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Rheology and the resource industries

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ABSTRACT

The world's resource industries, which include minerals, coal, and the sand mining of oil, are the world's largest producers of waste. Much of this waste is produced as a fine particle suspension which is pumped to a storage area generally at a low concentration where it behaves like a Newtonian fluid. Simply by removing water from the suspension and reusing and recycling water represents a step towards a more sustainable practice in this industry. As the concentration of such a suspension is increased as a result of dewatering, the materials exhibit non-Newtonian behaviour, characterised by shear thinning, a yield stress, and in some instances, by thixotropic behaviour. Such high concentration, non-ideal (dirty) suspensions in the resource industries has meant that new rheological methods and techniques were needed for both shear and compression rheology to measure and interpret the basic flow properties. Also, some older empirical techniques needed to be modified and interpreted in a more fundamental way so that the results could be used in design. The paper reviews these techniques and illustrates how the industry itself has motivated their development. Understanding and exploiting this rheology has resulted in dramatic improvement in the waste disposal strategy for some industries, but many have failed to embrace the available technology. Why? Is regulation the answer? Probably not. The paper concludes that a greater positive change in the waste management practice will occur in the future, motivated by a number of factors, including public perception and perhaps even by common sense accounting.
The paper is an overview of thirty years of work with the resource industries on environmental waste minimisation. Aspects have been published in the Proceedings of Paste and Thickened Tailings Conferences held annually since 1999.[1]

1. Introduction

In October 2004 the author attended an Inaugural Global Sustainable Development Conference sponsored by the Minerals Council of Australia, BHP Billiton and Rio Tinto, the two largest resource companies in the world. The theme of the conference was 'Sustainability and Innovation'. The outcome of the conference was to conclude that more sustainable development in the minerals industry can in fact lead to innovation and affect the bottom line in a positive way. What was noticeably absent in the conference was any discussion of the major amount of waste produced by this industry and any attempt to deal more effectively with the fine particle waste which is produced as a suspension and pumped to storage sites where it might remain for the life of the mine. Later conferences on sustainability and minerals have also avoided a serious discussion on the waste produced.

Professor Doug Furstenau from the University of California at Berkeley, in a presentation at Luleå University of Technology (Sweden) in November, 2001 entitled "Challenges in energy, environment and minerals" stated that in the USA alone, which is not normally considered a major producer of minerals, two billion tonnes of dry mineral waste is produced annually made up of about one-third from copper, one-sixth from iron ore, and one-fourth from phosphate rock. He suggested that this was 10 times the amount of municipal waste produced!! We estimate that at least 10 billion tonnes per year on a dry basis of fine particle waste is produced by this industry worldwide. Arguably then the minerals industry is the largest producer of waste in the world! Whilst there has been significant improvement in technology available for waste management, senior management in the industry seems, or would appear to be, in denial. The industry could be more proactive and move towards more sustainable practices in its handling of liquid wastes. Removal and reuse of water would be a good first step.

There is currently an unprecedented boom in the worldwide industry which will be accompanied by huge expansion which will generate even more waste. With the high demand and high price less rich ore bodies will become economically viable, which in turn will

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[1] Conference Proceedings are available from The Australian Centre for Geomechanics, Nedlands, Western Australia.

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generate even more waste. It would seem appropriate at this time of staggering profits by this industry that a more pro-active (and perhaps more costly) upfront approach should be taken in dealing with this waste.

Examples of massive mining operations where huge expansions are currently taking place are in the copper industry worldwide and in the oil sands industry in northern Alberta, Canada, to name but two. In a private communication in 2003 it was estimated that by 2010 the oil sands industry will be producing about one million barrels of oil per day from surface-mined oil sands. We suspect this figure is already exceeded. One million barrels of oil per day equates to about one million cubic metres of coarse tailings deposit per day and 200,000–300,000 m^3 of fine tailings per day. At the time of the private communication, the industry had produced 400 million cubic metres of fine tailings. These tailings are stored as a suspension in dams. Arguably the largest copper mine in the world is Escondida in Atacama Desert in Chile where there are current plans for further expansion. Currently about 230,000 tonnes of fine particle waste on a dry basis is produced per day by this mine and, once again, pumped at a low concentration as a Newtonian fluid to a disposal area.

Rheological knowledge can be exploited by this industry to drastically reduce the volume of waste currently produced and stored, and hence reduce the negative social and environmental impact of these industries simply by removing water from the suspension and handling the resultant non-Newtonian, paste-like fluid. If the waste, whether be it from minerals, coal, oil or human waste, is dewatered and the water is reused in the process, the footprint produced can be reduced dramatically. In fact, it is possible to go from wet to dry disposal. There are many incentives to do this ranging from conservation and reuse of water to reduction of the considerable risk involved in these dams. In the last twenty years there have been at least 44 tailings dam failures. The probability of such a failure apparently ranges from one in seven to one in 15 (www.wise-uranium.org/mdaf.html).

The consequence of a dam failure is dramatic and can be tragic. Perhaps the most publicised failure was the Boliden dam holding the waste from a lead–zinc mine in Spain in 1998. Five million cubic metres of water and particulates containing high levels of heavy metals poisoned two rivers and flooded crops. The company was fined 45 million euros; the miner sued the company who built the dam for 101 million euros; regional authorities sued the company for 89.8 million euros; shareholders apparently were suing the company for their losses as the company shares plummeted. Cleanup costs exceeded 250 million euros. This is a graphic example of what happens when such a tailings dam bursts; in this case, no lives were lost.

In another case, the Stava failure in Italy on 19 July 1985, 268 people lost their lives as a result of the tailings dam failure. In the most recent failure in September 2008 at the Tashan Mining Company in the Shangxi Province, China, a mud slide of iron ore tailings buried a market, several homes and a three-storey building. At least 254 people lost their lives and 35 were injured. A chronology of major tailings dam failures is available on the website (www.wise-uranium.org/mdaf.html).

The minerals industry looks very simple: the miners dig things from the ground, transport the ore to a processing plant where the ore is ground in water, with the ore then proceeding through the processing plant as a suspension where the good stuff is extracted, leaving behind the rest of the material as a fine particle suspension waste. The process is completed with separation processes, which generally involve thickeners of some sort where the thickener feed is flocculated with water soluble polymers, leaving behind a residue which is pumped to disposal. Rheology has not been important in the past because the waste was handled as a low concentration suspension Newtonian fluid and pumped into the sea, rivers, lakes or stored in huge tailings dams, which is the most popular current practice. Although disposal in the sea, lakes and rivers still occurs, the practice is declining.

A number of factors have contributed to the minerals industry having to improve its game in regard to waste disposal. As already mentioned, there have been and there continue to be some very high profile tailings dam failures and river pollution disasters; the recovery and re-use of water is becoming a major issue, particularly in arid countries, and of course there is a general attitude towards more sustainable practice.

The first step towards a more a more sustainable practice is to decrease the volume of waste which is most easily done by dewatering the waste suspension at the processing plant to higher concentration and to recycle the water. As the concentration of these suspensions increases the material properties proceed from being Newtonian to non-Newtonian, exhibiting, generally, pseudoplastic (shear thinning) characteristics. Further increase in the concentration sees the beginning of a yield stress, and ultimately, one generates a very high yield stress material which may be difficult, if not impossible, to pump. Thixotropic characteristics can also be observed. Materials with yield stresses up to 200 Pa can now be pumped with centrifugal pumps, and it is technically feasible to dewater and pump at such concentrations and dry stack, as is the case in the alumina industry. Therefore, if the industry is to reduce the volume of its waste it must learn how to deal with non-Newtonian materials in terms of dewatering, pumping and deposition. We call the application of basic rheological principles for waste minimisation in the resource industries *Environmental Rheology*.

2. Examples of progress towards a more sustainable practice

There is a growing awareness that effective waste management is essential for creating a more sustainable mining industry. Table 1 lists an order of movement from the least sustainable to the most sustainable practice associated with the liquid suspension wastes generated in the minerals industry. The least sustainable method is direct discharge into rivers or into the sea, and of course, the most sustainable practice would be the re-use of the tailings or in fact, placing it back as a dry material into the mine from which it was extracted. The alumina industry has made great strides towards a more sustainable practice, other industries have not.

2.1. Alcoa Alumina in Western Australia

In 1974 the author was approached by Alcoa of Australia with an enquiry about the rheological characteristics of the material they called red mud. At this time the research in rheology had been ongoing only for six years and was entirely related to the behaviour of polymers. It was, however, obvious after the meeting that the red mud at higher concentration exhibited thixotropic characteristics and it seemed as if the breakdown in structure in shear occurred at a more rapid rate than the rebuilding of that structure from rest.

Table 1
Sustainability of tailings management practice.

	Tailings management practice
Least sustainable	Riverine
	Submarine
	Conventional tailings dam
	Central thickened discharge
	Dry stacking
	Paste backfill
	Re-use of tailings
Most sustainable	Dry backfill

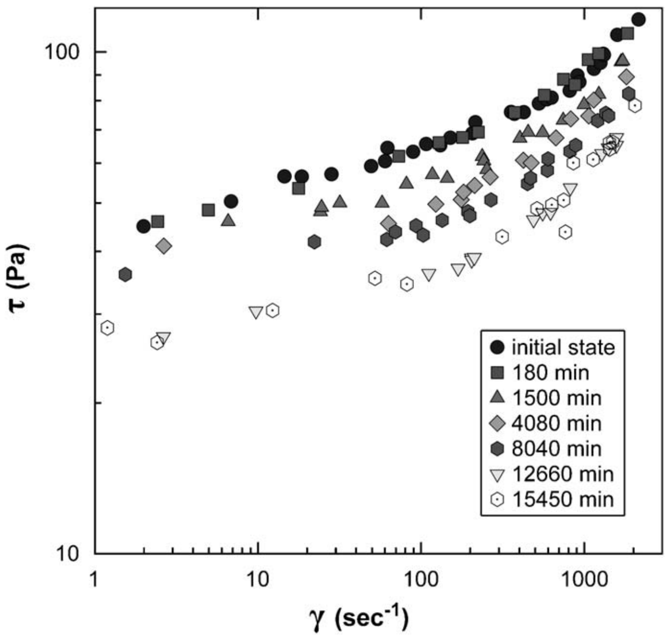

Fig. 1. Typical red mud shear stress–shear rate behaviour illustrating thixotropic behaviour. The data were obtained after shearing the mud at high shear rate for different times.

Fig. 2. Illustration of the effect of shear on a red mud filter cake.

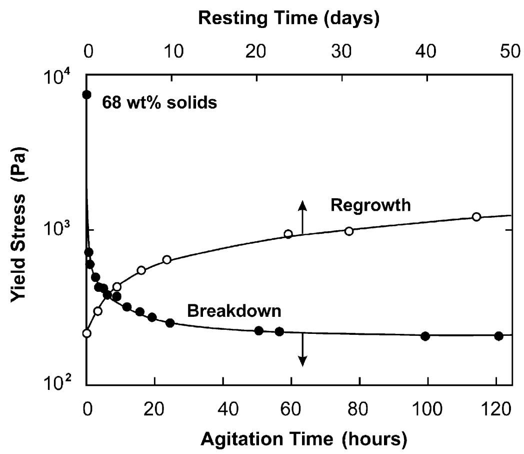

Fig. 3. Use of the vane yield stress measurement to illustrate the breakdown and recovery of the red mud structure.

In ideal thixotropic behaviour the two timescales are the same and there is no difference between breakdown and structural recovery. The enquiry was made by Alcoa because of the realisation that the current practice, which was pumping the red mud to the disposal area (a dam) at a concentration of between 15% and 20% by weight solids as a Newtonian fluid, at a pH of 13, into lakes of about a square mile in area, was presenting a problem; in fact, there was evidence that the lakes were leaking caustic into the ground water. They were motivated therefore to look at techniques whereby the mud could be dewatered and handled at as high a concentration as possible. They needed to understand the rheological characteristics of this material! Preliminary investigation determined that at low concentrations, i.e. at the level at which they were pumping, the material exhibited Newtonian fluid behaviour, while at higher concentrations, non-Newtonian shear thinning characteristics and a yield stress were observed. At even higher concentrations thixotropy was observed. Fig. 1 shows shear stress–shear rate data for a concentrated red mud suspension after being subjected to significant periods of shear with a helical ribbon mixer. The thixotropic characteristics of the material are obvious as the shear stress at a particular shear rate decreases significantly with mixing time. Fig. 2 illustrates the behaviour more graphically, where a filter cake is shown which can be formed into a spherical shape which, after mixing, flows like a paste.

What was also apparent simply by examining the mixing process was that the structural breakdown process occurred far more rapidly than the restructuring process. Thus one could exploit the thixotropic characteristics in the transportation of a high concentration mud to the disposal area, i.e., dewater the material, shear the mud to break the structure, and then transport it out to the tailings facility where the material would restructure slowly. To quantify this behaviour a single point flow property measurement was required. It was from this observation that the vane device was adopted from soil mechanics by Professor Dzuy Nguyen in his Ph.D. thesis and developed for the single point measurement of the rheological yield stress (Nguyen and Boger, 1983, 1985). Some very early data obtained with the vane showing the breakdown and recovery of the red mud are shown in Fig. 3. While the timescale of the breakdown process is measured in hours, the recovery process is measured in days, and the parameter used to establish this behaviour was the yield stress measured originally with the vane device. The vane was a perfect instrument to examine the thixotropic characteristics of the red mud.

It was apparent that once the material reached an equilibrium state in shear it took a long time for the recovery to take place and one could define the equilibrium shear stress–shear rate data, or the equilibrium viscosity-shear rate data. Such results as a function of concentration are shown in Fig. 4. The shear thinning characteristics of the material are apparent as the concentration increases, from Newtonian behaviour at the lowest concentration (36.2%) by weight. Data like that shown in Figs. 1, 3 and 4 formed a basis for understanding how to handle, pump, and produce the higher concentration material. Alcoa went through piloting processes to look at various dewatering devices and eventually ended up with the super thickeners which they now use today in the dry stacking technology. Figs. 5 and 6 compare the wet lakes of the 1970s to the dry disposal of the 1990s, while Fig. 7 illustrates the paste-like material produced with a compression thickener.

The impact of the alumina industry on research in rheology was immense because it became apparent that techniques were required for measuring the flow characteristics of these concentrated suspensions and one needed to understand yielding and thixotropic behaviour. Also, once the techniques were developed one could start making comparisons across this industry and others. For example,

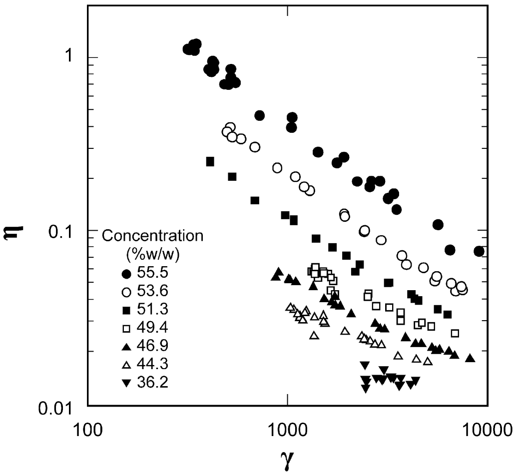

Fig. 4. Red mud equilibrium viscosity-shear rate data.

Fig. 5. Wet lake photograph in the 1970s (photograph courtesy of Alcoa of Australia).

Fig. 6. Alcoa Western Australia, bauxite waste dry stacking (photograph courtesy of Alcoa of Australia).

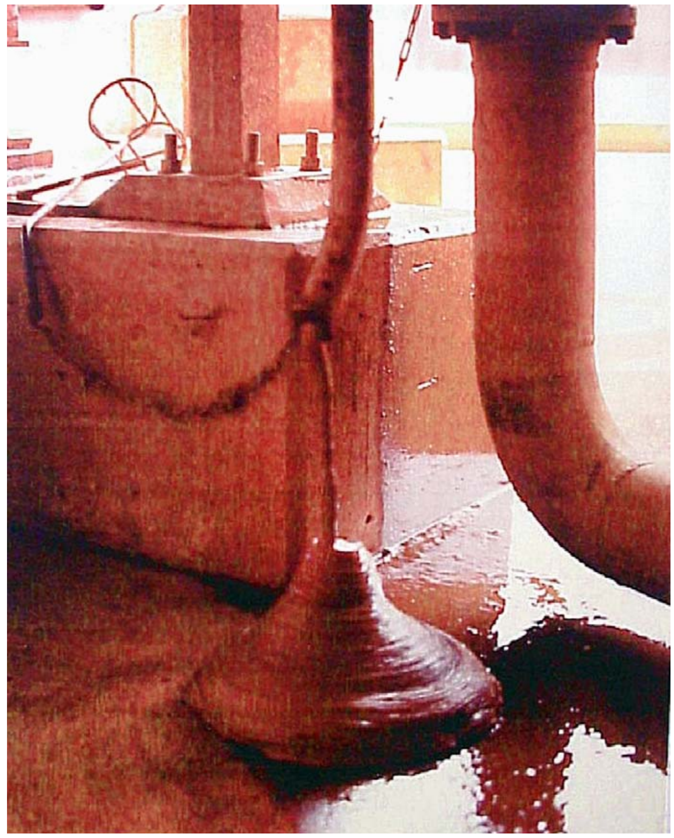

Fig. 7. Mineral waste produced with a compression thickener (photograph courtesy of Alcoa of Australia).

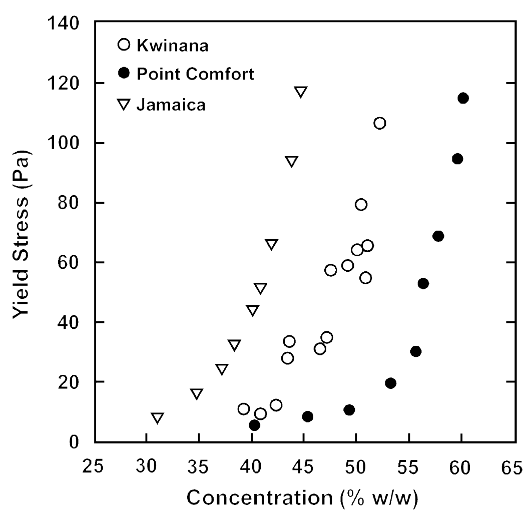

Fig. 8. Yield stress as a function of concentration for red mud from different alumina samples.

Fig. 8 illustrates the different red muds at the Alcoa Kwinana refinery in Western Australia, the Port Comfort refinery in the USA, and the refinery in Jamaica, with the yield stress forming a basis for comparison which is now used in the minerals industry as a whole to construct graphs like that shown in Fig. 8. Fig. 9 illustrates the very large range of yield stress determinations ranging from a coal mine tailings to a copper mine tailings where paste-like characteristics would

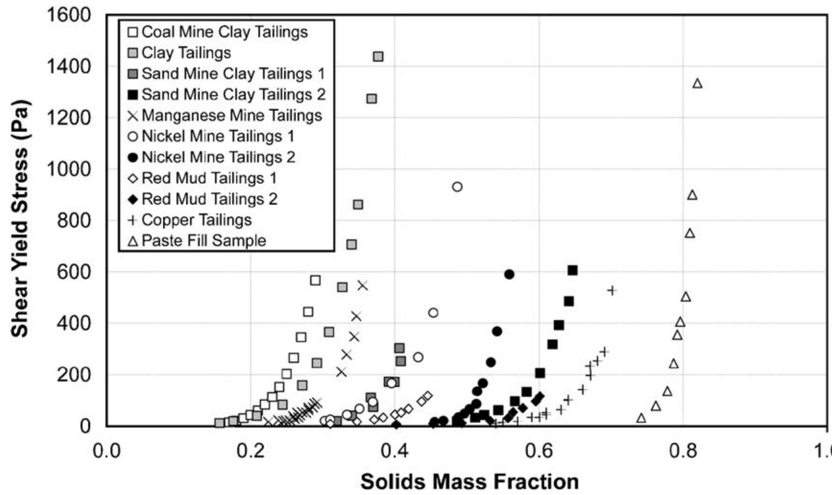

Fig. 9. A comparison of the yield stress concentration behaviour for the fine particle waste from a variety of minerals.

be observed as a yield stress of about 200 Pa, i.e. at a concentration of 24% and 67% by weight, respectively. Every industry is different.

The alumina industry was the first to discover and exploit an understanding of basic rheology in the handling of its waste. After the original consulting work, six Ph.D. students worked on the problem: Sarmiento (1979) on the rheology of lower concentration red muds; Nguyen (1983), who amongst other things established the vane device for yield stress measurement; de Guingand (1986), who was the first student to work on the compression characteristics of red mud; Pashias (1998), who did a comparative study of the red muds across the Alcoa organisation and established the slump technique for yield stress measurement; Sofra (2001), worked on the stacking angles for red mud. Cooling (2006) was the final Ph.D. student whose work was conducted at the refinery itself and was used to establish methods for sequestering CO_2 in the red mud.

2.2. The minerals industry as a whole

It was not until the late 1990s that other industries making a paste backfill (mine stope fill) realised that the alumina industry was making the same sort of material for distribution on the surface. It also was obvious that we were not aware of some the large international problems in the mining industry associated with the management of waste. At that time we thought that 15,000 tonnes per day on a dry basis, which represented an average sort of figure for the alumina industry, represented a large amount of waste. Little did we know until attending a Paste and Thickened Tailings Conference in Perth in 2000 that the copper industry, and for that matter the oil sands industry, were producing in excess of 200,000 tonnes per day from one operation. It has been through the annual Paste and Thickened Tailings meetings extending back to the year 2000 in Perth, Western Australia, where rheology was introduced to the minerals industry as a whole. The impact that rheology has had on the industry and the impact that the industry has had on developments in rheology has been significant. We will now review developments in rheology which were a direct response to the needs of the resource industries, and in particular, to the needs associated with waste disposal. We call this Environmental Rheology.

3. Basic rheological properties

For the suspensions encountered in paste and thickened tailings, non-Newtonian characteristics are generally observed at higher concentrations. Viscoelasticity is generally of no importance and the basic measurements required to characterise these materials include the viscosity and how it varies with shear rate and time of shear. The general definition of the viscosity is

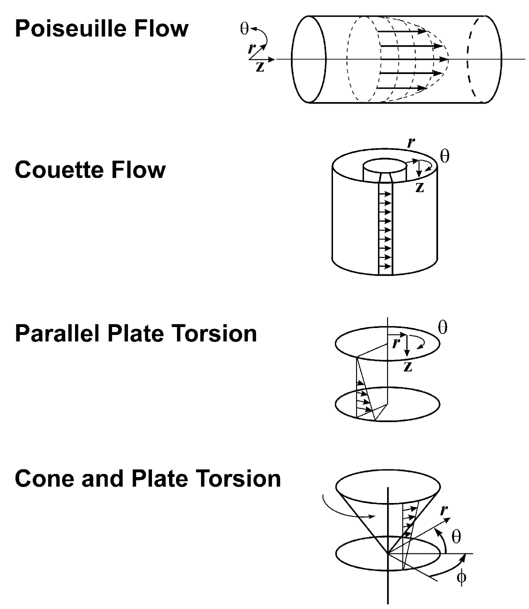

Fig. 10. Viscometric flows used for viscosity measurement of non-Newtonian fluids.

$$\eta = \frac{\tau}{\dot{\gamma}} \tag{1}$$

where τ is the shear stress and $\dot{\gamma}$ is the shear rate. In order to make the basic viscosity measurement one must use a device where both the shear stress and the shear rate can be defined. There are basically four flow fields called viscometric flows where the shear stress and the shear rate can be defined and hence one can define the viscosity for a non-Newtonian material. These flow fields are illustrated in Fig. 10. Each of these flows has its own significant advantages and disadvantages. Poiseuille flow involves measuring the pressure drop as a function of flow rate in a long straight tube; special capillary rheometers can be designed to make these measurements but the measurements can be labour intensive and often are associated with significant problems at the wall of the tube where slip can occur.

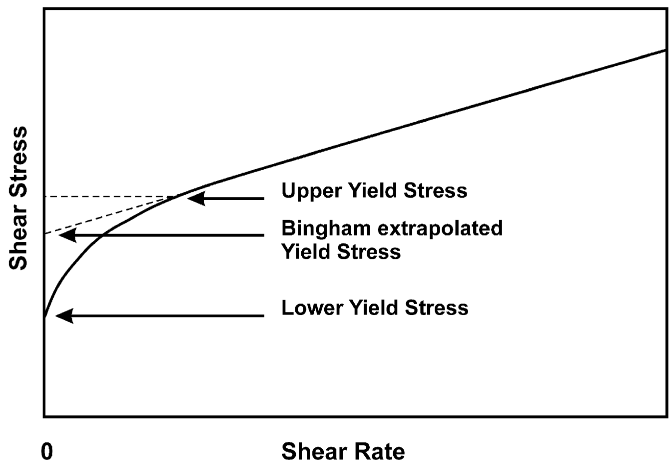

Fig. 11. Typical shear stress–shear rate behaviour illustrating the "yield stress".

The most common geometry used for measurement of shear stress and shear rate is Couette flow—a cup and bob rheometer. This geometry also has a distinct disadvantage for suspensions in that the gap has to be large enough so that the particles themselves do not interfere with the measurement. When the gap is large the analysis of data becomes complex and often is not understood. Slip is a problem and sedimentation can also occur. For parallel plate torsion flow almost no one uses this geometry for measurements of suspensions; again the problems are associated with sedimentation and slip and analysing the basic data. Cone and plate torsion flow, although good for measuring the properties of polymers and polymer solutions, again the gap in the instrument has to be very small for the analysis to be correct. Hence none of the above geometries, which form the basis of some very sophisticated and expensive instruments, are readily suitable for the measurements of the basic viscosity of a broad particle distribution mineral suspension waste. Yield stress measurements with conventional rheometric equipment can be equally as problematic.

3.1. Yield stress measurement

Fig. 11 illustrates typical shear stress–shear rate behaviour that is observed for a yield stress material. There are very significant misconceptions associated with yielding. Much of the data obtained for suspensions is not obtained at low enough shear rates to determine a true yield stress by extrapolation. Often the data are extrapolated from a linear region of behaviour at high shear rates to the axis to define what has been called the Bingham yield stress. The Bingham yield stress is a model fitting parameter and has no meaning whatsoever in terms of the true yielding of the material. We have seen many consulting reports in which this yield stress has been used as a basis for design. The yield stress is the value of the shear stress when the material initially flows, and in principal can be determined if the measurements of the shear stress as a function of shear rate are made at low enough shear rates. However, there are difficulties in reaching such low shear rates, slip invariably occurs in the concentric cylinder geometry at low shear rates. Thus extrapolated values of the shear stress–shear rate data are not easy to obtain and are often in significant error. Fig. 12 illustrates the potential errors associated with extrapolation, dependent upon the shear rate region in which data are available. The results in Fig. 12 were obtained with a capillary rheometer, a conventional Couette (concentric cylinder rheometer), and a vane in cup device used to eliminate slip. For the capillary the shear stress and shear rate were obtained from the measured pressure drop, Δp, as a function of volumetric flow rate, Q, in a tube of length, L, and diameter, D.

$$\tau_w = \frac{D\Delta p}{4L} \tag{2}$$

and

$$\dot{\gamma}_w = \frac{3n'+1}{4n'}\left(\frac{8V}{D}\right) \tag{3}$$

where V is the average velocity in the tube

$$V = \frac{Q}{\left(\dfrac{\pi D^2}{4}\right)}$$

and

$$n' = \frac{d\ln\tau_w}{d\ln\dfrac{8V}{D}} \tag{4}$$

which is the slope of a log–log plot of τ_w versus $8V/D$. Data obtained with the capillary and the Couette rheometers should agree as they do in Fig. 12 at the higher shear rates, but at the lower shear rates both deviate from the vane and cup results which extrapolates to the correct yield stress. Both the capillary and Couette data at shear rates less than about $300\,s^{-1}$ illustrate the dramatic influence of slip flow at a solid surface. At a shear rate of $10\,s^{-1}$ there is a factor of four differences in the observed shear stress.

3.1.1. The vane method

The true yield stress for the mine stope fill material shown in Fig. 12 was obtained with the vane. The extrapolation of the high shear rate data obtained and reproduced with a capillary and concentric cylinder device is 65 Pa, while the extrapolated value obtained from the lower shear rate data is on the order of 18 Pa. The true yield stress was 250 Pa!! The errors involved are immense and thus, if the true yield stress is needed, which is the case for rake design in thickeners and for pump re-startup and design in a pipeline, then conventional rheometry geometry generally should not be used and a device like the vane is appropriate.

The vane device and the principles involved are illustrated in Fig. 13, while the basic equation for analysing the data is given in Eq. (5).

$$T_m = \frac{\pi}{2}d^3\left(\frac{l}{d}+\frac{1}{3}\right)\tau_y \tag{5}$$

Basically, the vane is inserted into the suspension and rotated at a very low speed where the torque is observed as a function of time. The torque increases until reaching a maximum value, T_m, when the material yields. The maximum torque is related to the yield stress by Eq. (5), where d is the diameter of the vane and l is its height. Eq. (5) is valid if end effects are minimised and this is possible by using a large enough l/d vane. The great advantage of the vane is the material yields on itself, slip generally is not an issue and the vane can be inserted into the fluid in different regions. This technique is now used worldwide for measurement of yielding in all matter of materials. The development of the technique was motivated by a need generated by the alumina industry (Nguyen and Boger, 1983, 1985).

3.1.2. The slump method

Another even simpler method for a single point measurement of the yield stress is to exploit slump. Basically slump involves placing a paste-like material in a container open at both ends. The container is then lifted and the height of the material relative to the original container height is measured. This is the slump height. The civil engineering community for many years has used a conical device for

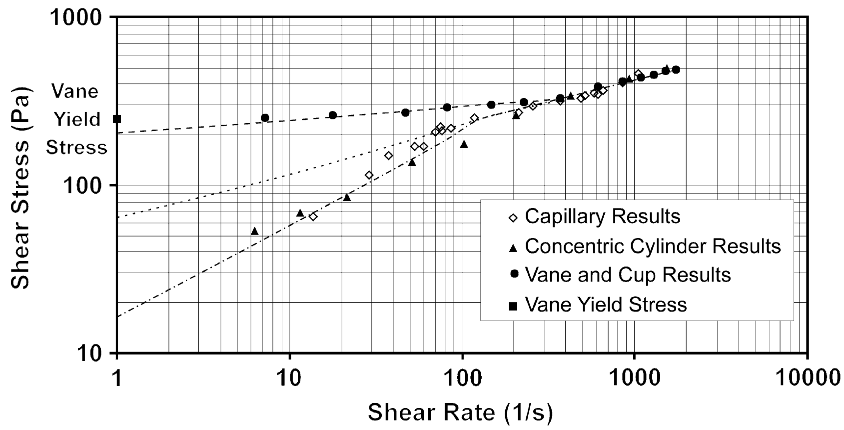

Fig. 12. Flow curve for a paste sample—yield stress = 250 Pa.

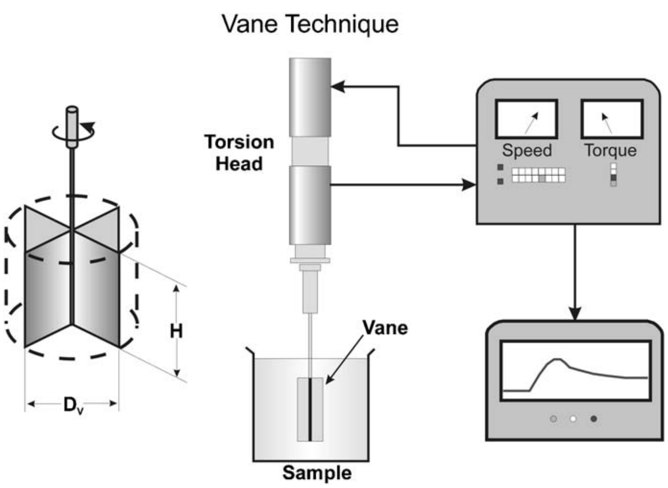

Fig. 13. Illustrating the vane device for yield stress measurement.

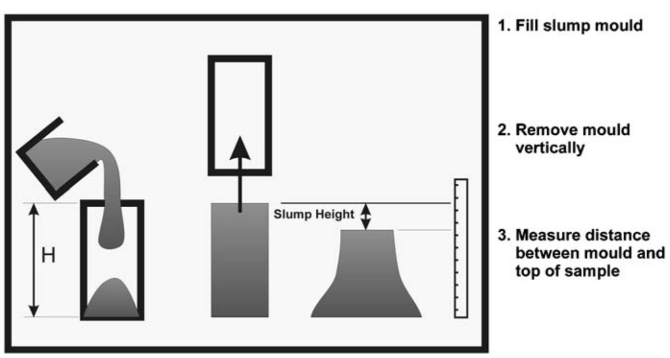

Fig. 14. The cylindrical slump test.

measuring the slump in concrete. The results of such measurements were reported in inches or centimeters of slump and were not related to any fundamental flow property. Pashias in his Ph.D. thesis (Pashias and Boger, 1996) took the idea of the slump, simplified the geometry to a cylindrical geometry and established a simple equation for relating the slump to the yield stress. Fig. 14 illustrates how the slump is measured while Eq. (6) is a simple interpretation of the

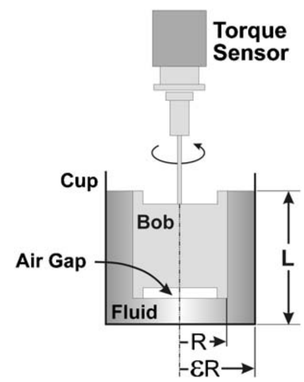

Fig. 15. Illustration of a Couette Rheometer.

slump measurement.

$$\tau_{y'} = \tfrac{1}{2} + \tfrac{1}{2}\sqrt{S} \quad (6)$$

$\tau_{y'}$ is a dimensionless slump ($\tau_{y'} = \tau_y/\rho gH$), and S is the dimensionless slump which is the actual slump divided by the height of the cylindrical slump vessel, H.

Numerous direct comparisons of the cylindrical slump measurement and the vane yield stress measurement are now available in the literature. One such comparison for different materials from our own work is shown in Fig. 16, which illustrates that the yield stress determined from the vane and the slump test are in agreement for engineering design purposes. The approximate solution for the slump is given by Eq. (6). The slump measurement was again motivated by a need in the alumina industry. Thus the alumina industry and the basic properties of the red mud motivated the development of two methods for single point yield stress measurement which are now used industry-wide and extend well beyond the industry into the world as a whole. On the basis of experience gathered with the alumina industry and with the minerals industry as a whole, it was obvious that a simple and perhaps even more effective method for determining the basic shear stress–shear rate data was needed.

3.2. Shear stress–shear rate measurements

As already stated, the Couette viscometer illustrated in Fig. 15 is the most commonly used for obtaining the shear stress–shear rate data for many materials and in many industries. The torque, T, on the bob is observed as a function of its rotational speed, Ω. The basic

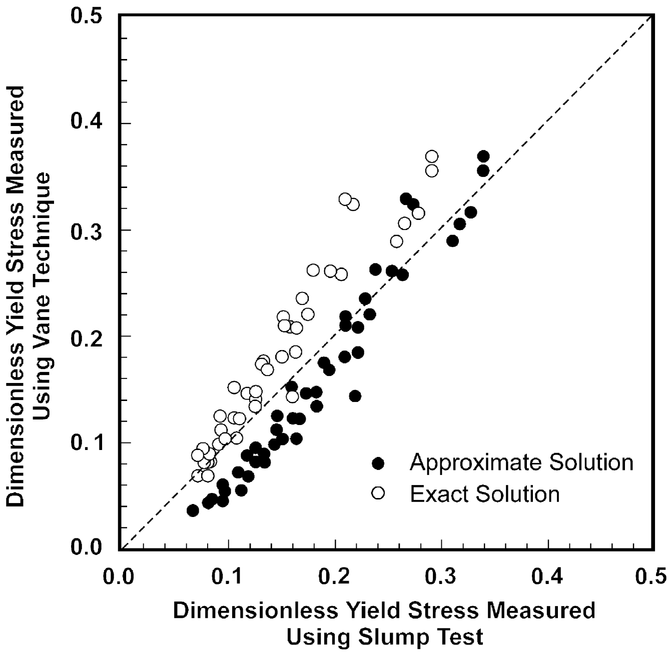

Fig. 16. Comparison of yield stress measuring techniques.

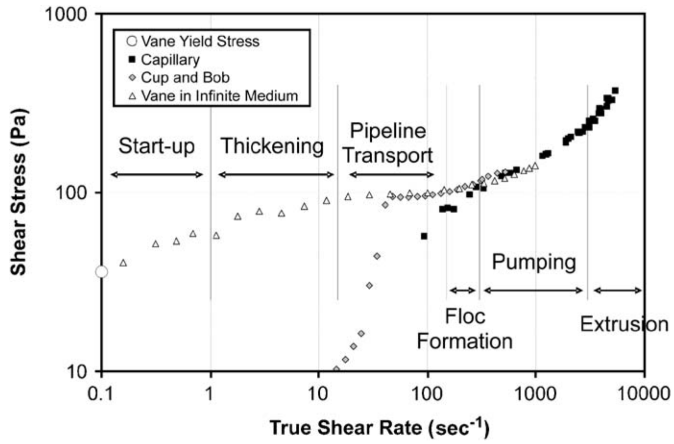

Fig. 17. Shear stress–shear rate data obtained for a 45.1 w/w limonite slurry illustrating the performance of the bucket rheometer.

equations used to analyse the data are Eq. (7) for the shear stress at the two surfaces and Eq. (8) for the shear rate.

$$\tau_1 = \frac{T}{2\pi R^2} L = \varepsilon^2 \tau_2 \tag{7}$$

$$\Omega = \int_{\tau_2}^{\tau_1} \frac{f(\tau)}{2\tau}\, d\tau \tag{8}$$

In the equations, τ_1 and τ_2, are the shear stresses at the surfaces of the bob ($r = R$) and the cup ($r = \varepsilon R$) and $f(\tau)$ is the shear rate, $\dot{\gamma}$. Note in Eq. (8) that the shear rate is hidden inside an integral. The fact that the shear rate is not explicitly defined causes some considerable difficulties in analysing the data. Integration of Eq. (8) depends on knowing a functional form between the shear stress and shear rate, i.e., substituting a fluid model. Such a model will not be available *a priori* hence approximate techniques are needed to evaluate the shear rate in the cup and bob rheometer, particularly when the gap is wide, which is necessary for paste or suspension-like material that are of interest here. Often a narrow gap assumption is made in order to define the shear rate simply by Eq. (9). This definition, often embedded in instrument software, is not valid for the wide gap required when dealing with paste-like systems.

$$\dot{\gamma}_1 = f(\tau_1) = \frac{2\Omega}{(1-\varepsilon^2)} \tag{9}$$

3.2.1. The bucket rheometer (Fisher et al., 2007)

Eq. (8) can be differentiated on both sides with respect to τ_1 if the outer radius of the cup becomes very large (goes to ∞). The result of this differentiation on both sides yields to the simple result given by Eqs. (10) and (11).

$$\tau_1 = \frac{T}{2\pi L R^2} \tag{10}$$

$$\dot{\gamma}_1 = \frac{2\Omega}{S_1} \tag{11}$$

where

$$S_1 = \frac{d \ln T}{d \ln \Omega} \tag{12}$$

The shear stress and the shear rate on the inner bob surface rotating in an infinite medium is now directly defined and not dependent on any particular model assumption. The procedure is as follows. The torque is measured as a function of rotational speed and plotted on a log–log graph. Generally, the slope of this graph will be a constant S_1. Once S_1 is known the shear rate is defined, as is the shear stress, from the torque measurements. The idea of a bob in an infinite medium has been a relatively obscure fact. Combining this analysis with the idea of using the vane itself as a rotational device, results in a new rheometer, the bucket rheometer. The vane itself has a distinct advantage that effectively slip is eliminated. Using the vane as the rotating bob allows measurements to be made in the absence of slip. The advantages of the vane rotating in an infinite medium, i.e., in a bucket of fluid, are obvious. All that is required is a vane and a torque measuring head and hence the device is portable. Additionally the shear stress and the shear rate data are easily determined. It should be noted that Eqs. (10)–(12) are also valid for yield stress materials. Fig. 17 illustrates some data obtained for a nickel laterite slurry, which is the feed to the extraction process. The figure illustrates the regions in which the data would be required and also illustrates clearly the slip problems associated with the cup and bob instrument and the capillary instrument. Also note that the vane and cup rotation device extrapolates to the vane yield stress measurement. The vane rheometer generally is not suitable for Newtonian (low viscosity) fluids (Barnes and Carnelli, 1990).

4. The impact of environmental rheology

4.1. In design

Fig. 18 illustrates a suggested approach for determination of a waste tailings disposal system. A common practice in the industry is to use the thickener to produce a clear overflow for recycle into the process, with the waste being produced at the bottom of the thickener as a low concentration Newtonian fluid suspension which is pumped in turbulent flow to a disposal area, usually a large dam. The figure illustrates the case where the disposal area is receiving a thickened tailings. Once the tailings is thickened, non-Newtonian characteristics prevail and it becomes essential to understand this behaviour. In a greenfield site it is suggested that the designer works backwards from the preferred method of disposal, through pumping, to the thickener. The disposal area compression rheological characteristics involving the compressive yield stress and the permeability are required to predict, for example, consolidation. Both shear

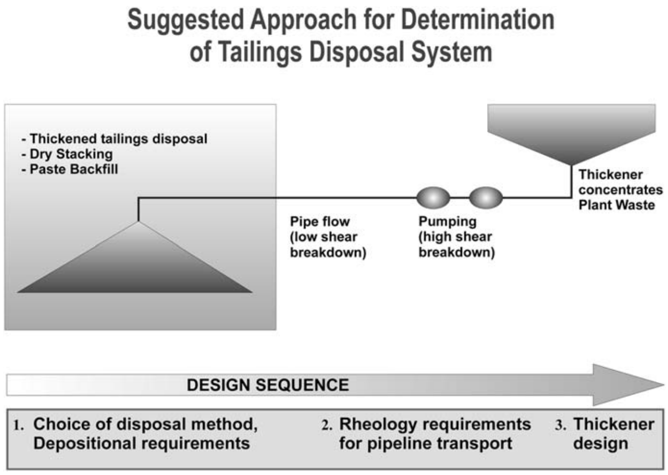

Fig. 18. A tailings disposal strategy.

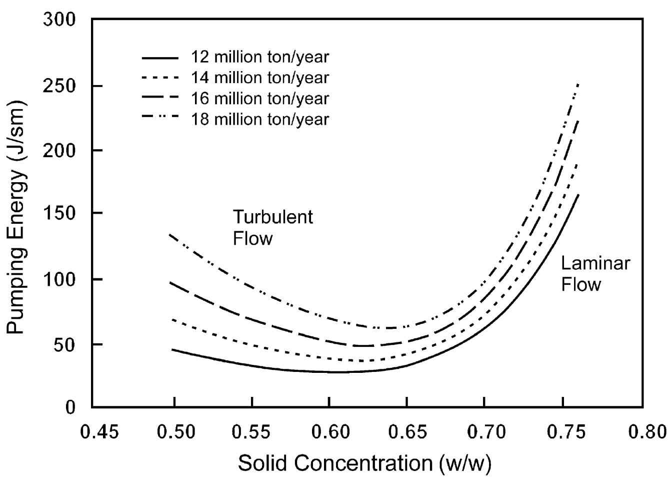

Fig. 19. Predicted pumping energy requirements based on normal shear stress–shear rate and yield stress data for a long distance fine particle suspension pipeline. The basis of the prediction is the delivery of dry solids.

stress–shear rate data and the yield stress are required as a first step for pipeline design and startup and for the design of the suction side of the pump and for the design of the thickener, and in particular, for the torque requirements for the rake.

Fig. 19 shows the predicted pumping energy as a function of solids concentration for a 20 in pipeline at various capacities for an existing pipeline. Important aspects of the curve to note are the reduction in pumping energy as the solids concentration is increased at a fixed delivery of dry solids. Each curve on the figure is calculated from the basic shear stress–shear rate and yield stress data for the delivery of dry solids. The minimum in the curve corresponds effectively to the transition between laminar and turbulent flow. Note that the concentration of suspension can be considerably increased for fixed pumping energy if one is willing to move from turbulent to laminar flow. One of the great impediments in moving from a wet (Newtonian) disposal strategy to a thickened disposal strategy is the reluctance and risk associated with pumping in laminar flow. The alumina industry in fact has made this transition and does pump suspensions in laminar flow. Nevertheless the basic rheological characteristics are required in order to make a prediction like that shown in Fig. 19. This, however, is not the end in terms of design because one has to learn about the sedimentation characteristics of the

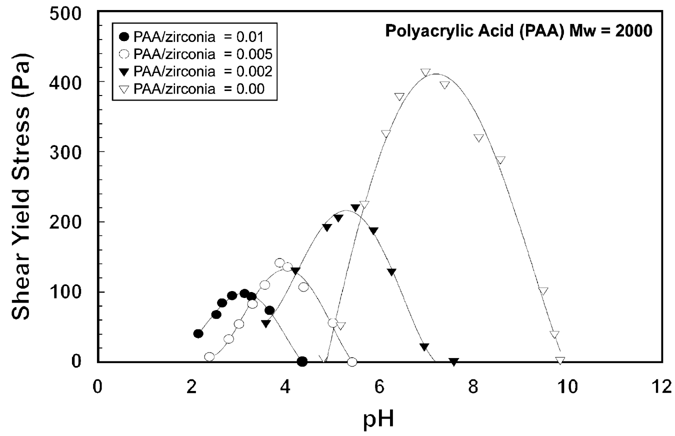

Fig. 20. Effect of low molecular weight polyacrylic acid on the shear yield stress-pH behaviour for a zirconia suspension at 57 wt%.

particular material being examined, not only for critical velocities in turbulent flow, but also for design in laminar flow.

As already stated, Fig. 9 illustrates the importance of being able to make a single point yield stress measurement in the industry. Here the yield stress as a function of mass fraction is compared for a variety of industries illustrating that the rheology of each of these systems is very different and needs to be understood if one is to design and operate a particular disposal strategy. Note that the pumping companies now talk about being able to pump a material at a yield stress of 200 Pa; this is in contrast to what was deemed appropriate five years ago, i.e. 30 Pa. Also note from the results in Fig. 9 the vast difference between the various industries: coal, sand mining, manganese, nickel, alumina, copper and a paste mine stope fill material. A yield stress concentration curve is the first step in effective evaluation of a disposal strategy. Without the techniques for single point determination of the yield stress such comparisons would be difficult.

4.2. In evaluation of the influence of surface chemistry

The yield stress concentration data shown in Fig. 9 are for the fine particle waste stream produced by these industries and discharged to a disposal area as a suspension. The use of the term fine particle is vague because these streams invariably have a broad particle size distribution but also have a fine particle fraction, sometimes significant, with the particles' size less than 20 μm. Also many of these streams have a clay content which can be very detrimental to the rheological behaviour of the material, particularly in terms of its settling characteristics in a disposal area. The presence of fine particles in these waste streams, i.e. particles less than about 20 μm, can dominate the rheology but also has the added advantage that the rheology often can be modified using "magic additives" which affect the surface chemistry.

The surface chemistry can be evaluated by using standard techniques to measure particle mobility as a function of pH. From such measurements the isoelectric point can be determined which is the pH of net zero charge or maximum van der Waals force of attraction. This point also coincides with the maximum yield stress for concentrated suspensions. Yield stress-pH results for an ideal zirconia suspension at 50% solids are shown in Fig. 20 (Zhou et al., 2001). Also shown is the influence of adding a dispersant (polyacrylic acid). The pH of maximum yield stress is shifted to lower values, as is the maximum yield stress significantly reduced as the concentration of polyacrylic acid is increased. If the lowest yield stress material shown in the figure is now shifted from its low pH to a value of 8.9

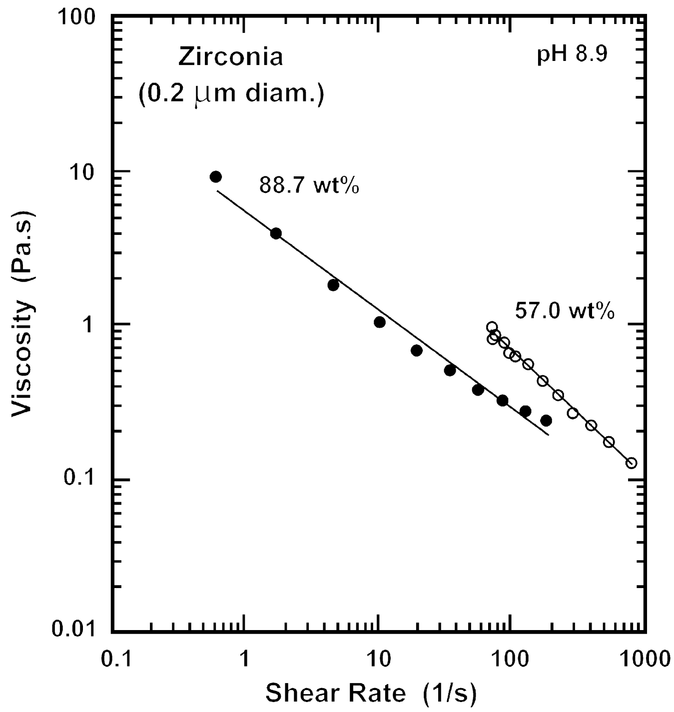

Fig. 21. Manipulating the flow characteristics of particulate fluids.

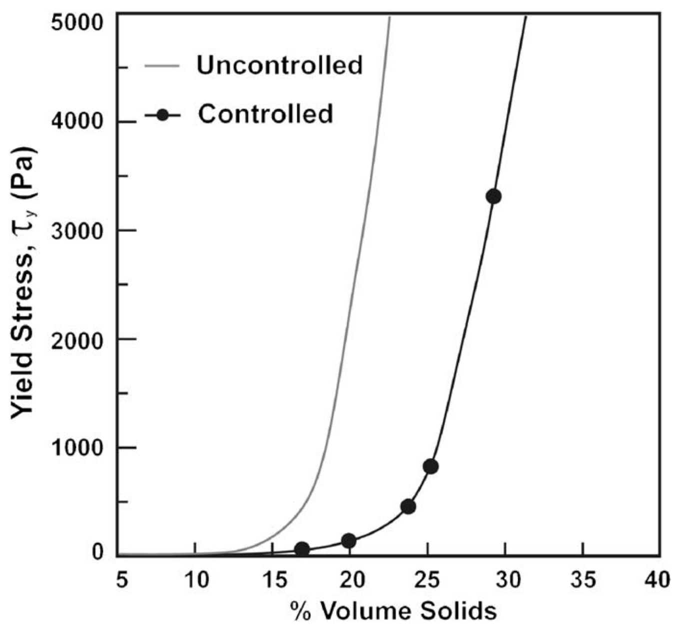

Fig. 22. Effect on yield stress versus volume fraction behaviour for clay dispersed in $CaCl_2$ and clay dispersed in water with $CaCl_2$ added later.

one can compare the viscosity-shear rate data for the zirconia with and without the additive. These results are shown in Fig. 21. Note the dramatic impact that the polyacrylic acid has had on the zirconia suspension's properties. The viscosity of a 57% by weight suspension is in fact higher than for the same material at a concentration of 88.7%. Such dramatic effects can be obtained with ideal suspensions and sometimes can be achieved in practice with fine particle waste streams. Additives sometimes can help dramatically in dewatering and in reducing the viscosity for waste stream suspensions. Here once again the techniques developed for environmental rheology are invaluable in evaluating the performance of such chemicals.

Clays can present huge difficulties in dealing with waste streams. The phosphate industry in Florida in the USA produces nearly 100,000 tonnes per day of waste clay on a dry basis. These waste clays create one of the most difficult disposal problems in the mining industry because of their dreadful sedimentation characteristics in a tailings disposal area, possibly because the clay has been defoliated in the extraction process itself. Fig. 22 illustrates the difference between a controlled method of dispersion of a montmorillinite clay experienced in a coal waste tailings stream versus controlled dispersion with calcium chloride. The effect is dramatic in terms of the influence on the yield stress. Note in this case that the yield stress is plotted as a function of percent by volume solids. The photograph in Fig. 23 illustrates the effect of controlled dispersion even more graphically, where 20 g of clay are dispersed in 60 g of water, on the left, and on the right, the same process takes place where the clay is dispersed directly in a 1 molar calcium chloride solution. The middle photograph shows the same process where the clay is first dispersed in water and then the calcium chloride is added. On the left-hand side the clay behaves like a potters clay, the uncontrolled dispersion results in a material which virtually never settles, whereas the controlled dispersion yields a clay which settles so effectively that remaining coal could be separated. The use of controlled dispersion in clays in the coal-mining industry has been effective on a number of occasions. Once again, the single point yield stress measurement was accomplished with the vane device which allowed for a straightforward and simple method for evaluation of dispersion methods in the clay system.

5. Conclusion

An application of very basic rheological principles involving measurements made with instruments specifically developed for the purpose is all that is needed to reduce the risk, recover water and reduce the footprint of the suspension waste produced in the minerals industry. Exploiting the rheology will decrease the negative social and environmental impact of the particulate fluid waste not only from the minerals industry, but also from the coal, oil and human waste industries. Has there been a significant penetration of this knowledge into the industry and have these techniques been used in industries other than alumina? The answer to both of those questions is yes. Industry is now well aware of rheology and its potential for exploitation in the production of thickened and paste tailings. However, there remain impediments to implementing this technology. While the technology exists and it has been proven in the alumina industry there is a risk associated with taking the big step from 15,000 tonnes per day on a dry basis of the alumina industry to 250,000 tonnes per day in industries like copper, coal, and oil in Canada. The risk here is largely associated with laminar flow pumping and our lack of understanding and practice in this area, and of course, with handling such a huge volume of material However, changes are in the wind. A huge amount of research has been conducted by the Canadian oil sands industry in co-disposal of sand with the fine particles and one would hope that this technique will be successful in the future. Likewise the copper industry in Chile in particular is now examining better methods to recover water, perhaps driven mostly by the fact that some of these mines are functioning in the driest place in the world, i.e. the Atacama desert.

The other issue that is generally raised immediately is cost. There is no profit associated with doing a better job with waste management and the better job generally involves significant investment in capital, as has been the case in the alumina industry. However the costing of this investment generally has a huge deficiency in that the cost of ultimate rehabilitation of a tailings disposal area is generally not included in the sum. The rehabilitation cost is listed as a liability

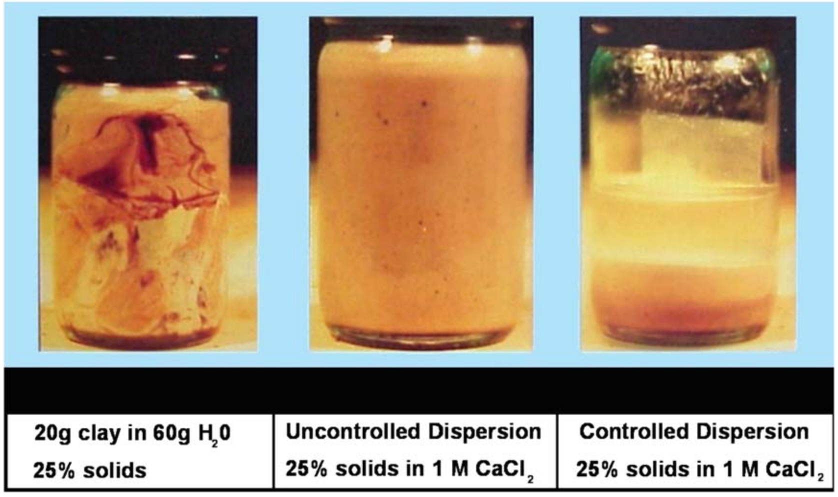

Fig. 23. Uncontrolled versus controlled dispersion.

in a company balance sheet. Often this is an unfunded liability so at the end of the day some companies have managed to escape the liability and the responsibility has been left with the taxpayer. One such example is in the phosphate industry in Florida where the State of Florida has had to deal with such issues. Florida is not unique in the world where there have been many cases, particularly in the past, where liabilities have escaped. Often in the past the costs associated with cleaning up a disposal area have been deferred until the end of the mine; this liability, although discounted and listed annually on a balance sheet, often has been unfunded and hence unless the company is a large one with huge resources they have been able to escape the liability. An attitude in the industry has perhaps been best summed up in the book *Collapse* by Gerard Diamond in his chapter on Montana.

> …In Montana as elsewhere, companies that have acquired older mines respond to demands to pay for clean-up in either of two ways. Especially if the company is small, its owners may declare the company bankrupt, in some cases conceal its assets and transfer their business effort to other companies or to new companies that do not bear responsibility for clean-up at the old mine. If the company is so large that it cannot claim that it would be bankrupt by clean-up costs the company instead denies its responsibility or else seeks to minimize the costs. In either case, either the mine site or the areas downstream remain toxic, thereby endangering people, or else US Federal Government and Montana State Government (hence, ultimately the taxpayers) pay for the clean-up through Federal super fund or corresponding Montana State fund. Montana is not unique in liability for abandoned mine sites being left to the taxpayer. Do our industries really want to be subsidized by the taxpayer in this way, or are we now in a position to move to more sustainable and responsible management of the waste that we produce.

Mining has a very poor record. According to the United States Environmental Protection Agency, mining has contaminated portions of the headwaters of 40% of watershed in the western continental USA and reclamation of 500,000(!!) abandoned mines in 32 states would cost tens of billions of dollars.[2]

[2] Environmental Protection Agency. "Liquid Assets 2000: Americans Pay for Dirty Water".

All, however, is not doom and gloom as governments and companies are becoming far more responsible. Performance bonds or environmental sureties have become a requirement in many companies as a means of protecting governments and the taxpayer from mine rehabilitation costs. The USA, Canada, Australia, Japan, South Africa, Indonesia and Malaysia require lodgement of environmental sureties. Europe will follow suit and perhaps other countries are doing the same thing. In addition, some countries are now setting up trust funds to deal with the ultimate cleanup issue.

Environmental rheology provides a tool to evaluate various waste disposal strategies for the minerals and energy industries. Technology exists to significantly reduce the volume of waste produced by this industry simply by recovering and recycling water. Regulation has not been successful in forcing industries down this track. The major driving force will be the lack of water and the need to recover water in the near future. This is already happening. For a comprehensive discussion on the issues associated with improved environmental practices in the resource industries refer to Jewell and Fourie (2006).

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