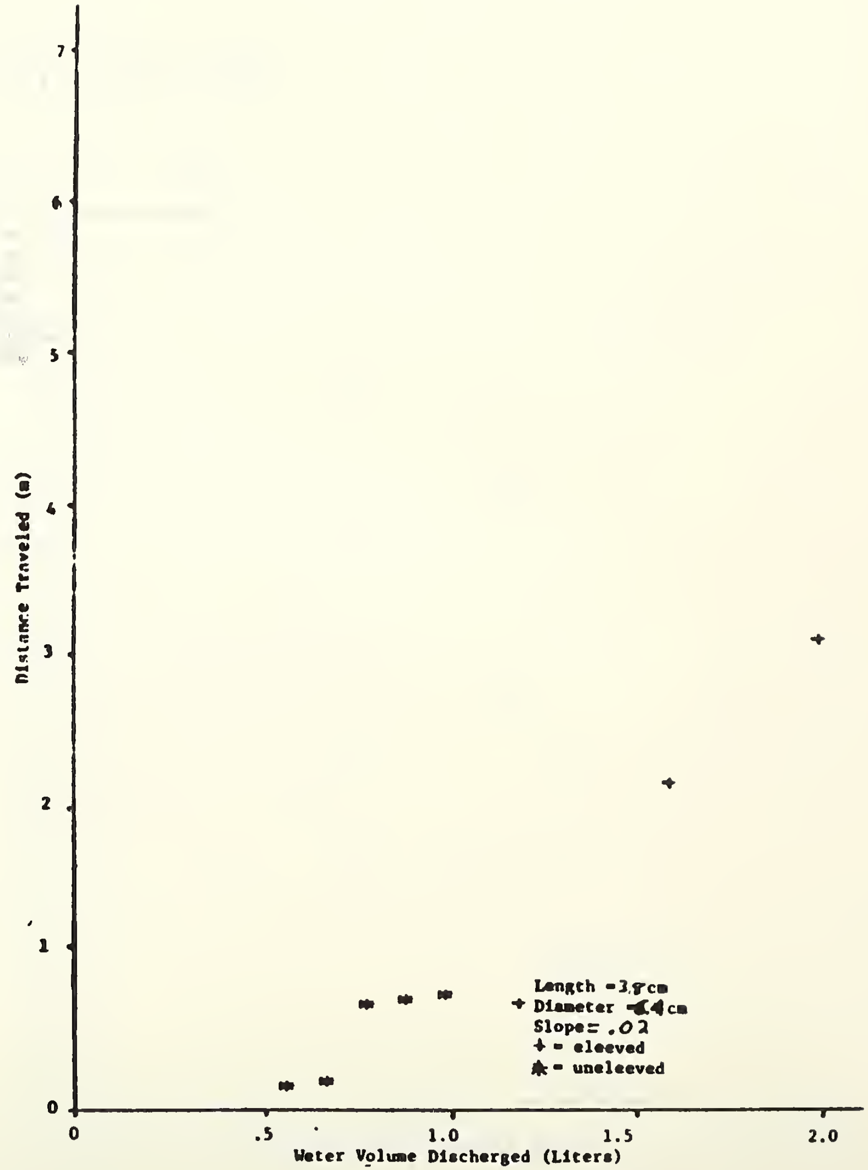
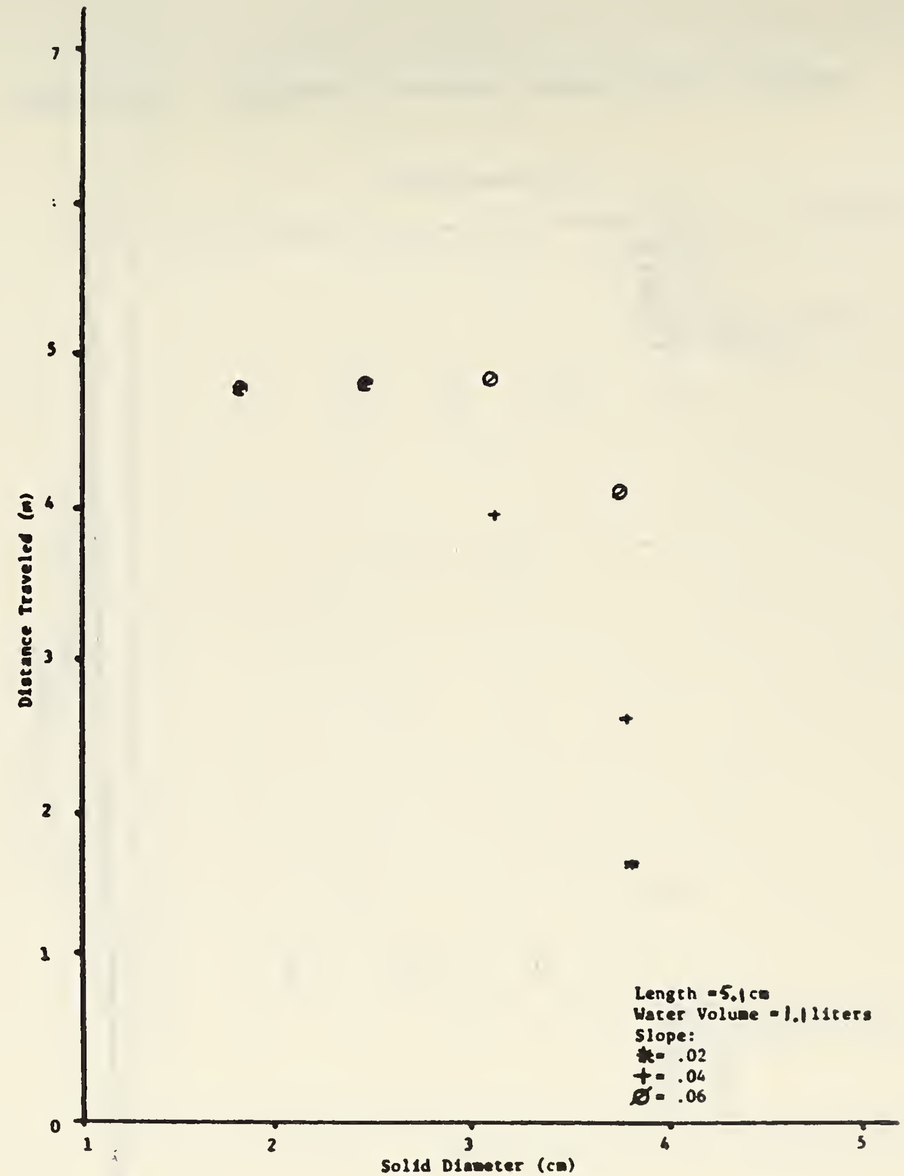


Figure 16-2. Distance traveled versus water volume used

Figure 17-1. Distance traveled versus solid diameter



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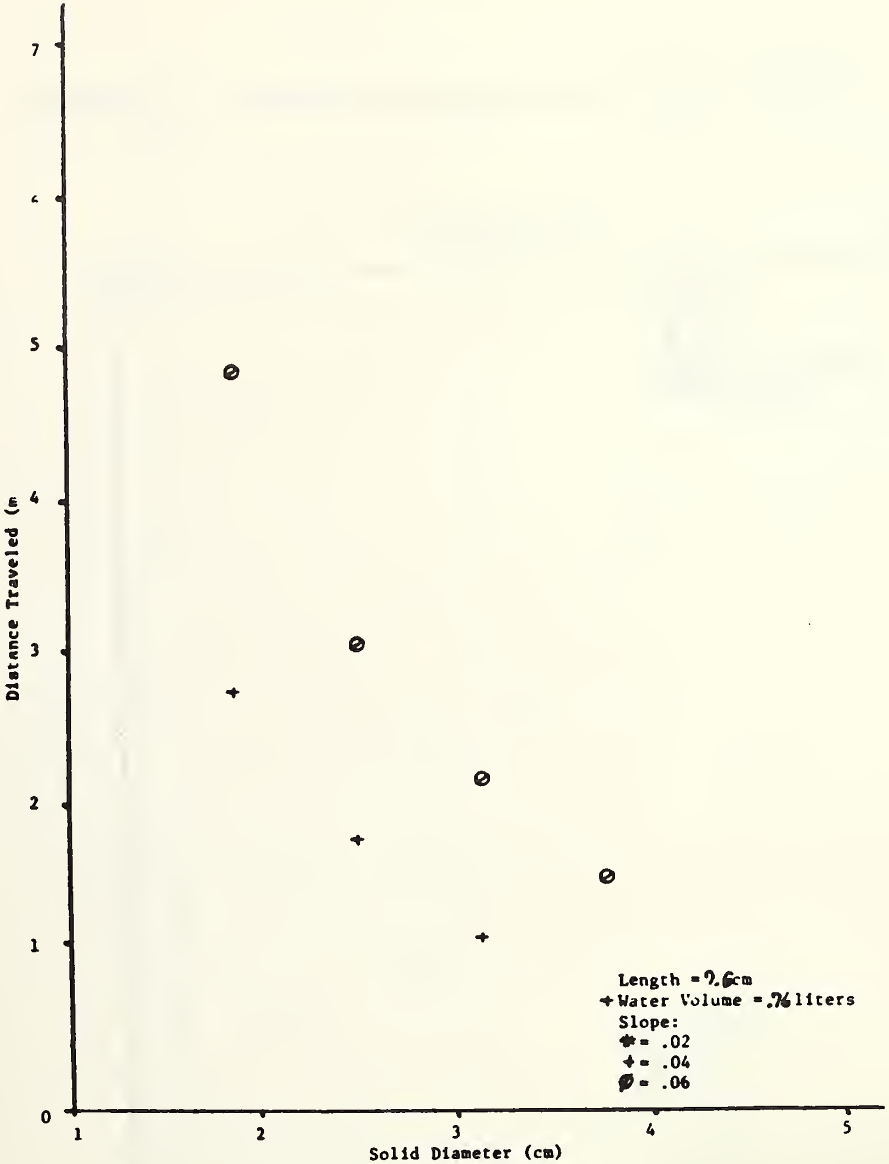

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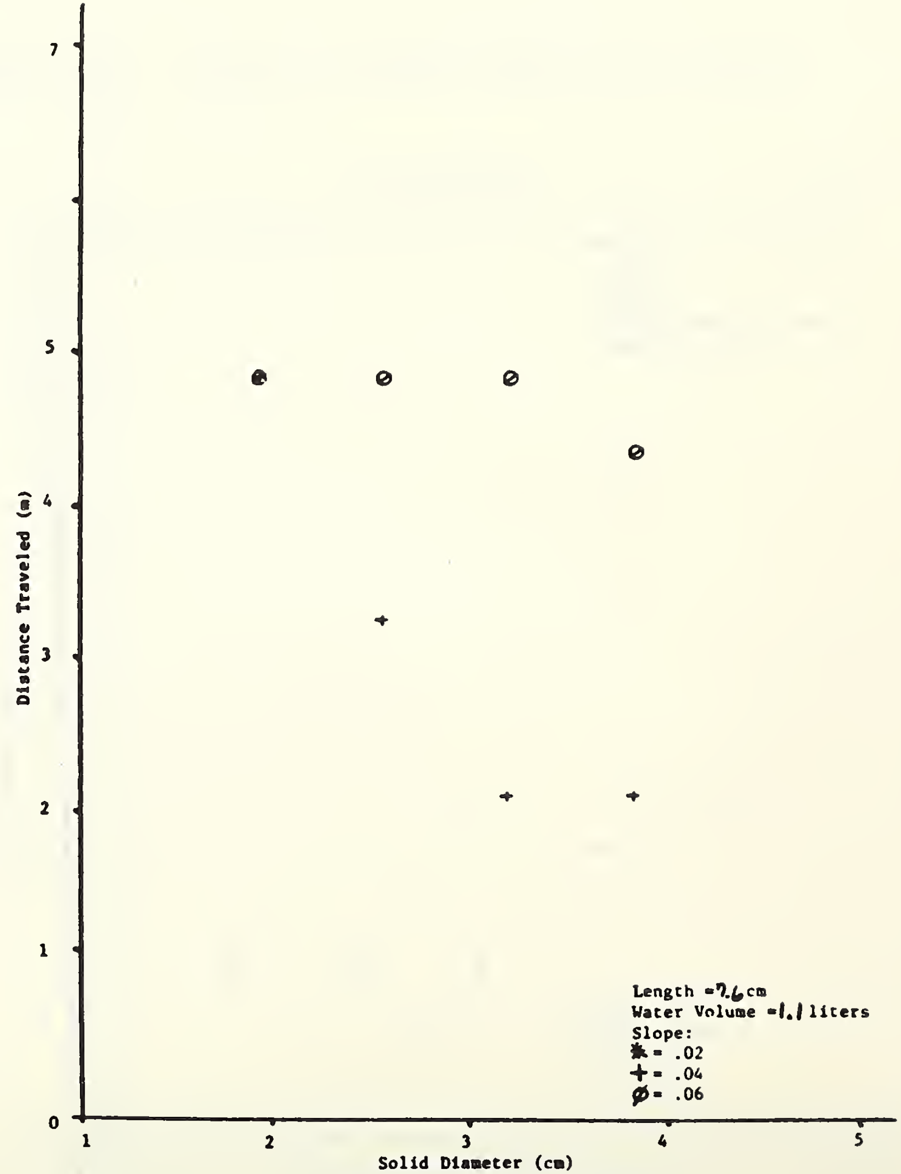

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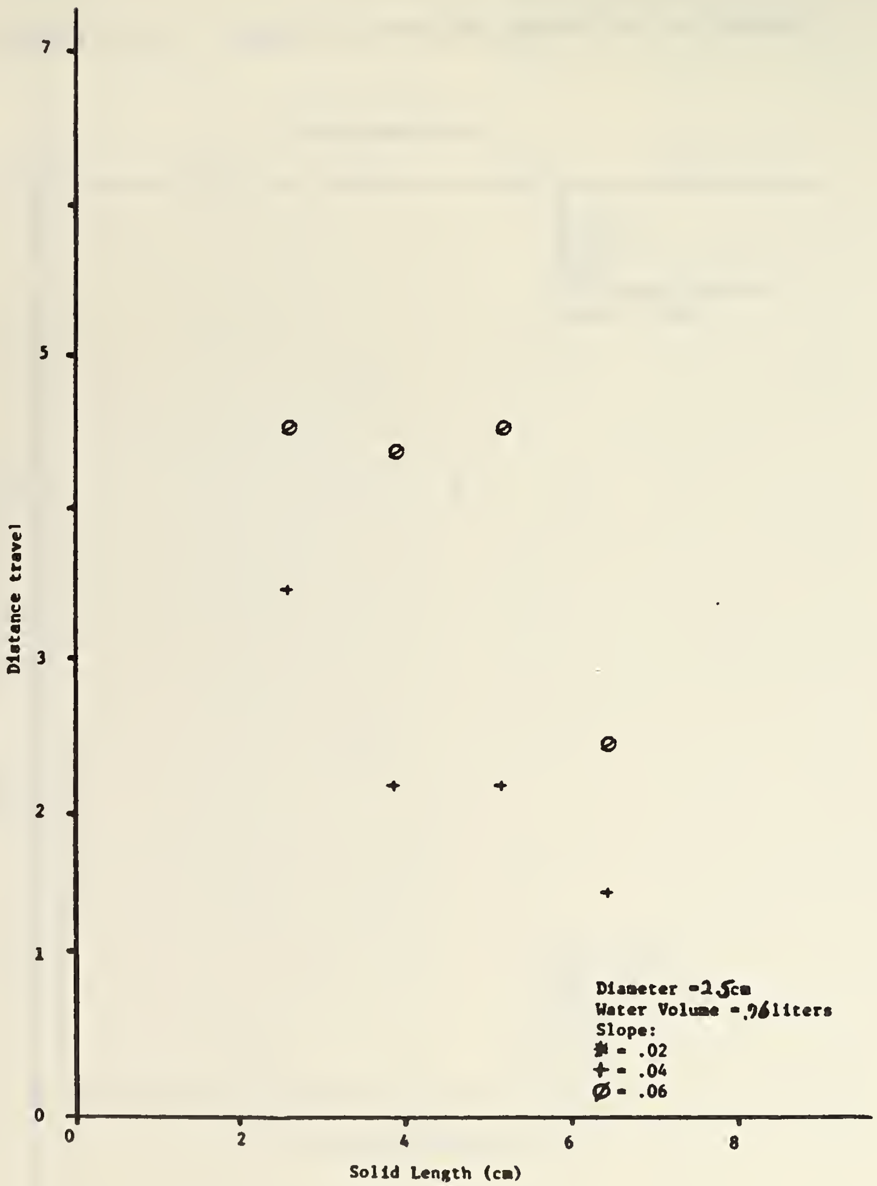
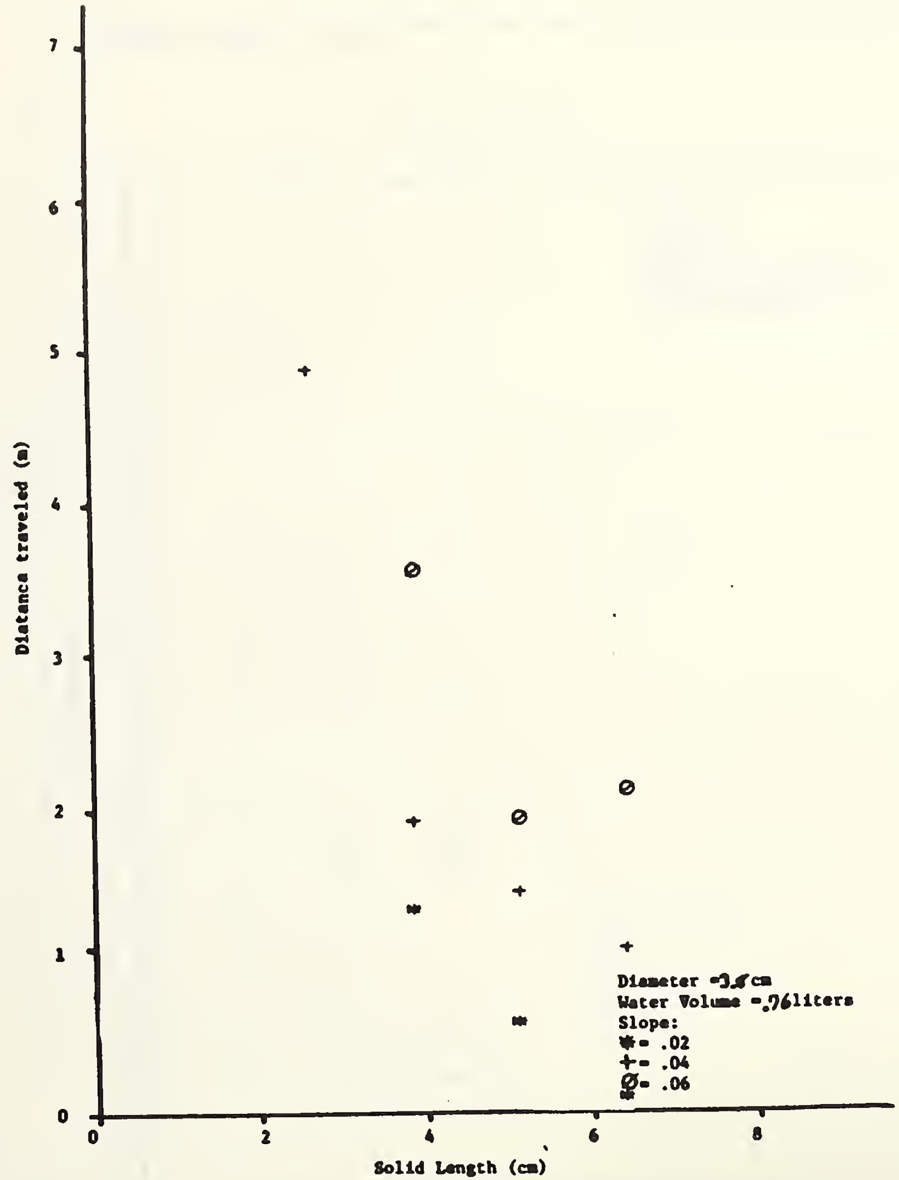


Figure 18-1. Distance traveled versus solid length

Figure 18-2. Distance traveled versus solid length



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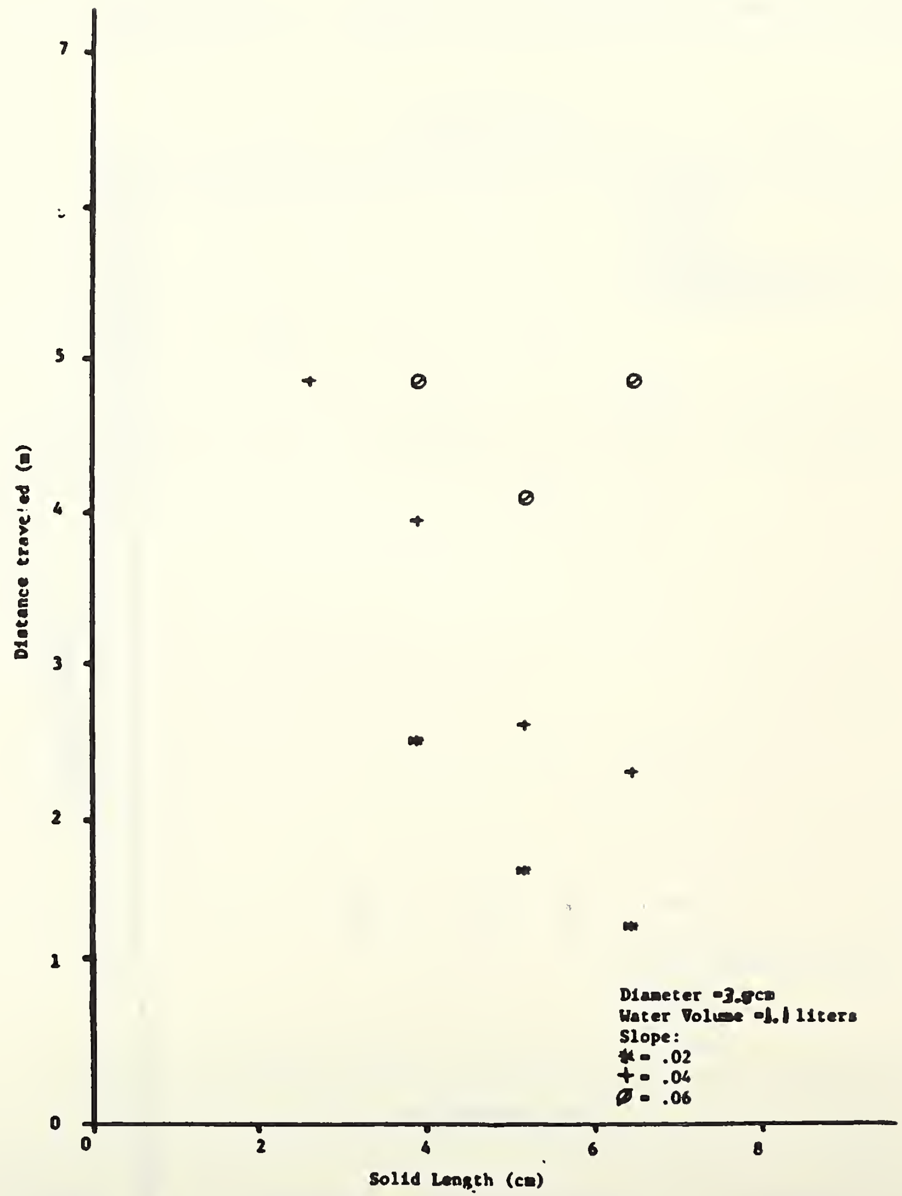

Figure 18-4. Distance traveled versus solid length

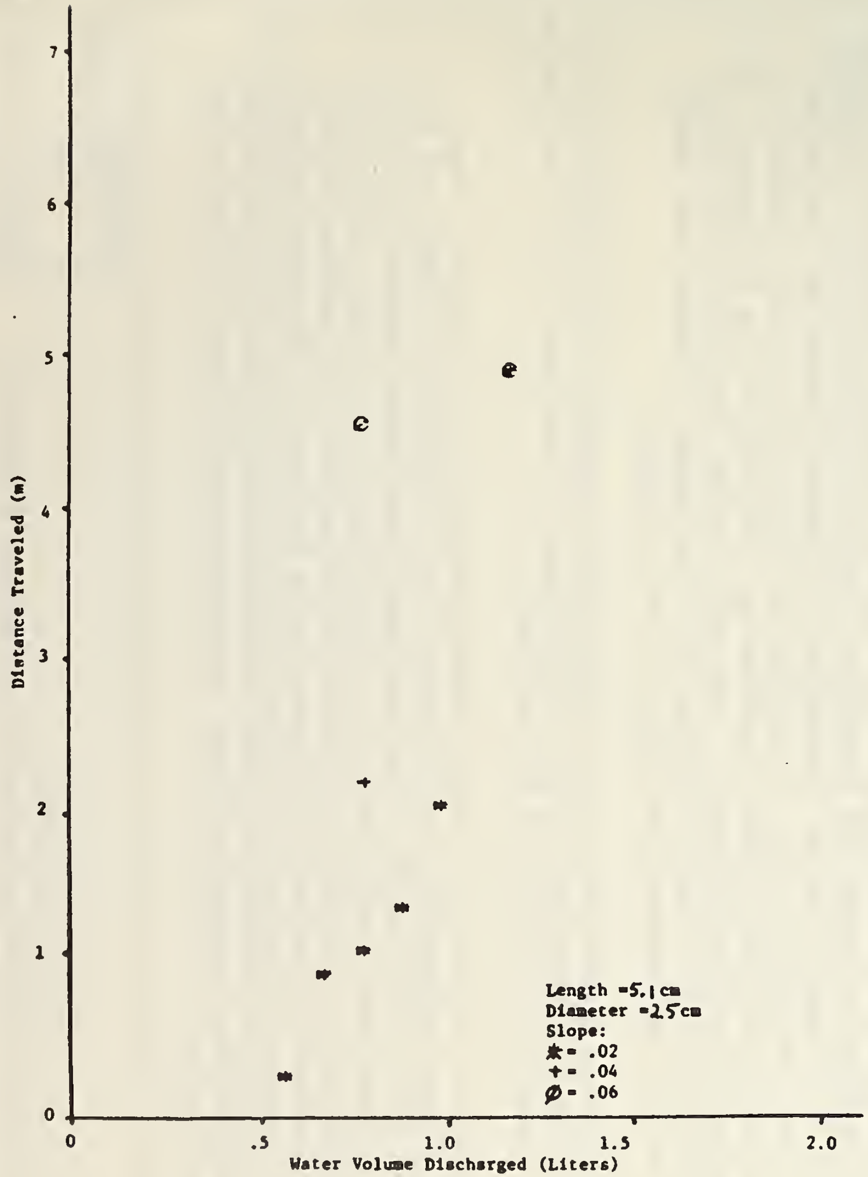

Figure 19-1. Distance traveled versus water volume used

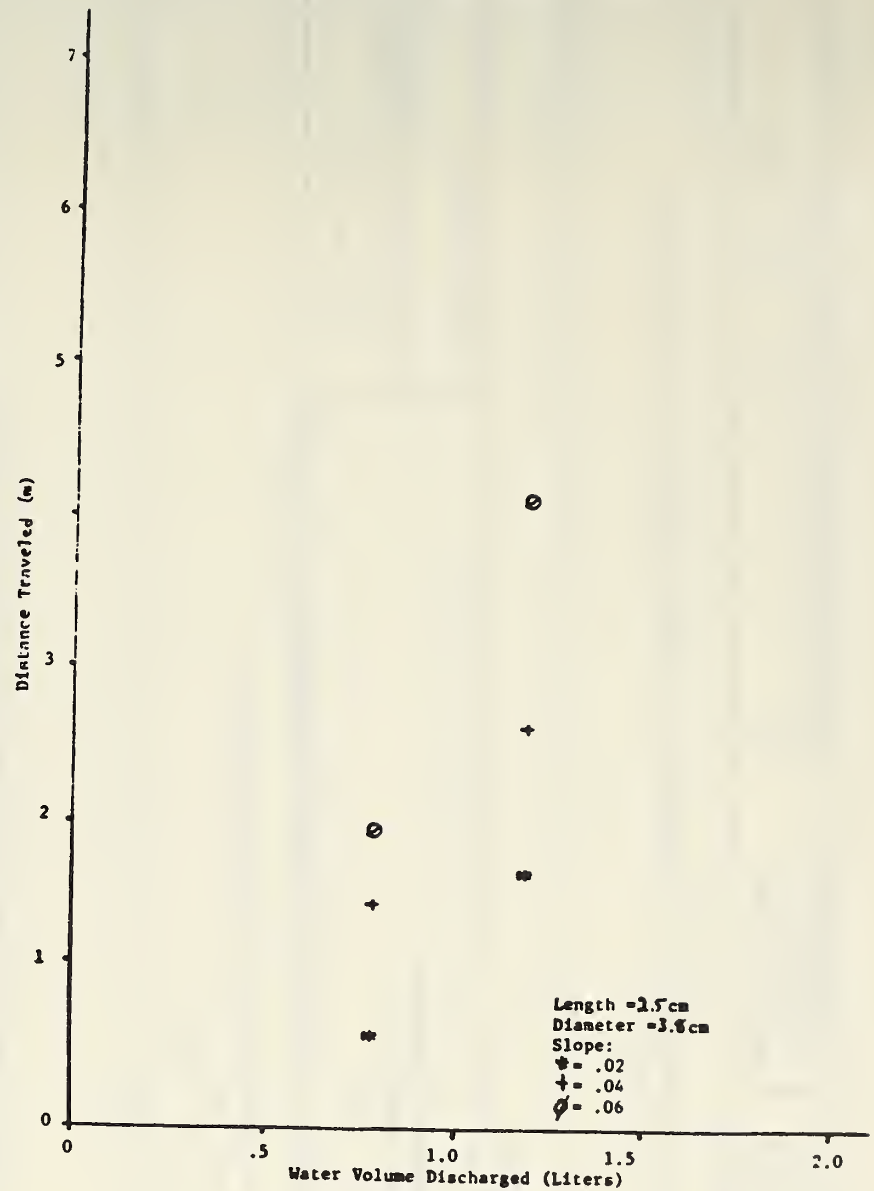

Figure 19-2. Distance traveled versus water volume used

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Bal M. Mahajan

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10. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)*

An exploratory experimental investigation of the hydro-transport mechanisms of finite solids with non-uniform, unsteady and transient water flow introduced into a pitched-horizontal drain (p-h drain) pipe by discharging a plumbing fixture was carried out. The purpose of the investigation was to examine the effects of relevant variables on the velocity attained and the distance traversed by the solid in the p-h drain. The variables selected for the study include: the water volume used (i.e., the volume of water discharged from the plumbing fixture into the drain), diameter and length of cylindrical solid, and diameter and slope of the p-h drain.

This report contains a description of the experimental equipment and procedures, and a summary of the data acquired during the solid transport experiment in 7.6 cm diameter drain pipe at a pipe slope of 0.02, 0.04, and 0.06.

The solid dragged on a thin film of water between the solid and drain wall when relatively small water volumes ($V_w \leq 1.9$ liters or 0.5 gallons) were used, and the solid moved like a waterborne object when relatively large water volumes ($V_w \geq 3.8$ liters or 1.0 gallons) were used. The solid velocity and the distance traversed by the solid increased with an increase in the water volume used, an increase in the drain slope, a decrease in the solid diameter, and a decrease in the solid length.

12. KEY WORDS *(Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)*

cylindrical; non-uniform; partially-filled; pitched-horizontal drain; slope; solid; velocity; volume; water.

13. AVAILABILITY

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