DRAG REDUCTION EFFECTS OF DILUTE POLYMER ADDITIVES ON DREDGE SPOIL PIPE FLOWS

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NOMENCLATURE

A	pipe cross sectional area
D	pipe diameter
f	Blasius friction factor
gal	gallons
g_c	gravitational constant, 32.2 lb_m-ft/lb_f-sec^2
GPM	gallons per minute
HP	horsepower
L	length of pipe test section
P	static pressure
psf	pounds force per square foot
psi	pounds force per square inch
Q	mass flow rate
Re	Reynolds number, VD/ν
RPM	revolutions per minute
U_τ	wall shear velocity, $(g_c/\rho \cdot D \, \Delta P_{H_2O}/4L)^{1/2}$
V	average fluid velocity
wppm	weight parts per million
ΔP	static pressure drop
ΔP_H	elevation pressure drop
ΔP_M	momentum pressure drop
ΔP_S	shear pressure drop
ΔP_T	total pressure drop

Δz	change in pipe elevation
μm	micrometer

GREEK LETTERS

Δ	difference
μ	dynamic viscosity of fluid
ν	kinematic viscosity of fluid
ρ	density of fluid
τ	wall shear stress

SUBSCRIPTS

DRS	drag-reduced solution

SPECIAL SYMBOLS

% DR percent drag reduction for a constant flow rate,

$$\% \text{ DR} = \left[\frac{P_{H_2O} - P_{DRS}}{P_{H_2O}} \right] 100$$

CHAPTER I

INTRODUCTION

For many years, several approaches have been tried in attempting to reduce the frictional pressure losses in turbulent flows of fluids in pipes and channels. These include boundary layer suction, the use of compliant boundaries, the use of miscible and/or immiscible fluids of low viscosity injected near the walls, and the injection of dilute concentrations of high molecular weight synthetic polymer solutions. (1). The latter has shown most favorable results for very low concentrations of polymer, i.e. less than 0.25 gram/liter. Frictional pressure losses have been reduced as much as 80% in this manner. This phenomenon is commonly referred to as drag reduction. Although, at present, no complete and accurate explanation exists for the flow mechanisms involved in polymer drag reduction, the feasibility for particular applicatons of the method may still be studied.

Much work, as mentioned, has been conducted with drag reduction techniques for liquid solutions. Also much has been done in the area of liquid-solids transport in pipes. Little or no study has been evidenced, however, for the drag reduction of liquid-solids slurries, that is, the merging of the drag reducing flow with the slurry flow. It would appear, therefore, that much information is to be gained from such an effort so that insight to possible commercial applications might be forwarded. Applications as mentioned here would certainly include short distance cross-country transport of solids and the flow of dredge slurries from dredge to disposal site. It is the intent of this thesis, therefore, to determine the feasibility of drag-reducing particular slurry flows by the injection of dilute concentrations of polymer solutions. Slurries of the dredge type are used to obtain data and to determine feasibility for an actual application.

The Problem

The majority of modern dredging operations transport solid particles from the floor of the waterway to either a temporary storage hold which is later pumped out to a shore pipeline (Figure 1) or directly to the shore pipeline. The mixture of solid particles and water is referred to as a spoil. It is found that the spoil is typically 10% by weight solids or approximately 5% by volume solids. The suspended solids may range in size from fine organic particles of silt to quite large objects such as bricks, bottles, or cans. When given the opportunity, the larger material will quickly settle out of the water and be disposed of easily whereas the smaller particles (sand, clay, gravel, silt) remain in suspension longer and are pumped in the pipeline flow. During the pumping procedure from dredge to disposal site there frequently arises the situation whereby the pumped flow rate in the pipeline is insufficient to avoid solids settling and pipeline blockage. When this occurs, pump efficiency and valuable pumpout time are lost. Excessive amounts of water must be pumped to wash the blocked section clean and resume operation. In a particular case, dredging time may consume about half an hour, travel to pumping site (if hopper type dredge is used) approximately an hour, while pumpout (either direct or from the hopper) may consume three or four hours.

This kind of flow blockage behavior is also experienced in many cases of cross-country transport of similar slurry flows. Pipelines of this type may range from perhaps 15 miles to 150 miles in length. Blockage of a 150 mile pipeline, for example, is even more undesirable than for the dredge pipeline. Again valuable time and efficiency are lost in locating the blocked section and clearing it. While the pipeline may not be totally shut down during the clearing operation, the restricted flow may overwork the pumps for an extended duration or with repeated behavior. It is therefore desired, for both the cross-country pipeline and the shorter dredge pipeline, to determine a method by which the flow rate may be increased with no increase in pump work over that done in pumping the same quantity of water. It is also desired to produce a sufficient amount of turbulent mixing to keep the solids suspended such that flow blockage is avoided and pumping efficiency is increased. A statement on the specific purpose of this investigation is then in order.

The Purpose

The objective of this study was to experimentally determine the amount of flow rate increase that may be obtained for typical dredge spoil samples and to study the effect of those parameters which govern the behavior of those nonNewtonian fluids. This was accomplished by studying the amount of friction reduction that may be produced for a given spoil. Friction reduction (drag reduction) refers to the decrease in wall shear obtained at a given flow rate. This may also be thought of as the increase flow rate obtained at a given wall shear. In order to apply this information to a representative situation, data correlation and scale-up relations were then examined to determine their validity for these spoils. It was then possible to apply these results to a typical dredge operation and predict pressure drop and flow rate for the drag-reduced spoil.

The Scope

In an early study by Mysels (2) during World War II, reduced pressure drop for some thickened fluids was attributed to the effect of a variable viscosity with shear rate, that is, the non-Newtonian shear thinning behavior of the fluid. This suggests perhaps that the shear thinning dredge spoils may exhibit such drag reduction characteristics in their untreated form. It was then decided to approach the problem by first determining the validity of this idea. This was accomplished by measuring pressure drop and flow rate for each spoil and comparing the data to water reference data. In no case did any untreated spoil demonstrate drag reduction characteristics. Shear thinning was present (more in some cases than others) and dilution of some spoils produced data along the water curve, yet none of these showed less pressure drop than water. These data appear in Appendix A.

Before proceeding to introduce drag-reducing agents into each spoil, scale-up was attempted for the untreated spoils. A friction factor versus Reynolds number diagram was used to scale-up the pipe flow data. A second method was also used in the scale-up procedure which was developed by Bowen in 1961 (3, 4, 5, 6). Laboratory pipe diameters of 0.425 inches and 0.835 inches were used for the testing.

Following the successful scale-up, it was then decided to introduce a dilute concentration of drag-reducing agent into each spoil to determine how much drag reduction was possible. Because recent work with polyethelene oxide and polyacryamide polymers (1) indicated significant amounts of drag reduction, several polymers of these types were screened to determine the most effective polymer and concentration for the spoil tests. A Dow Chemical Company polymer, Separan AP 273 (polyacrylamide), was selected to be used at a concentration of 100 weight parts per million (wppm) or 0.1 grams/liter. Because the polymer is fragile and requires special mixing and handling, it will be discussed in more detail in the following chapter.

Each spoil flow was then injected with polymer solution, and the pressure drop and flow rate were measured as before. Scale-up was investigated and successfully accomplished by the use of a third method. Because the spoils ranged in inlet suspended solids concentration from 2% to 20.9%, the effect of solids concentration was markedly evident in the results. Viscosity measurements were also obtained for each spoil. The effect of particle size distribution (approximately an order of magnitude greater than the spoils) to one of the spoil. The effect of dissolved solids concentration was investigated by adding known concentrations of sodium chloride to the AP 273 and repeating the test with Separan MG 200 to see if the difference in the ionic character of the polymer would produce any noticeable change. The analysis of these effects and experimental results is taken up in Chapter IV.

CHAPTER II

EXPERIMENTAL TECHNIQUES

This chapter presents a look at the materials used, the pipe flow facility, and test procedure. Also given is some information concerning the handling and mixing of the spoils and the polymer solution. The procedure and equipment used to determine viscosity and density are also discussed.

Materials

The dredge spoils used in this study were supplied by the U. S. Army Corps of Engineers for the primary purpose of testing hydrocyclone separators at the Mechanical Engineering Laboratory at Oklahoma State University (7). Upon completion of the hydrocyclone project, the remaining spoil samples were forwarded to this researcher for the undertaking of the drag reduction study.

The original six spoil samples were dredged at five sites in the United States. A gravimetric analysis was conducted during the hydrocyclone project for each spoil to ascertain the solids concentration by weight. These spoils are listed here by dredging location and the corresponding value of suspended solids concentration (grams/liter) as follows:

Location	Solids Concentration (g/l)
Mobile	184
Tampa	45
Lake Charles	179
Toledo (DE)*	209
Toledo (OF)**	53
Savannah	112

* DE - Discharge Effluent
** OF - OverFlow

Due to some apparatus limitations, the Mobile and Savannah spoils were diluted to quarter and half strength respectively before drag reduction tests were conducted. The quarter strength Mobile spoil is referred to herein as Mobile-A and the half strength Savannah spoil is referred to as Savannah-A. Also, a particle size analysis (hydrometer analysis) of each spoil (7) showed that all the spoils were of similar particle size character (10-100μm). The data are not shown in the interest of clarity. Also dissolved solids tests (7) verified that all are salt water spoils except those from Toledo which may be considered to be fresh water samples.

Two concentrations of a laboratory test clay, Roger Mills Gray Clay (from Roger Mills County, Oklahoma) were also tested. The test clay was chosen because its particle size distribution is approximately the same as the spoils. It was used to demonstrate the effect of suspended solids concentration at low concentrations.

After all the spoils had been tested, the remaining bits of spoils were combined to yield a 76 gram/liter spoil labeled OSU spoil. This was used, at full strength and half strength (referred to as OSU-A), in conjunction with Ottawa sand, to demonstrate particle size effects. The solids concentrations and density of each fluid is given in Table I.

Pipe Flow Facility

The pipe flow apparatus used for this study is shown in Figure 2. The spoil was placed in the upstream reservoir and pumped through each two interchangeable stainless steel pipe sections having diameters of 0.425 and 0.835 inches. Entry lengths of 129 and 86 diameters preceded the upstream pressure taps of the 0.425 and 0.835 inch pipes respectively to permit the full development of the flow before the test section. The test section of the 0.425 inch pipe was 57 inches and for the 0.835 inch pipe was 113.5 inches. Tests were purposely conducted on two pipes so that data correlation and scale-up could be verified for the resultant data. The spoil was kept well mixed with a mixing motor located on the upstream reservoir. A 1½ horsepower centrifugal pump handled pumping duties while a six GPM Fischer-Porter rotameter was calibrated for each spoil. Pressure drop was measured with an inverted U-tube manometer having a full scale deflection of 50 inches. It was found that errors in pressure drop measurements caused by the density difference between spoil and water (normally used as manometer fluid) could be eliminated by running straight spoil in the manometer.

For preliminary tests conducted without polymer additives, the spoil was recirculated to the upstream reservoir after passing through the test section. Because the addition of polymer solution changed the character of the original spoil (flocculation of solid particles), the drag-reduced fluid was discharged into a downstream reservoir and was subsequently disposed of.

Two major considerations prompted the implementation of a pressure blowdown polymer injection system as opposed to pumping the polymer-spoil mixture. First, the polymer consists of long chain molecules which may be delicate in nature and would not withstand the harsh agitation of the centrifugal pump impeller. Secondly, very rapid flocculation of solid particles in the spoil occurred when the two fluids were mixed and, because of the delicate nature of the polymer, the mixer on the upstream reservoir would destroy the polymer molecules if it was used. Pressure blowdown capability was then incorporated into the system to minimize mechanical degradation and mixing problems.

The polymer injection branch of the apparatus consisted of a 75 gallon pressure vessel which was blown down with the laboratory supply of air. For laboratory safety, the safety blowoff valve was set at 20 psi and this proved sufficient for testing. Because the polymer solution dilutes the spoil into which it is injected somewhat, each polymer batch was prepared at a concentration (500 wppm) greater than test strength (100 wppm). This assisted in polymer handling and also permitted the use of a flowmeter of smaller capacity than that for the spoil flow. The flowmeter was calibrated for the polymer before testing began.

Handling and Mixing of Spoils

Two 55 gallon drums of each spoil were shipped to the Mechanical Engineering Laboratory from their respective dredge sites. Each drum was inner-lined and sealed so that the spoils were protected from rust. These drums were stored indoors to avoid possible fluid property changes due to freezing weather and dilution by rain.

Because the suspended solid particles of each spoil precipitated out of suspension during storage, the pre-test mixing procedure was of primary importance to insure a homogeneous mixture of solids in the test solution. This was accomplished by first inserting a triangular baffle arrangement into the drum containing the spoil. A three-phase electric mixing motor was then mounted on top of the baffles with the shaft extending to the bottom of the drum. Two sets of four perpendicular blades affixed to the shaft produced a turbulent mixing effect as they rotated past the baffles and the solids soon became suspended. The time required to thoroughly mix each spoil varied with respect to solids concentration, however, each was allowed to mix for two hours, and this proved to be sufficient.

A one inch hose connected to the pump inlet was primed and the spoil was pumped into the upstream reservoir as the mixer continued to run. In all cases, a negligible amount of solids was lost in the transfer process. The mixing motor was then transferred to the upstream reservoir for which another set of baffles was made.

The dilution of the Mobile and Savannah spoils was carried out in the upstream reservoir due to its larger capacity over that of the drum and so that mixing could continue as dilution proceeded. Care was taken to maintain the same salinity for the diluted spoil by using rock salt. Mixing of the test clay solutions was also carried out in the upstream reservoir to minimize transfer losses.

Handling and Mixing of Polymer

As previously mentioned, water soluble synthetic polymers can be mechanically degraded and therefore require special handling to obtain scientific (reproducible) data. They are usually shipped and stored in small polyethylene coated cardboard drums. The polymers used in this study (Separan AP 273 and MG 200) were stored at room temperature and kept sealed to avoid pickup of atmospheric moisture, contamination, and thermal degradation. These polymers were stored only a few months before use so that degradation due to aging was negligible. Only after about a year does aging become significant.

Special mixing procedures were also used to prepare the dilute polymer solution. In order to dissolve the polymer quickly and completely, it is initially important to thoroughly disperse the particles so that the particle surfaces begin to absorb solvent immediately. This allows a viscous envelope to surround each particle so that the tendency to agglomerate is suppressed. The bulk viscosity also increases rapidly. These two effects help in obtaining a homgeneous well mixed solution.

There exist two basic methods by which to disperse the particles. The first involved baffles and a low speed stirring motor similar to those used for mixing the spoil. The method used in this case, however, is one of predispersion in a non-solvent fluid. Such polymers are insoluble in concentrated solutions of salts and alkalis and in certain water-miscilbe organic liquids such as anhydrous alcohols or glycols. In this case, the proper amount of anhydrous isopropanol was poured into a two liter graduate. The graduate was placed on top of a magnetic mixer with the magnet in the bottom of the graduate. As a vortex was formed in the alcohol, the polymer granules were slowly sprinkled in. After about two or three minutes, the suspension was added to the correct amount of tripple-filtered water. With the gentle stirring motion of a glass rod, all the polymer dissolved within 30 minutes.

Because a dilute solution such as this degrades after a couple of days and because drag reduction runs were generally made two or three days apart, a new batch of polymer solution was made anytime a batch became more than two days old. Each batch was prepared at 500 wppm or 0.5 grams/liter as previously indicated. Since no more than ten or twelve gallons was necessary for any set of runs, a batch represented approximately 15 gallons. The mixing proportions for a 500 wppm batch are as follows:

15 gallons - triple-filtered water
1420 ml - anyhdrous isopropanol
28.4 grams - polymer

The mixture was prepared in a 40 gallon stainless steel open top container located above the elevation of the polymer pressure vessel. The elevation difference allowed the mixture to be slowly gravity drained into the pressure vessel to avoid splashing and harsh agitation. Further description of polymer chemistry and preparation may be found in Reference 8.

Specific Gravity and Viscosity

The specific gravity was determined for each spoil for use in calculating the shear velocity and Reynolds number. Because the solids of each spoil tended to settle out somewhat over a brief time, use of a hydrometer was discouraged. Specific gravity was measured by weighing a well mixed 100 ml sample and calculating the density.

Vicosity measurements were also made for each solution tested (except the drag-reduced OSU spoils with sand due to solids flocculation). The viscosity of each spoil was measured with both a Brookfield

LVF Synchro-Electric Viscometer and a Fann Model VG Viscometer (by permission from School of Technology) and the data appear graphically in Figures 3-7.

The Brookfield and Fann viscometers are Couette type viscometers. Their dial readings must be converted to units of viscosity and shear rate. Thus there exist equations to convert angular indication of torque into centipoise and rotational spindle speed into shear rate (9). For the Fann viscometer the relationship is

$$\tau = \frac{k_s \beta}{2\pi R_B^2} \left[h_1 + \frac{h_2}{3\cos\alpha} \right]^{-1} \qquad 2.1$$

where k_s = spring constant = 387 dyne-cm/degree

R_B = radius of inner stationary cylinder = 1.725 cm

h_1 = height of inner stationary cylinder = 3.80 cm

h_2 = height of conical section - 0.70 cm

$\cos\alpha$ = 0.376

β = dial indication (degrees)

τ = shearing stress (dyne/cm^2)

Thus τ = 4.66 dyne/cm^2-degree

Viscosity is related to shearing stress through the rate of shear as defined by

$$\tau = \mu \frac{dU}{dy} \qquad 2.2$$

where μ = viscosity (centipoise)

$\frac{dU}{dy}$ = shear rate (sec^{-1})

It can be shown that

shear rate (sec^{-1}) = 1.703 X cylinder speed (RPM)

Thus

Speed (RPM)	Shear Rate (sec^{-1})	Viscosity (centipoise)
3	5.11	91.2β
6	10.22	45.6β
100	170.2	2.74β
200	340.4	1.37β
300	511.0	.91β
600	1022.0	.46β

yields the viscosity-shear rate relationship for the Fann VG Viscometer.

For the Brookfield Synchro-Electric Viscometer, the equations were obtained through private communication with Brookfield Engineering. Equations valid only for the LV1, LV4, and UL adapter spindles were available. The results of computations with those equations are as follows:

Speed (RPM)	Shear Rate (sec^{-1})		
	LV1	LV4	UL adapter
6	1.32	1.25	7.35
12	2.64	2.51	14.71
30	6.60	6.27	36.71
60	13.20	12.54	73.42

Viscosity is calculated by multiplying the dial reading by multiplication factors supplied by Brookfield.

Test Procedure

The testing procedure followed for measuring pressure drop and flow rate for each raw spoil is given in Appendix C. In general, the fluid is pumped through the test section over the length of which pressure drop is measured in inches of fluid with an inverted u-tube manometer. The flow rate is measured by the "watch and weight" method at the same time the pressure drop is recorded.

The procedure is basically the same for the drag-reduction tests with the dilute polymer solution being injected into the pipe flow at a distance of greater than 50 diameters upstream of the upstream pressure tap. The fluid is subsequently disposed of upon completion of the test.

CHAPTER III

EXPERIMENTAL DATA AND RESULTS

This chapter presents the pipe flow data for both the untreated spoils and the drag-reduced spoils and offers a brief interpretation of each. Also, correlation of the untreated spoil data is discussed first with regard to a simple friction factor vs. Reynolds number representation from which scale-up may be accomplished and secondly for a similar method (that of Bowen) which is also applied successfully. Because Bowen's method is more detailed yet more convenient, it is discussed more thoroughly and is illustrated for one of the actual spoils. The two methods are finally treated for the drag-reduced spoils for which it will be found that a third correlation method in conjunction with Bowen's method works. A sample calculation using the scaled-up drag reduction information is then offered to illustrate the measure of increased flow rate accomplished by the drag reduction procedure which, as the reader will recall, was the desired result.

Preliminary Measurements

Pipe flow data was first recorded for each of the untreated spoils and test clays. These data are given in Tables II, III, and IV and are plotted in Figures 8-15 (dashed lines). Figures 8 and 9, for example, show that the Mobile-A spoil and the Lake Charles spoil shear thin quite significantly as the flow rate increases. While all the spoils do not shear thin as much, each lies above and to the left of the water curve (solid line), i.e., none show less pressure drop than water. This indicates that no drag reduction was obtained. The term "percent drag reduction" as used here and throughout this paper is defined by the following expression:

$$\% \text{ Drag Reduction} = \left[\frac{\Delta P_{H_2O} - \Delta P_{DRS}}{\Delta P_{H_2O}}\right] 100 \qquad 3.1$$

where ΔP_{H_2O} and ΔP_{DRS} are measured at the same flow rate.

Zero drag reduction also proved to be the case for the OSU spoils (as would be expected) and for both concentrations of Roger Mills Gray Clay. The viscosity for these fluids (Figures 3-7) bear out their non-Newtonian shear thinning nature as indicated in Chapter I. As the spoil pipe flow curve approaches the water curve or begins to behave in a waterlike manner, calculation of the corresponding viscosity, using Newton's law of viscosity (equation 2.2), reveals that the viscosity curve begins to level off and verifies the waterlike Newtonian behavior.

Many times in an actual dredge or cross-country pipeline situation the fluid will have a density on the order of the Lake Charles spoil or even greater in which case a shear thinning behavior is almost assured. It is this sort of thickened condition that produces the flow blockage. For such a situation, drag reduction is desired at some point in the shear thinning region to help the fluid in its turbulent mixing and relieve the thickened condition at a lower wall shear.

Scale-up Technique for Untreated Spoils

In the application of our study to modern dredge operations and cross-country pipelines, it is important to be able to scale-up the data obtained in the laboratory with much smaller pipe diameters. In researching the literature (1, 3, 4, 5, 6, 10, 11), two methods for the scale-up of turbulent flow data appear most frequently. The first method is simply a plot of the pipe flow data on a friction factor as a function of Reynolds number diagram (Moody diagram). Because the shear thinned solution behaves in a waterlike manner as previously indicated, it would be expected that the spoil data would all fall along a single curve as does the water data. This is indeed so as can be seen from Figure 16 for the Toledo (DE) spoil for example. This means that the data is correlated with respect to the diametric dependence of the curve in the turbulent regime. That diametric dependence can be seen from the equation for the Darcy friction factor

$$f = 0.016 + 0.500/(\mathrm{Re})^{0.32} \qquad 3.2$$

for Reynolds numbers between 3,000 and 3,000,000. Equation 3.2 may be rewritten in the general form

$$f = \mathrm{constant}_1 + \mathrm{constant}_2/(\mathrm{Re})^b \qquad 3.3$$

where b is the slope of the curve in the turbulent regime. Taking a look at the Reynolds number reveals that:

$$(\mathrm{RE})^b = (\rho VD/\mu)^b \propto D^b$$

so that the diametric dependence of f vs. Re in the turbulent region is the slope b. For any waterlike fluid then, the slope b will be the same as for water, i.e., $b = 0.32$. Indeed this is the case, as calculation of the slope of the Toledo (DE) curve reveals that $b = 0.33$.

At this point one might question the fact that the Toledo (DE) curve falls below the water curve which may seem to indicate a drag reduction for this untreated spoil in contradiction to the statement made earlier that the untreated spoils showed no drag reduction. This, however, is not the case for at a constant wall shear (hence friction factor), the spoil viscosity, although being relatively constant with shear rate in the turbulent regime, is significantly larger than for water. Subsequently, the Reynolds number for the spoil at that friction factor will be significantly smaller than for water at the same friction factor. This, then, accounts for any false notion of drag reduction.

Since the data is then correlated on the Moody diagram, it is a rather straightforward matter to scale-up directly from this diagram. If one, for example, wishes to scale-up a given ΔP on the $D = 0.425$ inch and $L = 57$ inches pipe to the corresponding ΔP on a $D = 12$ inches and $L = 1500$ feet pipe, he would first calculate the friction factor for the ΔP of the small pipe. This is, of course, the same for the large pipe so that by substituting $D = 12$ inches and $L = 1500$ feet into his $f = f(\Delta P)$ equation, he would solve for the ΔP in the large pipe.

Bowen's method of data correlation and scale-up is similar in development to the Moody diagram method. Bowen began by investigating the various empirical equations that had been suggested for fully developed turbulent Newtonian flow. He found that the Blasius friction factor equation (¼ times a simplified Darcy relationship) described the non-Newtonian case very well at Reynolds numbers less than 100,000; however, errors arise at higher Reynolds numbers. Variations on

Blasius' relationship were suggested to more accurately describe the non-Newtonian behavior at Reynolds numbers of 3,000,000. Bowen noted, however, that the vast majority of non-Newtonian fluids are rather viscous so that any equivalent Reynolds number would rarely exceed 100,000. Use of a relationship of the form of the Blasius equation would therefore be an excellent approximation of those cases in which the data would be correlated on a Moody diagram and where the correlation could be reasonably fit with a straight line. Considering Blasius' equation, then, it states

$$f = 0.079/(Re)^{0.25} \tag{3.5}$$

which, in actual terms, reads

$$g_c D \Delta P/2\rho L V^2 = 0.079(DV\rho/\mu)^{-0.25} \tag{3.6}$$

rearranging equation 3.6 yields

$$D^{1.25} \Delta P/L = kV^{1.75} \tag{3.7}$$

$$\text{where } k = 0.158(\rho/\mu)^{-0.25}(\rho/g_c) \tag{3.8}$$

Equation 3.7 is given in the general form

$$D^{(1+b)} \Delta P/L = kV^{(2-b)} = kV^c \tag{3.9}$$

Equation 3.9 indicates that $D\Delta P/L$ must be multiplied by D^b for the turbulent data to correlate when plotted against velocity. This means that a logarithmic plot of $D^{(1+b)}\Delta P/L$ as a function of V yields a straight line of slope c along which all the data fall for all pipe diameters. Of course this works for the water data as well because it too satisfies the Darcy (hence Blasius) friction factor equation from which this correlation was determined. This diagram then facilitates the turbulent data correlation. As in the case of the Moody diagram method, the data may be scaled-up directly from this correlation diagram.

Figure 17 shows an example of this correlation for the Toledo (DE) spoil and verifies that both pipe diameters tested fall along the same curve having slope $c = 2-b \approx 1.6$. The reader should note that, because the shear thinning Toledo (DE) spoil behaves very much like water, it turns out that the straight line correlation curve for the Toledo (DE) spoil and the water are virtually the same. For discussion purposes then, Figure 19 may be used to talk about either fluid. Also, note that the appearance of what would seem to be a drag reduction effect does not appear in this correlation because the ordinate and abscissa are independent of viscosity which, as the reader will recall, produced the elusion on the Moody diagram.

The raw spoils and water data can thus be successfully scaled-up using either method. The Bowen method is perhaps a bit more useful because it requires no knowledge of the fluid viscosity as does the Moody diagram in the calculation of Reynolds number. This, of course, does not presume that all turbulent data correlate for this same diameter dependence as will be demonstrated clearly for the drag-reduced spoils.

Drag Reduction Measurements and Scale-up

Following each set of preliminary data, that same spoil or test clay was injected with polymer and drag-reduced. Table V gives the drag-reduced data for each of the original spoils; Table VI shows the two concentrations of test clay treated at two polymer concentrations; Table VII gives data illustrating the effect of adding larger particles to a spoil; and Table VIII shows those solutions tested for the effect of salinity. These data are plotted in Figures 8-15 and Figures 18 and 19 (centerline curves). The corresponding viscosity relationships are compared in Figures 3-7 with the untreated materials. Some viscosity measurements were unobtainable with either the Brookfield or Fann viscometer due to flocculated particles gumming up the Couette arrangement. Each of the above mentioned effects will be analyzed in the following chapter. It is more important at this point to set down the relationships and other information necessary for that analysis.

Of initial importance was the determination of a correlation parameter for the drag-reduced spoil which would allow it to be scaled-up to large pipe diameters in much the same way the untreated spoils were. This proved to be rather straightforward also as the data indicated a reasonable correlation with respect to water referenced wall shear velocity (and hence wall shear stress). This was established by plotting the standard drag reduction diagram of percent drag reduction as a function of wall shear velocity as shown in Figures 20-23. Drag reduction is again defined as

$$\%\text{ Drag Reduction} = \left[\frac{\Delta P_{H_2O} - \Delta P_{DRS}}{\Delta P_{H_2O}}\right] 100 \qquad 3.10$$

and wall shear velocity is defined as

$$U_\tau = (g_c/\rho \cdot D\,\Delta P_{H_2O}/4L)^{1/2} \qquad 3.11$$

As can be seen for the case of the original spoils and the test clays (for which data was taken on both pipe diameters), the data for both pipe diameters fall along the same curve. In most cases data on the 0.835 inch diameter pipe was not obtained at large values of drag reduction due to the limited amount of dredge material available. This shortage also limited the number of data points for the larger pipe.

Many more data points were allowable on the 0.425 inch diameter pipe as spoil consumption was not as critical at each flow rate. Although not a great deal of overlap in the data occurred between the two pipes, evidence of the correlation is adequate. This correlation was assumed to hold as well for the saline polymer-water solutions for which data was taken only on the smaller pipe. Confirmation of such data correlation may be seen by reviewing the work of Whitsett (10) and Donohue (12).

As indicated previously, the diametric dependence of the correlation is not the same for the drag-reduced spoils as for the untreated spoils. Figure 20, for example, illustrates that the data correlates with respect to wall shear velocity (hence wall shear stress) and not with respect to the same D^b as before. Thus, one would find that a transfer of the drag reduction data to the Moody diagram would produce separate and distinct curves for each pipe diameter with a given spoil. This is to be expected as the D^b dependence is built into the Moody diagram and cannot be removed. Therefore, it is inconvenient to talk about using the Moody diagram in conjunction with the drag reduction diagram of the Whitsett correlation for scale-up. This is not to say that it cannot be done with the Moody diagram; however, use of the Bowen correlation curve is much more convenient. The reasoning is rather straightforward. The drag reduction curve for any particular spoil and pipe diameter represents an equation in terms of the ordinate % DR and abscissa U_τ . The unknowns for the desired pipe diamter are ΔP_{H_2O} andΔP_{DRS}. The Bowen correlation for non-polymer water gives part of the information needed here. The flow rate (hence velocity) for the particular situation is, of course, a known quantity so that the value of $D^{(1+b)} \Delta P_{H_2O}/L$ may be picked off the curve. Thus ΔP_{H_2O} may be solved for and therefore eliminates one unknown from the drag reduction relationship. The value of ΔP_{DRS} may then be solved for as the system now consists of one equation and one unknown. If it is inconvenient to determine the equation of the drag reduction curve, this procedure can be carried out graphically by solving first for U_τ with the determined value of ΔP_{H_2O} and desired diameter, picking off the corresponding value of % DR from the graph, then solving for $\Delta P_{DRS} = \Delta P_{H_2O}(1-.01(\% \text{ DR}))$.

Also, if, instead of referencing drag reduction to the water curve, drag reduction was referenced to the untreated spoil curve, the procedure would be exactly the same using the Bowen untreated spoil correlation and the untreated spoil referenced drag reduction diagram. A sample calculation to demonstrate the feasibility of the drag reduction procedure is given in Appendix D. It will be shown that significant flow rate increase may be accomplished for the Toledo (DE) example in a 12 inch pipe.

CHAPTER IV

ANALYSIS OF DRAG REDUCTION RESULTS

This chapter deals with the effects that influence the behavior of the spoils. The effect of diluting a shear thinning spoil as an aid to drag reduction is discussed first. Then the effect of the suspended solids concentration of the spoils is discussed. The effect of dissolved solids concentration is dealt with next. Lastly, the effect of increased particle size is discussed as a possible agent for drag reduction. Viscosity, being the parameter governing the non-Newtonian character of the spoils, is of importance in analyzing the results. It is difficult, however, to isolate the effect of viscosity itself as the other effects discussed influence the viscosity differently. For example, the addition of salt and/or large particles to a solution influences the viscosity in a different manner. Consequently, the effect of viscosity is not independent of the other effects and cannot be discussed as a separate issue.

The reader will also note that the term "onset" is used several times in this chapter. This term refers to the value of wall shear velocity (hence wall shear stress) at which drag reduction begins for a particular fluid. This is also referred to as the critical wall shear velocity. This quantity allows an experimentalist to judge which fluid out of several exhibits the best drag-reduction characteristics. The fluid with the lowest onset wall shear would be the most effectively drag reduced.

Effect of Dilution by Polymer Injection

One can see, in the case of the OSU and OSU-A spoils, for example, that dilution of the shear thinning fluid moves the spoil pipe flow curve closer to the water curve. This, in essence, is a form of drag reduction because, at least in the shear thinning region, the pressure drop for the diluted spoil at a given flow rate is less than that for undiluted spoil at the same flow rate. This effect, however, is of minimal importance to this study in the respect that the excess amounts of water necessary to dilute a highly concentrated fluid are undesireable in a dredge or cross-country pipeline. In fact, the typical hopper dredge is filled to overflowing in order to obtain a higher concentration of solids in the dredge. Since many inland dredge disposal sites are small, excess water is avoided to make most efficient use of the available capacity. Only when the pipeline becomes blocked is excess water used.

Because the drag-reducing polymer is mixed in a water solution, some dilution takes place when the polymer solution is injected into the spoil. The polymer solution is mixed at a high concentration to reduce the amount of water per unit weight of polymer and thus decreases the dilution effect as much as is feasible. As previously mentioned, this also assists in the handling and control of the polymer flow. Since it is the purpose of this study to investigate the effects of the polymer additive and not that of dilution, the definition of percent drag reduction given earlier is referenced to the water curve. Knowing that no untreated spoil (diluted or not diluted), shows less pressure drop than water, then any pressure drop below the water curve will be due solely to the polymer addition.

Effect of Suspended Solids Concentration

In order to quantitatively judge the effect of suspended solids concentration, it is important to isolate the phenomenon, that is, eliminate the other significant effects such as salinity (dissolved solids) and particle size. This was accomplished with the test clay because it was mixed with fresh water. Only one kind of clay, having a single particle size distribution, was tested. Looking at the drag reduction curves (Figure 21) for the 2% RMGC and 5% RMGC treated with 100 wppm AP 273 and comparing them with the 100 wppm AP 273 water curve (equivalent to 0% clay), it can be seen that as suspended solids concentration increases, the onset of drag reduction shifts to higher values of shear stress. This indicates that the polymer is less effective on the higher concentration slurries or equivalently that the more concentrated fluids require a larger shear stress to reach onset.

Effect of Dissolved Solids Concentration

As discussed in the previous section, the critical or onset shear velocity of the clays and spoils as shown in Figures 20 and 21 increases as the suspended solids concentration increases. This is true for the most part, yet it may be noted that the Mobile-A and the Toledo (OF) spoil are both out of place with respect to this statement. The most reasonable explanation seems to rest with the effect of dissolved solids concentration (salinity) as Table I shows that the Mobile-A spoil, for example, has a high dissolved solids concentration.

Tests were therefore performed to verify the hypothesis that dissolved solids reduced the effectiveness of the polymer additives. Two concentrations of salt (NaCl) water were injected with AP 273 at 100 wppm and pressure drop and flow rate recorded as before (Table VIII). Figure 18 shows how the data plots on the pressure drop and flow rate diagram while Figure 22 indicates the amount of drag reduction. As hypothesized, the curves move to the right with increased dissolved solids concentration. Separan MG 200, a slightly anionic polymer, was tested in the same manner to determine if its lesser ionic character significantly changed the salinity effect seen with AP 273. Although the MG 200 is the overall inferior drag reducing agent, it showed the same type behavior in the saline solution as AP 273, that is, the saline curves rank to the right of the fresh water polymer curve with no improvement in saline drag reducing effect.

It is therefore evident that the effect of dissolved solids concentration displaces the above mentioned curves from their suspended solids rankings. It is further important to note that the onset shear stress does correlate with respect to total solids concentration. This is verified in Figure 24 which shows that as total solids increases, the critical wall shear velocity increases. Although the Toledo (OF) spoil ranks slightly out of place on the drag reduction curve with regard to the Savannah-A spoil, experimental error in the acquisition of the Savannah-A data most likely accounts for this discrepancy.

Effect of Particle Size

Since the particle size distribution of the spoils and clays (10-100μm) were very similar, it could only be assumed that any particle size effects for those drag reduction tests would be negligible or at best imperceptible within the error of the experimental measurements. Other tests were therefore arranged to investigate the possibilities of a significant contribution from particle size changes. These test were conducted by adding Ottawa sand (100-1000μm) to the madeup OSU spoil. The data are given in Table VII and plotted in Figure 15. Replotting this information in Figure 23 readily reveals an exceptional drag reduction assist from the sand. An attempt was made to obtain viscosity data for the drag-reduced OSU spoils with sand to verify this behavior, however, solids settling curtailed the acquisition of the data.

It is likely that the sand obstructs the vortex stretching in the fluid by virtue of its larger size rather than inhibiting the stretching elastically as the polymer is theorized to do (1), yet the result is much the same. The sand reacts on a discrete particle basis much more than the smaller particles which act in a more continuous manner. In any event, the effect of the larger sand particles on the drag reduction phenomenon is rather pronounced and obvious. It may be of value to study the combination of polymer and large particles further at some later date.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

This chapter briefly summarizes the conclusions based on the results of the previous chapters with regard to the initial statement of the problem. While polymer drag reduction and slurry pipeline flows individually have existed and been studied for many years, their combined feasibility is of brief origin as a survey of the technical literature reveals. This study is perhaps the initial attempt at researching this particular engineering application. With this in mind, several recommendations are suggested in this chapter.

Conclusions

It was initially determined that no untreated spoil tested demonstrated any drag reduction. In fact, a couple were significantly shear thinning in nature. It is also concluded that, even though both correlation and scale-up procedures for the spoil work, the Bowen procedure holds two advantages over the Moody diagram method. These include the fact that the Bowen method requires no viscosity information as does the Moody diagram method and that the Bowen correlation may be more conveniently used in conjunction with the drag reduction correlation of Whitsett to scale-up the drag-reduced data. The sample calculation then bears out the fact that the introduction of drag-reducing polymers does indeed assist in substantially increasing the pipeline flow rate. This puts the flow well into the regime of turbulent mixing such that the solid particles remain suspended in the liquid.

It was found that the suspended solids concentration of the spoil played a major part in dictating the amount of drag reduction obtainable at a particluar shear stress. It was also found that, in addition to suspended solids concentration, the dissolved solids concentration was a significant factor in ranking the spoils. It was then shown that the total solids concentration is the parameter that correctly accounts for the ranking of the spoils for drag reduction. Use of a less ionic polymer, however, did not help overcome the decrease in drag reduction with increased salinity. The addition of larger particles did assist in increasing the amount of drag reduction significantly. While a suggestion is offered to account for this, the actual explanation is not known at this time.

Recommendations

The pipe flow tests conducted show that the benefit of drag reduction in the transport of slurries in pipelines is of importance. Although very important initial steps have been taken here to introduce this particular application of drag reduction, much work in the area has yet to be done. It is therfore recommended that tests be conducted to 1). confirm the amount of drag reduction possible in such fluids, 2). verify the scale-up procedure used by testing a larger flow facility, and 3). study other parameters that effect the phenomenon as was done here with salinity and particle size. Of course, it is important to complete an economic feasibility study to determine if savings in time and power loss outweigh the additional cost of polymer injection capability.

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APPENDIX A

DATA TABULATIONS

TABLE I

SOLIDS CONCENTRATION AND DENSITY

Material	Density (lb_m/ft^3)	Suspended Solids (g/l)	Dissolved Solids (g/l)
Mobile-A	62.8	46	28.5
Lake Charles	69.5	174	20.3
Toledo (DE)	69.7	209	0.8
Toledo (CF)	63.3	53	1.6
Savannah-A	64.5	56	4.9
2% RMGC	62.7	20	0
5% RMGC	63.5	50	0
OSU	64.2	76	11.9
OSU-A	62.7	38	11.9

TABLE II

PIPE FLOW DATA FOR RAW DREDGE SPOILS IN D=0.425"(L=57") AND D=0.835"(L=113.5")

Pipe Diameter	Mobile-A		Lake Charles		Toledo (DE)		Toledo (OF)		Savannah-A	
	ΔP (in. H_2O)	Q (lb_m/min)	ΔP (in. H_2O)	Q (lb_m/min)	ΔP (in. H_2O)	Q (lb_m/min)	ΔP (in. H_2O)	Q (lb_m/min)	ΔP (in. H_2O)	Q (lb_m/min)
0.425"	9.37	13.55	15.40	4.75	8.47	12.00	6.60	11.50	7.65	12.00
0.425"	10.38	16.45	18.40	7.75	10.27	13.00	12.50	17.00	11.65	14.50
0.425"	11.80	13.75	19.30	7.25	17.30	19.00	17.45	19.50	18.20	16.00
0.425"	13.90	18.05	20.70	11.75	20.60	22.50	25.10	27.00	26.80	26.00
0.425"	14.65	18.95	24.90	15.00	35.40	29.50	34.50	30.00	31.90	28.00
0.425"	16.18	19.30	29.30	15.25						
0.425"	17.80	19.25	37.70	17.25						
0.425"	23.20	22.50								
0.425"	30.10	26.25								
0.835"	2.70	24.65	4.70	19.50	6.48	32.50	5.48	43.50	4.03	25.50
0.835"	2.90	27.25	12.90	42.00	13.30	67.00	8.94	57.50	11.05	65.00
0.835"	3.15	7.31	21.30	81.66	20.90	89.00	13.70	74.00	17.45	79.00
0.835"	3.50	26.60	29.30	110.00	25.70	101.00	24.10	94.00	24.40	93.00
0.835"	3.60	25.10	34.90	124.16	32.80	110.00	31.40	113.00	31.10	109.00
0.835"	5.15	35.25								
0.835"	6.20	42.00								
0.835"	10.35	58.40								
0.835"	11.80	61.60								
0.835"	17.90	80.00								
0.835"	24.00	96.30								
0.835"	30.60	112.16								

TABLE III

PIPE FLOW DATA FOR OSU AND OSU-A SOILS IN D=0.425"(L=57") AND D=0.835"(L=113.5")

Pipe Diameter	OSU		OSU with sand		OSU-A		OSU-A with sand	
	ΔP (in. H_2O)	Q (lb_m/min)	ΔP (in. H_2O)	Q (lb_m/min)	ΔP (in. H_2O)	Q (lb_m/min)	ΔP (in. H_2O)	Q (lb_m/min)
0.425"	2.5	1.75	1.3	2.50	0.9	3.50	0.6	0.50
0.425"	4.1	4.00	2.1	5.75	4.1	9.00	2.5	6.00
0.425"	5.2	7.50	2.9	7.25	11.0	13.50	3.6	8.75
0.425"	9.2	14.00	4.8	9.25	14.5	18.00	6.9	11.25
0.425"	11.7	14.00	6.4	11.00	16.0	19.50	15.9	19.00
0.425"	14.6	18.50	12.6	16.50	21.8	23.50	24.1	24.00
0.425"	18.6	20.50	22.9	23.00	21.8	23.50		
0.425"	23.2	24.00			35.1	30.50		
0.425"	32.0	29.00						
0.835"	2.5	17.50			1.9	19.50		
0.835"	5.0	34.00			4.0	32.00		
0.835"	6.3	39.00			7.0	45.50		
0.835"	8.5	45.50			9.4	54.00		
0.835"	10.6	47.00			13.2	66.00		
0.835"	12.3	62.00			19.0	86.00		
0.835"	16.1	79.50			25.0	95.00		

TABLE IV

PIPE FLOW DATA FOR CLAYS AND WATER IN D=0.425"(L=57") AND D=0.835"(L=113.5")

Pipe Diameter	2% RMGC		5% RMGC		H_2O	
	ΔP (in. H_2O)	Q (lb_m/min)	ΔP (in. H_2O)	Q (lb_m/min)	ΔP (in. H_2O)	Q (lb_m/min)
0.425"	9.2	13.50	7.8	12.50	1.8	5.00
0.425"	17.9	20.00	12.7	17.50	5.6	10.00
0.425"	26.0	25.00	19.6	22.00	11.8	15.50
0.425"			23.2	24.00	19.8	21.50
0.425"			28.7	27.50	25.7	25.25
0.425"			37.8	32.00	30.9	27.50
0.835"	5.7	41.00	10.4	58.00	0.5	9.50
0.835"	16.5	74.00	14.8	70.50	0.85	13.15
0.835"	25.2	99.00	17.5	80.00	3.15	29.25
0.835"			24.4	97.00	8.95	53.00
0.835"			36.1	117.00	11.50	63.00
0.835"					19.40	83.50
0.835"					25.70	100.00
0.835"					32.30	112.50

TABLE V

DRAG-REDUCED PIPE FLOW DATA FOR RAW DREDGE SPOILS IN D=0.425"(L=57") AND D=0.835"(L=113.5")

Pipe Diameter	Mobile-A 100wppm AP 273		Lake Charles 100wppm AP 273		Toledo (DE) 100wppm AP 273		Toledo (OF) 100wppm AP 273		Savannah-A 100wppm AP 273	
	ΔP (in. H_2O)	Q (lb_m/min)	ΔP (in. H_2O)	Q (lb_m/min)	ΔP (in. H_2O)	Q (lb_m/min)	ΔP (in. H_2O)	Q (lb_m/min)	ΔP (in. H_2O)	Q (lb_m/min)
0.425"	9.7	14.00	18.4	10.00	22.5	23.00	10.0	14.00	11.8	19.00
0.425"	11.9	17.00	20.1	23.00	24.2	29.00	14.5	22.00	13.2	26.50
0.425"	16.3	21.00	20.2	22.00	24.9	27.00	23.3	34.00	21.4	31.50
0.425"	18.7	27.00	24.5	30.00	31.7	35.00				
0.425"	21.0	30.00								
0.425"	24.0	36.00								
0.425"	26.3	45.00								
0.835"	3.7	26.00	14.3	52.00	8.0	43.00	6.5	45.00	6.8	44.00
0.835"	9.8	55.00	17.0	66.00	10.0	52.00	12.4	74.00	10.8	67.00
0.835"			19.0	75.00					11.1	65.00
0.835"			20.0	83.00						

TABLE VI

DRAG-REDUCED PIPE FLOW DATA FOR TEST CLAYS IN D=0.425"(L=57") AND D=0.835"(L=113.5")

Pipe Diameter	2% RMGC 50wppm AP 273		2% RMGC 100wppm AP 273		5% RMGC 50wppm AP 273		5% RMGC 100wppm AP 273	
	ΔP (in. H_2O)	Q (lb_m/min)	ΔP (in. H_2O)	Q (lb_m/min)	ΔP (in. H_2O)	Q (lb_m/min)	ΔP (in. H_2O)	Q (lb_m/min)
0.425"	6.0	18.00	9.2	26.00	9.4	15.50	10.4	20.50
0.425"	8.7	24.50	14.0	38.50	13.4	24.00	16.3	36.50
0.425"					16.8	35.50		
0.835"	3.4	40.00	1.8	27.00	4.0	35.00	2.5	28.00

TABLE VII

DRAG-REDUCED PIPE FLOW DATA FOR OSU AND OSU-A SPOILS IN D=0.425"(L=57") AND D=0.835"(L=113.5")

Pipe Diameter	OSU 100wppm AP 273		OSU with sand 100wppm AP 273		OSU-A 100wppm AP 273		OSU-A with sand 100wppm AP 273	
	ΔP (in. H_2O)	Q (lb_m/min)	ΔP (in. H_2O)	Q (lb_m/min)	ΔP (in. H_2O)	Q (lb_m/min)	ΔP (in. H_2O)	Q (lb_m/min)
0.425"	12.0	16.00	9.3	14.00	10.0	17.00	5.4	12.00
0.425"	18.0	25.00	14.3	20.00	11.8	20.00	6.7	16.00
0.425"	22.0	31.00	14.4	23.00	15.0	26.00	9.3	20.00
0.425"	27.8	46.00	21.0	33.00	18.0	37.00	11.0	23.00
0.425"	29.5	43.00	24.3	39.00			12.9	28.00
0.425"							15.3	32.00
0.835"	6.8	40.00			5.3	39.00		
0.835"	11.0	56.00						

TABLE VIII

DRAG-REDUCED PIPE FLOW DATA FOR SALINE SOLUTIONS IN D=0.425"(L=57") AND D=0.835"(L=113.5")

Pipe Diameter	100wppm AP 273 no NaCl		100wppm AP 273 11.9g/l NaCl		100wppm AP 273 26.5g/l NaCl		100wppm MG 200 no NaCl		100wppm MG 200 11.9g/l NaCl	
	ΔP (in. H_2O)	Q (lb_m/min)	ΔP (in. H_2O)	Q (lb_m/min)	ΔP (in. H_2O)	Q (lb_m/min)	ΔP (in. H_2O)	Q (lb_m/min)	ΔP (in. H_2O)	Q (lb_m/min)
0.425"	0.3	1.00	1.8	6.00	1.8	6.00	1.4	5.00	1.7	5.50
0.425"	2.1	8.00	3.7	12.00	3.3	10.00	2.4	7.00	5.8	15.00
0.425"	3.0	11.00	6.1	18.00	4.7	14.00	5.7	14.50	7.5	19.00
0.425"	5.2	18.00	9.7	27.00	7.9	20.00	7.0	18.50	10.2	26.00
0.425"	7.0	22.00	12.7	35.00	11.2	32.00	11.0	25.00	12.0	30.00
0.425"	12.1	34.00	15.7	42.00	15.0	41.00	13.1	34.00	13.4	33.00
0.425"	14.0	38.00					15.0	38.00	14.3	35.00
0.425"	18.6	50.00					20.5	51.00	15.0	37.00
0.425"	19.6	49.00							16.5	41.00

APPENDIX B

FIGURES AND ILLUSTRATIONS

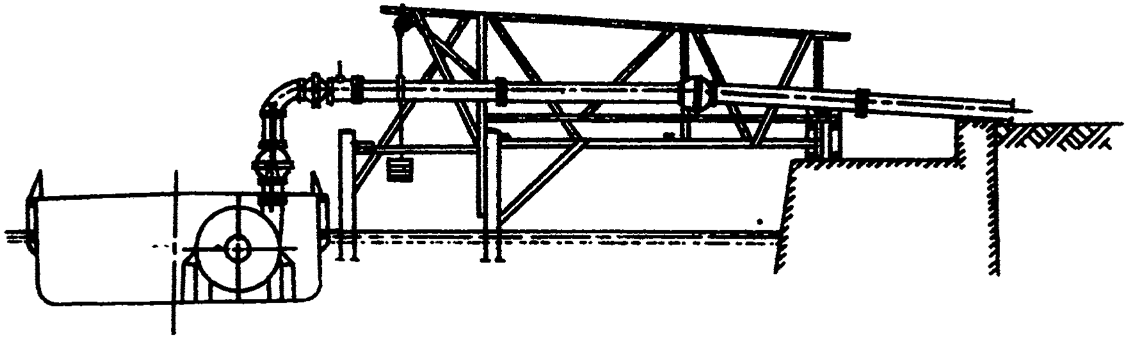

Figure 1. Hopper Dredge Unloading into Shore Pipeline

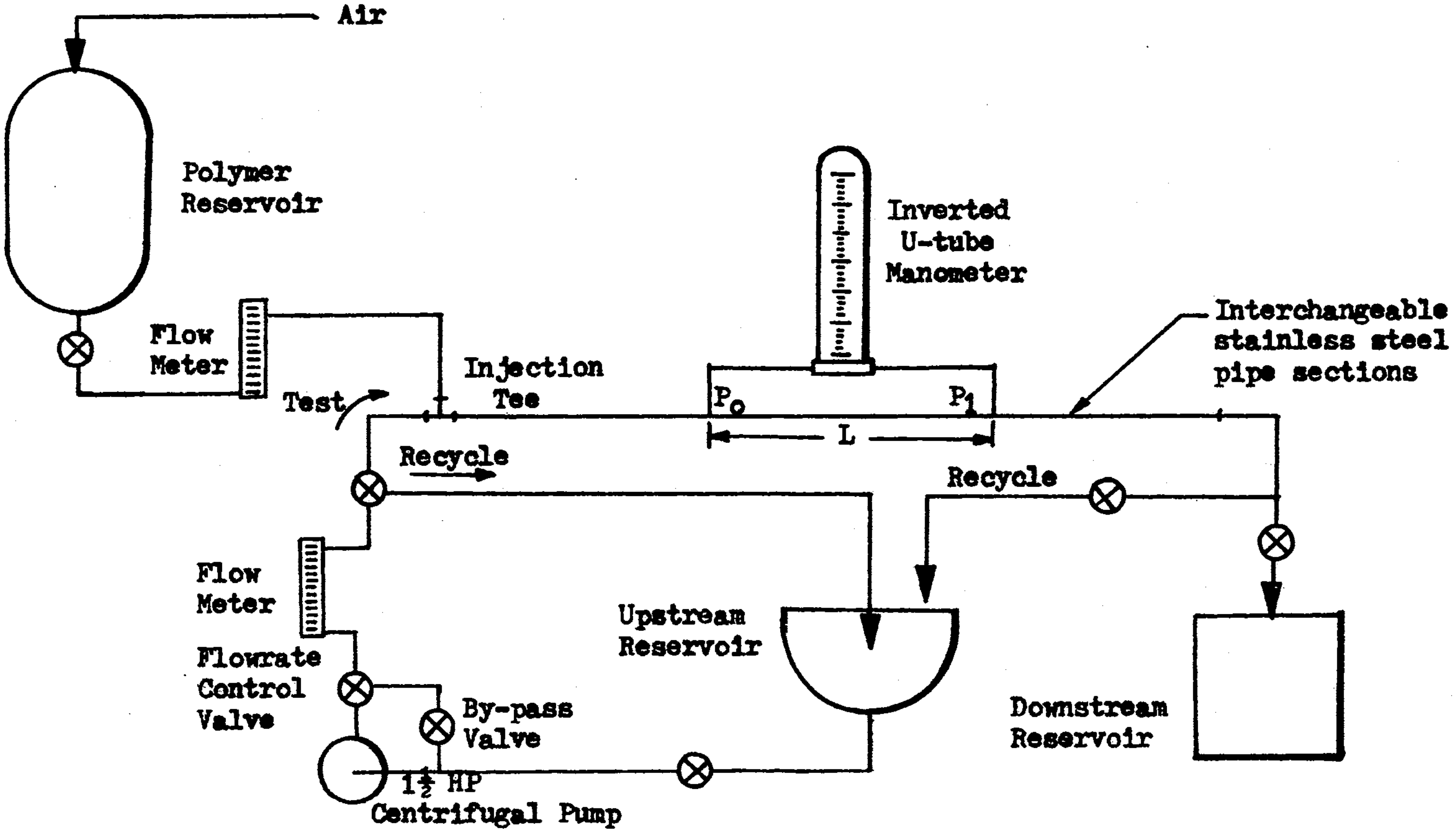

Figure 2. Pipe Flow Facility

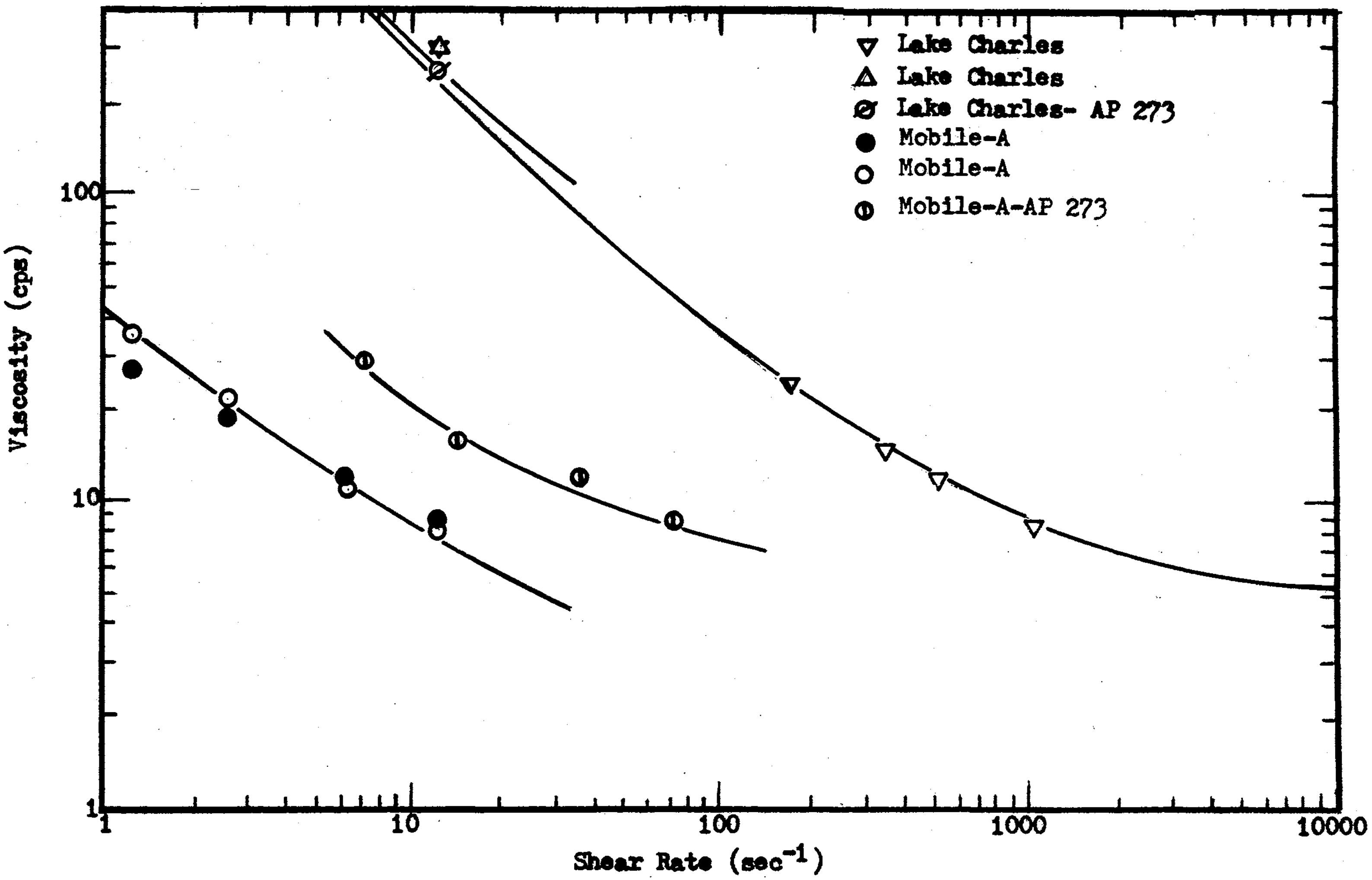

Figure 3. Viscosity Data for Lake Charles and Mobile-A spoils

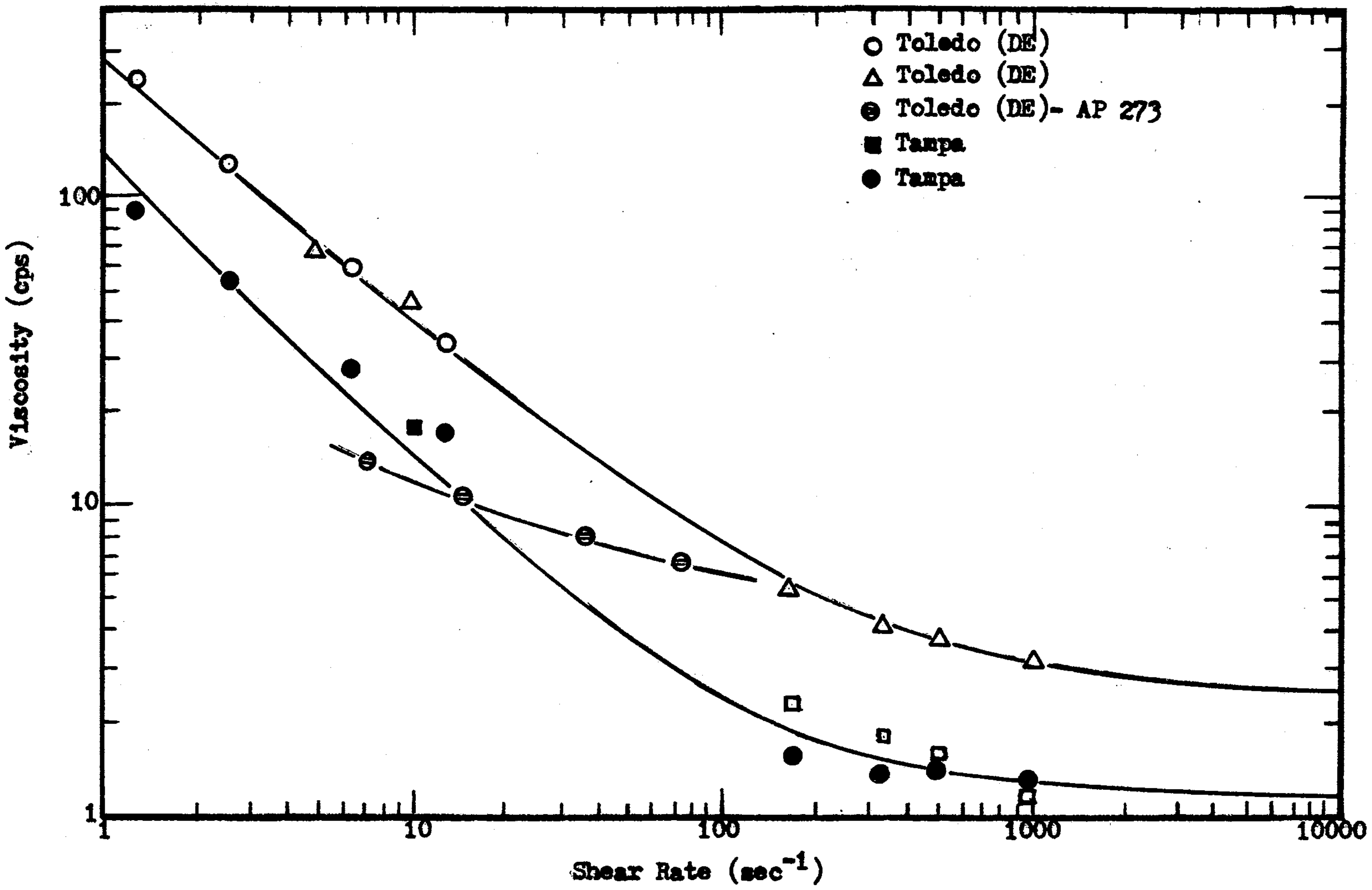

Figure 4. Viscosity Data for Toledo (DE) and Tampa spoils

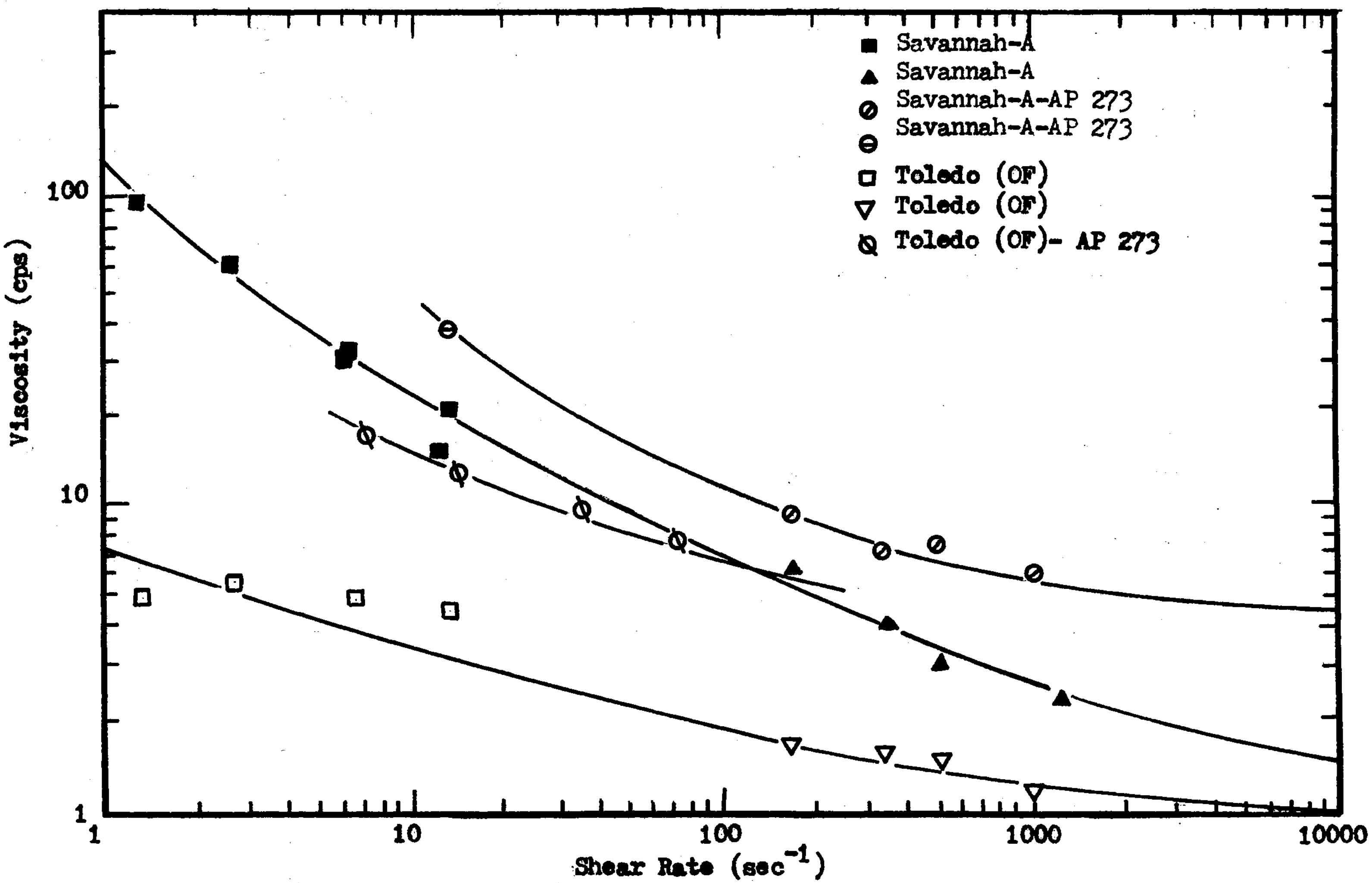

Figure 5. Viscosity Data for Savannah-A and Toledo (OF) spoils

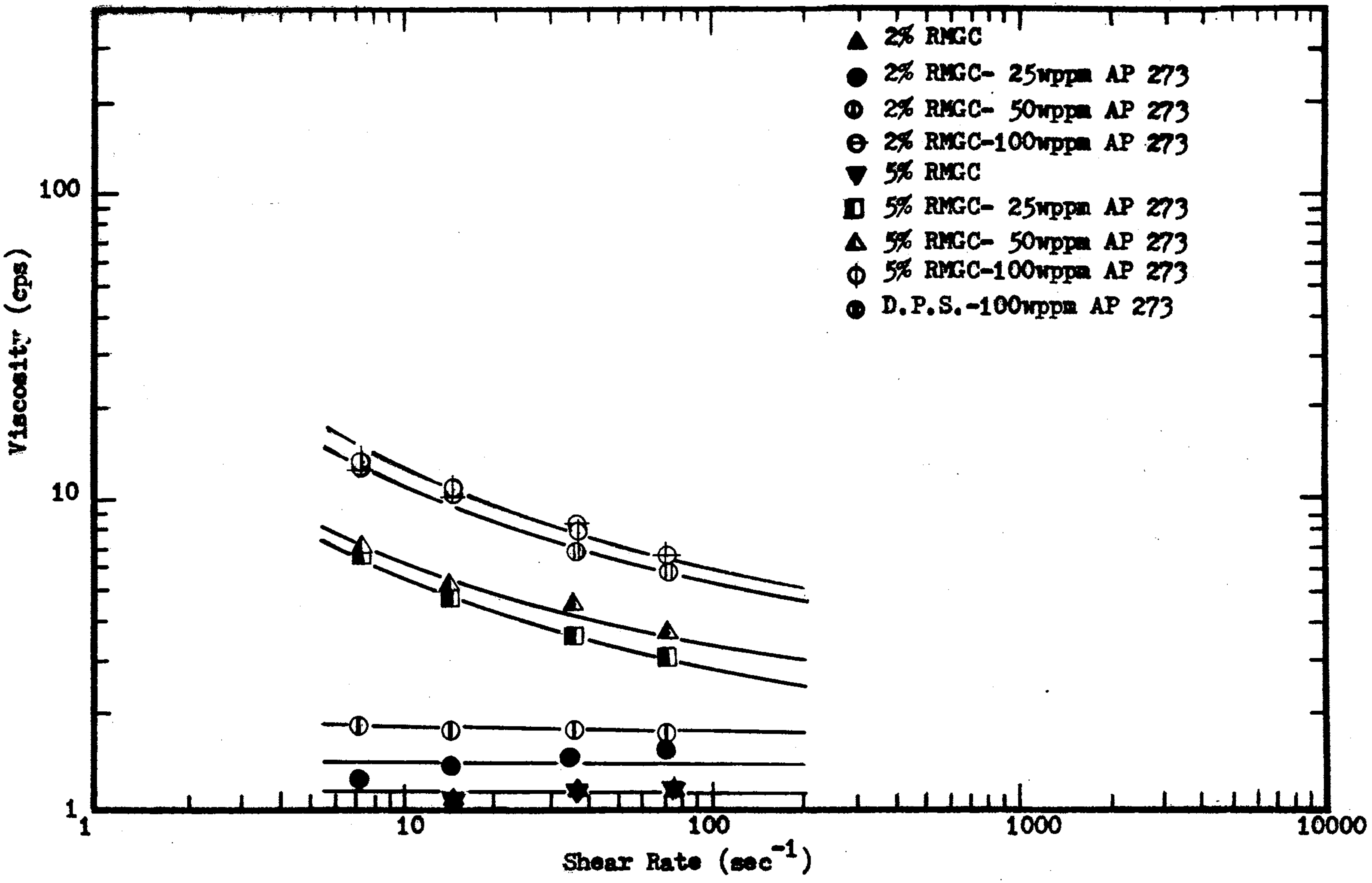

Figure 6. Viscosity Data for Test Clay Solutions

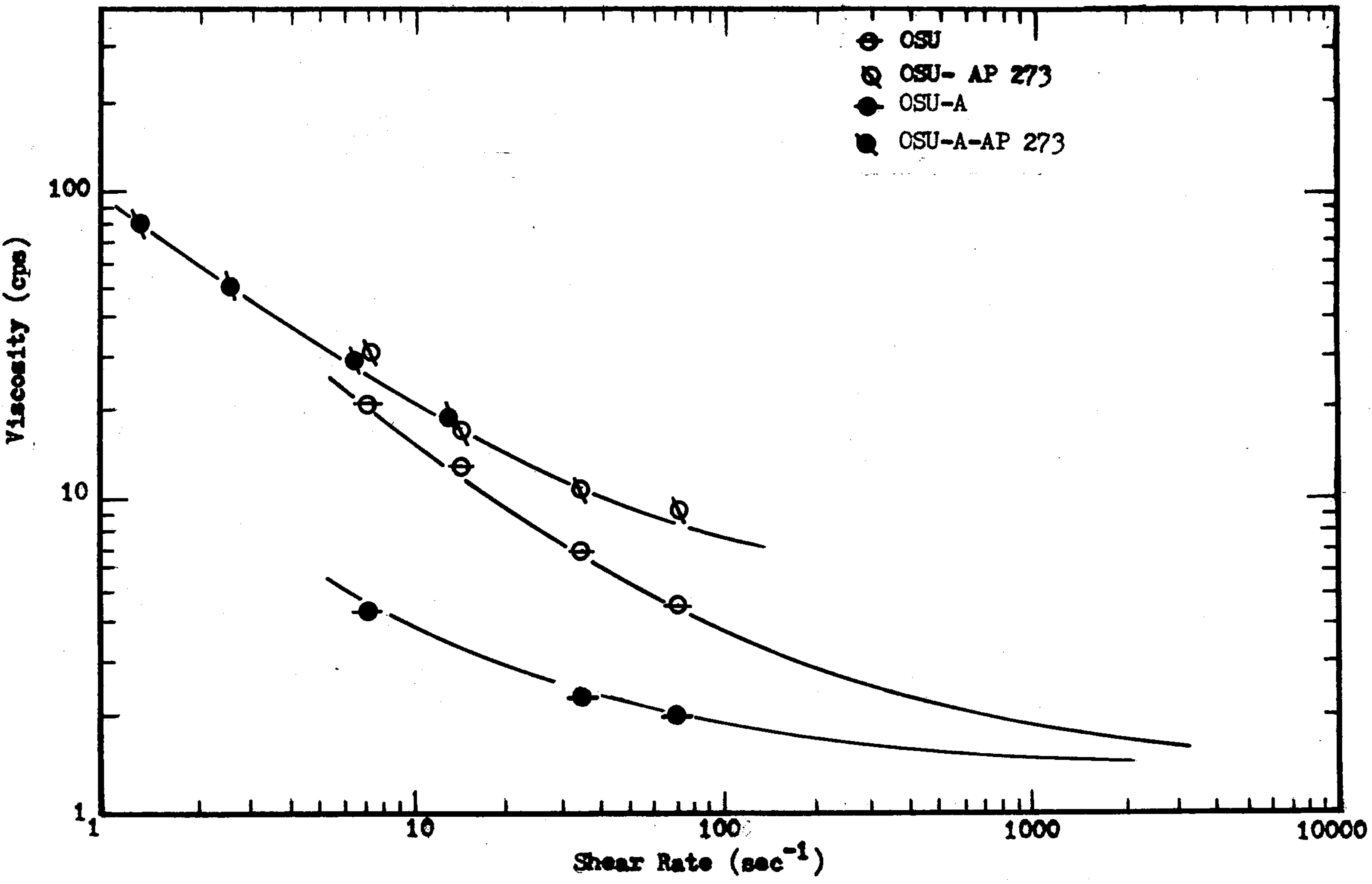

Figure 7. Viscosity Data for OSU and OSU-A spoils

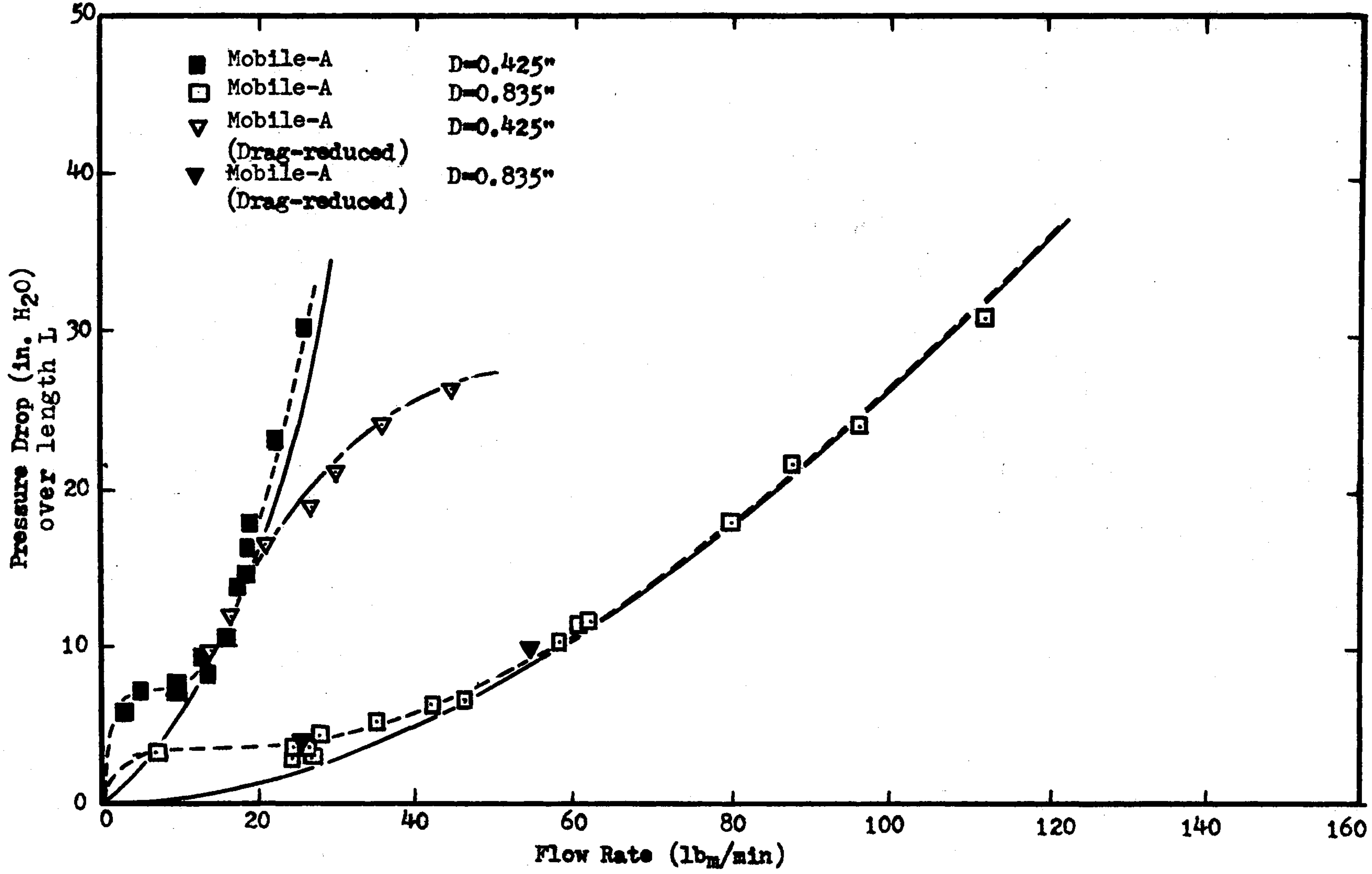

Figure 8. Pipe Flow Data for Mobile-A spoil in D=0.425" and D=0.835" Pipes

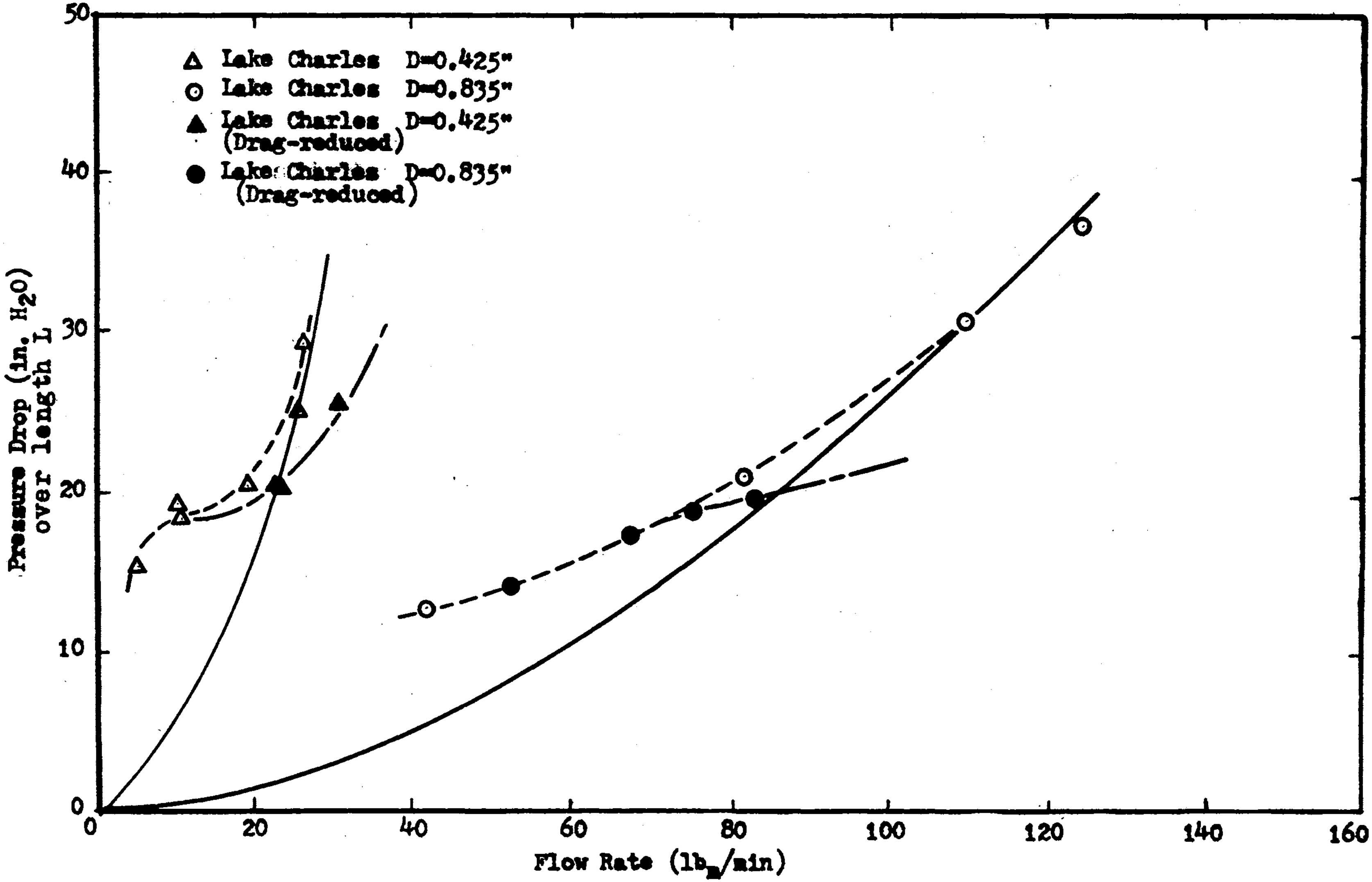

Figure 9. Pipe Flow Data for Lake Charles spoil in D=0.425" and D=0.835" Pipes

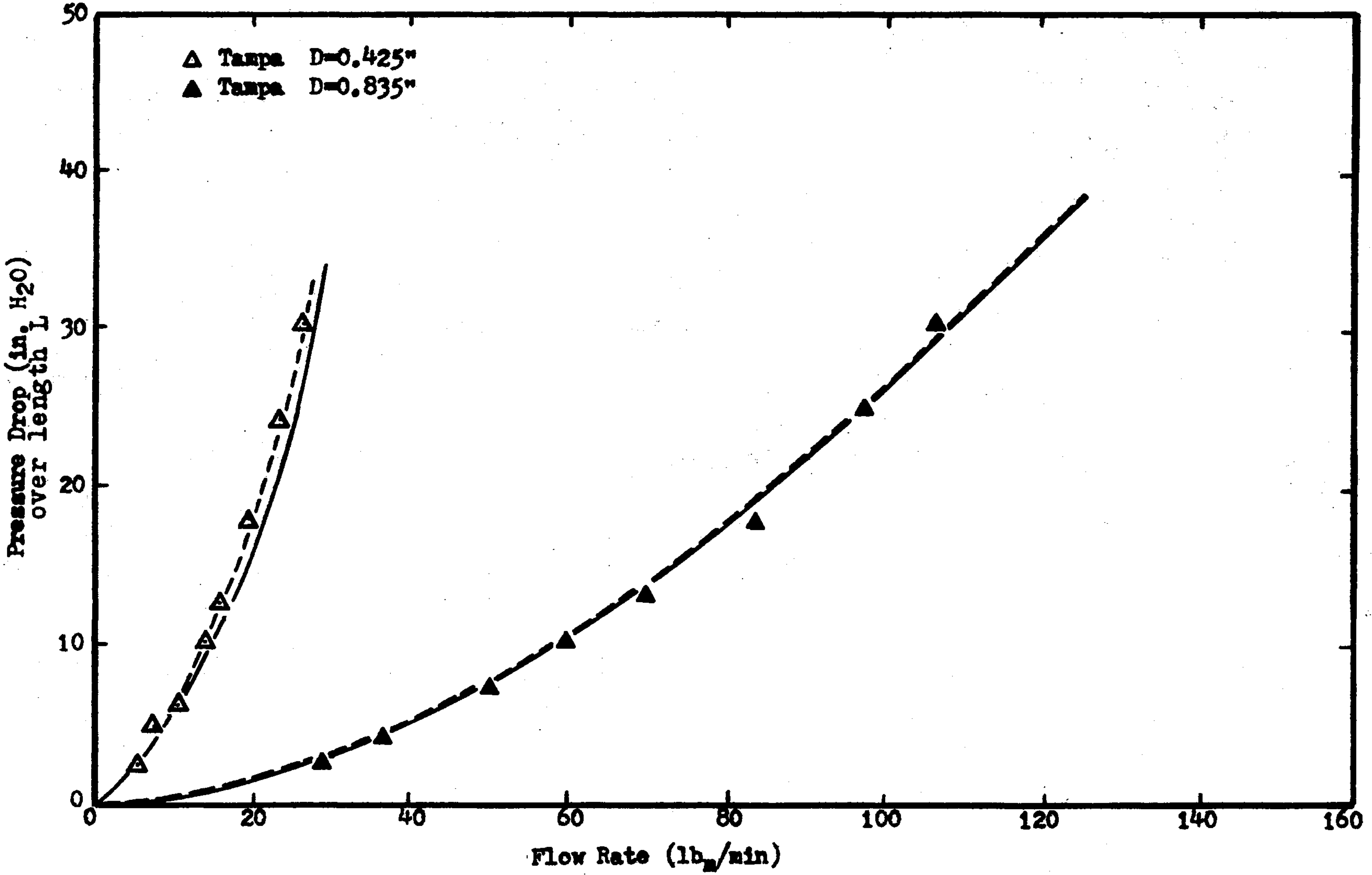

Figure 10. Pipe Flow Data for Tampa spoil in D=0.425" and D=0.835" Pipes

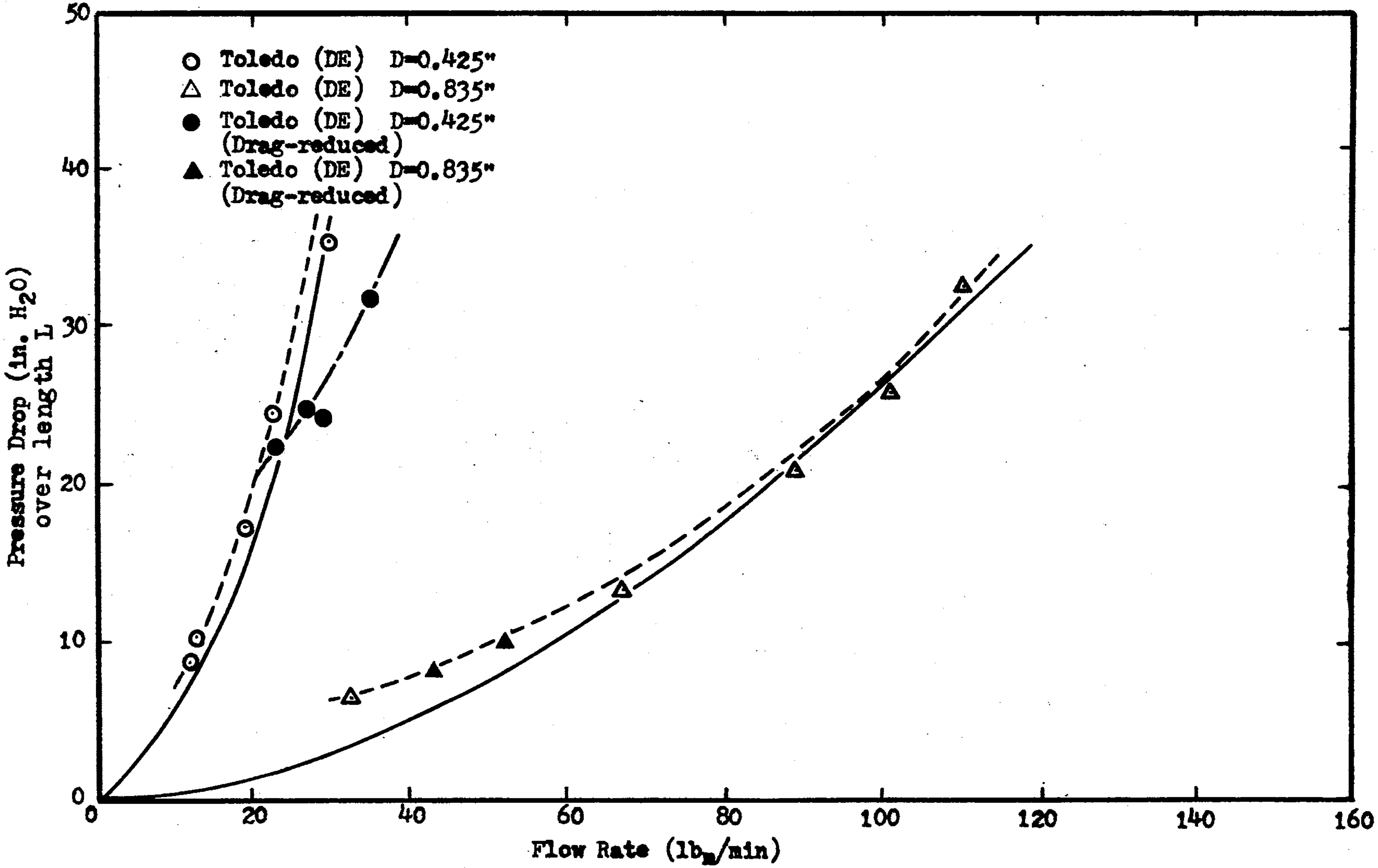

Figure 11. Pipe Flow Data for Toledo (DE) spoil in D=0.425" and D=0.835" Pipes

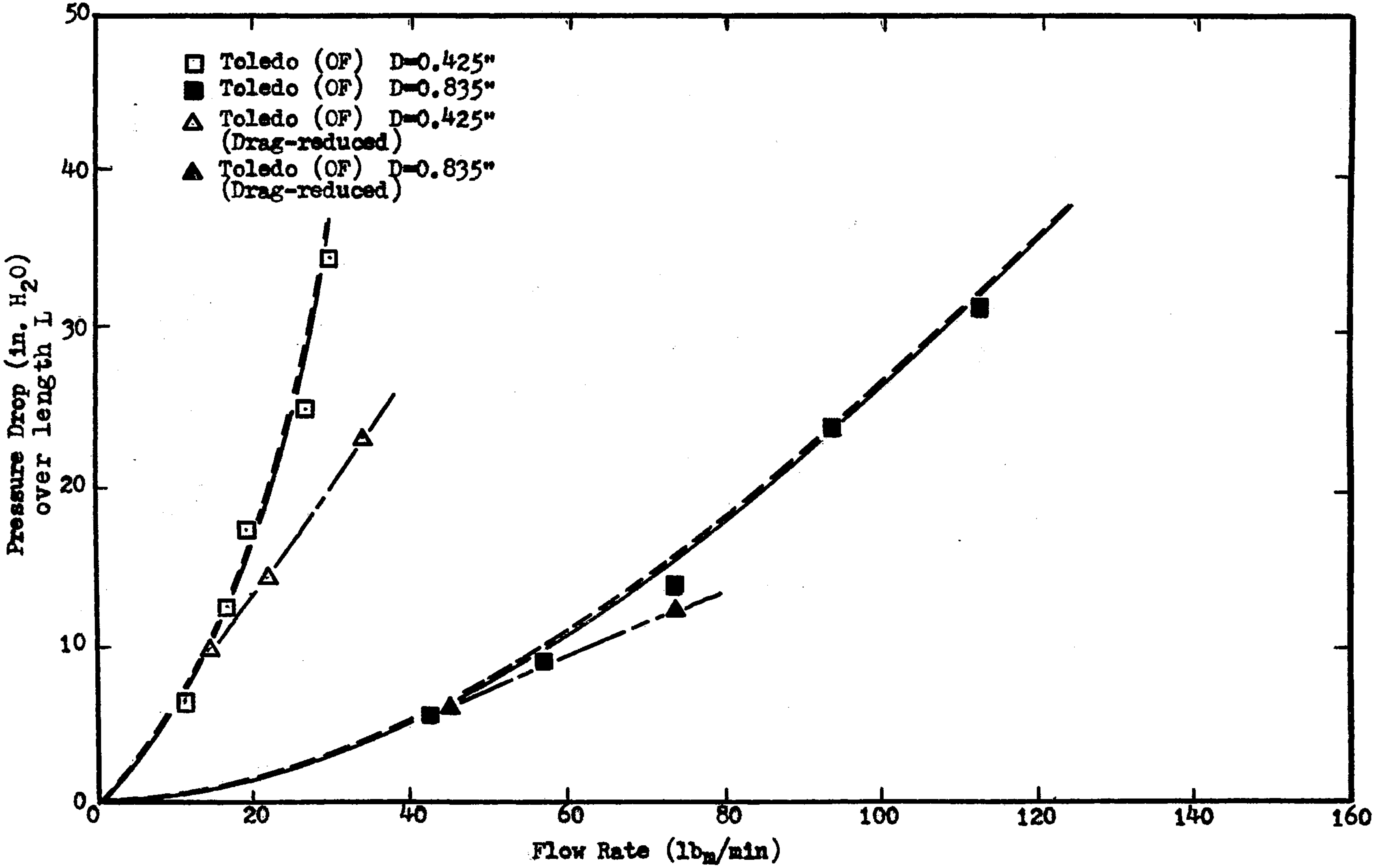

Figure 12. Pipe Flow Data for Toledo (OF) spoil in D=0.425" and D=0.835" Pipes

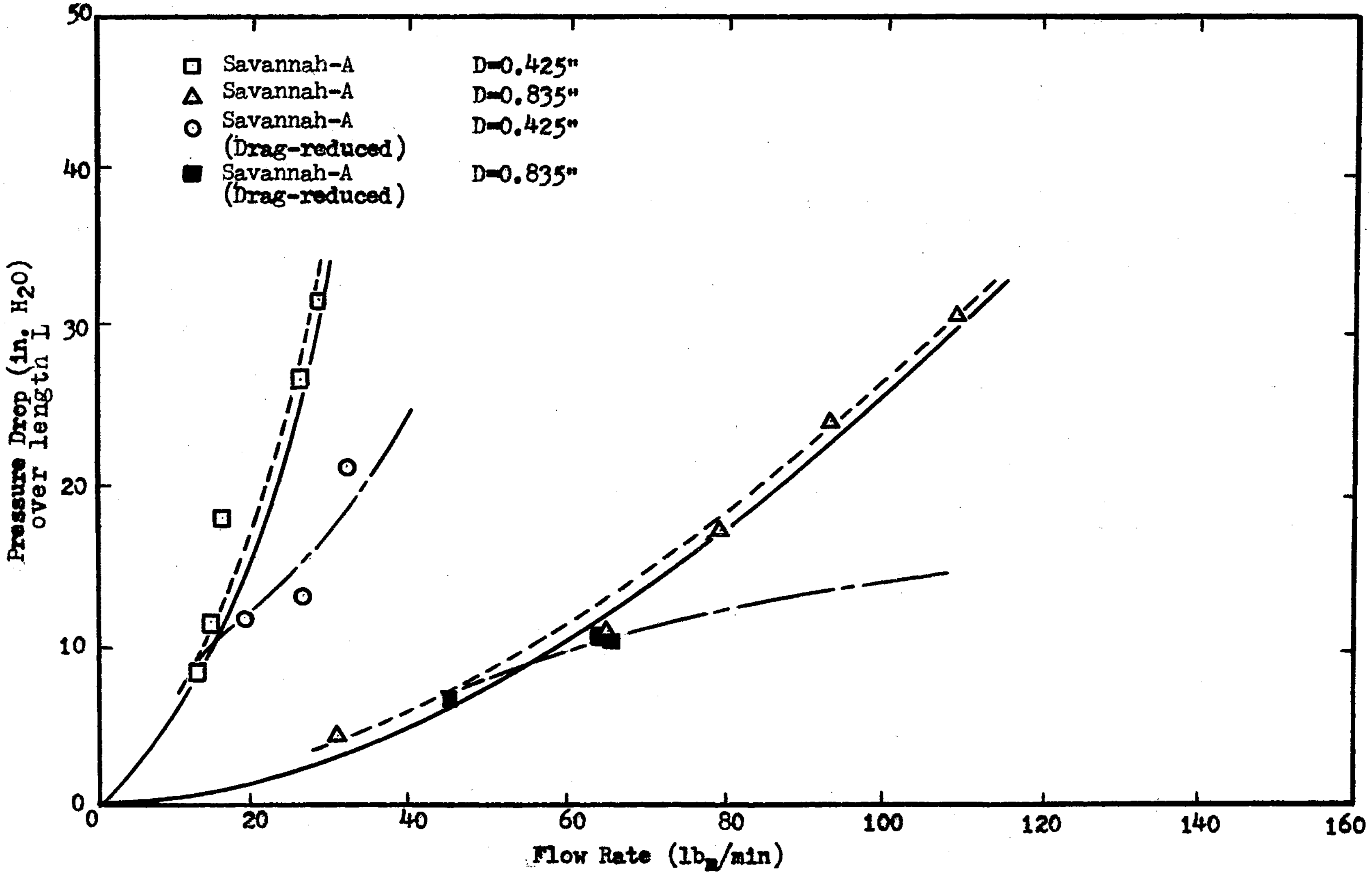

Figure 13. Pipe Flow Data for Savannah-A spoil in D=0.425" and D=0.835" Pipes

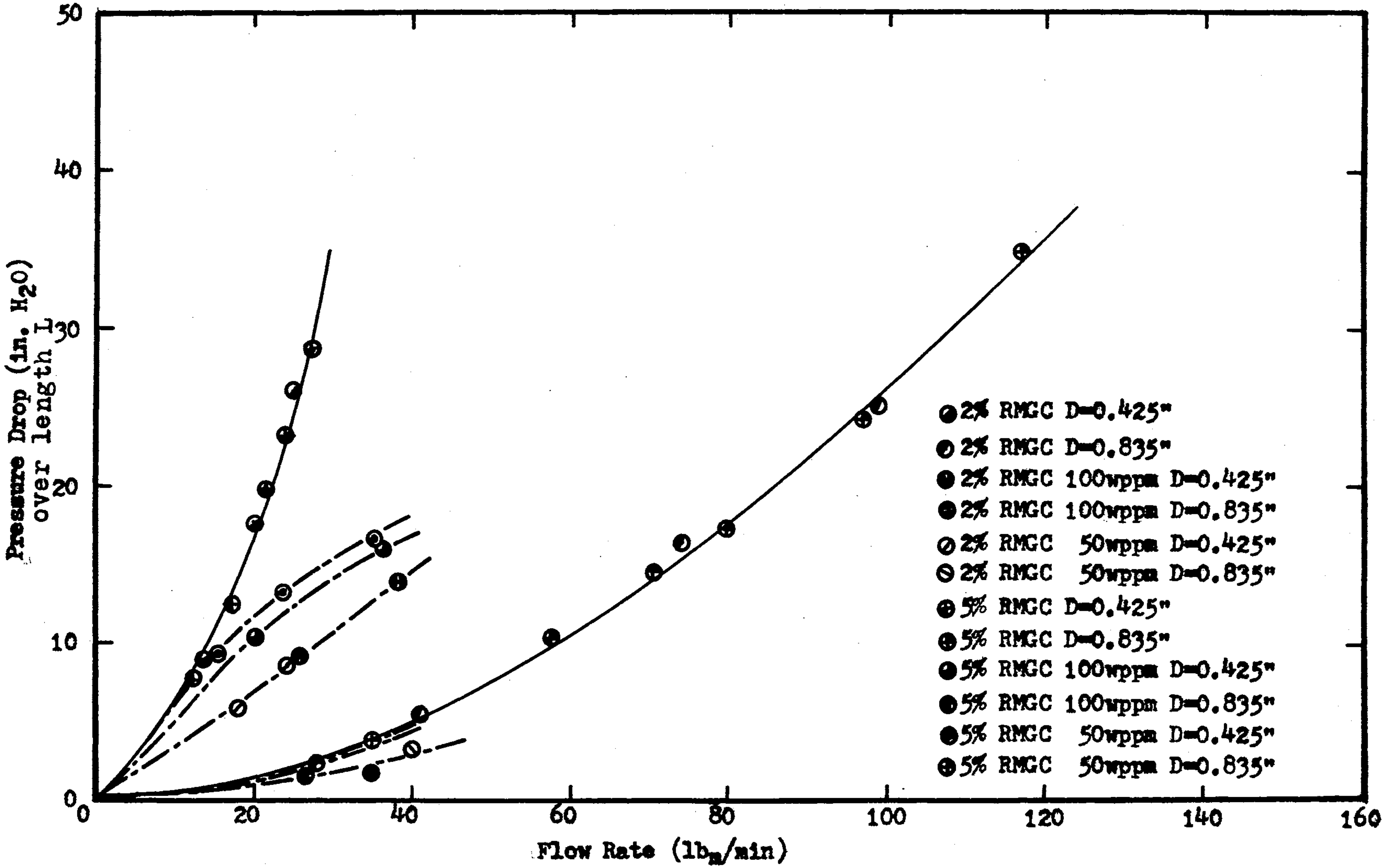

Figure 14. Pipe Flow Data for Test Clays in D=0.425" and D=0.835" Pipes

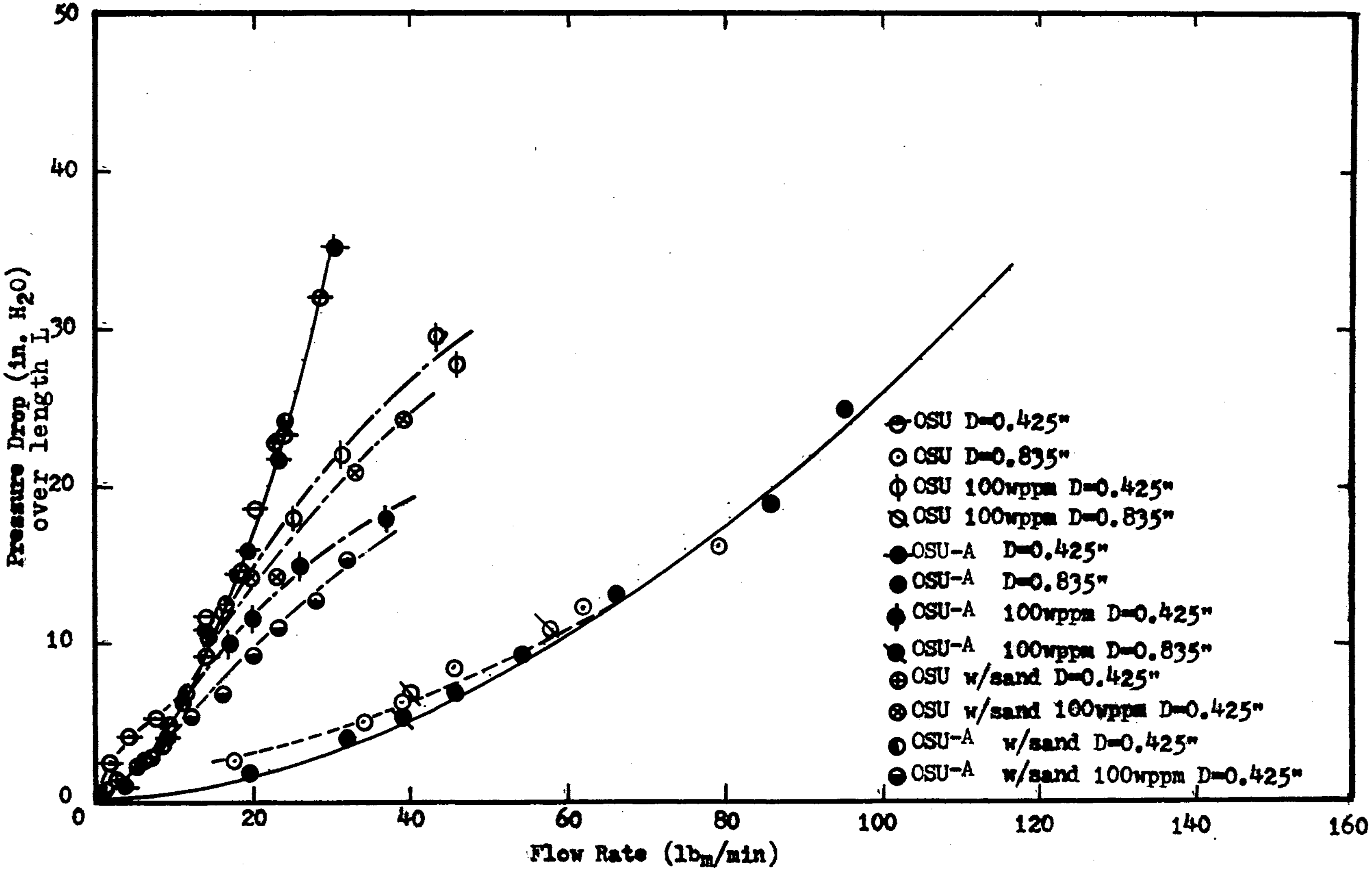

Figure 15. Pipe Flow Data for OSU and OSU-A spoils in D=0.425" and D=0.835" Pipes

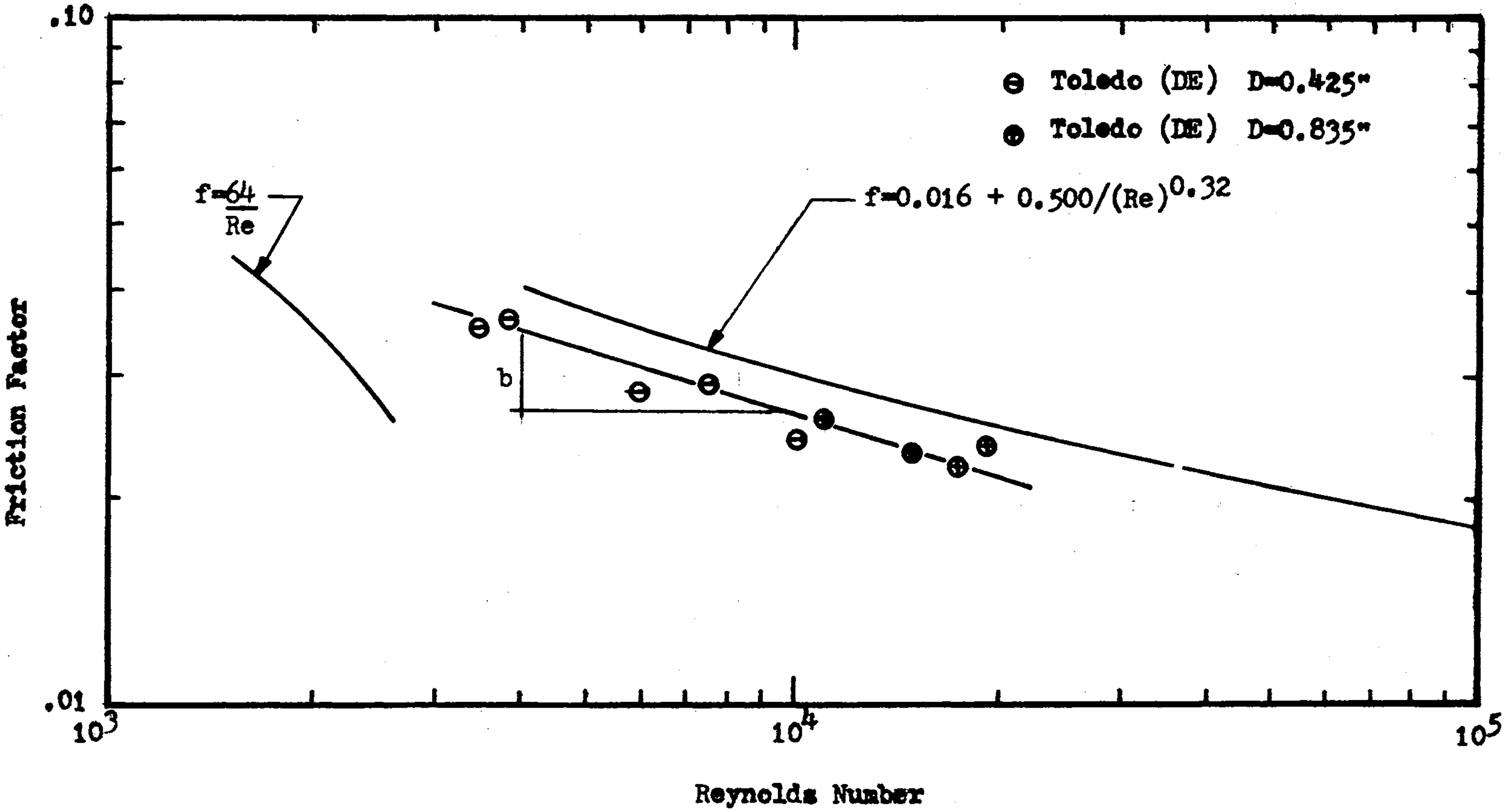

Figure 16. Moody Diagram Data Correlation for Toledo (DE) spoil

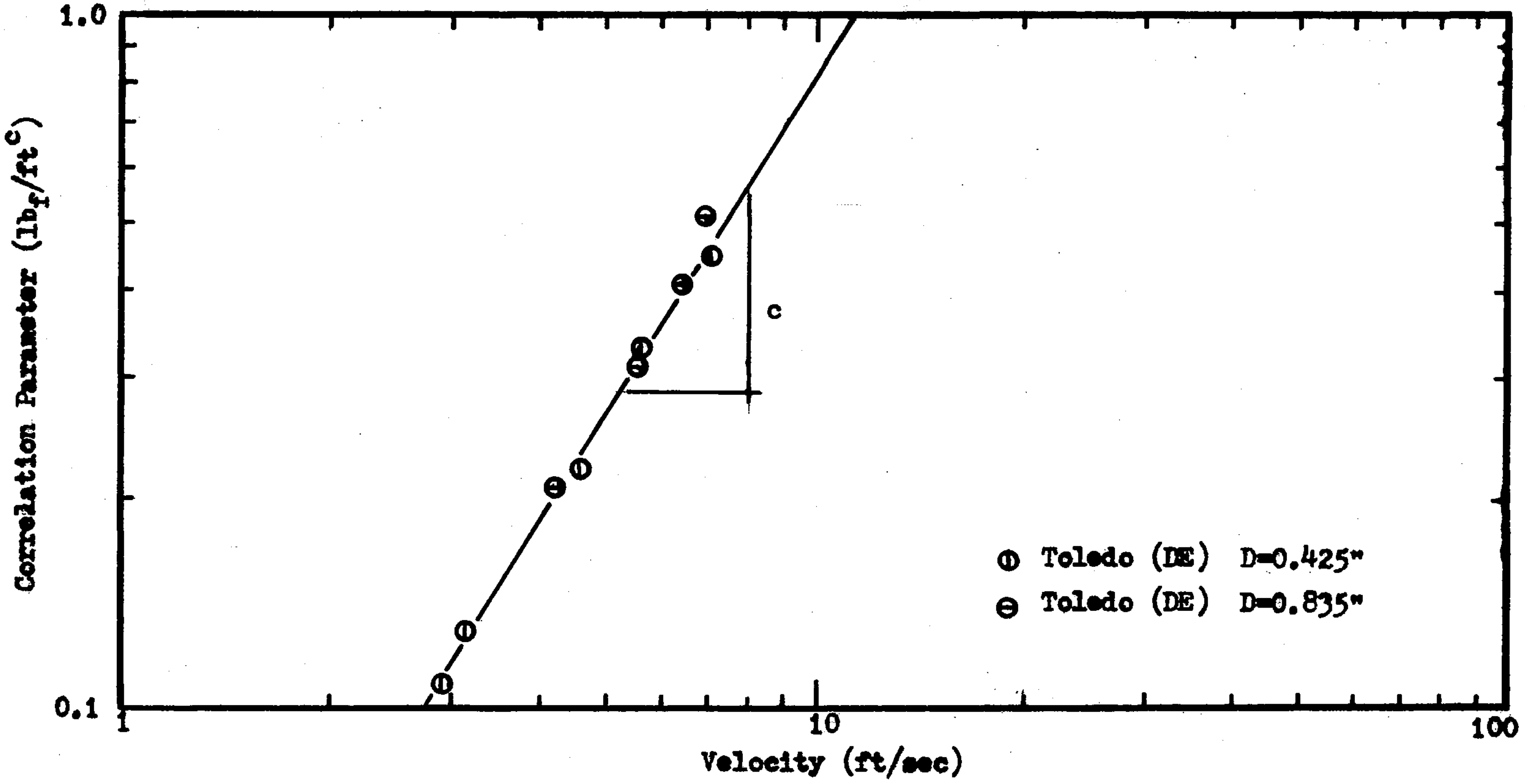

Figure 17. Bowen Data Correlation for Toledo (DE) spoil

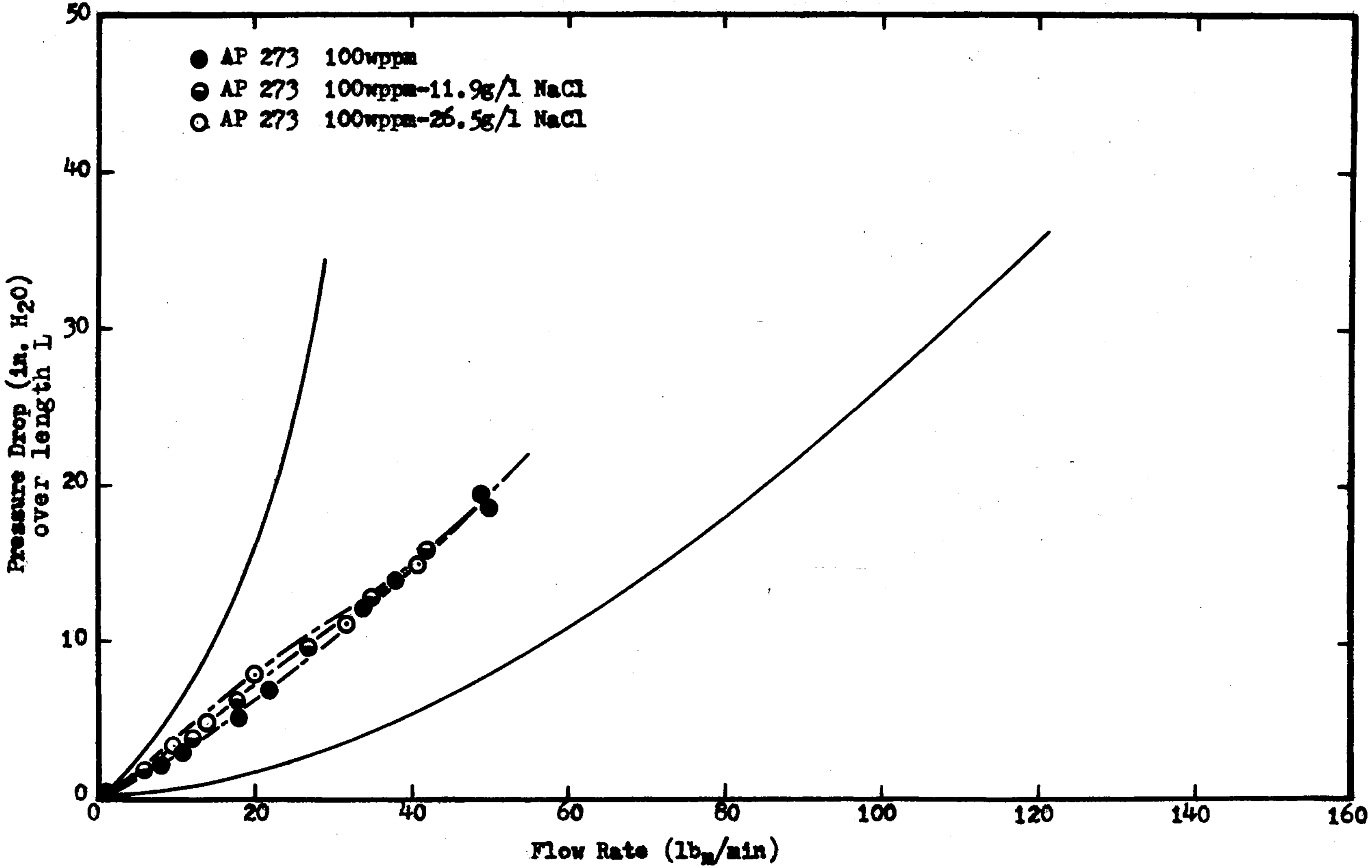

Figure 18. Pipe Flow Data for Saline(AP 273) Solutions D=0.425" and D=0.835"

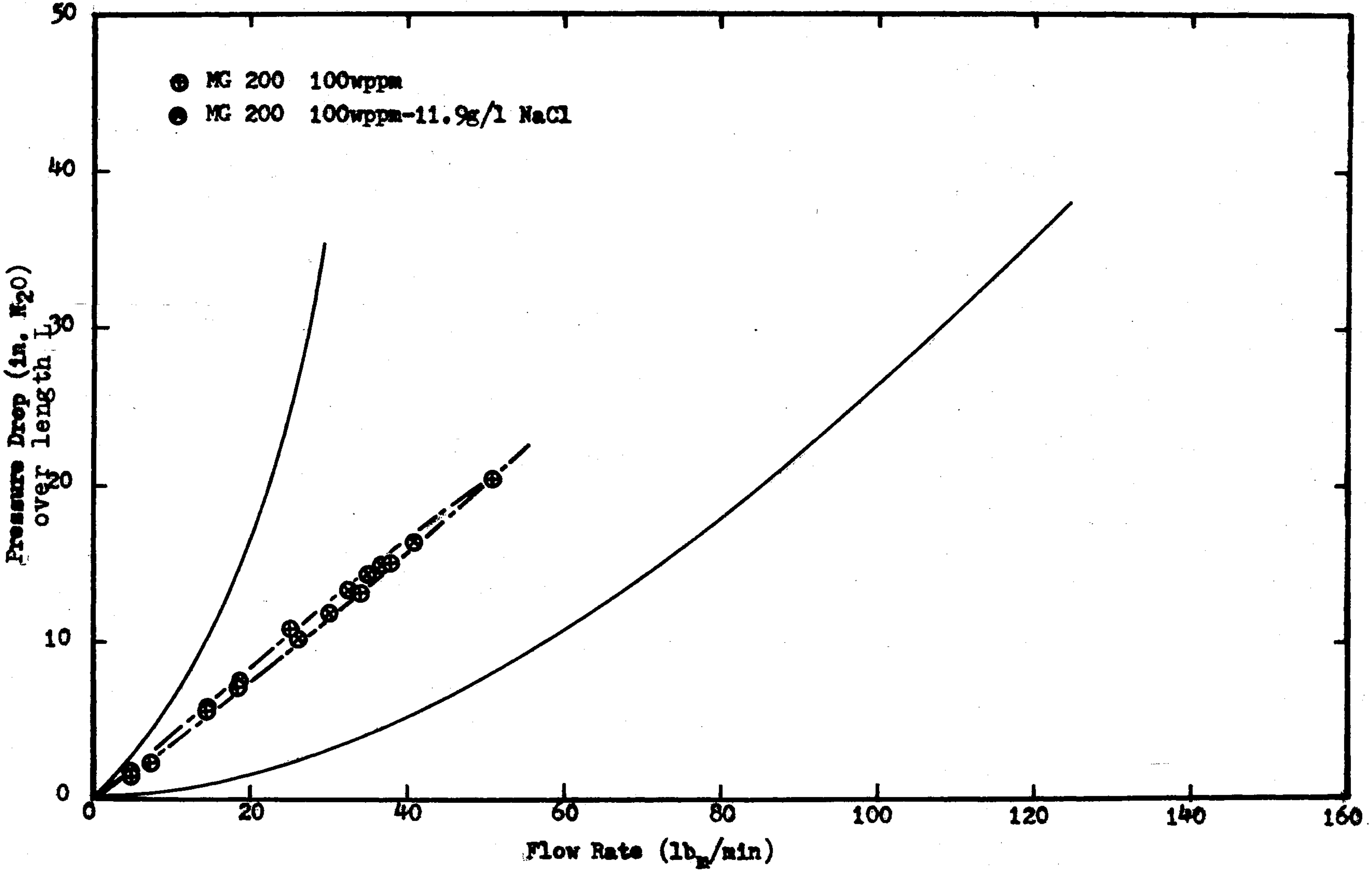

Figure 19. Pipe Flow Data for Saline(MG 200) Solutions in D=0.425" and D=0.835"

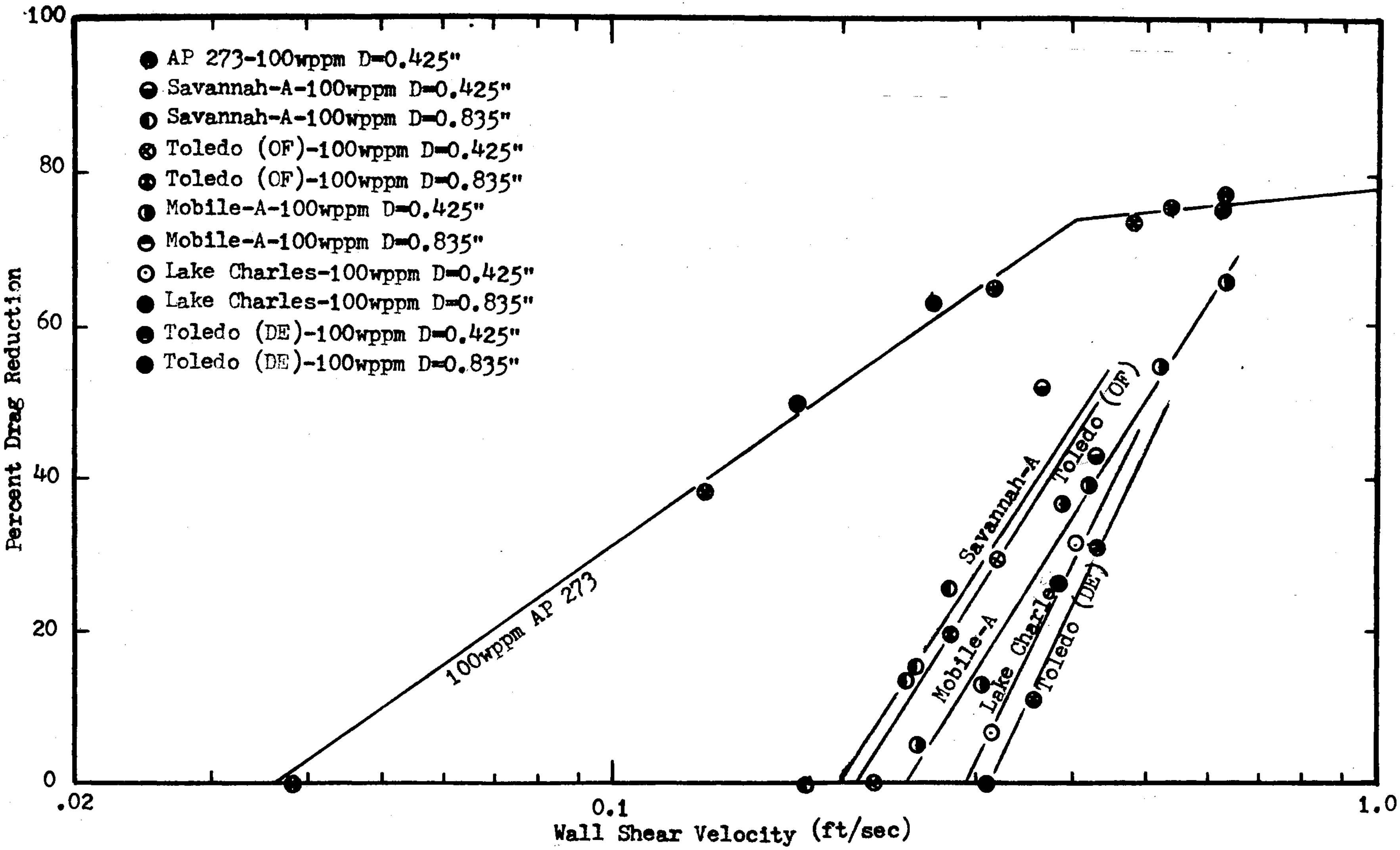

Figure 20. Drag Reduction Diagram for Dredge spoils and Water Reference

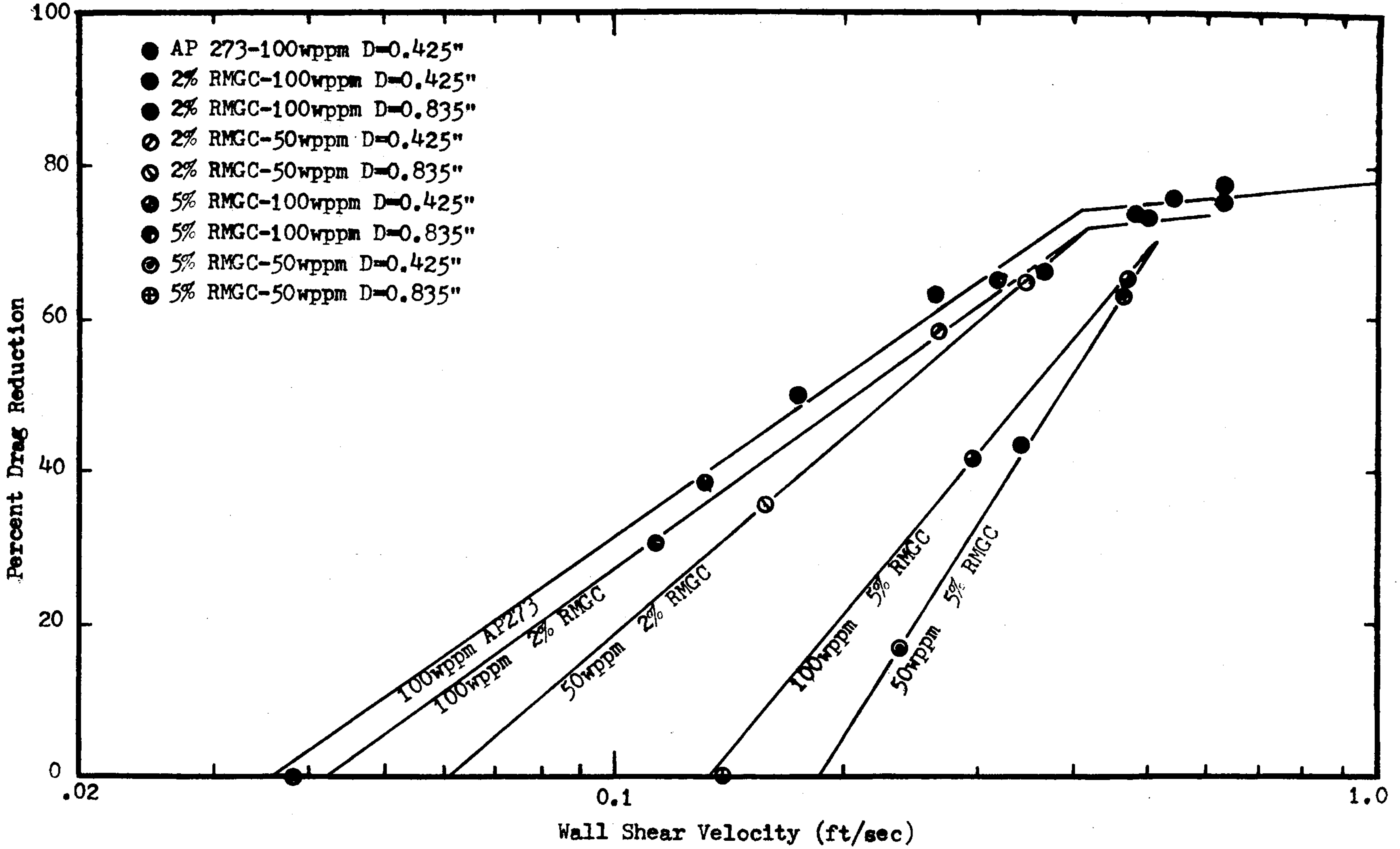

Figure 21. Drag Reduction Diagram for Determination of Suspended Solids Concentration Effects with Roger Mills Gray Clay Solutions

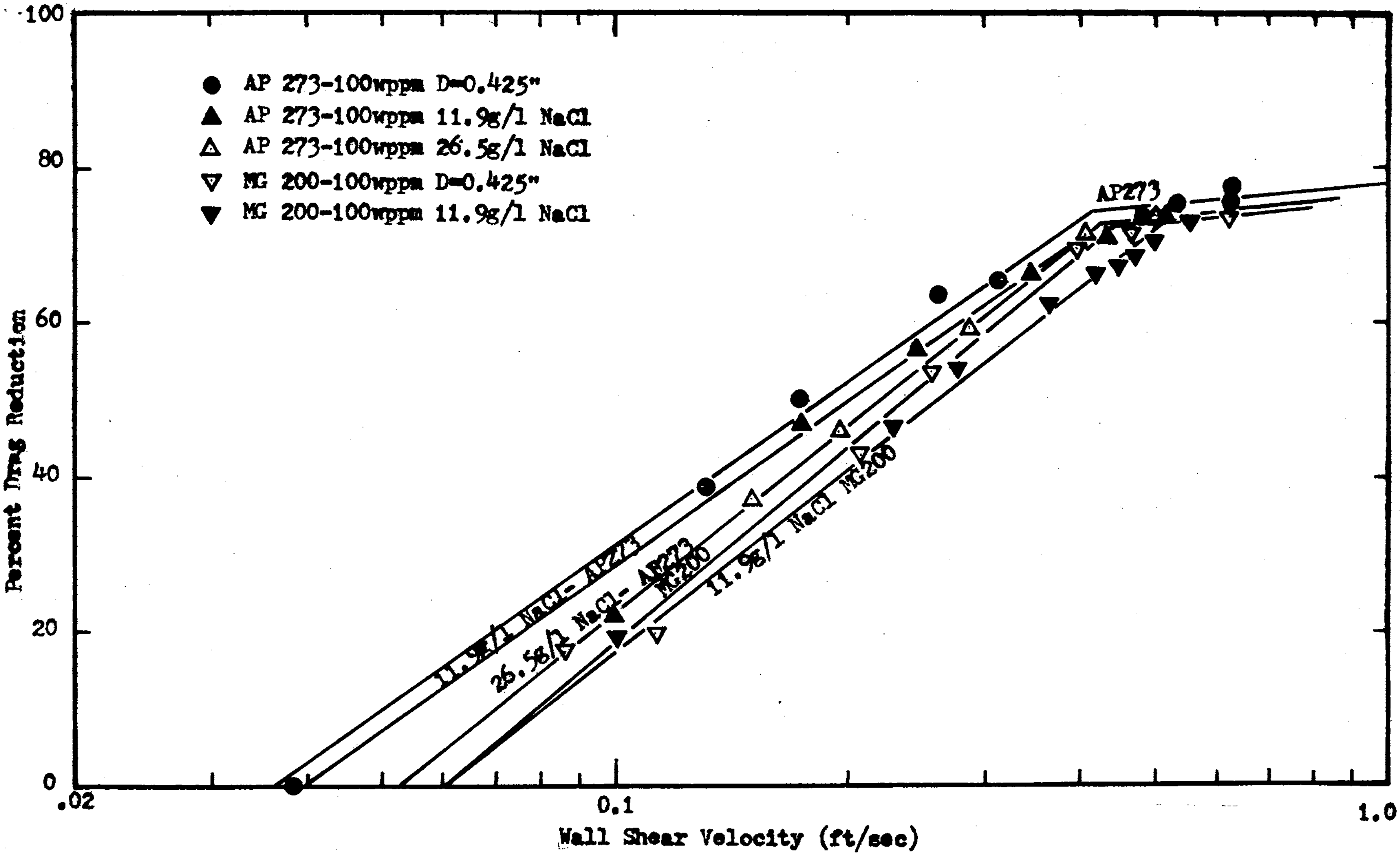

Figure 22. Drag Reduction Diagram for the Investigation of Salinity Effects and Ionic Charactor of the Polymers

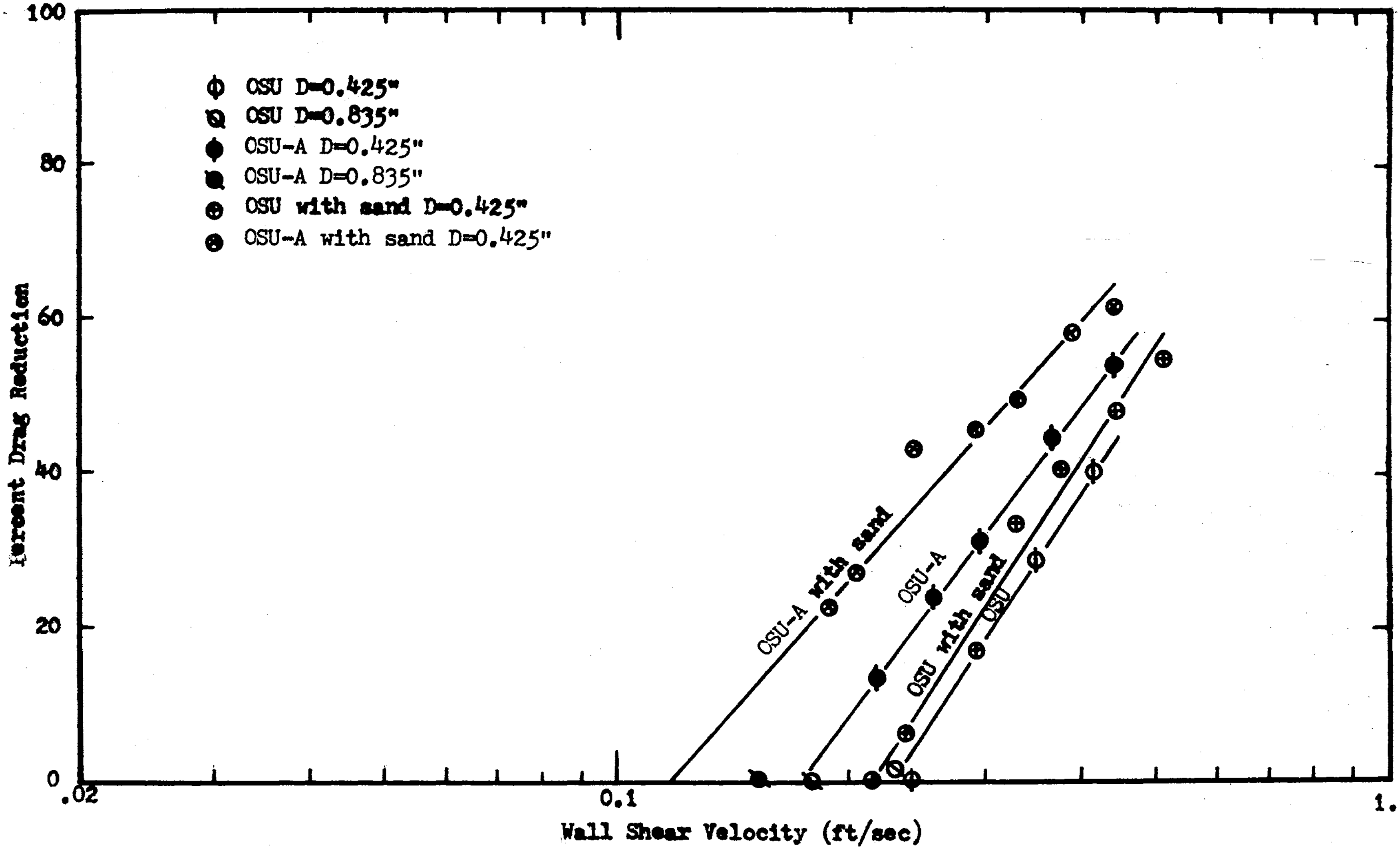

Figure 23. Drag Reduction Diagram for Particle Size Effects with OSU and OSU-A spoils

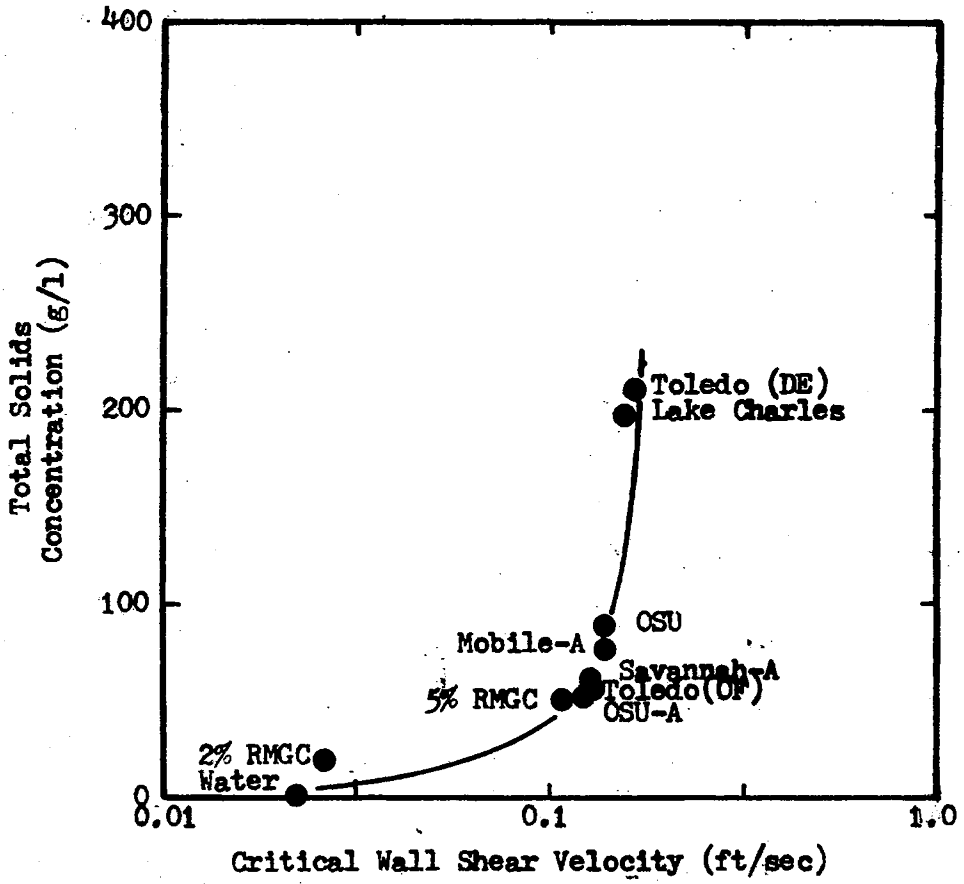

Figure 24. Correlation of Onset with Total Solids Content of the Spoil

APPENDIX C

TEST PROCEDURE

Tests without Polymer

1. Mix test solution in upstream reservoir for about one hour.
2. Open reservoir valve to prime pump.
3. Start pump to initiate pipe flow with injection tee capped off and downstream valving set to recirculate test solution.
4. Connect upstream pressure line to manometer and allow upstream side to fill with test solution.
5. Just before upstream side is completely filled, connect downstream pressure line.
6. Check null level of manometer for no flow condition.
7. Set desired flow rate with control valve and/or by-pass valve.
8. Collect efflux of pipe for a known time.
9. Read manometer fluid levels and flowmeter reading while collecting sample.
10. Weigh collected sample.
11. Record manometer readings, run time, sample weight, and flowmeter reading.
12. Repeat steps 7-11 until desired number of data points are obtained.

Tests with Polymer

1. Mix test solution in upstream reservoir for about one hour.
2. Drain polymer solution into pressure vessel and pressurize.
3. Open upstream reservoir valve to prime pump.
4. Start pump to initiate pipe flow with downstream valving set to recirculate test solution.
5. Connect upstream pressure line to manometer and allow upstream side to fill with test solution.
6. Just before upstream side is completely filled, connect downstream line.
7. Check null level of manometer for no flow condition.
8. Set desired test solution flow rate on flowmeter.
9. Switch downstream valving to discharge fluid into downstream reservoir.
10. Set corresponding flow rate (predetermined from preliminary test solution runs) on flowmeter to obtain an injected drag-reducing solution of desired polymer concentration.
11. Collect efflux of pipe for a known time.
12. Read manometer fluid levels while collecting sample.
13. Close polymer flow valve.
14. Switch downstream valving to recirculate test solution.
15. Weigh collected sample.
16. Record manometer readings, run time, and sample weight.
17. Repeat steps 8-16 until desired number of data points are obtained.

APPENDIX D

SAMPLE CALCULATION

For this calculation, the pumpout process of the HOFFMAN dredger is taken as the model. The HOFFMAN was observed by Dr. W. G. Tiederman on July 13, 1972, operating in Calumet harbor, Chicago, Illinois and the following was reported. The HOFFMAN employes a 410 HP pump which was used to unload the spoil through a 12 inch pipe. The line was about 14 feet between the pump and the pipe discharge. The pump efficiency was assumed to be 65% and the mechanical efficiency of the drive was 95%. Thus the work supplied to the fluid is

$$(.65)\ (.95)\ (410) = 253\ \text{HP}$$

where

$$253\ \text{HP} = (253\ \text{HP})\ (33{,}000\ \text{ft-lb}_f/\text{HP-min})$$

$$= 7.84 \times 10^6\ \text{ft-lb}_f/\text{min}$$

It was further assumed that the system of pump and pipeline would operate such that the product of flow rate and pressure drop would be at this value of 253 HP (7). For the Toledo (DE) spoil of density 69.7 lb_m/ft^3 and assumed flow rate of Q = 10,000 GPM, the calculations proceed as follows:

$$(Q_{GPM})\ (\Delta P_T\ \text{psi}) = \frac{(7.84 \times 10^6\ \frac{\text{ft-lb}_f}{\text{min}})(7.49\ \text{gal/ft}^3)}{(144\ \text{in}^2/\text{ft}^2)}$$

$$= 4.06 \times 10^5\ \text{lb}_f\text{-gal/min-in}^2$$

$$\Delta P_T = \frac{4.06 \times 10^5\ \text{lb}_f\text{-gal/min-in}^2}{10{,}000\ \text{gal/min}}$$

$$= 40.8 \text{ psi}$$

Calculating elevation pressure drop

$$\Delta P_H = \rho g \, \Delta z / g_c$$

$$= \left(69.7 \frac{\text{lb}_m}{\text{ft}^3}\right) (14 \text{ ft}) \left(\frac{32.2}{32.2} \frac{\text{lb}_f}{\text{lb}_m}\right) \left(144 \frac{\text{in}^2}{\text{ft}^2}\right)^{-1}$$

$$= 6.78 \text{ psi}$$

For momentum pressure drop

$$\Delta P_M = \rho V^2 / 2 g_c$$

$$= \rho Q^2 / 2 A^2 g_c$$

plugging in the numbers yields

$$\Delta P_M = 6.00 \text{ psi}$$

Then for shear pressure drop

$$\Delta P_S = \Delta P_T - \Delta P_H - \Delta P_M$$

$$= 40.8 - 6.78 - 6.00$$

$$= 28.02 \text{ psi}$$

Calculating wall shear velocity from equation 3.11

$$U_\tau = \left[\frac{\left(32.2 \dfrac{\text{lb}_m\text{-ft}}{\text{lb}_f\text{-sec}^2}\right) (28.02\text{psi}) \left(144 \dfrac{\text{in}^2}{\text{ft}^2}\right)}{\left(69.7 \dfrac{\text{lb}_m}{\text{ft}^3}\right) (4) (1500 \text{ ft})} \right]^{\frac{1}{2}}$$

$$= .558 \text{ ft/sec}$$

Then from Figure 20

$$\%DR = 53\%$$

Then

$$\Delta P_{S_{DRS}} = \Delta P_S (1 - .01(\% \text{ DR}))$$

$$= 28.02 \, (1 - .35)$$

$$= 18.2 \text{ psi}$$

For total (drag-reduced) pressure drop

$$\Delta P_{T_{DRS}} = \Delta P_{S_{DRS}} + \Delta P_{H} + \Delta P_{M}$$

$$= 18.2 + 6.78 + 6.00$$

$$= 30.98 \text{ psi}$$

Then

$$Q_{DRS} = \frac{(4.06 \text{ X } 10^{5} \text{ lb}_{f}\text{-gal/min-in}^{2})}{(30.98 \text{ psi})(144 \text{ in}^{2}/\text{ft}^{2})}$$

$$= 13{,}180 \text{ GPM}$$

and

$$\% \; Q_{increase} = \frac{13180 - 10000}{10000} \; 100$$

$$= (\frac{3180}{10000})$$

$$= 31.8\%$$

Although the amount of flow rate increase shown here is not exceptionally large, the effect becomes greater as the amount of drag reduction increases.

VITA

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Candidate for the Degree of

Master of Science

Thesis: DRAG REDUCTION EFFECTS OF DILUTE POLYMER ADDITIVES ON DREDGE SPOIL PIPE FLOWS

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