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The utilization of forward osmosis for coal tailings dewatering

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ABSTRACT

The feasibility of dewatering coal tailings slurry by forward osmosis (FO) membrane process was investigated in this research. A prototype cell was designed and used for the dewatering tests. A cellulosic FO membrane (Hydration Technology Innovations, LLC, Albany, OR) was used for the dewatering studies due to its high fouling resistance. Representative samples of coal tailings slurry were collected from the thickener outflow at American Coal Company (Galatia, Illinois). Characterization studies were conducted to obtain particle size distribution (PSD), total dissolved solids (TDS) and the solids content of the slurry. The impact of the slurry properties such as solids weight percent, osmotic pressure, and particle size on the dewatering rates was determined. Furthermore, the impact of slurry conditioning by the addition of flocculant and gypsum on the rate and extent of dewatering was also investigated. Dewatering to a total solids content of more than seventy weight percent from an initial solids content of approximately thirty percent was achieved in all cases. The dewatering rate and extent were found to be a function of particle size, particle shape, TDS content, and mixing. The membrane material was shown to withstand repeated use over a period of thirty trials without deterioration of performance. The results obtained from this research suggest that osmotic dewatering of coal refuse slurry is feasible.

1. Introduction

As-mined coal contains non-combustible impurities, sulfur containing minerals, and hazardous trace elements that need removal prior to use. The removal of impurities – coal cleaning or preparation – is predominantly carried out by water-based processes. The resulting waste streams in coal preparation plants are categorized by particle size distribution (PSD). The larger particle size fraction can be readily dewatered and disposed of in waste piles or used for backfilling. It is the fine size fraction that poses the greatest challenge due to the presence of clays, slimes, and other mineral impurities. This fine refuse stream typically constitutes only two to three percent solids. It is thickened to about thirty percent solids content before being discharged to impoundments (Parekh, 2009). Maintenance of impoundments is expensive and several well-publicized impoundment failures (Committee on Coal Waste Impoundments et al., 2002) have sharply raised awareness of the environmental hazards of storing such wastes. Therefore, new impoundments face greater opposition and older ones are filling up leading to concerns about waste disposal becoming a critical bottleneck in coal production.

Several options for dewatering fine coal and refuse are available to coal preparation plants (Nicol et al., 1997). However, cost effective dewatering continues to be a technical and economical barrier to the stabilization of coal tailings. Conventional techniques utilizing thermal or mechanical methods have been ineffective in dewatering tailings in an environmentally compatible and/or cost effective manner (Mohanty, 2007; Xian-shu et al., 2009). This has resulted in continued interest in the development of coal tailings dewatering methods. While substantial progress continues to be made in conventional dewatering technologies, a non-conventional approach to dewatering utilizing an osmotic gradient was investigated as a potentially simple, robust, and low-cost alternative.

Forward osmosis (FO) refers to net water flows driven by an osmotic pressure gradient arising from the separation of a feed solution of low solute concentration from a draw solution of a higher solute concentration when separated by a selectively-permeable membrane. Osmotic pressure (π) is the

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pressure which, if applied to the more concentrated solution, would prevent transport of water across the membrane. A selectively permeable membrane allows passage of water, but rejects solute molecules or ions. The FO process results in concentration of the feed stream and dilution of the highly concentrated stream (referred to as the draw solution). The osmotic pressure gradients can be utilized for a wide range of applications. These include pressure retarded osmosis (PRO) for power generation, water desalination; and dewatering (Cath et al., 2006). FO has attracted widespread attention due to potential advantages such as low energy requirements (McGinnis and Elimelech, 2007; Xu et al., 2010) and low propensity for membrane fouling (Achilli et al., 2009; Cornelissen et al., 2008; Holloway et al., 2007). The efficiency of the FO process is highly dependent on the membrane and draw solution selection (Garcia-Castello and McCutcheon, 2011). The desired membrane properties include high water permeability, low salt leakage, and stability (Chu and Hsiao, 2009; Ma et al., 2012; Tiraferri et al., 2012).

This research investigates the potential for dewatering of coal tailings slurry by forward osmosis. Additionally the robustness of the membrane material in terms of cleanability and reusability was examined for a limited period.

2. Material and methods

2.1. Materials

Super-Q water with a resistivity greater than 18.3 megaohms-centimeter (MΩ-cm) was used in preparing draw solutions and as feed for initial testing of all membranes. Magnesium sulfate heptahydrate ($MgSO_4{\cdot}7H_2O$) obtained from Walgreens Co. (Deerfield, IL) was used to prepare all 20% (w/w) $MgSO_4$ draw solutions. A commercially available FO membrane from Hydration Technologies Inc. (HTI) (Albany, Oregon) was used for all the dewatering studies. A total of twenty gallons of coal tailings was collected in three lots over a period of one year from the American Coal Company (Galatia, IL) and designated sample C2. The samples were collected from one of the discharge points of the thickener outflow stream. The polymeric flocculants AQ587 and AQ200 were obtained from AQUAMARK, INC. (Chesterland, Ohio). The gypsum used for slurry conditioning was obtained from Southern Illinois Power Co-operative (Marion, IL) as by-product of flue gas desulfurization.

2.2. Coal tailings characterization

Sample C2 was analyzed for total solids, total dissolved solids (TDS), ionic composition, and particle size distribution (PSD). The total solids of the original and dewatered samples were determined in-house by method SM 2540B (dried at 103–105 °C). The TDS was obtained by method SM 2540C at the Midwest Laboratories (Omaha, NE). The PSD analyses were carried out at the Particle Technology Labs (PTL) (Downers Grove, IL). The analysis was conducted using a Malvern® Mastersizer laser diffraction system (LD). This instrument is considered an ensemble analyzer that calculates a volume distribution from the laser diffraction pattern. The sample was sieved using #10, #14, #18, and #20 mesh screens to separate particles larger than 850 μm prior to the LD analysis.

2.3. Dewatering of C2 slurries

Fig. 1 shows a schematic diagram for the bench scale FO experimental system. The FO cell illustrated in Fig. 1 (labeled 6) was 3D-prototyped in-house to accommodate custom membrane sizes and to provide access to the cake layer. It was made of acrylic with separable top and bottom compartments. The top and bottom two compartments are separated by the semipermeable membrane (shown by dashed line) with sealing accomplished through O-rings. The fine coal tailings slurry is placed in the open top compartment. The draw solution is circulated at a rate of 350 mL/min inside the closed bottom compartment. To promote mixing of the draw solution, a plastic spacer was used in the draw solution channel. The active area of the membrane was 0.0026 m^2. The top of the membrane was covered with a 400 mesh (37 μm) stainless steel mesh to protect the membrane surface from potential abrasion caused by relative movement between the particles and the membrane on mixing. Observations in previous research (Rajagopalan and Patel, 2011) suggested that the formation of a consolidated cake layer was the dominant resistance to water transport and limited dewatering. In this work, by mixing the slurry manually with plastic scraper until the disappearance of free standing water, the formation of a consolidated cake layer was avoided during the initial stages of dewatering. The rheology of the C2 slurry changes markedly during dewatering. While high water content suspensions are easily mixed, the suspension becomes a stiff, viscous mass that is difficult to move during later stages. Typically, at this point, the mass was not mixed but allowed to dewater only under the osmotic pressure gradient.

The membrane was oriented with the active layer facing the draw solution while the support layer faced the feed solution. Each membrane was tested for absence of defects before use for coal tailings dewatering. This was achieved by obtaining the DI water flux and the $MgSO_4$ reverse salt flux and comparing them to the expected water flux and salt rejection. One liter of the 20% $MgSO_4$ draw solution was used for each dewatering test. The feed solutions were 50 mL of DI water for membrane testing followed by 50 mL C2, either artificially prepared or used as-received or after additional treatment. Experiments were conducted in duplicate to ensure data validity. Water flux was obtained by measuring the increase in weight of draw solutions using an electronic balance connected to a data logging system. The reported flux values are averages over the entire experiment except where noted. The water flux J_w (kg/sq.m./h equivalent to L/sq.m./h for an assumed water density of 1) in the system is calculated by:

$$J_w = \frac{\Delta M}{A.\Delta t} \quad (1)$$

where ΔM refers to the change in mass of draw solution with time, Δt, and A is the area of the membrane.

2.4. Adjusting the solids content of the slurry

Feed slurries of varying solids content were prepared using the separated solids fraction of sample C2. The solid content of C2 was separated from the sample using a centrifuge (Model j2-21m, Beckman Coulter, Brea, CA). Fine solids remaining in the supernatant were filtered and added to the settled solids. In order to remove the dissolved solids, DI water washes were utilized until conductivity reading was below 100 μS. The fine particulate material was then dried at 105 °C for 24 h. Feed slurries of 20%, 30%, and 50% (w/w%) were prepared by mixing the dried solids with pre-measured amounts of a synthetic saline wastewater prepared to mimic the average composition of ions in sample C2 as shown in Table 1.

2.5. Adjusting TDS of the slurry

The TDS of the C2 sample was adjusted by adding washed and dried solids to obtain a solids content of 30% (w/w) with a saline solution that corresponded to 100%, 50%, and 25% of the TDS in