Journal of Environmental Management 161 (2015) 113–123

Contents lists available at ScienceDirect

Journal of Environmental Management

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

Research article

A hybrid froth flotation–filtration system as a pretreatment for oil sands tailings pond recycle water management: Bench- and pilot-scale studies

Kavithaa Loganathan [a, **], David Bromley [b], Pamela Chelme-Ayala [c], Mohamed Gamal El-Din [c, *]

[a] Canadian Natural Resources Ltd., Fort McMurray, Alberta, T9H 3H5, Canada
[b] David Bromley Engineering Ltd., West Vancouver, British Columbia, V7S2N6, Canada
[c] Department of Civil and Environmental Engineering, University of Alberta, Edmonton, Alberta, T6G 2W2, Canada

ARTICLE INFO

Article history:
Received 3 November 2014
Received in revised form
4 April 2015
Accepted 18 June 2015
Available online xxx

Keywords:
Hybrid flotation–filtration system
Oil sands
Recycle water
Suspended solids
Water management

ABSTRACT

Through sustainable water management, oil sands companies are working to reduce their reliance on fresh water by minimizing the amount of water required for their operations and by recycling water from tailings ponds. This study was the first pilot-scale testing of a hybrid technology consisting of froth flotation combined with filtration through precoated submerged stainless steel membranes used to treat recycle water from an oil sands facility. The results indicated that the most important factor affecting the performance of the hybrid system was the influent water quality. Any rise in the levels of suspended solids or total organic carbon of the feed water resulted in changes of chemical consumption rates, flux rates, and operating cycle durations. The selections of chemical type and dosing rates were critical in achieving optimal performance. In particular, the froth application rate heavily affected the overall recovery of the hybrid system as well as the performance of the flotation process. Optimum surfactant usage to generate froth (per liter of treated water) was 0.25 mL/L at approximately 2000 NTU of influent turbidity and 0.015 mL/L at approximately 200 NTU of influent turbidity. At the tested conditions, the optimal coagulant dose was 80 mg/L (as Al) at approximately 2000 NTU of influent turbidity and <40 mg/L (as Al) at approximately 200 NTU of influent turbidity. Precoat loading per unit membrane surface area tested during the pilot study was approximately 30 g/m^2. The results of this study indicated that this hybrid technology can potentially be considered as a pre-treatment step for reverse osmosis treatment of recycle water.

1. Introduction

The Athabasca oil sands in northern Alberta, Canada, are one of the largest known crude oil reserves in the world with over 167.2 billion barrels of recoverable bitumen available, making Canada the country with the third largest oil reserves in the world (Energy Resources Conservation Board, 2014). During oil extraction, after separation from the bitumen, the waste product, consisting of residual bitumen, clays, slit and water, is sent to a tailing area, where the water (i.e., recycle water; RCW) is separated from solids and returned back into the process.

RCW (also known as oil sands process-affected water) is a very complex mixture of suspended solids, salts, inorganic compounds, dissolved organic compounds, and trace metals (Allen, 2008; Holowenko et al., 2002). Organic compounds found in RCW include naphthenic acids (NAs), benzene, humic and fulvic acids, and polycyclic aromatic hydrocarbons (PAHs), among others (Allen, 2008; Grewer et al., 2010). RCW from tailings ponds has been reported to cause both acute and chronic toxicity to a variety of organisms, including fish, amphibians, phytoplankton, and mammals (Debenest et al., 2012; Leung et al., 2001; MacKinnon and Boerger,

* Corresponding author. NSERC Senior Industrial Research Chair in Oil Sands Tailings Water Treatment, Helmholtz – Alberta Initiative Lead (Theme 5), Department of Civil and Environmental Engineering, University of Alberta, Edmonton, Alberta, T6G 2W2, Canada.
** Corresponding author. Technology Development-Horizon Oil Sands, Canadian Natural Resources Ltd., Fort McMurray, Alberta, T9H 3H5, Canada.
E-mail addresses: Kavithaa.Loganathan@cnrl.com (K. Loganathan), mgamalel-din@ualberta.ca (M. Gamal El-Din).

http://dx.doi.org/10.1016/j.jenvman.2015.06.031
0301-4797/

1986; Pollet and Bendell-Young, 2000; Yamano et al., 2006).

Through progressive water management, oil sands companies are working to reduce their reliance on fresh water by minimizing the amount of water required for their operations and by recycling water from tailings ponds where possible. Various treatment processes have been tested at the bench-scale level to treat RCW, including adsorption, advanced oxidation processes (AOPs), membrane processes, and biological treatments, among others (Islam et al., 2014; Kim et al., 2013; Pourrezaei et al., 2014; Zubot et al., 2012). However, to date there has been no full-scale treatment process implemented for the remediation of RCW. Natural *in situ* microbial degradation in tailings ponds has proven to be very slow (Han et al., 2009). Ozonation and AOPs have being used, at the bench-scale level, as treatment alternatives to remediate RCW (Martin et al., 2010; Perez-Estrada et al., 2011; Scott et al., 2008). As illustration, ozonation has been found to degrade NAs and acid-extractable fraction (AEF), increase RCW biodegradability, reduce the toxicity of RCW towards *Vibrio fischeri* (Gamal El-Din et al., 2011; Wang et al., 2013) and attenuate the RCW impacts on the growth and development of *Chironomus dilutes* (Anderson et al., 2012a, 2012b).

Among physical treatments, membrane filtration has been found to be an effective method of removing impurities from RCW (Alpatova et al., 2014; Kim et al., 2011; Loganathan et al., 2015). In particular, reverse osmosis (RO) and nanofiltration (NF) membranes have showed excellent capability of rejecting ionic species from RCW (Kim et al., 2011). However, the successful application of RO and NF membranes for RCW treatment is hindered by membrane fouling caused by colloids, organic matter, and bitumen residues that adhere to the surface and pores of the membrane (Peng et al., 2004). Due to the high solid and ionic contents in RCW, feed water pretreatments able to reduce foulants such as suspended and dissolved solids are required to minimize membrane fouling (Kim et al., 2011). As illustration, coagulation, flocculation and sedimentation (CFS) process has been effectively used to reduce solids and colloidal materials from RCW (Kim et al., 2011). This process causes the destabilization of suspended solids by reducing the surface ionic charges, resulting in the formation of flocs; then these flocs are precipitated in the sedimentation process.

Froth flotation, a surfactant-based separation processes, has been effectively used to remove emulsified oil from wastewater (Bunturngpratoomrat et al., 2013; Chavadej et al., 2004b), to control acid mine drainage in the mining industry (Alam and Shang, 2012), and to deink paper pulp (Theander and Pugh, 2004), among other applications. This process relies on the difference in surface chemistry of particles and their behavior in the gas/liquid, gas/solid and liquid/solid interphases (Al-Zoubi et al., 2009). In this process, a surfactant is added to an aqueous solution and air is sparged through the solution. The presence of surfactant located at the air–water interface in the flotation operations promotes the formation of froth. Dissolved molecules or ions, solid particles, or droplets of emulsified oil can attach to the air bubbles and be carried over to the top of a flotation cell with the froth, which is continuously skimmed off.

Hybrid flotation–membrane filtration systems have been found to be more effective not only in removing contaminants but also in reducing membrane fouling when compared to the single processes (Nenov et al., 2008; Peleka et al., 2009). In the present study, a pilot-scale test was conducted to demonstrate the ability of a hybrid system consisting of froth flotation combined with filtration through precoated submerged stainless steel membranes to effectively treat RCW from an oil sands facility. In this pilot-study, the use of high intensity mixing to generate froth produced a highly ionic and turbulent environment which caused rapid particle destabilization (Al-Zoubi et al., 2009). In the hybrid system, the membranes were precoated in an *in situ* operational environment with a highly charged precoat material to reduce the membrane fouling (Cai et al., 2013; Malczewska et al., 2015). The charged environment of the precoat caused solid destabilization in the water passing through the precoat where the colloids attached to the precoated powder or alternatively to each other, resulting in entrapment within the precoated powder. When the precoat was fouled, the precoat was removed by backwashing the membrane and was replaced with a new precoat. Instead of making the membrane surface a barrier for filtration, the precoat was a media. This media attracted the solids in the water to the media surface by dispersion interaction and polar interaction forces (Israelachvili, 2011).

This feasibility study evaluated and analyzed the potential of the hybrid system to achieve water quality requirements to feed unit effluent to a RO system. Along with the optimization of system performance, the target for treated water was to consistently maintain a silt density index (SDI) of less than 5. Another objective for the pilot-scale study was to determine the optimum ranges for operating parameters that impacted the full-scale sizing of the treatment system, including operating flux rates and maximum sustainable recovery rates. A significant amount of effort was placed on a bench-scale testing in order to identify the best chemicals and process settings to be examined in the pilot-scale experiments.

2. Materials and methods

2.1. Source water

RCW from Canadian Natural Resources Limited (CNRL) Horizon operation was used as feed water for this study. The water was drawn from a header of the main hydro-cyclones of the CNRL cooling water recycle system. The RCW in the storage tank was recirculated continuously in order to prevent the settling out of solids or separation of the hydrocarbon materials. Because significant variations in the source water quality were observed, the RCW was characterized before and after each stage of operation. Table 1 shows the main water quality parameters of the untreated RCW used in this pilot-scale study.

2.2. Pilot-scale tests

The pilot-scale facility was located on the CNRL Horizon site next to plant 99A, which is on the north side of the site, adjacent to a tailings pond. The pilot study was conducted in two stages. The first stage was initiated on September 16, 2012 and terminated on November 04, 2012, after major optimization activities were completed. The second phase of the pilot study required a modification to the existing system design and was started on December 18, 2012 and terminated on December 31, 2012.

The hybrid system was a stand-alone system fed with untreated RCW. The system incorporated three major processes: (1) froth flotation; (2) filtration using a precoat material applied directly on the membrane surface; and (3) filtration through submerged stainless steel membranes (Fig. 1). All process equipment used in the pilot study was supplied by David Bromley Engineering Ltd. (Vancouver, Canada).

The froth flotation system was similar to conventional flotation based solid–liquid separation. During regular operation of the system, froth was created in a froth generator using water, air, and surfactant. The generated froth was then injected in the raw water line before the RCW was pumped into the flotation tank. For the froth generation, the air–water ratio was 50/50. The air, however,