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HIGH DENSITY COAL ASH SLURRY TRANSPORT

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1. INTRODUCTION

The conventional method of disposing of flyash is to mix it with water to form a low density slurry and then pump it to ponds. Typically the solids concentration is about 30% by weight. This low solids concentration means large quantities of water need to be pumped with consequent large pipe sizes.

An attractive alternative is to pump the flyash at a much higher concentration, around 70%. Much less water is required and hence a smaller size pipe can be employed. The high density slurry also has advantages at the disposal site. Because of its high density the slurry is sufficiently thick to form a sloping deposit which maintains its slope when flow stops. If discharged from a single discharge point, the slurry will form a cone-shaped deposit having a surface slope of a few percent. The perimeter of the deposit is determned by the slurry density which also determines the deposit slope and the volume of material in the deposit. No perimeter walls are needed to contain the deposit.

2. FLYASH SLURRY PROPERTIES

Fig. 1 shows a typical particle size distribution. The top size is around 150 microns with the median particle size 15 to 20 microns. Typical solid specific densities can range between 2200 to 2700 kg/cub. metre.

At low solid concentrations, less than 40 to 50%, the flyash slurry behaves as a settling slurry ie. if left to stand in a container, the solids will settle to the bottom. For pipeline transport, the particles must be supported by the turbulent eddies. The solids increase the effective viscosity of the slurry. This viscosity can be measured in a viscometer.

Once the concentration exceeds a certain critical value, typically 40 to 50%, particle interaction becomes significant and the slurry begins to exhibit non-Newtonian characteristics. Fig.2 shows schematically typical rheological plots of shear stress versus shear rate. For a Newtonian fluid the plot passes through the origin. The slope of the line is the viscosity. Above the critical concentration, the non-Newtonian behaviour can most easily be described by the Binghan plastic model.

$$\tau = \tau_y + \eta \dot{\gamma}$$

Where τ_y is the yield stress and η is the plastic viscosity. This yield stress must be exceeded before any shearing can take place. The slope of the line above this stress level is termed the plastic viscosity. At stress levels below the yield value the slurry behaves as an elastic solid. A practical effect of this can be observed when pumping such a slurry. If a centrifugal pump connected to a horizontal pipeline is slowly increased in speed the pressure will slowly rise. However, no flow will take place until the pressure reaches a certain value such that the yield stress is exceeded. This is in contrast with for example water, where a small flow will occur even for the smallest applied pressure.

The presence of a yield stress causes the slurry to become non-settling in nature. The elastic structure can support the coarsest particles thereby preventing settling and any segregation of particle sizes. Thomas (1977) gave the following equation giving the required minimum yield stress required to prevent settling of particles of size d.

$$\tau_y = kgd \quad (P_p - P) \tag{1}$$

Where Pp is the particle density, P is the slurry density and g is the gravitational constant. For isolated coarse particles in an otherwise fine particle slurry, the value of the constant k was given as .092. Howver, for slurries having a continuous size distribution where the coarser particles also contribute to the rheology k was given as 0.46.

For a maximum particle size of 150 microns this indicates a required yield stress of between 0.5 and 1 Pascal.

Fig. 3 shows some typical rheology curves for a flyash slurry. Both the yield stress and the plastic viscosity are seen to be strong functions of solids concentration. For this particular slurry a yield stress of 0.5 to 1 Pa is reached at around 60% concentration.

3. PIPE FLOW BEHAVIOUR AT LOW DENSITIES

3.1 Pseudo-homogeneous Flow

At sufficiently high velocities, the slurry will behave as a pseudo-homogeneous fluid having near Newtonian properties ie. the turbulent flow friction factor in smooth pipes is determined by one parameter only, the Reynolds number given by

$$Re = VDP/\mu \qquad (2)$$

The Nikuradse smooth wall equation is

$$\frac{1}{\sqrt{f_N/2}} = 2.5 \; Ln \left(Re \sqrt{f_N/2} \right) \qquad (3)$$

where fN is the Fanning Friction factor given by

$$f_N = \frac{1}{2} \frac{\Delta P}{L} \frac{D}{\rho V^2} \qquad (4)$$

For rough walled pipes, the Colebrook-white equation is generally employed.

$$\frac{1}{\sqrt{f_N}} = 4 \; Log \frac{D}{2K} + 3.48 - 4 \; Log \left(1 + 9.35 \frac{D}{2K Re \sqrt{f_N}} \right) \qquad (5)$$

Where k is the pipe roughness. For new steel pipe k = .05 mm although with slurries the pipe is often smoothed due to slurry abrasion and k can end up closer to .01 mm.

Equation 5 is the basis of the common friction factor charts. It can be used to give an approximate value for the friction factor in the pseudo-homogeneous region although there is an additional complicating issue due to viscous sub-layer effects.

During turbulent pipe flow, a thin boundary layer exists adjacent to the pipe wall where viscous forces predominate. This is termed the viscous sub-layer. Its thickness δ is given by

$$\delta = \frac{5\mu}{\rho V \sqrt{f_N/2}} \quad (6)$$

The thickness of this layer is quite small. For example for water flowing at 4m/s in a 100mm pipe equation 6 indicates δ = 30 microns.

For more viscous fluids or slurries δ is larger.

Consider the flow of a low concentration flyash slurry for which the viscosity is similar to that of water. For the above conditions where δ = 30 microns, only particles significantly smaller than this will be able to physically "fit" into the sub-layer. Particles larger than δ will therefore not be able to contribute to any viscosity increase within the sub-layer. For the size distribution of Fig. 1 about 40% of the particles are larger than 30 microns. This means that the effective slurry viscosity in the viscous sub-layer is less than the full slurry viscosity. This results in the friction factor being less than that calculated using the measured slurry viscosity.

As the flow velocity decreases, δ increases. This means a greater proportion of the particles are smaller than δ and so the observed friction factor will more nearly equal the calculated value.

Fig. 4 shows data obtained in a 105mm pipe for a 51% flyash slurry. Viscometer measurements gave a yield stress of only 0.3Pa so the slurry can be considered almost Newtonian in behaviour with a viscosity of 7.2 mPas. The full line on Fig. 4 is the predicted Newtonian behaviour using the slurry density and the slurry viscosity. At velocities around 1.5 m/s this is seen to agree with the data.

The dashed line is the predicted Newtonian behaviour using the slurry density but the viscosity of water. The data is seen to approach this curve at high velocities. This difference in behaviour at high and low velocities is due in part to the aforementioned viscous sub-layer effect. This effect has been reported by Maude Whitmore (1958), Daily & Roberts (1969) and Thomas (1977, 1978)

3.2 Heterogeneous Effects

At low concentrations, flyash slurries exhibit settling tendacies such that under static conditions the solids will readily settle. During pipe flow at sufficiently high velocities the turbulent fluid motion will support the particles and result in a pseudo homogeneous behaviour. However as the velocity is reduced there is less support available and eventually a stationary bed of solids will form on the bottom of the pipe. For the data of Fig.4 this occurred below 1.1 m/s. At velocities just above this there will be heterogeneous behaviour in that there is both a concentration and velocity gradient in the vertical direction. The solid concentration will be higher and the velocity lower in the lower half of the pipe than in the top half.

The heterogeneous behaviour results in an increased pressure gradient above that for pseudo homogeneous flow. As the velocity increases this effect became less significant. The result is the pressure gradient/velocity plot exhibits a diverging away from the water curve as the velocity decreases. Thus part of the diverging behaviour in Fig 4 is due to these heterogeneous effects.

4. PIPE FLOW BEHAVIOUR AT HIGH DENSITIES

As the solids concentration is increased there is increasing interaction between particles. This reduces the settling tendancy. Eventually a stage will be reached where turbulence is not required to support the particles and the slurry will flow under laminar conditions.

For a slurry of sufficiently high concentration the laminar and turbulent flow behaviour can be predicted using single phase non-Newtonian methods.

Laminar flow of a Bingham plastic fluid is described by the Buckingham equation:

$$\frac{8V}{D} = \frac{\tau_w}{\eta}\left[1 - \frac{4}{3}\frac{\tau_y}{\tau_w} + \frac{1}{3}\left(\frac{\tau_y}{\tau_w}\right)^4\right] \qquad (7)$$

Where τ_w is the wall shear stress related to the pressure gradient by

$$\tau_w = \frac{D \Delta P}{4L} \qquad (8)$$

There is less agreement on the correct equation to predict turbulent flow behaviour. Many have been proposed, one of the most recent being that due to Wilson & Thomas (1985)

$$\frac{1}{\sqrt{f/2}} = \frac{1}{\sqrt{f_N/2}} + 2.5 \, Ln\left[(1-\xi)^2/(1+\xi)\right] + \xi\left[14.1 + 1.25\,\xi\right] \qquad (9)$$

Where fn is the Newtonian friction factor predicted by equation 3 using the plastic viscosity, and $\xi = \tau_y/\tau_w$.

This equation gives a friction factor lower than the Newtonian value in agreement with observed behaviour.

Fig. 5 shows data obtained from tests in a 105mm pipe on a 66% concentration flyash slurry. The Bingham parameters were τ_y = 2.7 Pa and η = 46 mPas

The full line curve on the left is the laminar flow prediction using equation 7 whilst the steeper curve on the right is the turbulent flow prediction using equation 9. The point where they intersect indicates the transition velocity (1.1 m/s)

The dashed line indicates the Newtonian prediction using equation 5 with the plastic viscosity.

The data points are seen to be predicted with reasonable accuracy in the turbulent flow regime. In the laminar flow region the data lie some 30% above the predicted curve. Furthermore, laminar flow could not be sustained below 0.72 m/s without a stationary bed of solids appearing. This is evidence of heterogeneous effects and explains why the data points lie above the homgeneous prediction line. These higher data points could also be partly due to errors in rheology measurement. Any errors there are directly reflected in laminar flow prediction. They are less significant in turbulent flow.

As predicted by the static stability criterion (Equation 1) this slurry was quite stable and settled only extremely slowly under static conditions. Nevertheless laminar flow without deposition was not sustainable below 0.72m/s.

Under static conditions the floc structure supports the coarsest particles and prevents segregation. During laminar flow this floc structure is broken and the particles may settle if the slurry is not viscous enough. Whether deposition occurs or not depends on whether there is sufficient pressure gradient to drive the settled solids along against the solid-solid friction between the settled bed and the pipe wall. From Fig 5 it is seen that deposition occured when the pressure gradient fell below 290 Pa/m.

If the slurry concentration were to be increased to say 70% the laminar flow curve, as shown on Fig 5, would exhibit a pressure gradient more than 290 Pa/m at all velocities. This would suggest that laminar flow without deposition could be achieved right down to zero velocity. However at the higher concentration there will be a greater friction force. The critical pressure gradient will therefore be somewhat higher than at 66% concentration and deposition would perhaps occur at around 0.1m/s.

Eventually however, a concentration will be reached for which flow without deposition occurs right down to zero velocity.

Consideration of Fig 4 shows that under turbulent flow conditions deposition occured below a pressure gradient of 200Pa/m. This is less than the 290 Pa/m required under laminar flow and reflects the role of turbulence in preventing settling. The difference will be more marked in larger pipe sizes. For turbulent flow, the pressure gradient required to prevent deposition will decrease roughly inversly with pipe diameter whereas for laminar flow it decreased less rapidly as the pipe size increases.

Apart from this deposition aspect there are other difficulties associated with high density flow.

For a given operating velocity the pressure gradient rises rapidly once the laminar flow regime is reached. For example Fig 6 is a plot of pressure gradient at a velocity of 1.5 m/s versus concentration based on Figs 4 & 5: Up to 67% concentration the pressure gradient rises relatively slowly with operation in the turbulent flow regime. Above this concentration there is a very rapid rise with the pressure gradient increasing by a factor of 7 between 67% and 75% concentration. This makes control difficult. Control should be based on viscosity measurement rather than density measurement since variations in flyash properties can affect the rheology even though the density remains constant.

5. PUMPING CONSIDERATIONS

Low density flyash slurries can be pumped using centrifugal slurry pumps. Higher density slurries will generally require positive displacement pumps. This is for a number of reasons:

(a) The efficiency of centrifugal pumps rapidly decreases as the slurry is made more viscous.

(b) Control is easier.

(c) Multi stages of centrifugal pumps would be required to pump any distance.

Consider the 75% concentration slurry of Fig 4. At a typical operating velocity of 1.5m/s the pressure gradient is 4300 kPa/km. A typical slurry pump produces around 50m head which for a slurry density of 1900 kg/cubic metre represents 930kPa so five pumps would be required to pump this slurry 1 km. Also their efficiency would be very low because of the high viscosity.

6. CONCLUSIONS

There are big advantages in pumping flyash at high densities. Much less water is required, the required pipe size is smaller and the advantage of slope disposal at the disposal area can be utilized.

At these high densities the flow is laminar. Homogeneous laminar flow without deposition is not always possible and one needs to be aware of this. Also the pressure gradient at a given velocity rises very rapidly with increasing concentration in the laminar region and this makes control more difficult than turbulent flow operation.

7. REFERENCES

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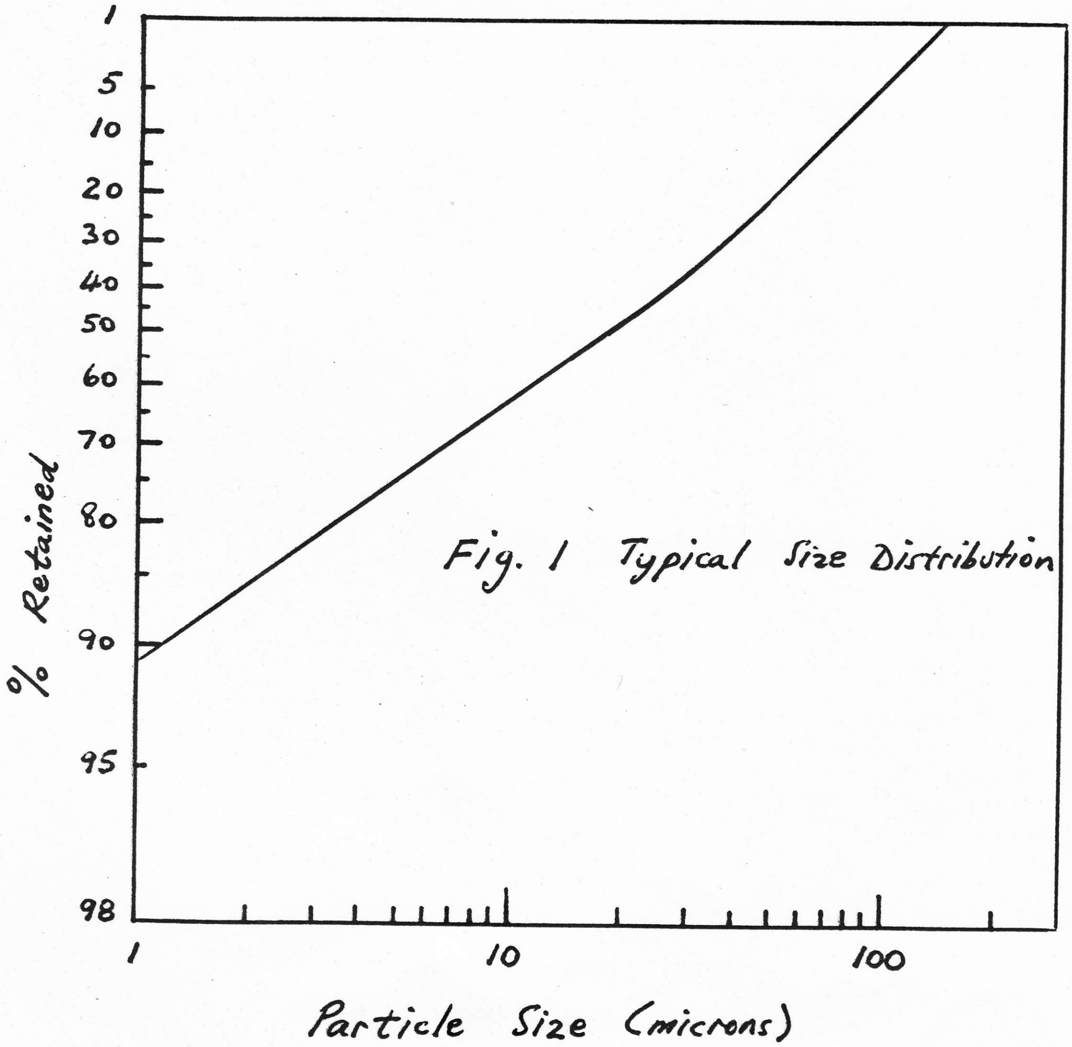

Fig. 1 Typical Size Distribution

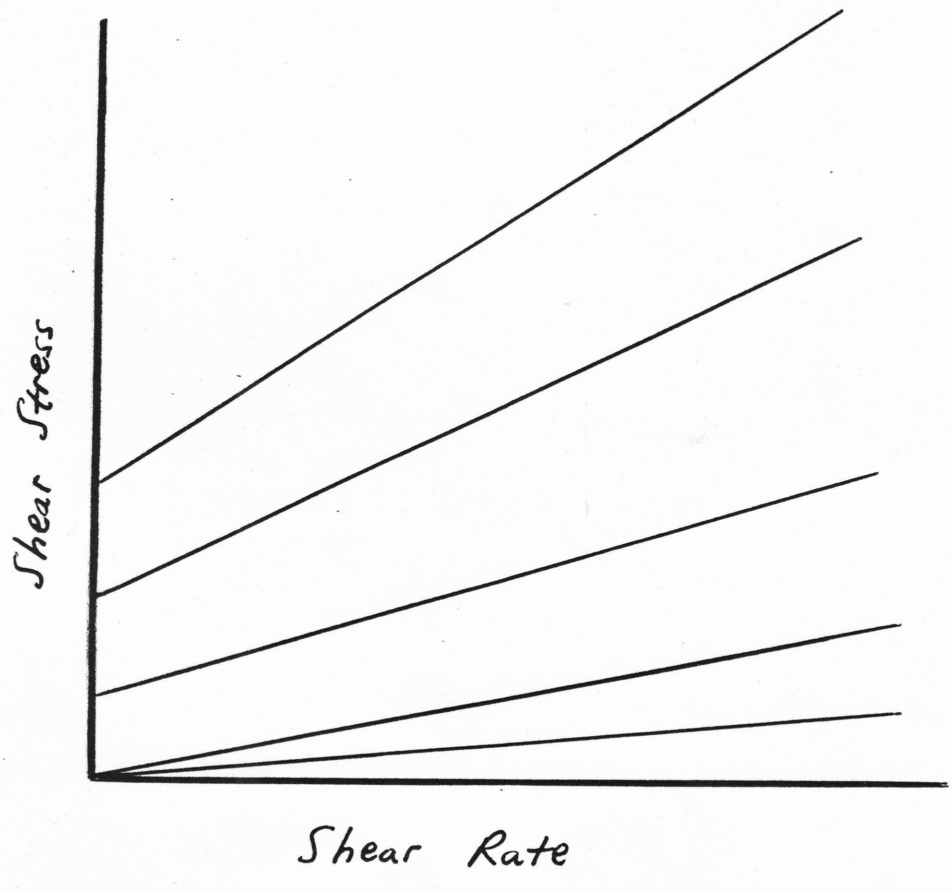

Fig 2. Typical Rheograms

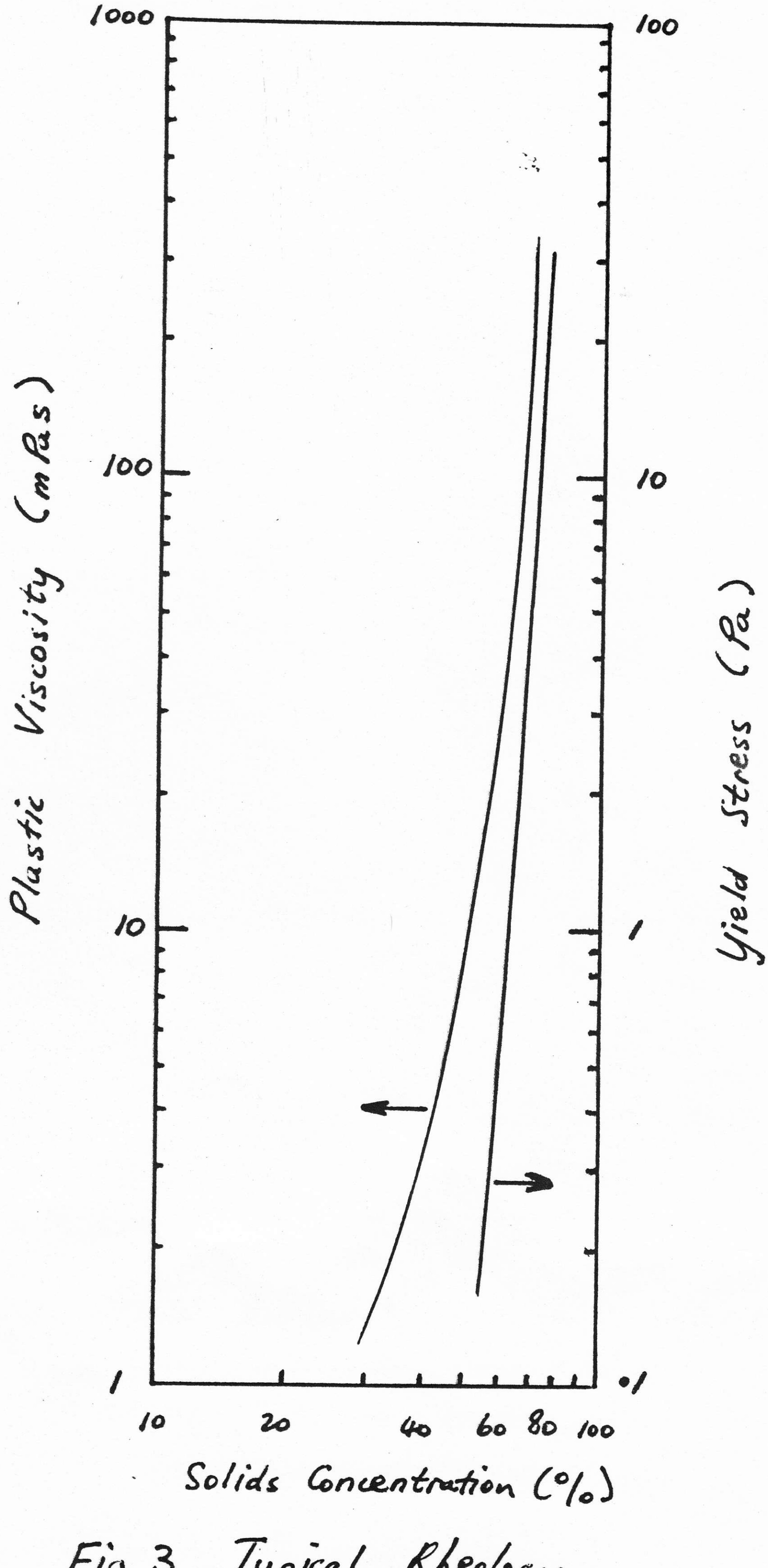

Fig. 3 Typical Rheology

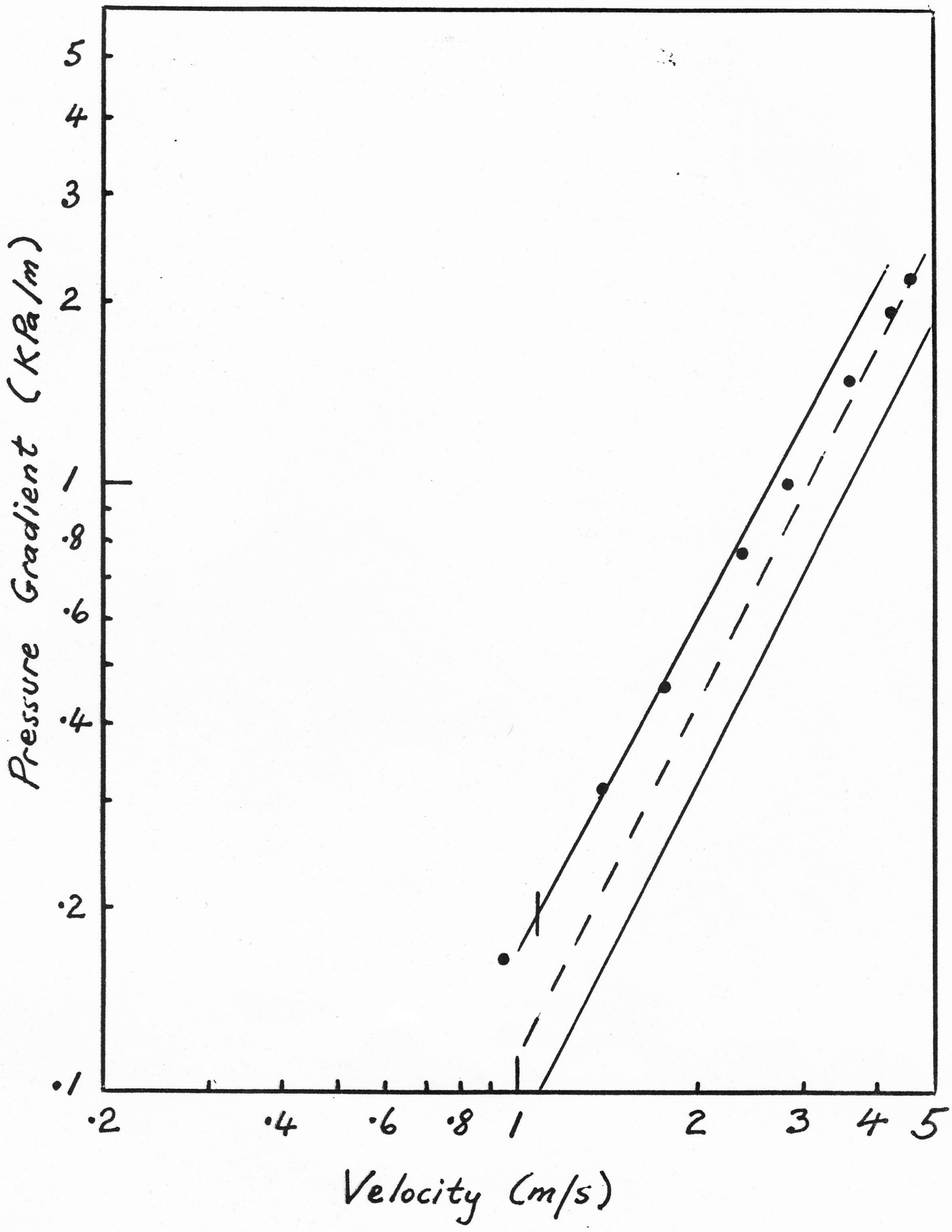

Fig. 4 Pipe Loop Results, 51%

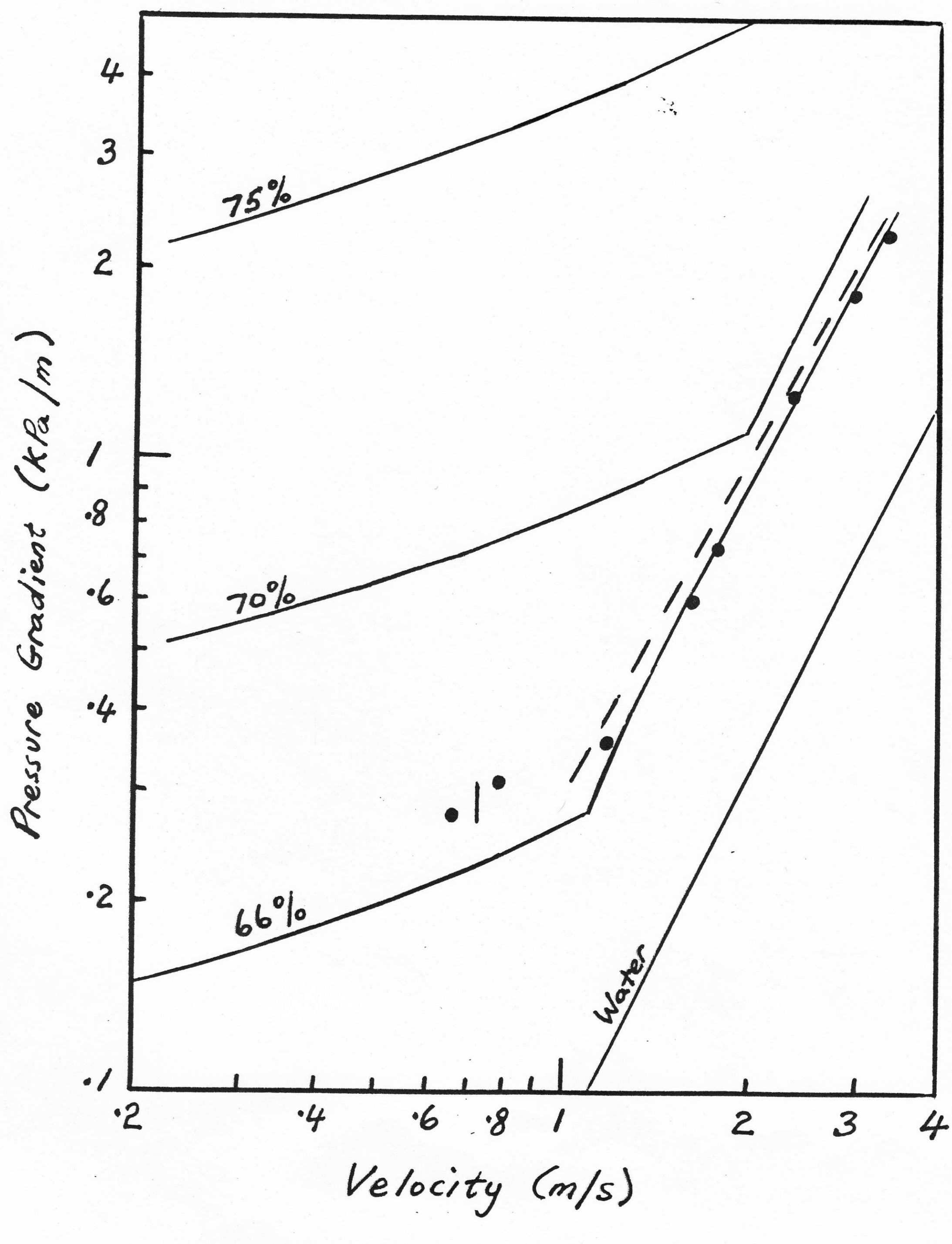

Fig. 5 Pipe Loop Results, 66%.

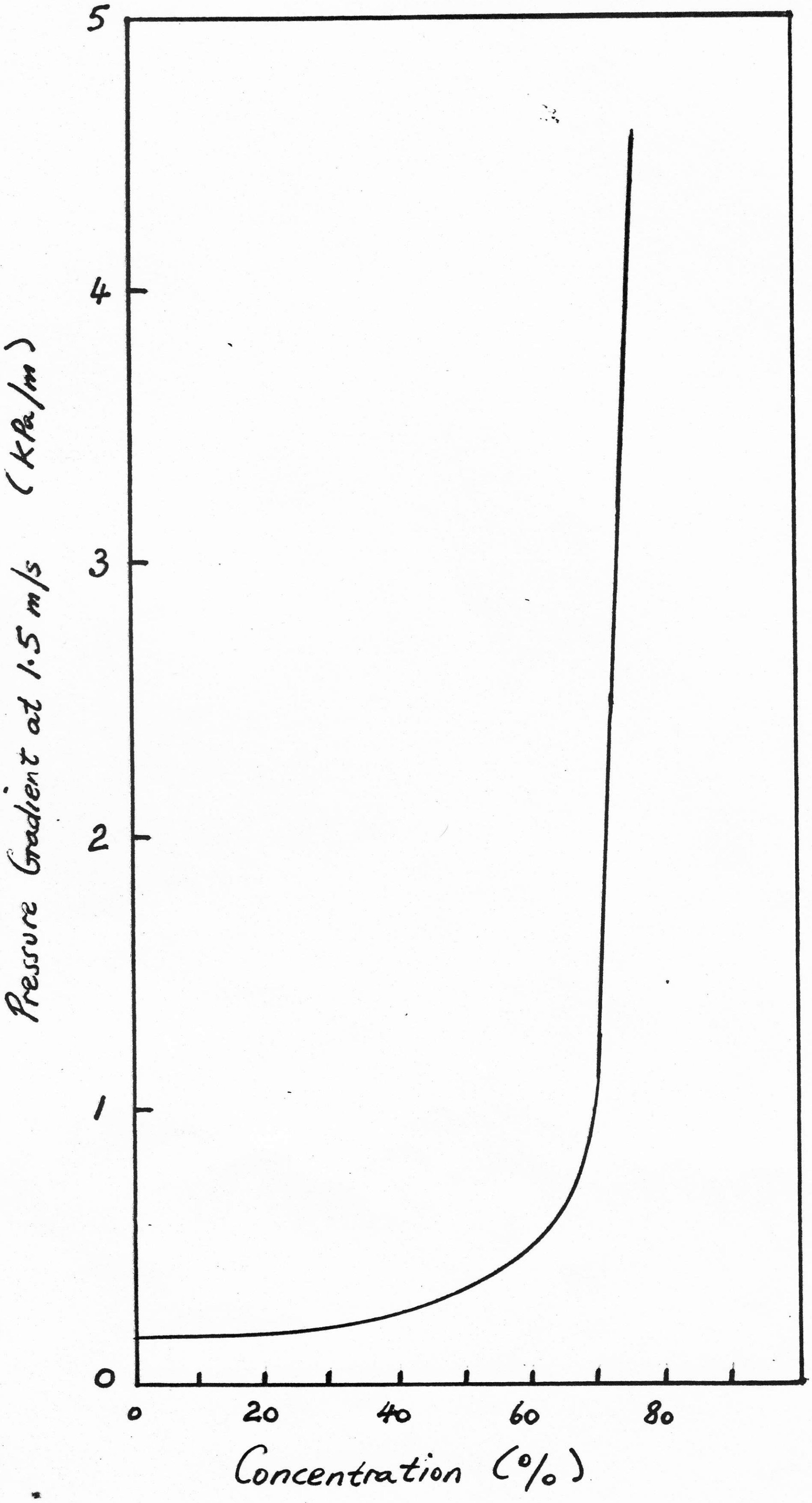

Fig. 6 Pressure Gradient at 1.5m/s