

## Parametric Modeling of Polymer-Assisted Slurry Sedimentation for Nickel Laterite Mining

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Received 15 March 2007; revised 12 October 2007; accepted 1 January 2008; published online 31 March 2008

**ABSTRACT.** The increasing world nickel demand coupled with depleting laterite reserves throughout the globe requires that metal extraction be extended to the entire ore body. To improve process throughput, the sedimentation behaviour of blended laterite slurries is modified in gravity thickeners using synthetic polymers. Based on  $2^4$  factorial design, ionic type, charge density, molecular weight, and dosage of polymers were varied in bench-scale sedimentation tests. An improvement of 20 times and a decrease of four times were observed in the  $k_i$  of the selected ore slurry. The corresponding  $e_f$  was found to range from 7.6 ( $s_f = 29.3\%$ ) to 10.8 ( $s_f = 22.7\%$ ). The sedimentation behaviour of polymer-modified slurries was found to obey linear  $k_i$  versus  $e_f$  relationships following direct proportionality for flocculation and inverse proportionality for dispersion. Test data were used in the analysis of variance (ANOVA) to develop a parametric model for predicting  $k_i$  ( $e_f$  obtained from the  $k_i$  versus  $e_f$  relationships) and deciphering the relative significance of the various polymer parameters on  $k_i$  variability. A new term, "parametric factor" ( $PF$ ) that combined the various polymer parameters, was defined and used to understand the complex colloid-water-polymer interactions. The significance of polymer parameters varied in the order  $C$ ,  $M$ ,  $T$ , and  $D$  and both the  $k_i$  and  $e_f$  were maximized for a  $PF = 2.25 \times 10^{-7}$  mol/L. The optimum polymer parameters for an improved sedimentation of the selected slurry were found to be  $T =$  cationic,  $C = 15\%$ ,  $M = 12 \times 10^6$  g/mol, and  $D = 4$  mg/L.

**Keywords:** parametric modeling, polymer modification, slurry sedimentation, nickel laterites, mining engineering, gravity thickeners, hydraulic conductivity, void ratio

### 1. Introduction

The increasing nickel demand coupled with depleting mine reserves throughout the globe necessitates that the pressure acid leach process of metal extraction be extended to the entire ore body (Georgio and Papangelakis, 1998). The sedimentation behaviour of blended laterite ore slurries (comprising of limonite through saprolite materials) governs the slurry throughput in the hydrometallurgical process. To improve the sedimentation rate and amount, synthetic polymers are added to the feed slurries in gravity thickeners (a cylindrical vessel with inverted conical base with or without a slow rotating rake mechanism). A high initial hydraulic conductivity ( $k_i$ ) during sedimentation and a low final void ratio ( $e_f$ ) at the end of sedimentation must be obtained simultaneously. Clearly, a sustainable (cost effective, environmentally friendly, and socially viable) ore beneficiation operation requires a fundamental understanding of the sedimentation behaviour of slurries amended with polymers.

Several engineering disciplines are concerned with the settling velocity ( $V_s$ ) of solids through liquids. In mass trans-

fer and hydrocarbon cracking, chemical engineers use the fluidization velocity for fluidizing solids with gases. This is the minimum velocity of the fluid phase required to keep the particles of a solid bed in suspension by upward flow (Richardson and Zaki, 1954). Despite being in the loosest possible state, the particles maintain a clear solid-liquid interface and their settling velocity is equal and opposite the fluidization velocity (Pane and Schiffman, 1997). Such hindered sedimentation conditions also exist in mine waste tailings and dredged coastal materials where soil particles do not transmit effective stresses and develop a spatial network that settles under self-weight (Been and Sills, 1981). For tailings management and onshore land reclamation, geotechnical engineers have traditionally used the settling velocity to determine  $k_i$  of the sedimenting slurries and to model the consolidation properties using the large strain theory. These engineering concepts can be applied to understand the dewatering behaviour of mine slurries during thickening.

Complex physicochemical phenomena, derived from ore geology and the metal extraction process, govern the sedimentation behaviour of slurries in a gravity thickener. This behaviour can be improved by agglomerating individual particles and/or particle groups to develop multi-particle flocs that can settle rapidly. The production of a slurry stream with superior dewatering properties by adding synthetic polymers requires the feed slurry to be at a low initial solids content ( $s_i$ ) thereby

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**Table 1.** Material Properties of the Selected Laterite Ore Slurry (Azam et al., 2005)

	Property	Value
Solid Chemistry	Minerals (%)	Goethite (50 ± 5); Hematite (20 ± 5); Maghemite (20 ± 5); Chrysotile (10 ± 5)
	Cation Exchange Capacity, CEC (cmol(+)/kg)	7.6
Water Chemistry	Anion Exchange Capacity, AEC (cmol(-)/kg)	6.8
	pH	7.2
	Electrical Conductivity, EC (µS/cm)	744.0
	Dissolved Ions (mg/L)	Na <sup>+</sup> (17.0); K <sup>+</sup> (1.1); Ca <sup>2+</sup> (19.5); Mg <sup>2+</sup> (87.0); Cl <sup>-</sup> (28.4); NO <sub>3</sub> <sup>-</sup> (1.3); HCO <sub>3</sub> <sup>-</sup> (24); SO <sub>4</sub> <sup>2-</sup> (386.0)
Index Properties	Specific Gravity, G <sub>s</sub>	3.15
	-0.075 mm (%)	93.0
	-0.002 mm (%)	35.0

maximizing colloid-water-polymer interactions (Azam, 2004). To design an efficient process that achieves a high sedimentation rate and amount in the thickener requires the screening of a number of polymers in bench-scale sedimentation tests. This allows the selection of appropriate polymers for a given slurry composition; solid particles (size distribution, mineralogical composition, and surface charges) and liquid medium (pH, electrical conductivity, and ion concentration).

The main objective of this paper was to understand and improve the sedimentation behaviour of laterite ore slurries. Initially, a blended slurry from an operating mine in the Philippines was selected and its engineering properties determined. This base-case slurry was modified using synthetic polymers of the polyacrylamide (PAA) type. Based on a 2<sup>4</sup> factorial design, the ionic type (*T*), charge density (*C*), molecular weight (*M*), and dosage (*D*) of the polymers were varied in bench-scale sedimentation tests. These test data were used in the analysis of variance (ANOVA) to develop a parametric model for predicting *k<sub>i</sub>* and deciphering the relative significance of the various polymer parameters on *k<sub>i</sub>* variability. A new term, parametric factor (*PF*) that combined the various polymer parameters, was defined and used to understand the complex colloid-water-polymer interactions.

## 2. Research Methodology

### 2.1. Material Composition

Table 1 summarizes the material properties of the selected laterite ore slurry provided by the Metallurgical Technologies Division of Dynatec Corporation, Canada. The solids of the slurry primarily consisted of heavy iron oxides (goethite, hematite, and maghemite) and chrysotile clay minerals, all of which cumulatively resulted in a specific gravity (*G<sub>s</sub>*) of 3.15. The exchange capacities corresponded to the mineralogy of the solids and indicated that the latter can be flocculated with both anionic and cationic polymers. The fine grained solids together with the near neutral water and the low dissolved ions were expected to provide favorable conditions for effective colloid-water-polymer interactions (Farinato et al., 1999).

The PAA-based polymers (provided by Ciba Specialty Chemicals Inc., Canada) were produced from repeated mo-

nomers (the basic building block), that is, (CH<sub>2</sub>-CH) to which amide (CONH<sub>2</sub>) is attached as a functional group. Two types of polymers were used, namely: (i) anionic, in which the amide group was substituted with a sodium acrylate (COONa) molecule; and (ii) cationic, in which Dimethylaminoethylacrylate methyl chloride [COOC<sub>2</sub>H<sub>4</sub>N(CH<sub>3</sub>)<sub>2</sub>Cl] replaced the amide group. In both cases, the macroions possessed formal polymer charges whereas the associated counterions (Na<sup>+</sup> and Cl<sup>-</sup>, respectively) ensured overall charge neutrality.

**Table 2.** Summary of Polymer Parameters

Type	C (%)	M × 10 <sup>6</sup> (g/mol)	D (mg/L)	PF × 10 <sup>-7</sup> (mol/L)
Anionic (- 1)	15	5	4	- 5.33
			12	- 16.0
	40	5	4	- 1.78
			12	- 5.33
			4	- 2.0
			12	- 6.0
Cationic (+ 1)	20	4	4	+ 5.0
			12	+ 15.0
	60	4	4	+ 1.67
			12	+ 5.0
			4	+ 1.67
			12	+ 5.0
	12	4	4	+ 0.56
			12	+ 1.67

Based on a 2<sup>4</sup> factorial design of experiment, *T*, *C*, *M*, and *D* were tested at two levels. Table 2 summarizes the various polymer parameters used in this study. The anionic polymers were negatively charged and the cationic polymers were positively charged. The average values of *C* and *M* pertained to industrial specifications whereas the polymer dosages of 4 mg/L (53 g/ton) and 12 mg/L (159 g/ton) were obtained from experience with similar slurries. The values of *D* were based on dry mass of polymer and solids in the slurry.

## 2.2. Laboratory Data Collection

The laboratory data was collected from the bench-scale sedimentation test on the laterite ore slurry modified with polymers; the slurry without polymers was also tested as a base case. The tests were performed in small graduated jars (internal diameters of 8.5 and 9.5 cm) due to the limited amount of available material. To facilitate visual observation of the fast moving interface through an opaque fluid, the initial sample heights were kept as 8.5 and 9.5 cm, respectively. The resulting height to diameter ratio of 1.0 at the test start minimized wall effects. To mimic process conditions and facilitate easy comparison, the initial solids content was kept at 15% that ensured negligible segregation (Azam, 2003). Based on consultations with the chemical and mining industry, the 15% initial solids content was the concentration at which interactions between the colloids of the laterite ore slurry and the pore water are at a maximum.

The slurry sample was poured into the graduated jars and was allowed to settle under gravity. The solid-liquid interface movement was captured at regular time intervals using a camcorder with macro lenses for up to 7 times image magnification. The camcorder was connected to a computer that stored the captured frames in a digital format. After test completion, the enlarged digital frame files were carefully viewed and the observed data were recorded as interface height versus time. The sedimentation test data was converted to solids content-time and void ratio-time plots. Both solids content and void ratio were calculated from volume changes of the sedimenting slurries.

The slope of the initial straight-line portion of the sedimentation curve was used to determine  $k_i$  using the Pane and Schiffman (1997) formulation. From the settling velocity of the solid-liquid interface, the initial void ratio ( $e_i$ ), and the unit weights of soil solids ( $\gamma_s$ ) and of the water ( $\gamma_w$ ),  $k_i$  was determined according to the following simplified equation:

$$k_i = \frac{\gamma_w V_s (1 + e_i)}{\gamma_s - \gamma_w} \quad (1)$$

A fresh concentrated stock solution was prepared for each test by dissolving the polymers in deionized water. To avoid polymer aging, this solution was instantly diluted to a test solution and immediately used. The stock solution was prepared by weighing 0.5 g of dry powdered polymer in a clean dry 250 mL beaker. Then, 1 mL of methanol (for anionic polymers) or acetone (for cationic polymers) was added as the powder was swirled for an even distribution. Next, 99 mL of water was added and a magnetic stirrer rod was immersed in the beaker. The beaker containing all of the above ingredients was put on a stirring machine for 60 minutes at a moderate speed of 12 rpm. Finally, the stock solution was diluted to 0.05% test solution for dosing by adding 10 mL of the former to 90 mL of water. Thus, 1 mL of the test solution contained 0.5 mg of dry polymer. When divided by the total volume of the slurry (L), this gave the amount of 1 mL of test solution in the slurry in mg/L. To get the vo-

lume of polymer dosage (in mL), the desired amount in mg/L of the slurry was divided by the amount of dry polymer in 1 mL of the test solution.

Test samples were prepared by mixing the required dosage from the test solution with the known volume of the slurry at 15% initial solids concentration (by weight). The desired polymer volume was introduced to the slurry sample using a graduated plastic syringe. To minimize floc breakage, ingredients were mixed using a steel plunger that was rotated at a rate of 12 rpm for 5 minutes.

## 2.3. Parametric Modeling

The ANOVA was conducted using the input values of the polymer parameters ( $T$ ,  $C$ ,  $M$ , and  $D$ ) given in Table 2. The resulting parametric model predicted the initial hydraulic conductivity and quantitatively determined the relative significance of the various polymer parameters on the variability of  $k_i$ . The analysis was conducted using MINITAB (Release 15.0). As discussed later in this paper, the final void ratio could be determined from knowledge of  $k_i$ .

The four polymer parameters were combined in a single term called as the parametric factor ( $PF$ ) according to the following equation:

$$PF \text{ (mol/L)} = (T \times D) / (C \times M) \quad (2)$$

The polymer factor (mol/L) represented the number (given by dosage) of polymer chains of a certain ionic nature (negative for anionic polymers and positive for cationic polymers), charge density, and molecular weight present in the slurry. Both  $k_i$  and  $e_f$  were separately plotted versus the polymer factor to understand the complex colloid-water-polymer interactions.

## 3. Laboratory Test Results

### 3.1. Base Case Slurry

Figure 1 depicts the bench-scale sedimentation test results for the laterite ore slurry without polymers. The interface height (a), solids content (b), and void ratio (c) are plotted versus the elapsed time on semi-logarithmic scales. The interface height-time curves were characterized by two regimes of change in interface height: (i) an initial rapid decrease under hindered sedimentation and (ii) a slowly diminishing decrease during self-weight consolidation. Hindered sedimentation refers to the settling of a spatial network of soil particles without measurable effective stresses (McRoberts and Nixon, 1976) whereas consolidation is that stage in the settling process in which the solid grains transmit effective stresses (Terzaghi et al., 1996). The two regimes smoothly transitioned as represented by the middle straight-line portion of the curves. Further, each of the solids content and the void ratio data set for the two tests (8.5 and 9.5 cm jar) collapsed onto a single curve. This confirmed that the sedimentation behaviour of the selected slurry was effectively determined by the test method.

Figure 2 plots the interface height for the first 30 mi-

minutes of the bench-scale sedimentation tests on a linear time scale. Both samples of the laterite ore slurry indicated the commencement of transition by exhibiting an upward departure from the initial straight-line portion of the sedimentation curves. The average settling velocity determined from this figure was 0.1436 cm/min. The  $k_i$  of the selected laterite ore slurry measured  $21 \times 10^{-3}$  cm/sec whereas the final solids content ( $s_f$ ) and the final void ratio at the completion of the test (after 1440 minutes) were 27% and 8.5, respectively. The relatively low sedimentation rate and amount of such heavy materials was required to be improved using polymers.

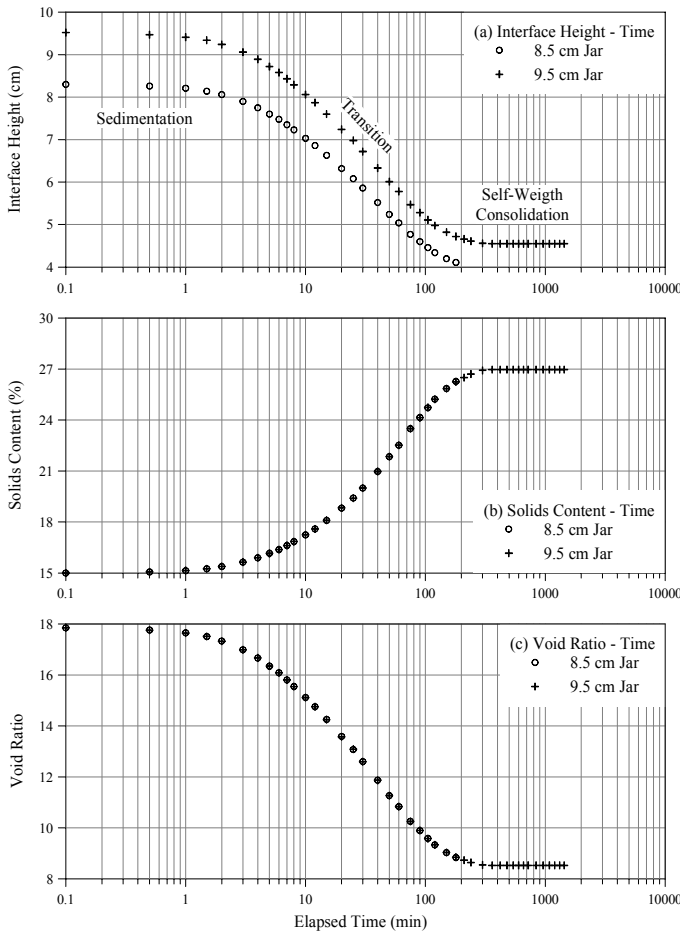


Figure 1. Bench-scale sedimentation test results for the laterite ore slurry.

### 3.2. Polymer-amended Slurry

Tables 3 and 4 summarize the bench-scale sedimentation test results in 8.5 cm and 9.5 cm jars, respectively. A comparison of these data with the base case reveals that polymer addition changed the initial hydraulic conductivity and the final void ratio of the ore slurry to different extents. A  $k_i$  improvement of about 20 times and a decrease of four times were observed. Likewise, the  $e_f$  was between 7.6 ( $s_f = 29.3\%$ ) and 10.8 ( $s_f = 22.7\%$ ). This wide range in the sedimentation

behaviour is attributed to the variable colloid-water-polymer interactions (Muthukumar, 1999).

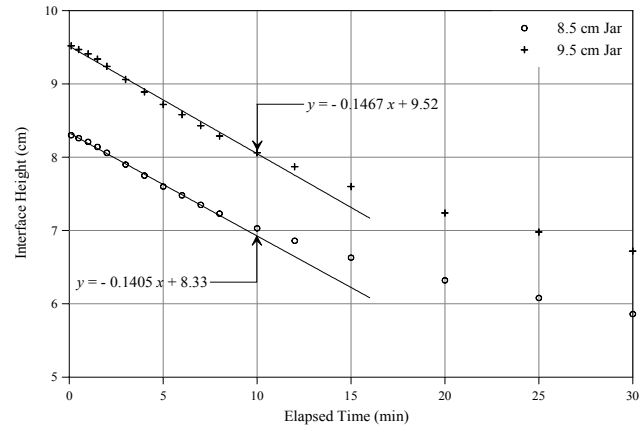


Figure 2. Interface height-time for the first 30 minutes of the bench-scale sedimentation test.

The  $k_i$  values depicted in Tables 3 and 4 indicate that the sedimentation tests were generally repeatable. The difference between the two data sets (using 8.5 and 9.5 cm jar) on the same materials was more pronounced at high initial hydraulic conductivity. This is attributed to the limited number of available data points in the initial straight-line part of the sedimentation curves for the fast moving slurries. The associated observational error can be minimized by using automated digital sensors during the bench-scale sedimentation testing (Azam, 2004).

The main source of repeatable experimental error in the determination of the initial hydraulic conductivity was polymer addition and mixing with the sedimenting slurry. The resulting turbidity and eddies offered difficulty in deciphering the solid-liquid interface movement, especially in the initial stages of the test. In the absence of a distinct interface, observational bias marginally contributed in overestimating the rate of sedimentation. The bias associated with such systematic errors can be minimized by conducting the test similar to the acid leach metal extraction process, that is, adding the polymers with the slurry stream prior to sedimentation (Xu and Hamza, 2003).

Figure 3 plots the initial hydraulic conductivity versus the final void ratio at the end of the bench-scale sedimentation tests. The sedimentation behaviour of the slurry modified with synthetic polymers is distinctly divided into two categories according to the predominant type of colloid-water-polymer interaction. When the slurry was flocculated, an increase in  $k_i$  was associated with an increase in  $e_f$ . The large flocs settled quickly during sedimentation but did not release the entrapped water under self-weight consolidation (Plewes et al., 2004). On the contrary, a  $k_i$  decrease resulted in an increase in the final void ratio for slurry dispersion. The ultra-fine solid particles settled slowly during sedimentation and the polymers caused interference in releasing the pore water under self-weight consolidation (Mpofu et al., 2004). These observations are based on ex-

**Table 3.** Bench-Scale Sedimentation Test Results in 8.5 cm Jars for 180 Minute Test Duration

Type	Polymer Parameters			Initial Test Conditions			During Testing		Final Test Conditions		
	$C$ (%)	$M \times 10^6$ (g/mol)	$D$ (mg/L)	$H_i$ (cm)	$s_i$ (%)	$e_i$	$V_s$ (cm/m)	$k_i \times 10^{-3}$ (cm/s)	$H_f$ (cm)	$s_f$ (%)	$e_f$
Anionic (-1)	15	5	4	8.5	15.0	17.9	0.050	7.3	5.0	23.2	10.5
			12	8.5	15.1	17.8	0.100	14.5	4.4	25.7	9.2
	15	4	4	8.5	15.0	17.9	0.600	87.5	3.8	28.3	8.0
			12	8.5	15.1	17.8	0.675	97.8	3.8	28.7	7.9
	40	5	4	8.5	14.9	18.1	1.600	235.2	4.0	27.0	8.5
			12	8.5	15.1	17.8	2.700	391.0	4.1	26.9	8.6
15	4	4	8.5	15.0	17.9	1.800	262.6	4.1	26.9	8.6	
		12	8.5	15.1	17.8	2.550	369.3	4.3	26.0	9.0	
Cationic (+1)	20	4	4	8.5	15.1	17.8	0.073	10.6	4.5	25.1	9.4
			12	8.5	15.2	17.6	0.094	13.5	4.1	27.0	8.6
	12	4	4	8.5	14.9	18.1	2.800	411.6	3.7	29.0	7.8
			12	8.5	15.1	17.8	0.031	4.5	5.2	22.7	10.8
	60	4	4	8.5	15.2	17.6	0.049	7.0	4.6	24.9	9.5
			12	8.5	15.1	17.8	1.350	195.5	4.1	26.9	8.6
12	4	4	8.5	15.0	17.9	1.225	178.7	4.0	27.3	8.4	
		12	8.5	15.0	17.9	2.700	394.0	4.3	25.7	9.1	

**Table 4.** Bench-Scale Sedimentation Test Results in 9.5 cm Jars for 1440 Minute Test Duration

Type	Polymer Parameters			Initial Test Conditions			During Testing		Final Test Conditions		
	$C$ (%)	$M \times 10^6$ (g/mol)	$D$ (mg/L)	$H_i$ (cm)	$s_i$ (%)	$e_i$	$V_s$ (cm/m)	$k_i \times 10^{-3}$ (cm/s)	$H_f$ (cm)	$s_f$ (%)	$e_f$
Anionic (-1)	15	5	4	9.5	15.1	17.8	0.050	7.2	5.2	24.4	9.8
			12	9.6	15.2	17.6	0.100	14.4	4.8	26.4	8.8
	15	4	4	9.6	15.0	17.9	0.585	85.4	4.3	28.3	8.0
			12	9.6	15.1	17.8	0.700	101.4	4.2	29.2	7.7
	40	5	4	9.6	15.0	17.9	1.600	233.5	4.5	27.4	8.4
			12	9.5	15.1	17.8	2.900	420.0	4.5	27.3	8.4
15	4	4	9.5	14.9	18.1	2.000	294.0	4.5	27.0	8.6	
		12	9.5	15.0	17.9	2.800	408.5	4.8	25.9	9.1	
Cationic (+1)	20	4	4	9.5	15.1	17.8	0.082	11.9	4.7	26.7	8.7
			12	9.5	15.1	17.8	0.094	13.6	4.5	27.3	8.4
	12	4	4	9.5	14.8	18.2	3.050	451.6	4.2	28.5	8.0
			12	9.5	15.1	17.8	0.034	4.9	5.6	23.3	10.4
	60	4	4	9.5	15.1	17.8	0.054	7.8	5.1	25.1	9.4
			12	9.5	15.0	17.9	1.400	204.3	4.5	27.2	8.4
12	4	4	9.5	15.0	17.9	1.250	182.4	4.1	29.3	7.6	
		12	9.5	15.1	17.8	3.000	434.5	4.9	25.8	9.1	

tensive annotations during testing.

#### 4. Parametric modeling

To predict the initial hydraulic conductivity during sedimentation and decipher the relative significance of polymer parameters on  $k_i$  variability, a parametric model was developed using multiple linear regression. The model equation is given as follows:

$$k_i = -134.3 - 31.9 T + 4.6 C + 12.7 M + 4.8 D \quad (3)$$

The ranges of polymer parameters for which the model can predict the initial hydraulic conductivity are as follows:  $T$ , -1 to +1;  $C$ , 15% to 60%;  $M$ ,  $4 \times 10^6$  g/mol to  $15 \times 10^6$  g/mol; and  $D$ , 4 mg/L to 12 mg/L.

Table 5 gives the summary statistics for the developed parametric model. The coefficient of determination ( $R^2 = 0.38$ ) implied that the model described 38% variability in  $k_i$ . An adjusted value ( $R^2_{\text{adj}} = 0.29$ ) should be considered more reliable since it does not increase automatically as new regressors are inserted into the model. The significance  $F$  of 0.01 indicated that the model can be described as "significant".

Figure 4 plots the measured  $k_i$  versus the predicted  $k_i$  for the ore slurry amended with polymers. The discrepancy in the predicted and the observed initial hydraulic conductivity values is primarily attributed to the limited amount of test data available for the development of the model. The observational and systematic errors (described earlier) associated with the bench-scale sedimentation test may have resulted in some data scatter. Nevertheless, Figure 4 illustrates a reasonable correlation between the observed and the estimated  $k_i$  values for the available data set. The distinct  $k_i$  versus  $e_f$  relationships for flocculation and dispersion (given in Figure 3) can be used in conjunction with the model equation (3) to predict  $e_f$  for a slurry after complete sedimentation.

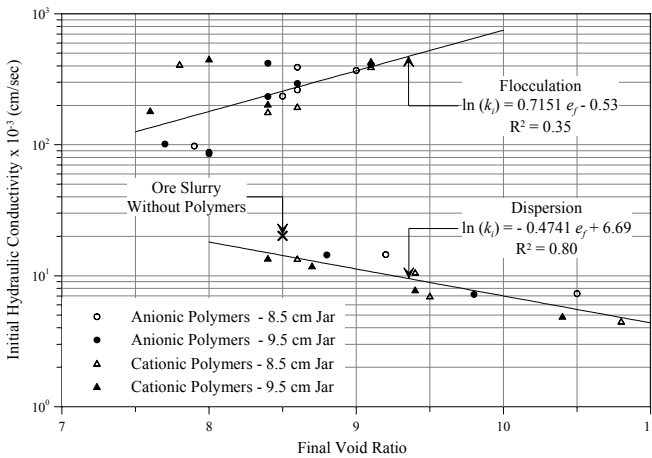


Figure 3. Initial hydraulic conductivity versus final void ratio.

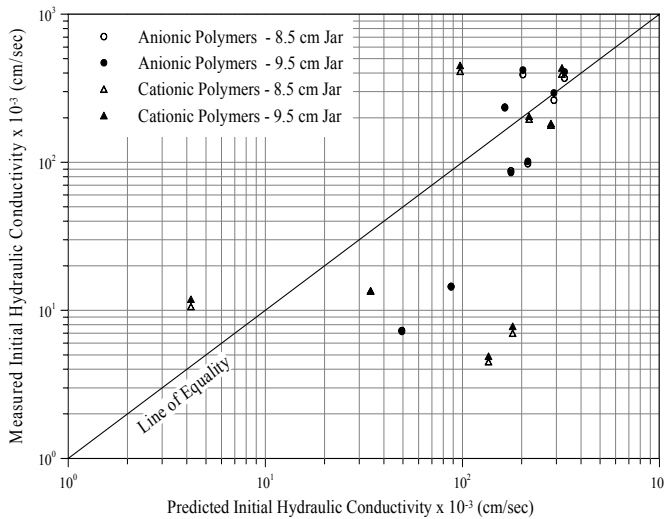


Figure 4. Measured and predicted initial hydraulic conductivity.

Table 6 gives the summary statistics for the polymer parameters. The analysis of variance results showed that the most significant factor affecting the initial hydraulic conductivity of the polymer-modified laterite slurry was charge density (p-

value of 0.04) followed by molecular weight (p-value of 0.027). The analysis further confirmed that the ionic type of the polymer was not a major factor (p-value of 0.242) during slurry sedimentation. For the investigated range of 4 mg/L to 12 mg/L, polymer dosage was found to be the least significant factor (p-value of 0.445).

The polymer parameters ( $T$ ,  $C$ ,  $M$ , and  $D$ ) governed the initial hydraulic conductivity of the selected ore slurry modified with synthetic polymers. Figures 5 and 6 give the initial hydraulic conductivity and final void ratio as a function of the parametric factor, respectively. Both  $k_i$  and  $e_f$  were found to increase with an increase in  $PF$  during flocculation whereas a reverse behaviour was observed during dispersion. Further, the figures indicate that both the initial hydraulic conductivity and final void ratio of the ore slurry were maximized for a  $PF = \pm 2.25 \times 10^{-7}$  mol/L. When examined in conjunction with Figure 3 and Tables 3 and 4, the polymer parameters yielding the optimum sedimentation rate and amount were chosen. The corresponding polymer parameters were found to be  $T =$  cationic,  $C = 15\%$ ,  $M = 12 \times 10^6$  g/mol, and  $D = 4$  mg/L. These polymer parameters are useful in improving the sedimentation behaviour of the selected laterite ore slurry only. Variations may occur when the composition of the solid and/or the liquid phases of the slurry are changed.

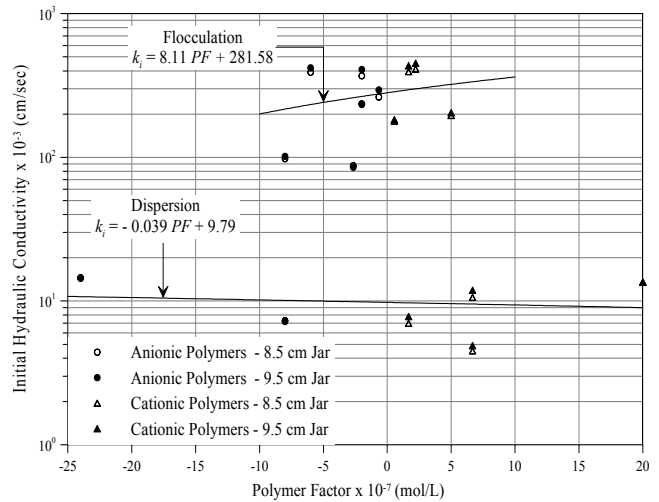


Figure 5. Initial hydraulic conductivity versus the parametric factor.

## 5. Analysis and Discussion

The sedimentation behaviour was found to be resulting from either dispersion or flocculation. These distinct phenomena are analyzed by understanding physicochemical interactions of individual polymer parameters with the investigated laterite slurry. The composition of the solid and the liquid phases of the slurry (Table 1) allowed colloid-water interactions with both anionic and cationic polymers thereby making polymer type a relatively insignificant parameter.

The ionic nature of a polymer affects the chain dimension in the slurry, with intramolecular charge repulsions tend-

**Table 5.** Summary Statistics for the Parametric Model

Source	DF	SS	MS	F	Significance F	R <sup>2</sup>	R <sup>2</sup> <sub>adj</sub>	Standard Error
Regression	4	314692	78673	4.11	0.01	0.38	0.29	138.38
Residual	27	517059	19150					
Total	31	831751						

Note: DF – Degree of freedom; SS – Sum of squares; MS – Mean sum of squares; F – F-test value

**Table 6.** Summary Statistics of Polymer Parameters

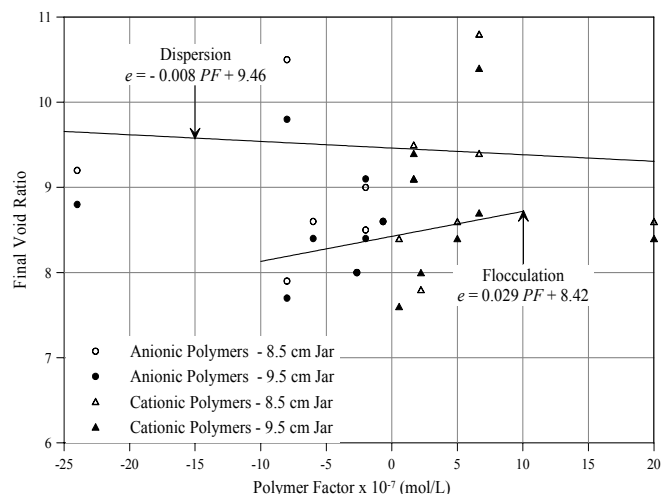
Predictor	Coefficients	Standard Error	t Ratio	p Value	Lower 95%	Upper 95%
Intercept	-134.2	88.36	-1.52	0.140	-315.6	47.0
T	-31.9	26.68	-1.20	0.242	-86.7	22.8
C	4.6	1.47	3.15	0.004	1.6	7.6
M	12.7	5.40	2.34	0.027	1.6	23.8
D	4.8	6.12	0.78	0.445	-7.8	17.3

ing to increase the adsorbed coil size (Farinato et al., 1999). The charge bearing moieties in anionic polymers were oxygen based whereas those in cationic polymers were nitrogen based. In both cases, these moieties helped the macroions to remain fully ionized over large pH ranges (Sworska et al., 2000). In a near-neutral liquid medium, the negatively charged anionic polymers were attracted to the positively charged iron oxide surfaces whereas the positively charged cationic polymers were attracted to the negatively charged clay surfaces (Azam, 2003). These interactions resulted in effective flocculation and, in turn, improved both the rate and amount of sedimentation. These observations are in accordance with experimental data presented by Yu and Somasundaran (1995) who reported that settling rates for flocculated slurries are maximized at the isoelectric point (pH at which the medium is essentially inert). Conversely, electrostatic repulsion between similar charges onto colloidal surfaces and the functional groups of the polymers led to slurry dispersion.

The charge density of a polymer refers to the number of unsatisfied charges on the polymer chain. During flocculation, a synthetic polymer with high *C* resulted in a stronger overall bond between the polymer and the colloid because the polymer could get attached to a single colloid at multiple points along its length (Hogg, 1999). Likewise, a single high *C* polymer was able to get bonded to a number of colloidal particles thereby increasing the floc size. The same high *C* was responsible for holding the large size flocs intact. Conversely, strong bonds and large floc sizes were not formed when low *C* polymers were added to the ore slurry (Besra et al., 2006). During dispersion, a high *C* polymer resulted in greater electrostatic repulsion and the reverse was true for low *C* polymers. Therefore, the polymer charge density governed the floc size and was the most significant factor affecting the initial hydraulic conductivity.

The molecular weight pertains to the total chain length of a synthetic polymer made up of an assemblage of a large number of monomers. The actual dimensions of ionic polymers in a slurry of known composition increase with charge density as high intra-molecular charge repulsions of the polymer chain tend to unfold the solvated coils (Masahiro and

Masataka, 2000). The contribution of polymer molecular weight depends on charge density and is considered to be embedded in the later. Therefore, *M* was the second most significant polymer parameter influencing the *k<sub>i</sub>* of the investigated polymer-modified slurry.

**Figure 6.** Final void ratio versus the parametric factor.

The term polymer dosage was used to quantify the amount of polymer added to the selected ore slurry as the actual amount of polymer adsorbed onto the colloidal surfaces could not be determined. The bench-scale sedimentation tests were conducted using the limiting values of the range of dosages (4 mg/L and 12 mg/L) but an optimum dosage for each combination of *C* and *M* was not determined. The marginal effect of *D* on the variability of *k<sub>i</sub>* is embedded in the significance of *C* and *M*. Additional data using several intermediate values of dosage (such as those reported by Yu and Somasundaran, 1995) are required to explain the variability of *k<sub>i</sub>* with respect to the amount of adsorbed polymer.

The microstructure of colloidal slurries depends on the type of adsorbed conformation of the polymer chains. At low

dosages, each polymer chain is grafted onto a colloid by one segment leading to a *mushroom* conformation. This is because of electrostatic repulsion between the colloid and the polymer and results in dispersion. Conversely, the chains overlap and stretch out perpendicular to the colloid at high dosages thereby adopting the *brush* conformation. The resulting flocculation mechanism is known as *charge-patching* in which more than one polymer chain is attached to the same colloid. An optimum dosage is one at which the polymer chain is flat enough to be bonded to a colloid at more than one points. The polymer chain at the optimum dosage assumes a *pancake* conformation. This polymer configuration results in a flocculation mechanism that is called as *bridging*. Here, each polymer chain is attached to more than one colloid but still precludes chain interference. The polymer conformations and the associated flocculation/dispersion phenomena depend on intricate relationship between the various polymer parameters (Hogg, 1999).

## 6. Summary and conclusions

Sustainable ore beneficiation operations require a fundamental understanding of the sedimentation behaviour of polymer-amended mine slurries. Parametric modeling of polymer-assisted sedimentation was conducted using a blended laterite slurry. Based on a  $2^4$  factorial design, the ionic type, charge density, molecular weight, and dosage of polymers were varied in bench-scale sedimentation tests: initial hydraulic conductivity and final void ratio were the output parameters. The main conclusions of this study can be summarized as follows:

The  $k_i$  of the ore slurry measured  $21 \times 10^{-3}$  cm/s whereas the  $s_f$  and  $e_f$  were 27% and 8.5, respectively. Polymer addition both improved and deteriorated the sedimentation behaviour. A 20 times improvement and a four times decrease were observed in the  $k_i$  of the ore slurry. The corresponding  $e_f$  was found to range from 7.6 ( $s_f = 29.3\%$ ) to 10.8 ( $s_f = 22.7\%$ ).

The sedimentation behaviour of the polymer-modified slurry was found to obey linear  $k_i$  versus  $e_f$  relationships following direct proportionality for flocculation and inverse proportionality for dispersion. Flocculation resulted in fast settling of the large flocs whereas dispersion led to the slow movement of ultra-fine particles under gravity.

Polymer parameters affected slurry sedimentation in the order  $C$ ,  $M$ ,  $T$ , and  $D$  as given by their p-values of 0.004, 0.027, 0.242, and 0.445, respectively. The new term, "parametric factor" effectively captured the complex colloid-water-polymer interactions of the investigated slurry; both  $k_i$  and  $e_f$  were maximized for a  $PF = \pm 2.25 \times 10^{-7}$  mol/L.

The model directly predicted  $k_i$  whereas  $e_f$  was obtained from  $k_i$  versus  $e_f$  relationships. The model parameters ranged as follows:  $T$ , -1 to +1;  $C$ , 15 to 60%;  $M$ , 4 to  $15 \times 10^6$  g/mol; and  $D$ , 4 to 12 mg/L. The optimum polymer parameters for sedimentation of the selected ore slurry were found to be  $T =$  cationic,  $C = 15\%$ ,  $M = 12 \times 10^6$  g/mol, and  $D = 4$  mg/L.

**Acknowledgments.** The author acknowledges the material support

extended by the industrial collaborators. Thanks to the University of Regina for providing laboratory space and computing facilities.

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