Effect of bitumen staining on the performance of Tempe cells

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Abstract: Tempe cells have been increasingly used in laboratory to determine soil water characteristic curves of treated oil sands tailings, a key input parameter in water balance and cover system design for the final closure landform. Bituminous staining of ceramic plates in the Tempe cell was observed after repeated usage. Concerns were raised over reduced hydraulic conductivity of the ceramic plate due to potential entrapment of bitumen in the ceramic plate. Regular water flushing tests were carried out to track the evolution of hydraulic conductivities over time. Results of this test program indicated that for the 5-bar ceramic plate, clogging of ceramic plate may have been reduced by water flushing, and that equilibration time remained consistent after repeated uses. We recommend regular flushing and cleaning of the ceramic plate be performed to extend its service life in oil sands applications.

Introduction

Tempe cells are a widely adopted apparatus for determining the soil water characteristic curve (SWCC), a key measurement in unsaturated soil mechanics. The typical assembly of a Tempe cell setup are shown in Figure 1. To measure the SWCC, a sample is placed in the cell body. The air pressure supply connected to the top of the cell body forces pore water to flow out of the sample through the microscopic pores of the porous ceramic plate. Expelled pore water is collected in the drainage tube. The ceramic plate at the bottom prevents air from entering unless the air-entry value of the ceramic plate is exceeded.

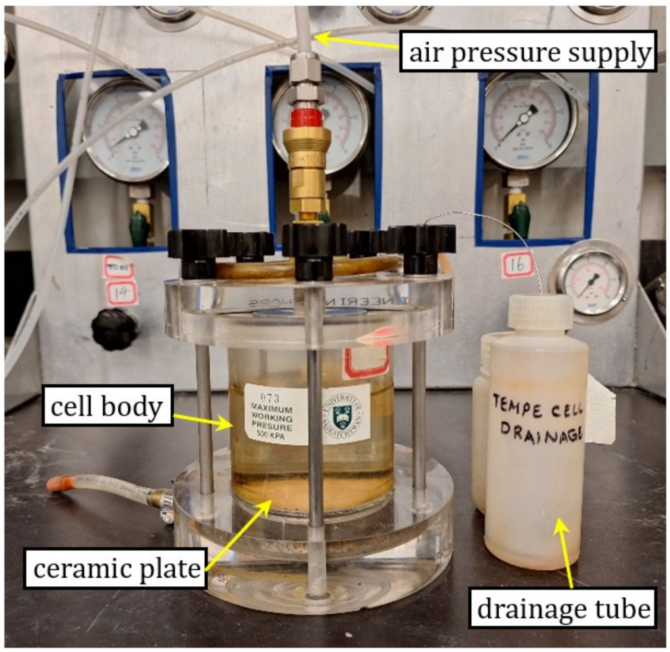

Figure 1: Tempe cell set up overview

The mass of the Tempe cell is measured frequently until equilibrium is reached under a given air pressure. The applied air pressure is then increased, and this process is repeated to produce a set of paired mass and air pressure measurements. The axis translation principle is applied to convert the applied air pressure into an equivalent matric suction, and the mass measurements are used to determine other geotechnical paraments [1].

Tempe cells are used to characterize the unsaturated behaviour of oil sands fine tailings, which are a waste by-product of bitumen mining in Northern Alberta [5]. The behaviour of oil sands fine tailings is controlled by the fraction of clay minerals, and this contributes challenging engineering behaviours such as slow consolidation and large volume changes upon drying [2] [3]. As a result, reclaiming oil sands tailings to a sustainable landform is an ongoing challenge.

Oil sands tailings contain residual bitumen from the extraction process, which leaves stains on the ceramic plates as shown in Figure 2. The purpose of the ceramic plate is to allow the flow of water out of the Tempe cell body through small pores in the ceramic while restricting the flow of air [6]. Concerns have therefore been raised regarding whether bitumen and small clay particles may clog the pores of the ceramic plate and reduce the hydraulic conductivity of the ceramic plate over time. This is of specific concern for oil sands tailings because determining the SWCC can take several weeks due to low hydraulic conductivity of clays. From a laboratory perspective, it is desirable to not unnecessarily extend the time required to perform these critical tests by reducing equipment degradation.

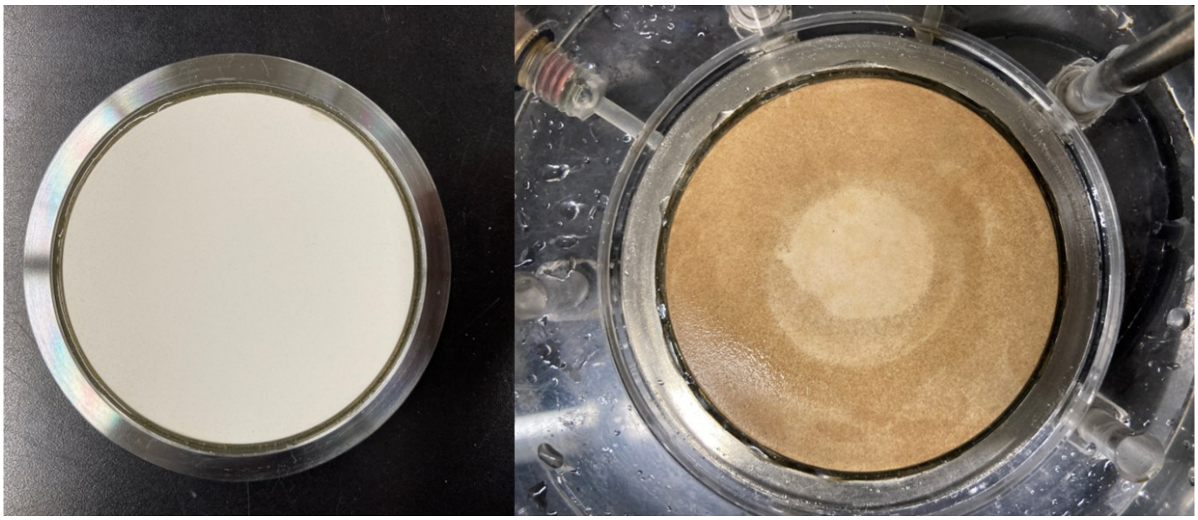

Figure 2: Comparison between a new (left) and a used, bitumen-stained (right) ceramic plate.

To investigate the effect of bituminous staining, a laboratory test program was undertaken to measure the changes in the hydraulic conductivity of ceramic plates over time. The goal of this test program is to assess the degree to which clogging reduces the hydraulic conductivity of ceramic plates and develop recommendations to maintain long term performance.

Materials and Methods

Over a period of two years, ceramic plates from the University of Alberta Unsaturated Soils Laboratory were regularly tested for hydraulic conductivity. During this period, the ceramic plates in Tempe cells were used in a variety of research projects testing oil sands fine tailings with a plasticity index of 30. After each test was completed, the hydraulic conductivity of the ceramic plate was measured, and all ceramic plates were stored in de-ionized water while not in use to ensure full saturation.

The ceramic plates in the Tempe cells are moderately fired clay and talc materials with a thickness of 8 mm and a diameter of 67.5 mm. Effective porosities for the 1-bar and 5-bar plates are 0.34 and 0.31 respectively [7]. Ceramic plates with an air-entry value of 1-bar (100 kPa) and 5-bar (500 kPa) were tested, which corresponds to the approximate pressure above which air will diffuse through the porous ceramic [6].

Hydraulic Conductivity Test Procedure

The hydraulic conductivity of the ceramic plate was measured using a modified version of the flushing test developed by Padilla et al. [6]. To perform the test, the Tempe cell was filled with approximately 250 mL of deionized (DI) water, flushed to remove any air bubbles in the tubing, and weighed. Air pressure was then applied at 10% of the air-entry value of the ceramic plate. The applied air pressure force water through the ceramic plate and out of the Tempe cell body. Over time, the level of water in the Tempe cell reduces, similar to a falling head test. After some free-standing water in the Tempe cell had drained, but before the cell became empty, the air pressure was removed, the tubing was flushed again to remove air bubbles, and the final weight of the Tempe cell was recorded.

Darcy's law describes flow through a porous medium using equation (1) where q is the seepage rate, K is the hydraulic conductivity, i is the hydraulic gradient, A is the cross-sectional area through which flow is occurring and n_e is the effective porosity of the ceramic plate. The purpose of dividing by the effective porosity is to determine the seepage through specifically the pores of the ceramic plate and evaluate the degree to which they are being clogged.

$$q = \frac{KiA}{n_e} \qquad (1)$$

To calculate the hydraulic conductivity, the flow rate through the ceramic plate was calculated in equation (2) by dividing the change in mass (g) of the water in the Tempe cell body (equal to the change in volume assuming a density of 1 g/cm^3 for water) by the duration of the applied pressure (t).

$$q = \frac{\Delta m}{\Delta t} \qquad (2)$$

The hydraulic gradient (i) was also calculated from the change in head (Δh) and the seepage length (L) in equation (3). Since the water is flowing from the Tempe cell body, which is experiencing an applied pressure above atmospheric pressure, to a drainage collection bottle, which is under atmospheric pressure, the change in total head is equal to the applied air pressure (assuming 1 m of head is equal to 9.81 kPa in pressure units). The seepage length ΔL is the thickness of the ceramic plate.

$$i = \frac{\Delta h}{\Delta L} \qquad (3)$$

The hydraulic conductivity was then calculated from Darcy's law using the flow rate, the hydraulic gradient, effective porosity and area of the ceramic plate as shown in the equation below.

$$K = \frac{qn_e}{iA} \qquad (4)$$

Between each hydraulic conductivity test, the ceramic plate was gently cleaned with sponges and warm soapy water. The Tempe cell is then used in testing oil sands fine tailings with the one-step technique [5]. The hydraulic conductivity test procedure was repeated after each Tempe cell test for SWCC.

Results

The results of the hydraulic conductivity testing are shown in Figure 3 and 4 below. In Figure 3, each test number refers to a ceramic plate used repeatedly for a single type of material. In Figure 4, the test numbers are denoted by a combination of letters and numbers to distinguish between test operators. Each letter refers to a ceramic plate used repeatedly for a single type of material. Hydraulic conductivity values provided by the ceramic manufacturer are 3.46×10^{-9} m/s and 9.66×10^{-11} m/s for the 1-bar and 5-bar plates respectively.

Hydraulic conductivities in the 1-bar plates are generally less-than-an-order-of-magnitude higher than the values provided by the manufacturer. No discernible trend in hydraulic conductivities can be observed in the 1-bar plates. Hydraulic conductivities in the 5-bar plates are also slightly higher than the manufacturer values except Test T2. A decreasing trend was observed in most tests with values reaching stable values after the 4th test. Test Y1 to Y4 also showed a decreasing trend; however, it is not clear if the hydraulic conductivities have stabilized due to limited number of tests.

Figure 5 shows the number of days for oil sands fine tailings to reach equilibrium in the Tempe cell under the 400 kPa matric suction. Differences in the number of days to reach equilibrium are due to the amount of sample placed in the Tempe cell (i.e. more samples required longer time to reach equilibrium). No discernible increase in the time to reach equilibrium can be observed.

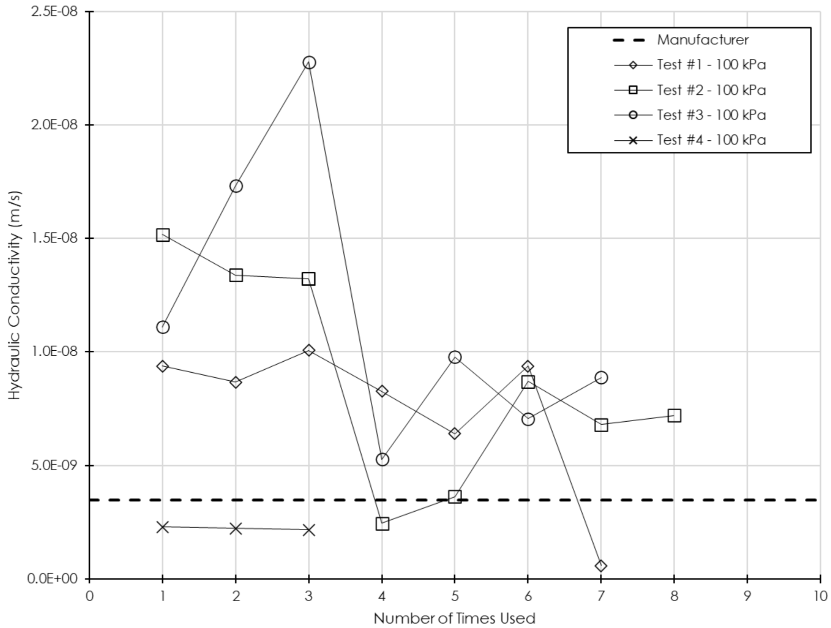

Figure 3. Evolution of hydraulic conductivity in ceramic plates with air-entry value of 100 kPa

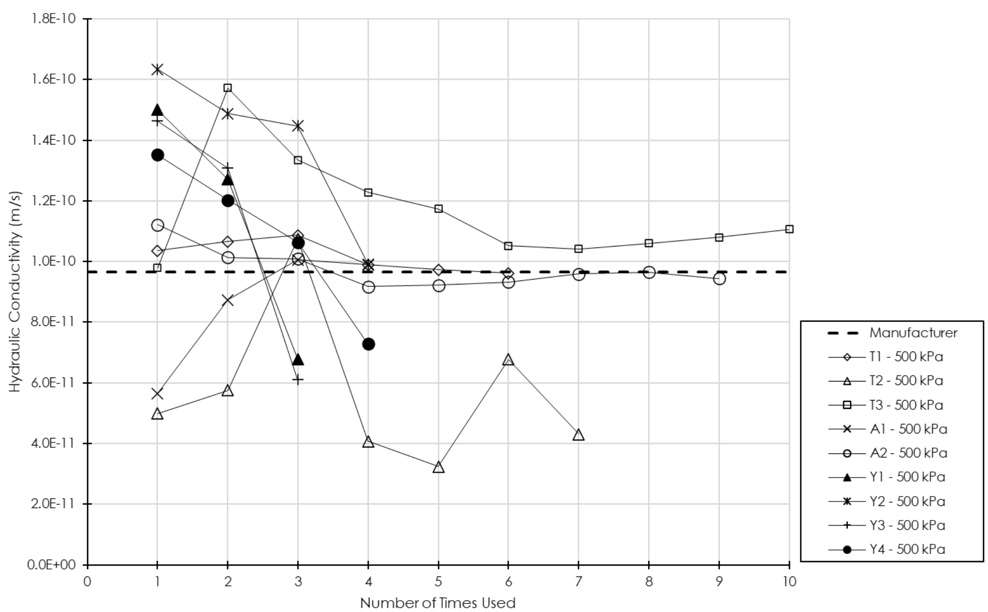

Figure 4. Evolution of hydraulic conductivity in ceramic plates with air-entry value of 500 kPa

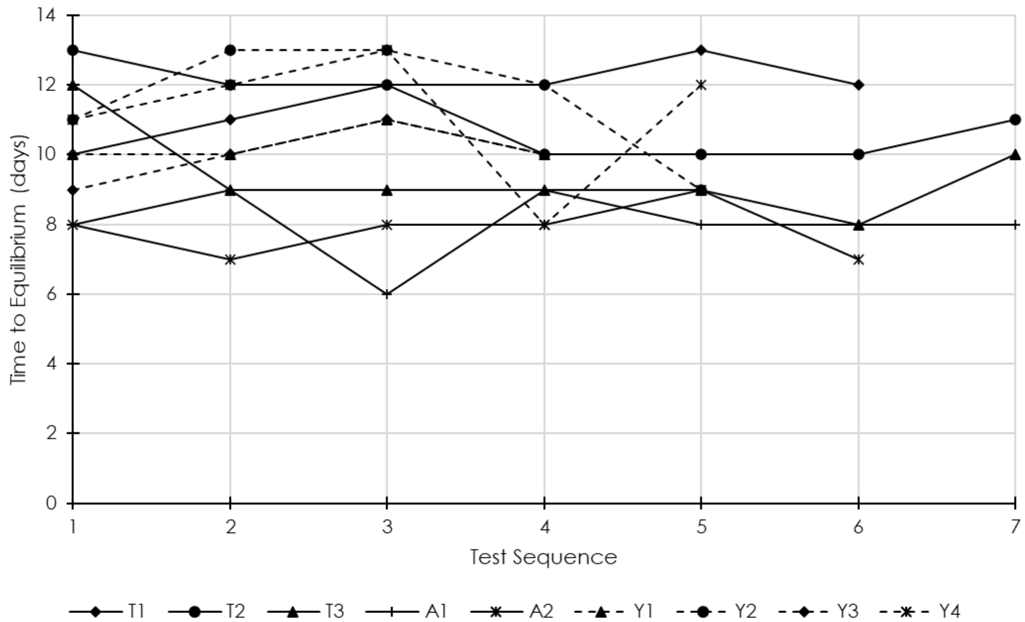

Figure 5. Evolution of time for oil sands fine tailings to reach equilibrium in ceramic plates with air-entry value of 500 kPa

Discussion

The ratio of the measured hydraulic conductivity (K_m) to the initial hydraulic conductivity (K_1) for each ceramic plate was calculated for all tests. If K_m/K_1 was greater than 1, the hydraulic conductivity increased compared to the first test, and if K_m/K_1 was less than 1, the hydraulic conductivity decreased. Results are presented for 1-bar plates and 5-bar plates in Figure 6 and Figure 7 respectively. The ratio remained consistent in the dataset for the 5-bar ceramic plate while K_m/K_1 for the 1-bar plates decreased over time. This may be the result of larger pores in the ceramic that are more effective at trapping bitumen and clay particles compared to smaller pores.

Somewhat serendipitously, it is possible that the test program itself prevented the formation of staining and led to good long term performance. That is, the water flushing test itself along with regular washing may have removed any remaining bitumen and clay particles in the pore space of the ceramic plate after each test. Considering the trendline in Figure 5 where no increases in equilibration time are observed, this study indicates that regular flushing and washing of the 5-bar ceramic plate will maintain its hydraulic conductivity and extend its service life in applications for oil sands tailings. For the 1-bar ceramic plate, slight decreases in hydraulic conductivity overall were observed. A more aggressive cleaning procedure is likely required to remove clay and bitumen particles from the larger pores of the 1-bar ceramic plates.

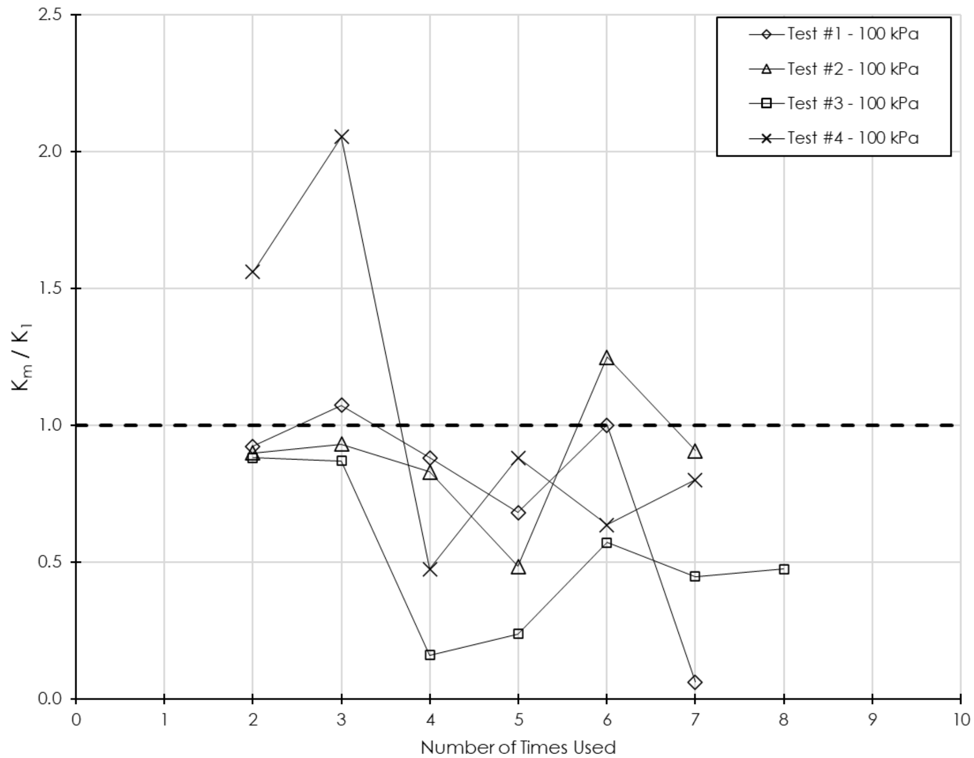

Figure 6. Comparison of subsequent hydraulic conductivity measurements with the first test in ceramic plates with air-entry value of 100 kPa.

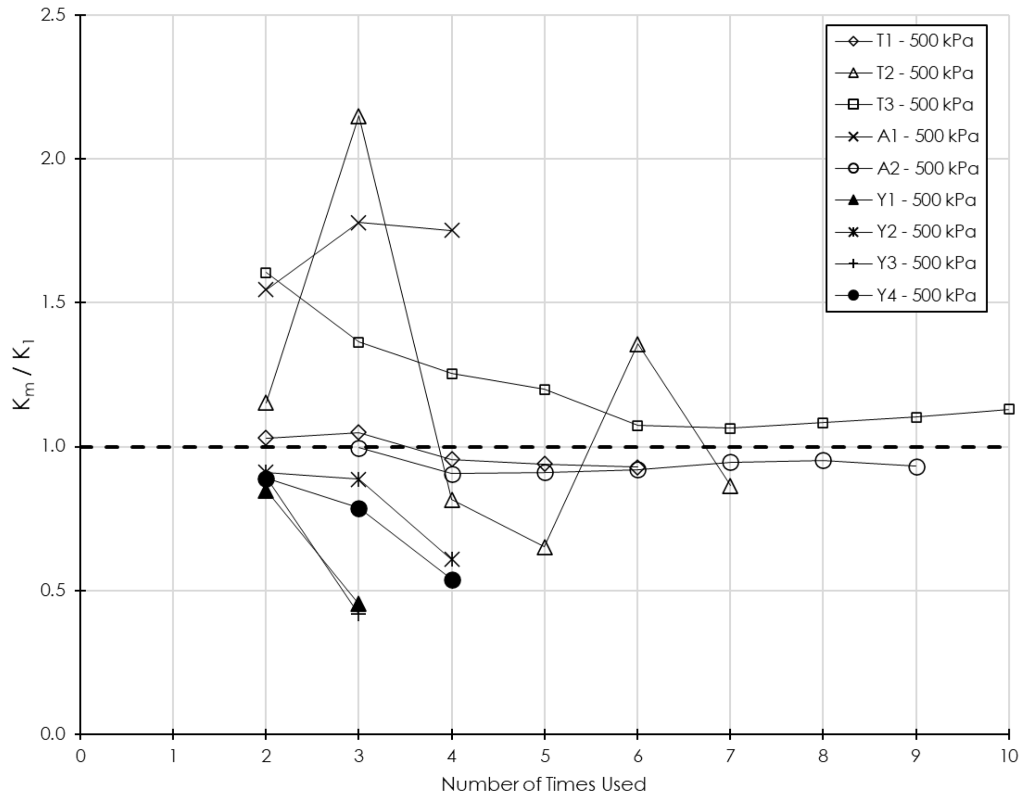

Figure 7. Comparison of subsequent hydraulic conductivity measurements with the first test in ceramic plates with air-entry value of 500 kPa

Conclusion

A series of hydraulic conductivity tests conduced at the University of Alberta Unsaturated Soils Laboratory over a period of two years found that there was not a significant reduction in the 5-bar ceramic plate performance due to bitumen and clay staining. We recommend regular flushing of the ceramic plate with clean water combined with gentle washing with dish soap and water as an effective method to maintain its hydraulic conductivity and extend its service life in applications for oil sands tailings. For the 1-bar ceramic plate, a slight decreasing trend in hydraulic conductivity was observed, suggesting a more aggressive cleaning and maintenance protocol is required.

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