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Geotechnical behavior of uranium mill tailings from Saskatchewan, Canada

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ABSTRACT

This paper investigates the geotechnical behavior of uranium mill tailings from Saskatchewan, Canada. The 4% tailings were well-graded with 29% fines whereas the 5% and 6% tailings were gap-graded with 49% fines. All samples exhibited a negligible strength (0.4 kPa) up to 60% solids, followed by a rapid increase. The 4% tailings exhibited a lower rate and amount of settlement than 5% and 6% tailings. The k_i decreased from 10^{-2} to 10^{-4} m/s with a decrease in e_i from 16 to 4 and a decrease in e_f from 8 to 4 such that 4% tailings showed one order of magnitude lower values than the 5% and 6% tailings. The settling potential decreased ten times (50%–5%) for 4% tailings and four times (60%–15%) for 5% and 6% tailings. The effective stress increased from 80 to 260 Pa in the settling tests. The 4% tailings were less prone to segregation when compared with 5% and 6% tailings. The average solids content after settling was 35% for 4% tailings, 40% for 5% tailings and 39% for 6% tailings with a solids content deviation of ±3%, ±8%, ±6%, respectively. All materials were essentially non-segregating at 40% initial solids.

1. Introduction

The Key Lake operation in Saskatchewan, Canada is the largest uranium mill in the world, producing 13% of the world's uranium, stated in *Forward Focus: 2012 Annual Report*, Cameco Corporation, Saskatoon and *World Uranium Mining*, World Nuclear Association, London. The Key Lake site receives high grade ores (up to 21% U_3O_8 in 2010, as reported by Yun, McNamara, Murdock) from McArthur River, which are diluted to a nominal 4% grade using Deilmann special waste, Gaertner special waste and mineralized waste from McArthur prior to milling [1]. The special wastes have a U_3O_8 grade between 0.05% (environmental cut-off) and 0.19% (economic cut-off). Cameco is assessing the feasibility of milling higher grade material of up to 6% U_3O_8. This work focuses on geotechnical investigation of current (4%) and future (5% and 6%) mill tailings.

Previous geotechnical investigations on uranium tailings include the following: liquefaction assessment of tailings embankment at Elliot Lake, Ontario, tailings consolidation at Thuringia, Germany, and historical tailings performance at Key Lake, Saskatchewan, and a summary of experience with containment facility design in Saskatchewan [2–5]. Most such studies have focused on tailings behavior in the containment facilities. An efficient containment design requires a clear understanding of slurry behavior throughout the tailings life-cycle. Rheological properties are important to optimize slurry transport through pipes to the disposal areas. Post-deposition, tailings segregate due to preferential settling of coarse particles with respect to the fines. This process affects the rate and amount of tailings dewatering thereby influencing the storage capacity of the containment facility. Furthermore, the segregated tailings can produce zones of higher and lower hydraulic conductivity which could result in higher fluxes through the tailings after closure. Therefore, a clear understanding of the slurry behavior is required for developing an effective tailings management scheme.

The main objective of this study is to understand the geotechnical behavior of uranium mill tailings. A detailed laboratory investigation program was developed to characterize three tailings streams (4%, 5% and 6%). First, geotechnical index properties were determined for material classification. Second, rheological characteristics were determined using vane shear apparatus. Third, dewatering properties were determined using self-weight settling test. Finally, segregation behavior was evaluated using settling column tests.

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2. Mining operation and tailing production

The Key Lake mill process is comprised of the following components: crushing and grinding, sulfuric acid leaching, counter current decantation, solvent extraction, yellowcake precipitation, and product crystallization. In the first stage, large chunks of Key Lake special waste rock are crushed and blended with mineralized wastes from McArthur River using mill process water. The resulting slurry is mixed with the high-grade McArthur River ore slurry and Falcon concentrator rejects. The Falcon concentrator separates uranium-rich materials from concrete-rich materials contained in the mineralized waste rock from McArthur River. The uranium-rich materials are fed to the mill along with the ore whereas the rejects are mixed with the tailings, stated in *Key Lake Extension Project-Project Description: Safety, Health, Environment and Quality*, Cameco Corporation, Saskatoon, 2010. Through a combination of atmospheric and pressure leaching using sulfuric acid, the uranium is dissolved, along with other metals and salts. The slurry is then transferred to the counter current decantation circuit. This circuit completes the leaching process and separates the barren solids from the uranium bearing solution through a series of thickeners (circular vessels with inverted conical bases). The wash solution is gradually impregnated with uranium as it flows downstream. The pregnant solution, clarified by passing through sand filters is fed to the solvent extraction circuit for purification and concentration through selective extraction from the pregnant liquor. Uranium is then stripped off the aqueous solution using $(NH_4)_2SO_4$ and the loaded strip solution is precipitated as yellowcake. This material is converted to uranium oxide (U_3O_8) by heating to 800 °C in the calcining circuit and the product is put in drums for shipment.

Fig. 1 is a simplified schematic of the tailings production process. The slurry (leach residue) from the counter current decantation (CCD) circuit, the underflow streams from bulk neutralization thickeners and underflow solids from clarifier tank after pH adjustment are fed to a mix box (tailings feed box). The bulk neutralization process consists of a series of four neutralization pachucas (high narrow tanks with air agitation) followed by a molybdenum/selenium removal thickener. The pH adjustment is done using two small air-agitated tanks and a clarifier tank. The tailings neutralization section consists of a small splitter tailings feed box and two large agitated tailings holding tanks connected to the tailing pumps. The combined slurry flows to the two tailings holding tanks where it is adjusted to a pH of 10.5–11.0 using lime. The slurry is then pumped to a 30 m diameter thickener where it achieves a solids content of 35%–40%. The thickener underflow (final tailings) is transferred using positive displacement pumps to the Deilmann Tailings Management Facility (DTMF). The DTMF (1300 m long, 600 m wide and 170 m deep) was commissioned in January 1996. It receives tailings at a rate ranging between 1500 and 2400 m^3/day; the total tailings volume at the end of 2013 is estimated to be 8.86×10^6 m^3.

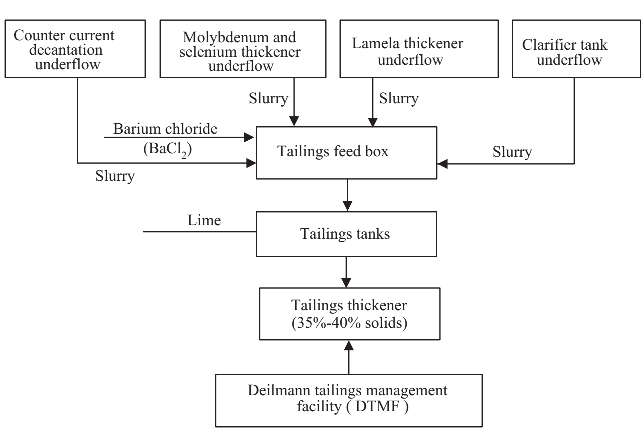

Fig. 1. Schematic of uranium mill tailings production.

3. Research methodology

The Key Lake Operation of Cameco Corporation, Canada, provided uranium mill tailing samples, containing Falcon concentrator rejects at 1:1 ratio. A detailed laboratory investigation program was developed to understand the behavior of current tailings (4%) and future tailings (5% and 6%). All of the tests were performed at the Radioactive Tailings Research Laboratory at the University of Regina in accordance with the occupational health and safety requirements. The laboratory investigations comprised the following: index properties, vane shear tests, self-weight settling tests, and segregation tests along with grain size distribution.

The specific gravity (G_s) was measured according to *Standard Test Methods for Specific Gravity of Soil Solids by Water Pycnometer*, ASTM International, West Conshohocken, PA, United States of America, ASTM D854-10, such that samples were heated at a reduced temperature of 60 °C to reduce the error due to gypsum dehydration. Likewise, the grain size distribution was determined according to *Standard Test Method for Particle-Size Analysis of Soils*, ASTM International, West Conshohocken, PA, United States of America, ASTM D422-63, 2007, using wet sieving followed by hydrometer analyses. The wet sieving of oven dried samples was conducted by using distilled water that may result in partial dissolution of precipitates. Hydrometer analyses on material finer than 0.075 mm (defined as fines (f)) were performed to determine the actual grain sizes of the fines. Sodium hexametaphosphate (5 g powder) was diluted in 125 mL distilled water and added to the sample. The sample was soaked for 8 h and was put into the hydrometer jar, and then the volume was made up to 1000 mL by adding distilled water. Depending upon the availability of tailings specimens, sub-samples of 20 ± 5.0 g were used for hydrometer analysis.

The yield stress was measured at various solids content in accordance with *Standard Test Method for Laboratory Miniature Vane Shear Test for Saturated Fine-Grained Clayey Soil*, ASTM International, West Conshohocken, PA, United States of America, ASTM D4648/D4648M-10, using the vane shear apparatus comprising a 12.7 mm blade height and 12.7 mm diameter (1:1 vane blade). The slurry was placed in the cylindrical mold and the vane was pushed into the slurry sample up to a depth equal to the height of the vane. The vane blade was rotated at a rate of 2 r/min. The resistance offered by the soil to the rotating blade was measured and used to calculate the shear stress (τ_y). The applied torque (product of the maximum angular rotation of the torsion springs and the calibration factor of the spring) was divided by the vane dimension constant to determine the yield stress. The gravimetric water content (w) was measured after each of the above tests according to *Standard Test Methods for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass*, ASTM International, West Conshohocken, PA, United States of America, ASTM D2216-10, using representative samples from the cylindrical mold. Slurry samples were initially oven dried overnight at 105 °C to evaporate the bulk of the tailings water. Thereafter, several hours of additional oven drying (at a lower temperature of 60 °C) was carried out until the weight stabilized, to obtain completely dry samples, stated in *Key Lake Operation-Deilmann Tailings Management Facility-2009 Tailings Investigation and Monitor Well Construction*, Cameco Corporation, Saskatoon, 2010. The low temperature was used to prevent the removal of structural water from gypsum (present in the tailings) thereby ensuring an accurate determination of water content.