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Report No. 112

ASH TRANSPORT IN GALVANISED STEEL PIPES

by

K.C.Yong and P. B.Stone

May, 1969

The University of New South Wales
WATER RESEARCH LABORATORY

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Preface

The work reported herein was carried out by arrangement with the Electricity Commission of New South Wales using test equipment provided by the Commission at Leichhardt, N. S. W.

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Summary

This report gives the results of an experimental programme carried out by the Water Research Laboratory to evaluate the headlosses of ash slurry flow (for Vales Point and Wangi ash) in one-inch and two-inch galvanised steel pipes carrying ash concentrations ranging from 10 to 60 per cent by weight. The experimental results were compared with the theoretical results as predicted by the effective viscosity method (Ref. 1). It is indicated in Figures 4, 5, 6 and 7, that within the limit of experimental accuracy (± 8 per cent), the effective viscosity method can be used to predict the headlosses of ash slurry flow (for ash concentrations up to 50 per cent by weight) in galvanised steel pipes, which are relatively smooth.

To evaluate the effect of pipe roughness on the validity of the effective viscosity method, further tests should be carried out for ash slurry flow in rough pipes, such as steel, cast iron or corrugated plastic pipes.

Other points of interest are that a uniform procedure should be followed in determining the ash particle specific gravities; that the headlosses of ash slurry flow are sensitive, neither to the variation in ash particle specific gravity, nor to the variation in effective viscosity, and that a reduction of headloss was effected with the introduction of a small percentage of detergent in the ash slurry.

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1. Introduction

The studies to investigate the hydraulic characteristics of fly ash slurry flow in pipes have been extended to include a programme of testing to evaluate the fluid properties of ash slurries in galvanized steel pipes. The investigation was carried out at the Electricity Commission's Project Division Laboratory at Leichhardt by members of staff of the Water Research Laboratory. The results of previous tests on the ash slurry flow in various sizes and types of pipes are reported by Coulter et alia (Ref. 1).

The test programme included the measurement of headlosses for fly-ash slurries (Vales Point Ash and Wangi Ash) in 1-inch and 2-inch nominal diameter pipes for a range of flow velocities (10.0 to 2.0 f.p.s.) and ash concentrations (approximately 10 to 60 per cent by weight). These results were used to check against the validity of the "effective viscosity method" as proposed by the Electricity Commission for the prediction of headloss. The effective viscosity method was developed as a result of an analysis of test data as obtained by the Water Research Laboratory (W.R.L.) at Manly Vale, the Australian Mineral Development Laboratories (A.M.D.L.) at Adelaide and the Electricity Commission (E.C.) of New South Wales during previous investigations. Details of the studies are given by Coulter et alia in Reference 1.

This report describes the results of this investigation for evaluating the headloss characteristics of ash slurry flow in galvanized steel pipes. The comparison made between the experimental results and the results as predicted by the effective viscosity method is also included.

2. Test Rig

For a detailed description of the Leichhardt test rig, the reader is referred to Reference 1. In brief, the test rig was fitted with a $1\frac{1}{2}''$ and a $3''$ mono pump, each driven by a 20 h.p. variable speed commutator motor through an automotive gear box. The pumps were connected so that either one could feed the test circuits or agitator nozzles fitted to the mixing tank. The general layout of the test rig is shown in Figures 1 and 2.

The test rig was also fitted with a vortex mixing bowl for preparing ash slurries. This apparatus consisted of a tank 2 feet in diameter and 3 feet 6 inches deep, into which two agitator nozzles were fitted. The nozzles could be fed by either pump and when positioned correctly, a strong vortex is formed. Ash dropped into the vortex, is rapidly mixed and maintained in suspension.

Six manometer tappings were made at equal intervals along each test pipe for pressure measurements. These tappings were connected to a pressurized manometer system which included facilities for flushing.

Flow velocities were obtained from the flow rate and the pipe cross-sectional area. Flow rates were measured using a calibrated volumetric tank which was mounted above the mixing tank. Two way valves were fitted to each pipe above the calibration tank so that the flow could be diverted into either the mixing tank or the calibration tank as required.

A water jacket around the mixing tank gave reasonably good temperature control. Slurry temperature was measured by a temperature recorder, while the slurry density was determined by weighing a known volume of slurry sample in an 800 ml measuring cylinder.

3. Properties of Fly-ash

3.1 General

For the entire test series, one batch of each type of ash was used. It should be noted here that the samples taken for both the particle specific gravity and particle size tests were taken from the last bags of ash left over at the end of the test series. Hence the results (Section 3.2 and 3.3) derived from the above ash samples, should not be considered as well-represented for the ash properties.

3.2 Particle specific gravity

It has been pointed out by Coulter et alia (Ref. 1) that the measured specific gravity of flyash depends upon the method followed in carrying out the test. In the tests reported here, it was decided to determine the ash specific gravity by shaking (to release air from voids) the ash slurry in the pycnometer with water so as to conform with methods usually employed by the Electricity Commission. It must be pointed out here that the Electricity Commission measured and has measured, in the past, specific gravity of only a fraction of the sample (for ash particles with sizes less than 53 microns), whereas, the Water Research Laboratory used the total sample. For the sake of consistency in test results, the specific gravities determined by the Electricity Commission were used for subsequent calculations given in this report.

Numerous tests were carried out for each ash type. It was revealed that even with the shaking method, the results were inconsistent among the tests. After a number of trials the following method was found to yield fairly consistent results. Three pycnometers each filled with approximately equal amount of ash, were used. The first pycnometer was shaken by hand for 15 seconds for every 60 seconds for a duration of 180 seconds. The same procedure was applied to the 2nd and 3rd pycnometers, but for durations of 360 seconds and 720 seconds respectively.

At the same time, samples of each ash type were sent to the Electricity Commission Central Chemical Laboratory for further tests. The results of these tests, together with results of mean particle size, are given in Table 1.

Table 1: Data Summary of Ash Samples tested in Leichhardt test rig.

Origin	Date of Collection	*Solid S. G.		+Median Grain Size	Remarks
		W. R. L.	E. C.		
Vales Pt. Ash 2A/6 and 2A/7	7.5.68	1.90	1.94	0.042 mm	
Wangi Ash	3.6.68	1.95	1.91	0.033 mm	0.031 mm (W. R. L.) 0.035 mm (E. C.)

* Particle specific gravity given for each ash type is representative of average of three values for W. R. L. data and representative of average of two values for the E. C. data.

\+ See Section 3.3 for comments.

3.3 Particle Size

The sizes of ash particles used in the tests have been determined by the Water Research Laboratory using the hydrometer technique and by the Electricity Commission using a Balco dust sizer. The results for Vales Point Ash and Wangi Ash are given in Table 1 and Figure 3. As can be seen in Figure 3, the d_{50} size for Vales Point Ash is indicated as 0.042 mm by both methods of analysis, whereas for finer particle size range (d_o = 0.002 mm to d_{45} = 0.04 mm) the hydrometer technique seems to indicate particle sizes larger than those given by Balco dust sizer. It is also indicated in the same figure that the d_{50} size for Wangi Ash is 0.031 mm by hydrometer analysis and 0.035 mm by the Balco dust sizer. The d_{50} size for Wangi Ash can be taken as 0.033 mm. For finer particle size range (d_o = 0.001 mm to d_{40} = 0.027 mm), the hydrometer analysis also gives particle sizes larger than those given by Balco dust sizer.

4. Pipe Properties

4.1 Diameter of Pipes

The nominal diameters of the two test pipes were 2 inches and 1 inch. The cross-sectional area of each pipe was determined by measuring the volume of water in a given length of pipe. From the cross-sectional areas, the actual diameters of the two test pipes were found to be 2.085" and 1.08". The calculated diameter of the test pipes were used in the analysis of test results.

4.2 Roughness of Galvanised Steel Pipes

Before the ash slurry tests, the rig was tested with water to obtain a representative headloss gradient for water for both test pipes. Based on these water lines, the friction factors and Reynolds numbers were calculated using the following equations:-

Darcy-Weisbach equation

$$\frac{\Delta H}{L} = f \frac{V^2}{2gD} \qquad (1)$$

and

$$\mathbb{R} = \frac{VD}{\nu} \qquad (2)$$

where $\frac{\Delta H}{L}$ = headloss in ft. per foot of pipe

L = length of pipe in ft.

V = flow velocity in f.p.s.

g = gravitational acceleration in ft./sec.

D = diameter of pipe in ft.

$\mathbb{R}$ = Reynolds number

ν = Kinematic viscosity of water in ft.^{2}/sec.

f = friction factor

The values of friction factors and the corresponding values of Reynolds numbers were plotted on the diagrams (see Figures 4 and 5) to establish relationship among friction factor, Reynolds number and the relative roughness of each pipe. The averaged roughness (k) values for both pipes together with the roughness (k) values for other size and type of pipes (Ref. 1) are given in Table 2 for purpose of comparison.

Table 2: List of roughness (k) values for different size and type of pipes

Nominal Diameter of pipe (inches)	Type of pipe	Roughness height (k) (ft.)	Remarks
2-1/4	Asbestos cement	0.000019	E. C. tests from Ref. 1, 1967.
4	Asbestos cement	0.000033	
8	Asbestos cement	0.000017	
1-1/2	Steel	0.001	A. M. D. L. tests from Ref. 1, 1967.
6	Asbestos cement	0.00003 *	W. R. L. tests from Ref. 1, 1967.
6	Asbestos cement	0.00006	
4	Asbestos cement	0.00008	
1	Galvanized steel	0.000076	W. R. L. tests 1968.
2	Galvanized steel	0.000069	

* Test data indicated a k-value varying from 0.000025' to 0.00012'; k-value of 0.00003' was assumed by taking the weighted mean of 10 experimental points on Rouse Chart.

5. Test Procedure

5.1 Water Tests

The pumping rig was calibrated with water to ensure the pressures measured at various tapping points along the pipe circuits were consistent. Concurrently, the pressure gradients and the flow velocities were also measured. These results were then plotted on log-log paper to establish a straight line relationship between pressure gradients and flow velocities. Any departure from straight line relationship on log-log plot would indicate errors in the test rig. These were corrected before the ash slurry tests were carried out.

5.2 Ash Slurry Tests

After the test rig had been properly calibrated, slurries of Vales Point and Wangi ash were tested. The ash slurries were tested at concentrations approximately 10, 20, 30, 40, 50 and 60 per cent by weight. In each test, for each type of ash at a specific ash concentration, the headloss gradient was determined for a range of flow velocities from about 10 to 2 f.p.s.

For each test, the following data were obtained:

(i) The flow rate from volume and time measurements.
(ii) The density of ash slurry
(iii) Ash slurry temperature
(iv) The averaged pressure difference (four readings) between each successive tapping points, in some cases only three out of four were in agreement, the fourth one was disregarded.
(v) Time and date of the test.

The results were expressed in terms of headloss in feet of water per foot length of pipe and the mean velocities in f.p.s.

The test data are given in the tables as listed below:-

Table 3: Headloss data for fresh water in 2" diameter galvanised steel pipe.

Table 4: Headloss data for fresh water in 1" diameter galvanised steel pipe.

Table 5: Headloss data for Vales Point ash slurry in 2" diameter galvanised steel pipe.

Table 6: Headloss data for Vales Point ash slurry in 1" diameter galvanised steel pipe.

Table 7: Headloss data for Wangi ash slurry in 2" diameter galvanised steel pipe.

Table 8: Headloss data for Wangi ash slurry in 1" diameter galvanised steel pipe.

Table 9: Headloss data for Vales Point ash slurry with 1 per cent detergent in 2" diameter galvanised steel pipe.

The headloss data for fresh water as well as for ash slurries in both pipes are plotted in Figures 4, 5, 6 and 7. The headloss gradients as predicted by the effective viscosity method are also plotted as full lines on these graphs for purpose of comparison. The water line is also included as a broken line in each diagram.

Among the above slurry tests, there was one test carried out specifically for Vales Point ash at the highest concentration to evaluate the effect of the introduction of detergent on the headloss gradient of the ash slurry flow in 2" diameter pipe. This result is given in Table 9 and Figure 4.

6. Analysis of Results

6.1 General

The experimentally determined results of headloss gradients and mean velocities for water and ash slurry in 2-inch and 1-inch galvanised steel pipes are analysed (see Sections 6.2 and 6.3) and are given in Tables 1 to 9 and in Figures 3 to 8.

6.2 Water Tests

The headloss gradients of water in 2" diameter and 1" diameter pipes are shown on log-log plots on the upper left hand corner of Figures 4 and 5 respectively. An average line was drawn to get a representative line for each pipe. These lines are representative of the characteristics of pipes both before and after the ash slurry tests. As can be seen from these graphs, the slopes on the log-log plot of $\frac{\Delta H}{L}$ vs V were found to be 61.45° for 2" diameter pipe and 61.2° for 1" diameter pipe. From these representative headloss gradients, the friction factors (f) and the corresponding Reynolds numbers for each pipe were calculated and plotted on Moody chart to determine the flow regime. As can be seen from the lower left hand corner of Figures 4 and 5 that the flow regime falls between the smooth wall turbulent and rough wall turbulent region, the Colebrook and White's equation as given below can be used to approximate the relationship between friction factor, the Reynolds number and the relative roughness of pipe.

$$\frac{1}{f^{\frac{1}{2}}} = 1.74 - 2 \log_{10} \left(\frac{2k}{D} + \frac{18.7}{\mathrm{I\!R} f^{\frac{1}{2}}} \right) \qquad \ldots\ldots\ldots\ldots (3)$$

where f = friction factor

$\mathbb{R} = \frac{VD}{\nu}$ Reynolds Number

V = flow velocity in f. p. s.

D = diameter of pipe in ft.

ν = kinematic viscosity of water in ft^2/sec.

k = the roughness element of pipe in ft.

The values of k/D for each pipe were calculated by substituting the above determined values of f and $\mathbb{R}$ into equation 3. The values of k/D were averaged and the mean value of roughness (k) for each pipe is given in Table 2. These values are used in equation 3 for calculating the effective viscosities of ash slurries, with friction factors determined from test data.

6.3 Ash Slurry Tests

The headloss gradients of ash slurries flow in pipes for Vales Point ash and Wangi ash are shown on log-log plot in Figures 4, 5, 6 and 7. The headloss gradient versus flow velocity for each concentration (approximately 10 to 60 per cent by weight, at an interval of 10 per cent by weight) is plotted separately on each figure. The headloss gradient vs velocity plot as predicted by the "effective viscosity method" is also plotted as full lines on each graph for purpose of comparison for ash slurry concentrations up to 50 per cent by weight. Comparison can be made between the headloss gradients for water, for ash slurries from experimental tests and for ash slurries as predicted by "effective viscosity method" on one graph. The effect of the introduction of detergent into ash slurry on the headloss gradient for ash slurry flow in pipe can be easily depicted from the diagram given in the lower right hand corner of Figure 4.

7. The "Effective viscosity method" for predicting headloss gradients for ash slurry flow in pipes

The governing equation for prediction of headloss (ΔH) for homogeneous suspensions in horizontal pipeline is given below:-

$$\frac{\Delta H}{L} = f \frac{V^2}{2gD} (1 + (S - 1) C) \quad \dots\dots\dots\dots \quad (4)$$

where $\frac{\Delta H}{L}$ = headloss in ft. per foot length of pipe expressed in terms of water,

f = friction factor
D = diameter of pipe in ft.
S = specific gravity of solids
C = concentration of mixture by volume
V = velocity of mixture in f. p. s.
(1 + (S - 1) C) = specific gravity of ash slurry.

The headloss per foot length of pipe for a specific type of ash slurry and known ash concentration in a given size of pipe at a given flow velocity can be estimated from equation 4, provided f is known. The friction factor (f) can be estimated using the usual relationship of f, $\mathbb{R}$ and $\frac{K}{D}$ for pipes, provided the Reynolds number is calculated using the effective viscosity of ash slurries. A relationship between the ratio of effective viscosity of ash slurries and viscosity of water at the same temperature, and the ash concentrations by volume has been correlated (Ref. 1) from experimental data for ash concentration up to 25 per cent by volume. This relationship in the form of an equation is given below:-

$$\frac{\nu \text{ effective}}{\nu \text{ water}} = 1 + 9.52\, C \quad \text{---------(5)} \qquad 0 \leq C \leq 0.25$$

where

ν effective = effective viscosity of ash slurries
ν water = viscosity of water at the same temperature
C = ash slurry concentration by volume expressed in fraction.

The use of equations 3, 4 and 5 to predict the headloss gradients for ash slurry flow in pipes is termed as the 'effective viscosity method' (Ref. 1).

8. Discussion of Results

8.1 General

No measurement was in fact carried out to determine the homogeneity of ash slurry flow during the course of this study. But tests carried out previously for similar type of ash had demonstrated that the ash slurry flow was homogeneous for ash concentrations up to 40 per cent by weight and mean pipe flow velocities from 3 to 9 f. p. s. (References 1 and 2). It was also demonstrated in Reference 1 that in the turbulent flow, the homogeneous ash slurry suspension behaved almost as a Newtonian fluid. When the homogeneous suspension has exhibited Newtonian characteristics, the headloss can be computed by the Darcy-Weisbach equation, provided the density and viscosity of the suspension are used.

8.2 Accuracy of experimental results

The accuracy of the experimental results can be estimated by examining the component errors that would likely occur during the experimentation. These are estimated as given below:-

(a) Error in measuring the specific gravity of ash slurry = $\pm$ 1 per cent,
(b) Error in measuring the mean velocity of slurry flow = $\pm$ 4 per cent,
(c) Error in measuring headloss $\pm$ 3 per cent.

If the component errors are considered additive, the overall error in the experimental results is about $\pm$ 8 per cent.

8.3 Effect of degree of ash slurry mixing on particle specific gravity

While it is true that the particle specific gravities determined using pycnometers by shaking, by boiling, and by applying a high vacuum, give progressively greater values of particle specific gravity, it is difficult to determine which method would simulate most closely the ash slurry conditions as experienced in a pumping plant. Although the ash particle specific gravities were determined in the laboratory using the shaking method, the results were inconsistent, as can be seen in Table 1. Until there is experimental evidence to suggest the best method to be used in the laboratory, it is suggested that in future, ash particle specific gravities should be determined during the experimental tests, from ash slurry samples taken from the mixing tank. The procedure involved is to determine the weight of a known volume of ash slurry and the dry weight of ash particles in that volume. From these data, the particle specific gravity can be deducted, using equation 6.

$$\text{Particle specific gravity} = \frac{W_D - W_c}{(W_D - W_c) + (W_E - W_w)} \qquad \ldots\ldots\ldots\ldots (6)$$

where W_c = weight of the graduated container (800 c.c.)
W_W = weight of container with a given volume ash slurry
W_D = weight of the container with oven-dried ash sample
W_E = weight of the container filled with equal volume of water.

This procedure makes use of the ash slurry conditions actually experienced in a pumping plant, and with some care, the experimental error can be maintained well below 2 pc. The field method is in fact more reliable and provided there are no great objections on the basis of tests already processed, a change should be made.

8.4 Effect of variation in ash particle specific gravity on headloss

The results of tests on the particle specific gravities for both Vales Point and Wangi ashes at the Water Research Laboratory and the Electricity Commission's Chemical Laboratory indicate inconsistency in results, although a similar procedure was followed in the tests. Even in the Commission tests, specific gravities from total sample is consistently lower than S. G. from subsieve sample (for ash particle size less than 53 microns). In order to allow for the variation in particle specific gravity such as might be encountered in the actual installation, an estimate was made to evaluate the resulting variation in headloss for a given percentage variation in particle specific gravity. To this end, equations, 3, 4 and 5 were used to calculate the resulting variations in theoretical headloss, assuming the diameter of pipe, relative roughness of pipe, ash slurry specific gravity and mean flow velocity are known due to a given variation in particle specific gravity. The results indicate that a variation of ± 5 pc. in the particle specific gravity causes a variation of ± 1 pc. in headloss. Although ash slurry headloss is not very sensitive to variation in particle specific gravity, yet in calculating the economics of disposing of a given tonnage of fly ash, the particle specific gravity in the suspension is important. The pumping equipment and pipelines will be sized correctly but the estimate of the total power bill could be in error.

8.5 Effect of detergent in ash slurry on headloss

Test results obtained for Vales Point ash slurry (high concentration) in 2" diameter pipe both with and without the introduction of detergent (about one per cent concentration) into the ash slurry demonstrated that a decrease of 10 per cent headloss was effected. Further work would be warranted if a preliminary assessment indicated that the addition of detergent, in concentration of the same order as those tested, was likely to be economic, and that no troublesome side effects were likely.

8.6 Pipe Roughness

The purpose of this investigation was to evaluate experimentally the fluid properties of ash slurries in rough pipes and to compare these headloss data with those calculated from the effective viscosity method (developed from test data by testing ash slurries of different types and concentrations in various size and type of pipes with roughness k-values varying from 0.000017' to 0.00008'). This comparison would provide evidence to evaluate the validity of the effective viscosity values determined previously to be used for predicting the headlosses in rough pipes. A study of Table 2 reveals that the roughness k - values of galvanised steel pipes is of the same order of magnitude as the roughness k-value for asbestos cement pipes but about 14 times smoother than steel pipes. It is clear that the commercially available galvanised steel pipes cannot be classified as rough pipes as is also substantiated by experiments with homogeneous suspensions (Ref. 3) in galvanised steel pipes which behaved hydraulically smooth. In order to evaluate the validity of the "effective viscosity method" for predicting headlosses in rough pipes, it is suggested that further tests should be carried out with either steel pipes or cast iron pipes or corrugated plastic pipes. It should be noted that more problems will be experienced in getting satisfactory pressure tappings in rough pipe than in smooth pipe.

8.7 Comparison of calculated (using effective viscosity method) and experimentally measured results.

The reader is referred to Figures 4, 5, 6 and 7 for the discussion that follows. It should be noted here that ash particle specific gravities of 1.94 for Vales Point ash and 1.91 for Wangi ash were used in calculating either the ash slurry concentration by volume or ash slurry concentration by weight.

Within the experimental accuracy (∓ 8 pc.), the 'effective viscosity method' can be used to predict adequately the headloss of ash slurry flow (for concentrations up to 50 per cent by weight) in 1-inch and 2-inch diameters galvanised steel pipes, as is evidenced by the fairly good agreement between the calculated and the experimentally measured results given in the above mentioned figures. It is pointed out earlier (Section 8.6) that the galvanised steel pipes cannot be classified as rough pipes. It is therefore very unlikely that the slight deviation of the experimental points from the calculated lines should be attributed to the effect of roughness of galvanised steel pipes.

The ash slurry headloss gradients for both types of ash can be considered as almost parallel to the water lines. It has been demonstrated (Figure 8) that for a slight deviation of headloss gradient from parallelism to the water line would cause a wide variation in effective viscosity. In other words, for a given ash concentration, the slurry headloss gradient is insensitive to the variation in effective viscosity. Figure 8 also indicates the fact that for a given ash concentration, the effective viscosity of ash slurry varies with flow velocity and it decreases as the velocity increases.

9. Conclusions

From the foregoing, the following conclusions are drawn:-

(1) Within the limits of accuracy of experimental results, the "effective viscosity method" can be used to predict the headloss of Vales Point and Wangi ash slurry flow in 1-inch and 2-inch diameter galvanised steel pipes.

(2) Experimental evidence indicates that the commercially available galvanised steel pipes cannot be classified as rough pipes.

(3) A uniform procedure should be followed in determining the ash particle specific gravities. It would be more realistic if the ash particle specific gravities were determined from ash slurry samples taken from the mixing tank during the experimental tests.

(4) In order to evaluate the effect of pipe roughness on the validity of the 'effective viscosity method' for ash slurry flow headloss prediction, it is suggested that further tests should be carried out for ash slurry flow in rough pipes, such as steel, cast iron or corrugated plastic pipes.

(5) The headloss of ash slurry flow in pipes is insensitive to the variation in ash particle specific gravity as well as to variation in effective viscosity.

(6) The introduction of 1 per cent of detergent in Vales Point ash slurry (63 per cent concentration by weight) in 2-inch diameter pipe reduced the headloss by 10 per cent.

(7) For a given ash concentration the effective viscosity of ash slurry varies with the flow velocity and it decreases as the velocity increases.

Table 3: Headloss data for fresh water in 2-inch diameter galvanised steel pipe.

No.	Date	Conc. Pc. by wt.	S. G. Slurry	Liquid Temp. ^oF	Velocity ft/sec.	Head-loss ft/ft	Remarks
1	10.5.68	0.0	1.00	73	1.35	0.004	Before Vales Point ash slurry tests.
2	"	"	"	73	1.82	0.007	
3	"	"	"	76	2.30	0.011	
4	"	"	"	73	2.74	0.015	
5	"	"	"	73	3.39	0.022	
6	"	"	"	73	3.98	0.030	
7	"	"	"	76	4.58	0.039	
8	"	"	"	73	5.02	0.046	
9	"	"	"	76	5.60	0.055	
10	"	"	"	73	6.19	0.068	
11	"	"	"	72	7.06	0.085	
12	"	"	"	72	8.04	0.109	
13	"	"	"	72	9.25	0.142	
14	"	"	"	72	10.20	0.173	
15	30.5.68	"	"	68	1.47	0.005	After Vales Point and before Wangi ash slurry tests.
16	"	"	"	68	1.86	0.008	
17	"	"	"	68	2.28	0.011	
18	"	"	"	68	2.62	0.015	
19	"	"	"	68	3.18	0.020	
20	"	"	"	68	3.80	0.029	
21	"	"	"	68	4.25	0.035	
22	"	"	"	63	4.85	0.045	
23	"	"	"	63	5.92	0.065	
24	"	"	"	63	6.92	0.086	
25	"	"	"	62	8.08	0.115	
26	"	"	"	62	9.11	0.141	
27	"	"	"	62	10.67	0.194	
28	18.7.68	"	"	60	1.76	0.007	After Wangi ash slurry tests.
29	"	"	"	60	2.62	0.016	
30	"	"	"	60	3.65	0.028	
31	"	"	"	59	3.72	0.029	
32	"	"	"	59	4.88	0.045	
33	"	"	"	59	6.00	0.068	
34	"	"	"	59	7.96	0.109	
35	"	"	"	59	9.00	0.142	

Table 4: Headloss data for fresh water in 1-inch diameter galvanised steel pipe.

No.	Date	Conc. Pc. by wt.	S. G. Slurry	Liquid Temp. °F	Velocity ft/ sec.	Head-loss ft/ ft	Remarks
1	31.5.68	0.0	1.00	65	1.44	0.012	Before Vales Point ash slurry tests
2	"	"	"	65	2.09	0.022	
3	"	"	"	65	2.78	0.038	
4	"	"	"	64	3.54	0.058	
5	"	"	"	64	3.92	0.069	
6	"	"	"	64	4.86	0.101	
7	"	"	"	64	5.97	0.150	
8	"	"	"	64	6.67	0.186	
9	"	"	"	64	7.34	0.220	
10	"	"	"	64	8.57	0.292	
11	"	"	"	64	10.50	0.423	
12	"	"	"	64	12.07	0.553	
13	27.6.68	"	"	57	1.90	0.018	After Vales Point and before Wangi ash slurry tests
14	"	"	"	57	2.23	0.026	
15	"	"	"	57	3.05	0.045	
16	"	"	"	57	4.03	0.072	
17	"	"	"	57	4.86	0.100	
18	"	"	"	57	5.75	0.138	
19	"	"	"	57	5.83	0.142	
20	"	"	"	57	6.18	0.163	
21	"	"	"	57	6.68	0.179	
22	"	"	"	57	6.73	0.184	
23	"	"	"	57	7.34	0.216	
24	"	"	"	57	8.49	0.284	
25	"	"	"	57	9.01	0.309	
26	"	"	"	57	10.60	0.424	
27	"	"	"	57	11.00	0.448	
28	"	"	"	57	12.76	0.605	
29	18.7.68	"	"	60	1.82	0.017	After Wangi ash slurry tests
30	"	"	"	60	3.21	0.050	
31	"	"	"	60	5.03	0.108	
32	"	"	"	60	5.86	0.155	
33	"	"	"	60	6.33	0.170	
34	"	"	"	60	7.18	0.216	
35	"	"	"	60	9.47	0.348	
36	"	"	"	60	11.89	0.527	

Table 5: Headloss data for Vales Point ash slurry in 2-inch diameter galvanised steel pipes.

No.	Date	Conc. Pc. by wt.	S. G. Slurry	Liquid Temp.^{o}F	Velocity ft/sec.	Headloss ft/ft	Viscosity Ratio
1	21.5.68	11.69	1.060	67	2.07	0.011	-
2	"	11.69	1.060	67	2.76	0.018	-
3	"	12.04	1.062	67	3.08	0.026	3.42
4	"	12.04	1.062	66	3.56	0.034	3.56
5	"	12.77	1.066	66	4.23	0.040	1.77
6	"	12.97	1.067	66	4.93	0.052	1.60
7	"	12.94	1.067	66	6.13	0.076	1.44
8	"	13.13	1.068	66	7.13	0.100	1.40
9	"	13.13	1.068	64	8.51	0.136	1.20
10	"	13.50	1.070	64	9.40	0.163	1.13
11	13.5.68	22.20	1.121	71	1.31	0.006	-
12	"	22.20	1.121	71	2.43	0.017	-
13	"	22.50	1.123	71	3.27	0.028	2.43
14	"	22.30	1.122	71	4.26	0.044	2.20
15	"	22.56	1.124	71	5.96	0.077	1.67
16	"	22.50	1.123	70	7.11	0.105	1.52
17	"	22.70	1.122	70	8.56	0.146	1.40
18	"	23.40	1.128	70	9.42	0.171	1.17
19	22.5.68	33.00	1.191	74	1.56	0.008	-
20	"	33.00	1.191	75	2.28	0.017	-
21	"	33.00	1.191	75	2.62	0.023	-
22	"	32.94	1.190	76	3.63	0.036	2.66
23	"	33.23	1.192	76	4.53	0.051	2.05
24	"	33.51	1.194	76	5.85	0.079	1.74
25	"	33.51	1.194	75	7.38	0.115	1.24
26	"	33.95	1.197	75	8.63	0.151	1.06
27	"	33.95	1.197	75	9.64	0.188	1.13
28	14.5.68	45.50	1.283	74	1.34	0.012	-
29	"	45.50	1.283	74	1.55	0.014	-
30	"	45.50	1.283	74	1.87	0.018	-
31	"	45.50	1.283	76	2.38	0.023	-
32	"	46.02	1.287	76	2.88	0.030	-
33	"	45.64	1.284	76	3.33	0.040	5.89
34	"	46.02	1.287	76	3.61	0.045	5.30
35	"	46.02	1.287	76	4.40	0.065	5.70
36	"	46.02	1.287	76	5.59	0.096	4.98

Table 5 (cont'd.)

No.	Date	Conc. Pc. by wt.	S. G. Slurry	Liquid Temp. °F	Velocity ft/ sec.	Headloss ft/ ft	Viscosity Ratio
37	14.5.68	46.50	1.290	76	6.29	0.118	4.80
38	"	46.50	1.290	76	7.02	0.145	4.98
39	"	46.50	1.290	76	8.39	0.200	5.00
40	"	46.60	1.293	76	9.22	0.249	6.42
41	16.5.68	49.60	1.317	74	2.15	0.022	
42	"	50.03	1.320	74	2.60	0.030	
43	"	50.03	1.320	74	3.04	0.039	
44	"	49.78	1.318	75	3.16	0.041	
45	"	50.03	1.320	75	4.05	0.062	
46	"	50.53	1.324	75	4.88	0.088	
47	"	50.38	1.323	75	5.96	0.126	
48	"	50.60	1.325	75	6.73	0.153	
49	"	50.26	1.322	74	7.76	0.202	
50	"	50.26	1.322	74	8.54	0.238	
51	"	50.03	1.320	74	9.11	0.282	
52	22.5.68	53.20	1.347	74	2.46	0.030	
53	"	53.27	1.348	74	2.83	0.038	
54	"	53.38	1.349	74	3.56	0.060	
55	"	53.50	1.350	74	4.43	0.083	
56	"	53.50	1.350	74	5.45	0.119	
57	"	53.62	1.351	73	6.39	0.156	
58	"	53.62	1.351	73	7.49	0.208	
59	"	53.62	1.351	72	8.21	0.238	
60	23.5.68	63.0	1.440	84	1.26	0.079	
61	"	63.0	1.440	84	1.81	0.089	
62	"	63.0	1.440	85	2.23	0.096	
63	"	63.0	1.440	86	2.64	0.097	
64	"	63.0	1.440	86	3.44	0.114	
65	"	63.0	1.440	86	4.47	0.143	
66	"	63.0	1.440	86	5.71	0.177	
67	"	63.0	1.440	86	6.96	0.225	
68	"	63.0	1.440	86	8.33	0.284	
69	"	63.0	1.440	85	9.22	0.334	

Table 6: Headloss data for Vales Point ash slurry in 1-inch diameter galvanised steel pipe.

No.	Date	Conc. Pc. by wt.	S. G. Slurry	Liquid Temp. °F	Velocity ft/ sec.	Headloss ft/ ft	Viscosity Ratio
1	7.6.68	13.50	1.07	65	1.82	0.018	-
2	"	"	"	65	2.25	0.027	-
3	"	"	"	65	2.91	0.042	-
4	"	"	"	66	3.33	0.053	0.96
5	"	"	"	66	4.10	0.078	1.01
6	"	"	"	66	4.98	0.108	0.81
7	"	"	"	66	5.29	0.124	0.96
8	"	"	"	66	6.26	0.167	0.88
9	"	"	"	66	7.07	0.206	0.75
10	"	"	"	66	7.78	0.248	0.80
11	"	"	"	66	9.08	0.326	0.66
12	"	"	"	66	10.81	0.452	0.64
13	"	"	"	66	13.21	0.654	0.49
14	7.6.68	20.60	1.111	68	1.42	0.014	-
15	"	20.60	1.111	68	1.91	0.023	-
16	"	22.10	1.120	68	3.03	0.054	1.99
17	"	22.10	1.120	68	3.67	0.072	1.52
18	"	22.27	1.121	67	4.75	0.114	1.46
19	"	22.10	1.120	68	5.01	0.125	1.45
20	"	22.27	1.121	67	6.15	0.185	1.48
21	"	22.27	1.121	67	6.46	0.210	1.94
22	"	22.27	1.121	67	6.54	0.218	2.09
23	"	22.27	1.121	67	7.62	0.268	1.38
24	"	22.27	1.121	66	9.19	0.369	1.09
25	"	22.10	1.120	66	11.32	0.537	0.94
26	"	22.10	1.120	66	13.15	0.702	0.77
27	11.6.68	32.38	1.186	63	1.93	0.028	-
28	"	32.38	1.186	63	2.24	0.037	-
29	"	32.38	1.186	63	2.96	0.057	-
30	"	"	1.186	63	3.75	0.088	2.32
31	"	"	1.186	63	4.89	0.138	2.10
32	"	32.80	1.189	63	6.05	0.200	1.90
33	"	"	1.189	63	6.71	0.239	1.85
34	"	"	1.189	63	7.60	0.298	1.75
35	"	"	1.189	62	9.01	0.393	1.38
36	"	32.38	1.186	60	10.81	0.554	1.47
37	"	32.80	1.189	60	12.89	0.747	1.07

Table 6 (cont'd.)

No.	Date	Conc. Pc. by wt.	S. G. Slurry	Liquid Temp.°F	Velocity ft/sec.	Headloss ft/ft	Viscosity Ratio
38	12.6.68	45.30	1.281	70	1.87	0.022	-
39	"	"	1.281	70	2.11	0.038	-
40	"	"	1.281	70	2.83	0.064	-
41	"	"	1.281	70	3.78	0.109	4.30
42	"	46.02	1.287	70	4.79	0.160	3.68
43	"	45.39	1.282	70	5.79	0.221	3.53
44	"	46.40	1.290	70	5.86	0.225	3.36
45	"	46.40	1.290	70	6.63	0.281	3.39
46	"	45.39	1.282	70	7.28	0.323	3.02
47	"	45.50	1.283	70	8.59	0.429	2.82
48	"	46.02	1.287	69	10.78	0.623	2.02
49	"	46.02	1.287	69	13.26	0.890	1.76
50	18.6.68	53.50	1.350	65	1.26	0.083	
51	"	"	"	65	1.91	0.102	
52	"	"	"	65	2.23	0.112	
53	"	"	"	64	2.80	0.128	
54	"	"	"	64	3.74	0.170	
55	"	"	"	63	4.94	0.238	
56	"	"	"	62	6.02	0.319	
57	"	53.50	1.350	62	6.68	0.402	
58	"	"	"	69	8.31	0.497	
59	"	53.50	1.350	69	9.20	0.610	
60	"	"	"	69	10.18	0.693	
61	"	"	"	69	12.05	0.90	
62	"	53.50	"	69	12.68	0.972	
63	25.6.68	62.20	1.432	77	1.95	0.163	
64	"	"	"	77	2.58	0.193	
65	"	"	"	79	3.70	0.232	
66	"	"	"	79	5.56	0.367	
67	"	"	"	80	8.28	0.490	
68	"	"	"	80	10.23	0.667	
69	"	"	"	80	11.53	0.778	
70	"	62.20	1.432	80	11.89	0.889	

Table 7: Headloss data for Wangi ash slurry in 2-inch diameter galvanised steel pipe.

No.	Date	Conc. Pc. by wt.	S. G. Slurry	Liquid Temp. °F	Velocity ft/sec.	Headloss ft/ft.	Viscosity Ratio
1	28.6.68	10.20	1.051	56	1.58	0.006	-
2	"	"	"	"	1.87	0.008	-
3	"	"	"	"	2.33	0.013	-
4	"	"	"	"	3.15	0.023	1.44
5	"	"	"	"	3.77	0.022	1.49
6	"	"	"	"	4.54	0.046	1.72
7	"	"	"	"	5.69	0.065	1.23
8	"	"	"	"	7.11	0.100	1.41
9	"	"	"	"	8.31	0.131	1.24
10	"	10.20	1.051	"	9.22	0.161	1.38
11	1.7.68	20.28	1.107	53	1.41	0.007	-
12	"	"	"	"	1.77	0.009	-
13	"	"	"	"	2.35	0.015	-
14	"	"	"	"	3.15	0.025	1.59
15	"	"	"	"	3.80	0.035	1.61
16	"	"	"	52	4.59	0.048	1.39
17	"	"	"	"	5.86	0.076	1.54
18	"	"	"	"	7.37	0.111	1.19
19	"	"	"	"	8.30	0.142	1.40
20	"	20.28	1.107	"	9.07	0.171	1.63
21	2.7.68	30.18	1.168	57	1.40	0.008	-
22	"	"	"	"	1.67	0.010	-
23	"	"	"	"	2.12	0.014	-
24	"	"	"	"	2.62	0.021	-
25	"	"	"	"	3.23	0.029	2.15
26	"	"	"	"	3.89	0.041	2.33
27	"	"	"	56	4.77	0.058	2.09
28	"	30.18	"	"	5.93	0.085	1.97
29	"	30.18	"	"	6.88	0.119	2.84
30	"	"	"	"	8.41	0.160	1.97
31	"	"	"	"	9.31	0.187	1.64

Table 7 (cont'd.)

No.	Date	Conc. Pc. by wt.	S. G. Slurry	Liquid Temp °F	Velocity ft/sec.	Headloss ft/ft	Viscosity Ratio
32	4.7.68	39.78	1.234	57	1.23	0.012	-
33	"	"	"	"	1.53	0.013	-
34	"	"	"	"	1.84	0.015	-
35	"	"	"	"	2.21	0.020	-
36	"	"	"	56	2.72	0.028	-
37	"	"	"	"	3.68	0.045	4.14
38	"	"	"	"	4.57	0.064	3.67
39	"	"	"	55	5.50	0.092	4.28
40	"	"	"	54	6.87	0.136	4.00
41	"	"	"	"	8.06	0.178	3.68
42	"	"	"	"	9.00	0.219	3.88
43	8.7.68	50.00	1.312	74	1.93	0.021	
44	"	"	"	75	2.49	0.027	
45	"	"	"	"	3.19	0.038	
46	"	"	"	"	4.20	0.064	
47	"	"	"	"	5.08	0.088	
48	5.7.68	"	"	58	6.20	0.144	
49	"	"	"	56	7.54	0.205	
50	"	"	"	"	8.41	0.262	
51	"	"	"	"	9.07	0.305	
52	"	60.60	1.397	86	1.44	0.070	
53	"	"	"	"	1.87	0.081	
54	"	"	"	"	2.57	0.097	
55	"	"	"	"	2.81	0.113	
56	"	"	"	87	3.53	0.133	
57	"	60.60	1.397	87	4.35	0.163	
58	"	"	"	88	5.44	0.214	
59	"	"	"	"	5.95	0.292	
60	"	"	"	"	7.92	0.327	
61	"	"	"	"	8.81	0.390	

Table 8: Headloss data for Wangi ash slurry in 1-inch diameter galvanised steel pipe.

No.	Date	Conc. Pc. by wt.	S. G. Slurry	Liquid Temp. °F	Velocity ft/sec.	Headloss ft/ft.	Viscosity Ratio
1	28.6.68	10.20	1.051	56	2.00	0.023	-
2	"	"	"	"	2.76	0.039	-
3	"	"	"	"	4.03	0.080	1.30
4	"	"	"	"	5.11	0.121	1.16
5	"	"	"	55	6.23	0.172	1.07
6	"	"	"	"	6.99	0.212	1.05
7	"	"	"	"	7.72	0.258	1.13
8	"	"	"	"	9.12	0.354	1.21
9	"	"	"	54	11.05	0.488	0.86
10	"	"	"	"	12.42	0.600	0.78
11	1.7.68	20.28	1.107	58	2.03	0.024	-
12	"	"	"	"	2.66	0.038	-
13	"	"	"	"	3.74	0.069	0.93
14	"	"	"	"	5.00	0.117	0.92
15	"	"	"	"	6.21	0.176	0.97
16	"	"	"	"	6.45	0.201	1.43
17	"	"	"	"	6.90	0.218	1.10
18	"	"	"	"	7.61	0.269	1.32
19	"	"	"	56	9.20	0.363	0.90
20	"	"	"	56	11.32	0.508	0.51
21	"	"	"	56	12.36	0.622	0.73
22	2.7.68	30.18	1.168	56	2.00	0.028	-
23	"	"	"	55	2.39	0.038	-
24	"	"	"	"	3.04	0.058	1.81
25	"	"	"	"	4.05	0.093	1.51
26	"	"	"	"	5.29	0.150	1.49
27	"	"	"	54	6.35	0.209	1.45
28	"	"	"	"	6.44	0.223	1.81
29	"	"	"	"	6.92	0.249	1.62
30	"	"	"	"	7.76	0.313	1.77
31	"	"	"	"	9.12	0.424	1.90
32	"	"	"	52	10.42	0.519	1.40
33	"	30.18	"	"	11.95	0.656	1.22

Table 8 (cont'd.)

No.	Date	Conc. Pc. by wt.	S. G. Slurry	Liquid Temp. °F	Velocity ft/ sec.	Headloss ft/ ft.	Viscosity Ratio
34	4.7.68	39.78	1.234	64	1.96	0.033	-
35	"	"	"	"	2.27	0.038	-
36	"	"	"	"	2.78	0.055	-
37	"	"	"	"	3.89	0.097	2.20
38	"	"	"	"	4.91	0.161	3.48
39	"	"	"	"	6.04	0.223	2.85
40	"	"	"	"	6.09	0.232	3.22
41	"	"	"	"	6.76	0.279	3.18
42	"	"	"	"	6.92	0.308	4.13
43	"	"	"	"	8.56	0.423	3.04
44	"	"	"	63	10.51	0.597	2.62
45	"	"	"	"	12.26	0.756	1.93
46	5.7.68	50.0	1.312	78	1.97	0.086	
47	"	"	"	"	2.63	0.090	
48	"	"	"	"	3.84	0.106	
49	"	"	"	"	5.19	0.153	
50	"	"	"	77	6.16	0.232	
51	"	"	"	78	6.32	0.217	
52	"	"	"	77	6.86	0.313	
53	"	"	"	"	7.66	0.342	
54	"	"	"	78	9.16	0.513	
55	"	"	"	"	11.42	0.748	
56	"	50.0	1.312	"	13.15	0.972	

Table 9: Headloss data for Vales Point ash slurry in 2-inch diameter galvanised steel pipe

No.	Date	Conc. Pc. by wt.	S. G. Slurry	Liquid Temp. ^{o}F	Velocity ft/ sec.	Headloss ft/ ft.	Remarks
1	16.7.68	63.0	1.44	77	1.22	0.093	Without detergent
2	"	"	"	"	1.44	0.100	
3	"	"	"	"	1.76	0.103	
4	"	"	"	"	2.16	0.116	
5	"	"	"	78	2.63	0.133	
6	"	"	"	"	3.44	0.163	
7	"	"	"	"	4.20	0.194	
8	"	"	"	"	5.30	0.258	
9	"	"	"	"	6.51	0.323	
10	"	"	"	"	7.62	0.396	
11	"	"	"	"	8.34	0.463	
12	16.7.68	63.0	1.44	78	1.27	0.087	With detergent about 1 pc. by volume
13	"	"	"	"	1.49	0.090	
14	"	"	"	"	1.81	0.099	
15	"	"	"	"	2.23	0.111	
16	"	"	"	"	2.76	0.128	
17	"	"	"	"	3.58	0.153	
18	"	"	"	76	4.35	0.188	
19	"	"	"	"	5.58	0.234	
20	"	"	"	"	6.86	0.289	
21	"	"	"	"	7.96	0.344	
22	"	"	"	"	8.79	0.389	

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3. Graf, W. H. and Acaroglu, E. R., "Homogeneous Suspensions in Circular Conduits" Journal of the Pipelines Division, ASCE Vol. 93, No. PL 2, Proc. Paper 5352, July 1967, pp. 63-69.

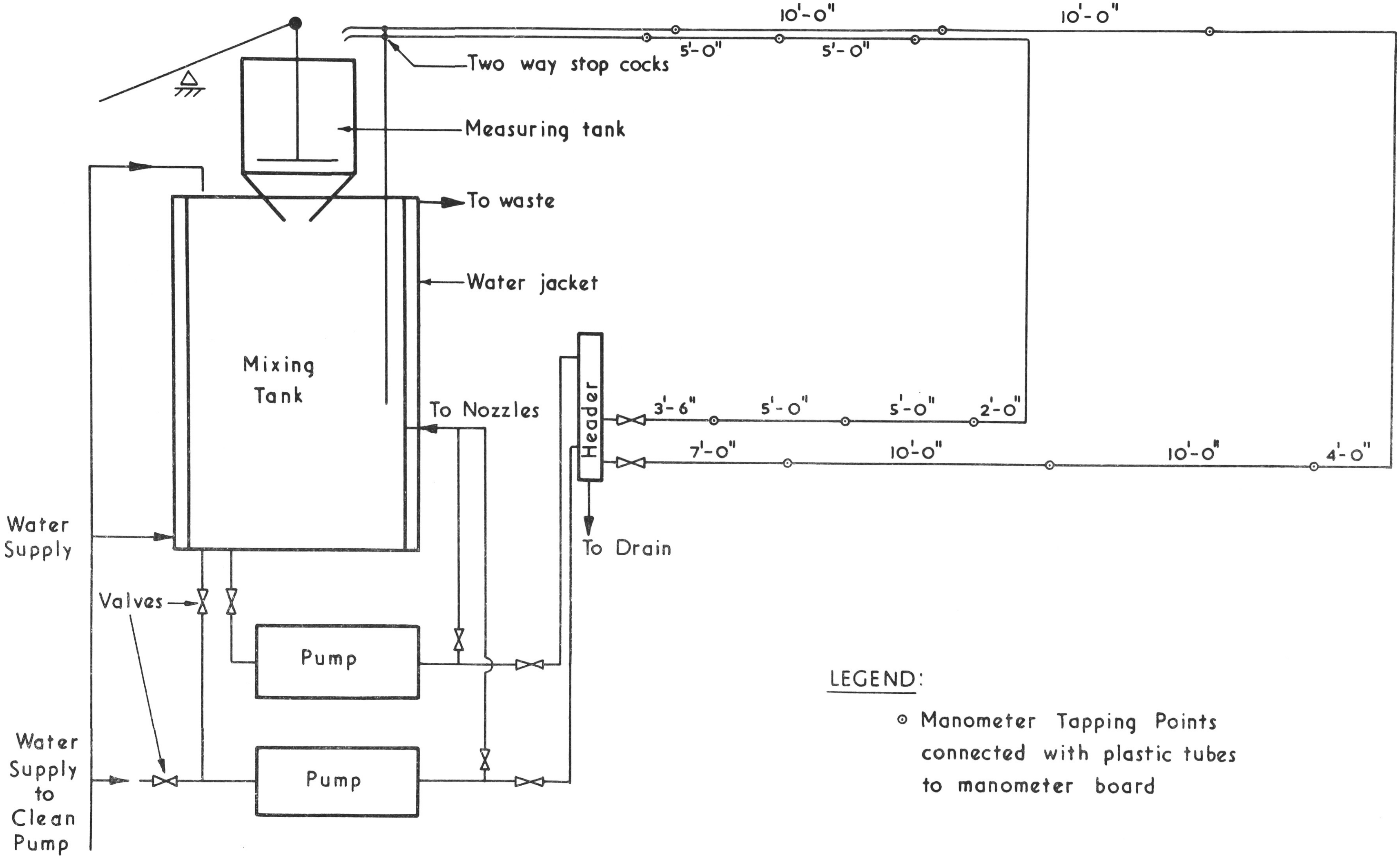
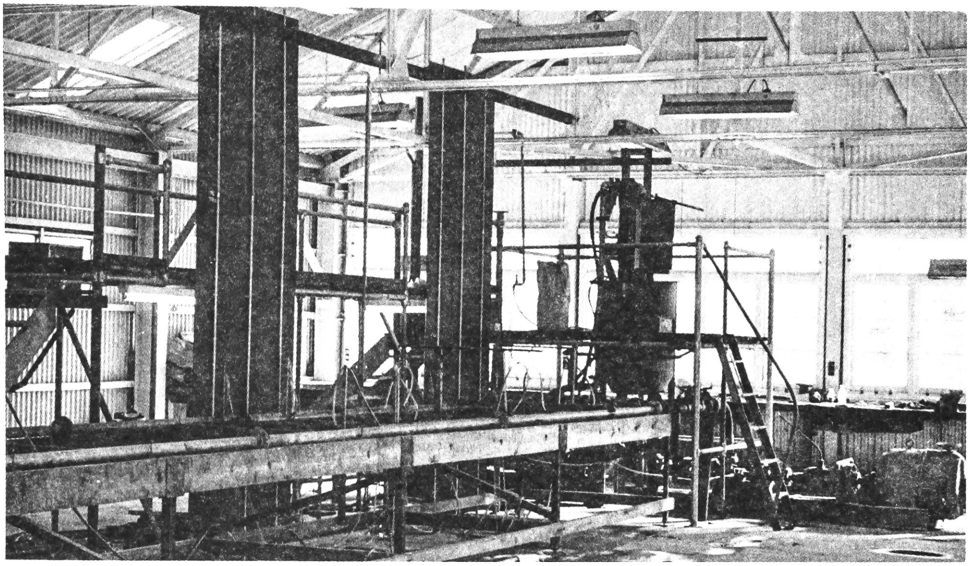
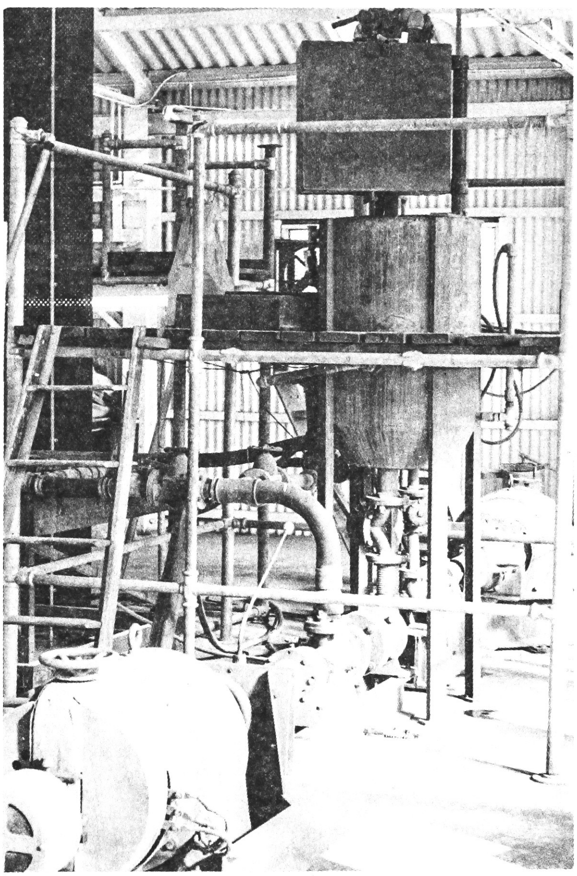


Figure 1: General layout of test rig.



Test pipes, pressure tappings, manometer boards, measuring tank, mixing tank and pumps.



Measuring tank, mixing tank and pumps.

Figure 2: Photographs of test rig.

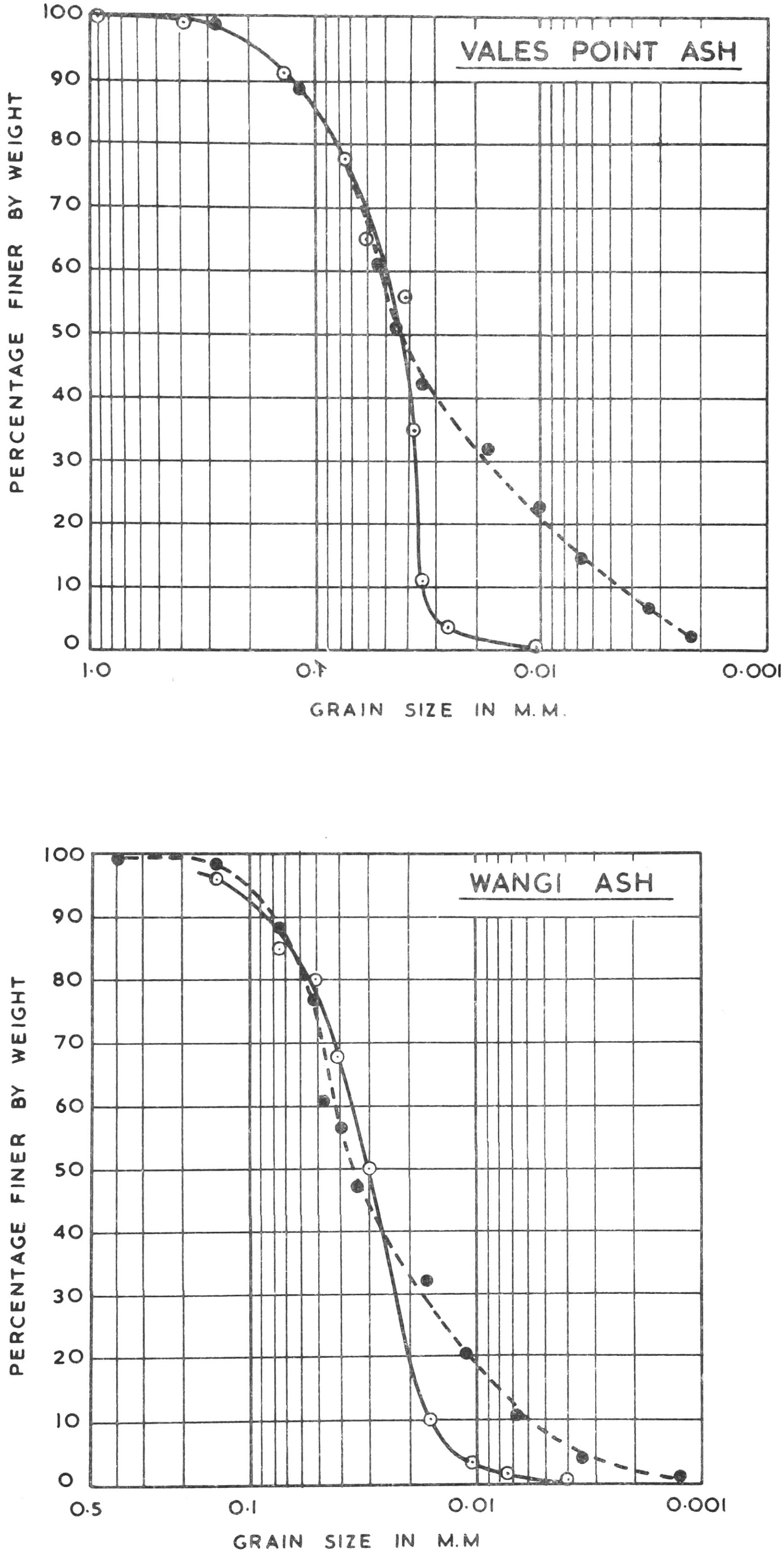


Figure 3: Fly-ash particle size grading.

LEGEND:

—○—Hydrometer analysis

--●--Bahco dust sizer analysis

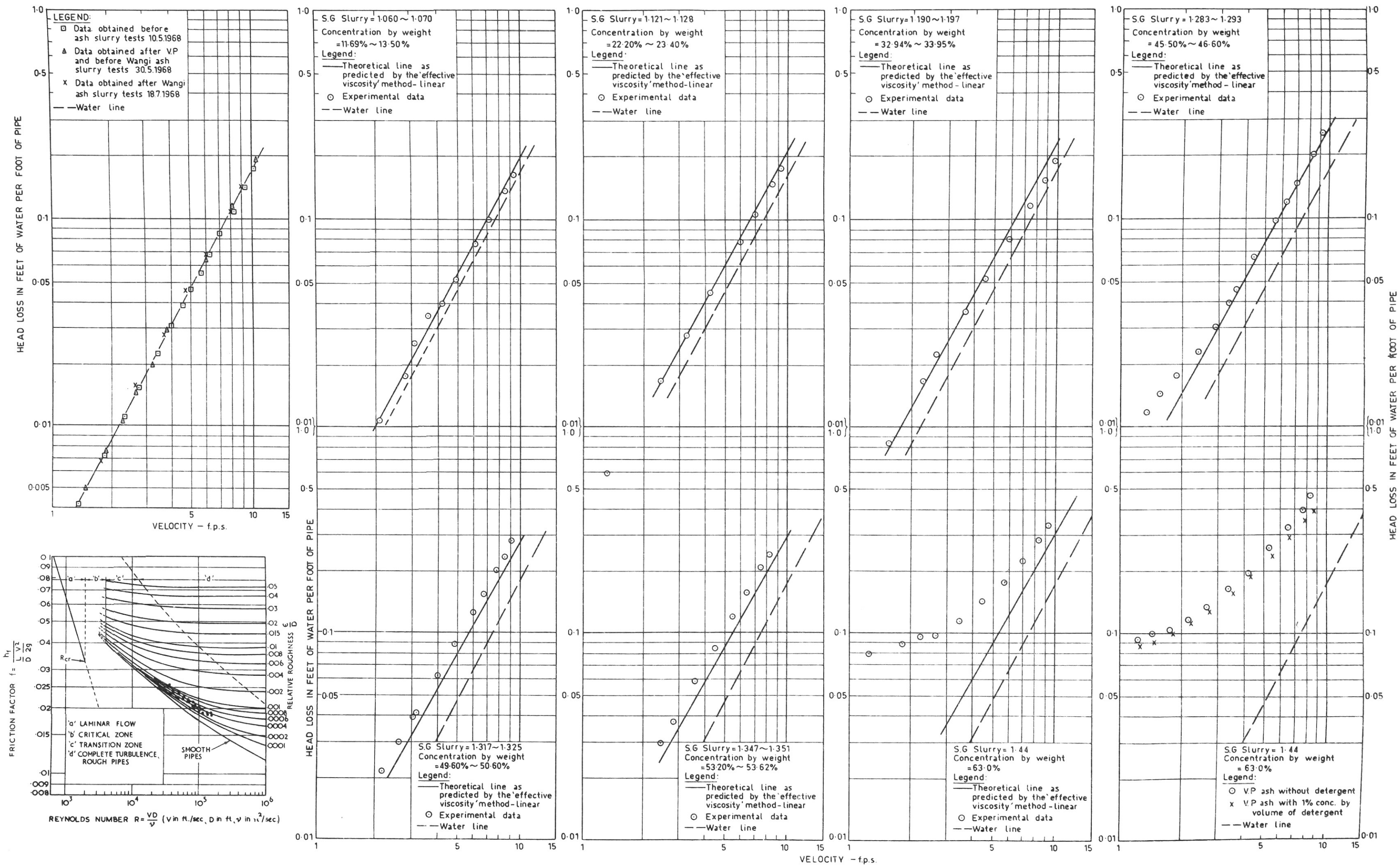


Figure 4: Headloss gradient for Vales Point ash slurry in 2" diameter pipe.

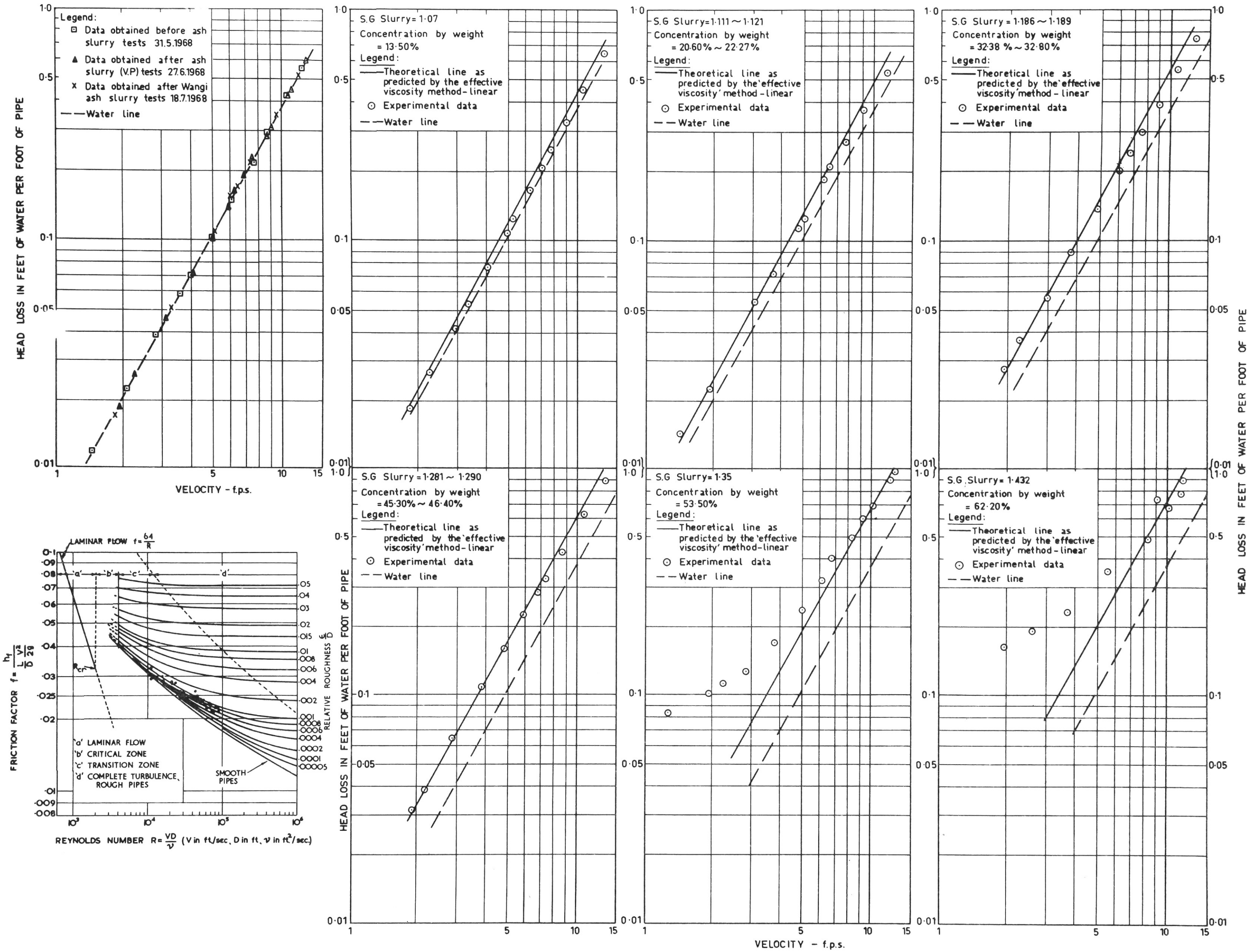


Figure 5: Headloss gradient for Vales Point ash slurry in 1" diameter pipe.

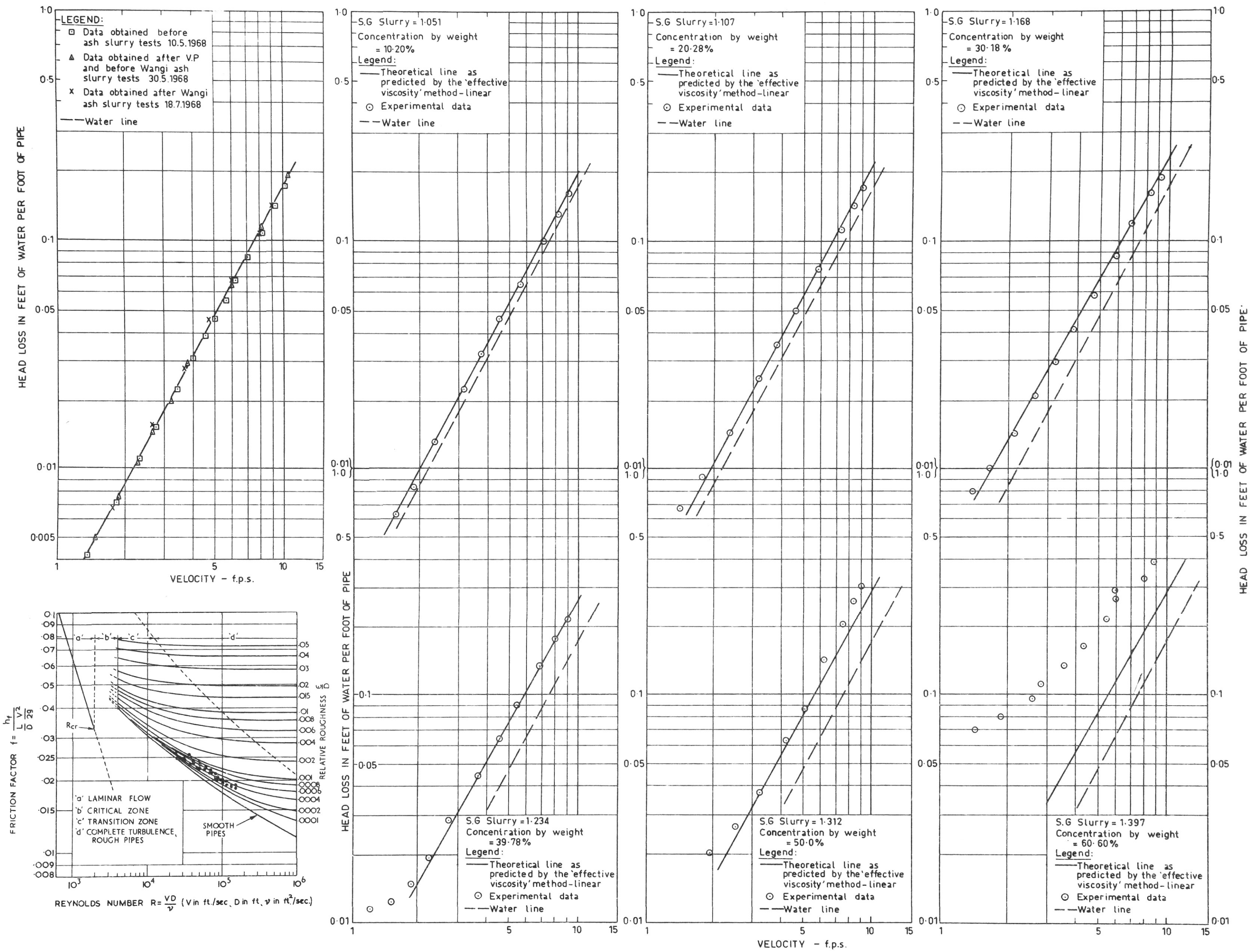


Figure 6: Headloss gradient of Wangi ash slurry in 2" diameter pipe.

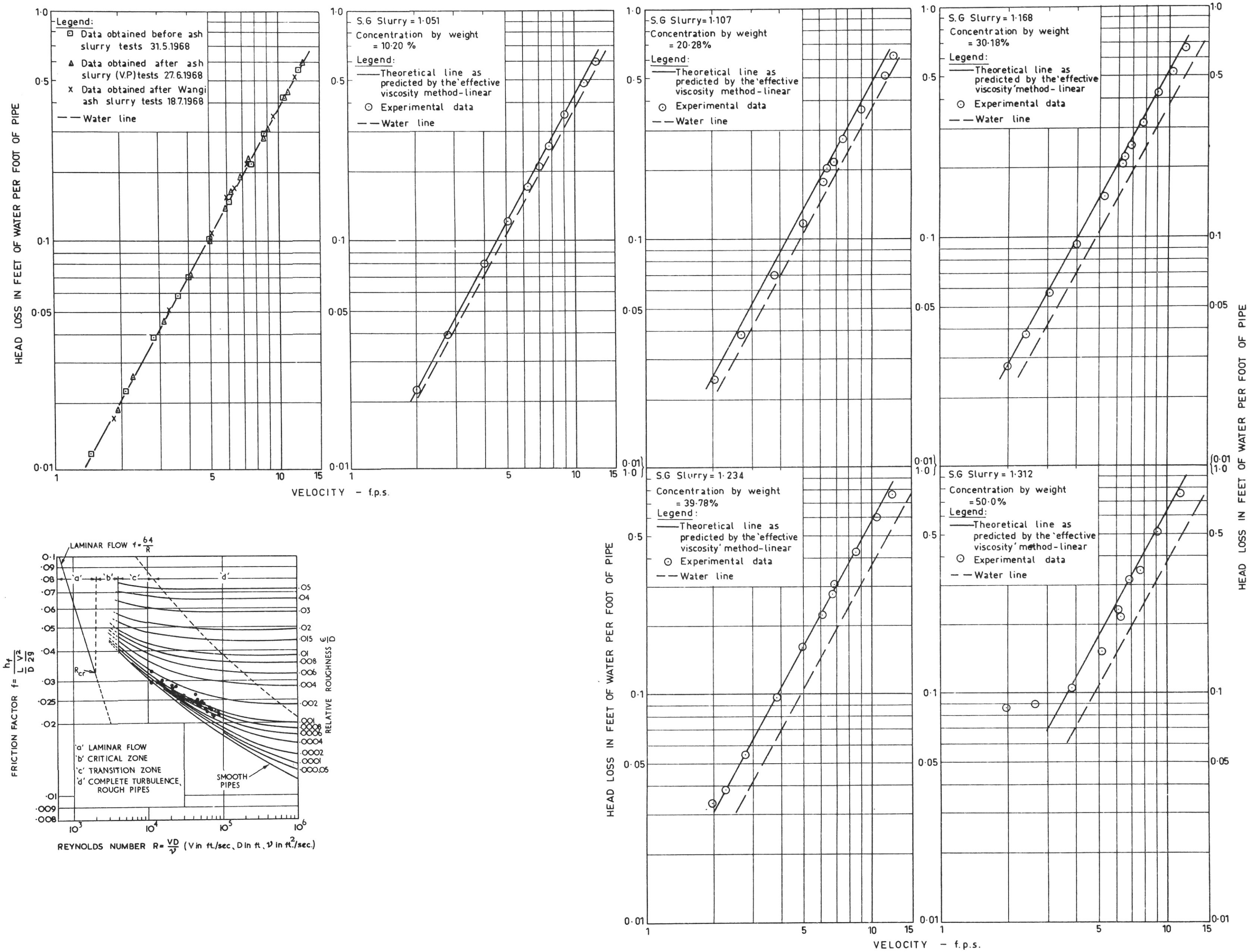


Figure 7: Headloss gradient for Wangi ash slurry in 1" diameter pipe.

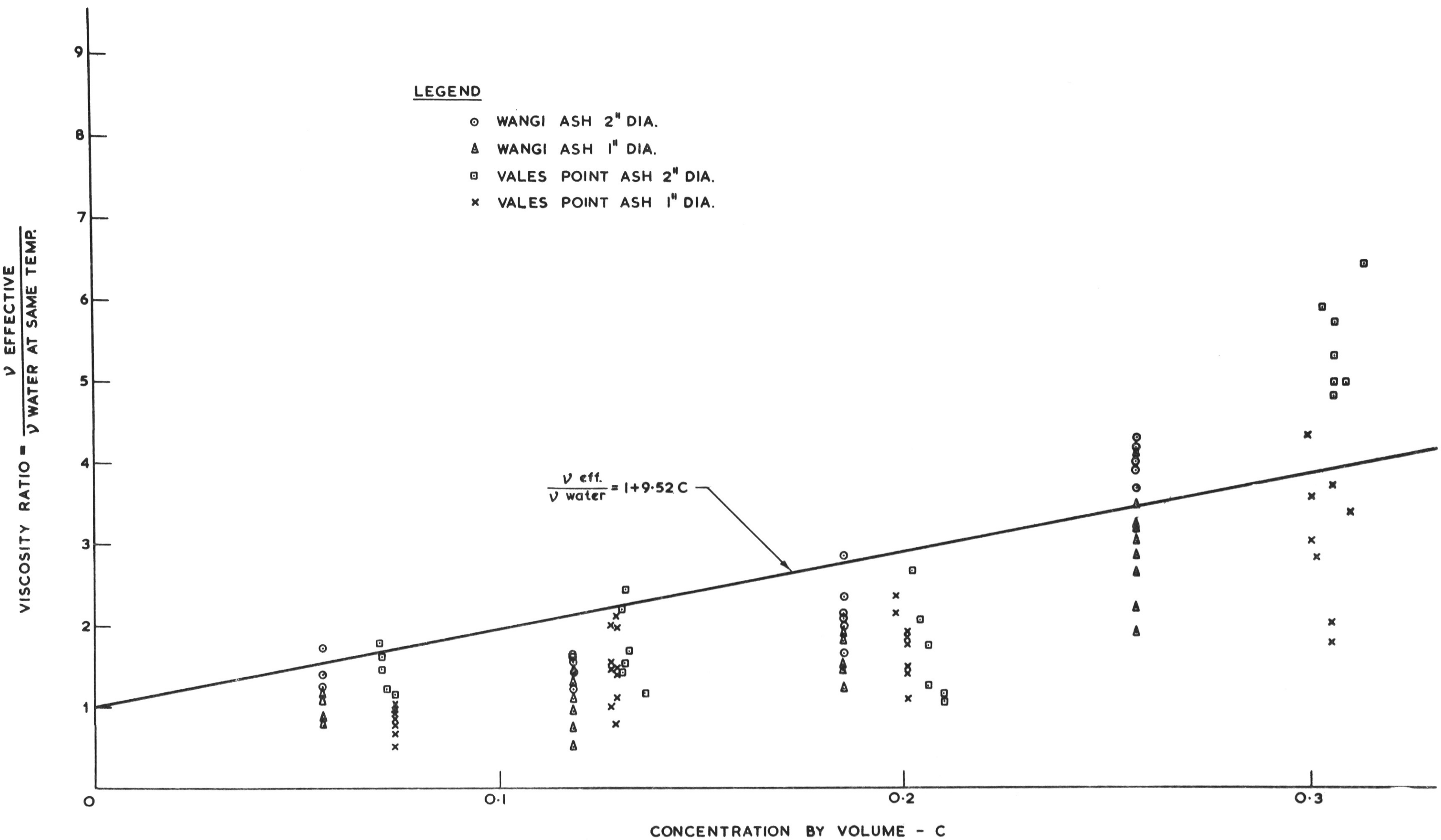


Figure 8: Relationship between effective viscosity and concentration of ash slurry.