# The flow behaviour of inorganic - wood fibre slurries in pressurised pipes

MICHAEL WALMSLEY* , CRAIG BERRY**

*Senior Lecturer,
Department of Materials & Process Engineering,
University of Waikato,
Hamilton, New Zealand

**Process Engineer,
CHH Whakatane Mill,
Whakatane, New Zealand

## SUMMARY

Understanding the flow behaviour of inorganic–wood fibre slurries is important for developing new process equipment for the cement fibreboard industry. Little is reported in the technical literature and generally slurry flow knowledge is limited to a few engineers within the industry. Pipe friction loss characteristics and the settling behaviour of inorganic-wood fibre slurries were studied and data were obtained in pressurised horizontal pipes ranging from 25 to100mm diameter at flow velocities up to 8m/s. The inorganic solids studied were cement and fine silica of size range 10 to 150μm. Solids concentrations ranged from 5-20% and fibre concentrations from 0- 2%.

Wood pulp fibre suspensions at low fibre concentrations form a structured carrier medium with the ability to support fine particulate solids. Unlike fibre-free suspensions, no permanent stationary deposit formed and therefore no minimum settling velocity exists. At low flow rates particles are trapped in the fibre plug and the friction loss is above water. At high flow rates the particles are still supported but the fibres dislodged from the central plug core damp turbulence and friction losses for the cement-silica-fibre system are less than water (drag reduction). The overall flow behaviour is similar to and consistent with previous data reported for coal-fibre slurries. Fibre concentration has a significant affect on the onset of drag reduction and friction loss increases with fibre concentration as with conventional fibre suspensions. Pipe diameter has a minimal effect on the onset of drag reduction but friction loss decreases with diameter as with conventional fluids.

## INTRODUCTION

Refined wood pulp fibre is a key component of inorganic-bonded fibre composite materials (commonly known as cement fibreboard). The material is made using a wet forming process similar to papermaking and the process technology used is a mixture of mineral processing and turn-of-the-century paper processing technologies. Opportunity exists to use modern pressurised paper processing methods in place of largely atmospheric processing methods. Current methods included open conical tank dewatering, shaking screen table slurry cleaning and drum roller filter forming. Pressurised equipment such as hydrocyclones, pressurised screens, distributed flow boxes and twin wire formers are not used.

As a step to adopting pressurised processing methods the flow and settling behaviour of inorganic – wood fibre slurries needs to be better understood. Little is reported in the technical literature, although the flow behaviour is similar to that of wood pulp fibre suspensions. In this paper the pipe friction loss characteristics and settling behaviour of cement-silica-fibre slurries is reported. Data were obtained in straight horizontal pipes ranging from 25 to100mm diameter at flow velocities up to 8m/s. Cement-silica particulate solids concentrations ranged from 5-20% and fibre concentrations from 0- 2%.

### Cement fibre board production

Inorganic-wood fibre slurries are used extensively in the production of cement fibreboard. The fibreboard process is similar to paper making where wood pulp fibres are dispersed in a pulper, stored and processed in tanks, and transported by pipeline to the board forming and press-drying operations. Cement, silica, wood pulp fibre and water make up the slurry, and the relative proportions can vary within the process. Some unique flow behaviour and operating problems of plant equipment have been observed, but no systematic study over a wide range of conditions has been reported in the literature. Little is known about the rheology of these slurries.

The formulation, preparation, and transport of the inorganic-wood fibre slurries are vital parts of all fibreboard production plants. Predried and baled kraft wood pulp fibre is pulped in water, refined, and mixed with fine cement and ground silica ready for subsequent processing as a complex slurry. As in papermaking the freshly prepared slurry is diluted, cleaned and fed to a former, where a thin wet mat is pre-formed on a moving wire or mesh. The wire for this process passes over a rotating drum which acts as the former as it collects the solid mat by suction from a continuous stream from the vat of slurry. Large quantities of water and fine solids pass through the drum leaving a layered multiply board and creating a filtrate that is used to dilute fresh slurry being prepared for the process. Excess filtrate is fed to settling tanks to recover fibre and particulate solids and to facilitate further recycling of water and chemicals.

### Literature

As described the slurry is a two-phase, multi-component mixture of fine silica and cement, wood pulp fibre and water. The slurry without fibre can be readily classified as a settling slurry and the research reported in the literature for fine particulate materials is extensive (1-4). The flow behaviour of mechanically flocculated fibre suspensions has also been extensively investigated, mainly by researchers targeting the paper industry (5-8). This industrial involvement has resulted in extensive literature on fibre flocculation and related flow behaviour topics (9,10). The combination of settling slurries and flocculated fibre suspensions has been the focus of only two major studies. The first involved the slurry transportation of medium to coarse coal particles and capsules in fibre suspensions by Walmsley and Duffy (11,12). The second involved transport of fibre-cement-silica slurries in various diameter pipes by Walmsley and Berry (13). The work focused on the ability of wood pulp fibres to hinder settling and modify flow behaviour of fine slurries. Settling and pipe friction loss data are reported and the various mechanisms that cause flow modification due to the fibres are described. This paper further reports on this work.

## EXPERIMENTAL

Two horizontal flow loops consisting of 25, 32, 40, 50, 65, 80 and 100mm nominal diameter pipes in series were used to obtain pipe friction data and settling data for cement-silica-fibre slurries as a function of pipe diameter, fibre concentration and particulate solids concentration. Unbleached pinus radiata kraft fibre was used. Solids were a mixture of cement and silica with particle sizes ranging from 10 to 150 micron. Flow velocity, pressure differential and bed height data were recorded.

Silica and cement solids were initially dispersed in the tank using a pump and recycle line to produce a cement-silica slurry. Particulate solids were added progressively for each subsequent solids concentration, and the fibre concentration was increased when necessary, by simply adding fibre directly to the tank. A small amount of sugar was added to retard cement curing. At the commencement of each run, the tapping points were cleared and air bubbles in the tapping lines removed with purge water. Also samples of slurry were obtained from the return line for the determination of the overall solids concentration.

## RESULTS

### Effect of fibre on slurry settling

Structured fibre networks have previously been shown (11,12) to inhibit particle settling in stationary and flowing slurries. It was found that fibre suspensions supported medium to large particulates thereby preventing complete settling. Consequently it was expected that similar behaviour would result in less solids settling in stationary cement-silica-fibre slurries with the possible elimination of stationary deposit formation at the bottom of the pipe (no minimum settling velocity) with flowing slurries. Several clear pipe sections were inserted in the flow circuit to observe and confirm this postulate.

Settling of slurries at zero velocity was also tested in measuring cyclinders. Photographs of typical cylinder settling results are presented in Figures 1 and 2. For the fibre-free slurries stationary bed heights as a percentage of the pipe diameter (Bed Height Ratio) were measured at different bulk velocities, for start-up and shut-down of the pipeline. Typical data are presented in Figures 3 and 4.

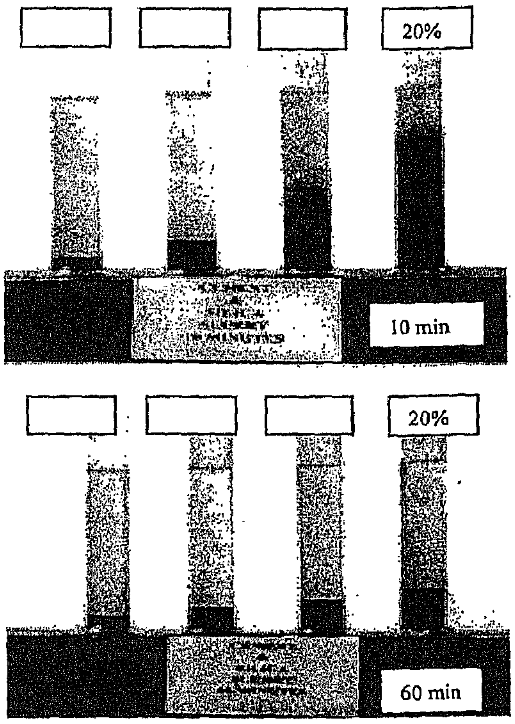



Figure 1. Comparison of settling behaviour of 5, 10, 15 and 20 mass percent cement-silica slurries (fibre-free slurries) after 10 minutes and 60 minutes.

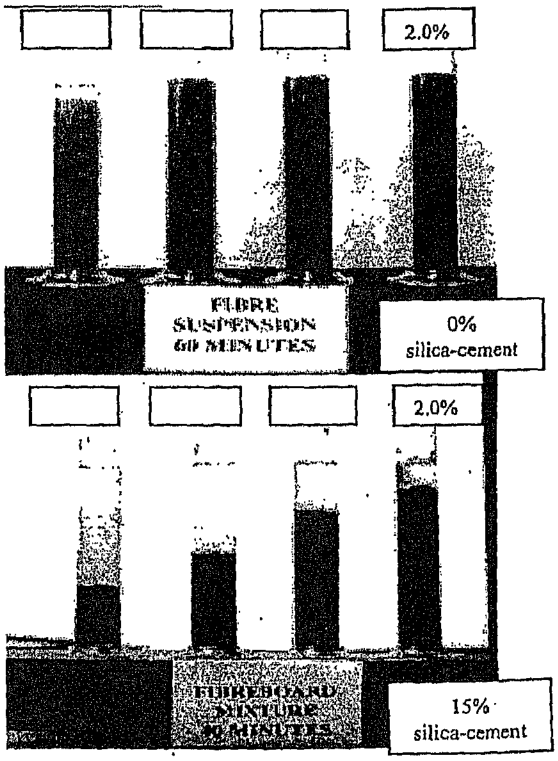


Figure 2. Comparison of settling behaviour of 0.5, 1.0, 1.5 and 2.0 mass percent wood fibre and 0% and 15% silica-cement after 60 and 40 minutes.

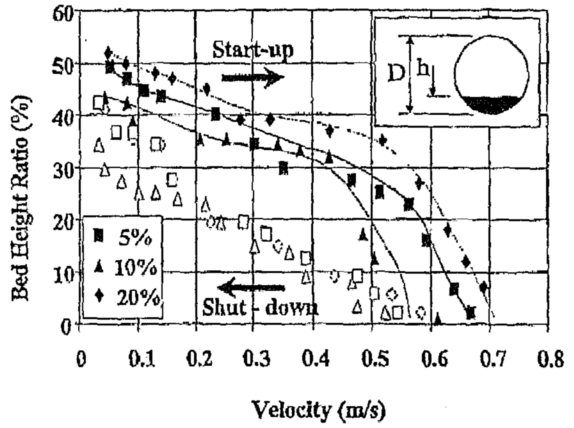



Figure 3. Comparison of settling behaviour during start-up and shut-down of 5, 10 and 20 mass percent cement-silica slurries (fibre-free slurries) in a 90mm diameter pipe.

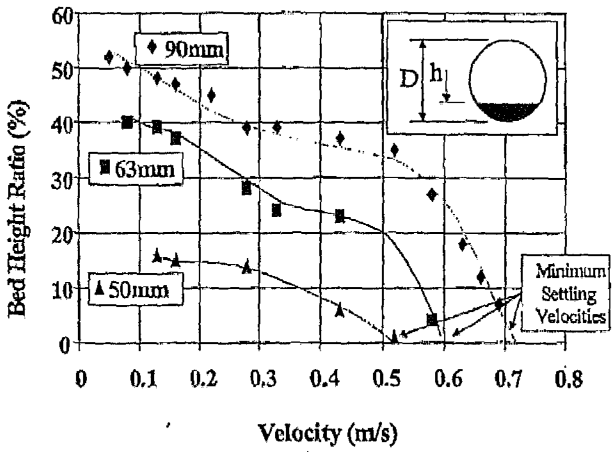



Figure 4. Effect of pipe diameter and velocity on the settling behaviour of a 20 mass percent cement-silica slurry (fibre-free slurry) during pipeline start-up.

**Pipe friction loss data**

A summary of the pipe flow experimental programme is presented in Table 1. The average temperature ranges are also given. Freeness is a measure of the drainability of the pulp suspension and is altered by refining the fibres (high freeness corresponds to the unrefined as-received pulp). Several tests were performed using particulate solids in water-only for comparison with other conventional slurries. A set of these results is presented in Figure 5. Most other tests were carried out using fibre. Typical pipe friction loss data for silica-cement-fibre suspensions are presented in Figures 6 to 8. Solids and fibre concentrations are in mass percent of total slurry mass.

Table 1. Summary of Pipe Flow Experiments.

| Pipe (mm) | Pipe Type | Solids % | Fibre Type | Fibre % | Temp °C |
|---|---|---|---|---|---|
| 25 | PVC | 0 -25 | LF UKP | 0 - 2 | 24-27 |
| | PVC | 0 - 20 | HF UKP | 0 - 2 | 20-23 |
| 32 | PVC | 0 - 25 | LF UKP | 0 - 2 | 21-24 |
| | | 0 - 20 | HF UKP | 0 - 2 | 20-23 |
| 40 | PVC | 0 - 25 | LF UKP | 0 - 2 | 27-32 |
| 50 | PVC | 0 - 25 | LF UKP | 0 - 2 | 26-31 |
| | PVC | 0 - 20 | HF UKP | 0 - 2 | 21-25 |
| | Galv | 0 - 20 | HF UKP | 0 ,1,2 | 25-27 |
| | Galv | 0 - 20 | HF UKP | 0,1,2 | 34-37 |
| 65 | PVC | 0 -20 | LF UKP | 0 - 2 | 24-29 |
| | | 0 -20 | HF UKP | 0 – 2 | 23-28 |
| | | 0 -20 | HF UKP | 0,1,2 | 17-24 |
| 80 | PVC | 0 - 20 | LF UKP | 0 - 2 | 23-28 |
| | | 0 -20 | HF UKP | 0 – 2 | 23-28 |
| | | 0 - 20 | HF UKP | 0,1,2 | 17-24 |
| 100 | PVC | 0 -20 | LF UKP | 0 - 2 | 20-25 |
| | | 0 -20 | HF UKP | 0 - 2 | 21-26 |

## DISCUSSION

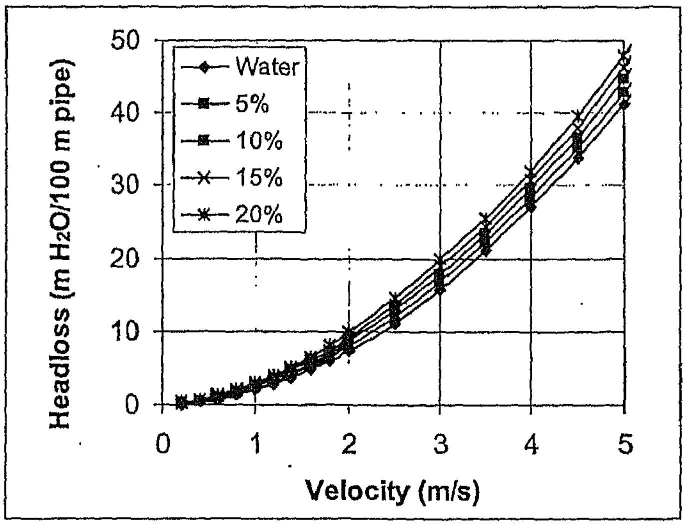
**Cylinder settling results**

Cement-silica slurries were observed to quickly settle with a diffuse interface to form a packed bed at the bottom of the cylinder (see Figure 1). The diffuse interface was caused by the mixed size distribution of silica and cement particles which ranged in size from 10 to 150 µm. Wood fibre suspensions and wood fibre containing cement-silica slurries, in contrast, were observed to only partially settle depending on the fibre concentration (see Figure 2). With no solids wood fibre suspensions remain suspended as a quasi-stable fibre network that fills most of the cylinder. When silica and cement is added the fibre network entraps most of the particulate solids and slowly the network is compressed by the weight of the trapped solids. A small number of particles passed through the network and settled on the bottom of the cylinder.

**Pipe settling results**

Fibre-cement-silica slurries were observed to flow as a sliding bed even at low velocities for fibre concentrations above about 0.5 percent. No permanent stationary deposit formed on the bottom of the pipe and hence no minimum settling velocity was obtained. The asymmetric, flexible fibres interlock to form a structured carrier medium that entraps the silica and cement particles and prevents them from settling. On start-up the suspension slides as a plug in a similar manner to pulp suspensions, and the fibre plug sweeps along any solids in contact with the bottom pipe surface. At high flows some degree of mixing existed but the movement was directional rather than chaotic.

Without fibre in the suspension the cement-silica slurries formed stationary deposits at low velocities. This occurred at velocities between 0.5 and 0.7m/s (minimum settling velocity) as the solids concentration increased between 5 and 20 percent by mass (see Figure 3) and the pipe diameters increased from 50 to 90mm (see Figure 4).



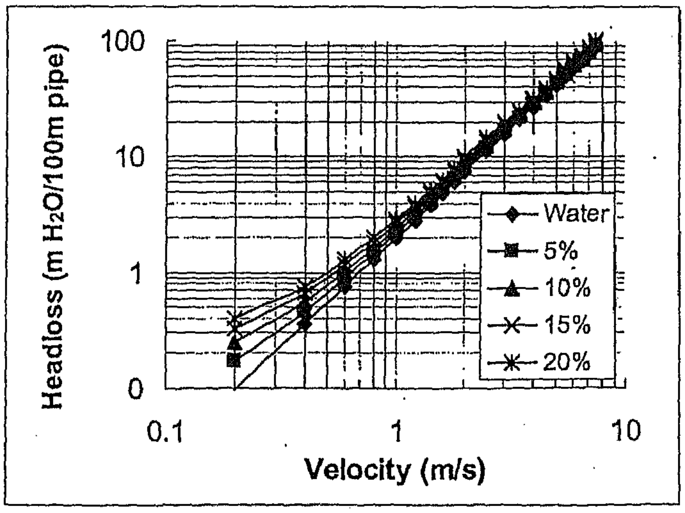




Figure 5. Pipe friction head loss data for fine cement and silica particles (5-150 microns) in water in a 50mm nominal diameter PVC pipe: (a) linear-linear plot (b) log-log plot.

Once a stationary deposit formed on the bottom of the pipe, the bed height increased linearly with further reduction in velocity (shut-down). On start-up the bed height followed a different relationship with velocity (see Figure 3). The bed height decreased slowly at first and then rapidly as the bulk velocity neared the minimum settling velocity. The minimum settling velocity was slightly higher for start-up conditions compared to shut-down conditions and also increased with solids concentration and pipe diameter (see Figure 4).

**Pipe friction loss results**

The friction head loss curves for fine cement and silica in water are similar to those obtained by other workers for fine settling slurries (1). They show divergence from the water curve with increasing flow velocity (see Figure 5a). The divergence from the water curve increases with increasing solids concentration and drag reduction does not occur.

As flow velocity decreases the friction head loss curves initially converge and then diverge from the water curve (see Figure 5b). The velocities where divergence is significant is below the minimum settling velocity of the slurry (0.5–0.7m/s). Stationary solids that have settled restrict the flow and cause further increase in friction head loss compared to water. A small finite stress is thus required to initiate solids flow in the pipe and the level of stress increases with slurry solids concentration.

The curves of friction head loss versus velocity are notably different for cement-silica-fibre-water mixtures as shown in Figures 6-8. At low particle concentrations, the magnitude of the pipe friction loss is similar to the fibre suspension alone without solids. As the flow increases fibres dislodged from the plug-like structure damp turbulence and drag reduction occurs (the curves fall below the water curve). Increasing the solids concentration increases pipe friction at low to medium flow velocities in all cases. However, at higher flow velocities the higher solids concentration mixtures surprisingly seem to enhance drag reduction. This may not be due to the particulate solids themselves. The solids may interpose fibres and flocs to make them more effective drag reducing elements.

A finite shear stress is required to initiate flow of cement-silica-fibre-water mixtures in the pipe. This is illustrated in Figures 6b and 7b. Like fibre suspensions at low velocities, the friction head loss is very sensitive to changes in fibre concentration and only slightly sensitive to velocity indicating the predominance of friction between the fibre-solids plug and pipe wall.

**Effect of flow parameters**

Effect of solids concentration: Increasing solids concentration either increases or decreases the pipe friction loss depending on the flow velocity and ratio of solids to fibre. Increasing the cement-silica solids concentration without fibre at low velocities has only a minor effect on pipe friction head loss (see Figure 5). There is divergence from the water curve with increasing velocity that is enhanced with increasing solids concentration. With the introduction of fibre into the slurry there is a dramatic change in the characteristic of the friction head loss, as seen in Figure 6 when 1% fibre is added.

Increasing the particulate solids concentration of cement-silica-fibre slurries at low flow velocities results in an increase in pipe friction head loss. When the solids concentration is low (<5%) the particles are suspended in the flocculated network, particle collisions with the wall and each other are minimised, and the pipe friction head loss is similar to the fibre suspension. When the solids concentrations are higher (>10%), particles tend to reduce the network coherence (interfloccular strength), but particles are supported by the integrity of the local discrete flocs. Pipe friction loss curves for the cement-silica-fibre systems do not exhibit the characteristic maxima and minima of chemical pulp fibre suspensions (see Figure 6). Although the combined mobility of the solids-fibre mixture is reduced, plug flow still exists, and the basic mechanisms of shear at the wall remain the same except for the additional drag caused by particles protruding from the plug surface and dragging on the wall.

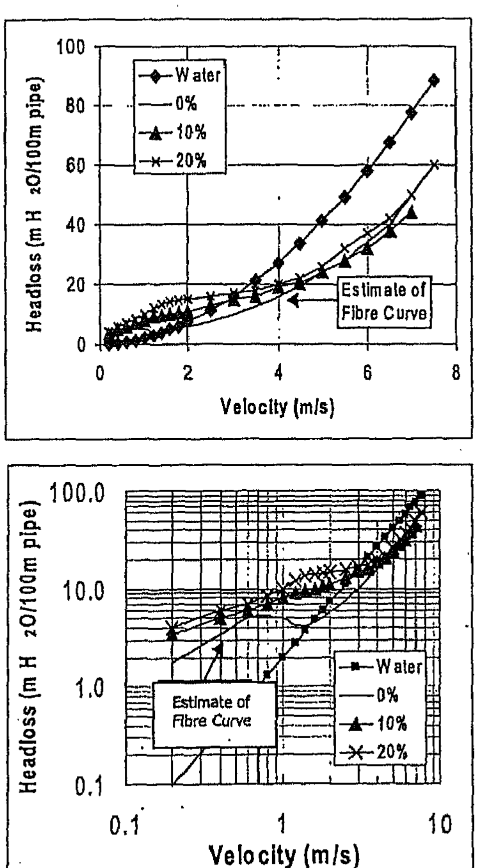



Figure 6. Pipe friction head loss data of fine cement and silica (5-150 microns) and 1 percent high-freeness kraft fibre, in water in a 50 mm nominal diameter PVC pipe: (a) linear-linear plot (b) log-log plot.

In addition, the increase in net downward force caused by the increased effective density of the suspension from increased solids concentration must be transmitted to the pipe wall resulting in extra wall drag. As a result higher pipe friction losses are registered for the fibre-cement slurries than for the fibre suspension only(see Figure 4). This is consistent with earlier workers (1) who found that the additional head loss above the water curve was directly proportional to the solids concentration in the slurry.

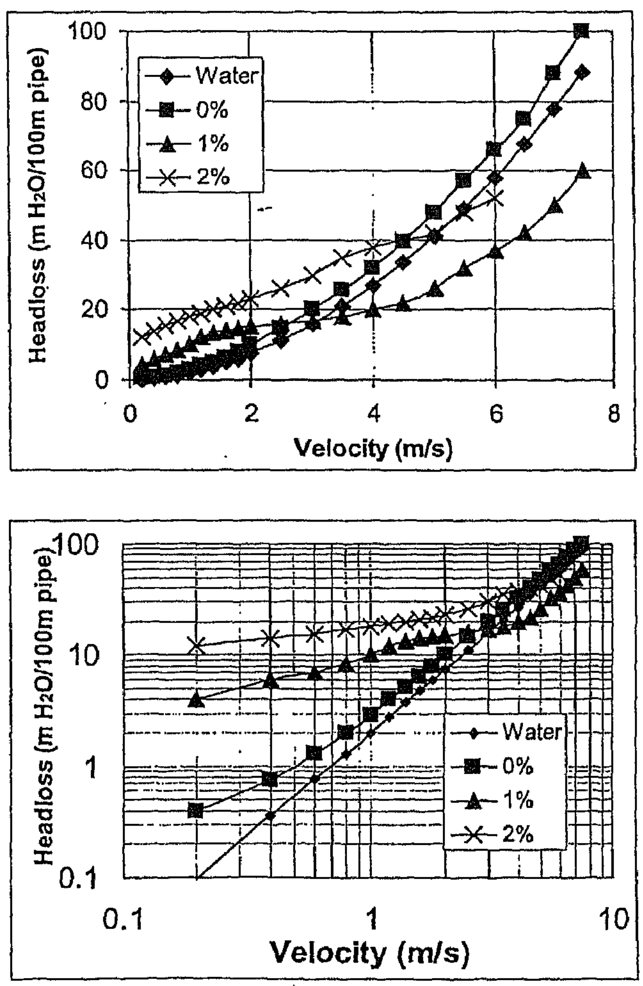



Figure 7. Pipe friction head loss data for fine cement and

silica (5-150 microns) and high freeness kraft fibre, in water at 20 percent solids in a 50 mm nominal diameter PVC pipe: (a) linear-linear plot (b) log-log plot.

At very high velocities the effect of increasing the solids concentration again changes. The reduced mobility of the concentrated mixture acts to enhance drag reduction and lower pipe friction losses compared with mixtures of lower solids concentrations. It is assumed this trend is true for all pipe sizes.

Effect of fibre concentration: The effect of fibre concentration on the flow of a 20 percent solids slurry, with-and-without fibre is reported in Figure 7. The pipe friction loss for water is included for comparison. Pipe friction loss with fibre (1% and 2% fibre) is well above water at low flow velocities and well below water at high flow velocities (drag reduction). With increasing fibre concentrations pipe friction curves shift upward to the right and no maxima and minima in friction loss are observed.

Data presented in Figures 6 and 7 are significant from a pumping cost point of view. They indicate that a small quantity of fibre can dramatically increase or partially decrease the pipe friction loss of cement-silica slurries. At flow velocities below 1m/s, 1 percent fibre can increase pipe friction loss of a conventional slurry by over 300 percent and 2 percent fibre can increase pipe friction by over 600 percent. At very high velocities (>10m/s) the effect of fibre concentration on pipe friction loss reverses. The 2 percent fibre slurry curve trends below the 1 percent curve and enhanced drag reduction occurs due to the extra fibres. At moderate flow levels the curve for the fibre-containing slurry mixture crosses below the water curve into the drag reducing region. The velocity at the water cross-over point increases with fibre concentration and to a lesser extent with increasing solids concentration.

Effect of pipe diameter: The effect of diameter on pipe friction head loss of solid-fibre slurries follows a negative power law relationship. With increasing diameter there is a reduction in pipe friction loss at the same flow velocity (see Figure 8). However, relative to the water curve the friction loss ratio or drag ratio (friction loss for the slurry divided by friction loss for water at the same pipe diameter) is similar and the water cross-over velocity is independent of pipe diameter. These trends are confirmed in Figure 9 where drag ratio is plotted against slurry velocity for three different slurries in three different pipe sizes.

**Drag Reduction**

A unique feature of particulate solids-fibre slurries is the ability for the flow to occur with friction losses below those of water. This phenomenon is clearly observed at high flow velocities and can also occur at moderate flow rates as evidenced in Figures 8 and 9.

In general the flow curves cross below the water curve at a characteristic velocity and increase to a velocity of maximum drag reduction (minimum drag ratio) after which they tend back toward the no-solids fibre suspension curve. These trends are more easily compared when data are presented in terms of the drag ratio as shown in Figure 9. The drag ratio is the friction head loss of the slurry divided by the friction head loss of water at the same velocity.

The water cross-over point (onset of drag reduction) takes place at a drag ratio of unity, and the points of drag reduction maxima (drag ratio minima) are dependent on both the fibre and solids concentration. As the fibre concentration increases from 1 to 2 percent, both the cross-over velocity and velocity at which the maximum drag reduction occurs increases by up to 2m/s. As the solids concentration increases the same trends occur but to a lesser extent. The cross-over velocity and the velocity of maximum drag reduction both increase by less than 0.5m/s as the solids concentration increases from 10 to 20 percent. Lower concentrations of solids or fibres also tend to reduce the overall amount of drag reduction.

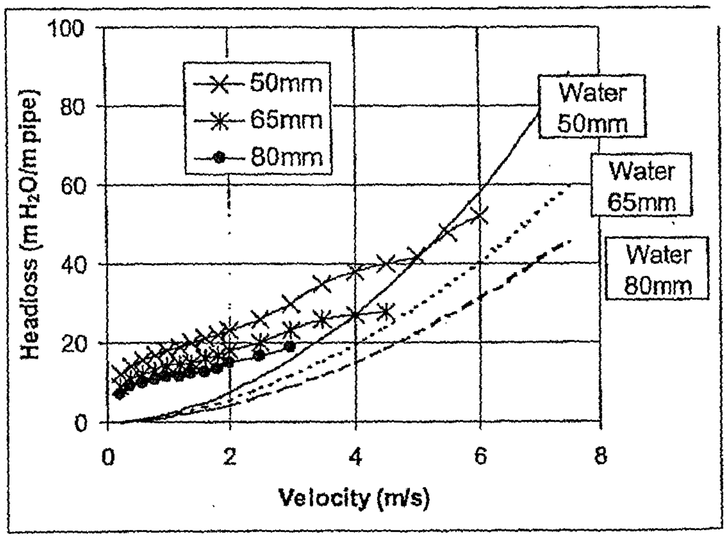



Figure 8. Pipe friction head loss data of 2 percent fibre, 20 percent cement-silica mixture in water in 50, 65 and 80mm nominal diameter PVC pipes.

The flow behaviour of solids-fibre slurries with regards to drag reduction is very similar to the flow behaviour of wood pulp suspensions. In both cases drag reduction does not develop abruptly and the point of maximum drag reduction can be as high as 45 percent. Because of this, it is likely that the mechanisms of drag reduction are also similar.

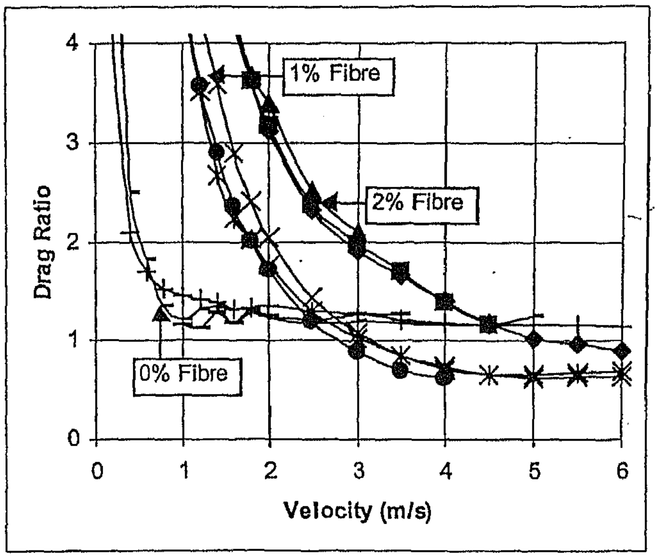



Figure 9. Drag ratio results for 0, 1 and 2 percent fibre, 20 percent cement-silica mixture in water in 50, 65 and 80mm nominal diameter PVC pipes.

At low flow rates the solids-fibre slurry moves as a plug or in some cases as a sliding bed. As the shear rate increases, the outer peripheral layers of the plug are deformed and a clear water annular layer in laminar shear develops which reduces friction and moves the level closer to that of water flowing alone. Some solid particles become part of the water layer and act to increase friction, preventing in most cases, the formation of a minimum in the friction loss curve.

Further increases in the flow velocity cause turbulent shear stresses to develop in the water layer, which causes fibres, fines and small particles to be dislodged from the plug surface. The presence of elastic fibres in the turbulent water region modifies the turbulence through viscous damping and a reduction in the rate of friction loss development occurs. As flow increases further, the friction loss curve of the slurry crosses below the water curve and drag reduction commences. At this stage the solids-fibre slurry is flowing as a central undisrupted solids-fibre core.

At very high flow rates the central core reduces in size and is surrounded by a turbulent layer of fibres, flocs and fine particulate solids. Drag reduction passes through a maximum (drag ratio minimum). Further flow increases produce fully developed turbulence and drag reduction reduces back to near a drag ratio of unity.

## CONCLUSION

This investigation has shown that wood pulp fibre suspensions significantly modify the settling behaviour and flow characteristics of inorganic-wood fibre slurries like cement-silica-fibre slurries. Fibres entrap solids and prevent permanent settling of cement and silica solids at very low flow velocities and cause plug flow characteristics to dominate for most velocities. Fibres increase pipe friction head loss at low flows and decrease pipe friction head loss at moderate to high flows. The overall flow behaviour is similar to flocculated fibre suspensions flowing with no solids. Drag reduction (friction loss levels below that of water) arises at moderate to high flow velocities, and the level and onset velocity increases significantly with fibre concentration and a little with solids concentration. Pipe diameter has minimal affect on the onset velocity but friction loss decreases with increasing pipe size similar to flow with any Newtonian fluid.

## REFERENCES


1. Newitt, D.M., Richardson, J.F., Abbot, M., Turtle, R.B.; Trans. Inst. Chem. Engs., 33, 93 (1995).
2. Bain, A.G., Bonnington, S.T.; " The Hydraulic Transport of Solids by Pipeline", Pergamon Press, Oxford (1970).
3. Durand, R.; Minnesota Int. Hydraulics Convention, Proc. 89, International Association for Hydraulic Research, (1953).
4. Govier, G.W., Aziz, K.; "The Flow of Complex Mixtures in Pipes", Van Nostrand Reinhold, New York (1977).
5. Duffy, G.G., Titchener, A.L., Lee, P.F.W., Moller, K.; Appita, 29, 363 (1976).
6. Norman, B.G., Moller, K., Ek, R., Duffy, G.G.; Transactions of the Fundamental Research Symposium, British Paper and Board Industry Federation, Oxford, Vol. 1, 195 (1977).
7. Duffy, G.G., Lee, P.F.W.; Appita 31, 4, 280 (1978).
8. Lee, P.F.W., Duffy, G.G.; A.I.Ch.E. J,. 22, 4, 750 (1976).
9. Robertson, A.A., Manson, S.G.; Tappi, 40, 326 (1957).
10. Warhen, D.; Svensk Papperstrdn, 67, 378 (1964).
11. Walmsley, M.R.W.; PhD Dissertation, University of Auckland (1988).
12. Duffy, G.G.; Proc. 9th International Conference on the Hydraulic Transport of Solids in Pipes, Rome, Italy, Paper E2, pp227-236, Oct (1984).
13. Walmsley, M.R.W., Berry, C., Duffy, G.G.; Proceedings of Hydrotransport 14, pp319-332, (1999).