ENVIRONMENTAL RHEOLOGY – RHEOLOGY AND THE TRIPLE BOTTOM LINE

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Summary

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 behavior, characterized by shear thinning, a yield stress, and in some instances, by thixotropic behavior. Understanding and exploiting this rheology can result in dramatic improvement in waste disposal strategy. The paper illustrates how this industry has influence the development of specific simple rheological measurement techniques to obtain the parameters needed for design. The topic area is called environmental rheology.

1. Introduction

It is surprising that so few people are aware of the triple bottom line. The three lines represent Society, the Economy and the Environment. Society depends on the economy, and the economy depends on the global ecosystem, whose health represents the ultimate bottom line. More precisely, the triple bottom line now focuses corporations, not just on the economic value that they add, but also the environmental and social value they add and/or destroy. At its narrowest it is a framework for measuring and reporting corporate performance against economic, social and environmental parameters. Sustainable development is linked to the triple bottom line in that it is about strengthening the business while reducing negative social and ecological consequences. Many corporations now report relative to the triple bottom line.

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 a storage sites where it might remain for the life of the mine.

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 ten times the amount of municipal waste produced!! We estimate that at least ten billion tones 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 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 meters of coarse tailings deposit per day and 200,000-300,000 cubic meters of fine tailings per day. At the time of the private communication, the industry had produced 400 million cubic meters of fine tailings. This tailings is 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.

How can rheology influence the triple bottom line? Rheological knowledge can be exploited by many industries 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 fluid. The disposal area is invariably a very large dam; in fact, disposal areas approaching half the size of Singapore are present in the world. If the waste from such a mine, whether it be from minerals, coal, oil or human waste, is dewatered and the water is reused in the process, the footprint produced by the dam 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 forty-four tailings dam failures. The probability of such a failure apparently ranges from one in seven to one in fifteen [www.wise-uranium.org/mdaf.html].

The consequence of a dam failure is dramatic and can be tragic. The photograph in Figure 1 shows the rupture in a tailings dam holding the waste from a lead-zinc mine in Spain in 1998. Five million cubic meters 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.

Figure 1. Failure of the Boliden lead-zinc tailings dam in 1998 (www.wise-uranium.org/mdaf.html)

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. The probability of such failures can be minimized by moving from wet, Newtonian fluid suspension disposal to a highly concentrated, non-Newtonian fluid disposal simply by understanding and exploiting very basic shear and compression rheology. As the water is removed and the concentration is increased the material becomes non-Newtonian and appears more paste-like.

On the surface 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 was not 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.

What has changed? 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 sustainability, particularly in regard to the triple bottom line associated with profit, the environment and social impact.

The first step towards improved performance 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 being 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 Pascals 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. Rheology is the science that deals with the deformation and flow of anything but in particular is concerned with the deformation and flow of non-Newtonian fluids. 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 minimization 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.

	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

Table 1. Sustainability of Tailings Management Practice.

2.1. Alcoa Alumina in Western Australia

In 1974 the author was approached by Peter Colombera and Mark Want from Alcoa of Australia with an enquiry about the rheological characteristics of the material they called "red mud". At this time our research in rheology had been ongoing only for six years and was entirely related to the behavior 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 associated with thixotropy in shear occurred at a more rapid rate than the rebuilding of that structure. In ideal thixotropic behavior 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 realization that the current practice, which was pumping the red mud to the disposal area (a dam) at a concentration of between 15-20% 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 behavior, while at higher concentrations, non-Newtonian shear thinning characteristics and a yield stress were observed. At even higher concentrations thixotropy was observed. Figure 2 shows shear stress-shear rate data for a concentrated red mud suspension after being subjected to significant periods

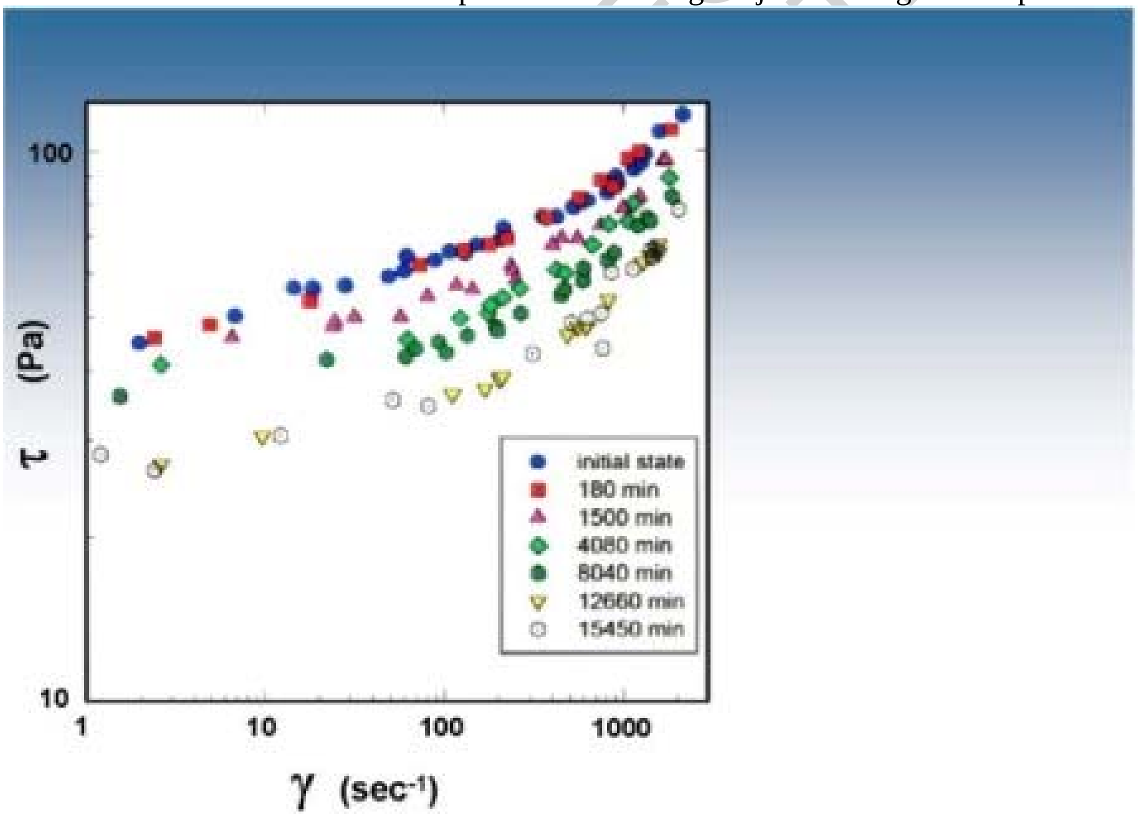

Figure 2. Typical red mud shear stress-shear rate behavior illustrating thixotropic behavior.
The data were obtained after shearing the mud at high shear rate for different times.

Figure 3. Illustration of the effect of shear on a red mud filter cake

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. Figure 3 illustrates the behavior 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 it appeared as if one could exploit the thixotropic characteristics in the transportation of a high concentration mud to the disposal area, i.e., dewater the material by “brute force”, shear the “hell” out of it to break the structure, then transport it out to the tailings facility where the material would restructure slowly. To quantify this behavior 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 PhD thesis and developed for the single point measurement of the rheological yield stress, a fundamental fluid property. Some very early data obtained with the vane showing the breakdown and recovery of the red mud are shown in Figure 4. 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 behavior 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 also became 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 Figure 5.

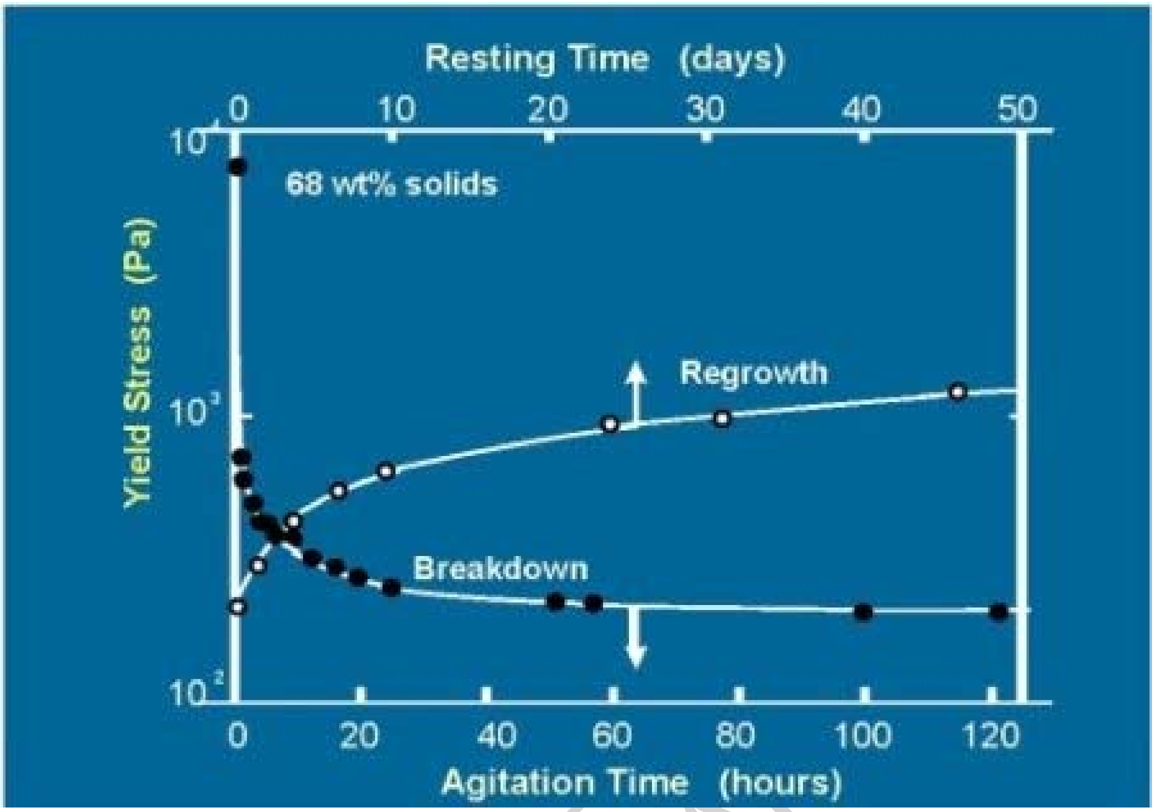

Figure 4. Use of the vane yield stress measurement to illustrate the breakdown and recovery of the red mud structure

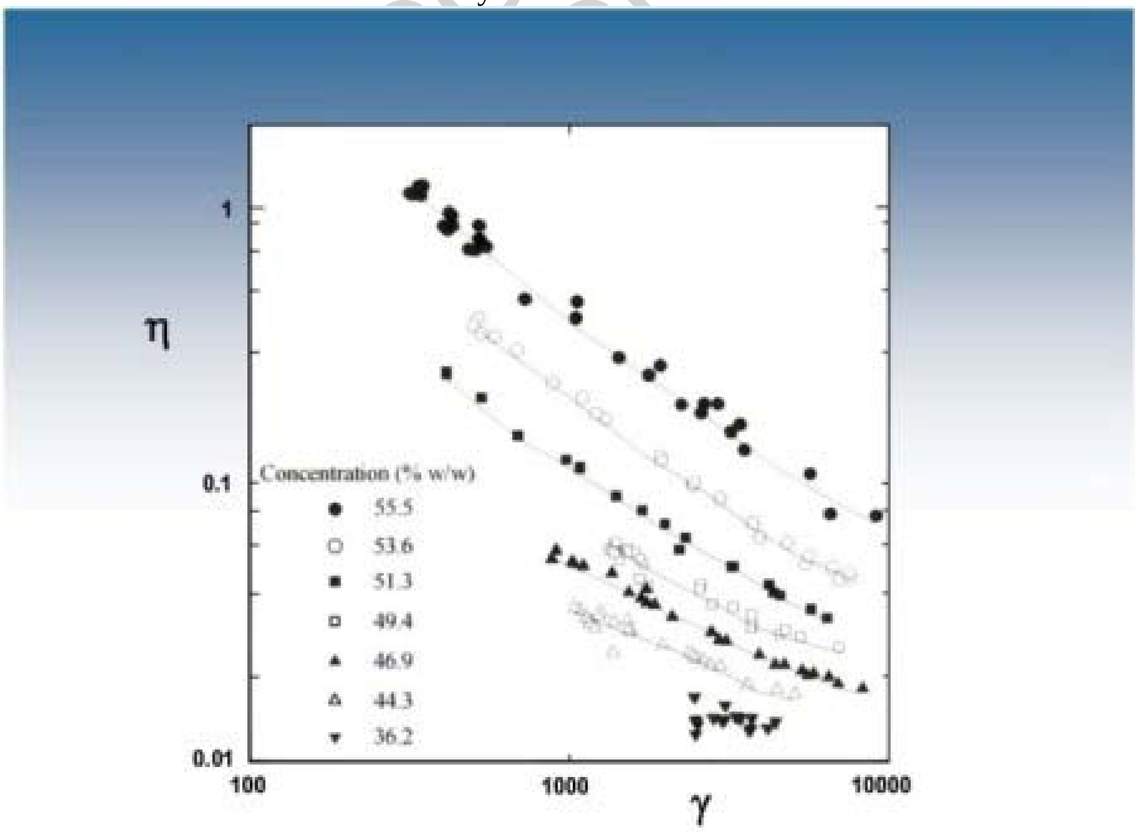

Figure 5. Red mud equilibrium viscosity shear rate data

Figure 6. Wet lake photograph in the 1970s (Photograph courtesy of Alcoa of Australia)

Figure 7. Alcoa Western Australia, bauxite waste dry stacking
(Photograph courtesy of Alcoa of Australia)

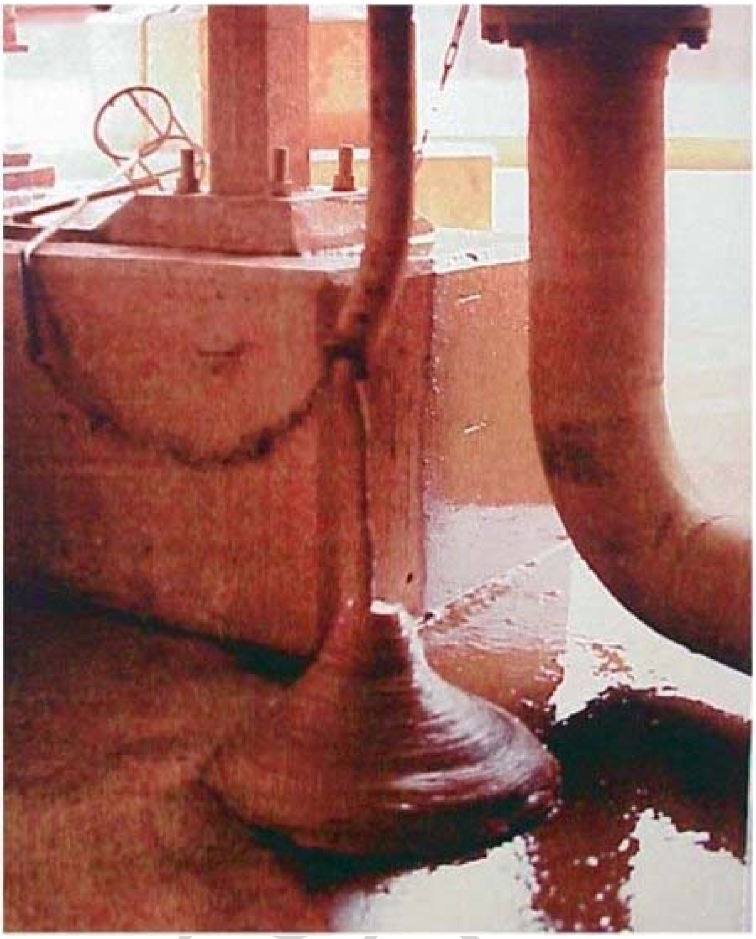

Figure 8. Mineral waste produced with a compression thickener (Photograph courtesy of Alcoa of Australia)

The shear thinning characteristics of the material are apparent as the concentration increases, from Newtonian behavior at the lowest concentration (36.2%) by weight. Data like that shown in Figures 2, 4 and 5 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. Figures 6 and 7 compare the wet lakes of the 1970s to the dry disposal of the 1990s, while Figure 8 illustrates the paste-like material produced with a compression thickener.

The impact of the alumina industry on our research 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 behavior. Also, once the techniques were developed one could start making comparisons across this industry and others. For example, Figure 9 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, of course, is now used in the minerals industry as a whole to construct graphs like that shown in Figure 9.

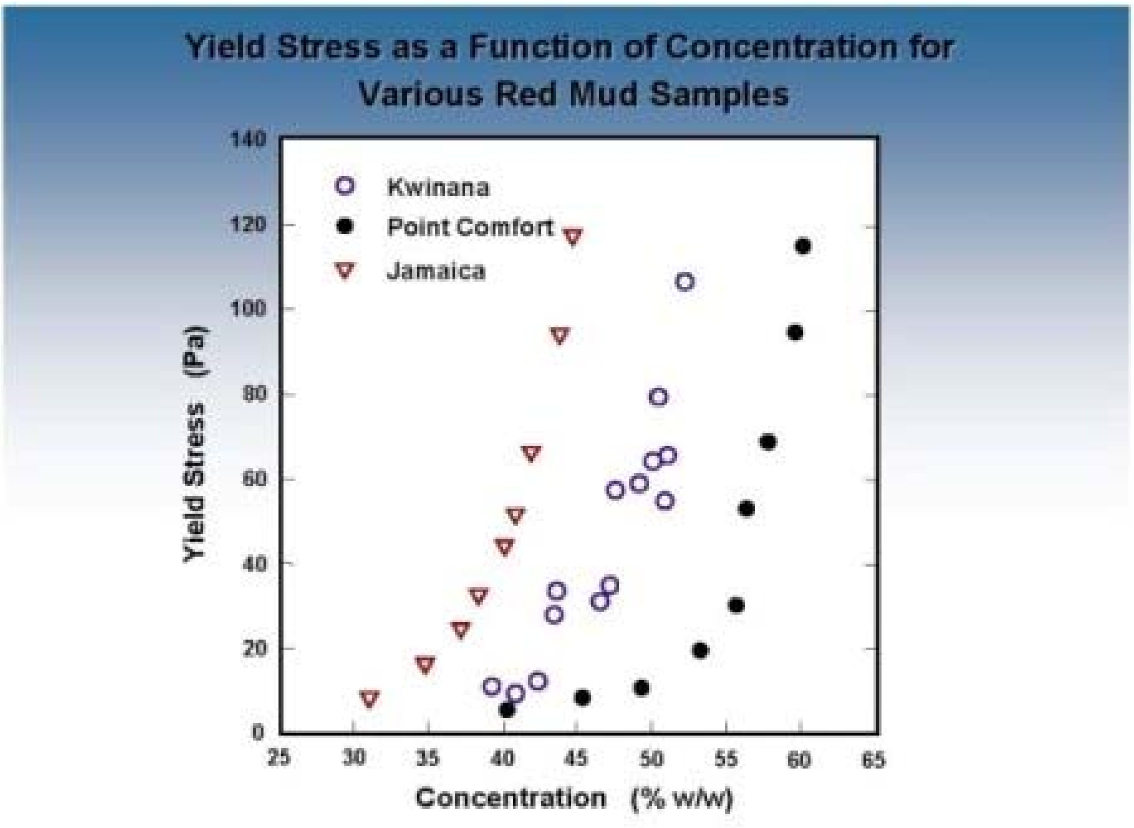

Figure 9. Yield stress as a function of concentration for red mud from different alumina samples

The alumina industry was the first to discover and exploit an understanding of basic rheology in the handling of its waste. The rest of the story is history. After the original consulting work, six PhD students worked on the problem: Dr Guillermo Sarmiento on the rheology of lower concentration red muds; Professor Q D Nguyen, who amongst other things established the vane device for yield stress measurement; Dr N J de Guingand, who was the first student to work on the compression characteristics of red mud; Dr Nick Pashias, who did a comparative study of the red muds across the Alcoa organization and established the slump technique for yield stress measurement; Dr Fiona Sofra, worked on the stacking angles for red mud. Dr David Cooling was the final PhD student whose work was conducted at the refinery itself and was used to establish methods for sequestering CO_2 in the red mud. David Cooling had a huge impact earlier because it was his Masters thesis from the University of Western Australia which formed a basis for Alcoa moving to the use of super compression thickeners.

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Biographical Sketch

David Boger was educated in the United States receiving a PhD in chemical Engineering from the University of Illinois in 1965. In Australia he has held positions in Chemical Engineering at both Monash University and the University of Melbourne.

Currently he is Laureate Professor and Professor of Chemical Engineering at the University of Melbourne. He is immediate past Director of the Particulate Fluids Processing Centre (a Special Research Centre of the Australian Research Council), past Head of Chemical Engineering and former Deputy Director of the Advanced Mineral Products Centre. His research is in non-Newtonian fluid mechanics with interests ranging from basic polymer and particulate fluid mechanics to applications in the minerals, coal, oil, food, and polymer industries. From 1991-2002 Professor Boger was Chairman of the Trade Waste Acceptance Advisory Committee, a group which advised the City of Melbourne on industrial trade waste discharges to the trunk sewer system. He held the position of BHP Billiton Fellow from 2000-2003.

Highlights of his research include the discovery of constant viscosity elastic liquids (Boger fluids); detailed experimental investigations using such materials to define fluid elasticity effects in important flows; the linking of basic surface chemistry to the continuum properties and the processing of particulate fluids; developing novel methods for flow property measurement; and the linking of the basic research to significant industrial outcomes in the petroleum, food and minerals industries. He is well-known for exploiting rheology for waste minimization in the minerals industry.

David Boger has received many awards which include The Australian Prime Minister's Prize for Science in 2005, the 2002 Victoria Prize, the Gold Medal of the British Society of Rheology in 2001 and the Walter Ahlström Prize of the Finnish Academies of Technologies in 1995. In 2007 he was elected to the

Royal Society