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LABORATORY INVESTIGATIONS OF A SLURRY PIPELINE FOR THE YUMA DESALTING PLANT

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16. ABSTRACT

Laboratory tests were conducted to evaluate pumping a slurry of precipitated calcium carbonate sludge and sedimentation basin grit to a disposal site. The sludge will be a waste product of a partial lime-softening pretreatment process proposed for the Yuma Desalting Plant.

Hydraulic tests were conducted using a nominal 6-in i.d. pipeline loop. The general operation of this pipeline was observed. Total solids concentration, $Mg(OH)_2$ (magnesium hydroxide) concentration, and pH level were varied in the tests. Friction losses, deposition velocities, rheological properties, and settling rates were measured.

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PURPOSE

This study was conducted to aid in the design of a slurry disposal pipeline for the Yuma Desalting Plant. Current plans propose mixing waste calcium carbonate sludge and sedimentation basin grit with water and pumping it through a pipeline to a disposal site.

Changes in plant operation and uncertainty of the length of pipeline needed prompted this study. Previous tests performed at the CSMRI (Colorado School of Mines Research Institute) [1]* and the YDTF (Yuma Desalting Test Facility) [2] were reported in March and May 1978, respectively. These studies used 2- and 2½-in-diameter pipes in their test loops. No rheological data were collected in the CSMRI study and the YDTF rheology was incomplete; therefore, scaling these test results to include different pipe diameters was impossible.

INTRODUCTION

A 90-Mgal/d desalting plant is currently under construction near Yuma, Arizona. This plant will use reverse osmosis membrane reactors to treat Colorado River water before it enters Mexico. A partial lime-softening pretreatment system will be used to treat the feedwater to the desalting plant. Up to 300 tons of calcium carbonate sludge and 30 tons of sedimentation basin grit, which can accumulate in the pretreatment system each day, will have to be transported to a disposal site. A slurry pipeline is being considered as a means to transport this waste.
Because this slurry, even in small solids concentrations, behaves as a non-Newtonian fluid, the traditional equations used to design water-conveyance systems are not applicable. The nonlinearities of the fluid must be defined before a confident design can be attempted.

A laboratory pumping test is the best method for defining critical flow parameters. However, because of the difficulty in collecting accurate and complete rheological data, scaling pumping test results to include other pipe diameters can be precluded. Without good rheological data, pipeline loop data can be expanded to include only pipe diameters 1 inch larger or smaller than the pipe diameter tested.

SUMMARY AND CONCLUSIONS

Laboratory data were collected to evaluate pumping waste sludge and grit as a slurry to a disposal site. The pipeline loop tests used a nominal 6-in i.d. pipe with sludge from the YDTF. Test runs

* Numbers in brackets refer to entries in the bibliography.

were made varying the total solids concentration, pH, sedimentation-basin grit content, and $Mg(OH)_2$ content.

1. All slurries tested in the pipeline loop behaved as non-Newtonian fluids in laminar flow for solids concentrations from 17 to 39 percent by weight.

2. Friction losses increased with increasing solids concentration.

3. Friction losses increased with increasing $Mg(OH)_2$ concentration, particularly when the slurry pH was 11 and above.

4. The addition of sedimentation-basin grit compounded the problem of heterogeneity because the larger (heavier) particles settled at higher pipeline velocities than the fine calcium carbonate sludge particles.

5. Deposition velocities increased slightly with an increase in solids concentration. However, increases in deposition velocities were even more evident with an increase in $Mg(OH)_2$ concentration.

6. The pipeline operating velocity should be at least 1 ft/s in excess of the deposition velocity of the first settled particles.

7. Rheological investigations showed that viscosity increased with increasing shear rate (dilatent behavior).

8. Viscosity tended to increase quite dramatically with solids concentration. The pH level, in conjunction with the $Mg(OH)_2$ concentration, was an important variable. The pH level indicated that the more basic the slurry, the higher the viscosity.

9. Comparison of quiescent settling rates showed important general trends that can be related to the flow properties of the slurry.

10. The 6-in pipeline loop showed significantly less friction loss than the previously tested 2- and 2½-in pipeline loops. Typical Newtonian scaling laws cannot be used to predict the actual friction-loss values.

HYDRAULIC TESTS

The Model

The pipeline loop facility used for the hydraulic tests is shown on figure 1. The loop consisted of a 6 x 6 Denver SRL centrifugal slurry pump and approximately 200 ft of pipe. Friction head loss was measured with differential manometers in two horizontal test sections. The first test section was a 60-ft length of epoxy-lined asbestos-cement pipe; the second section was a 40-ft length of heavy-walled unlined steel pipe. Prior to model construction, measurements showed a mean i.d. (inside diameter) of 0.48 ft for the asbestos-cement pipe and 0.532 ft for the steel pipe. A 6-ft length of clear plastic pipe was used to observe flow conditions and settling characteristics.

The sludge used in the laboratory tests was a product of the pilot plant at the YDTF. It had been dewatered to a solids concentration of about 65 percent by weight and shipped in 55-gal drums. A propeller mixer mixed the sludge, grit, and water into a slurry in the mixing tank. The pump circulated slurry from the mixing tank through the pipeline and back to the tank. Flow rates in the pipeline were set by throttling a gate valve directly downstream from the pump. A Foxboro 6-in magnetic flowmeter was used to measure the flow rate of slurry through the pipeline. The flowmeter was calibrated with a volumetric tank. A high-speed digital voltmeter monitored the output of the flowmeter. A pitot-type sediment sampler was used to gather slurry samples at various levels in the pipe.

Model Calibration and Shakedown Run

Testing in the 6-in pipeline loop began with clear water in a calibration and equipment shakedown run. Water was pumped through the loop to ensure that all elements of the model were working properly. A range of flow rates was set and data points were gathered for the magnetic flowmeter calibration. Flow was diverted into the volumetric tank and timed for several flow rates. Some additional calibration points were taken at a solids concentration of 4 percent by weight. Using the respective cross-sectional areas of the two kinds of pipe, a curve was developed showing mean linear velocity versus voltmeter reading (fig. 2). This calibration assumed that the pipe was flowing full and that the pipe area was unrestricted by deposition of solids in the pipe bottom.

Pipeline Loop Test Procedure

For each test, the sludge, grit, and water quantities were adjusted to achieve a targeted slurry mix. The slurry was circulated through the pipeline at several different flow rates. At each flow rate, several tasks were completed:

1. The digital voltmeter reading was recorded.

2. The pressure differentials on the manometers were recorded.

3. The flow was observed in the clear plastic pipe, and comments were recorded.

4. A slurry sample was taken from the mixing tank to determine the specific gravity by hydrometer and the total solids concentration.

5. Slurry samples were taken at two levels in the pipe with a pitot-type sediment sampler to determine any variation in the solids concentration.

TEST RESULTS

After the initial calibration and shakedown runs, several test runs were made. These test runs were designed to evaluate varying the total solids concentration from approximately 20 to 40 percent (simulating the range of combined sludge and grit load expected at the plant), adjusting the pH level up to 11, and increasing the solid $Mg(OH)_2$ concentration up to about 8 percent by weight. The test procedure described in the previous section was followed for each run. A synopsis of the runs is shown in table 1.

In addition to the results presented in table 1, an estimate of the deposition velocity of the slurry was made by comparing the solids concentration of samples taken from the pipeline. The samples were extracted from locations along the vertical centerline of the pipe, 1 inch below the crown and 1 inch above the invert. Sediment sampler data from runs 3, 6, and 7, are presented on figures 13, 14, and 15, respectively. The deposition velocity is noted by v_d.

Standard Chemical Tests and Rheology

Chemical tests on the slurry were conducted by the Chemistry Laboratory staff. Several tests and measurements were taken on each slurry sample. These tests included percent solids by weight, specific gravity measured by hydrometer, pH level, percent grit by weight, and percent $Mg(OH)_2$ by weight. In addition, quiescent settling rates and viscosities were measured for a variety of slurry samples.

The total solids concentration by weight was determined by the techniques described in *Standard Methods*, [5]. The sample was evaporated to near dryness on a steam bath, then oven-dried at

Table 1. – Synopsis of test runs.

Run No.	Total solids concentration % by wt	Added grit concentration % by wt	Specific gravity	pH	Magnesium hydroxide % by wt	Figure No.
1	3	–	1.018	9	3.01	–
2	14.1	–	1.100	9	3.01	–
3*	17 (I)** 8 (F)	2	1.136 1.048	9	3.01	3
4	20.4 (I) 17.5 (F)	2	1.130 1.120	9	3.01	4
5	21.1 (I) 18.9 (F)	2	1.152 1.120	9	3.01	5
6	22.4 (I) 16.9 (F)	2	1.160 1.112	9	3.01	6
7	23.4 (I) 17.5 (F)	2	1.166 1.120	9	3.01	7
8	38.6 (I) 37.6 (F)	–	1.340 1.315	9	3.01	8
9	35.6 (I) 33.6 (F)	–	1.300 1.280	11	4.15	9
10	37.1 (I) 36.7 (F)	–	–	11.3	5.21	10
11	34.2 (I) 33.8 (F)	–	–	11.0	6.96	11
12	37.5 (I) 35.7 (F)	–	–	11.2	7.7	12

* During run 3 it was noted that water was being added to the pipeline loop through the packing gland of the slurry pump. In subsequent runs, sludge was added to the mixing tank throughout the test run to keep the solids concentration as constant as possible.
** (I) and (F) denote the solids concentration at the start (initial) and end (final) of the test run, respectively.

105 °C overnight. The dry weight was compared with the wet weight, and the percent of total solids by weight was calculated. The total solids concentration was determined for each sample taken during the pipeline loop tests and for each sample mixed in the chemistry laboratory for additional settling and viscosity measurements. The specific gravity was measured by hydrometer. Two different hydrometers were used because of the large range of specific gravities measured. Figure 16 shows the relationship between slurry specific gravity and total solids concentration. Specific gravity was not measurable with the hydrometer for some of the slurry mixtures tested. A combination electrode meter was used to determine the pH level at room temperature. A series of acid insolubility tests determined the concentration of sedimentation-basin grit. The $Mg(OH)_2$ concentration was determined by comparing the sample with a 5-percent $Mg(OH)_2$ standard, using atomic absorption spectrophotometry.

The settling velocity is one of the more important pipeline design parameters. The value of settling velocity can best be determined by actual pipeline tests; however, through quiescent settling tests, some valuable information can be learned about the consistency and dewaterability of the slurry. The quiescent settling tests consisted of placing a well-mixed sample in a graduated cylinder and recording the location of the settled interface at various times. A comparison of figures 17 and 18 shows the effect of pH on settling for slurries ranging from 20.8 to 53.6 percent total solids concentration by weight with an 8-percent $Mg(OH)_2$ concentration. Figure 19 shows a group of slurries at a pH of 11 with a $Mg(OH)_2$ concentration of 2 percent.

Discussion and Analysis

Non-Newtonian fluids are defined as materials that do not conform to a direct proportionality between shear stress and shear rate. An almost infinite number of rheological relationships exist for this class of fluids. Through experimentation, a great number of these fluids were found to be described by a two-constant power function of the form:

$$\tau = K\left(\frac{-dv}{dr} \right)^n \tag{1}$$

where:

τ = shear stress

K = viscous consistency factor (pseudoviscosity)

$\frac{-dv}{dr}$ = shear rate for flow in a circular pipe

n = power law index

The power law model, as this function is called, is empirical in nature. Newtonian behavior is described by the power law for the special case where n equals 1 and K equals the Newtonian viscosity. Values of n between 0 and 1 characterize pseudoplastic fluids for which the apparent viscosity, μ (du/dr), decreases with increasing shear rate (μ is the viscosity). Conversely, values of n greater than 1 correspond to dilatent fluids, for which the apparent viscosity increases with shear rate.

The model data was analyzed using the power law and a modification of Prandtl's mixing length concept detailed by Hanks [3]. Using this model with the Fanning friction factor, $f=2\tau_w/\overline{V}^2$, and the Metzger-Reed generalized Reynolds number (eq 2), allowed meaningful presentation of the model data.

$$Re' = 8\left(\frac{n}{4+3n}\right)^n \left(\frac{\rho\, r_w^n\, \overline{v}^{2-n}}{K}\right) \qquad (2)$$

where:

ρ = density

$\overline{v}$ = mean velocity

r_w = pipe radius

τ_w = shear stress at the pipe wall

Plotting ln $\Delta PD/4L$ vs. ln $8\overline{v}/D$ (where: ΔP = *pressure drop in length L,* and D = pipe diameter) yields the value of n, the power law index, as the slope of this line. Then the mixing-length model can be applied and plots of the friction, f, vs. generalized Reynolds number can be made.

The pipeline loop data taken in runs 9 through 12 are shown in the form described above on figure 20. All the data points on the plot fall on the laminar-flow line defined by $f = 16/Re'$. This is somewhat surprising, especially because some data points were taken at pipeline velocities in excess of 10 ft/s. Dilatent fluids, while having lower critical Reynolds numbers for transistion than Newtonian fluids, also have longer transition zones. In this slurry flow, the boundary layer is highly stable; this aids in keeping the flow laminar. Unlike water, a fairly large disturbance is necessary to push the boundary layer into unsteady behavior and induce turbulent flow [4]. In the laboratory test loop, a stable boundary layer developed in the relatively short measuring sections, leading one to believe that the prototype flow behavior will be similar.

Undoubtedly, areas of turbulent flow existed in the model and will exist in the prototype. Most of the literature suggests that non-Newtonian fluids will behave as Newtonian fluids in the turbulent region. Any major disturbance in the flow, such as valves or elbows, will probably cause turbulent flow to occur. However, a relatively short, straight, undisturbed section of pipe is all that is required to change the flow back to laminar.

The shortness of the pipeline test loop, compared with the proposed prototype lengths, is certain to cause some differences in flow characteristics. Probably the most easily predictable difference will be a higher deposition velocity in the prototype. For this reason, the prototype design velocity should be at least 1 ft/s above the deposition velocity found in the model.

Rheological data can allow the designer to scale friction losses for different pipe diameters and roughnesses. However, many problems can prevent accurate and complete viscometric measurements. With a pseudohomogeneous fluid, such as this slurry, particles can settle during the viscosity measurement – effectively changing the total solids concentration of the sample. When this gradual settling occurs, the fluid appears to be thixotropic (or having a viscosity that is dependent on the amount of shearing it has experienced). However, what appears to be thixotropic behavior by this slurry can be explained simply by the drop in solids concentration as particles settle during the viscosity measurements.

In practice, the rheological properties of a slurry are not unique over a wide range of shear stresses. Therefore, rheological parameters should be evaluated for the expected wall shear stresses in the actual prototype application. Designers should be careful to avoid scaling parameters outside the range covered by any rheological measurements.

The best source for slurry pipeline design parameters is from data taken on a model pipeline loop with a similar diameter.

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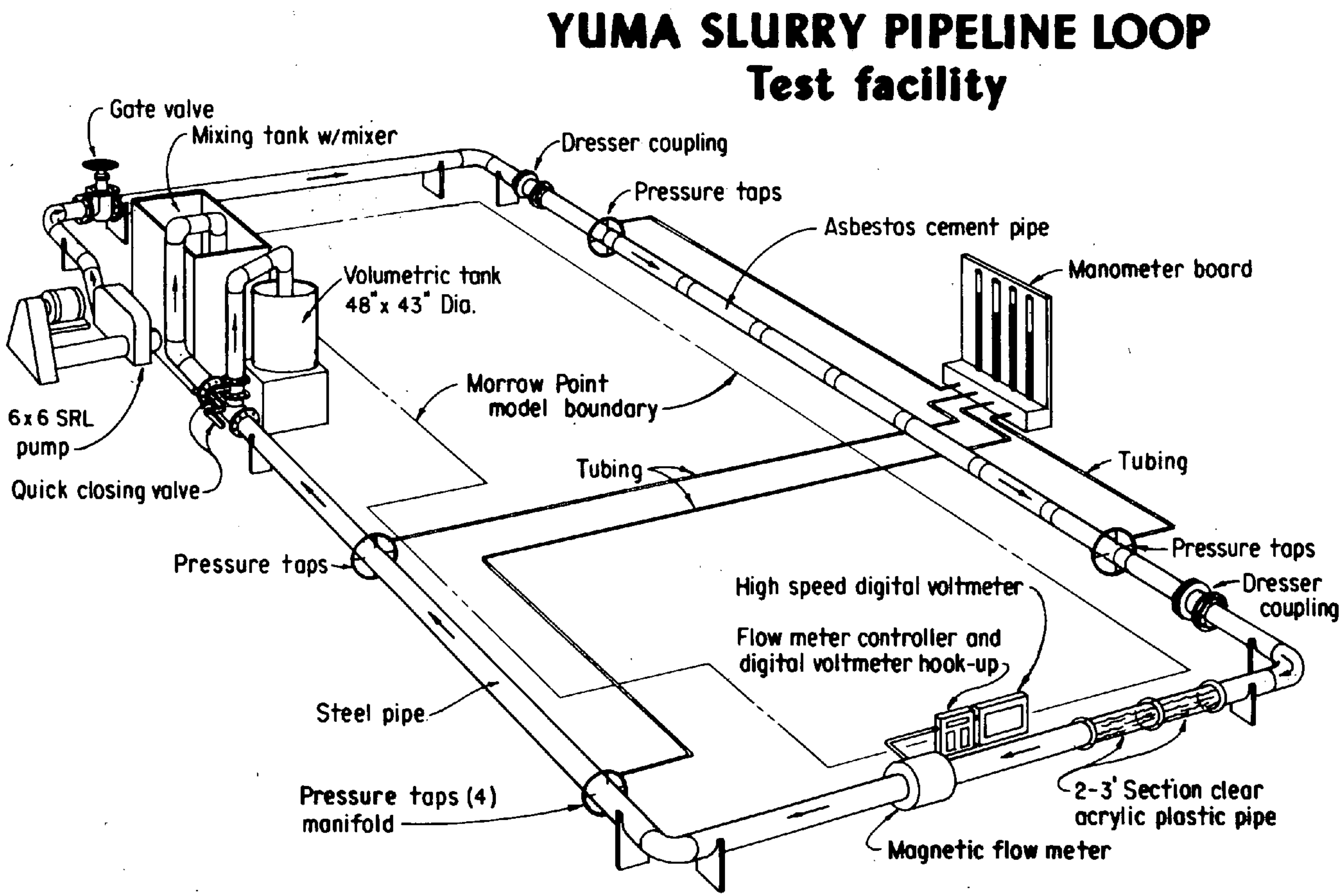

Figure 1. – Pipeline loop test facility with 6-in i.d. pipe.

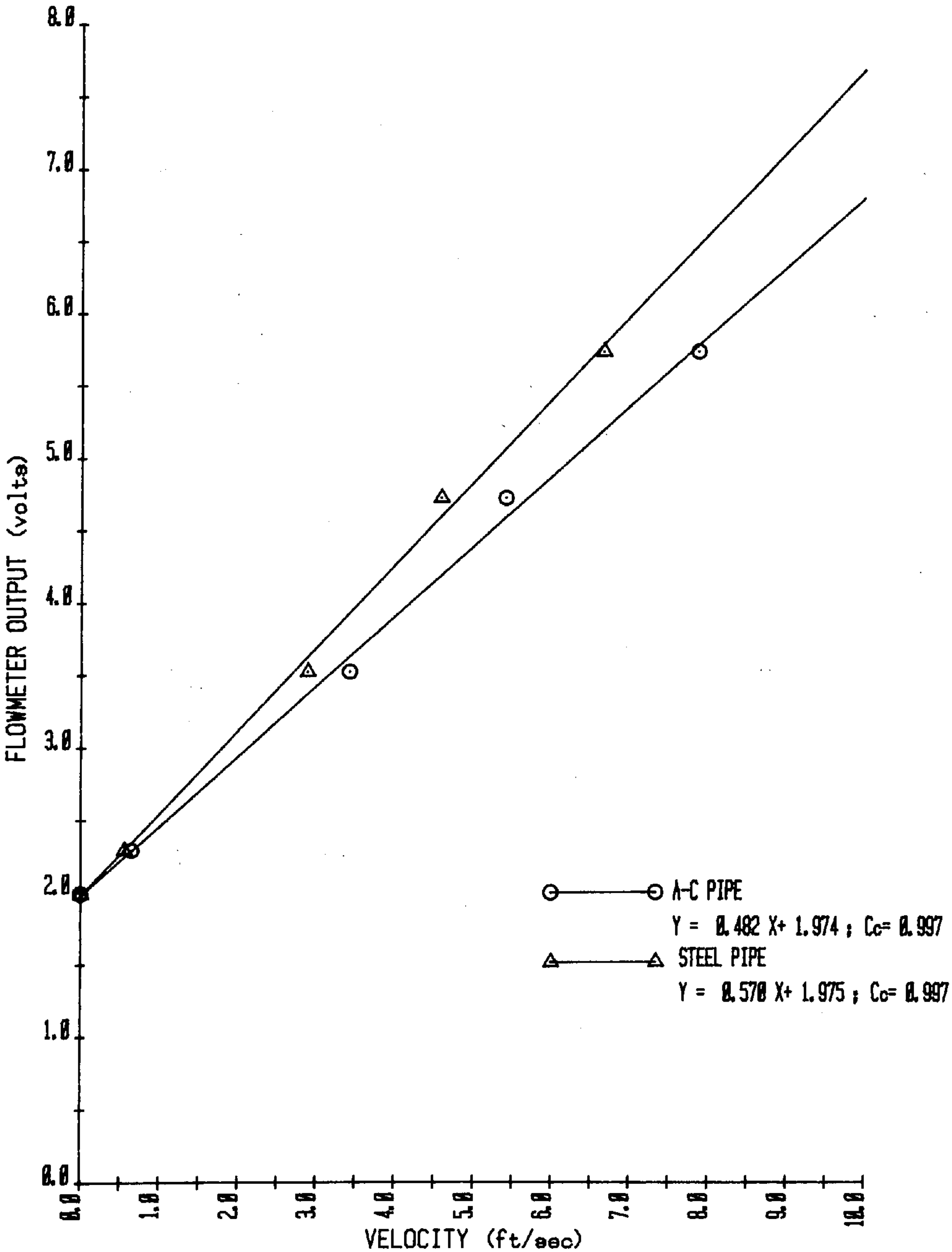

Figure 2. – Mean linear velocity vs. voltmeter reading: unlined steel pipe and asbestos-cement pipe.

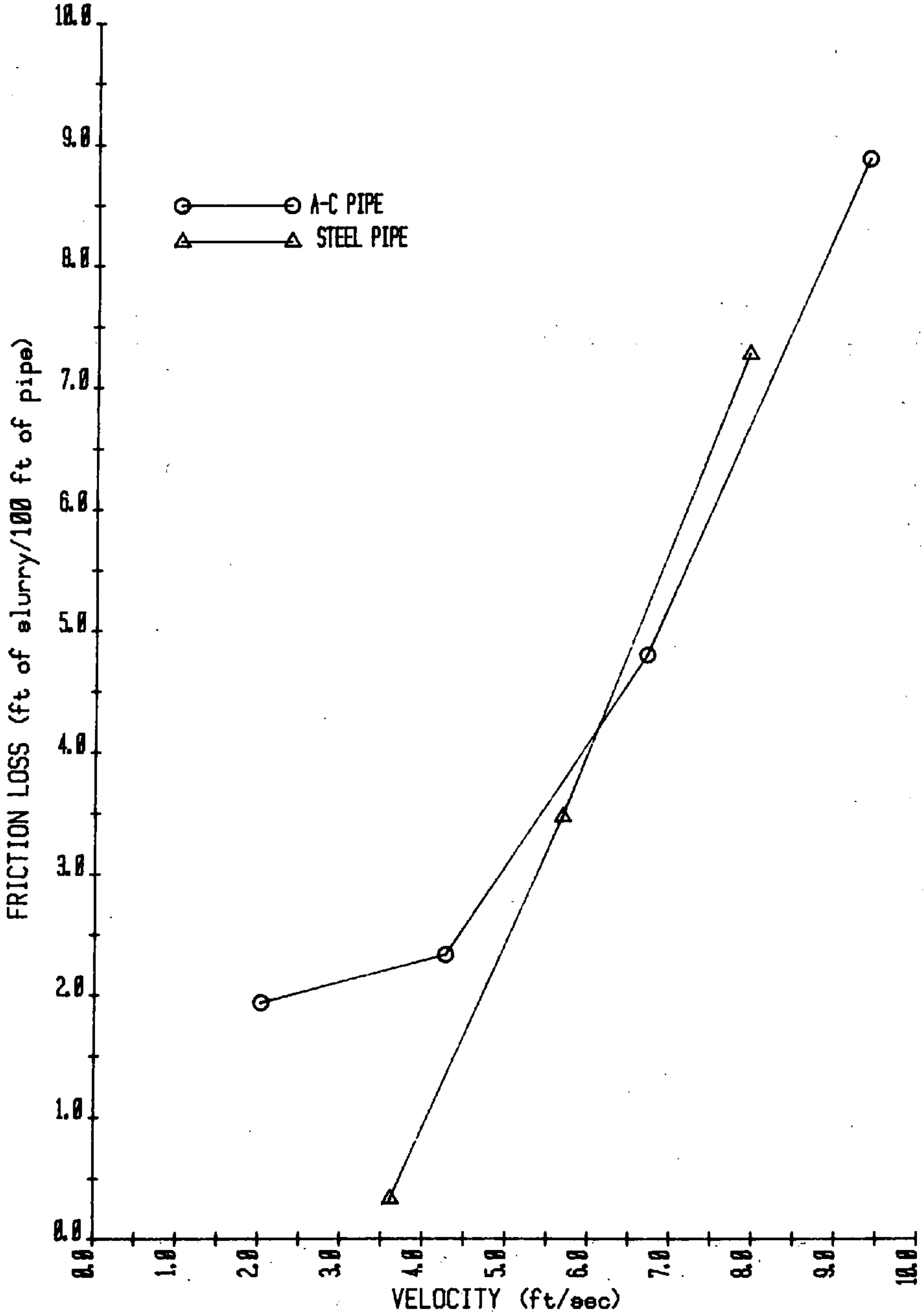

Figure 3. – Test loop data, run 3: solids – 17 percent, added grit – 2 percent, pH – 9, $Mg(OH)_2$ – 3.01 percent.

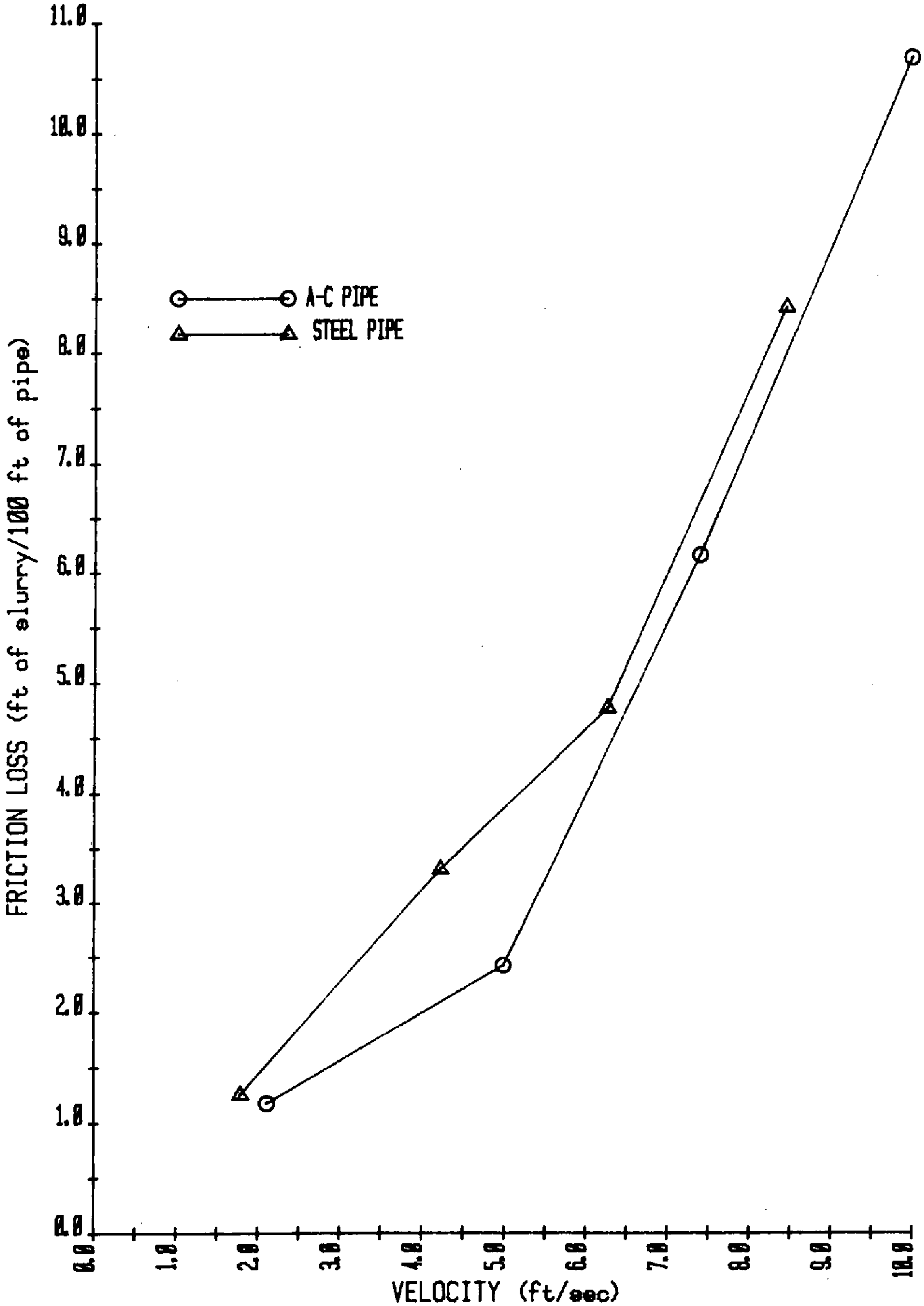

Figure 4. – Test loop data, run 4: solids – 20.4 percent, added grit – 2 percent, pH – 9, $Mg(OH)_2$ – 3.01 percent.

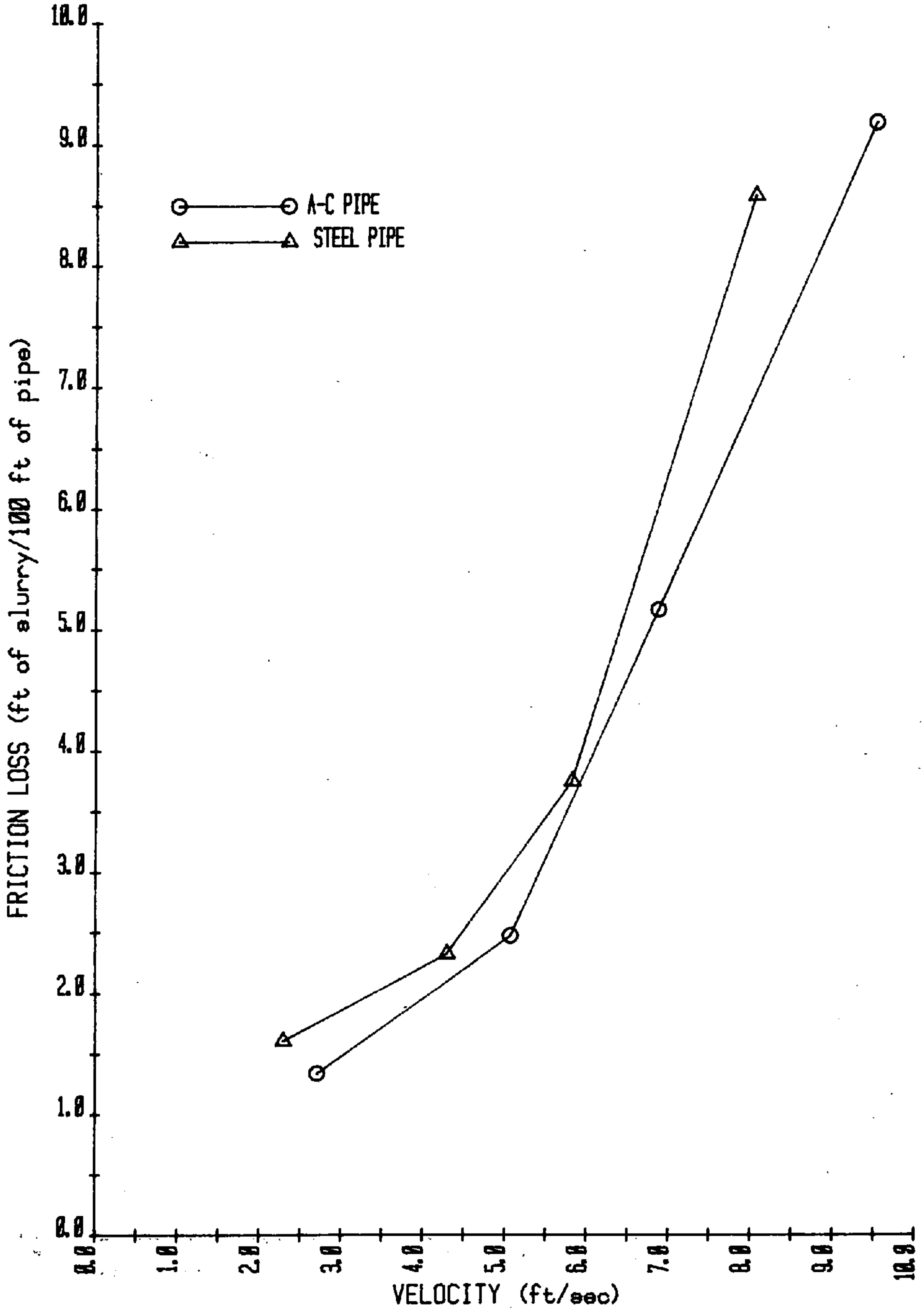

Figure 5. – Test loop data, run 5: solids – 21.1 percent, added grit – 2 percent, pH – 9, $Mg(OH)_2$ – 3.01 percent.

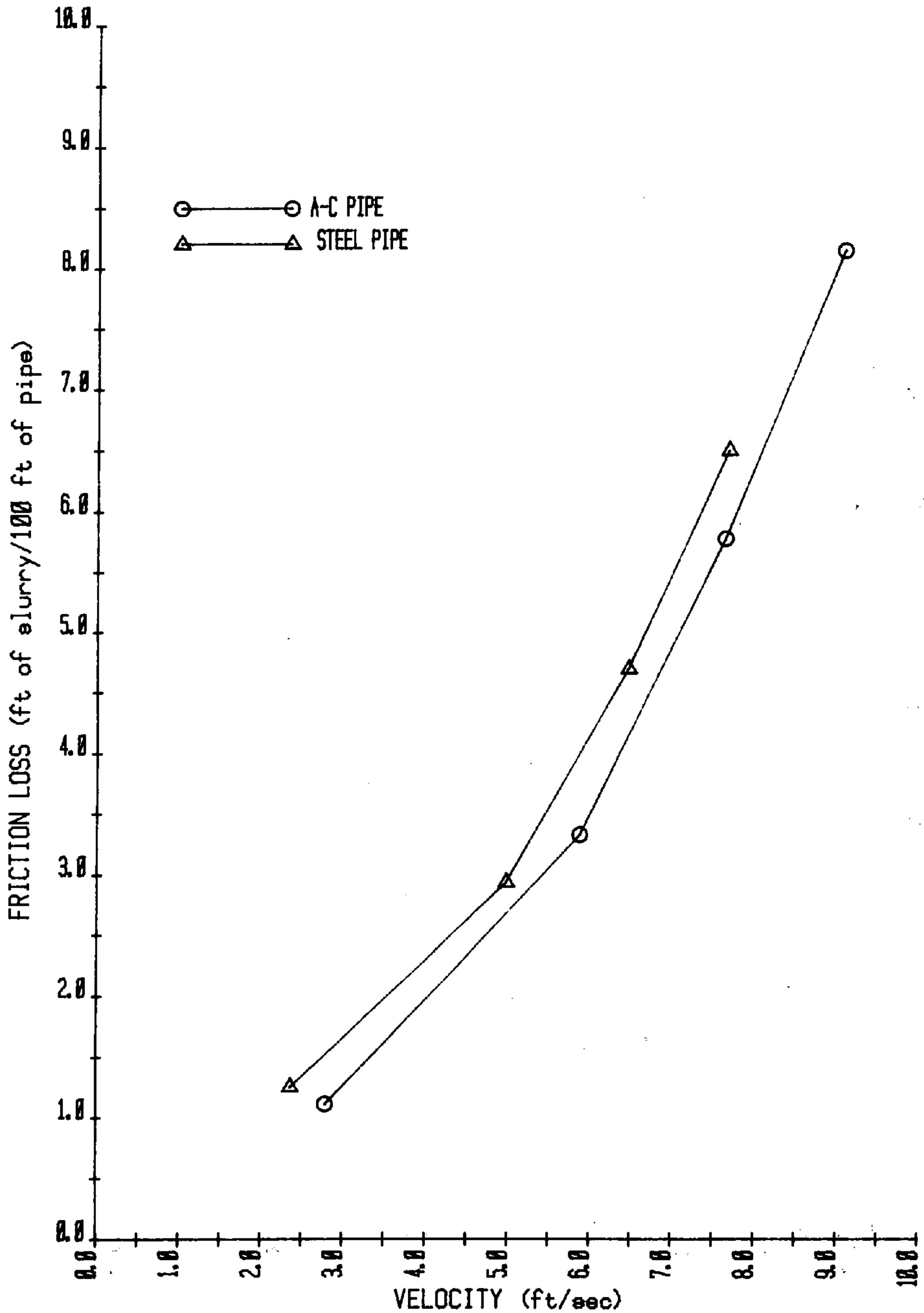

Figure 6. – Test loop data, run 6: solids – 22.4 percent, added grit – 2 percent, pH – 9, $Mg(OH)_2$ – 3.01 percent.

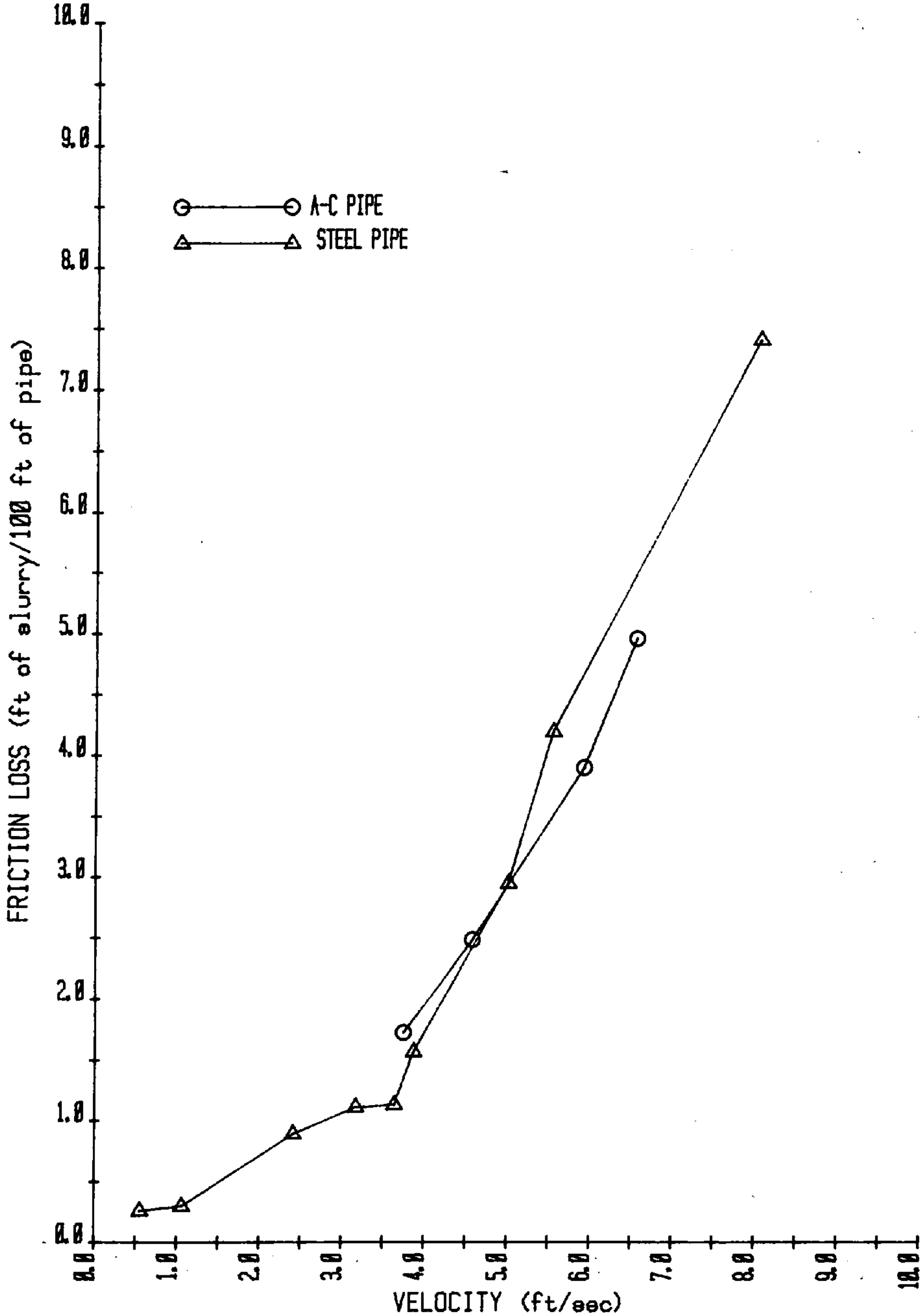

Figure 7. – Test loop data, run 7: solids – 23.4 percent, no added grit, pH – 9, $Mg(OH)_2$ – 3.01 percent.

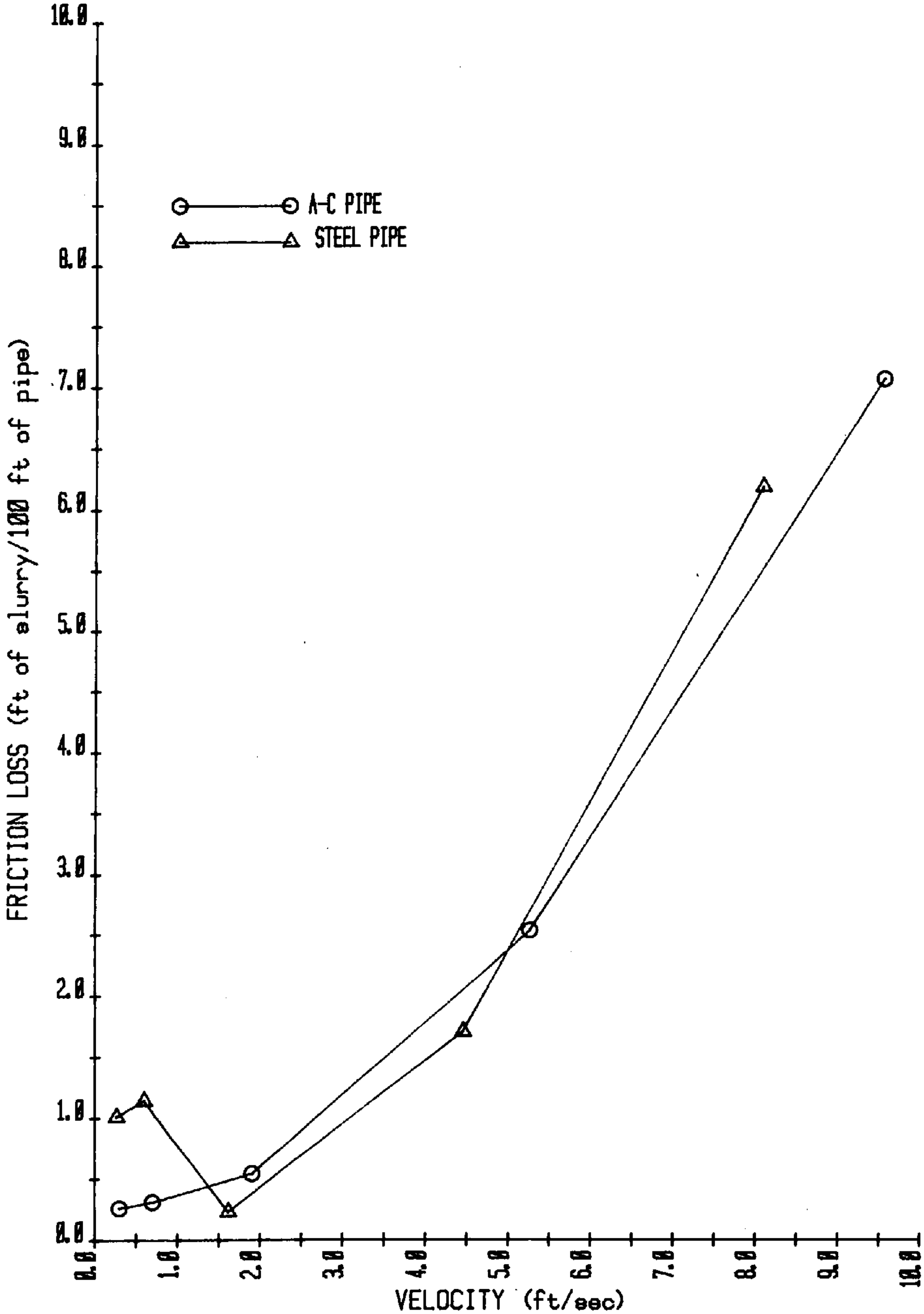

Figure 8. – Test loop data, run 8: solids – 38.6 percent, no added grit, pH – 9, $Mg(OH)_2$ – 3.01 percent.

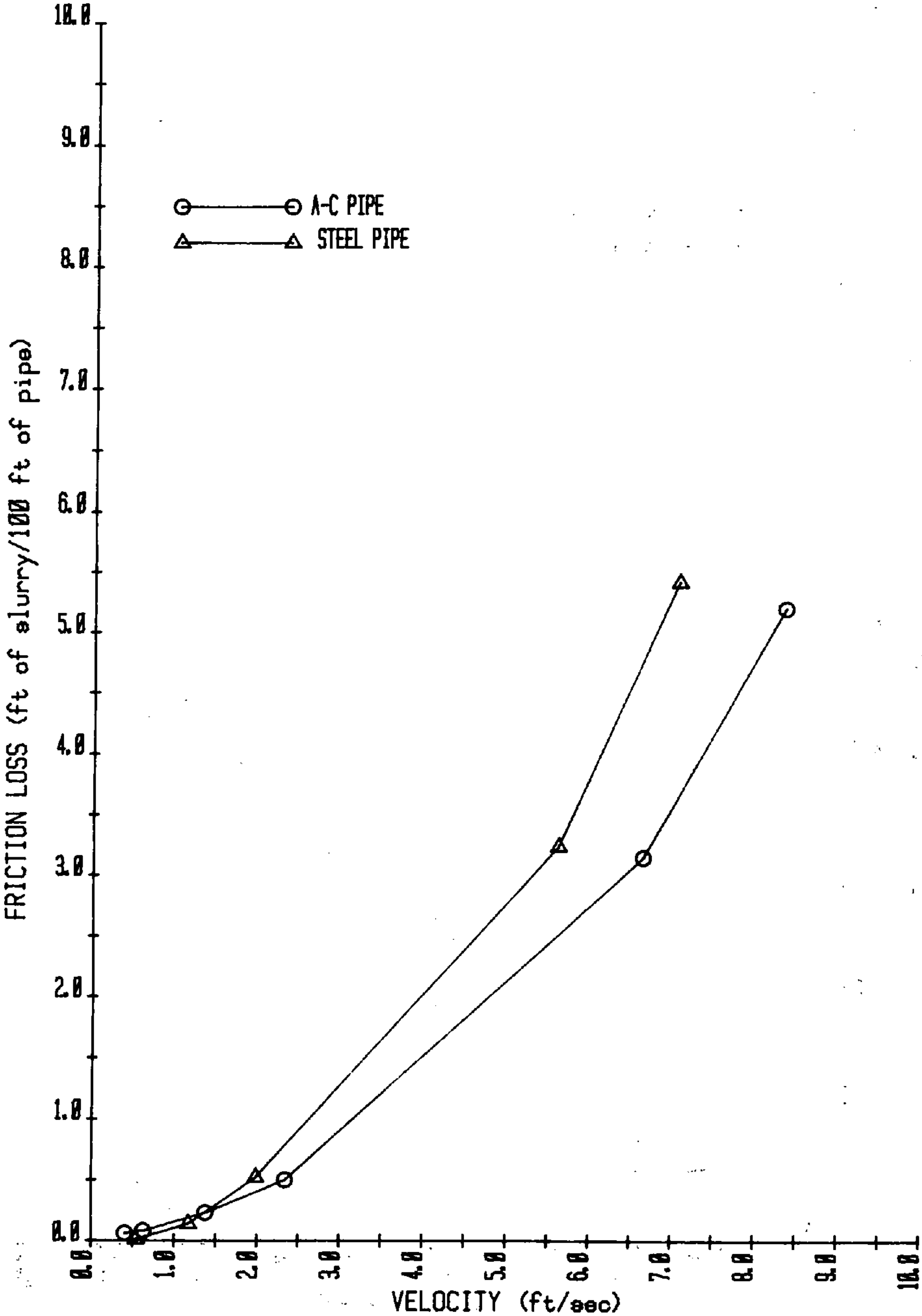

Figure 9. – Test loop data, run 9: solids – 35.6 percent, no added grit, pH – 11, $Mg(OH)_2$ – 4.15 percent.

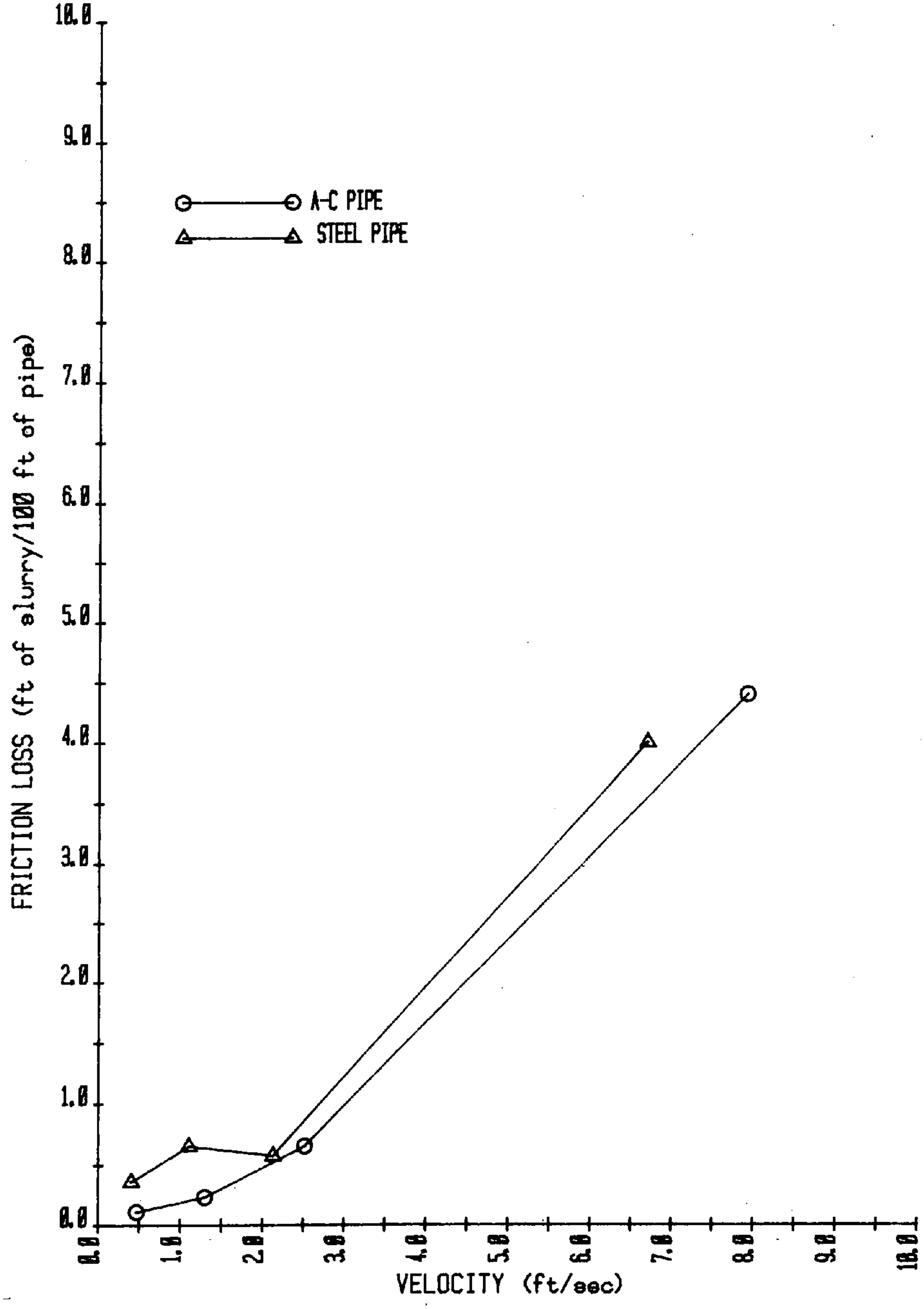

Figure 10. – Test loop data, run 10: solids – 37.1 percent, no added grit, pH – 11.3, $Mg(OH)_2$ – 5.21 percent.

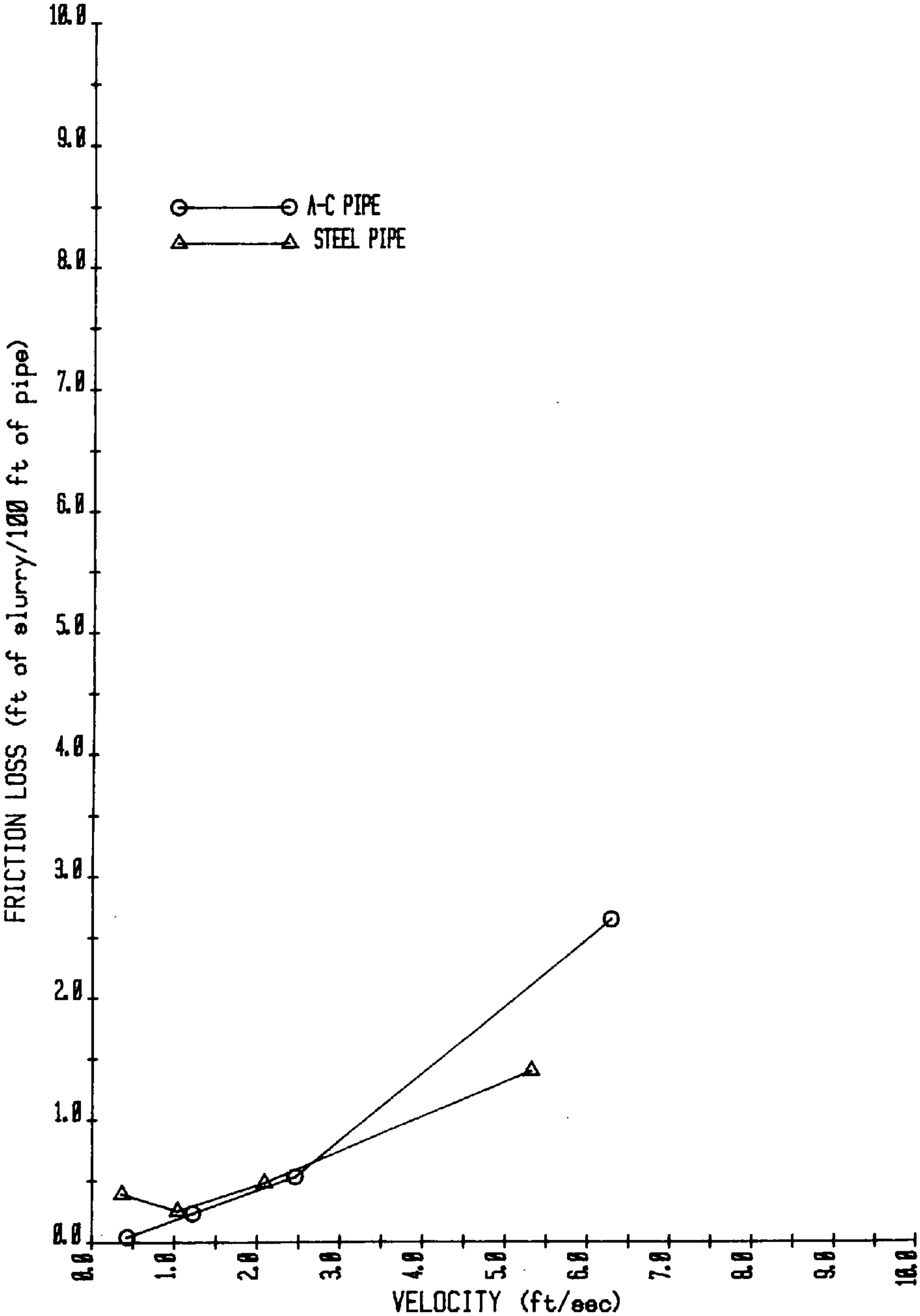

Figure 11. – Test loop data, run 11: solids – 34.2 percent, no added grit, pH – 11.0, $Mg(OH)_2$ – 6.96 percent.

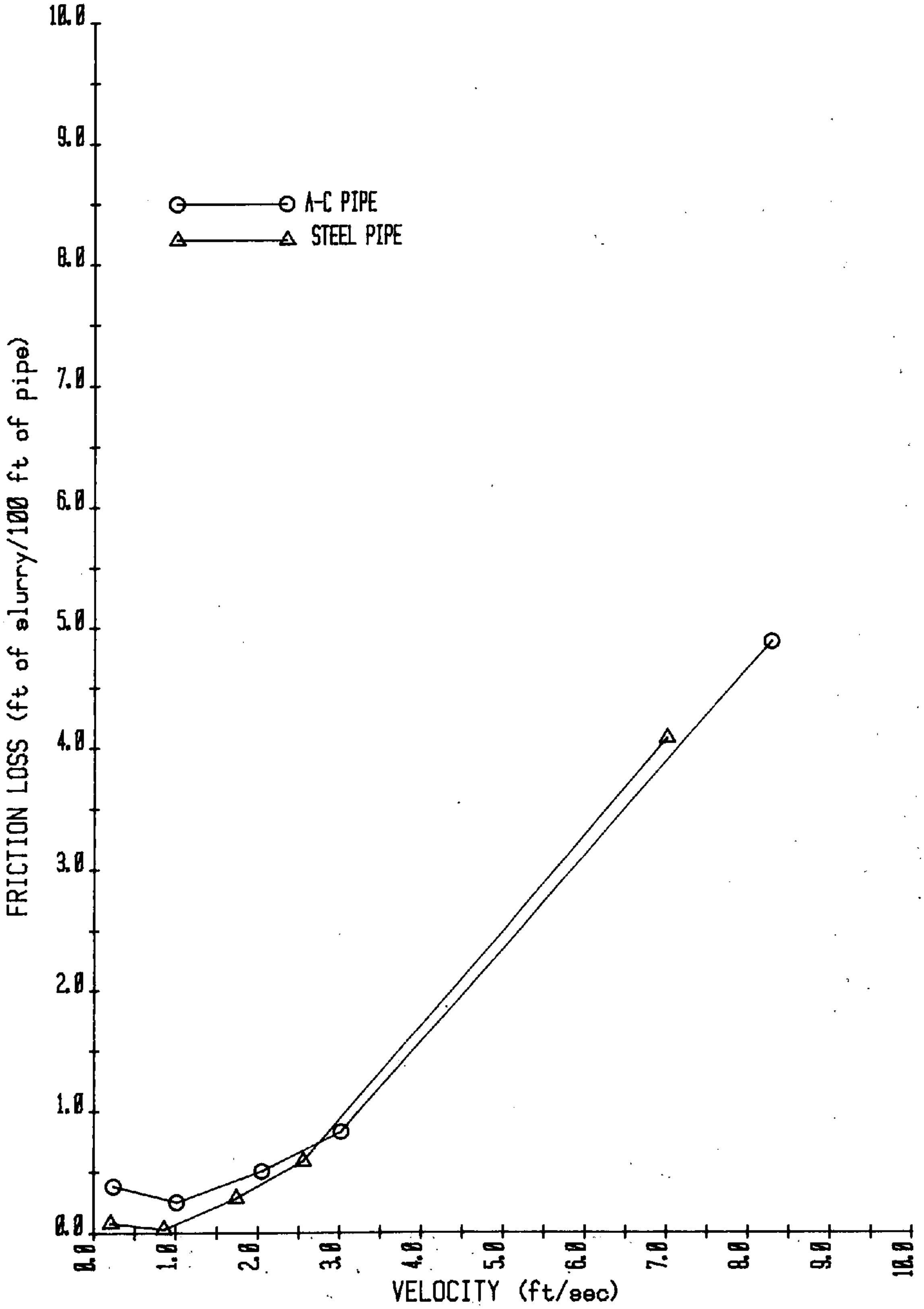

Figure 12. – Test loop data, run 12: solids – 37.5 percent, no added grit, pH – 11.2, $Mg(OH)_2$ – 7.7 percent.

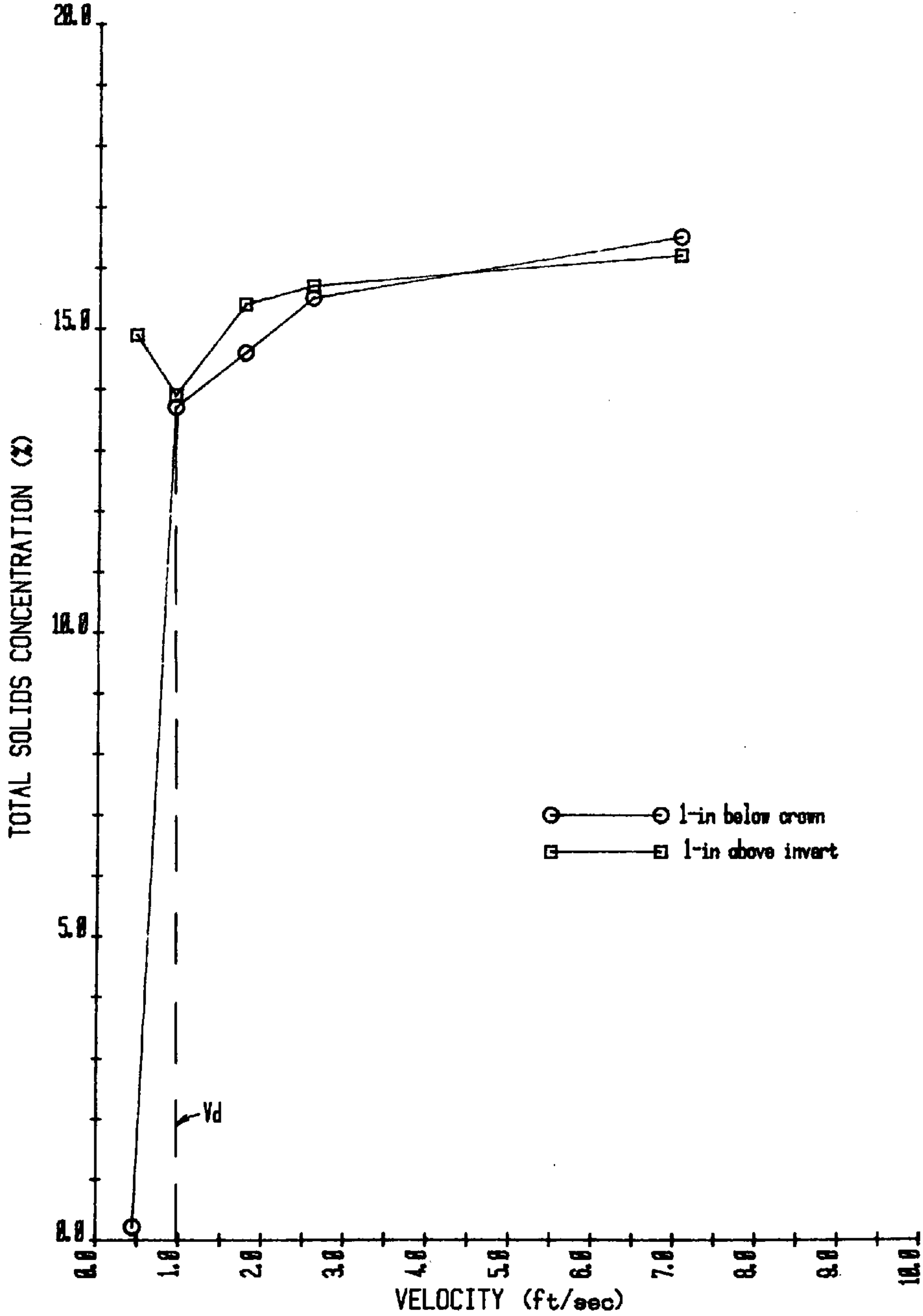

Figure 13. – Sediment sampler data, run 3.

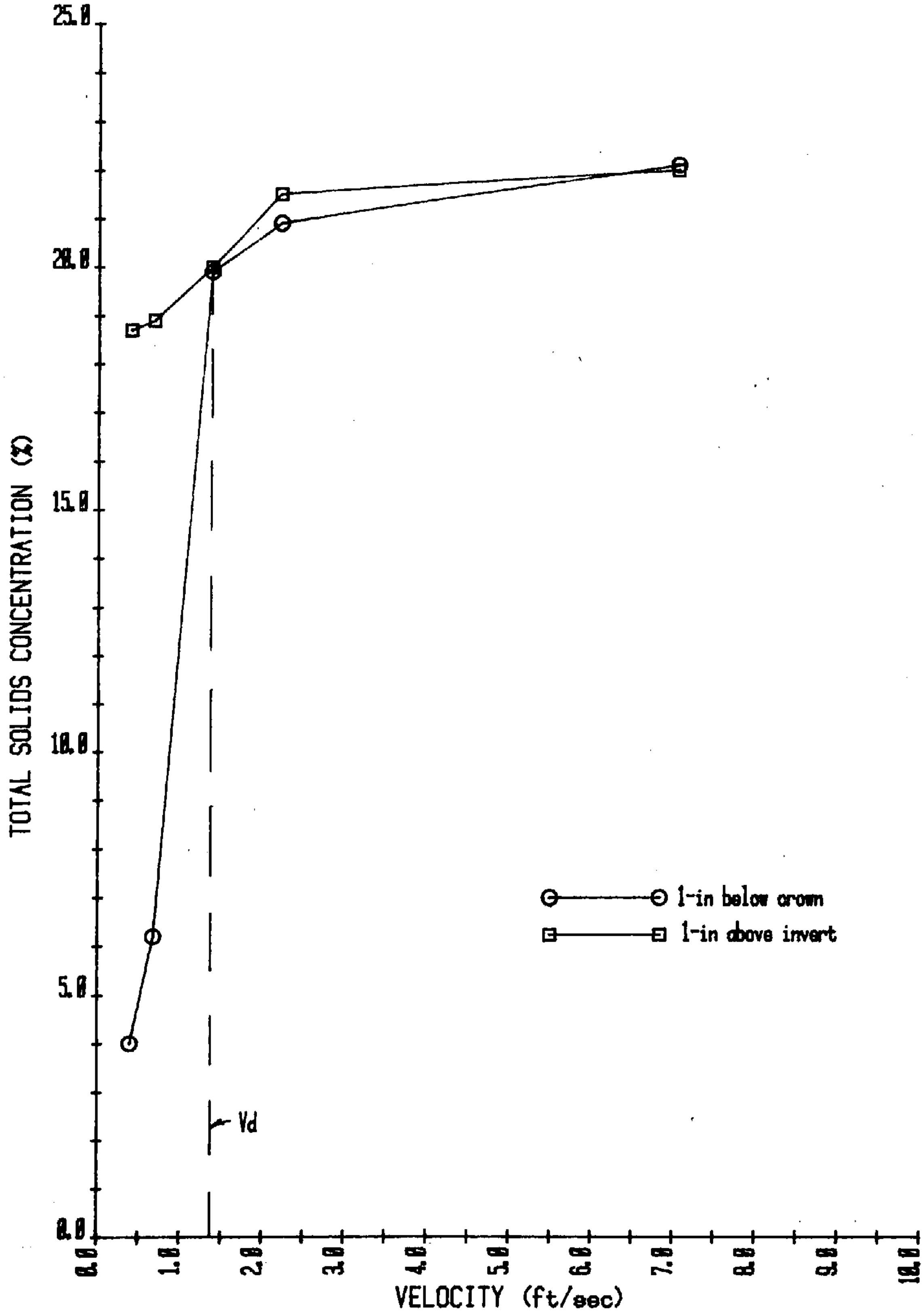

Figure 14. – Sediment sampler data, run 6.

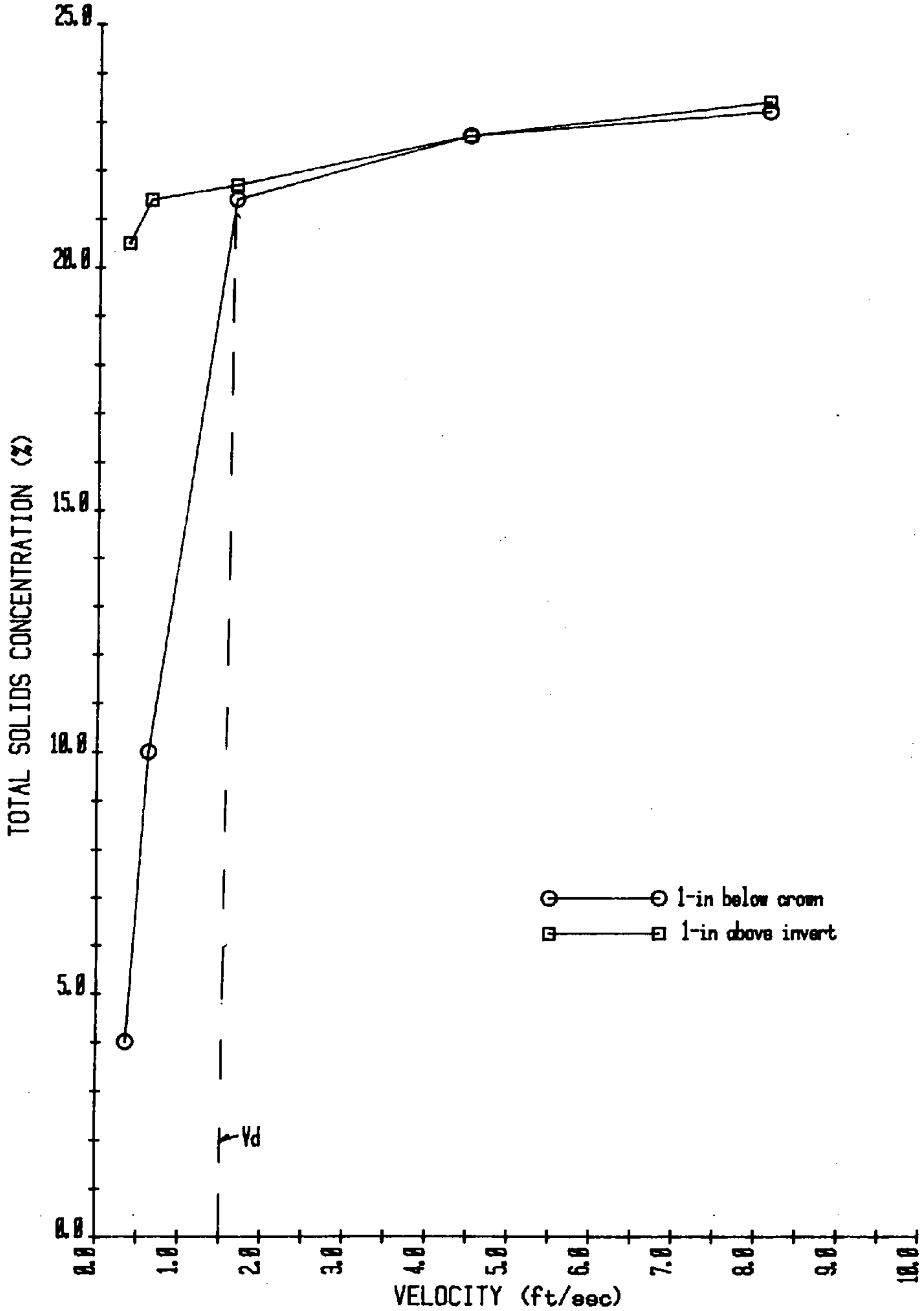

Figure 15. – Sediment sampler data, run 7.

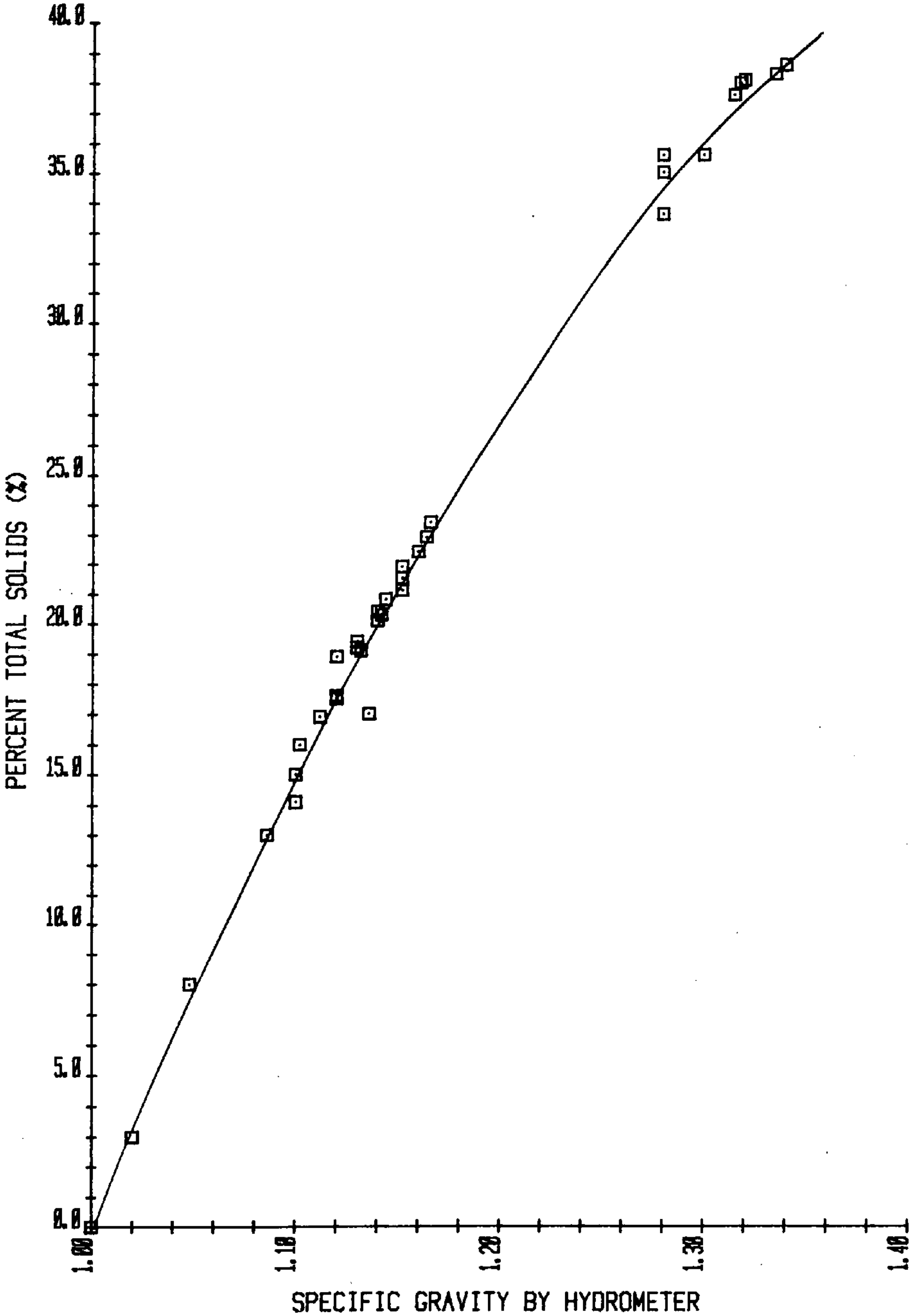

Figure 16. – Specific gravity measured by hydrometer vs. total solids concentration.

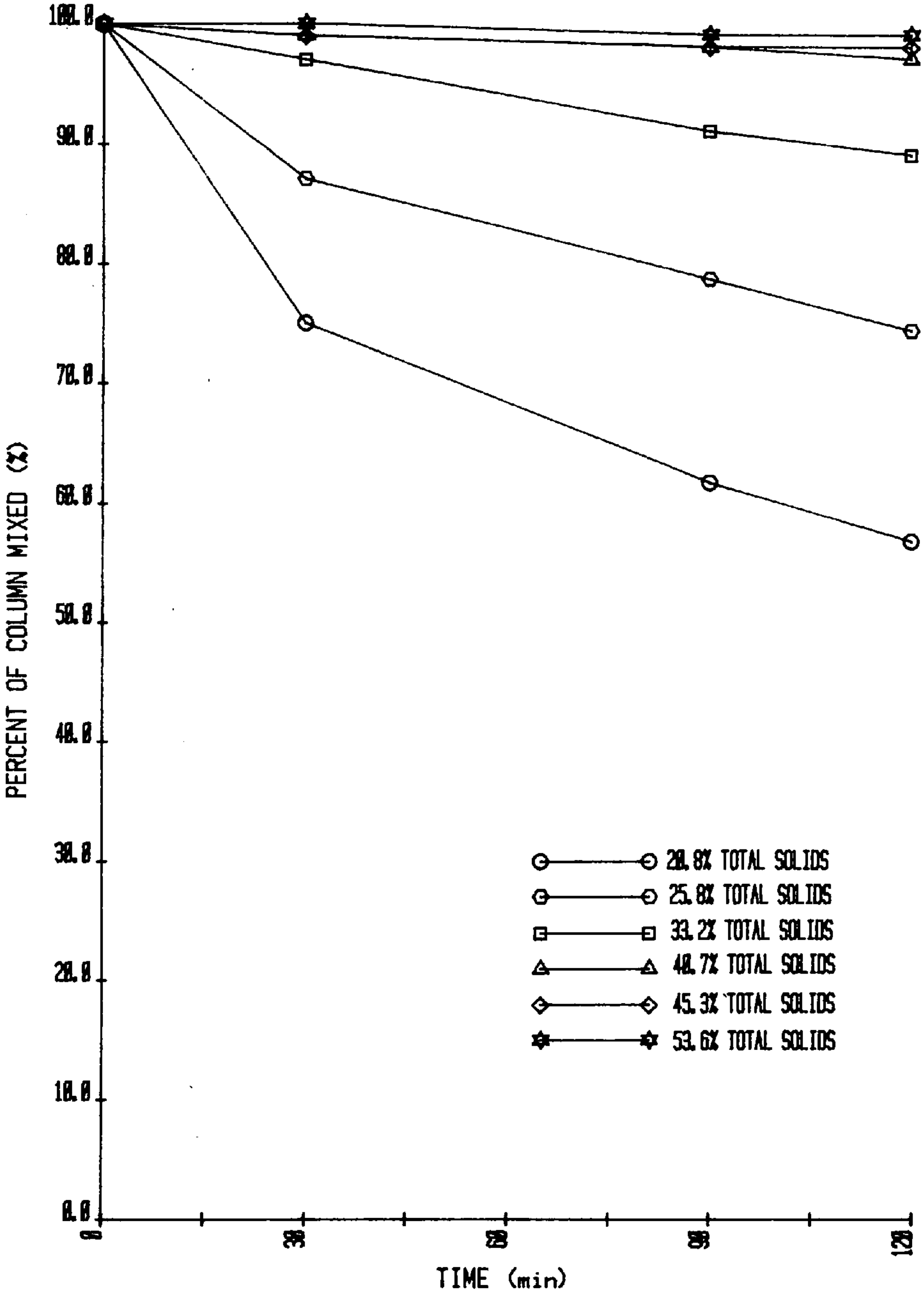

Figure 17. – Quiescent settling rates: pH – 9, $Mg(OH)_2$ – 8 percent, total solids – 20.8 to 53.6 percent.

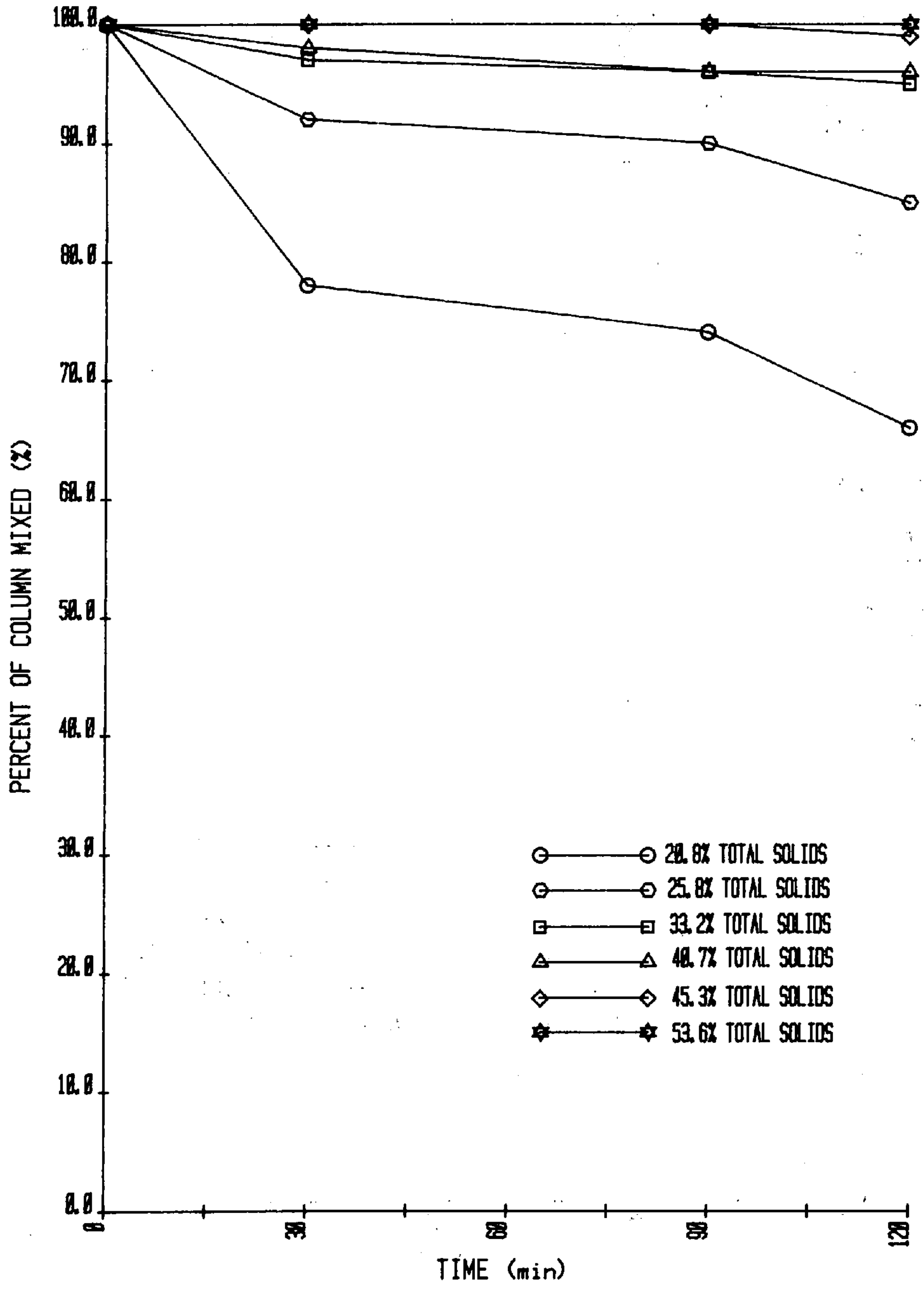

Figure 18. – Quiescent settling rates: pH – 11, $Mg(OH)_2$ – 8 percent, total solids – 20.8 to 53.6 percent.

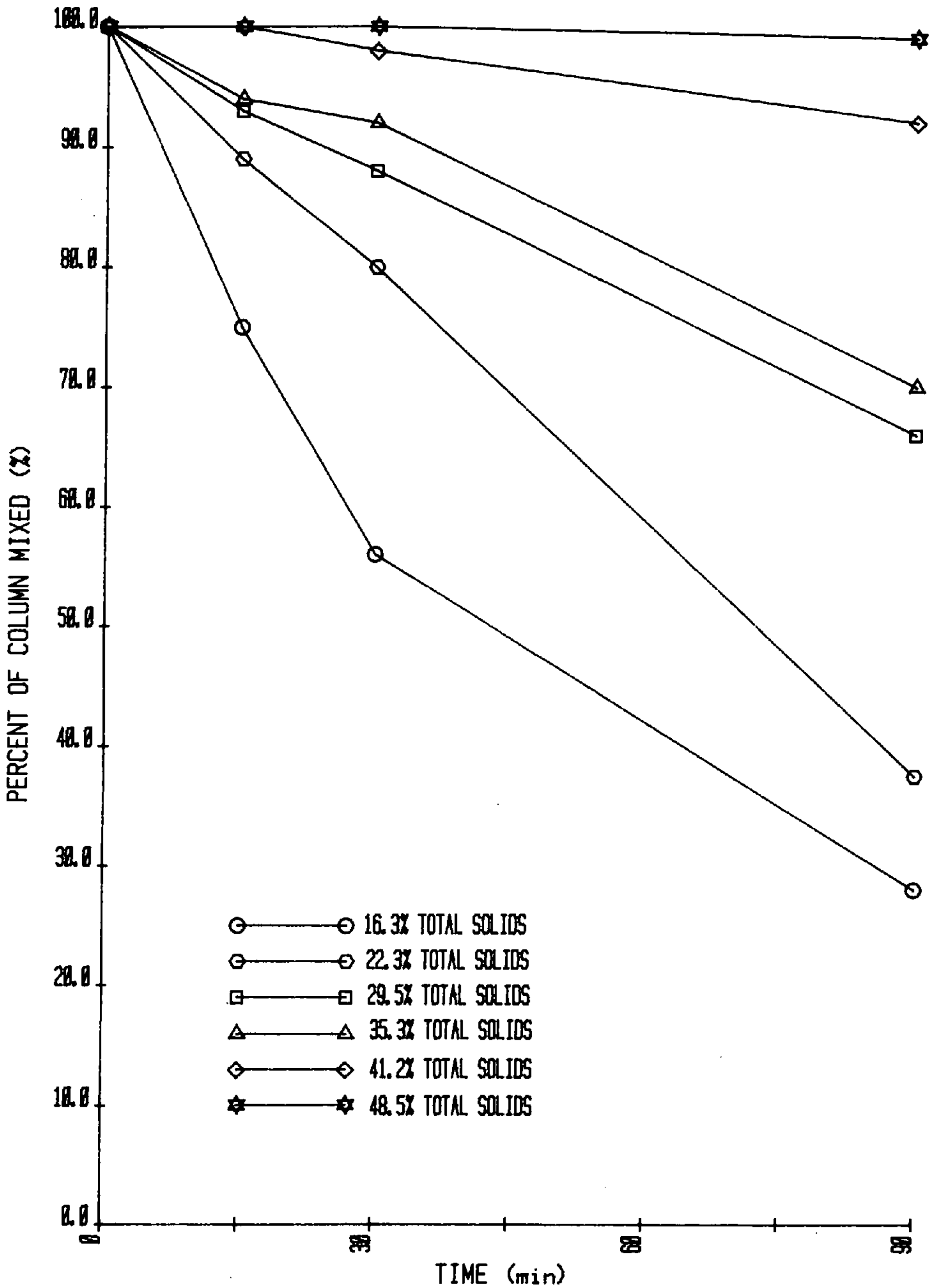

Figure 19. – Quiescent settling rates: pH – 11, $Mg(OH)_2$ – 2 percent, total solids – 16.8 to 48.5 percent.

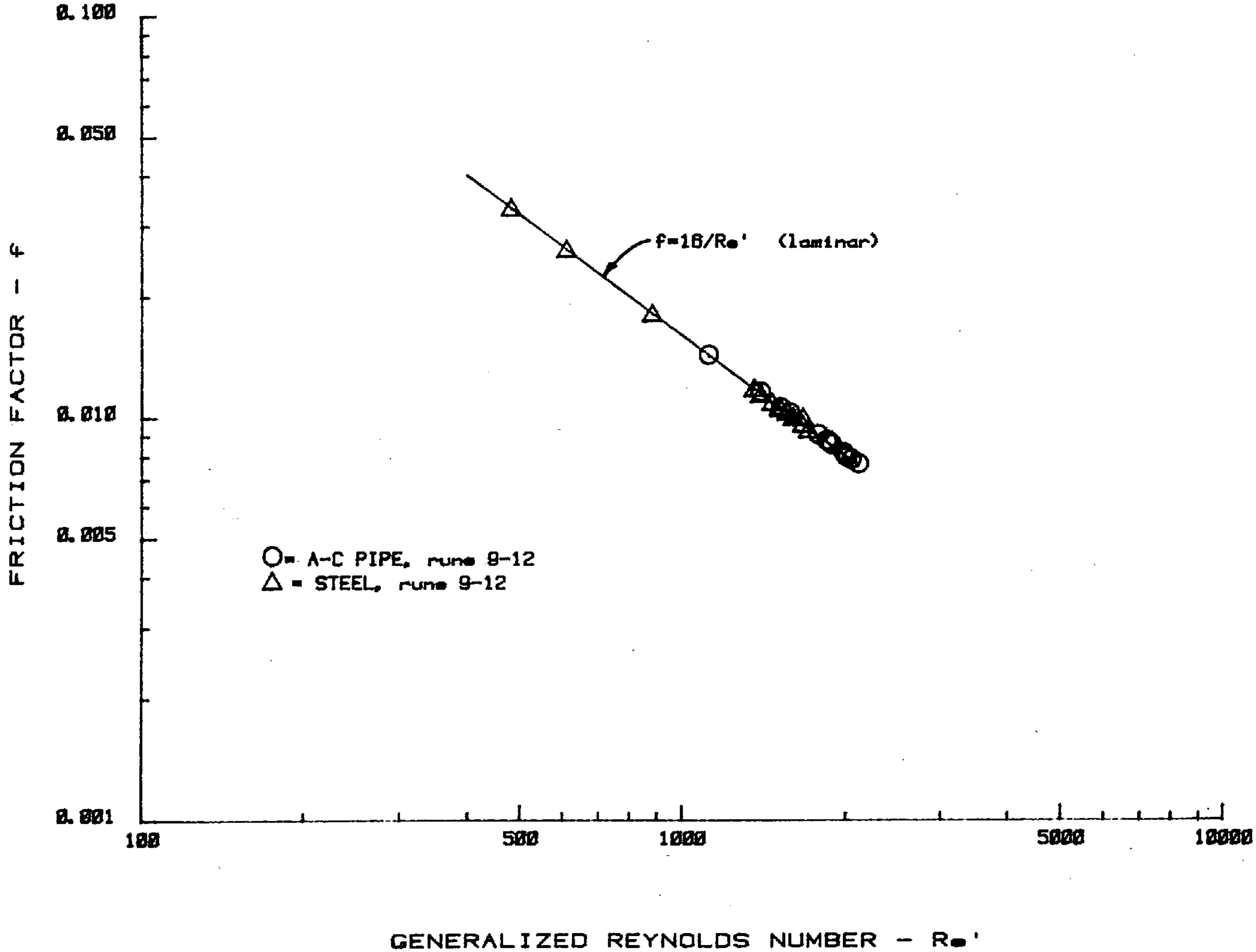

Figure 20. – Friction factor vs. generalized Reynolds number, test loop data, runs 9-12.

Mission of the Bureau of Reclamation

The Bureau of Reclamation of the U.S. Department of the Interior is responsible for the development and conservation of the Nation's water resources in the Western United States.

The Bureau's original purpose "to provide for the reclamation of arid and semiarid lands in the West" today covers a wide range of interrelated functions. These include providing municipal and industrial water supplies; hydroelectric power generation; irrigation water for agriculture; water quality improvement; flood control; river navigation; river regulation and control; fish and wildlife enhancement; outdoor recreation; and research on water-related design, construction, materials, atmospheric management, and wind and solar power.

Bureau programs most frequently are the result of close cooperation with the U.S. Congress, other Federal agencies, States, local governments, academic institutions, water-user organizations, and other concerned groups.