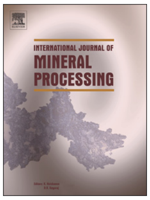
International Journal of Mineral Processing 161 (2017) 41–49

Contents lists available at ScienceDirect

International Journal of Mineral Processing

journal homepage: www.elsevier.com/locate/ijminpro



Electrophoresis and its applications in oil sand tailings management☆

Raquibul Alam *, Julie Q. Shang, Shriful Islam

Department of Civil and Environmental Engineering, Western University, Canada

ARTICLE INFO

Article history:
Received 8 September 2016
Received in revised form 14 January 2017
Accepted 14 February 2017
Available online 16 February 2017

Keywords:
Electrophoresis
Bitumen
Electric field intensity
Mature fine tailings
Coagulant

ABSTRACT

Oil sands mines generate tailings during the extraction process, which are a mixture of water, clay, sand and residual bitumen. When the tailings are released to tailings ponds, the coarse solids settle quickly, whereas fine solids containing clay minerals, namely mature fine tailings (MFT), remain suspended for years, even decades. A study is carried out to assess the suitability of electrokinetic (EK) sedimentation to accelerate sedimentation of MFT. A series of laboratory-scale column experiments are carried out to examine the effects of electrophoresis during settling processes. The investigation focuses on the effects of EK sedimentation as related to the initial solid content of the tailings suspension, applied electric field intensity, water pH, and the use of an optimized coagulant $FeCl_3$. Based on the experimental data, an electric field intensity of 150 V/m along with an initial tailings solid content of no >5% are the optimum condition for EK sedimentation of MFT, in terms of reducing the overall sedimentation time and increasing the final solid content. The results show that the current density of EK sedimentation for MFT should not be >20 A/m^2 to control the bubble effect and reduce power consumption.

1. Introduction

Canadian oil sands cover an area of about 142,000 square kilometers (km^2) (NEB, 2004). Oil sand tailings, the end products of the oil sands mining operation, are pumped into large tailings ponds. The coarse solids, mostly sands, settle down quickly. However, fine solids, remain suspended in tailings ponds, which take years to consolidate and are known as mature fine tailings (MFT) (Johnson et al., 1993). The MFT is a mixture of residual bitumen, sand, silt, and clay particles. Due to the poor water release ability, low permeability, and low strength (susceptible to compaction) of the MFT, dewatering under natural conditions is not realistic (Mikula et al., 1996). Currently >170 km^2 of Alberta's lands are covered by tailings ponds, and expected to occupy an area of 250 km^2 by 2020, (Government of Alberta, 2012), which causes serious environmental concerns, such as impacts on public health, land use, water supply and air quality (Farkish, 2013). Consequently, various regulations and requirements have been implemented for tailings operations associated with oil sands mining in order to preserve the environment (ERCB, 2009). The main objective in oil sands tailings management is to thicken and consolidate the MFT to reduce the dedicated disposal areas (DDAS) (Farkish, 2013). Several studies have been done on these aspects (Sworska et al., 2000; Guo and Shang, 2014).

The tailings thickening is a dewatering process for slurries with low solid content, in which the first phase is sedimentation of suspended fine solids. Flocculants are commonly used in thickening processes to increase the settling velocity and reduce the thickener size (Jewell and Fourie, 1999). Flocculants are organic, high molecular weight synthetics or natural polymers that help to enhance the settling velocities of suspended solids by adsorbing onto solid particles, forming flocs (Barbour and Wilson, 1993). The centrifuging technique is also an option of thickening, which can produce filter cakes with up to 60 wt% solids (OSRIN Report, 2010). Filtration is also one of the basic methods by using pressure or a vacuum to separate coarse and medium particles from water (OSRIN Report, 2010).

Electrokinetic thickening is a potential option to enhance the thickening process of fine oil sand tailings. Electrokinetics has been studied extensively in geotechnical engineering applications (e.g. Fourie et al., 2007, Mohamedelhassan, 2008; Rittirong et al., 2008, Shang et al., 2009), including consolidation of soft clays, dewatering of mine tailings, strengthening of marine sediments and so on. The research on dewatering of oil sands MFTs using EK technology has been reported (Guo and Shang, 2014), which focused on the assessment of the effectiveness and efficiency of EK dewatering of MFT. Guo and Shang (2014) observed that the EK dewatering significantly increased the undrained shear strength and reduced the water content of MFT samples. There are several advantages of EK treatment including limited production of waste, and no requirements of chemicals. The major disadvantage of EK is the consumption of high energy. However, optimization of an EK cell using solar energy stored in a DC battery as the sole power source can minimize the operational cost (Huang et al., 2016).

This study was focused on the electrokinetic sedimentation of the MFT to reduce the settling time. In this study, the MFT is characterized for the composition, followed by a study on the effect of electrokinetic

---

☆ A version of this paper has been presented in GeoRegina 2014, the 67th Canadian Geotechnical Conference. Regina, SK, Canada.

* Corresponding author.
E-mail address: ralam7@uwo.ca (R. Alam).

http://dx.doi.org/10.1016/j.minpro.2017.02.006

sedimentation (EK). The influencing factors investigated in this study include the initial solid content of the MFT suspension, electric field intensity, electrolytic bubbles, water pH, and the use of an optimized coagulant $FeCl_3$.

2. Theory of electrokinetic sedimentation

The thickening of solids in water typically goes through two stages; the first stage is known as sedimentation and the second as consolidation (Mohamedelhassan and Shang, 2001). The sedimentation stage consists of two stages: free settling and hindered settling. At the free settling stage, solids in a suspension are settled at a constant rate. When the free settling stage approaches to the end, a transition stage is observed, which is known as the hindered settling stage. The suspension velocity during the free and hindered settling stages can be expressed as (McRoberts and Nixon, 1976; Russel et al., 1989 and Shang, 1997):

$$U = \beta \cdot u \cdot n^{r} \qquad (1)$$

where U (m/s) is the suspension settling velocity, u (m/s) is the particle settling velocity, β is a factor which represents an average velocity of all particles, n is the porosity of the suspension, and r is the coefficient of sedimentation. In the free settling stage, the suspension settling velocity can be computed by replacing porosity, $n = 1$ in Eq. (1):

$$U = \beta \cdot u \qquad (2)$$

Electrokinetic sedimentation can enhance the free settling velocity significantly of a clay suspension. The principle of electrokinetic sedimentation of clay suspension is discussed by Shang (1997). Clay particles carry permanent negative charges due to the crystal structure and isomorphous substitution when they are in contact with water (Mohamedelhassan and Shang, 2001) and therefore repel each other when they are suspended in water. Consequently, the suspension remains stable without significant settlement for a long time. When the suspension is subjected to an external dc electric field, the negatively charged particles move towards the positively charged anodes (Shang, 1997). This phenomenon is known as electrophoresis (EP), which can generate electrokinetic sedimentation. Electrophoresis has been applied to accelerate sedimentation of the Welland River sediment (Buckland et al., 2000) and cohesive soils (Kim et al., 2008).

Mohamedelhassan and Shang (2001) suggested that the overall particle settling velocity subjected to an external DC electric field is the summation of gravity (u_g) and electrokinetics (u_{ek}):

$$u = u_g + u_{ek} \qquad (3)$$

where, for laminar flow conditions, the classic Stock's laws can be used to represent the settling velocity, u_g of a single, discrete, non-flocculating particle by gravity (Metcalf and Eddy Inc., 1991):

$$u_g = \frac{g(\rho_s - \rho_w)d^2}{18\mu} \qquad (4)$$

where u_g is the particle settling velocity (m/s), g is the gravitational acceleration (m/s^2), ρ_p is the mass density of the particles (kg/m^3), ρ_w is the mass density of water (kg/m^3) and μ (N-s/m^2) is the viscosity of water.

On the other hand, the velocity of individual particles induced by electrophoresis can be expressed as (Shang, 1997; Russel et al., 1989, Hunter, 1981):

$$u_{ek} = \frac{\varepsilon_w \xi}{\mu} E \qquad (5)$$

where u_{ek} (m/s) is the particles velocity induced by electrokinetics, ε_w (F/m) is the permittivity of water, ζ (V) is the zeta potential, and E (V/m) is the electric field intensity. As the settling velocity of a soil suspension is not uniform due to the wide distribution of grain sizes, therefore, the average particle settling velocity of suspended soil solids can be evaluated as suggested by Mohamedelhassan and Shang (2001):

$$u = \sum_{i=1}^{N} (f_i - f_{i+1}) \left(\frac{(u_{g(i)} + u_{g(i+1)})}{2} \right) + u_{ek} \qquad (6)$$

where, f_i is the fraction of the suspension finer than the grain size d_i, and $u_{g(i)}$ is the gravitational settling velocity of an individual particle with the grain size di.

Eq. (5) suggests that the free settling velocity of particles increases with an increase of the electric field intensity (V/m). However if the electric field intensity exceeds a certain value, the free settling velocity might not increase with electric field intensity. According to the Ohm's law, the current of a sedimentation column increases with an increase of applied voltage. If the current exceeds a certain value, oxygen bubbles are produced near anode at the bottom of the sedimentation column. According to the Faraday's law, generating rates of oxygen bubbles from electrolysis of water is directly proportional to the current density (Chen and Chen, 2010). At a high current density, significant amount of O_2 bubbles are generated from the bottom electrode (Anode) as shown in Eq. (7)

$$2H_2O \rightarrow O_2 + 4H^+ + 4e \qquad (7)$$

Oxygen bubbles rise to the surface of the sedimentation column and hence negatively affect the overall EK sedimentation process. In an EK sedimentation process, cathode is placed at the top of the slurry; hence the effect of H_2 bubbles generated on the cathode in the sedimentation process is negligible.

Based on above analysis, one can introduce another term in Eq. (3), i.e.

$$u = u_g + u_{ek} - u_f \qquad (8)$$

where, u_f is the bubble-particle aggregate velocity acting upward in the EK sedimentation cell. Sarkar (2012) gave an expression for the rising velocity of the bubble-particle aggregate equating the buoyancy, weight and drag forces:

$$u_f = \frac{g}{18\mu_{pulp} d_{bP}} \left[{d_b}^3 (\rho_{pulp} - \rho_b) - N_p {d_p}^3 (\rho_p - \rho_{pulp}) \right] \qquad (9)$$

where, ρ_{pulp} is the pulp density, ρ_b and ρ_p are the density of bubble and particle respectively, μ_{pulp} is the absolute viscosity of pulp; d_b and d_p are the dia of bubble and particle respectively. Therefore, the average particle settling velocity of suspended soil solids can be evaluated:

$$\begin{aligned} u = {} & \sum_{i=1}^{N} (f_i - f_{i+1})(f_f) \left(\frac{(u_{g(i)} + u_{g(i+1)})}{2} \right) \\ & + \frac{\varepsilon_w \xi}{\mu} E - \sum_{i=1}^{N} (f_i - f_{i+1})(1 - f_f) \left(\frac{(u_{f(i)} + u_{f(i+1)})}{2} \right) \end{aligned} \qquad (10)$$

where, f_f is the fraction of free particle (i.e. not attached to the bubbles). Koh and Schwarz (2006) and Sarkar (2012) gave an expression to estimate the number of particle free at time t from which f_f can easily be computed:

$$f_f = \left[1 - \frac{\int_0^t K_1 N_p N_{bT} dt}{N_p} \right] \qquad (11)$$

where K_1 is the particle-bubble attachment rate constant, Np is the number of particles and N_{bT} is the total number of bubbles generate in the flotation cell per second which can be approximated from O_2