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Polymer Aids for Settling and Filtration of Oil Sands Tailings

by

Xiaoyan Wang

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Examining Committee

Jacob H. Masliyah, Chemical and Materials Engineering

Zhenghe Xu, Chemical and Materials Engineering

Yang Liu, Civil and Environmental Engineering

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Abstract

Commercial Magnafloc 1011 and in-house synthesized Al-PAM were used as flocculants for treating model tailings, laboratory extraction tailings and tailings from paraffinic froth treatment unit. The polymers were tested for their ability for flocculation of tailings in settling and filtration.

For model tailings, both polymers showed excellent ability to improve the settling and filtration performance. Magnafloc 1011 is found more sensitive to overdosing than Al-PAM within the tested range.

For the laboratory extraction tailings, both polymers showed excellent ability to enhance settling. Al-PAM performed very well as a filtration aid. The moisture of the cake obtained from tailings derived from a low fines ore was 6.6 ± 1.2 wt% and that from a high fines ore was 16.9 ± 0.8 wt%. However, Magnafloc 1011 was found not effective as a filtration aid.

For the froth treatment tailings, Al-PAM improved the settling and filterability dramatically. Although the moisture of the cake obtained was 42.5 wt%, no free water is seen visually in the cake. The solid cake is self-supportive and remains intact.

This class of Al-PAM polymers can provide an alternative approach for oil sands tailings disposal that can potentially eliminate tailings ponds.

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Chapter 1 Introduction

Oil sands tailings are aqueous suspensions of coarse sands, fine solids and clays with some fugitive residual bitumen at pH between 8 and 9. They are the reject stream after bitumen extraction from the oil sands ores. As in many other resource processing industries, the reject stream is fed to large tailings ponds for storage and water recycle. In the tailings ponds, the coarse sands settle quickly when deposited, while much of the fine solids and residual bitumen remain suspended, leading to the formation of mature fine tailings (MFT) containing typically 30 wt% of solids after two to three years of settling. Further consolidation of MFT without treatment would take hundreds of years [1]. At present, MFT is being gradually processed using consolidated tailings technology (CT) through the addition of gypsum. Meanwhile, the surface mining oil sands industries are testing several alternatives to consume the fluid mature fine tailings into a trafficable deposit which can eventually be reclaimed, while a maximal amount of process-affected water can be recycled. Unfortunately the inventory of fluid mature fine tailings contained in the tailings ponds continues to grow rapidly until the new technologies are implemented. There are growing concerns regarding the accumulation of fluid fine tailings and the impact of tailings accumulation on resource conservation and reclamation risks.

According to the recently released ERCB Directive 074 [2], the appropriate tailings management objectives for oil sands mines should be to: *(1) minimize and eventually eliminate long-term storage of fluid tailings in the reclamation landscape; (2) create a trafficable landscape at the earliest opportunity to facilitate progressive reclamation; (3) eliminate or reduce containment of fluid fine tailings in an external tailings disposal area during operations; (4) maximize intermediate process water recycle to increase energy efficiency and reduce fresh water import*; *(5) minimize resource sterilization associated with tailings ponds; and (6) ensure that the liability for tailings is managed through reclamation of tailings ponds.*

Although CT has been applied commercially for more than ten years, the operators are yet to produce effective CT mixture and transform CT ponds into trafficable deposits. In the CT process, MFT is dredged from the tailings ponds and combined with cycloned coarse solids from the bitumen extraction plant together with gypsum as a flocculant. The mixture is pumped to the ponds and water is released over a short period of time, leaving behind a sediment at about 80 wt% solids if process and deposition conditions are all on-spec. The CT ponds need further reclamation to transform them into reclaimed areas. Alternative tailings treatment technologies to improve the transformation of fluid fine tailings into a trafficable deposit remain to be developed [3].

Filtration is an effective method to separate solids from solid-liquid suspensions into a trafficable deposits and is widely used in the mineral processing industry. If oil sands tailings can be effectively filtered, then warm water can be recycled immediately back to the bitumen processing plant and the storage of process-affected water would be minimized. With effective filtration operation, large tailings ponds can be eliminated and a self-supported, trafficable deposit can be created at the same time of operation. Therefore, filtration technology would be a technology that perhaps has the potential to meet the tailings management objectives.

There are only few open literature publications dealing with filtration of whole extraction tailings. In early 1980s, a patent was issued using lime as a process aid to cause fine solids to agglomerate with coarse solids followed by filtration of the whole extraction tailings under 52 kPa vacuum. In this early study, the solids content in the filtrate was high at 4 wt% [4]. Xu et al. studied the filterability of the paste obtained after the whole oil sands tailings were flocculated with polymers. The filterability of the paste was found two orders of magnitudes higher than the original untreated tailings [5]. No systematic studies were published on the use of polymer as flocculants to enhance filtration of whole oil sands tailings, which is the theme of this thesis research.

In this study, we report on a suitable polymer which can effectively flocculate and enhance filtration of the whole oil sands tailings.

This thesis is divided into nine chapters. Chapter 1, *Introduction*; Chapter 2, *Literature review*; Chapter 3, *Al-PAM synthesis and characterization*; Chapter 4, *Settling and flocculation experimental procedure*; Chapter 5, *Effect of Magnafloc 1011 addition on setting and filtration of tailings*; Chapter 6, *Effect of Al-PAM addition on settling and filtration of tailings*; Chapter 7, *Filtration theory analysis on effect of polymer addition on the filtration of oil sands tailings*; Chapter 8, *Conclusions*, and Chapter 9, *Recommendations for future research*.

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Chapter 2 Literature review

2.1 Nature of oil sands tailings and management difficulties

The oil sands deposit in Athabasca area, northeast of Alberta, Canada, is the largest in the world [1, 2]. Based on the available data, it is estimated that the ultimate oil sands volume in-place to be 400 billion cubic meter. Of this amount, about 22 billion cubic meter is at a depth of less than 75 m, where surface mining is economically feasible [2].

In commercial surface mining oil sands plants, the bitumen is separated from the ore using a variation of Clark hot water extraction (CHWE) technology [3]. Oil sands are mined and mixed with hot water and a small amount of caustic soda (NaOH) as process aid. The slurry is sent to Primary Separation Vessel (PSV) via hydrotransport pipeline, where bitumen is liberated and aerated. The aerated bitumen is recovered through flotation in separation vessels and/or flotation cells. The bitumen froth is de-aerated and further treated in froth treatment units, where the fines and water trapped in the bitumen froth are removed. All tailings from separation vessels and froth treatment plants need containment. A typical CHWE bitumen extraction process is shown in Figure 2-1-1.

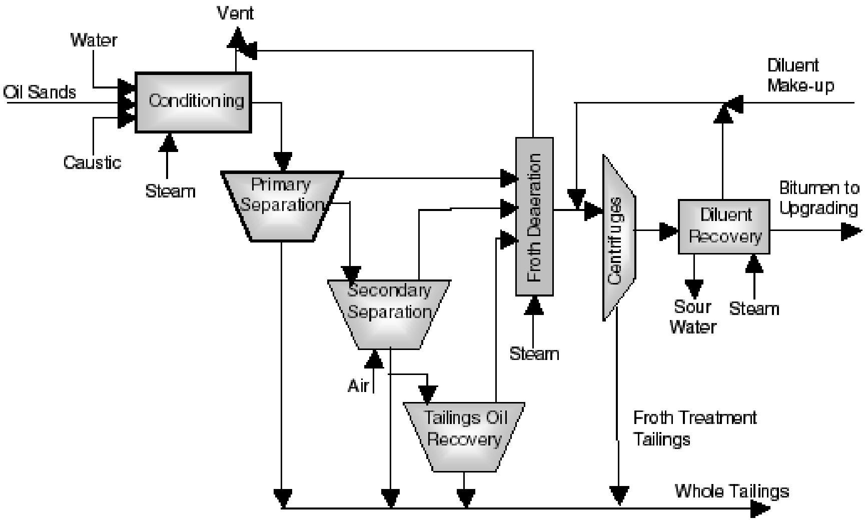

Figure 2-1-1 Schematic of a typical CHWE bitumen extraction process [4]

The tailings slurry is a warm aqueous suspension of sand particles, dispersed fines, water and residual bitumen with a pH between 8 and 9. The total solids are about 55 wt%, of which about 80 wt % is sand, 20 wt% is fine mineral solids smaller than 44 micron and residual hydrocarbons [5]. When the tailings are discharged, the coarse sand settles out relatively quickly to form a compact deposit, however, most of the fine solids segregate and run off into settling basins along with the process affected waters. Over 2-3 years, the fine solids form a slurry structure with solids content of about 30 wt%, which is called mature fine tailings (MFT) [6]. About 50 % of the mineral solids in the MFT are clays (mainly kaolinite and illinite clays) and 90wt % are smaller than 44 micron [5]. Under the water chemistry condition of tailings, the clay particles repel each other and remain suspended in the tailings water, making the consolidation of MFT extremely slow.

The water in the tailings ponds contains high concentrations of salt and organic contaminants, which are highly toxic. With the “zero-discharge” policy, the surface mining oil sands companies retain all the wastes from the process in the tailings ponds [5, 6].

The challenge in managing fine tailings arises from huge volumes, fluid character and long consolidation time of the MFT. For every barrel of oil produced, approximately 1 cubic meter of coarse sand tailings and 0.25 cubic meter of fine tailings are created. As the size of tailings ponds increases with time, it is expected that the volume of Suncor and Syncrude’s tailings ponds will exceed one billion cubic meter by 2020 [2]. The huge size of the tailings ponds is one of the major environmental issues facing the surface mining oil sands industry.

2.2 Development and available technologies for oil sands tailings treatment

Over the past several decades, considerable efforts have been made to reduce the inventory of the already existing tailings ponds and to develop the necessary technologies to eliminate the creation of new ones.

2.2.1 Early studies

Early studies on the reduction of oil sands tailings include dry tailings filtration [7], centrifugation and other mechanical enhancements.

As disclosed in the Canadian Patent 1103184, Liu et al. attempted to filter the whole extraction tailings by adding 300 ppm to 700 ppm lime [7]. They claimed that the fines and coarse particles agglomerated (Figure 2-2-1). Feeding the 75 Celsius degree mixture to a nylon belt filter (Area: 10 ft^2; pore size: 250 micron; vacuum: 52 kPa) at about 4 tons/hr, a cake with 15 wt% moisture could be obtained. The filtrate typically contained 4 wt% of solids and less than 3 wt% fine solids. The filter cloth needed to be cleaned by hot water to remove the bitumen.

Coarse Particles Fines Particles Agglomerated Particles

Figure 2-2-1 Illustration of typical particles in the whole tailings before and after lime is added (revised from [7])

Bakhshi et al. tried to filter Suncor’s tailings using Buchner funnel by adding fly ash. The optimum dosage was as high as 6g fly ash per 50g tailings [8]. The fly-ash requirement would be very large and many material handling problems are associated with this approach.

Though those early research studies were not developed to commercial stage, they indicated that the addition of lime can convert the extraction tailings into non-segregating mixtures thereby setting the stage for the development of composite tailings (CT) technology.

2.2.2 Commercial processes

At present, there are two processes used in commercial plants, one is the CT process employed in Suncor and Syncrude [6] and the other is thickener technology in Albian Sands Energy [9, 10].

2.2.2.1 Composite tailings (CT) process

As shown in Figure 2-2-2, in the CT process, coarse tailings from the underflow of the cyclone mixed with the MFT are bonded together through the addition of a coagulant. The design target of CT is that, when the slurry is deposited, the water could be released rapidly [11] with no segregation between the fine solids and the coarse fraction [12]. Various coagulants have been shown to be effective, such as lime, H_2SO_4, gypsum, alum ($Al_2(SO_4)_3 \cdot 14.3H_2O$) and organic polyelectrolytes (such as Percol LT27A from Allied Colloids). Though the impact of polymers on water quality is negligible, the de-watering and stability of the deposits obtained from the use of polymers are incomparable to the inorganic coagulants. As a result, their use is still not sufficiently robust for commercial application. Considering the segregation, depositional and geotechnical characteristics of CT mixes that are formed with various chemical aids, Syncrude and Suncor chose gypsum as the preferred coagulant for their implementation of CT. But the increase of salinity, especially the increase of divalent cations in the recycled water due to the addition of gypsum raises the potential of scaling in process units, increased corrosion of susceptible metallurgy and detrimental effect on bitumen recovery in extraction [13, 14]. Also the general increase in salinity, sodium and sulphate content, pH and alkalinity of the water in CT mix may influence the reclamation planning of CT affected area [15].

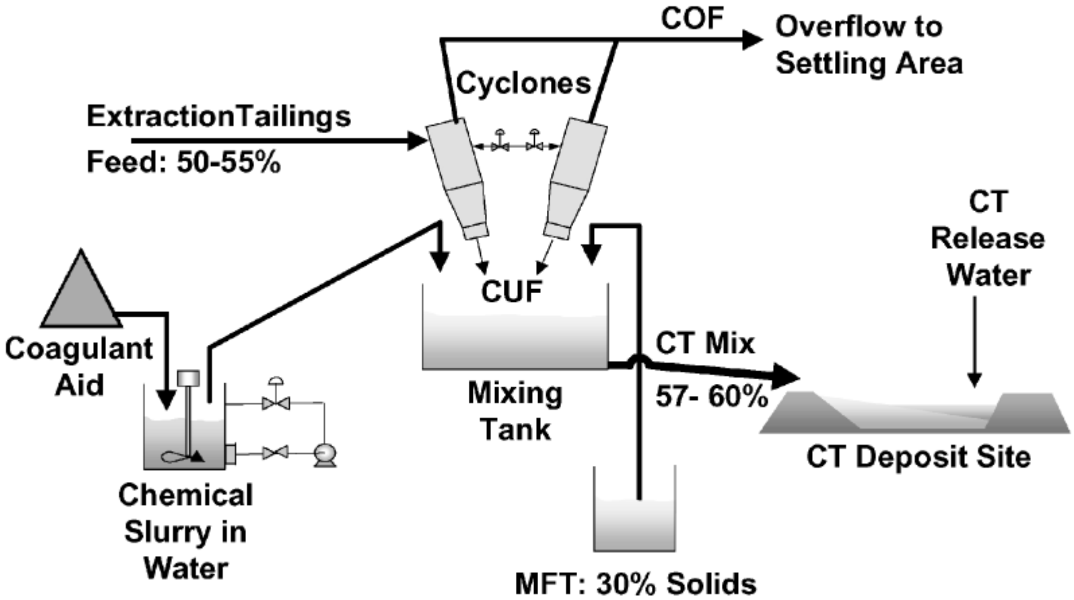

Figure 2-2-2 Schematic of a CT Process [16]

Although consolidated tailings (CT) technology has been applied commercially for more than 10 years, operators are yet to produce effective CT mixture and transform CT ponds into trafficable deposits.

2.2.2.2 Paste technology

The CT process can reduce the volume of MFT in already existing tailing ponds. However, it would be better if the creation of new tailings ponds can be eliminated. For paste technology, the fine tailings that are traditionally sent to the tailings ponds are sent instead to thickeners, where synthetic organic flocculants are added to allow for rapid solids settling. The warm water (overflow) from the thickener is recycled to the extraction process, and the flocculated paste (underflow) is pipelined to the mined-out pit. As planned objective, the thickened tailings deposits can be capped with tailings sand or overburden and eventually reclaimed as dry land after a few years [17,18]. The polymer flocculants have negligible effect on the water chemistry of the recycled water [16]. Paste technology offers a possible solution for treating fine tailings arising from present and future oil sands processing plants. It would eliminate the need for large MFT storage ponds, reduce land disturbance and allow quick reclamation of the mined areas. It also reduces the cost of final tailings disposal [9]. But, what has been adapted by Albian Sands Energy is conventional thickener, not paste thickener. So far, no paste thickener has been commercially used in oil sands operations yet.

There is always a need to develop alternative technologies to reduce the tailings volume or even eliminate the tailings ponds. Much effort by the industry and academic institutions are set to develop new and economically feasible technologies. One straightforward way is to filter the whole tailings. In this approach, warm water can be immediately recycled back to the extraction plant, consolidated filter cake can be sent to reclamation sites and reclamation can be initiated much earlier in the life time of an oil sands mine. In this thesis, we propose the possible use of filtration of whole oil sands tailings.

2.3 Research on flocculation studies for oil sands tailings

Flocculation destabilizes the dispersion through binding the colloidal particles together by polymeric flocculants. The formed large flocs will undergo gravity settling and the released water can be recycled back to the process. The mechanisms of polymer flocculation include bridging, charge neutralization, polymer-particle surface complex formation and depletion flocculation or the combination of all of the afore-mentioned mechanisms [19,21].

Ramachandra et al. flocculated oil sands tailings by anionic Polyacrylamide (PAM) after pre-treatment with optimum concentration of magnesium ions, Mg^{2+}, and/or calcium ions, Ca^{2+}. The obtained compact flocs carried less than 40 wt% moisture [20].

Xu et al. carried out flocculant screening tests on Syncrude extraction tailings. The fines (<22 microns) were 50 and 85 wt% of solids in the flotation tailings and de-sanded tailings, respectively. Their results showed that only anionic polymers with a narrow range of charge densities can flocculate the fine oil sands tailings at a process pH of 8.5. Higher molecular weight flocculant can form large flocs, resulting in increased settling rates. For most polymers tested, the settling rate increased with increasing polymer dosage. However, Percol LT27A and Percol 727 showed overdosing behaviour. The initial settling rates (ISRs) with the addition of the afore-mentioned two polymers were about 33 and 42 m/h at the optimum dosage. However, Xu et al. were unable to obtain a clear supernatant even at dosages above 20 mg/L. The best water clarity achieved was 0.6 % solids content. Clear water was obtained by adding low molecular weight, highly charged cationic polymer Percol 368 to the supernatant. But the flocs generated by Percol 368 were very fluffy and the sediment contained much water. For the tested flotation tailings and de-sanded tailings, the solids content in the paste were 60 wt% and 40 wt%, respectively. Xu et al. also checked the specific filtration resistance (SRF) of the paste, which were two magnitudes lower than the that without polymer addition [9].

Sworska et al. flocculated de-sanded Syncrude fine tailings (13.5 to 15.5 wt% solids, 65 % < 25 micron) with Percol 727 [21]. They found that at basic pH (pH >

8), the ISRs were low and the supernatant has relatively high solid content (2 wt%). The addition of Ca^{2+} and Mg^{2+} ions dramatically improved the clarity of the supernatant (<0.3 wt%). They found that for Percol 727, adequate mixing did not improve the clarity of the supernatant, which remained in a range from 1 to 2 wt% [22]. However, suitable mixing conditions improved the distribution of the polymer in the flocculating suspension and resulted in a lower polymer requirement to obtain good flocculation. They also tried polyethylene oxide (PEO) (MW: 8×10^6 g/mol) on Syncrude fine tailings. With proper mixing procedure, the ISRs were fast and the solids content was 0.2 to 0.3 wt% in the supernatant. The resulting flocs were stable and could not be easily reslurried [22].

Latest research studies tried polymer as extraction aids for poor processing ores, and the settling rates of the extraction tailings were reported. When 400 ppm of temperature - sensitive polymer (NIPAM) was added in the extraction process, the ISRs of tailings at 40 Celsius degree increased from 0.2 to 2.5 m/h and clear supernatant was obtained [23]. When 20 ppm of Al-PAM was used in a laboratory loop extraction tests, the tailings had fast settling rates and smaller final sediment volumes were obtained [24].

To summarize the above: (1) high molecular weight anionic polymers with a narrow range of charge, like Percol 727, can effectively flocculate oil sand tailings, and high settling rate can be obtained, however, the supernatant has relatively high solid content; (2) cations or cationic polymers can improve the supernatant clarity; (3) the flocculation performance is strongly affected by mixing conditions.

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Chapter 3 Al-PAM synthesis and characterization

3.1 Al-PAM synthesis

Al-PAM used in this study were in-house synthesized by polymerization of acrylamide in $Al(OH)_3$ colloidal solution.

3.1.1 Materials

All chemicals for the synthesis of Al-PAM were purchased from Fisher Scientific, including ammonium carbonate, aluminum chloride, acryl amide (monomer), sodium bisulfite and ammonium persulfate (initiators) [1, 2].

3.1.2 Al-PAM synthesis process

Al-PAM is a hybrid of $Al(OH)_3$ colloid and polyacrylamide (PAM). The synthesis process involves three steps. First step was to prepare the $Al(OH)_3$ colloid. In this regard, 75 g solution of 0.1 M $(NH_4)_2CO_3$ was added into 50 g solution of 0.1 M $AlCl_3$ of room temperature. To obtain colloids of narrow size distribution, the solution in 250 ml beaker was well mixed with the magnetic bar at 1200 rpm during $(NH_4)_2CO_3$ addition. The particle size distribution and zeta potential of the formed colloid were analyzed using ZetaPALS (Brookhaven Instruments Corporation, NY). The second step was to synthesize the hybrid polymer. In this case, 4.5 g monomer acrylamide (AM) was added into 25.5 g $Al(OH)_3$ colloid suspension in a 250 ml round-bottom flask. Before the initiators (1.35 ml $NaHSO_3$ and 3.15 ml $K_2S_2O_8$, both 5 g/L concentrations) were added, nitrogen gas was purged through the flask for 30 minutes to eliminate the pre-existed oxygen. The polymerization lasted for 8 hour at 40 Celsius degree with the protection of N_2 blanket. The last step was to purify the polymerization product. The formed gel was dissolved in 1000 ml Milli-Q water, followed by precipitation with acetone (volume ratio of acetone to solution is 2:1) to remove the un-reacted $Al(OH)_3$ colloid and acrylamide. The precipitates were extracted with acetone for overnight and dried at room temperature in a vacuum oven until constant weight.

3.2 Characterization of Al-PAM

3.2.1 The intrinsic viscosity measurement

The intrinsic viscosity of Al-PAM in Milli-Q water was measured using Ubbelohde viscometer (Φ75, CANNON® Instrument Company, PA, USA) at 25 ± 0.5 Celsius degree. The flux-times of Al-PAM solutions were recorded with the accuracy of ± 0.01 s. According to the Huggins equation $\eta_{sp}/c = [\eta] + k_h[\eta]^2 c$, the intrinsic viscosity $[\eta]$ can be experimentally determined from the y-intercept by plotting η_{sp}/c against c of the polymer solutions [1, 3].

3.2.2 Al content

A volume of 2 ml of 2 g/l Al-PAM solution was deposited on the clean silica surface and dried in the vacuum oven overnight. Then the Al content in Al-PAM was analyzed using X-ray Photoelectron Spectroscopy (XPS) (*Axis 165,* Kratos Analytical, NY, USA). The characteristics of Al-PAM are listed in Table 3-2-1.

The Al-PAM is an ionic bond hybrid with the negative end group of PAM chain in conjunction with the positive $Al(OH)_3$ colloidal particles [2, 4]. According to colloid chemistry principles, positive $Al(OH)_3$ colloids would attach to negative ions to neutralize the charge. Therefore, negative ions ($S_2O_8^{2-}$) from the initiators can adsorb on $Al(OH)_3$ surfaces. At the reaction temperature, $S_2O_8^{2-}$ reacts with SO_3^{2-} to produce ionic free radicals (SO_4^{2-}), which initiate the polymerization of AM, forming PAM on positive $Al(OH)_3$ colloid particles [2, 4].

Table 3-2-1 Characteristics of Al-PAM

$Al(OH)_3$ colloid		Al-PAM	
Size (nm)	Zeta potential (mV)	Al Content (wt%)	Intrinsic viscosity (ml/g)
126	+20	2.80	459.6

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Chapter 4 Settling and flocculation experimental procedure

4.1 Materials

4.1.1 Polymers

The two polymers, Magnafloc 1011, formally sold as Percol 727, purchased from Ciba Specialty Chemicals and in-house synthesized Al-PAM polymer, were used as settling and filtration aids. Magnafloc 1011 is a partially hydrolyzed polyacrylamide with a high molecular weight of about 17.5 million Daltons and of a medium charge density of around 27 % [1]. The synthesized Al-PAM is a hybrid $Al(OH)_3$-polyacrylamide, with ionic bond between $Al(OH)_3$ colloids and polyacrylamide chains [2].

4.1.2 Model tailings

For model tailings slurry, kaolin (K2-500, Fisher Scientific) and sand (7030, Sil Industrial Minerals Inc., AB, Canada) were used as model fines and coarse sand respectively. The particle size distribution of kaolin and sand were analyzed using Mastersizer (Hydro2000SM, Malven, MA, US). As shown in Figure 4-1-1, d_{50} of kaolin and sand were 8.0 and 197.8 micron, respectively.

According to the study of CT process, the sand to fine ratio (SFR) should be above 4 in order to obtain efficient consolidation of non-segregating tailings [3]. Therefore, a fixed SFR of 4 was used here for the model tailings. The typical solid content of extraction tailings is about 50 to 55 wt%. The total solid content in this study varied from 25 to 55 wt%.

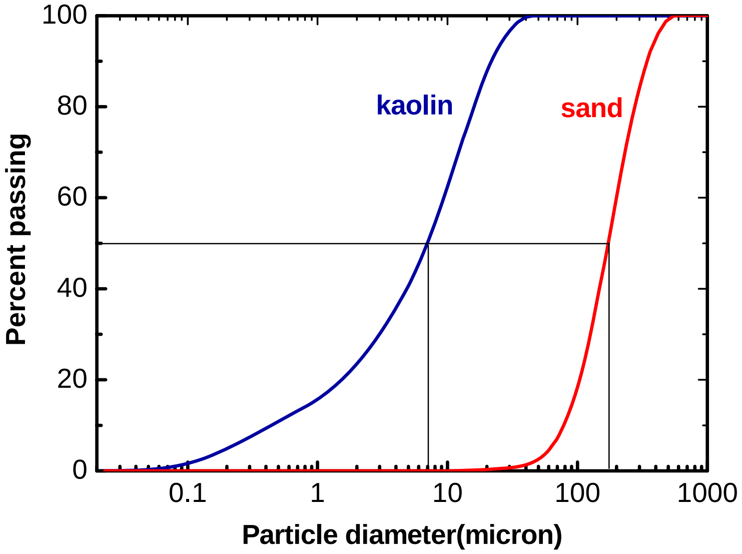


Figure 4-1-1 Particle size distribution of kaolin and sand in model tailings slurry

Aurora process water was used to constitute the model tailings slurry. The ionic composition and pH of Aurora process water are given in Table 4-1-1.

Table 4-1-1 Ionic composition of Aurora process water (mg/L)

K^+	Na^+	Mg^{2+}	Ca^{2+}	Cl^-	NO_3^-	SO_4^{2-}	HCO_3^-	pH*
20	612	16.2	22	405	5.7	114	742	7.8

* measured with Accumet Basic pH meter, Fisher Scientific

4.1.3 Laboratory extraction tailings

Two types of whole tailings from laboratory extraction tests were used; one from low fines ore and the other from very high fines ore. Here fines are defined as mineral solids smaller than 44 micron. Bitumen extraction was conducted using Aurora plant process water. The composition of the tailings samples was determined using the industrial standard procedure (Dean Stark). The results are given in Table 4-1-2. The particle size distribution of the solids in the tailings was analyzed using Mastersizer (Hydro2000SM, Malven, MA, US). As shown in Figure 4-1-2, the fines content in the mineral solids of the two tailings were 4.2 and 40.1 wt% respectively. The fines content of tailings from high fines ore is quite high. Such a high fines ore is used to illustrate tailings filtration under extreme conditions of high fines.

Table 4-1-2 Composition of laboratory extraction tailings (wt%)

Tailings	Water	Bitumen	Solids	Fines in solids
Low fine tailings[1]	76.4	1.1	22.5	4.2
High fine tailings[2]	85.7	0.8	13.5	40.1

[1] Whole tailings from Denver cell extraction of a low fines ore

[2] Whole tailings from laboratory loop extraction of a high fines ore

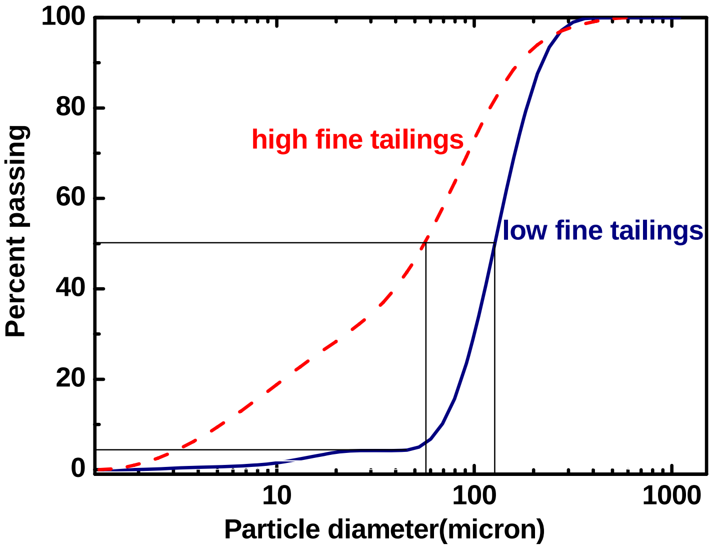
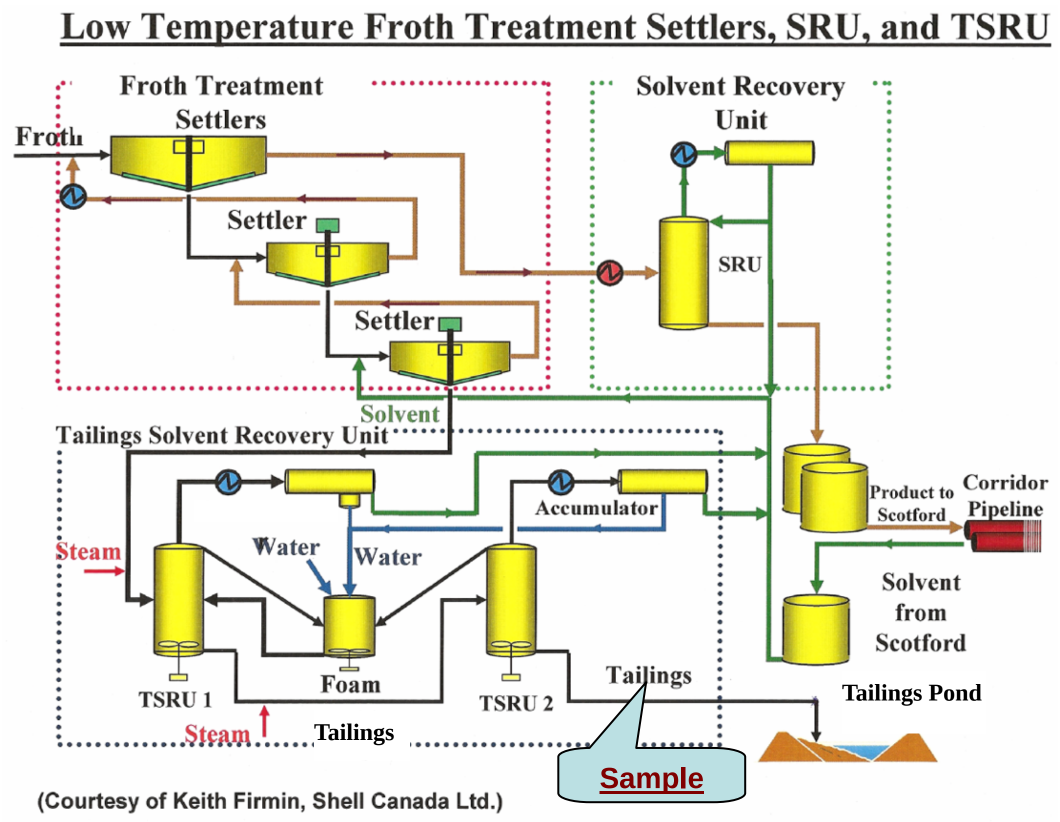


Figure 4-1-2 Particle size distribution of the solids in laboratory extraction tailings

4.1.4 Paraffinic froth treatment tailings

Paraffinic froth treatment tailings were concentrated tailings from Tailings Solvent Recovery Unit in the froth treatment plant of Albian, as shown in Figure 4-1-3 (courtesy of Muskeg River Mine, Albian Sands Energy).

The composition of paraffinic froth treatment tailings analyzed by the industrial standard procedure of Dean Stark is shown in Table 4-1-3. The hydrocarbon content of the paraffinic froth treatment tailings is as high as about 10 wt%. As shown in Figure 4-1-4, fines content in the solids was 43.9 wt% and the d_{50} was around 50 micron. The paraffinic froth treatment tailings were rich in fine and hydrocarbon constituting of precipitated asphaltenes with residue bitumen and solvent.



(Courtesy of Keith Firmin, Shell Canada Ltd.)

Figure 4-1-3 Flow sheet of froth treatment unit at Albian Sands Energy

Table 4-1-3 Composition of paraffinic froth treatment tailings (wt%)

Tailings	Water	Hydrocarbon	Solids	Fines in Solids
Paraffinic froth treatment tailings	75.6	10.0	14.4	43.9

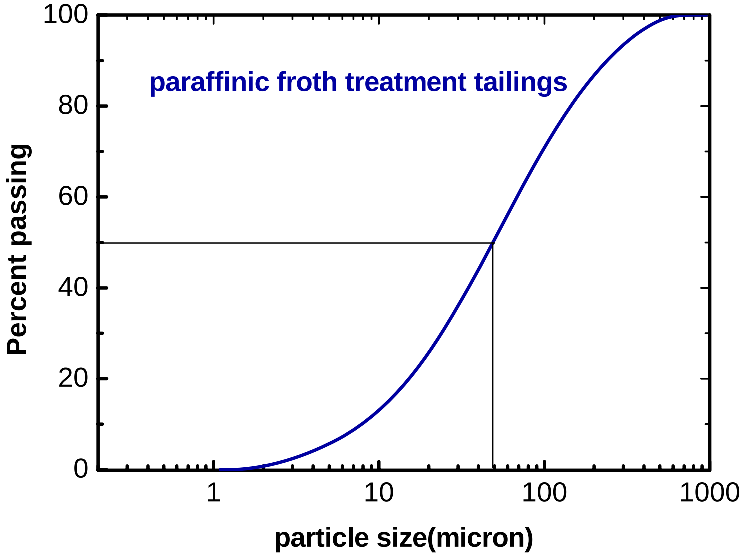


Figure 4-1-4 Particle size distribution of the solids in paraffinic froth treatment tailings

4.2 Settling tests

4.2.1 Settling tests procedure

In the current study, flocculant dosages are expressed on the basis of tailings slurry weight. Flocculant stock solutions of 500 ppm were prepared in deionized water one day prior to their use.

For each settling test, 100 g of tailings slurry was placed into a 250-ml standard baffled beaker [4] and mixed at 500 rpm for 2 minutes, followed by flocculant addition to the slurry under mixing at 300 rpm. After mixing, the slurry was transferred into a 100-ml graduated cylinder, and the suspension mud-line was recorded during the settling period. Each test was repeated three times, the average data were reported.

4.2.2 Data processing from settling tests

For the settling tests, the normalized mud-line height (h/H) and initial settling rate (ISR) were used to evaluate the performance of the polymers on the settling characteristics of the tailings. Here, h is mud-line height at time t and H is the initial mud-line height at time zero. A suspension that is not amenable to settling would give an h/H value of unity. After 10 minutes settling, the turbidity of the supernatants was determined using a Turbidimeter (HF Scientific DRT-15CE Portable Turbidimeters, Fisher Scientific). Few fresh supernatant drops were placed on TEM grids and the solids in the supernatants were checked under TEM (Philips / FEI (Morgagni) Transmission Electron Microscope with CCD camera (TEM-CCD)).

4.3 Filtration tests

4.3.1 Filtration tests procedure

The filtration tests were carried out in a laboratory filtration unit (LPLT300, Fann Instrument Company) with filtration area of 45.8 cm^2. A specially hardened filter paper of 2-5 micron pore size (N87000, Fann Instrument Company) was used as the filter medium. After mixing, the tailings slurry was immediately filtered under 15 kPa pressure. The weight of the filtrate was monitored continuously by an electronic balance interfaced with a computer (Figure 4-3-1). The formed cake was dried in an oven at 105 Celsius degree to a constant weight for cake moisture analyze. Each test was repeated three times, the average data were reported.

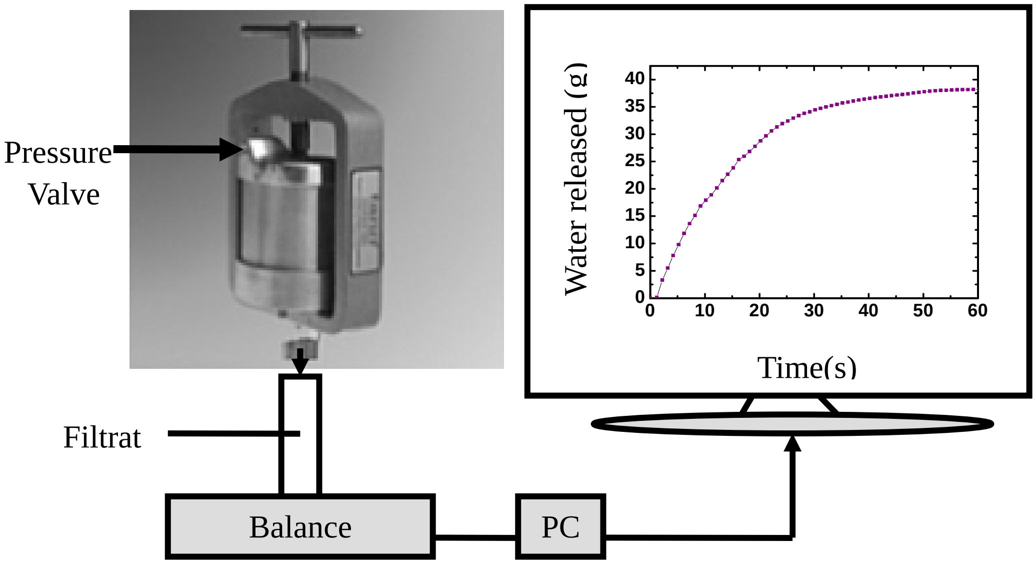


Figure 4-3-1 Laboratory filtration unit used in this study

4.3.2 Data processing from filtration tests

For the filtration tests, the moisture in the slurry above the filter paper is defined as the mass of water in the filter press divided by the mass of total slurry in the filter press at a given time t. The moisture content is given by

$$\text{Moisture} = \frac{\text{Mass of water in filter press at time t}}{\text{Mass of total slurry in filter press at time t}}$$

$$\text{Moisture} = \frac{W_{\text{slurry}} + W_F - W_{\text{ft}}}{M_{\text{slurry}} + M_F - W_{\text{ft}}} \times 100\%$$

where

W_{slurry}: mass of water in the slurry at time zero

W_F: mass of water in the added flocculant solution

$W_{ft:}$ mass of filtrate at time t, which is monitored by computer

M_{slurry}: mass of slurry at time zero

M_F: mass of added flocculant solution.

The final cake moisture $\frac{M_{wet} - M_{dry}}{M_{wet}}$ was checked as well, where M_{wet} and M_{dry} are the mass of the cake before and after drying in the oven at 105 Celcius degree for 12 hours respectively.

The ionic concentrations in the filtrate were analyzed using AA (AA880, Varian) and IC (DX-600, Dionex). The pH of the filtrate was measured using pH meter (Accumet Basic pH meter, Fisher Scientific). The filtrate was analyzed using FTIR (Nicolet 6700 FT-IR Spectrometer, Therno Fisher Scientific, MA, USA) for residue Al-PAM.

Reference

1. Li, H.; Long, J.; Xu, Z.; Masliyah, J. H., *Synergetic role of polymer flocculant in low-temperature bitumen extraction and tailings treatment.* Energy & Fuels **2005,** 19, (3), 936-943.

2. Yang, W. Y.; Qian, J. W.; Shen, Z. Q., *A novel flocculant of AI(OH)(3)-polyacrylamide ionic hybrid*. Journal of Colloid and Interface Science **2004,** 273, (2), 400-405.

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4. Edward L. P., V. A. A. a. S. M. K., Handbook of Industrial Mixing: Science and Practice. **2003,** Chapter 6.

Chapter 5 Magnafloc 1011 effect on settling and filtration of tailings

Magnafloc 1011 was tested as flocculant for both settling and filtration of model tailings. The model tailings were made up of kaolin as model fines with sand to fines ratio (SFR) of 4. The total solids content was 25, 40, 50 and 55 wt%. As shown in Figure 4-1-1, d_{50} of kaolin and sand were 8.0 and 197.8 micron respectively.

For the case of the two laboratory extraction tailings, the total solid content was 13.5 and 22.5 wt%, respectively.

5.1 Magnafloc 1011 effect on model tailings

5.1.1 Effect of Magnafloc 1011 addition on settling of the model tailings

It is shown in Figure 5-1-1 that Magnafloc 1011 significantly improved the settling of the model tailings. For the model tailings with 25 wt% solids, the solids content in the sediment reached 61 wt% at the end of ten minute settling when the dosage of Magnafloc 1011 was 10 ppm. For tailings with 50 wt% solids and 20 ppm Magnafloc 1011 addition, the solids content also reached 61 wt% in ten minute.

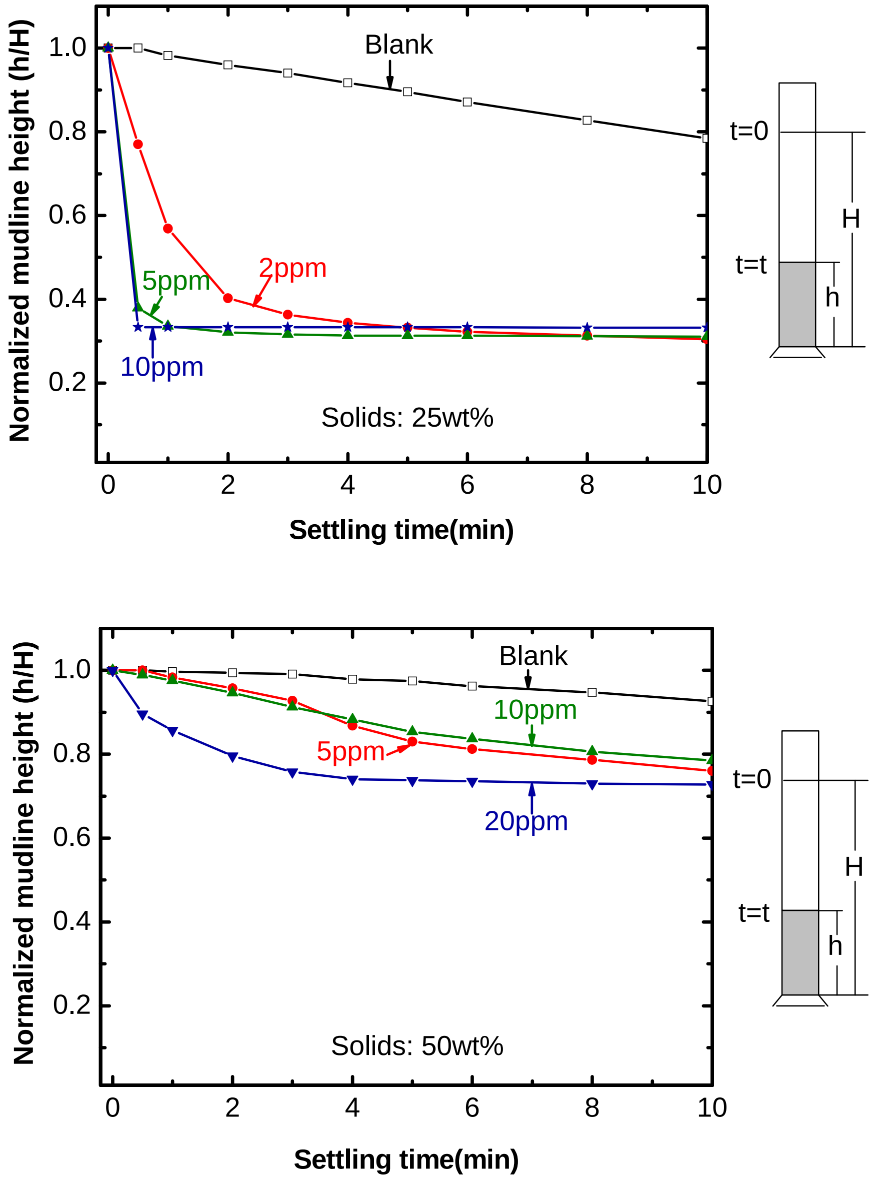


Figure 5-1-1 Effect of Magnafloc 1011 addition on settling of model tailings

As illustrated in Figure 5-1-2, the initial settling rate (ISR) increased with increasing polymer dosage. For model tailings with 25 wt% solids, the ISR increased from being marginal to about 27 m/h when the dosage of Magnafloc

1011 increased from 0 to 10ppm. The model tailings with 50 wt% solids also exhibited the same trend. However its ISR was only 3.1 m/h when 20 ppm Magnafloc 1011 was used, which was much lower than that of 25 wt% of solids system. This result suggests that the ISR of the tailings with higher solids content was lower than that of a diluted suspension.

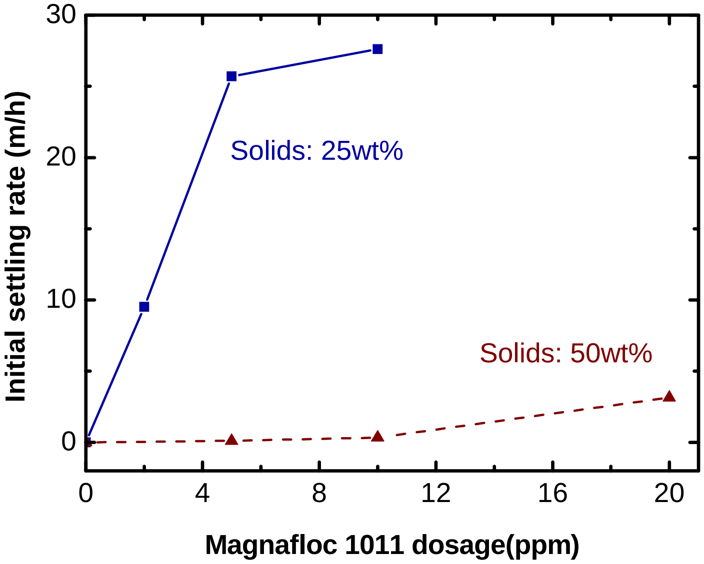


Figure 5-1-2 Effect of Magnafloc 1011 addition on ISR of model tailings with different solids contents

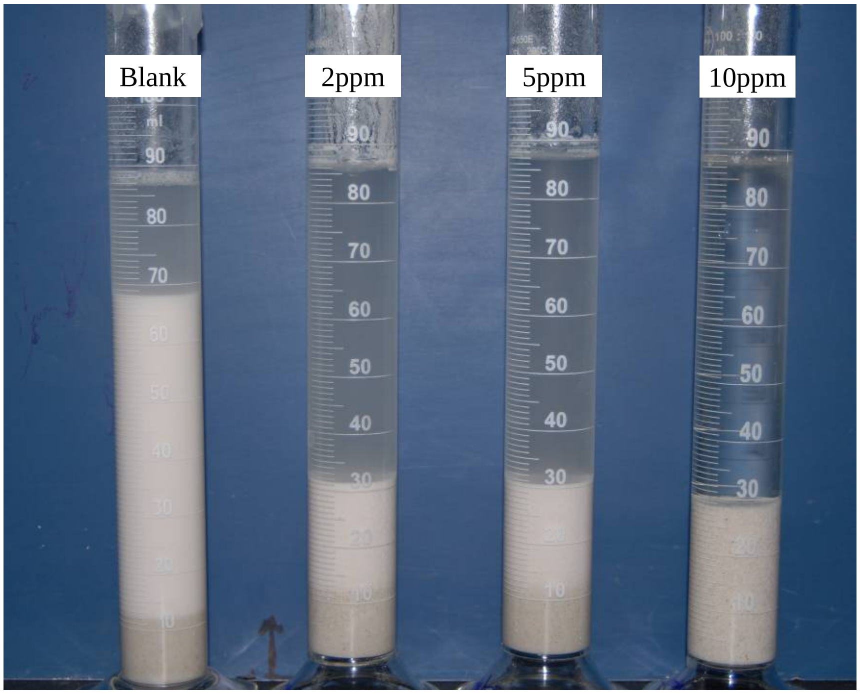


Figure 5-1-3 Photographs of model tailings with the addition of Magnafloc 1011 after 10 minutes of settling (Solids: 25 wt %)

It was observed from Figure 5-1-3 that, non-segregation tailings formed as the polymer dosage was above a certain level, i.e. the flocculated fines and the sand remained mixed and settled together, without distinct fine/sand layers. For the slurry with 25 wt% solids, the dosage required to obtain non-segregating tailings should be higher than 5 ppm, and the corresponding point for 50 wt% solids slurry was 10 ppm.

The supernatants of model tailings with the addition of Magnafloc 1011 were almost clear after 10 minute settling. The turbidity of the supernatants of Magnafloc 1011 treated model tailings (Solids: 25 wt%) were reduced from 380

NTU to 15 NTU when the dosage is increased from 0 to 10 ppm.

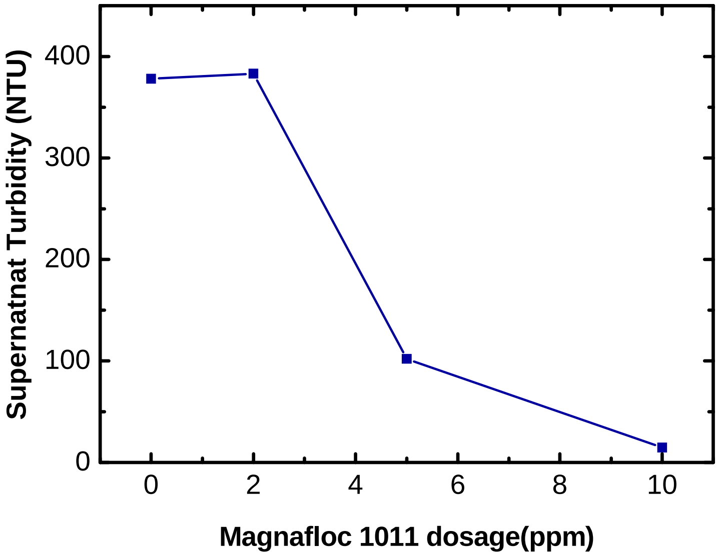
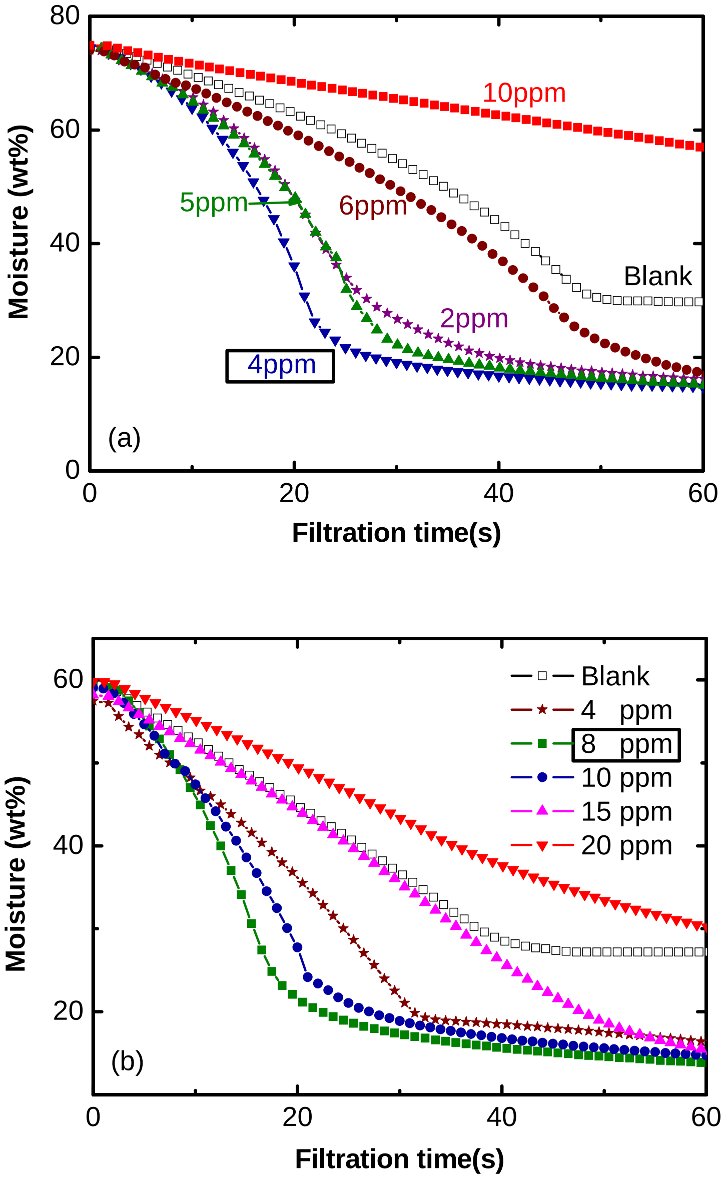


Figure 5-1-4 Turbidity of the supernatants of model tailings after 10 minutes of settling time with the addition of Magnafloc 1011 (Solids: 25 wt %)

The above experimental results showed that Magnafloc 1011 dramatically increased the settling rate of the tested model tailings. Thus it may be a good candidate as filtration aid.

5.1.2 Effect of Magnafloc 1011 addition on filtration of model tailings

Fixed SFR of 4 was used for filtration tests of model tailings. Total solids content was varied from 25 to 55 wt%, where four different solids contents were examined in the filtration tests with the addition of Magnafloc 1011.


80
60
40
20
0
10ppm
5ppm
6ppm
Blank
2ppm
4ppm
(a)
0
20
40
60
Moisture (wt%)
Filtration time(s)
60
40
20
(b)
Blank
4 ppm
8 ppm
10 ppm
15 ppm
20 ppm
0
20
40
60
Moisture (wt%)
Filtration time(s)

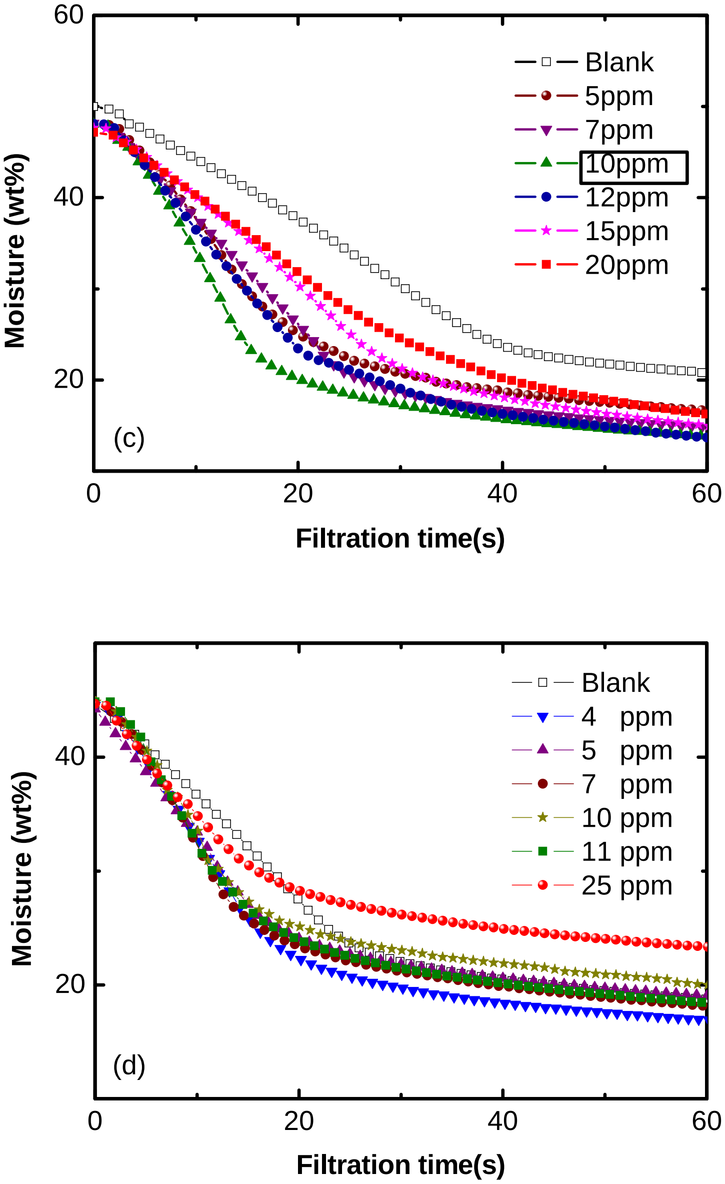


Figure 5-1-5 Magnafloc 1011 effect on filtration of model tailings, where the total solids content was: (a) 25 wt% (b) 40 wt% (c) 50 wt% and (d) 55 wt%

It is observed from Figure 5-1-5 that, for the model tailings with solids content of 25 wt%, 40 wt% and 50 wt%, there was an optimal dosage for the best filtration for each system, which was 4 ppm, 8 ppm and 10 ppm (in term of slurry), respectively, which is close or equal to 100 ppm in terms of fines content in the slurry. The filtration rate would be slower if the dosage was not optimal. When the dosage was much higher than the optimal value, the filtration rate was even slower than that without polymer addition. It was established that the dominant mechanism for the adsorption and conformation of PAM chain to kaolinite is via the hydrogen bonding, between the silanol and aluminol OH groups on the kaolinite surface and amide groups on the polymer [1]. However, in addition to the adsorption, there is an additional antagonistic effect resulting from electrostatic repulsive interactions between the polymer's carboxylic groups and negatively charged kaolinite surface sites, which would lead to the formation of looser, more open and more fragile flocs with poor compaction. Excessive addition of flocculant is know to induce steric stabilization of fine solids which would affect the filtration rate when the polymer dosage is very high [2].

Comparing the optimal dosage of filtration for each slurry system with the best settling dosage obtained from the settling tests, it is concluded that the best settling performance doesn't lead to a good filtration scenario. Although increasing the polymer dosage leads to faster settling, it does not guarantee good filtration performance. Therefore, the dosage screening in the settling tests results can not be applied directly to the filtration tests.

Figure 5-1-6 compares the filtration rate of three model tailings at their optimal filtration dosages. It showed that the water release rates at early filtration times were very close. For the 50 wt% solids system, it took 15 second to obtain 30 g water; for the 25 wt% solids system, it took 30 second for 65 g water.

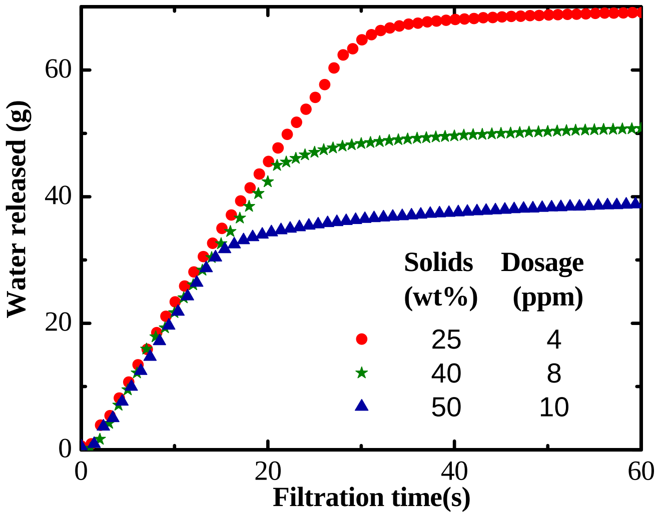


Figure 5-1-6 Filtration curves of model tailings at their optimal dosage of Magnafloc 1011

For a more concentrated system (Figure 5-1-5 (d)) of solids content as high as 55 wt%, the dosage of Magnafloc 1011 has negligible effect on the slurry filtration. When the dosage was 25 ppm, the filtration rate was slower than the case without polymer addition. However the difference was smaller than the case for 25, 40 and 50 wt% solids systems. Studies from Cymerman et al. also revealed that with 55 wt% of total solids and high SFR, the settling of the slurry itself was high [4]. Thus the polymer effect on the concentrated system would be less than that for more diluted ones.

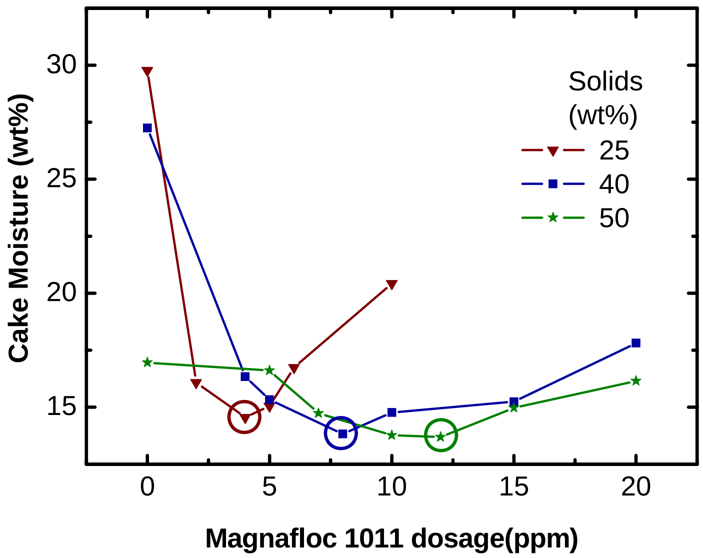


Figure 5-1-7 Cake moisture of model tailings with the addition of Magnafloc 1011

(Total solids: 25, 40, 50 wt %)

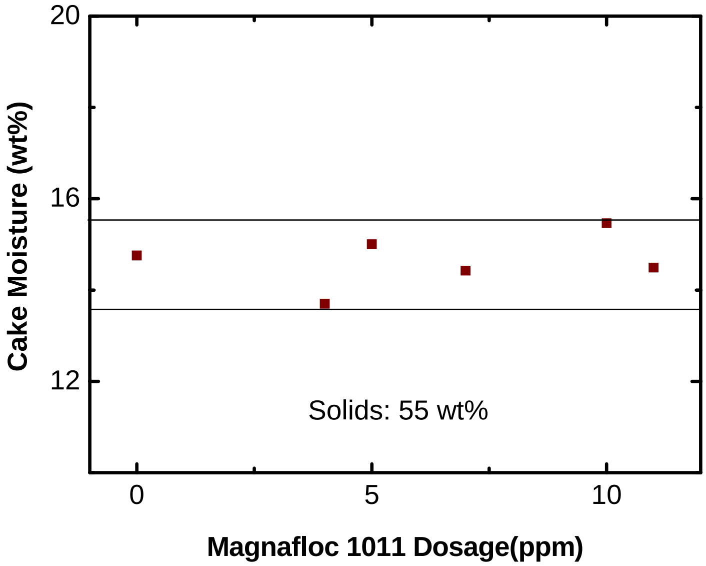


Figure 5-1-8 Cake moisture of model tailings with the addition of Magnafloc 1011

(Total solids: 55 wt %)

Figure 5-1-7 shows that for the model tailings with 25, 40 and 50 wt% solids, Magnafloc 1011 effectively reduced the cake moisture. The lowest cake moisture obtained for each system was 14.5 wt%, 13.8 wt% and 13.8 wt%, respectively. The optimal dosages to obtain the lowest cake moisture for these systems were consistent with those for obtaining the fastest filtration, i.e., 4 ppm, 8 ppm and 10 ppm, respectively.

But for the model tailings with 55 wt% solids, the cake moisture was in the range of 14.6±0.9 wt%, independent of Magnafloc 1011 addition (Figure 5-1-8). In addition, the filtration rate was not related to the dosage of Magnafloc 1011. Magnafloc 1011 has a negligible effect on filtration of such condense slurry system.

Model tailings of total solids: 25, 40 and 50 wt% at SFR = 4

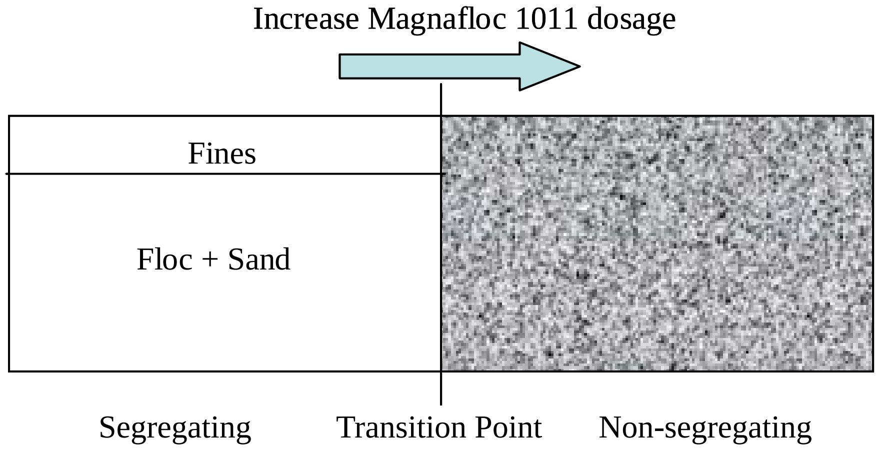


Figure 5-1-9 The effect of Magnafloc 1011 on the cake structures of model tailings (Total solids: 25, 40 and 50 wt %)

As illustrated in Figure 5-1-9, there is a critical dosage that affected the cake structure of each tested model tailings, in which the total solids content was 25, 40 and 50 wt%. When the dosage was lower than the critical dosage value, there were still un-flocculated fines on top of the formed cakes; whereas when the polymer dosage was higher than the critical dosage, the flocculated fines and sand were well mixed, forming non-segregating cake deposit. For the model tailings with 55 wt% solids, no critical dosage was observed. In this case fines and the sand were well mixed without segregation regardless of flocculation.

5.2 Effect of Magnafloc 1011 addition on laboratory extraction tailings

As discussed above, Magnafloc 1011 can effectively improve the settling and filtration performance of the model tailings at the appropriate dosage. It is further tested on flocculation or filtration of the two laboratory extraction tailings, the low and high fine tailings of 4.2 and 40.1 wt% fines, respectively. The total solids content of the two laboratory extraction tailings were 22.5 and 13.5 wt% for the low and high fine tailings, respectively, as shown in Table 4-1-2.

5.2.1 Effect of Magnafloc 1011 addition on settling of laboratory extraction tailings

The settling test results of the laboratory extraction tailings with the addition of Magnafloc 1011 are shown in Figure 5-2-1.

It was observed that Magnafloc 1011 was a good flocculant for both laboratory extraction tailings (Figure 5-2-1). Without polymer addition, the settling rates of the two tailings were extremely poor.

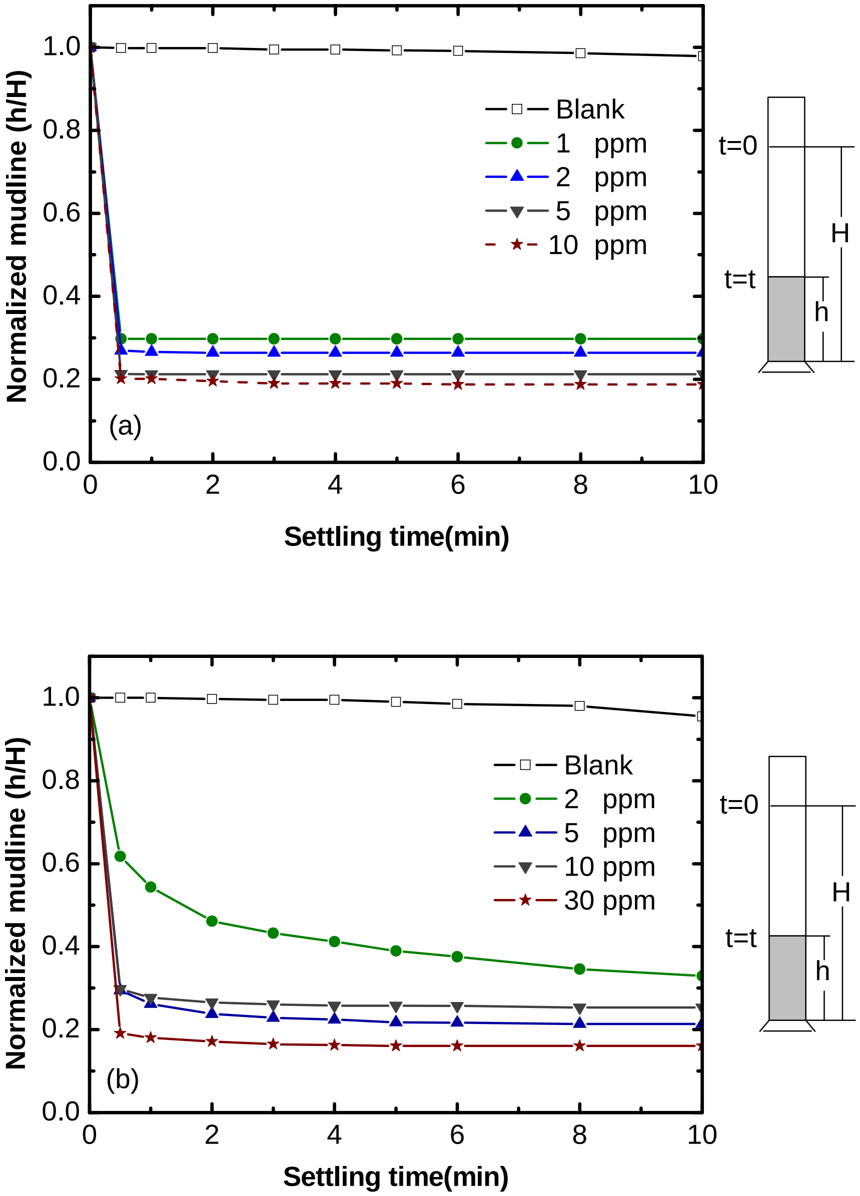


Figure 5-2-1 Effect of Magnafloc 1011 addition on settling of laboratory extraction tailings: (a) low fine tailings (b) high fine tailings

For the low fine tailings, the normalized mud-line height, h/H, reached 0.2 within 30 second when 10 ppm of Magnafloc 1011 was added. The dosage required to obtain fast settling of the high fine tailings was higher than that for the low fine tailings. A Magnafloc 1011 dosage of 30 ppm was needed to reach similar settling rates for the high fine tailings. The ISR of the low fine tailings reached about 35 m/h when 10 ppm Magnafloc 1011 was used. The ISR of high fine tailings could reach about 42 m/h with the addition of 30 ppm Magnafloc 1011. These results are comparable to the results reported by Cymerman, where the ISR of sand containing fine tailings was about 20-30 m/h when 20 ppm of Percol 727, known as Magnafloc 1011 now, was added [4].

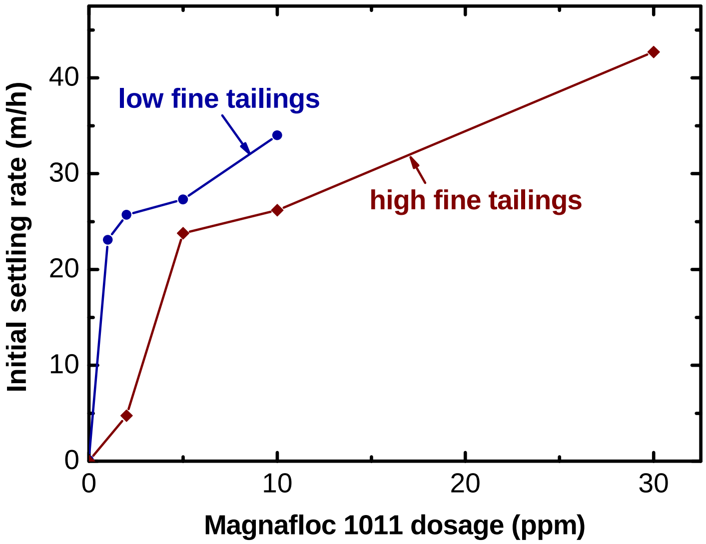
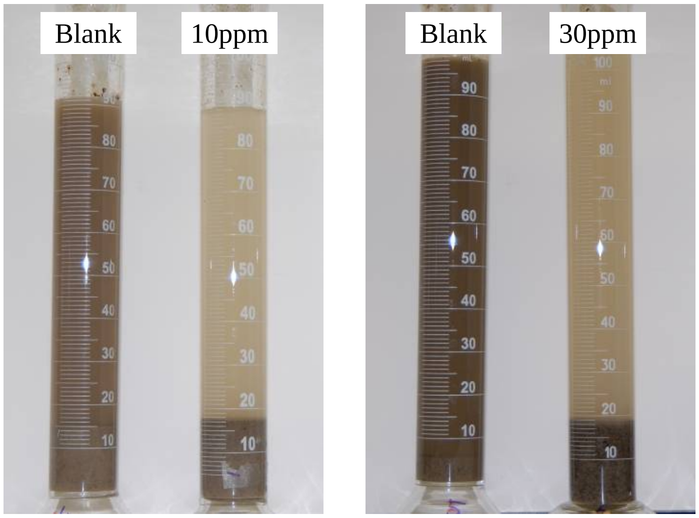


Figure 5-2-2 Effect of Magnafloc 1011 addition on the ISR of laboratory extraction tailings

For the two tested laboratory extraction tailings, when 10ppm and 30ppm Magnafloc 1011 were added, the solids content of the sediment at the end of ten minute settling time reached 76 wt% and 50 wt%, respectively.

As shown in the photographs of Figure 5-2-3, non-segregating tailings formed as high settling rate was achieved, i.e. the flocculated fines and the sands were mixed and settled together, without visible fine/sand layer. A general observation of settling was that all the supernatants of laboratory extraction tailings after Magnafloc 1011addition were not as clear as those of model tailings. After one hour settling, the supernatants were still not clear.



(a) (b)

Figure 5-2-3 Photographs of laboratory extraction tailings after ten minutes of settling time with the addition of Magnafloc 1011: (a) low fine tailings (b) high fine tailings

Interestingly, the turbidity of supernatants with the addition of Magnafloc 1011 was higher than that without polymer addition, as illustrated in Table 5-2-1.

Table 5-2-1 Comparison of supernatants turbidity of laboratory extraction tailings with the addition of Magnafloc 1011, after one hour settling (NTU)

Dosage (ppm)	Blank	1	2	5	10	30
Low fine tailings	260	1035	1038	1043	339	N/A
High fine tailings	145	N/A	10170	693	868	470

5.2.2 Effect of Magnafloc 1011 addition on filtration of laboratory extraction tailings

Since Maganafloc 1011 could improve the settling performance of laboratory extraction tailings, it was further tested as a filtration aid.

For both tailings, when no flocculant was added, the filtration rate was extremely slow. In the tested dosage range, the initial filtration rates were slightly improved; but within the tested range, no matter how much of Magnafloc 1011 was added, filtration of both tailings for 180 seconds was slower than that without flocculant addition. And no filter cakes were formed after 180-second filtration in both cases.

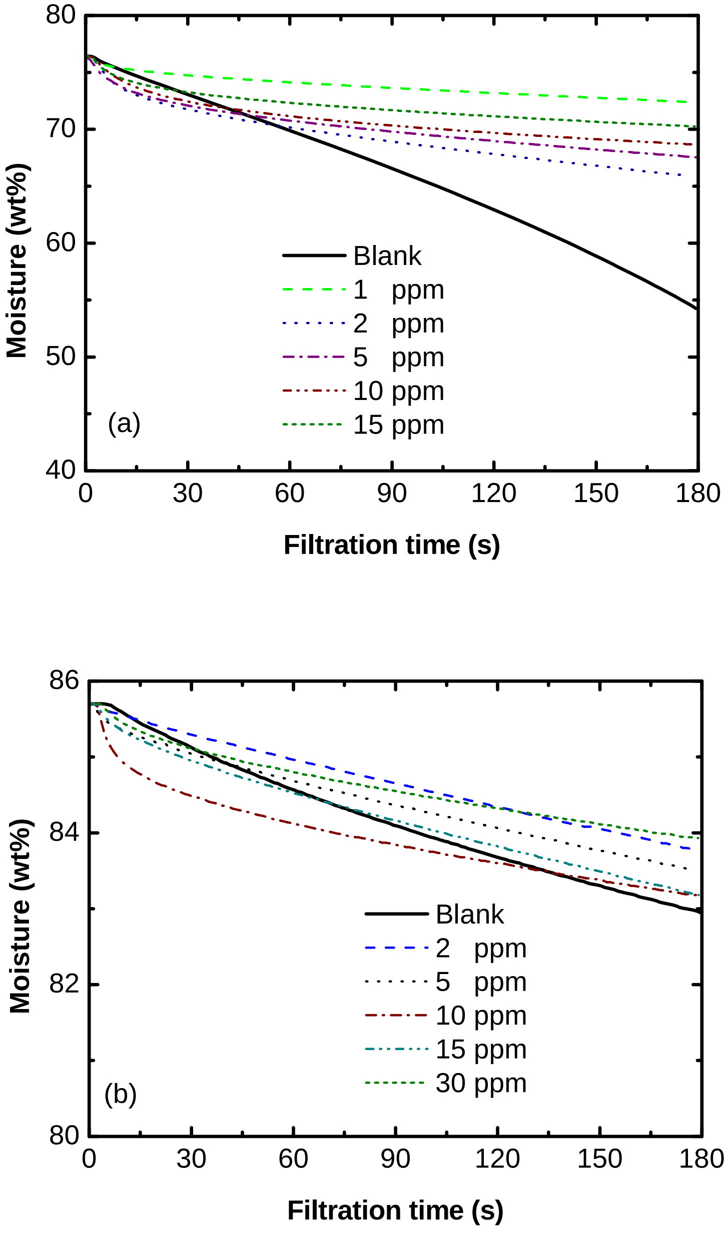


Figure 5-2-4 Effects of Magnafloc 1011 addition on the filtration of laboratory extraction tailings: (a) low fine tailings (b) high fine tailings

5.3 Discussion on the possible mechanism of Magnafloc 1011 addition on filtration of laboratory extraction tailings

As listed in Table 5-3-1, the surfaces of sand grains, clays and bitumen are all negatively charged in the process water. Magnafloc 1011 is an anionic polymer having net negative charge. Therefore, there is an electrostatic repulsion between the polymer molecules and the afore-mentioned surfaces. However, once the polymer molecules attach to these solid surfaces, the adhesion forces due to hydrogen bonding would tend to hold them together. Therefore, the probability for the polymer molecules attaching to these surfaces is directly related to the magnitudes of both the electrostatic repulsion and adhesion forces between flocculant and solid surfaces. Bitumen is of the most negatively charged surface (-45 mV) and the bonding between bitumen and Magnafloc 1011 is the weakest (40 pN). Subsequently, the probability for the polymer molecules to attach to the bitumen surface is much less than that for attaching to the clay surface which has the least negative charge (-20 mV) and bears the strongest hydrogen bond force with the polymer (100 pN). In addition, the edge of clay may well be positively charged [3], allowing the polymer molecules to attach to clay particles. Subsequently, Magnafloc 1011 would selectively adsorb on the clay surface instead of on the bitumen surface [6]. Since its weak adsorption on the bitumen surface would not allow the bitumen droplets or the bitumen contaminated clays to aggregate in the tailings, the remaining bitumen droplets or the bitumen contaminated clays in the tailings would blind the filter medium, resulting in the failure of the filtration of laboratory extraction tailings, which contain both residual bitumen and bitumen contaminated fines.

Table 5-3-1 Zeta potential and desorption force of Magnafloc 1011 in process water (pH = 8.4) [5]

Surface	Zeta potential (mV)	Desorption force of single strands (pN)
Silica	-30	50 ± 6.3
Bitumen	-45	40 ± 4.8
Mica	-20	100 ± 6.9

5.4 Summary

Magnafloc 1011 was found to be a good flocculant for both settling and filtration of the model tailings. The total solids content of model tailings sediments after 10 minute settling both reached 61wt% when 10 and 20 ppm of Magnafloc 1011 were added to solid suspensions, 25 wt% and 50 wt%, respectively. The corresponding ISR reached 27 m/h and 3 m/h. The supernatants of model tailings after the addition of Magnafloc 1011 were clear after a 10-minute settling.

The optimal dosage for the fastest filtration rate of the model tailings containing 25 wt%, 40 wt% and 50 wt% of solids was 4 ppm, 8 ppm and 10 ppm, respectively. The corresponding cake moisture was also the lowest at 14.5 wt%, 13.8 wt% and 13.8 wt%, respectively. The optimal dosage was a critical value for each model tailings, above which there was no segregation of solids. However, for the model tailings with 55 wt% solids, Magnafloc 1011 has a negligible effect on the filtration rate and on the cake moisture content. In all cases, the cakes were all non-segregating for the 55 wt% solids tailings.

For the laboratory extraction tailings tested, Magnafloc 1011 was a good flocculant for the settling. The dosage required to obtain fast settling for the low and high fine tailings was 10 ppm and 30 ppm, respectively. The ISRs of the low and high fine tailings were improved from being close to zero to 35 and 42 m/h, respectively. However, the supernatants after the addition of Magnafloc 1011 were not clear. Of importance, Magnafloc 1011 failed to perform well as a filtration aid: no filter cakes were formed after 180-second filtration for the two tested laboratory extraction tailings.

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Chapter 6 Al-PAM effect on settling and filtration of tailings

As discussed in Chapter 5, Magnafloc 1011 demonstrated to be a good aid for both the settling and filtration of the model tailings. However, for the laboratory extraction tailings, Magnafloc 1011 improved the settling but failed as a filtration aid.

In this chapter we will discuss the effect of Al-PAM addition on the settling and filtration of model tailings and two oil sands tailings obtained from laboratory oil sands extraction tests. As well, settling and filtration tests were conducted on one paraffinic forth treatment tailings, the composition of the tailings is provided in Table 4-1-3.

6.1 Effect of Al-PAM addition on model tailings

6.1.1 Effect of Al-PAM addition on settling of model tailings

As discussed in Chapter 5, for the model tailings, kaolin was used as model fines and sand to fines ratio (SFR) of 4 was used. The total solids (sand plus kaolin) content was varied from 25 to 50 wt%.

As shown in Figure 6-1-1, the settling at the end of ten minutes without the addition of the polymer was marginal. It is shown in Figure 6-1-1 that the settling of the model tailings was improved dramatically when Al-PAM was added. For model tailings with 25 wt% and 50 wt% of solids, the solids concentration of the sediment reached 64 wt% after ten minute settling, when the dosage of Al-PAM was 10 ppm and 20 ppm, respectively.

For both model tailings of 25 and 50 wt% solids, the increase in ISRs is comparable to the case with Magnafloc 1011 with increasing dosage of Al-PAM (Figure 6-1-2). For the model tailings with 25 wt% solids, the ISR increased from almost zero to about 21 m/h when the dosage of Al-PAM increased from 0 to 10 ppm; and to 3.5 m/h for the tailings of 50 wt% solids. Consequently, within the tested conditions, both Al-PAM and Magnafloc 1011 were good flocculants for the settling of the model tailings, and the corresponding dosages required to obtain similar ISRs were similar (Figure 6-1-2).

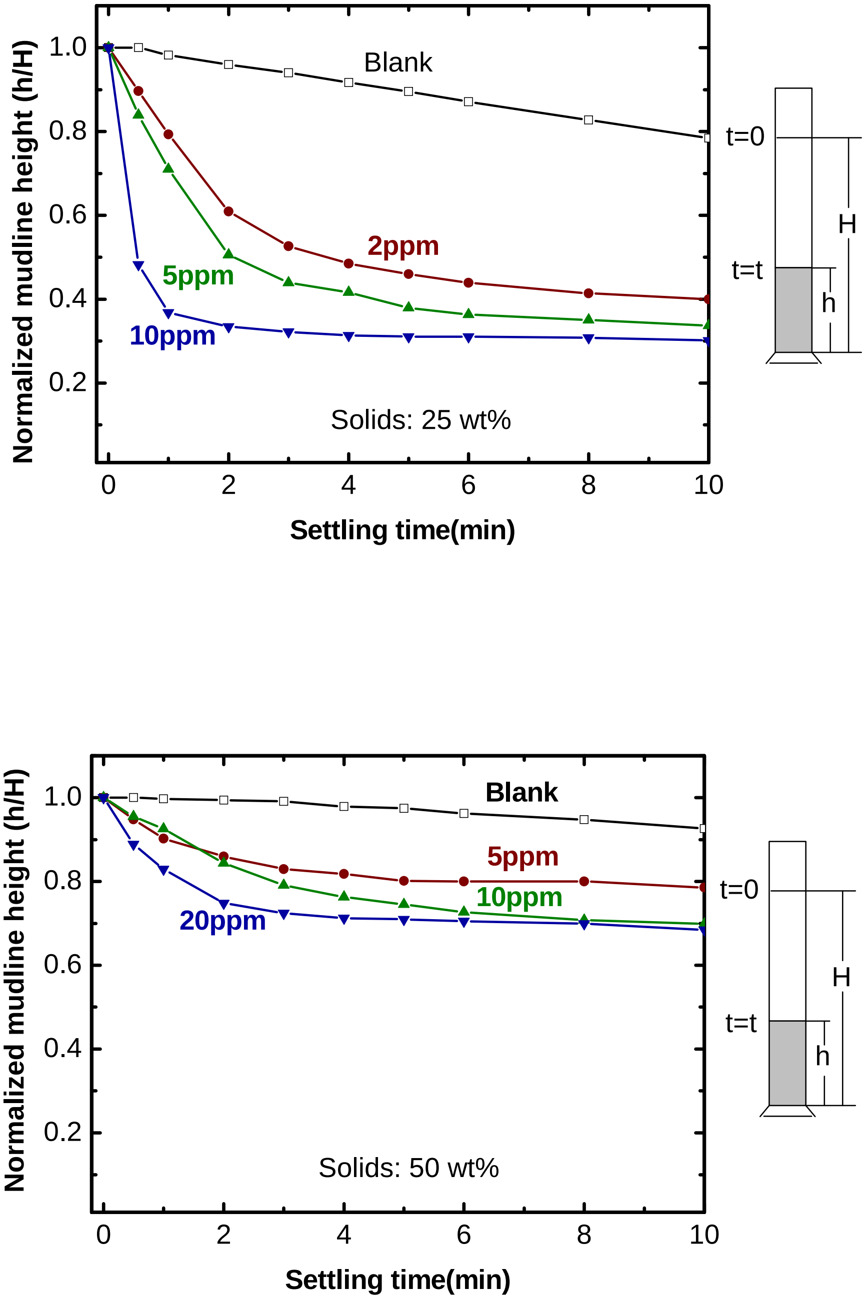


Figure 6-1-1 Effect of Al-PAM addition on settling of the model tailings

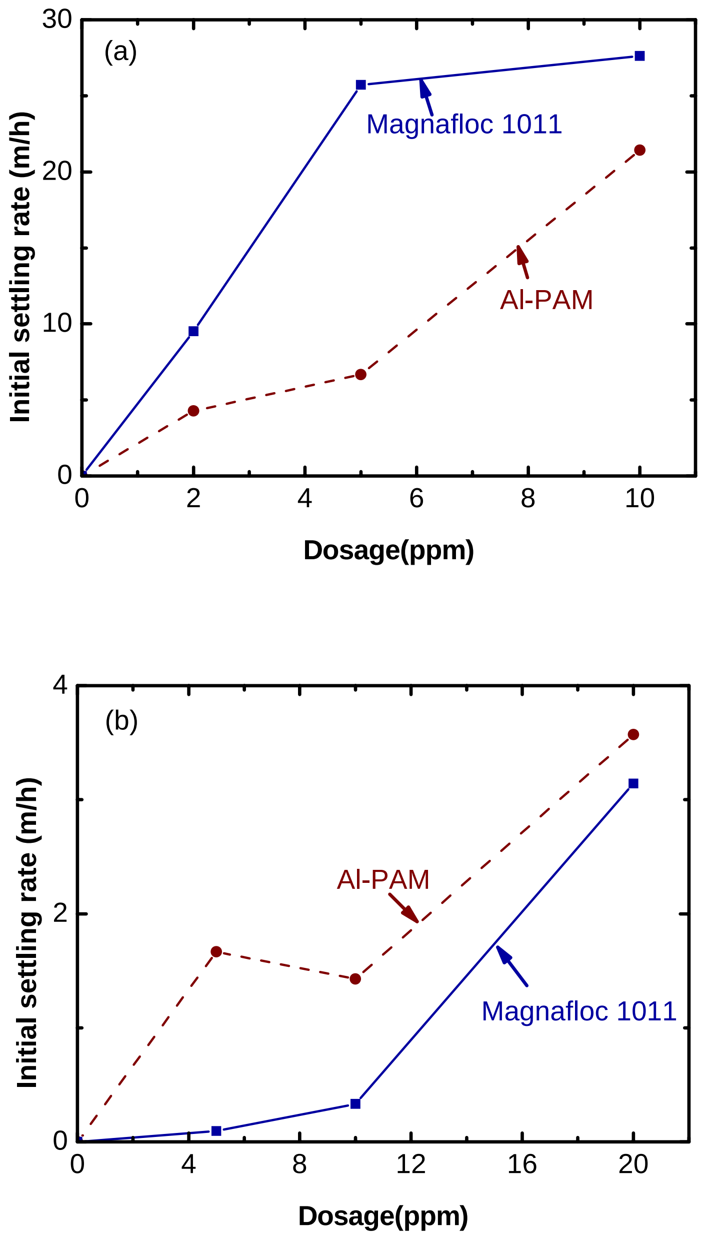


Figure 6-1-2 Comparison of ISR of model tailings with the addition of Al-PAM and Magnafloc 1011 where the solids content is: (a) 25 wt % and (b) 50 wt %

Another similarity between Magnafloc 1011 and Al-PAM was the formation of non-segregating tailings (NST) as the polymer dosage was above a certain critical value: 5 ppm and 10 ppm for model tailings of 25 and 50 wt% solid, respectively, as shown in the Figure 6-1-3. In addition, the supernatants of the model tailings were both clear with the addition of either Magnafloc 1011 or Al-PAM polymers. The turbidity of the supernatants of the model tailings with original solid content of 25 wt% was reduced from 380 NTU to 31 NTU as Al-PAM dosage increased from 0 to 10 ppm (Figure 6-1-4).

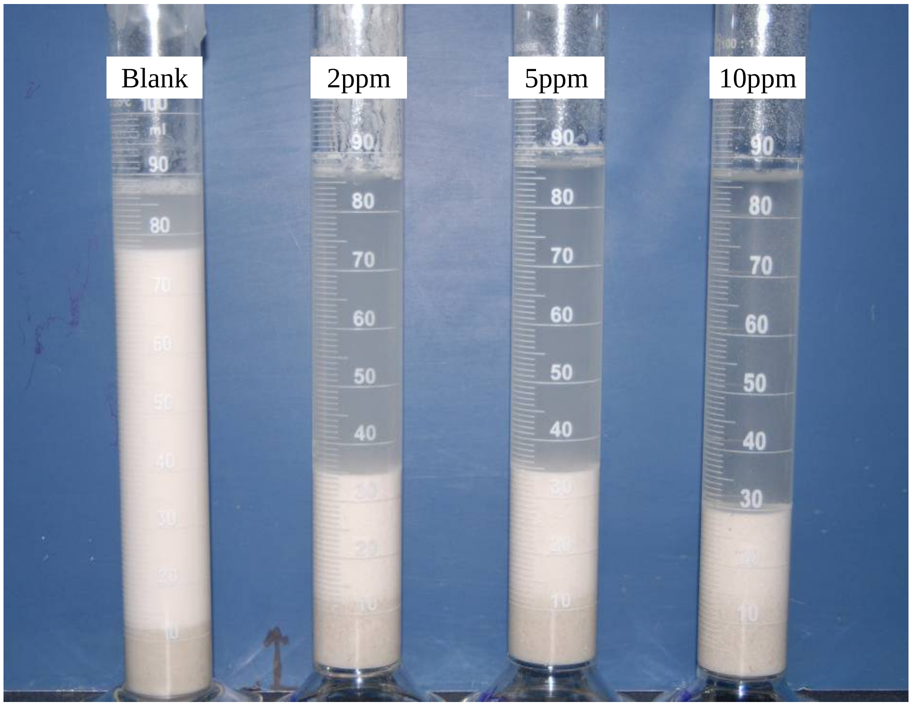


Figure 6-1-3 Photographs of model tailings with the addition of Al-PAM after ten minutes of settling time (Total solid content: 25 wt %)

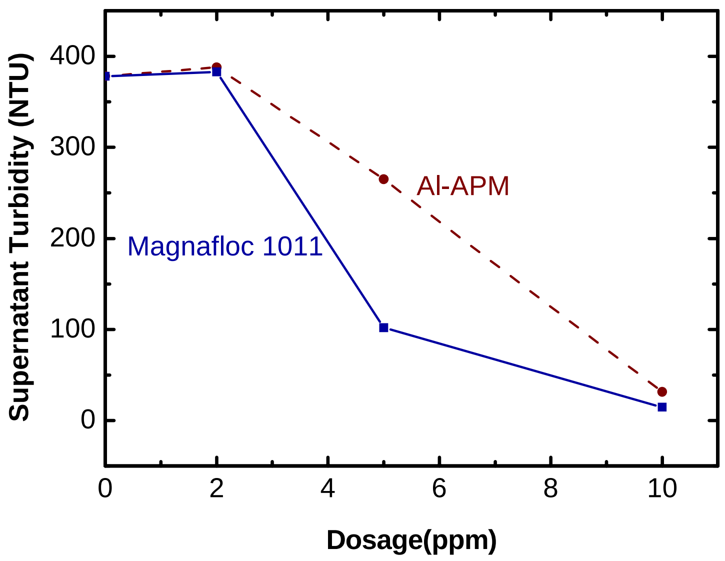
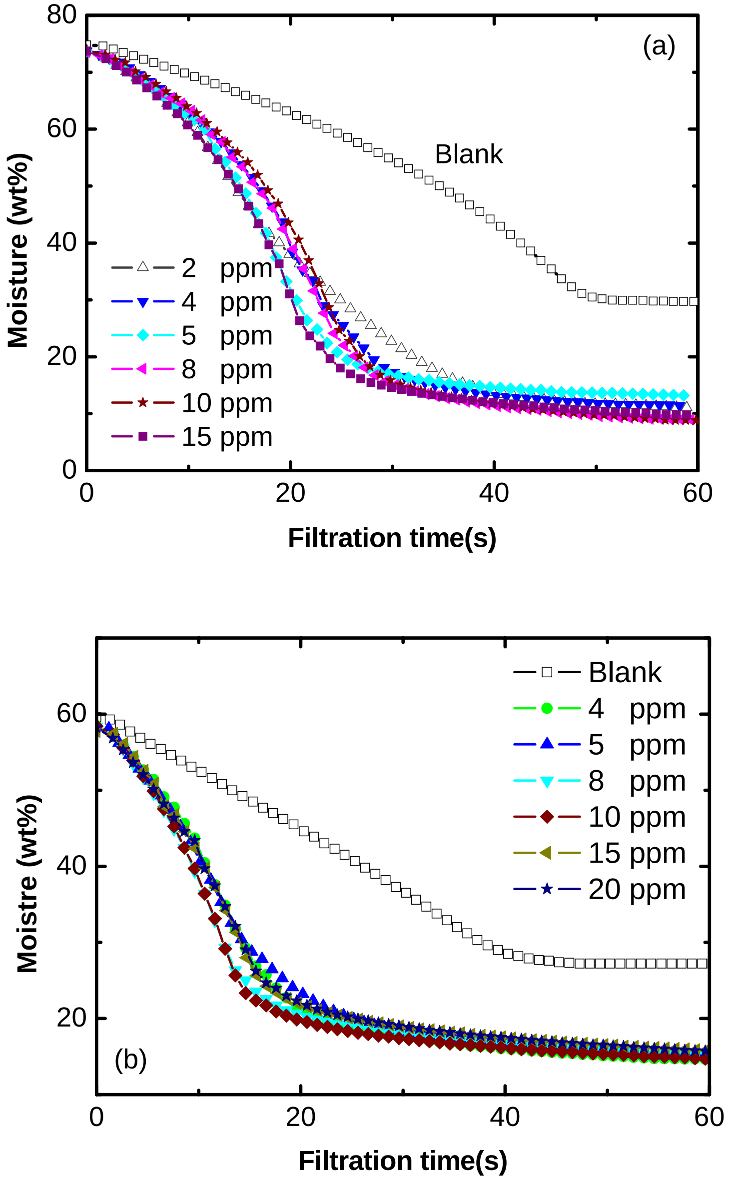


Figure 6-1-4 Turbidity of supernatants of model tailings after ten minutes of settling time with the addition of Al-PAM and Magnafloc 1011 (Total solid content: 25 wt %)

To summarize, addition of either Magnafloc 1011 or Al-PAM can dramatically increase the settling rate of the tested model tailings. Such an improvement in tailings settling indicates that they are good candidates for filtration of the model tailings.

6.1.2 Effect of Al-PAM addition on filtration of model tailings

The effect of Al-PAM on the filtration of three model tailings of solids content varied from 25, 40 to 50 wt%, and SFR of 4 was similar to the tests conducted with Magnafloc 1011.



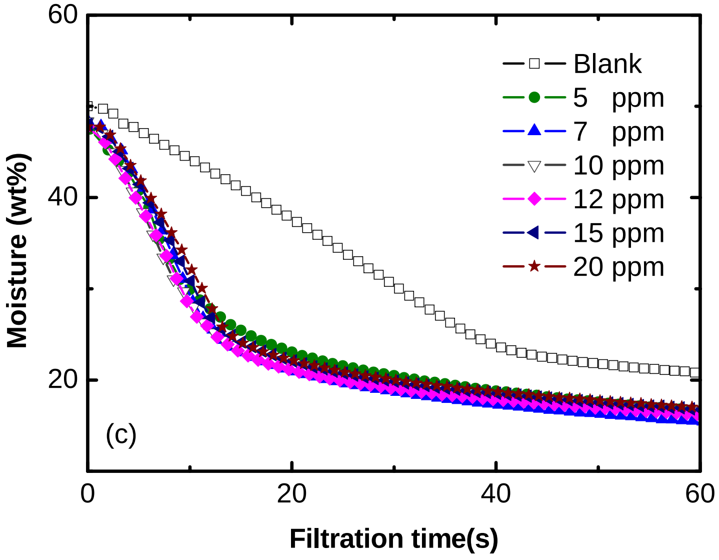


Figure 6-1-5 Effect of Al-APM addition on filtration of model tailings where solid content is: (a) 25 wt % (b) 40 wt % (c) 50 wt %

Similar to the case of Magnafloc 1011 (Figure 5-1-5), under the test condition, Al-PAM improved the filtration of model tailings. However, different from Magnafloc 1011, the filtration of model tailings was not sensitive to the Al-PAM dosage, i.e., there was no clear overdose for all three model tailings within Al-PAM concentration range tested.

Both Al-PAM and Magnafloc 1011 remarkably lowered the cake moisture content for model tailings of varying solid contents (Figure 6-1-6). The general trend was that with Al-PAM addition, the cake moisture content was lower than that with Magnafloc 1011 addition. Possible reasons for lower cake moisture could be that the flocs formed with the addition of Al-PAM are dense, in comparison to the flocs produced with Magnafloc 1011 (Figure 6-1-7).

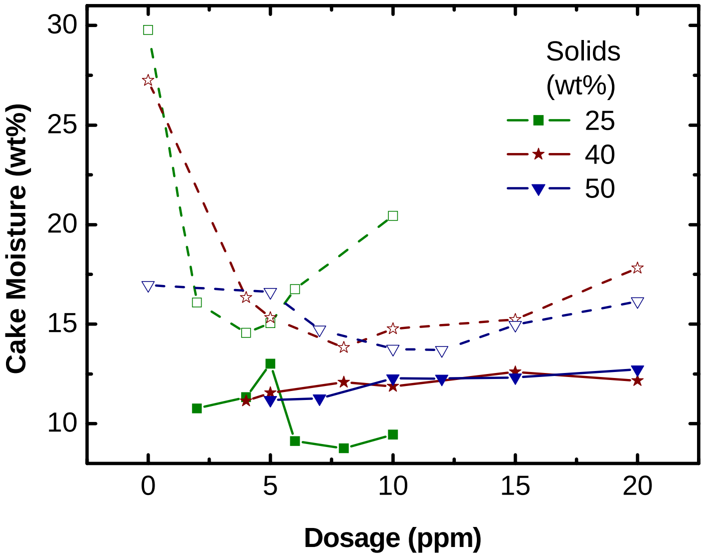


Figure 6-1-6 Cake moisture of model tailings with the addition of Al-APM and Magnafloc 1011 (Filled symbols: Al-PAM and Open symbols: Magnafloc 1011)

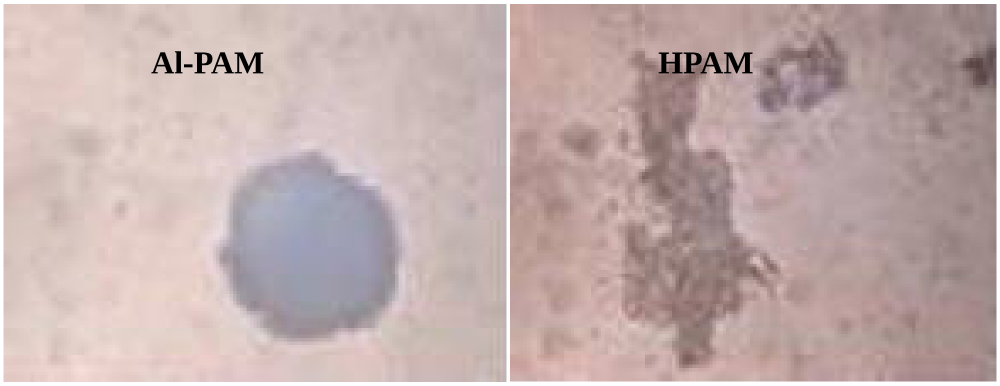


Figure 6-1-7 Morphology of the floccules formed from kaolin suspensions by Al-PAM and HPAM [4]

Subsequently, the water retained in the flocs formed by Al-PAM would be lower, i.e., the cake moisture content would be lower [4].

Consistent with what was observed in the settling tests, the cake formed with the addition of both polymers changed from being segregated to non-segregated as the dosage increased (Figure 6-1-8).

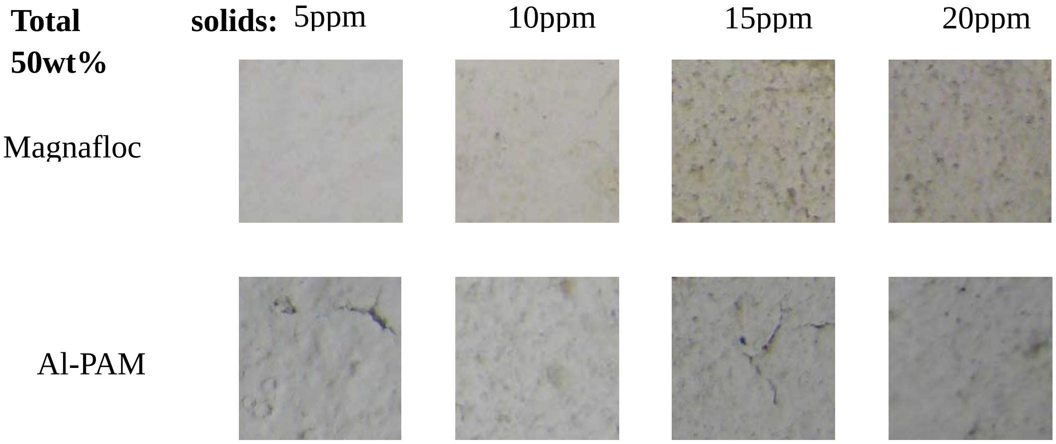


Figure 6-1-8 Comparison of the cake structure with the addition of Magnafloc 1011 and Al-PAM

Similar to the case of Magnafloc 1011, Al-PAM was a good chemical aid for both settling and filtration of the model tailings. The dosage required to reach similar ISR was close to that needed for Magnafloc 1011. However, at the tested conditions, the filtration of the model tailings was not sensitive to the dosage of Al-PAM, which is contrast to Magnafloc 1011. In addition, the cake moisture content of the model tailings was lower when Al-PAM was used than when

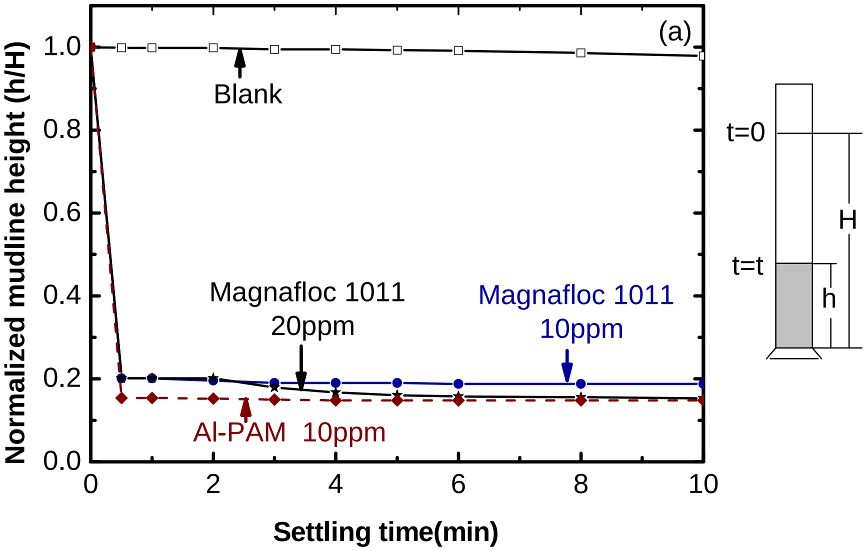
Magnafloc 1011 was used.

Based on the success of Al-PAM as an aid for settling and filtration of the model tailings, it was tested on laboratory extraction oil sands tailings.

6.2 Effect of Al-PAM addition on laboratory extraction tailings

6.2.1 Effect of Al-PAM addition on settling of laboratory extraction tailings

As a settling aid, Al-PAM was tested on the two laboratory extraction tailings. Similar to the case of Magnafloc 1011 (Figure 5-2-1), Al-PAM was found to be a good flocculant for the settling of laboratory produced extraction tailings (Figure 6-2-1).



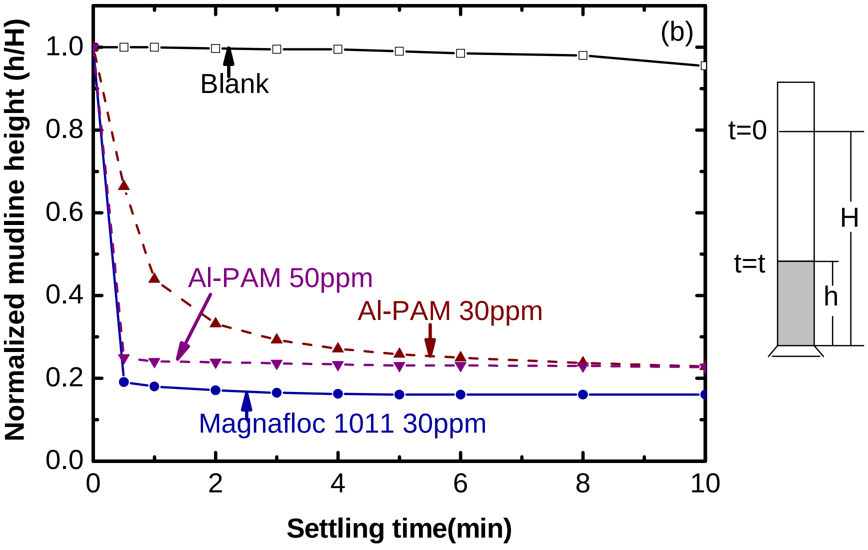


Figure 6-2-1 Comparison of the settling of the laboratory extraction tailings with the addition of Al-PAM and Magnafloc 1011 (a) low fine tailings (b) high fine tailings

For the low fine tailings, the normalized mud-line height, h/H, reached less than 0.2 within 30 seconds when 10 ppm of Al-PAM was added, which was comparable to the addition of 10 ppm Magnafloc. For the high fine tailings, the dosage required to obtain fast settling with Al-PAM was higher than that with Magnafloc 1011. A 50 ppm Al-PAM was needed to obtain similar settling results as with 30 ppm Magnafloc 1011.

As compared in Figure 6-2-2, the ISR of the low fine tailings reached about 36 m/h when 10 ppm of Al-PAM was added, which was very close to the ISR when 10 ppm of Magnafloc 1011 was used. However, for the high fine tailings, ISR was 19 m/h when 30 ppm of Al-PAM was added; in order to reach about 40 m/h ISR, 50 ppm Al-PAM was needed, which was higher than the required 30 ppm for Magnafloc 1011.

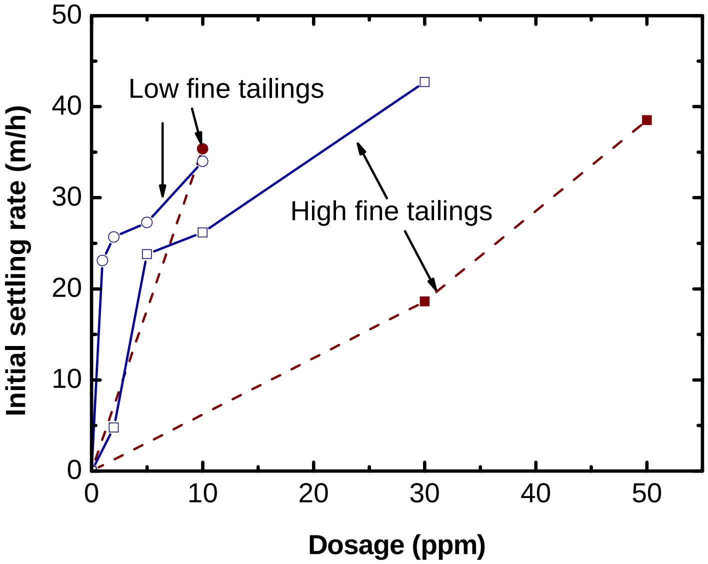
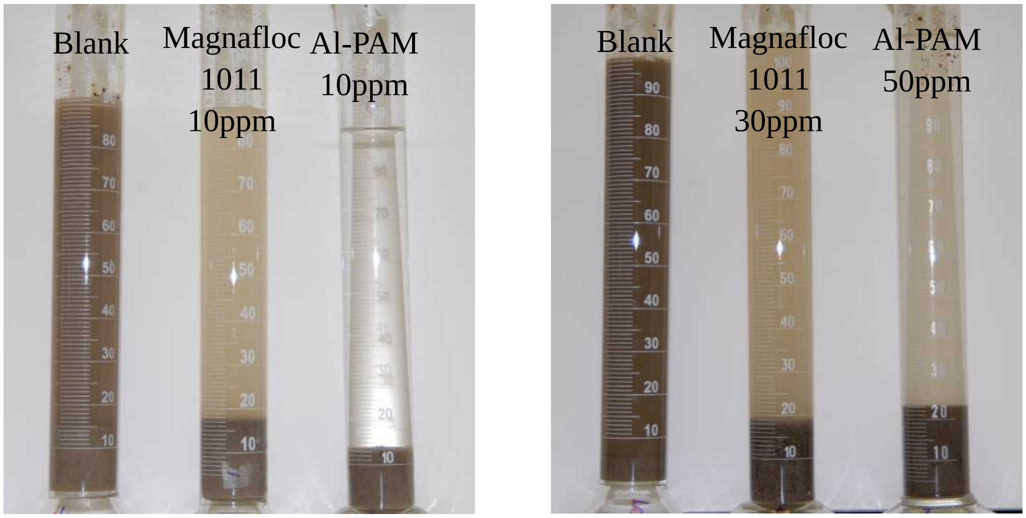


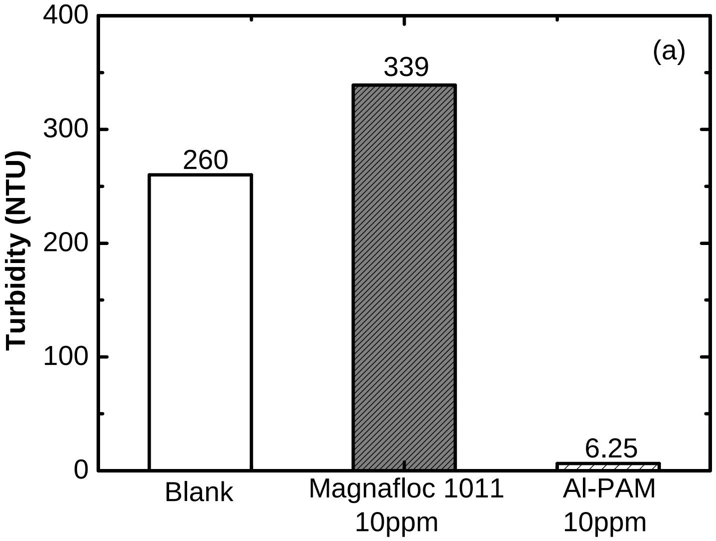
Figure 6-2-2 ISRs of the laboratory extraction tailings with the addition of Al-PAM and Magnafloc 1011(Dash: Al-PAM and Solid: Magnafloc 1011)

What we noted for the settling of the model tailings was that when either Al-PAM or Magnafloc 1011 was added, the supernatants were clear. However, for the laboratory extraction tailings, the supernatants after the addition of Al-PAM were much clearer than that with Magnafloc 1011 addition. The turbidity data after one hour settling are compared in Figure 6-2-4.



(a) (b)

Figure 6-2-3 Photographs of the laboratory extraction tailings with the addition of Al-PAM and Magnafloc 1011 after ten-minute settling time: (a) low fine tailings and (b) high fine tailings



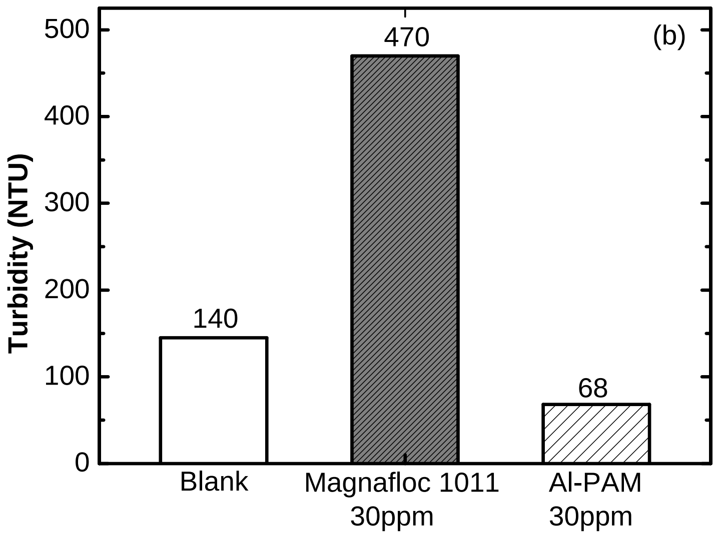


Figure 6-2-4 Comparison of the turbidity of supernatants with addition of Al-PAM and Magnafloc 1011 after one hour settling: (a) low fine tailings and (b) high fine tailings

When used for the filtration, would Al-PAM be effective in contrast to Magnafloc 1011, which failed as a filtration aid as we discussed in Chapter 5?

6.2.2 Effect of Al-PAM addition on filtration of the laboratory extraction tailings

Filtration rates and cake formation for both laboratory extraction tailings with the addition of Magnafloc 1011 were worse than without polymer addition. However, the addition of Al-PAM significantly improved filtration performance for both laboratory extraction tailings (Figure 6-2-5).

Furthermore, a more extensive mixing significantly improved the filtration of the high fine tailings when 50 ppm of Al-PAM were added (Figure 6-2-6).

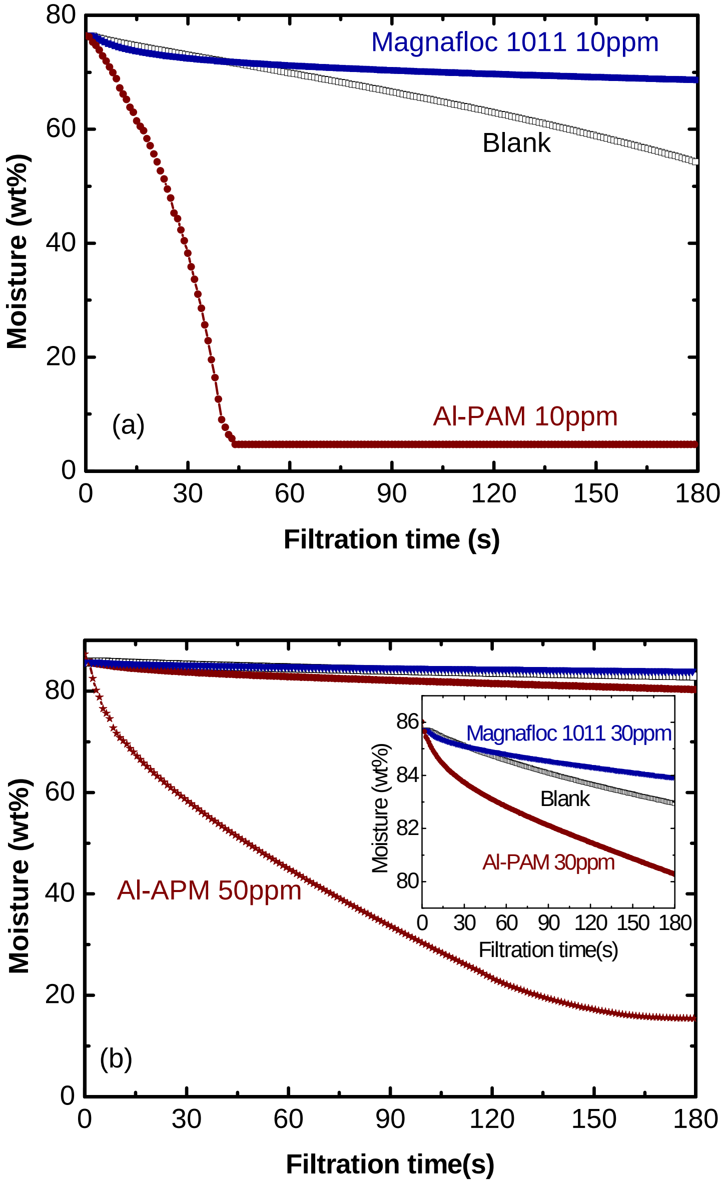


Figure 6-2-5 Filtration of laboratory extraction tailings with the addition of Al-PAM and Magnafloc 1011: (a) low fine tailings and (b) high fine tailings

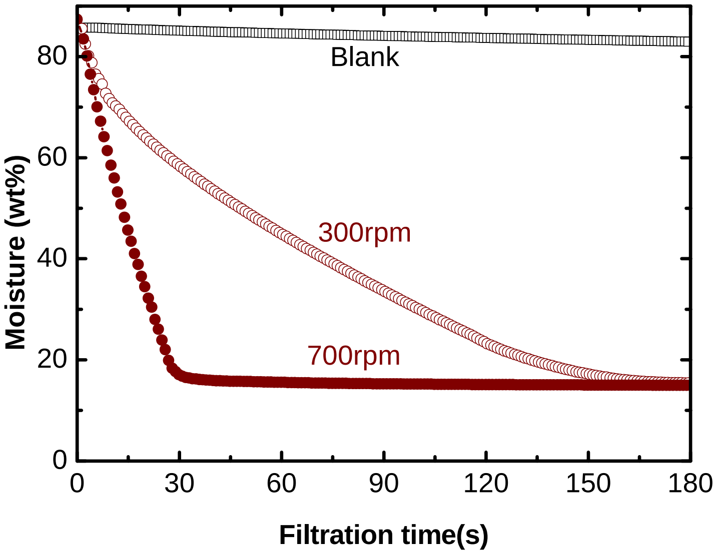
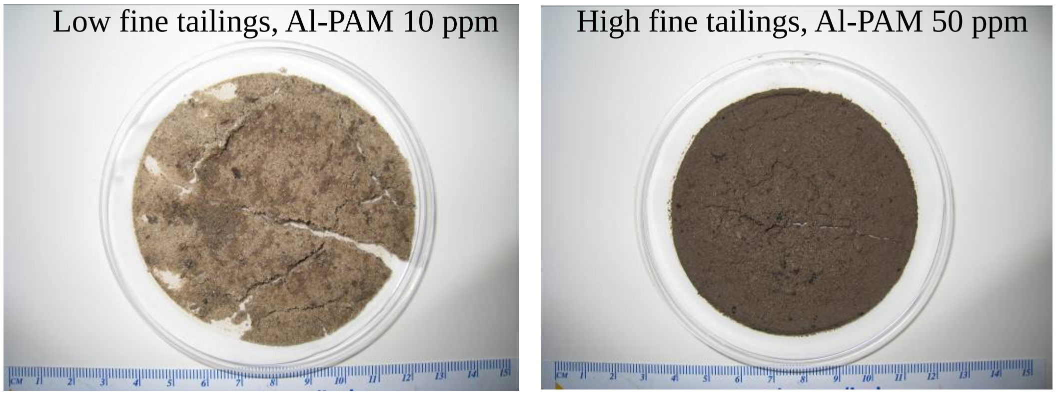


Figure 6-2-6 Effect of mixing on the filtration of the high fine tailings with the addition of 50 ppm Al-PAM

For the low fine tailings case, the moisture of the cakes obtained after 180-second filtration with the addition of 10 ppm Al-PAM was 6.6 ± 1.2 wt%, and for the high fine tailings, it was 16.9 ± 0.8 wt% when 50 ppm Al-PAM was added.

Two typical photographs of filter cakes obtained from the filtration of the low and high fine tailings are shown in Figure 6-2-7.


Low fine tailings, Al-PAM 10 ppm

High fine tailings, Al-PAM 50 ppm

Figure 6-2-7 Photographs of filter cakes obtained from filtration of the laboratory extraction tailings with the addition of Al-PAM

6.3 Effect of Al-PAM addition on paraffinic froth treatment tailings

Based on the successful experience of Al-PAM as an aid for settling and filtration of the laboratory extraction tailings, it was further tested on a paraffinic froth treatment tailings stream, which was rich in both fines and hydrocarbon (Table 4-1-3).

6.3.1 Al-PAM effect on settling of paraffinic froth treatment tailings

The settling tests of paraffinic froth treatment tailings were carried out in 1 L graduated cylinders. With the addition of 450 ppm of Al-PAM, the settling of paraffinic froth treatment tailings was fast (Figure 6-3-1), and the turbidity of the supernatants decreased from 429 NTU to less than 10 NTU after ten minutes of settling.

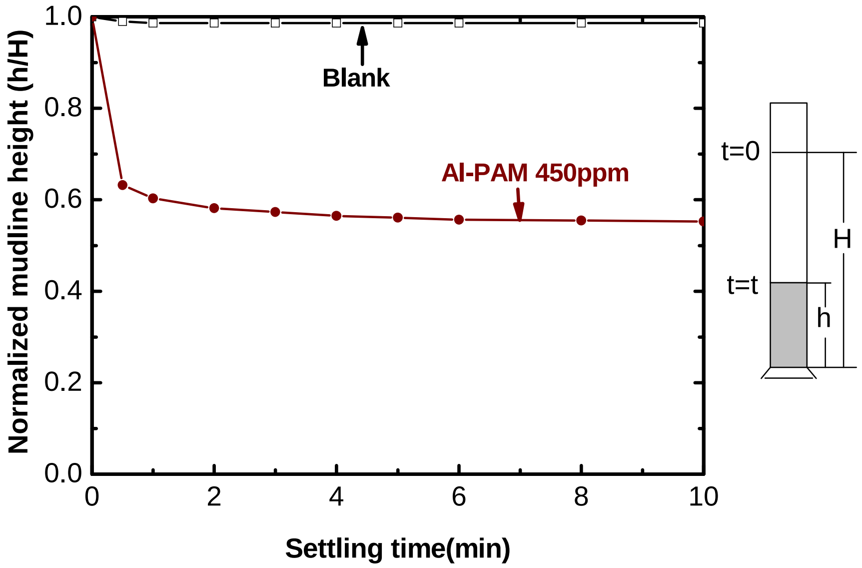


Figure 6-3-1 Effect of Al-PAM addition on settling of paraffinic froth treatment tailings

It is important to note that the fines and solid contents in the high fine tailings and paraffinic froth treatment tailings are comparable, i.e. solids content of the paraffinic froth treatment tailings is 14.4 wt% and fines are 43.9 %, and solids content of the high fine tailings is 13.6 wt% and fines are 40.1% (Table 4-1-2 and 4-1-3). However, the Al-PAM dosage required to obtain fast settling for the paraffinic froth treatment tailings (450 ppm) was much higher than that for the high fine tailings (30 ppm). A distinct difference between these two tailings was the hydrocarbon content, 10 wt% in the paraffinic froth treatment tailings, and 0.8 wt% in the high fine tailings. Therefore, one possible reason for the higher dosage required for the paraffinic froth treatment tailings was the consumption of Al-PAM by the hydrocarbon droplets in the paraffinic froth treatment tailings.

Another observation was that, the flocs formed from the paraffinic froth treatment tailings were less compacted than those from the laboratory extraction tailings. The final normalized mud-line height after 24 hours settling was only about 0.5, compared to 0.25 for the high fines tailings.

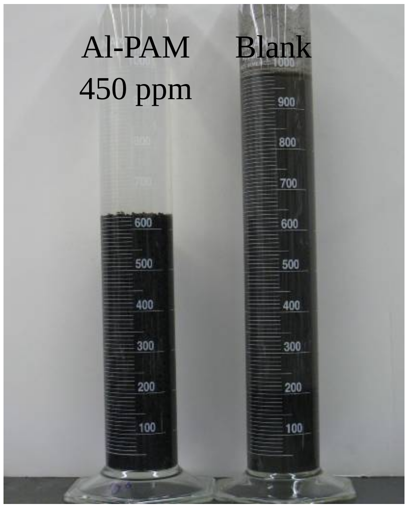


Figure 6-3-2 Photographs of the paraffinic froth treatment tailings with or without the addition of Al-PAM after ten minutes settling time

6.3.2 Effect of Al-PAM addition on filtration of paraffinic froth treatment tailings

As shown in Figure 6-3-3, the filtration of the paraffinic froth treatment tailings was marginal when no polymer was added. However, by adding 400 ppm Al-PAM, the tailings filterability was significantly improved.

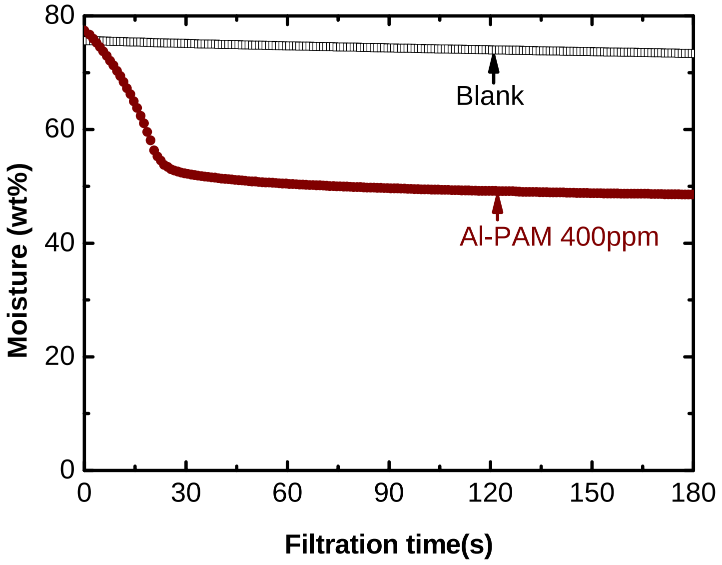


Figure 6-3-3 Effect of Al-PAM on filtration of paraffinic froth treatment tailings

Although the cake moisture was found to be 42.5 wt% after 180-second filtration with 400 ppm Al-PAM addition, the solid cake is self-supportive and remains intact without visible free water (Figure 6-3-4). In this case, the high cake moisture does not affect the reclamation measures. In the paraffinic solvent froth treatment process, most of the water and solids in the froth were contained in the network of asphaltenes and settled out from the froth to produce clean bitumen product [6]. As a result, much of the small water droplets were encapsulated by the asphaltene or residual bitumen. When Al-PAM was added to the paraffinic froth treatment tailings, the droplets were flocculated by Al-PAM, but the water inside the asphaltene flocs could not be released. Therefore, though the apparent moisture of the cake was high, it is mechanical intact, and can be sent to the reclamation site right away.

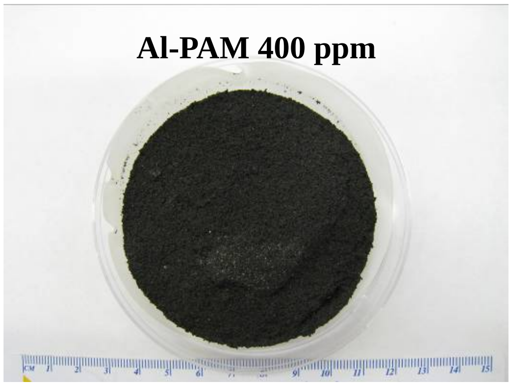
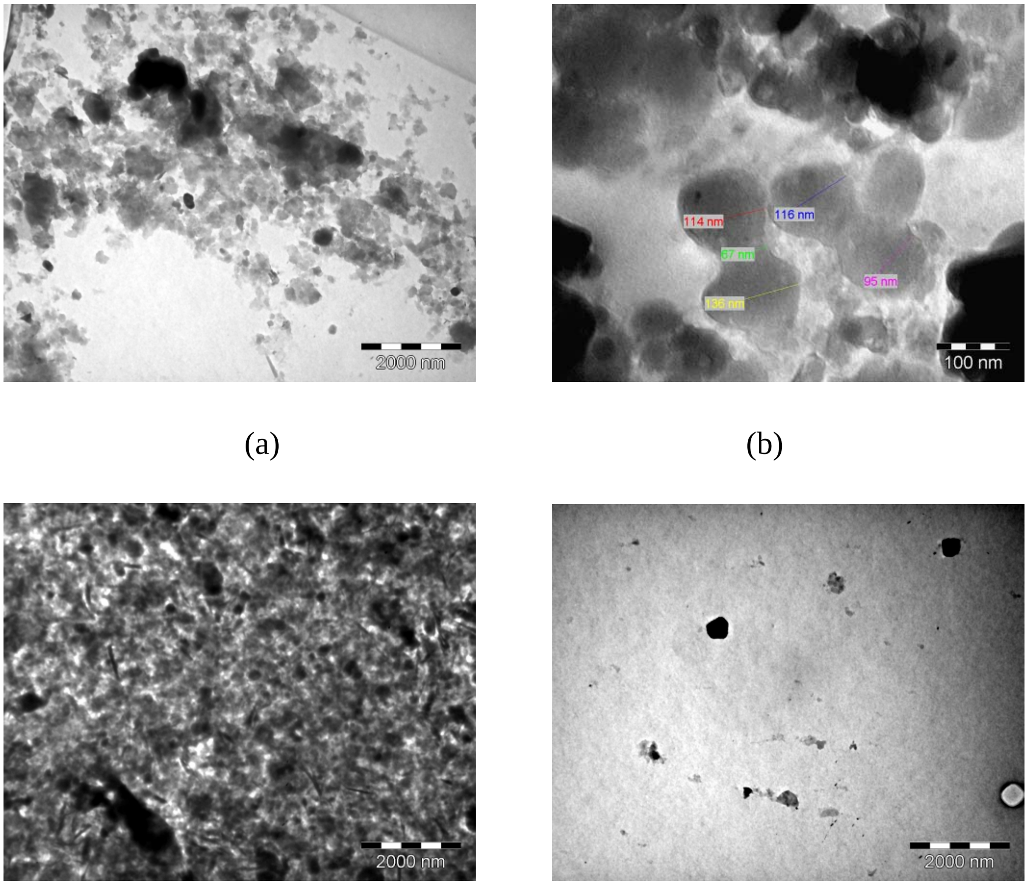


Figure 6-3-4 Photograph of cake obtained from filtration of paraffinic froth treatment tailings with the addition of 400 ppm Al-PAM

6.4 Discussion on the possible mechanism of Al-PAM enhanced filtration of oil sands tailings



(a) (b)

(c) (d)

Figure 6-4-1 TEM micrographs of the solids from supernatants of settled high fine tailings: (a) Blank, 22 X 1000; (b) Blank, 110 X 1000; (3) with the addition of Magnafloc 1011 30 ppm, 8.9 X 1000; and (d) with the addition of Al-PAM 50 ppm, 8.9 X 1000.

The effectiveness of polymer as filtration aids depends on whether or not it can flocculate the fines in the tailings. According to the research from Kotlyar group, kaolinite and mica with average size of about 50 to 400 nm were the main crystalline components of the colloidal solids in the oil sands tailings; and it was also found that the surface of the colloidal solids was contaminated with relatively polar organic matter [7-10]. The adsorbed organic matter with a number of ionized sites and high electronegativity increased the negative charge of clay and the stability of clay suspension through electrostatic and steric repulsion [11].

As shown in Figure 6-4-1, the size of fines in the supernatants of the high fine tailings was around 200 nm. We could note that there were more fines in the supernatant when Magnafloc 1011 was used (Figure 6-4-1 (c)) than without polymer addition (Figure 6-4-1 (a)), but very few particles were left in the supernatant when Al-PAM was added (Figure 6-4-1 (d)).

Why the supernatant of Al-PAM treated tailings can be so clear, i.e. the flocculation of the fines is better? There are three possible mechanisms of Al-PAM to get the clay particles flocculated.

The first mechanism is linked to the function of aluminum on polyacrylamide polymer chain. There is a strong affinity between aluminum and oxygen in the form of -O-Al-O-, and Al, Si and O are the main elements of clays [12]. Therefore, the Al-PAM can strongly attach to the clay surface in the form of -O-Al-O-]-Al-PAM binding. The presence of $Al(OH)_3$ as a functional group in Al-PAM molecular structure may help the adsorption of the Al-PAM on a clay surface [3]. The second mechanism is associated with the electrostatic interaction between Al-PAM and clay. The zeta potential of $Al(OH)_3$ colloid core of Al-PAM is about +20 mV (Table 3-2-1). There exists an electrostatic attraction between the positively charged core and the negatively charged clay fines [3]. Therefore, in addition to common adsorption of the polyacrylamide chains on clay particles by hydrogen binding, the cationic $Al(OH)_3$ cores in the Al-PAM are attracted to the negatively charged clay particles by electrostatic attractions, enhancing Al-PAM adsorption on clay surfaces. The third mechanism is attributed to the star-like structure of Al-PAM [4]. The clay floccules formed by Al-PAM were larger and denser than those formed by Magnafloc 1011. These floccules have a spherical shape (Figure 6-4-2) compared to an irregular shape induced by Magnafloc 1011.

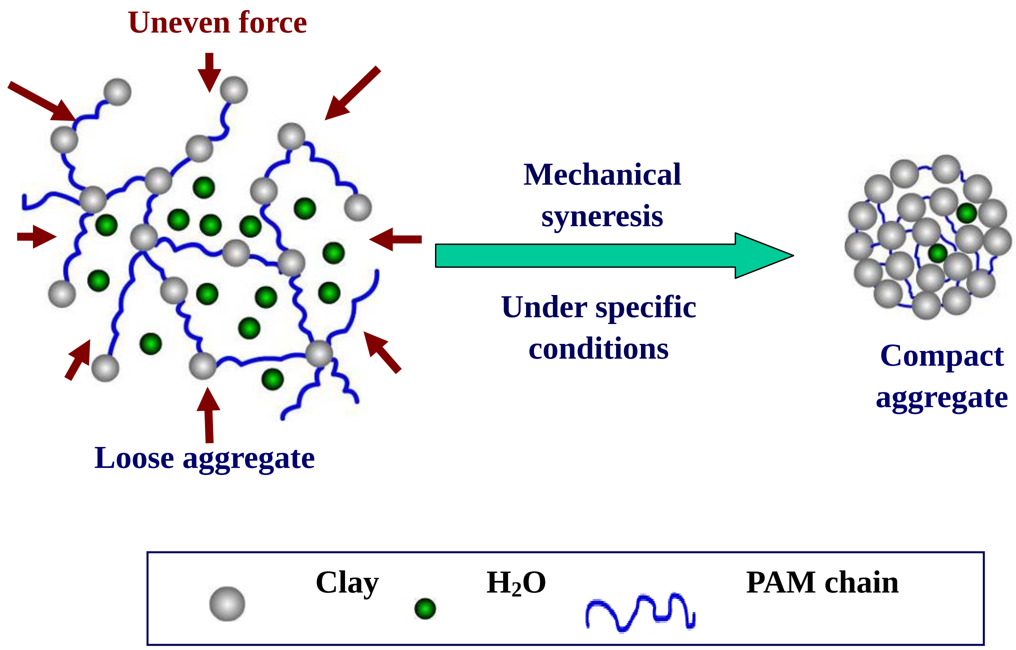
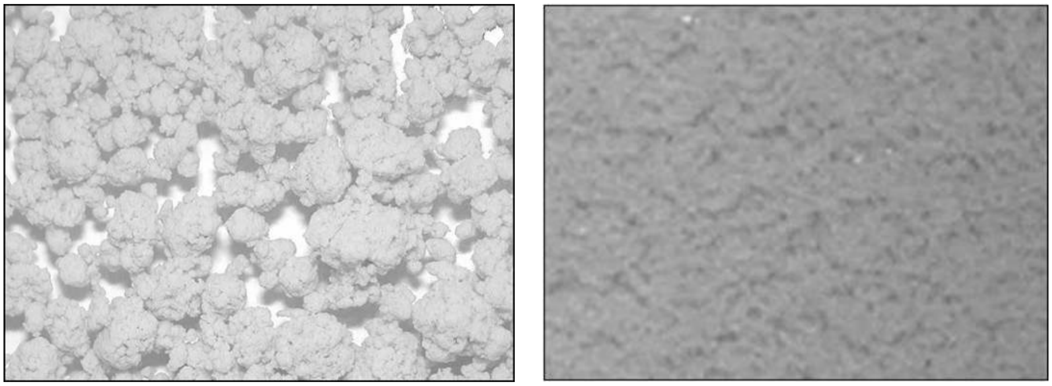


Figure 6-4-2 Illustration of Al-PAM flocculation [13]



(a) (b)

Figure 6-4-3 Flocules formed with the addition of: (a) Al-PAM; (b) Magnafloc 1011

In addition to having the clay fines in the tailings well flocculated by Al-PAM, the polymer is also an excellent flocculant of fine bitumen droplets. Emulsified bitumen in the tailings can be flocculated in the presence of Al-PAM.

The presence of Al-PAM changes bitumen-water interfacial properties. As the dosage of Al-PAM is increased, the contact angle of water on bitumen surface increases (Figure 6-4-4), thereby rendering the bitumen surface more hydrophobic. As a result, the bitumen droplets in the tailings water due to their increased hydrophobicity would more likely aggregate to form large flocs. Indeed, large bitumen lumps were observed in bitumen extraction tests with Al-PAM addition [3].

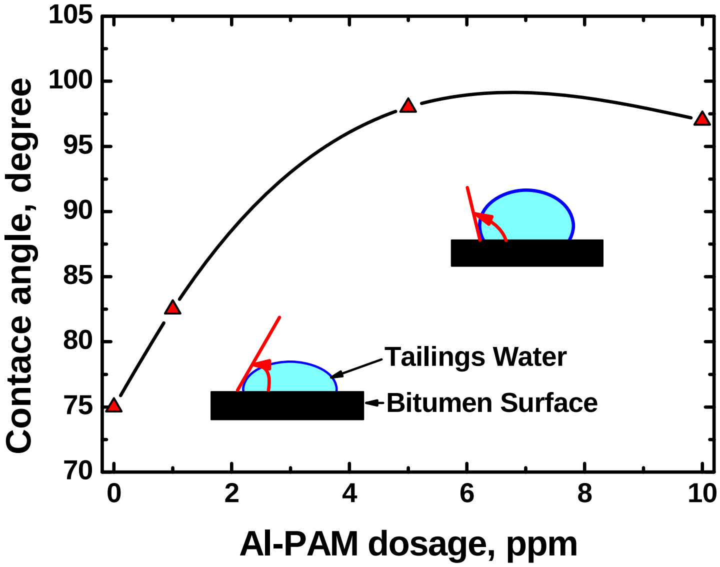


Figure 6-4-4 Contact angle of tailings water on a bitumen surface as a function of Al-PAM dosage (revised from [3])

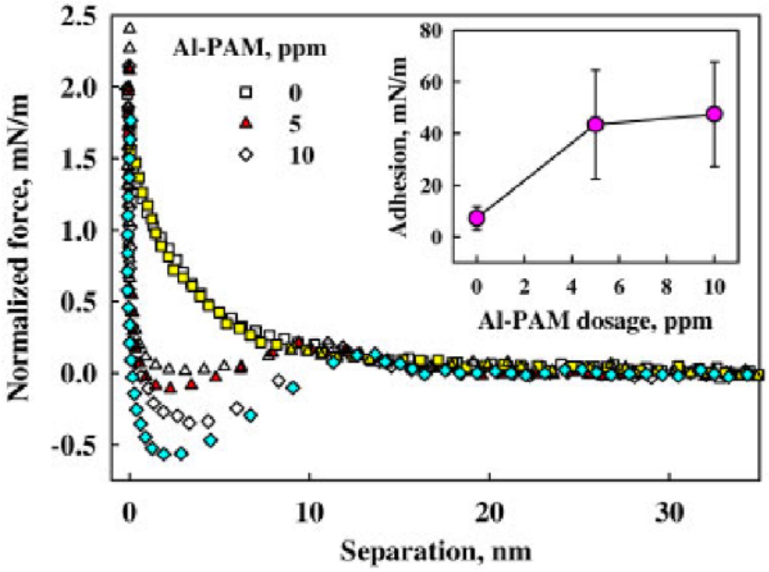


Figure 6-4-5 Bitumen-bitumen adhesion forces as a function of Al-PAM dosage[3]

The increased attraction between bitumen droplets has been confirmed previously from the atomic force microscope (AFM) colloidal force measurements by Li et al.

[3]. It was reported that the presence of Al-PAM enhanced the adhesion of bitumen droplets, most likely due to the improved hydrophobicity and decreased surface charge of bitumen upon Al-PAM adsorption, thereby leading to strong bridging. As bitumen is normally negatively charged in an alkaline solution [13], the long-range interactions between bitumen-bitumen are purely repulsive in the absence of polymer addition. When Al-PAM is added, the repulsive forces remain unchanged beyond 10 nm separation distance. Since there exists electrostatic attraction between the positively charged $Al(OH)_3$ cores in the Al-PAM molecules and the negatively charged sites on the bitumen surface, the extruded polymer chains adsorbed on one surface will attach to the other surface within 10 nm when they approach each other. As shown in Figure 6-4-5, the adhesion force between bitumen and bitumen increased from being negligible to about 40 mN/m as Al-PAM dosage increased from 0 to 10 ppm [3]. The presence of an attractive long range interaction and a strong adhesion between bitumen surfaces facilitates coalescence of bitumen droplets, whereby aggregating the residual fine bitumen droplets in the tailings into larger blobs. Such large bitumen blobs have less opportunity to block pore passages of the filter cake and the filter medium. Elimination of the fine bitumen drops from the tailings is a key process parameter that should be considered in oil sands tailings filtration. Presence of Magnafloc 1011 in the tailings water did not show the same ability to flocculate the residual emulsified bitumen.

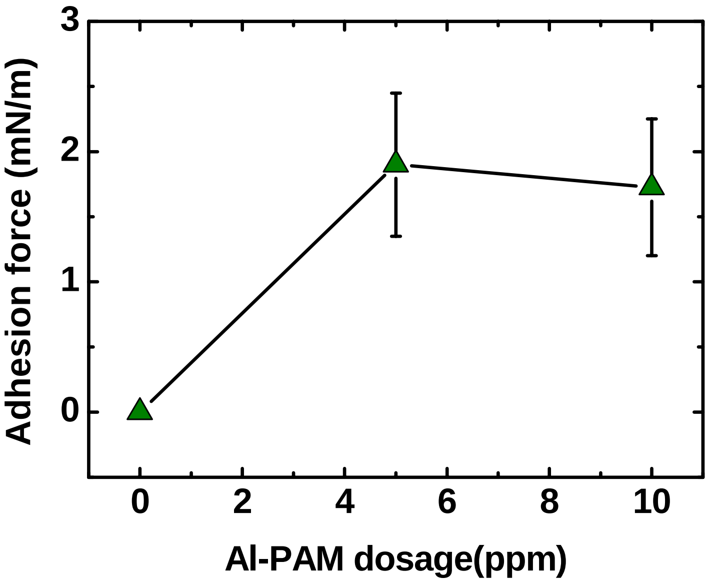


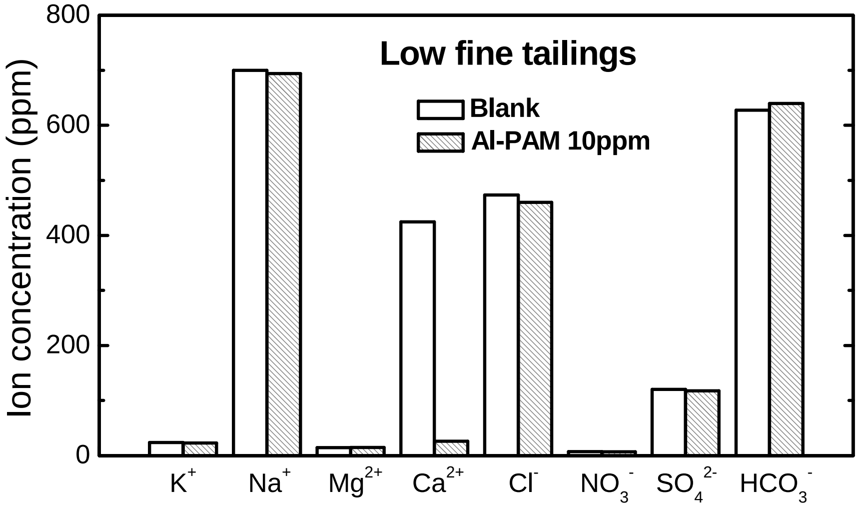
Figure 6-4-6 Clay-silica adhesion forces as a function of Al-PAM dosage (revised from [3])

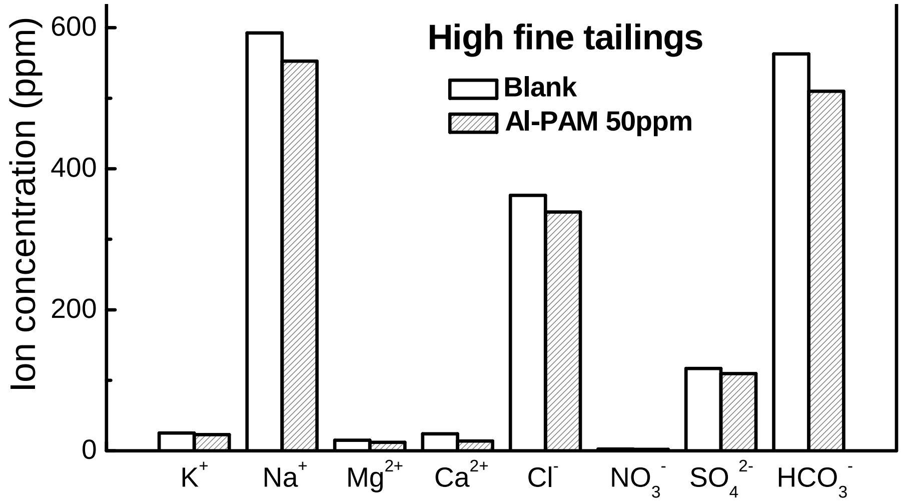
Furthermore, the addition of Al-PAM is beneficial for the clay–sand attachment in the tailings. Without polymer addition, the adhesion force between clay particles and the silica wafers (representing sand grains in oil sands) is zero, and the measured long-range force is purely repulsive [15]. The combination of a strong long-range repulsion and zero adhesion indicates that the fine solid particles in the tailings slurry would remain in a well-dispersed state. However, when Al-PAM is added, the long range repulsion force is depressed, while the adhesion force increased from 0 to about 2 mN/m. Such strong adhesion forces are induced by the formation of polymer bridges between the aluminum cores of Al-PAM and the negatively charged sites on the silica and/or clay surface [3]. The solids are bridged by PAM chains, leading to flocculation of fines and fast settling of fines in the tailing slurry.

Since Al-PAM can flocculate the clay particles and coalesce bitumen droplets into large blobs in the tailings, we can assume that the hydrocarbon-contaminated clay particles in the tailings can be either effectively flocculated similar to clean clay particles or aggregated similar to bitumen droplets or both. When Al-PAM is used to treat the oil sands tailings, fines in the tailings would be well aggregated, keeping the filter cloth and cake from being blocked. Moreover, Al-PAM increases the clay-sand attachment, which further facilitates non-segregating settling of coarse sands from fines. All the aforementioned aspects contribute to the good performance of Al-PAM on the settling and filtration of oil sands tailings.

6.5 Effect of Al-PAM addition on water quality of filtrate

The ion concentrations of filtrate after the addition of Al-PAM are compared in Figure 6-5-1.


Low fine tailings
Blank
Al-PAM 10ppm
Ion concentration (ppm)
0
200
400
600
800
K^+
Na^+
Mg^{2+}
Ca^{2+}
Cl^-
NO_3^-
SO_4^{2-}
HCO_3^-


High fine tailings
Blank
Al-PAM 50ppm
Ion concentration (ppm)
0
200
400
600
K^+
Na^+
Mg^{2+}
Ca^{2+}
Cl^-
NO_3^-
SO_4^{2-}
HCO_3^-

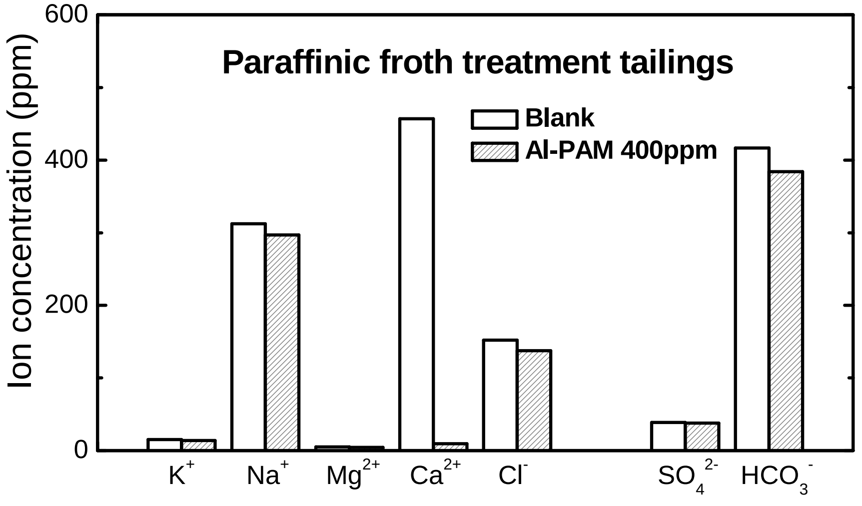

Paraffinic froth treatment tailings
Blank
Al-PAM 400ppm
Ion concentration (ppm)
0
200
400
600
K^+
Na^+
Mg^{2+}
Ca^{2+}
Cl^-
SO_4^{2-}
HCO_3^-

Figure 6-5-1 Effect of Al-PAM on the ion concentrations of filtrate: (a) low fine tailings; (b) high fine tailings; (c) paraffinic froth treatment tailings

It is consistent with the conclusions from other researchers [16], that the polymer addition has a negligible effect on the water chemistry. For the low fine tailings and the paraffinic froth treatment tailings, the concentration of calcium in the filtrate with Al-PAM was much lower than that without Al-PAM addition. A possible reason is that the adsorption of calcium on the clay surface was increased with the presence of Al-PAM, such that less calcium remained in the filtrate [16].

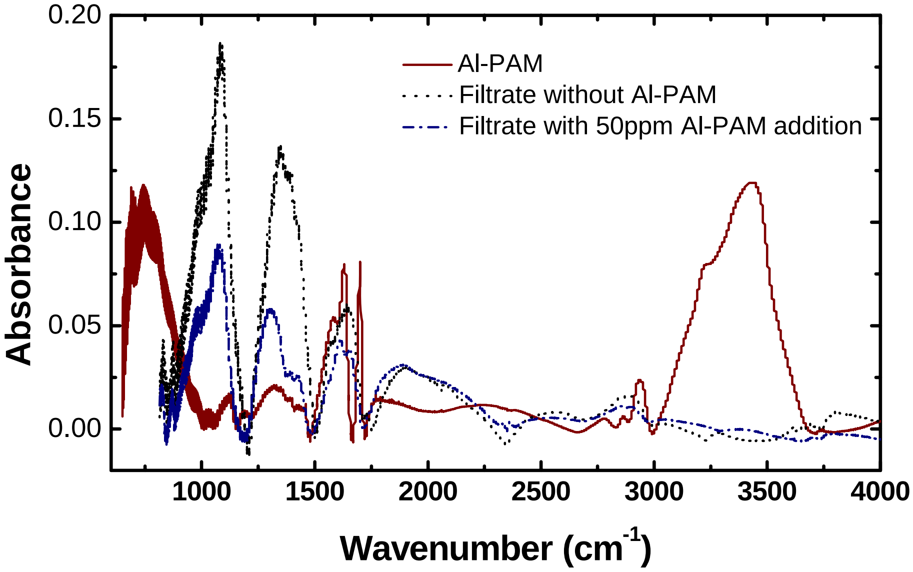


Figure 6-5-2 Effect of Al-PAM on the FTIR of filtrate of the high fine tailings

FTIR was used to analyze the filtrate with and without Al-PAM addition of for the high fine tailings. As shown in Figure 6-5-2, no Al-PAM peaks were observed in the filtrate when 50 ppm of Al-PAM was used. Thus we can assume that the concentration of polymer in the filtrate is negligible, but further analysis is needed to obtain the exact Al-PAM concentration. The extraction tests from our group indicated that with 0 to 20 ppm of Al-PAM addition in the extraction process, the bitumen recovery of poor ore dropped a little, but the froth quality was improved [3]. Without knowing the exact concentration of polymer in the filtrate, it is too early to conclude whether or not there is a detrimental effect of residual Al-PAM from the recycled filtrate to the extraction process.

6.6 Summary

Al-PAM was found to be a good flocculant for both settling and filtration of the model tailings. The solids content in the sediments of 25 wt% and 50 wt% model tailings both reached 64 wt% after ten minutes of settling when 10 and 20 ppm of Al-PAM were added, respectively. The corresponding ISRs reached 21 m/h and 3.5 m/h. The supernatants of model tailings after the addition of Al-PAM were clear after 10 minute settling. In contrast to Magnafloc 1011, Al-PAM showed no sensitivity to dosage over the concentration range for the filtration of tested model tailings. The cake moistures with the addition of Al-PAM were all lower than those with the addition of Magnafloc 1011.

For the actual tailings from laboratory extraction and paraffinic froth treatment tailings tested, Al-PAM was also found to be good flocculant both for settling and filtration. The dosage required to obtain fast settling was 10 ppm and 30 ppm for the low and high fine tailings, respectively, and was 400 ppm for the paraffinic froth treatment tailings. The ISRs of the low and high fine tailings were improved from marginal to 36 and 19 m/h, respectively. The supernatants of the settled tailings after the addition of Al-PAM were clear. The turbidity after one hour settling at optimal dosage reached 6 and 68 NTU, respectively.

At appropriate dosage and mixing condition, dry cakes were obtained when Al-PAM were added for all three tested real tailings. The required dosage of Al-PAM to obtain fast filtration increased with increasing fines and hydrocarbon content in the tailings. The dosage required for the low fine tailings and the high fine tailings was 10 ppm and 30 ppm, respectively. However, for the paraffinic froth treatment tailings, 400 ppm was required to obtain effective filtration. The cake moisture obtained with the addition of Al-PAM was 6.6±1.2 wt% for the low fine tailings and 16.9±0.8 wt% for the high fine tailings. The cake moisture of the paraffinic froth treatment tailings was 42.5 wt%, but the cake essentially feels dry.

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Chapter 7 Filtration theory analysis on the effect of polymer addition on filtration of oil sands tailings

Filtration is a unit operation dealing with the separation of solids from a suspension through a permeable medium that retains the particulate matter. Filtration processes are usually divided into two classes: deep bed filtration and cake filtration [1]. Deep bed filtration is suitable for suspensions having low solids concentration normally less than 0.1 wt%, where the particulates are considerably smaller than the pores of the medium whereby they can be captured and attached to the medium as they penetrate through the bed. Deep bed filtration is commonly used for clarification of, for example, drinking-water or waste water treatment. Cake filtration, in which the solids are deposited in the form of a cake on the up-stream side of a relatively thin medium, is suitable for suspensions with higher solids concentrations. It is widely used in the industry, and is very well suited to the filtration of concentrated suspensions and the recovery of large quantities of solids.

The most important factors which affect the rate of cake filtration include: (1) the pressure drop across the medium; (2) the area of the filter surface; (3) the viscosity of the filtrate; (4) the resistance of the filter cake, (5) permeability of formed cake, and (6) the resistance of the filter medium and initial layer of the deposited cake [1, 2].

There are two modes of operation in a cake filtration: one is at constant pressure drop (ΔP =constant) and another one at constant filtration rate, i.e. $\frac{dV}{dt}$ = constant. The modified Darcy equation can describe the factors controlling cake filtration:

$$u = \frac{1}{A}\frac{dV}{dt} = \frac{\Delta P}{\mu_f (R_c + R)} \tag{1}$$

where:

u : Superficial velocity of filtration (m/s)

A : Area of filter (m^2)

V : Collected volume of filtrate in time t (m^3)

t : Filtration time (s)

ΔP : Pressure drop (Pa)

μ_f : Viscosity of filtrate (Pa.s)

R_c : Resistance of cake (m^{-1})

R : Resistance of media, e.g. filter paper (m^{-1})

Assume that the cake is incompressible, then resistance of cake R_c would be directly proportional to the amount of cake deposited, i.e.

$$R_c = SRF \cdot \omega \tag{2}$$

where SRF is the specific cake resistance (m/kg) and ω is the mass of cake deposited per unit area (kg/m^2).

For the cake which is incompressible, the mass of cake deposited per unit area, ω, would be related to the cumulative volume of filtrate V at time t by

$$\omega \cdot A = c \cdot V \qquad (3)$$

where c is the solid concentration of solids in the suspension (kg/m^3) [2].

Then, by substituting equation (3) into (2), one obtains

$$R_c = SRF \cdot c \cdot \frac{V}{A} \qquad (4)$$

When substitute (4) into equation (1), we have

$$\frac{dV}{dt} = \frac{A \cdot \Delta P}{\mu_f \cdot SRF \cdot c \cdot \frac{V}{A} + \mu_f \cdot R} \qquad (5)$$

If the pressure drop is constant and the cake is incompressible with the initial condition of V=0 at t= 0, then integration of equation (5) leads to

$$t = \frac{\mu_f \cdot SRF \cdot c}{2\Delta P \cdot A^2} V^2 + \frac{\mu_f \cdot R}{\Delta P \cdot A} V \qquad (6)$$

Dividing both sides of equation (6) by V, one obtains

$$\frac{t}{V} = \frac{\mu_f \cdot SRF \cdot c}{2\Delta P \cdot A^2} V + \frac{\mu_f \cdot R}{\Delta P \cdot A} \qquad (7)$$

For the case where the constant pressure drop is applied from the commencement of filtration, i.e. V=0 at t=0, and the cake is incompressible, then the plot of $\frac{t}{V}$ against V would be a straight line. However, if compaction of the filter bed occurs, the curve of $\frac{t}{V}$ vs. V would be exponentially increasing, as shown in Figure 7-1.

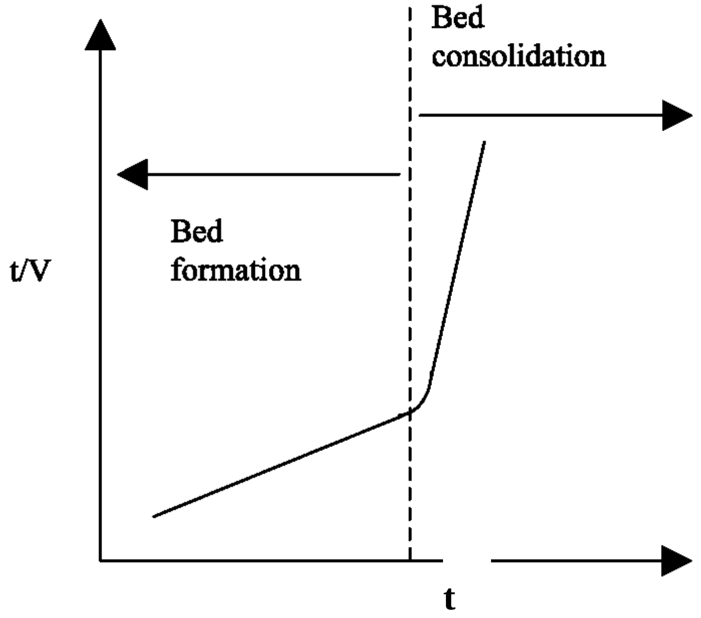

Figure 7-1 Typical filtration curve [3]

The specific resistance to filtration (SRF) is a quantitative measure of the filterability of a suspension. The more permeable the filter cake is, the smaller is the SRF value [4]. As described in equation (7), assuming that the filter cake is incompressible, SRF can be calculated from the slope b of $\frac{t}{V}$ against V profile by:

$$SRF = \frac{2 \cdot \Delta P \cdot A^2}{\mu_f \cdot c} \cdot b \tag{8}$$

In this study, ΔP was fixed at 15×10^3 Pa, the filter area A was 45.8×10^{-4} m^2, and the viscosity μ_f of filtrates was measured at room temperature using an Ubbelohde viscometer (Φ75, CANNON® Instrument Company, PA, USA), to be about 1×10^{-3} Pa.s.

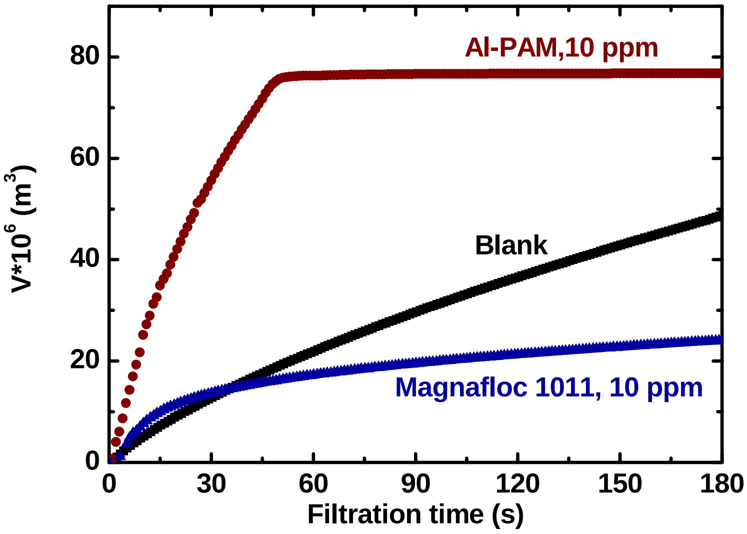

Figure 7-2 Effect of Magnafloc 1011 and Al-PAM addition on filtration of low fine tailings

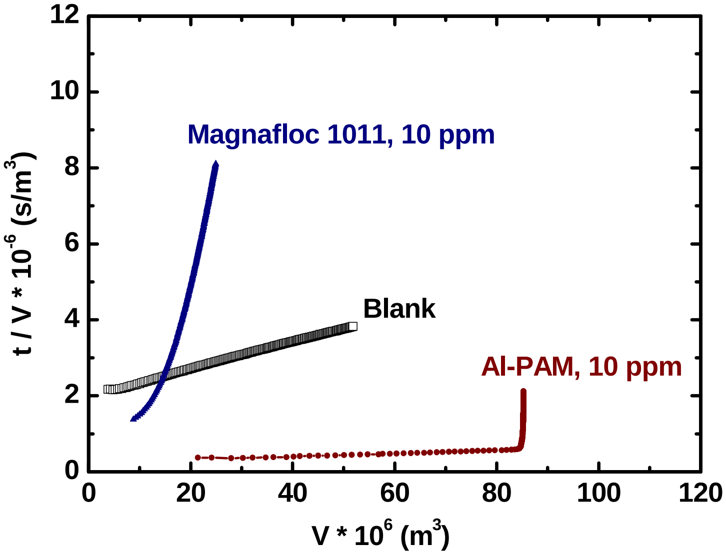

Figure 7-3 Effect of Magnafloc 1011 and Al-PAM addition on $\frac{t}{V}$ vs. V plot for the low fine tailings

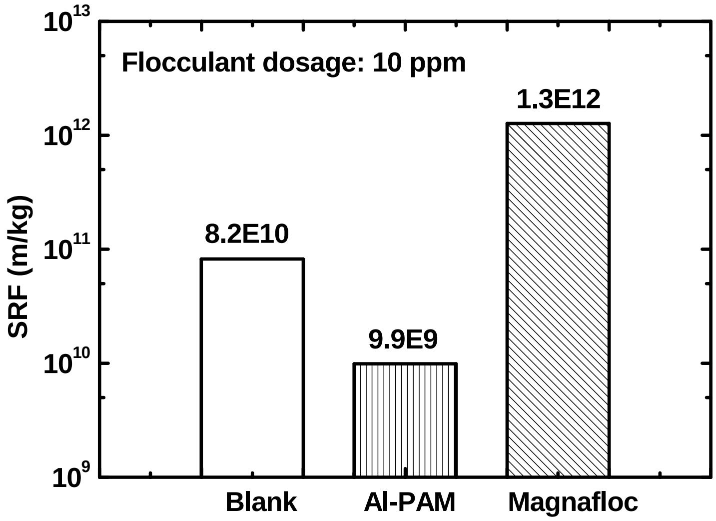

Figure 7-4 Effect of Magnafloc 1011 and Al-PAM addition on SRF of the low fine tailings

As illustrated in Figure 7-4, for the low fine tailings, the SRF decreased from 8.2 $\times 10^{10}$ to 9.9 $\times 10^{9}$ m/kg with the addition of 10 ppm Al-PAM, but the addition of Magnafloc 1011 increased the SFR.

Similar trends were observed for the filtration of the high fine tailings (Figure 7-5 and 7-6). SFR decreased from 1.5×10^{12} to 5.0 $\times 10^{9}$ m/kg with the addition of 50 ppm Al-PAM at 700 rpm mixing (Figure 7-7). However, SFR increased when Magnafloc 1011 was added.

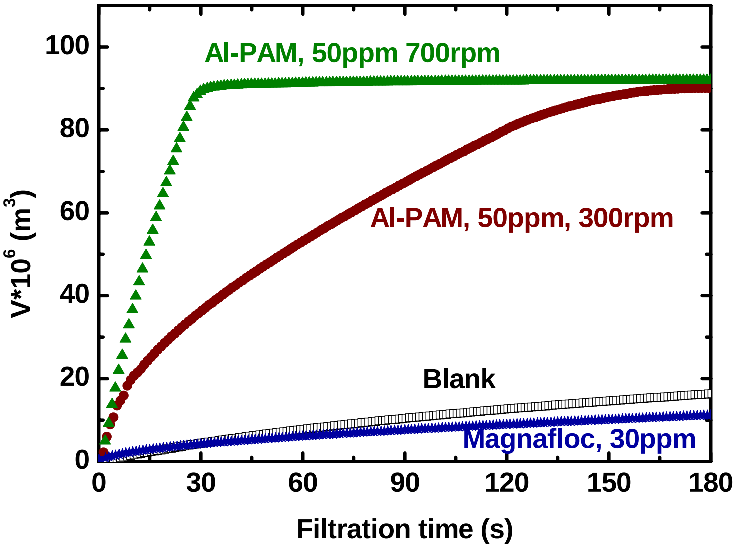

Figure 7-5 Effect of Magnafloc 1011 and Al-PAM addition on filtration curve of the high fine tailings

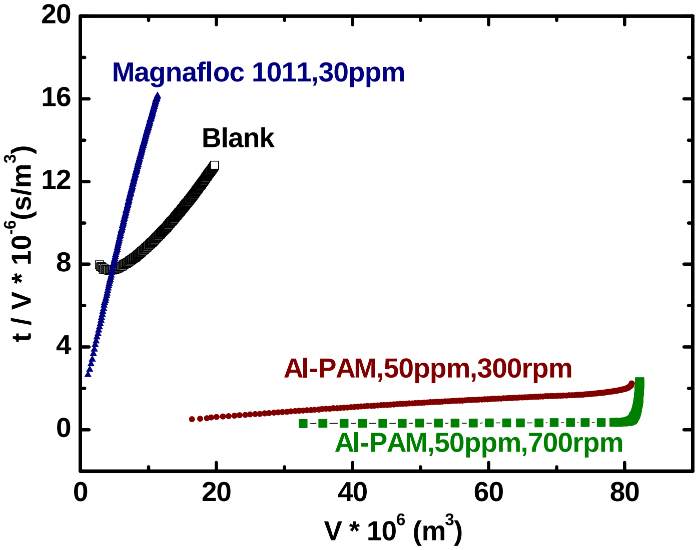

Figure 7-6 Effect of Magnafloc 1011 and Al-PAM addition on $\frac{t}{V}$ vs. V plot of the high fine tailings

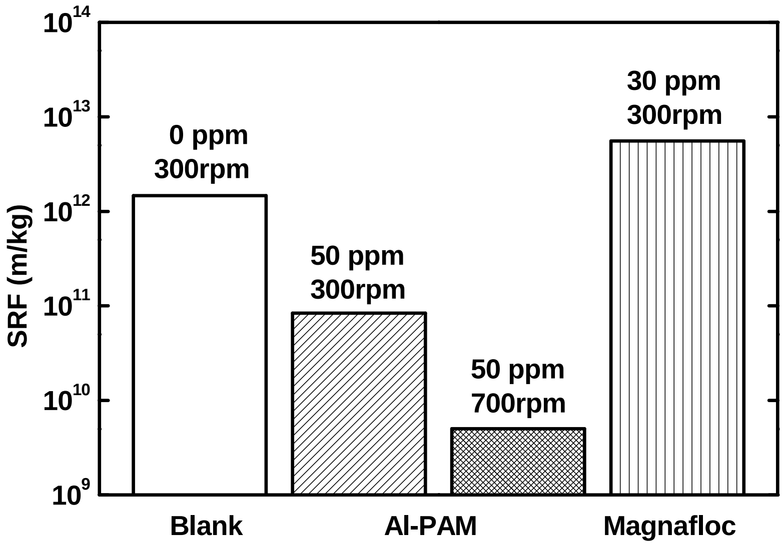

Figure 7-7 Effect of Magnafloc 1011 and Al-PAM addition on SRF of the high fine tailings

For the paraffinic froth treatment tailings tested, as illustrated in Figure 7-8, 400 ppm Al-PAM addition dramatically accelerated the filtration and the slope of $\frac{t}{V}$ vs. V was much lower than the case without polymer addition (Figure 7-9). The corresponding SRF was 5.9×10^{9} m/kg, which was almost three order of magnitude lower than that of the blank case.

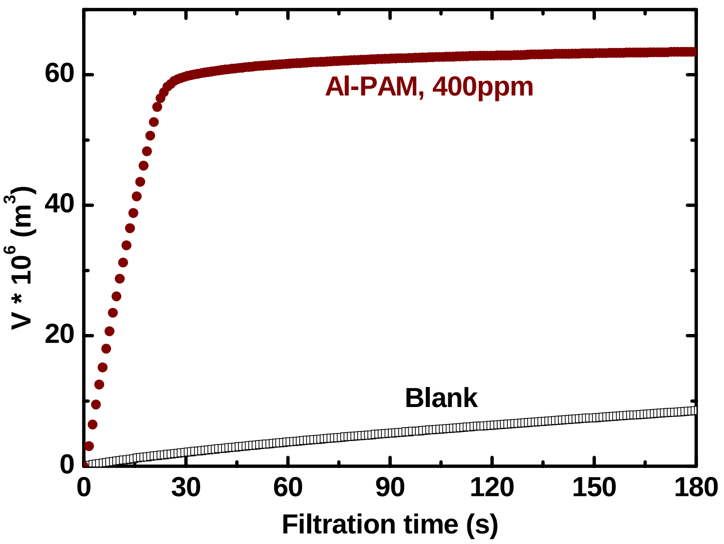

Figure 7-8 Effect of Al-PAM addition on filtration curve for the paraffinic froth treatment tailings

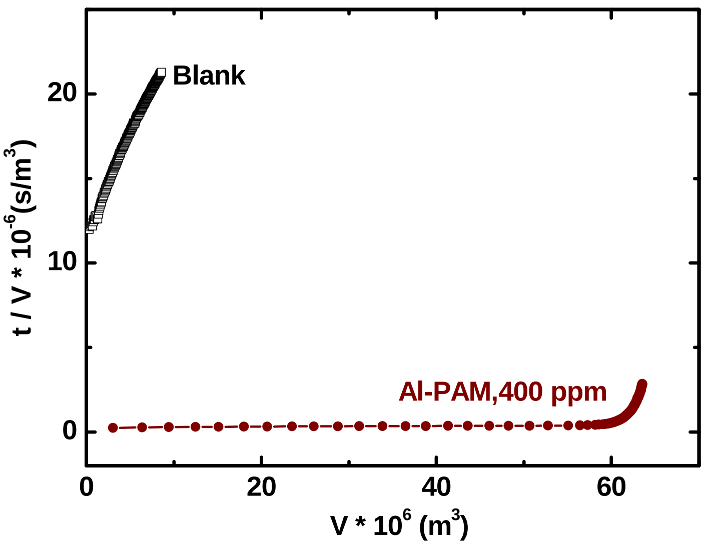

Figure 7-9 Effect of Al-PAM addition on $\frac{t}{V}$ vs. V plot of the paraffinic froth treatment tailings

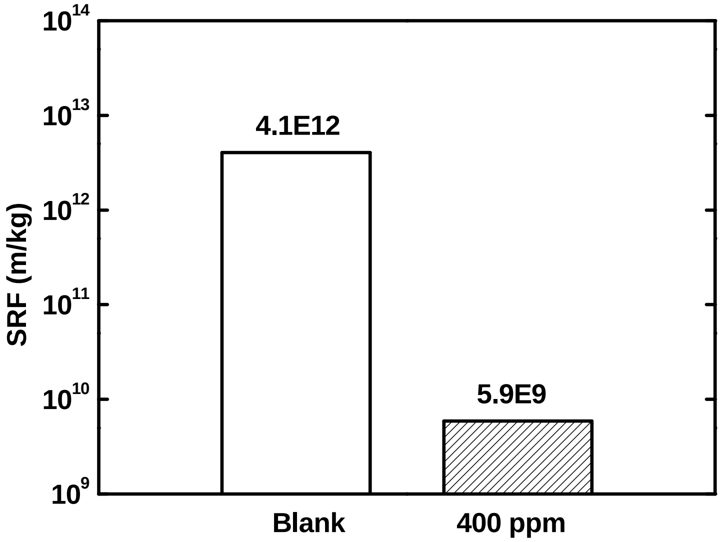

Figure 7-10 Effect of Al-PAM addition on the SRF of paraffinic froth treatment tailings

Xu et al. filtered the sediment of low to high fines tailings, in which fines content varied from 4.3 to 83.3 wt% [5]. Their conclusion was that, for low fine tailings (10-20 wt% fines), the SFR can be reduced three orders of magnitude from 10^{11} to 10^{8} m/kg range by adding an anionic, high-molecular weight, polyacrylamide-based polymer, which makes filtration of low fine tailings practical. However, for high fine tailings (45 to 83 wt% fines) they tested with flocculant addition, the SRF values were still around 10^{12} to 10^{13} m/kg range. Therefore they concluded that it would be a challenge to filter total tailings for low-grade oil sands ores. As discussed above, our results for high fine tailings (40.1 % fines) indicated that, when Al-PAM is used as a flocculant, at appropriate dosage and mixing conditions, the SFR values can be reduced from 10^{12} to 10^9 m/kg range, suggesting that filtration of total tailings from high fines ores with Al-PAM addition is promising.

Summary

For the laboratory extraction tailings and the paraffinic froth treatment tailings tested in this study, Al-PAM effectively decreased the SRF values. For the low fine tailings, SRF decreased about one magnitude when10 ppm of Al-PAM was used as a flocculant. For the high fine tailings case, SRF decreased from 1.5×10^{12} to 5.0×10^9 m/kg when optimal Al-PAM dosage and mixing were applied, i.e. 50 ppm of Al-PAM at 700 rpm mixing. For the paraffinic froth treatment tailings, the SRF decreased around three order of magnitude, from 4.1×10^{12} to 5.9×10^9 m/kg when 400 ppm Al-PAM was added. However, Magnafloc 1011 did not show any effectiveness on the reduction of SRF.

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Chapter 8 Conclusions

In this study, for the model tailings, kaolin was used to represent fine solids and sand was used as model coarse solids. The sand to fines ratio, SFR, was kept at 4 and the total solids content of the slurry was varied from 25 to 50 wt%. Both Magnafloc 1011 and Al-PAM were found to be good chemical aids for both settling and filtration within the tested conditions.

When Magnafloc 1011 or Al-PAM were added respectively, for a model tailings with initial solid content of 25 and 50 wt%, the solids content of the sediment reached 61 to 64 wt% after 10 minute of settling. The corresponding initial settling rates, ISRs, were 27 m/h and 3 m/h, respectfully, for Magnafloc 1011; and 21 m/h and 3.5 m/h, respectfully, for Al-PAM. After 10 minute of settling after the addition of either Magnafloc 1011 or Al-PAM, all supernatants of model tailings were clear.

For Magnafloc 1011, there was an optimal dosage to obtain the fastest filtration for the model tailings, which was also the dosage to achieve the lowest cake moisture and the transition point to get non-segregating tailings. For model tailings with 25, 40 and 50 wt% solids content with 5, 8 and 10 wt% fines content, the optimal dosage was 4 ppm, 8 ppm and 10 ppm, respectively, with corresponding cake moisture contents of 14.5 wt%, 13.8 wt% and 13.8 wt%. However, when the solids content in the model tailings was increased to 55 wt%, Magnafloc 1011 showed a negligible effect on the filtration rate and cake moisture, i.e., the filtration rates were similar and the tailings were all non-segregating regardless of Magnafloc 1011 addition. As opposed to Magnafloc 1011, when Al-PAM was used as filtration aids of model tailings, it was not sensitive to the dosage. With the addition of Al-PAM, the cake moistures were lower than those with the Magnafloc 1011 addition.

However, for the laboratory extraction tailings, including low and high fines tailings, and for the paraffinic froth treatment tailings, Magnafloc 1011 was capable of accelerating the settling, but failed to improve filtration. The dosage required to achieve fast settling for the low and high fines tailings was 10 ppm and 30 ppm, respectively. The ISRs for low and high fines tailings were improved from almost zero to 35 and 42 m/h, respectively. Contrary to model tailings, the supernatants of both the low and high fines tailings after the addition of Magnafloc 1011 were not clear. There was no filter cake formed after 180-second filtration for both tested laboratory extraction tailings.

However, for the three tested real tailings, Al-PAM was found to be effective for enhancing settling and filtration. The Al-PAM dosage required to obtain fast settling increased when the fines and hydrocarbon content increased in the tested tailings, which was 10 ppm and 30 ppm for the low and high fines tailings, respectively, and 400 ppm for the paraffinic froth treatment tailings. The corresponding ISRs for the low and high fines tailings were improved from being close to zero to 36 and 19 m/h, respectively. In contrast to the performance of Magnafloc 1011, the supernatants after the addition of Al-PAM were clear. The turbidity after 1hr settling at optimal dosage reduced to 6 and 68 NTU, respectively.

When Al-PAM polymer was added for the two laboratory extraction tailings and the paraffinic forth treatment tailings, dry cakes were obtained at appropriate polymer dosage and mixing conditions. For the low fines and high fines tailings, the dosage required for effective filtration was found to be 10 ppm and 30 ppm, respectively. However, for the paraffinic froth treatment tailings, 400 ppm was required to achieve fast filtration. The cake moisture obtained with the addition of Al-PAM was 6.6±1.2 wt% for the low fines tailings and 16.9±0.8 wt% for the high fines tailings. Although the moisture of the cake obtained from the filtration of the paraffinic froth treatment tailings was 42.5 wt%, the cake still looks and feels dry.

To summarize, Al-PAM type polymer is good candidate for the filtration of extraction tailings and paraffinic froth treatment tailings where dry cakes of low moisture content were produced. This study clearly demonstrated that Al-PAM type of polymer makes filtration an effective alternative for the oil sands tailings disposal to eliminate the necessity of large tailings ponds.

Chapter 9 Recommendations for future research

The recommendations for future research on the filtration of oil sands tailings are listed as following:

1) Explore the relationship between Al-PAM characteristics (colloid size, Al-content and molecular weight) with filtration performance.
2) Test the adaptability of Al-PAM and try Al-PAM on various real tailings.
3) Study the mechanisms of Al-PAM reaction with ultra-fines (hydrophilic clay, hydrophobic clay and bitumen droplets) in the oil sand tailings.
4) Track the water chemistry with or without the addition of Al-PAM, especially the residue polymer effect on bitumen extraction.
5) Carry out filtration tests on different types of filters and find the best type, and search for optimal operation conditions and carry out economic evaluation.