Improving Clay-Based Tailings Disposal: Case Study on Coal Tailings

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The role of swelling clays in hindering the compressional dewatering characteristics of coal-mine tailings is examined. The effects of electrolyte concentration and ion exchange in improving the shear and compressional rheology are compared. Suspensions studied include actual mine tailings (thickener feed and thickener underflow) as well as synthetic clay dispersions made from clay collected from the coal seam. It was shown that the most important parameter in controlling the properties of the tailings suspension is "controlled" dispersion in the presence of a Ca^{2+} electrolyte concentration in excess of that required to (1) prevent initial swelling and (2) provide full cation exchange of the clay. Under these electrolyte conditions, complete delamination of the clay did not occur, and both the dewatering and handling characteristics of the resultant suspensions improved dramatically.

Introduction

Swelling clays, montmorillonite in particular, are often associated with mineral deposits and, consequently, often end up as a constituent of mineral tailings. These clays can severely hinder the dewatering and disposal of the tailings (Clement and Bonjer, 1975; Vick, 1983) due to swelling and gelation phenomena. Problems with swelling clays exist, for example, in the coal industry (Brown, 1986; Ellis et al., 1979; Ward, 1980), the Florida phosphate mining industry (Somasundaran et al., 1975; Deason and Onoda, 1984; Smelley and Scheiner, 1985), and also in gold-ore processing.

Swelling clay-based tailings are characterized by complex shear rheological properties and exceptionally poor dewaterability, whether through an applied dewatering force, or by sedimentation under gravity. Conventional dewatering technology is either inefficient at dewatering the tailings or can only perform dewatering after substantial capital expenditure. In many cases, the final stage of the tailings disposal system involves pumping of the tailings as a suspension to a tailings dam where, theoretically, sedimentation under gravity occurs. In practice, however, the presence of the clay leads to very little sedimentation and the resultant lakes of mud lead to a myriad of environmental problems, not the least of these being an inability to reclaim the land associated with the dams.

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The dewaterability problem of montmorillonitic clay-based tailings is still poorly understood in terms of the link between surface chemistry and the relevant engineering properties of the waste, such as sedimentation rate and ultimate solids concentration, shear, and compressive rheology. The key to the efficient dewatering and disposal of clay-based tailings is in the manipulation of the surface chemistry of the clay component of the tailings. A knowledge of the nature and properties of clay minerals is critical to this end.

The most common clay minerals encountered in tailings systems are kaolinite, illite, montmorillonite, and mixed-layer illite/montmorillonite clays (Vick, 1983; Tsai, 1982). All of these minerals, while having differing molecular structures, have a flat platelike, high-aspect-ratio, particle shape (Grim, 1968). In increasing order of aspect ratio, the minerals are generally ranked kaolinite, illite, and montmorillonite. The mineral that presents the most difficulties in the dewatering of tailings is montmorillonite, due to a combination of factors of which the most important are its swelling properties. The presence of even small amounts of montmorillonite in tailings has been shown to severely hinder the effectiveness of dewatering operations (McKee and O'Brien, 1989; Smitham and Loo, 1989).

The structure of most clays is such that a charge deficiency exists in the crystal lattice due to isomorphous substitutions of lower valence cations for the aluminum and silicon that constitute the alumina and silica sheets within a crystal (Grim, 1968; Weaver, 1989). To compensate for the resulting net negative charge of the platelet faces, cations are adsorbed in between adjacent platelets or layers. These cations are exchangeable and, on wetting, are released to water to give a surface of net negative charge that is compensated (neutralized) by double-layer ions (Van Olphen, 1977).

Montmorillonite commonly occurs in nature with sodium as the interlayer cation, and the properties of Na-montmorillonite are the cause of the dewatering problems. In the dry state, the spacing between individual montmorillonite lamellae is about 2.5 Å (Grim, 1968). On immersion in an aqueous environment, interlayer cations hydrate and equilibrate with the surrounding suspension. The net negative charge on the platelets forces the layers apart due to electrical double-layer repulsion (Norrish, 1954) and, if unrestricted, will completely separate. Even at low volume fraction, the suspension then becomes a space-filling, thixotropic gel consisting of the platelets randomly oriented in a structure that has been likened to a card house (Van Olphen, 1977; Khandal and Tadros, 1988). The resulting random, voluminous nature of the clay platelet network produces a poorly compressible network and creates a difficult to dewater system. An important point is that the degree of swelling exhibited in a Na-montmorillonite can be limited by increasing the ionic strength of the suspending medium. The simple addition of salt retards the swelling process by restricting the double-layer repulsion.

The addition of calcium ions to improve the dewatering efficiency is common in tailings dewatering operations involving montmorillonite (Ellis et al., 1979; Kessick, 1980; McKee and O'Brien, 1989). The role of calcium is to ion-exchange the clay from the sodium to the calcium form. The calcium ion has a twofold effect; being a divalent ion, it has a higher neutralizing power than sodium, resulting in coagulation of the platelets at lower concentrations and, more importantly, it promotes face–face aggregation of the montmorillonite platelets, as opposed to random coagulation (Norrish, 1954; Kjellander et al., 1988). The former condition reduces the effective volume of the clay network and improves dewatering properties.

The primary aim of this work was to illustrate the effect, on clay tailings dewatering and disposal, of the conditions of dispersion of an Na-clay in water during the coal-washing process. A postulate is that if the ionic strength of the aqueous dispersing medium is high and calcium ions are present, then (1) initial swelling of the clay, on wetting, will be restricted due to compression of the electrical double layer resulting from the high ionic strength, and (2) ion exchange from sodium to calcium simultaneously occurs. Once ion exchange is complete, swelling is further restricted. The resultant suspension will consist of larger particles due to the prevention of breakup of the clay in its as-mined, face–face oriented form, and the net number of interactions between particles in suspension will be decreased, resulting in improved sedimentation, compressive, and shear properties. This has been termed controlled dispersion by Deason and Onoda (1984) and has had only minimal investigation (Deason and Onoda, 1984; Tanihara and Nakagawa, 1973).

Previous results indicate substantial improvements in settling properties of controlled dispersed clays compared with the alternative. Uncontrolled dispersion occurs where the electrolyte concentration of the water that initially wets Na-montmorillonite is insufficient to suppress swelling, and dispersion of the clay occurs into, in the worst case, individual platelets. Limitations of the work to date are the absence of an evaluation of the rheology of the systems and explicit studies of particle size. Additionally, "processed" clay samples were used where the initial particle size of the dry material was quite small, presenting an upper limit to the potential size of the clay aggregates produced through controlled dispersion. This article aims to investigate the relationship between rheology, particle size, and electrolyte concentration for controlled dispersion.

As a case study, the effect of manipulating the surface chemistry of montmorillonite on the dewatering and disposal of a black coal tailings in the Hunter Valley region of New South Wales, Australia, was examined. The mine of interest was at Warkworth and has a tailings-disposal problem resulting from the unavoidable presence of sodium montmorillonite in the tailings. The problem has been acknowledged as one of the most severe cases in the area (Ward, 1980). The operation involves conventional coal processing (washing) in which tailings from the plant are thickened and pumped to a disposal dam. Both water recovery and reclamation of the dam are on-going processes, although the latter is severely hindered by the properties of the tailings.

In this context, a shear and compressional rheological characterization of real samples of the tailings was performed. An investigation of the effect of calcium ion-exchange on the system properties of a simulated tailings sample (initially with no additives) was then completed. Finally, a study of the effect of dispersion conditions on the properties of suspensions of the clay alone was completed in terms of rheology and settling properties, along with a comparison of a coal–clay suspension produced through controlled dispersion and the real mine samples. The key factor in the investigation was the use of an understanding of the surface chemical behavior of the montmorillonite in the tailings and its effect on the macroscopic suspension properties. The results presented are relevant to any mineral processing operation where swelling clays are a problem and are discussed with regard to their practical implications.

Experimental Section

Materials

During the course of the investigation, tests were performed on a variety of suspensions. These included samples of thickener feed and thickener underflow from the plant and a clay-rich tailings sample prepared from ground coal and clay from the band in the coal seam. The latter sample is referred to as simulated tailings. The relationship between clay-dispersion conditions and rheology was investigated using suspensions of clay alone from the mine, and a final sample was investigated by combining a controlled dispersed clay suspension with ground coal from the mine, referred to as controlled dispersed simulated tailings.

The samples of thickener feed and underflow were analyzed for ash (clay mineral) content by Carbon Consulting International Pty. Ltd. (CCI) and the results are listed in Table 1. The average solids densities of the respective sam-

Table 1. Density and Clay Content of Samples Used in this Study

Sample	Density ($kg \cdot m^{-3}$)	Clay (%)
Thickener feed	1,940	51.2
Thickener underflow	1,800	51.5
Simulated tailings	2,200	64.0
Uncontrolled dispersion	1,990	64.0

ples are also shown. A detailed mineralogical analysis is presented elsewhere (de Kretser, 1995). The pH of the suspensions was 8.0 ± 0.5 and the conductivity, 12.0 $mS \cdot cm^{-1}$. Experiments where the properties of the thickener feed and underflow were evaluated at a range of solids concentrations involved concentration of the suspensions using vacuum filtration. Subsequent dilution was performed using the filtrate of each respective sample.

Experiments on the effect of calcium ion exchange on the properties of the tailings suspensions in the absence of flocculant were completed on the simulated tailings suspension. The suspension was prepared from clay and fine coal from the mine, dispersed in water. The Na-montmorillonite clay swells and breaks up giving a well-dispersed system on which to perform ion exchange. The ash content and solids density of the simulated tailings suspension are also listed in Table 1. The suspension pH was 8.8 ± 0.2 and the conductivity 1.75 $mS \cdot cm^{-1}$. The cation exchange capacity (CEC) of the tailings was determined, using the method of Hang and Brindley (1970), as 40 milliequivalents (meq) per 100 g of solids. The ion-exchange experiments involved adding the relevant amount of $CaCl_2$ to the suspension at 5.7 wt. % (2.8 vol. %) solids and mixing for 15 min. Samples were then centrifuged in a Beckmann Laboratories JT-21 centrifuge at a speed of 7,000 rpm (7,250 g) and allowed to stand for one week before testing. Subsequent testing of suspensions was performed over a range of solids concentrations, with dilution performed using the supernatant from centrifugation.

Tests investigating dispersion conditions as a function of the ionic strength of the dispersing medium were performed on suspensions of clay alone, taken from the coal seam. Analysis revealed the presence of montmorillonite, kaolinite, and illite in decreasing order of abundance with montmorillonite and illite being present as a mixed-layer material. There was a distinct segregation of the mixed-layer material and kaolinite bands. The clay had a CEC of 65 meq/100 g, which is the range to be expected for predominantly montmorillonitic clay (Weaver, 1989) and an average density of 2.6 $g \cdot cm^{-3}$. For the dispersion tests, the clay was broken up into sub-1-cm-sized particles.

Controlled dispersion suspensions were prepared by adding clay to make a 5.7 wt. % solids suspension to 1,500 cm^3 of a 0.0566-M $CaCl_2$ solution. The suspension was then stirred at 500 rpm for one hour using a Heidolph variable-speed mixer with a horizontal turbine-type impeller and then allowed to stand for one week, reslurried for 45 min, allowed to settle, and finally concentrated in a Sigma 3K10 centrifuge at speeds ranging from 1,500 to 3,000 rpm.

Uncontrolled dispersion suspensions were prepared by dispersing enough clay to make a 5.7 wt. % solids suspension in 1,500 cm^3 of millipore filtered water (Milli-Q) and stirred as before. After one week the suspension was remixed for 15 min, and then the appropriate amount of $CaCl_2$ was added and the mixing continued for another 30 min. The clay was concentrated in either a Sigma 3K10 centrifuge or in a Beckmann JT-21 centrifuge at speeds ranging from 7,000 to 10,000 rpm (7,250 and 15,300 g).

Controlled dispersed simulated tailings were generated from a controlled dispersed-clay sample at 0.5 M $CaCl_2$, produced according to the procedure described earlier and mixed with fine coal taken from the filtered solids of the thickener feed. Separation of the coal and clay from the thickener feed solids was performed using repeated sedimentation and dilution. Since some finer coal was lost during the separation, coal used in the production of the controlled dispersed simulated tailings was ground in a mortar and pestle. The clay mineral content and average solids density are listed in Table 1. The controlled dispersed simulated tailings sample was produced such that the clay mineral content was at the high end of the range encountered in practice. The aim was to demonstrate the controlled dispersion effect on a sample representing one of the worst-case scenarios in terms of dewaterability.

Techniques

Rheological data in the form of shear stress (τ) vs. shear rate ($\dot{\gamma}$) data were obtained for the controlled dispersed simulated tailings using a Haake RV3 viscometer in a concentric cylinder configuration using analysis techniques described by Nguyen and Boger and Leong (Nguyen and Boger, 1987, 1992; Leong, 1988). The flow data, in the form of shear stress (τ) vs. apparent shear rate (8V/D), were used to compute pumping energy requirements for the pipeline transportation of the tailings. In the laminar flow regime, direct scale-up of the results was possible. In the turbulent flow regime, the method of Dodge and Metzner (1959) was used for prediction of turbulent friction factors from laminar flow data (Darby et al., 1992). The pipeline data were calculated based on the conditions existing at the mine where tailings disposal occurs through a 0.1524-m-ID pipe at disposal rates ranging from 800 to 1,500 tons per day of dry solids (tpd). Three dry solids throughputs were evaluated; 1,500, 1,000, and 800 tpd.

The shear yield stress (τ_y) of a suspension was evaluated as a function of volume fraction solids (ϕ) using a Haake RV3 viscometer with a vane attachment. Analysis was performed according to the method of Nguyen and Boger (1983, 1985).

Settling tests were completed on samples at an initial solids concentration by *mass* of 5.7% solids in 2.3-cm-ID tubes commencing at an initial height of 9.0 cm. The solids concentration used corresponds to a typical solids concentration of the thickener feed at the coal mine on which this project was based. Results are described in terms of the initial sedimentation rate (u_i) determined from the linear portion of the initial stages of the sedimentation test and the final sediment volume fraction solids (ϕ_{sed}). The compressive properties of the suspension were measured to evaluate the behavior in either pressure filtration or the compression that occurs in a deep cone thickener or the compression zone of a conventional thickener. The compressive yield stress (P_c) was the experimentally determined parameter.

The concept of the compressive yield stress is that in a flocculated sediment a network strength is developed, due to attractive interactions between particles, which resists compression. If a frame of reference is moved from the top of the sediment downwards, as the depth within the sediment is increased, the net downwards pressure on the solids network due to the overlying sediment also increases. Given the compressibility of the loosely bound flocs in the sediment, the increasing compressive force with depth in the sediment results in a squeezing of the flocs and consequent dewatering. If the gravitational force on the sediment as a whole is constant, then the sediment structure will compress and dewater to a state where the network strength at all depths in the sediment is in equilibrium with the compressive force at all depths. A solids concentration gradient will exist, increasing to a maximum at the base of the sediment and, at any solids concentration (level) within the sediment at equilibrium, the compressive force on the sediment at that point will be equal to the compressive yield stress corresponding to the solids concentration at that point. Hence, the compressive yield stress for a suspension at a particular solids concentration is the compressive force that must be exceeded for further consolidation of the sediment to occur.

Data for the compressive yield stress of the samples were obtained using the Buscall–White theory of compression of flocculated sediments (Buscall and White, 1987; De Guingand, 1986). The application of the theory is detailed elsewhere (Green et al., 1996). The theory equates the equivalent height of suspension (H_i) in a batch-thickening operation, at the initial concentration, required to generate a particular compressive force, and hence solids concentration at the base of the sediment, due to the sediment mass. The value of H_i is an equilibrium quantity and, while tending to underestimate compression zone depths actually required, it does provide a figure for comparative purposes.

Particle size was evaluated using a Coulter LS130 particle-size analyzer. The tests were completed at the appropriate concentration of electrolyte within the particle sizing apparatus in order to preserve the clay-particle structures (Grim, 1968).

Results and Discussion

Real tailings suspensions

Shear Rheology. The shear rheology of the thickener feed and underflow was evaluated elsewhere (de Kretser and Boger, 1992; de Kretser, 1995), and indicated that the tailings exhibited non-time-dependent, shear-thinning, yield-stress flow behavior. The viscosity (η) decreased by an order of magnitude with a corresponding increase in shear rate ($\dot{\gamma}$). de Kretser (1995) showed that the flow model of Casson (1959) adequately described the flow behavior of the suspensions. There was little difference in the flow behavior of the thickener feed and underflow at all of the solids concentrations evaluated, indicating that the presence of flocculant used in the thickener had little apparent effect on the shear rheology.

From the flow data, pumping energy requirements for the pipeline transportation of the thickener underflow were calculated. Calculated results, based on three dry solid throughputs, 1,500, 1,000 and 800 tpd, are shown in Figure 1. The most distinctive feature of Figure 1 is the presence of an optimum concentration for the pumping of the slurry, the actual value of which depends on the solids throughput. It ranges from 22 vol. % solids for 1,500 tpd to about 18% for 800 tpd. Where the suspensions are dilute, high-velocity turbulent flow exists, and where they are concentrated, the flow is slow and laminar. The optimum corresponds with the transition between the laminar and turbulent flow regimes. Previous work on the disposal of bauxite residue (Nguyen and Boger, 1983; Darby et al., 1992) has shown similar results, and, furthermore, results have been shown to extrapolate to industrial scale.

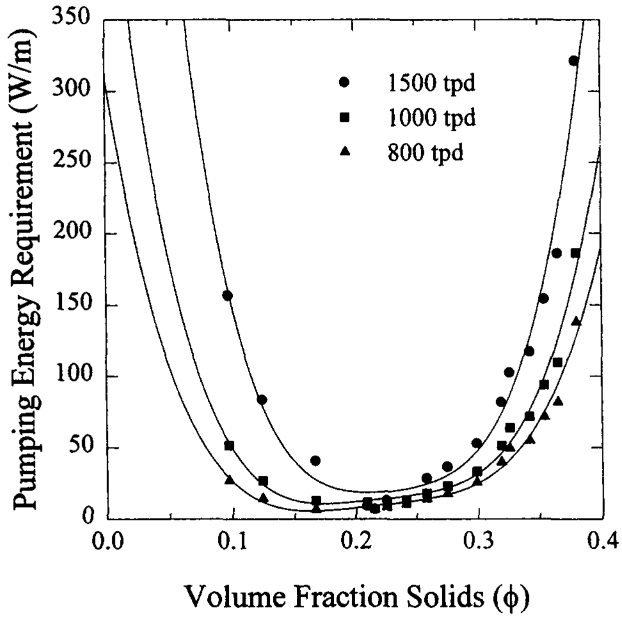

Figure 1. Pumping energy requirements vs. solids concentration for thickener underflow material for three dry solids throughputs.

See text for calculation details.

Current practice at the mine is to dispose of the tailings at low concentrations (10–15 vol. % solids). Figure 1 shows that pumping at low solids loadings is in turbulent flow, which is not optimal in terms of energy requirements. Furthermore, the energy required to pump a 10 vol. % solids suspension at 1,500 tpd is the same as that for the same suspension at 35% solids. The advantages of pumping higher solids include lower flow velocities resulting in less mechanical wear in pumps and pipeline and, most significantly, the volume of waste to be accommodated at the disposal site is substantially reduced. Settling of the solid material within the pipeline is not a problem due to the poor settling properties of the tailings, particularly at high solids concentrations where the suspension has a substantial yield stress. The results presented dispel the popular view that more energy and pressure with the pipeline are required to transport a concentrated suspension and suggest that handling of the suspension at high concentrations is feasible. The next step was to examine methods of dewatering to these higher concentrations.

Compressive Rheology. Compression data were obtained for the as-received thickener feed and underflow using the theory of Buscall and White (1987) to analyze the results. Data for the thickener underflow and feed are presented in Figure 2 as a plot of P_c vs. ϕ for an initial solids concentra-

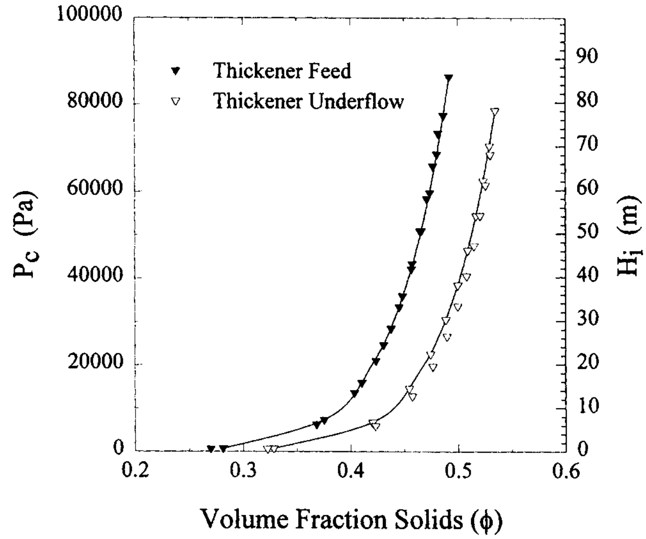

Figure 2. Compressive yield stress of thickener feed and underflow material as a function of volume fraction as measured by the centrifugation method of Buscall and White (1987).

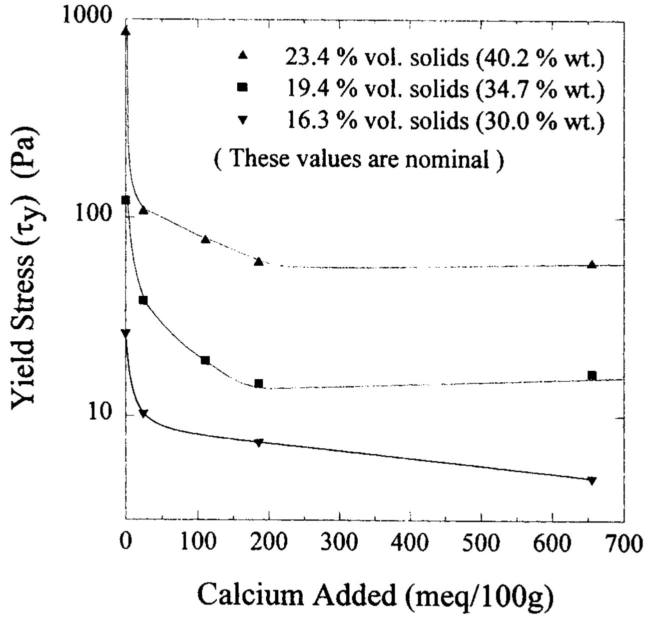

Figure 3. Shear yield stress of suspensions of 16.3, 19.4 and 23.4 vol. % simulated tailings as a function of added calcium-ion concentration.

tion of 19.9% volume. The values for P_c show a similar dependency on ϕ, as was exhibited by the shear rheology (η, τ_y) (de Kretser and Boger, 1992) and, at high concentrations, almost solidlike behavior. Figure 2 also shows H_i, the initial depth of suspension at the initial solids concentration required to produce a given compressive force at the sediment base. Note that a small percentage increase in the initial sediment height at initial sediment heights required to give low underflow concentrations will result in a large percentage increase in the output concentration. The importance of a knowledge of the compressional behavior of a sediment is well demonstrated. These data are also significant when it is considered that even for a sediment height of 1 m, an output of 30 to 35 w/w % solids is possible. This is significantly higher than obtained in practice, suggesting that much better performance could be obtained from conventional thickeners if a deeper compression zone were allowed to develop. Nonetheless, as a word of caution, it should be noted that the batch thickener heights presented in Figure 2 will be less than those required for a continuous thickener, which does not operate at equilibrium.

Effect of calcium ion exchange

Calcium ion-exchanged simulated tailings were produced with calcium concentrations ranging from 0.00744 to 0.2-M $CaCl_2$ (24.4 to 655.7 meq/100 g solids, based on the initial suspension solids concentration of 5.7 wt. % solids). The simulated tailings in their unmodified from contained Na-montmorillonite and exhibited thixotropic behavior. Details of the thixotropic behavior of the simulated tailings and samples of the clay alone are presented elsewhere (de Kretser and Boger, 1997; de Kretser et al., 1997); however, on addition of calcium ions, the thixotropy in the system became insignificant relative to the time scale of measurement. The viscosity of the suspensions was evaluated (de Kretser, 1995) over a range of solids concentrations, and, as for the thickener feed and underflow, shear thinning, yield-stress behavior was exhibited. When prepared in the manner described, the simulated tailings suspensions exhibited a decrease in viscosity, yield stress, and compressive yield stress with added calcium. This is attributed to face–face aggregation of the platelets into quasicrystals or tactoids, thus effectively lowering the number of interacting particles in the suspension. Such results have been observed by other investigators (Keren, 1988; Stanley et al., 1984; Kessick, 1980).

The change in the value of τ_y with added calcium is illustrated in Figure 3 for three solids concentrations (the concentrations illustrated are nominally $\pm 0.2\%$ solids). The majority of the change in the rheology of the suspensions occurs within the first 50 meq/100 g of added calcium. Given that the cation exchange capacity of the tailings is 40 meq/100 g, the results indicate that the change in properties of the suspensions is the direct result of ion exchange. At each solids concentration, the decrease in τ_y is of one order of magnitude, indicating that (assuming the yield stress is proportional to the number of interactions, which is directly related to the number of interacting particles present) the average number of platelets per quasi-crystal has increased.

Thus, calcium ion exchange has a beneficial effect on the rheology of swelling-clay-based tailings systems due to the powerful face–face aggregating nature of the calcium ion (Kjellander et al., 1990). This is in addition to other documented improvements with respect to flocculation efficiency and sedimentation rates (Ellis et al., 1979; Stanley and Scheiner, 1986). However, it will be shown that, despite the improvements produced through calcium ion exchange (full ion exchange of the clay is a critical aspect of a complete tailings-disposal system), the effect of ion exchange on the properties of the montmorillonite is small in comparison with the effects of controlling the initial dispersion of the clay.

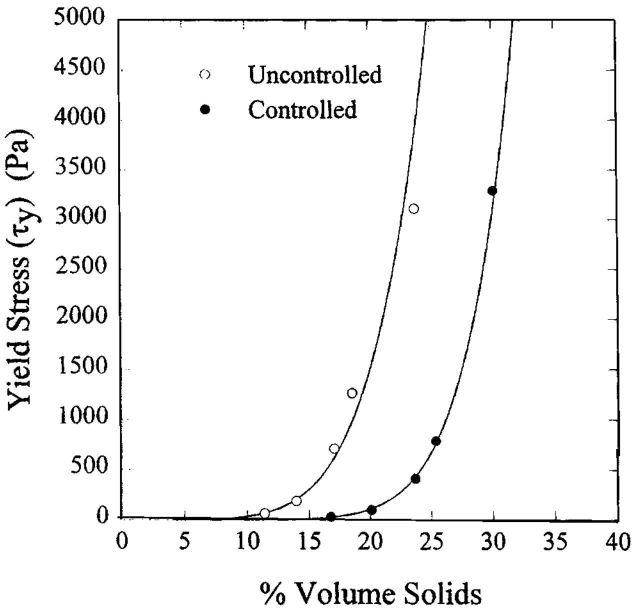

Figure 4. Shear yield stress of suspensions of clay dispersed in a controlled and uncontrolled fashion as a function of volume fraction.

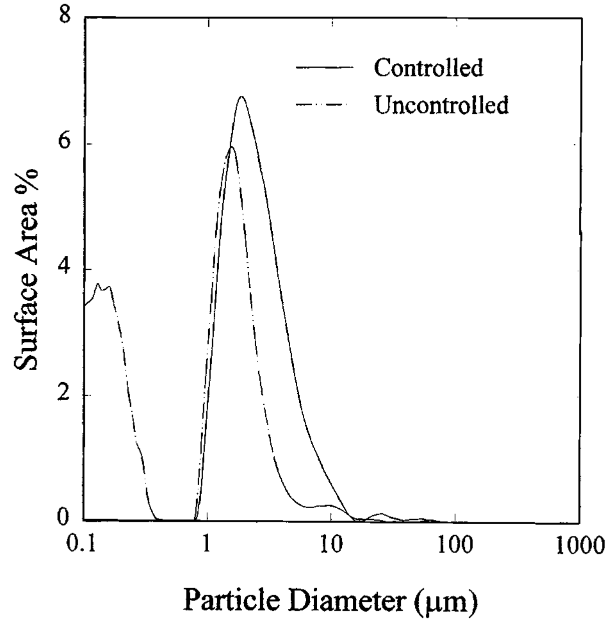

Figure 5. Particle sizes for the case of controlled and uncontrolled clay dispersion.

Effect of the clay dispersion conditions

The dispersion condition investigations were conducted on suspensions of clay alone. A $CaCl_2$ concentration of 0.0566 M was used in these experiments to produce an equivalent conductivity to that measured for the real tailings (i.e., 10–12 $mS \cdot cm^{-1}$). Results of τ_y vs. ϕ for the comparison of the two dispersion conditions (controlled and uncontrolled) at a $CaCl_2$ concentration of 0.0566 M are shown in Figure 4. A large difference between the two conditions is observed, characterized by a shift to higher concentrations in the case of controlled dispersion.

The observed shift in Figure 4 can be explained by considering two factors. The first is that with controlled dispersion in $CaCl_2$, clay swelling is controlled by both double-layer compression and ion exchange. Second, relating to statistical considerations, if the fact that a clay seam consists of a number of different clay minerals, segregated into bands is considered, then obviously, when the Na-clay is allowed to completely disperse, the particles of the different clays become mixed. The potential minimum in the interaction energy curve described by Kjellander et al. (1990) when $CaCl_2$ is added has a coagulating effect and will tend to collapse the montmorillonite platelets face to face. However, the aggregation will be dependent on platelet orientation in the suspension (Pashley and Quirk, 1984) and their proximity to other montmorillonite platelets. It is obvious that the initial ordered state, where kaolinite platelets are isolated from the montmorillonite and illite platelets, will never be restored. Thus, the most important consideration in improving the dewaterability of clay wastes is the preservation of the sedimentary structure of the clay seam, and in particular, the face–face orientation of the platelets (i.e., the most efficient packing orientation).

The particle-size distributions created by the two types of dispersion are compared in Figure 5. The difference between the two is easily observed; the mean size for the controlled case being 6.4 μm compared with 1.6 μm for the uncontrolled case. The other point to note is the presence of fine particles below about 1 μm in the case of the uncontrolled dispersion that are not present for the controlled dispersion. Thus, it can be seen that the dispersion conditions have a significant impact on the particle size and hence, the improved shear rheology and settling properties (de Kretser, 1995) of the suspensions.

In order to understand the controlled dispersion process further, the effect of the electrolyte concentration of controlled dispersion on the rheology was investigated. The results for the tests on the effect of electrolyte concentration on controlled dispersion are shown as plots of τ_y vs. vol. % solids at each calcium concentration in Figure 6. It is clear that the critical factor in the dispersion conditions is the suspending electrolyte concentration and the effect of suppressing the initial swelling of the sodium form of the clay. The changes in the yield stress for the addition of calcium, post swelling (Figure 3), were small in comparison.

The actual effect of electrolyte concentration can best be seen from the change in the maximum packing volume fraction (ϕ_{max}) with calcium concentration. ϕ_{max} is volume fraction where the τ_y data tend toward infinity—in this work, an approximation for ϕ_{max} of the value of ϕ where τ_y reached 10,000 Pa was used. The variation in ϕ_{max} with calcium concentration is shown in Figure 7, along with the final sediment solids volume fractions (ϕ_{sed}) obtained from settling tests. The lowest two values of [Ca^{2+}] are below the concentration required to completely exchange the clay from its Na-form. As a result, the lowest two values of ϕ_{max} and ϕ_{sed} are very low due to the gelled nature of these materials (ϕ_{sed} for the lowest [Ca^{2+}] was not even measurable due to its poor settling properties). As the clay was exchanged the value of these parameters increased rapidly. Note that the curve for ϕ_{max} vs. [Ca^{2+}] reaches a plateau at lower [Ca^{2+}] than the ϕ_{sed} from

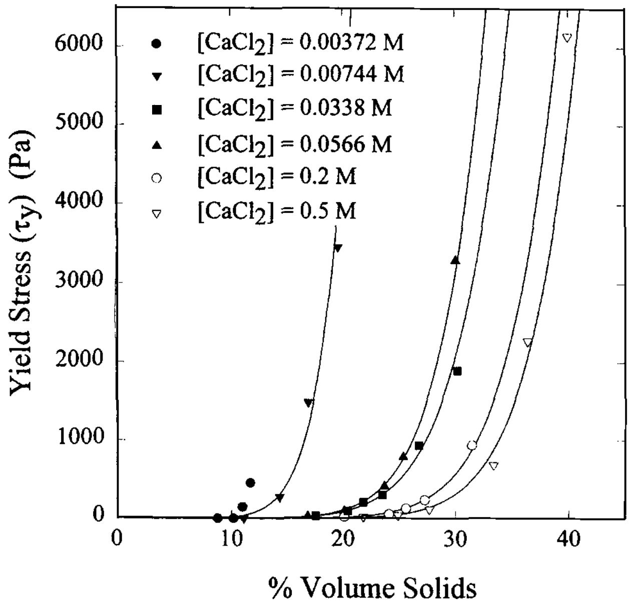

Figure 6. Shear yield stress for a range of initial concentrations of $CaCl_2$ for controlled dispersed clay as a function of volume fraction.

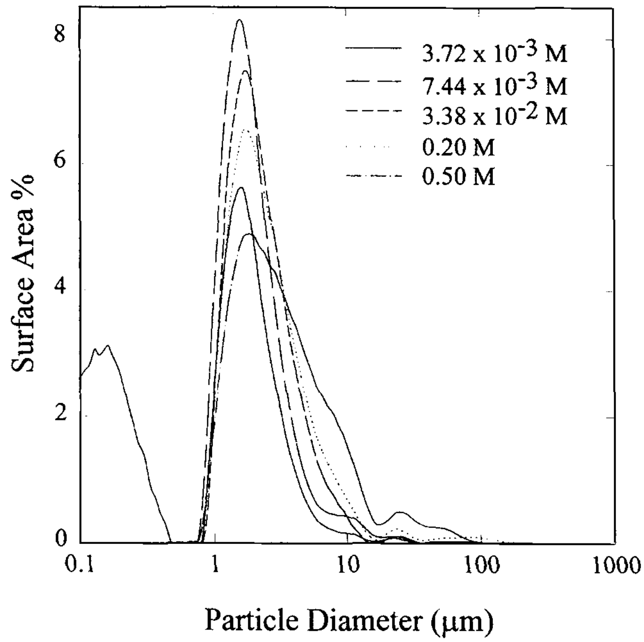

Figure 8. Particle size vs. the initial concentration of $CaCl_2$ for the controlled dispersed clay.

the settling data. In the shear tests from which ϕ_{max} is determined, improvements in particle packing efficiency, and thus rheology, due to the increased size of the clay aggregates at high ionic strength are offset by the increased attrition of these larger particles under shear. More importantly, the very high ionic strengths compress the double layer surrounding the aggregates, increasing the interaggregate attraction. It is at these higher values of [Ca^{2+}] that the benefits of the larger aggregate size on the rheology begin to be negated by the increased strength of attractive interaction. Settling properties, however, are minimally influenced by particle attrition effects and are best understood in terms of the increased aggregate size and interaggregate attraction being additive. As a result, the sediment solids volume fractions continue to increase with [Ca^{2+}], supporting the view of Kleijn and Oster (1982) that the size of tactoids or quasi crystals of Ca-montmorillonite would continue to increase with ionic strength if not limited by mechanical factors such as attrition by shear. The settling rates (de Kretser, 1995) show no tendency to plateau at higher ionic strength for the same reasons as discussed for ϕ_{sed}.

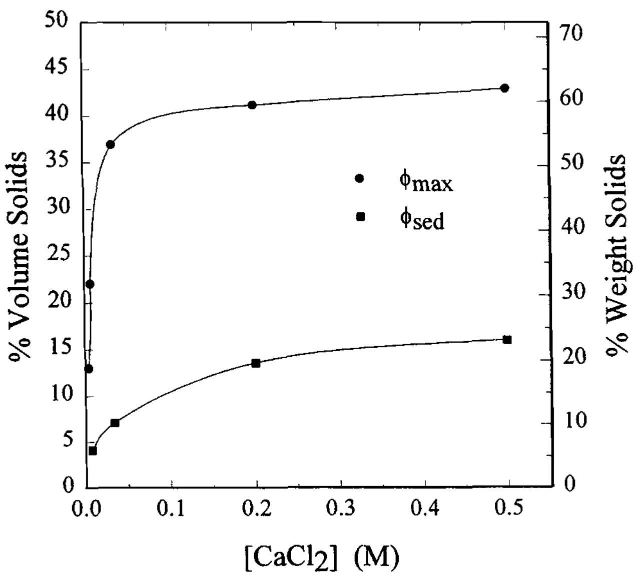

Figure 7. Effect of the initial concentration of $CaCl_2$ on both the maximum packing volume fraction (from rheological measurements) and the final sediment volume fraction solids for the controlled dispersed clay.

Particle sizes as a function of calcium concentration are presented in Figure 8. The data follow the trend of the yield-stress and sediment-solids concentration data precisely. Of note is that there is a significant sub-1-μm component of particles in the case of the incompletely exchanged clay, and that above the point where the ion exchange is complete, changes in the particle-size distribution occur at larger rather than smaller sizes.

Tests on the controlled dispersed simulated tailings

Figure 9 shows a comparison of the sedimentation behavior of the controlled dispersed simulated tailings with data for the thickener feed and underflow, presented as sediment height vs. time data. The controlled dispersion sample has a higher sedimentation rate and settles to a more concentrated sediment than either the thickener feed or underflow. The difference between the thickener feed and underflow can be attributed to the presence of flocculant in the underflow. Yet, while no flocculant is present in the controlled dispersion sample, its sedimentation rate is the greatest. The values for the initial sedimentation rate, u_i, were 0.991, 0.147 and 1.10 $\times 10^{-3}$ cm·min^{-1} for the controlled dispersed tailings and the thickener underflow and feed, respectively. The value of

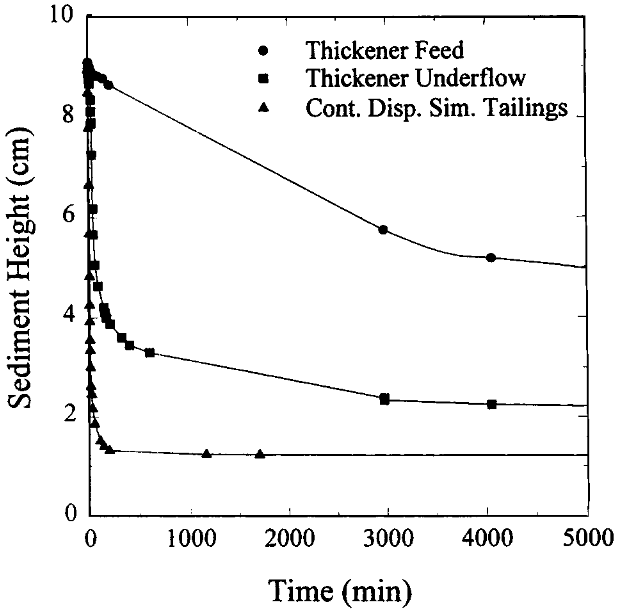

Figure 9. Sedimentation data for the thickener feed, thickener underflow, and controlled dispersed simulated tailings as a function of time.

The simulated tailings sample had the greatest clay content.

ϕ_{sed} for the controlled dispersed simulated tailings was 21.8 vol. % solids (36 wt. % solids), which is well above the levels of solids concentration currently being achieved at the mine. The origins of the improved settling properties of the simulated tailings lie in the large increases in average clay particle size obtained by limiting the initial swelling and breakup of the clay on wetting due to the dispersing electrolyte concentration of 0.5 M $CaCl_2$ (de Kretser and Boger, 1994).

Compression behavior of the controlled dispersed sample, the thickener underflow, and the thickener feed are compared in Figure 10; results for H_i, the initial depth of an 11.6 vol. % solids suspension required to produce the corresponding compressive force at the base of the sediment, are presented as the righthand axis. For a given compressive force or value of H_i, the resulting underflow concentration (at equilibrium) would be highest for the thickener underflow and controlled dispersed simulated tailings, which were identical in behavior within experimental error. The difference in the results for the thickener feed and underflow can again be attributed to the presence of flocculant in the system. That the controlled dispersed simulated tailings and the thickener underflow exhibited the same results is remarkable, given both the absence of flocculant and the higher clay content in the controlled dispersed case. Note that the results in Figure 10 indicate that for a 2-m-deep compression zone, an underflow concentration of around 35 vol. % solids (52 wt. %) could be expected at equilibrium. The fact that conventional thickeners are operated at nonequilibrium conditions will reduce the value of the underflow concentration expected for a given compressive force or value of H_i; however, a value of at least 25 vol. % solids is indicated. The results in Figure 10 also demonstrate the significant effect of small increases in the depth of the compression zone on the underflow concentration at values of H_i of less than 10 m.

Results for pumping-energy requirements for the pipeline transport of three fixed dry-weight amounts of controlled dispersed simulated tailings are presented in Figure 11. The plots are similar to Figure 1, exhibiting an optimal pumping-energy solids concentration. Energy requirements for the thickener underflow suspension at 1,500 tpd are also illustrated in Figure 11, and it can be seen that the controlled dispersed simulated tailings exhibit a higher optimal pumping-energy solids concentration. For the energy requirement of the present mine tailings-disposal conditions [around 100 W/m (de

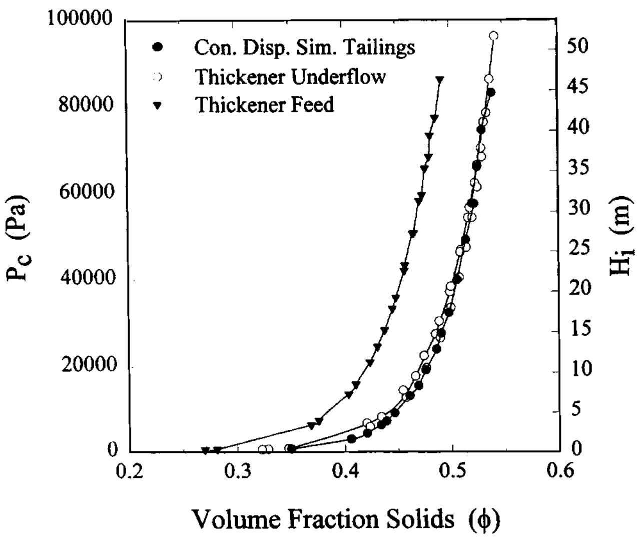

Figure 10. Comparison of compressive properties of controlled dispersed simulated tailings and thickener feed and underflow material.

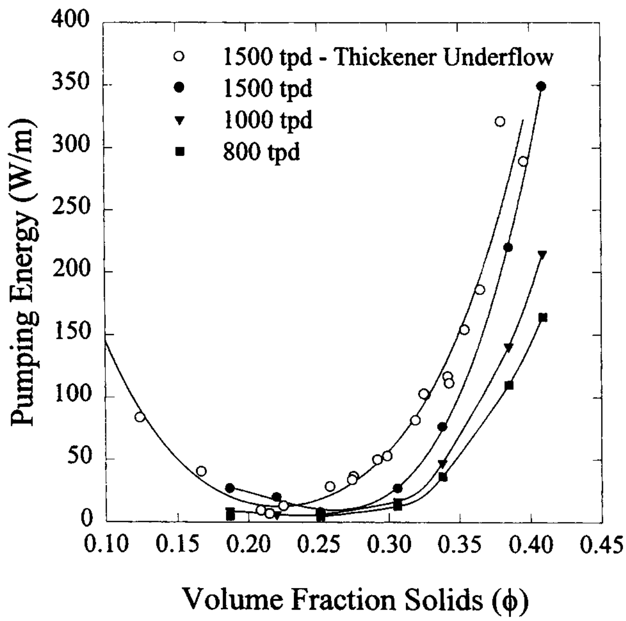

Figure 11. Pumping energy requirements vs. solids concentration for controlled dispersed simulated tailings for three dry solids throughputs.

Results are compared to a previous result from Figure 1 for the case of the thickener underflow.

Kretser and Boger, 1992)], a controlled dispersed simulated tailings suspension of between 35 and 37 vol. % solids (52–54 wt. %) could be pumped. As discussed previously, transportation of concentrated suspensions at low flow velocities has a number of advantages, and problems with sedimentation within the pipeline would not be encountered due to the presence of a yield stress in the suspension. A disposal method incorporating these pipeline energy considerations has already been developed by Alcoa of Australia Limited for the disposal of bauxite residue in Western Australia (Glenister and Abbott, 1989).

Conclusion

The implications of the results presented here are significant in terms of both the impact of the controlled dispersion effect and the general operating practices of tailings dewatering circuits. The controlled dispersed simulated tailings clearly have dewatering properties better than or equal to those of the thickener underflow sample, despite the lack of any flocculant. The ability of controlled dispersion to produce a rapidly settling tailings slurry with larger clay particles and reductions of the net solids surface area in suspension may negate the use, or at least significantly reduce the consumption, of polymeric flocculant, particularly as flocculant consumption is affected by the surface area available for adsorption. The practical application of the controlled dispersion effect would be through the maintenance of high electrolyte levels in the wash water, and ensuring that only high electrolyte concentration wash water was used in the initial wetting of the as-mined clay.

To this end, if as-mined coal is stockpiled for long periods of time prior to processing, as is often the case, spraying of a Ca^{2+} ion solution over the stockpile is recommended. Thus, processing difficulties due to the clay having initially been wet by rainwater (uncontrolled swelling) should be avoided. Furthermore, as clay from the sprayed stockpiles will then have already been ion-exchanged, the calcium requirement for the eventual processing of the tailings will be less, hence the procedure should not involve a large overall increase in Ca^{2+} consumption.

A more general point is that, given the rapid settling behavior of the controlled dispersed simulated tailings and the compression results for relatively small depths of compression zone in the thickener, substantially better performance in terms of dewatering level can be achieved through simply changing the operating practice of a conventional thickener. Pumping-energy results indicate that the higher solids concentration underflows produced should present no problems in terms of handleability, allowing efficient transportation to the disposal area.

In terms of economics, it is clear that to maintain a high electrolyte concentration in the wash water would require a larger consumption of $CaCl_2$. There are a number of factors that would more than balance this extra cost. Flocculant requirements will almost certainly be less, water recovery will be greater, and the rate of consumption of tailings storage space will be decreased. Furthermore, the overall processing rate of a washery is limited by the slowest step which, in the case of swelling-clay-based tailings, is the tailings dewatering step. Thus, an increased tailings processing rate will increase the overall productivity of the mine. All of this can be achieved with minimum capital expenditure and alterations to existing conventional dewatering operations.

It should be stressed that, at present, the postulated procedure has not been evaluated at full scale and it is possible that higher levels of corrosion of plant equipment would ensue. Despite this possibility, the results are promising in terms of both economic and practical considerations.

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