Hydraulic conductivity of compacted clay liners moisture-conditioned and permeated with saline coal seam gas water

La conductivité hydraulique de l'humidité argile compactée doublures conditionné et imprégné avec de l'eau salée gaz de houille couture

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ABSTRACT: The effects on the hydraulic conductivity of compacted clays, commonly used for lining coal seam gas (CSG) water storage ponds, of moisture conditioning and permeating with CSG water are investigated. Four kaolinite-dominant clays were mixed with CSG and deionised waters, compacted to varying degrees at different gravimetric moisture contents. The compacted specimens were subjected to 100 kPa hydraulic loading with CSG or deionised waters in compaction mould permeameters, and 100 kPa applied stress in oedometers, with the specimens placed in a bath of CSG or deionised water to match the water used to prepare the specimens. The 100 kPa loading represented the expected maximum pond water depth. The test results show that the hydraulic conductivity of clay specimens moisture-conditioned and permeated with both CSG and deionised waters decreased with time due to rearrangement of the clay particles. At the end of the tests with CSG and deionised waters, the clay specimens were found to have very low hydraulic conductivities of the order of 1E-11 m/s. The hydraulic conductivity values measured using the compaction mould permeameters were found to be reasonably comparable to those calculated from oedometer test data.

RÉSUMÉ: Les effets du contrôle en humidité et de l'imprégnation en eau venant de la production du gaz de houille, sur la conductivité hydraulique des argiles compactées (couramment utilisés pour le revêtement des bassins de stockage de cette eau) sont étudiés. Quatre argiles majoritairement kaolinites ont été mélangées avec le gaz de houille et de l'eau dé-ionisée, compactés à des degrés divers et à différentes teneurs en eau gravimétrique. Les échantillons compactés ont été soumis à un chargement hydraulique de 100 kPa avec le gaz ou l'eau dé-ionisée dans des perméamètres à moules de compactage, à une contrainte appliquée de 100 kPa dans des œdomètres, les échantillons étant placés dans un bain de gaz ou d'eau dé-ionisée pour correspondre à l'eau utilisée pour préparer les échantillons. Le chargement de 100 kPa correspondait à la profondeur maximale prévue pour le bassin d'eau. Les résultats des essais montrent que la conductivité hydraulique des échantillons d'argile à l'humidité contrôlée imprégnés à la fois de gaz de houille et d'eau dé-ionisée a diminué avec le temps en raison du réarrangement des particules d'argile. A la fin des essais avec le gaz et l'eau dé-ionisée, les échantillons d'argile ont présentés une très faible conductivité hydraulique de l'ordre de 1E-11 m/s. Les valeurs de conductivité hydraulique mesurée en utilisant les perméamètres à moules de compactage ont été jugées raisonnablement comparables à ceux calculés à partir des données de test œdométriques.

KEYWORDS: compacted clay liner, dispersion, hydraulic conductivity, kaolinite, oedometer, compaction mould permeameter.

1 INTRODUCTION

Rigid-wall hydraulic conductivity testing can be carried out using a compaction mould permeameter or an oedometer. A compaction mould permeameter allows the direct measurement of hydraulic conductivity, while hydraulic conductivity is calculated from the rate of consolidation in an oedometer test and the values obtained have been found to be too low (e.g., Taylor 1942; Mitchell & Madsen 1987).

Natural and compacted clays have been used in Queensland, Australia, as a liner for the storage of saline water produced during coal seam gas (CSG) production to limit seepage to the underlying soil and groundwater. Under the prevailing semi-arid climatic conditions, the available clays are typically dry and require moisture conditioning to achieve the moisture content specified for compaction. The most readily available water for moisture conditioning is the saline CSG water. This paper investigates the effects of moisture conditioning and permeating with CSG water on the hydraulic conductivity of these clays, with testing using deionised water used as a reference.

2 MATERIALS TESTED

Kaolinite-dominated clay samples, labelled herein as SB1, SB2, SB3 and DT, were obtained from a CSG production site in Queensland, Australia. The sand, silt and clay fractions are shown in Table 1. The liquid limits of SB1, SB2, SB3 and DT were 64.4%, 44.0%, 61.9% and 65.9%, and the plasticity indices were 43.6%, 25.2%, 45.2% and 51.1%, respectively. According to the Unified Soil Classification System (USCS), SB1 and DT were classified as clays of high plasticity (CH), SB2 was classified as a sandy clay of low plasticity (CL), and SB3 was classified as a sandy clay of high plasticity (CH).

Table 1. Particle size distributions of clay samples.

Sample	Particle size		
	Sand (%)	Silt (%)	Clay (%)
SB1	4.1	26.1	69.8
SB2	26.2	24.7	49.1
SB3	20.6	18.6	60.8
DT	13.3	19.9	66.8

The electrical conductivity (EC) of the saturated paste extracts, corresponding to about the liquid limits, were 13.4 dS/m, 8.7 dS/m, 14.6 dS/m and 14.6 dS/m, for SB1, SB2, SB3 and DT, respectively. The exchangeable sodium percentages were 41.3%, 33.2%, 39.0% and 45.1%, respectively. Based on these two parameters, the clay samples were classified as saline-alkali soils (Richards 1954).

Sample preparation for the hydraulic conductivity testing involved moisture conditioning with saline CSG water (CW) and deionised water (DW), and compaction to 90%, 95%, 98% and 100% of the maximum dry densities (MDD) at the optimum moisture contents (OMC) and at a nominal 3% wet of the optimum moisture contents (wet of OMC), based on the compaction curves shown in Figure 1. The concentrations of the major ions, EC, and pH of the CW are presented in Table 2.

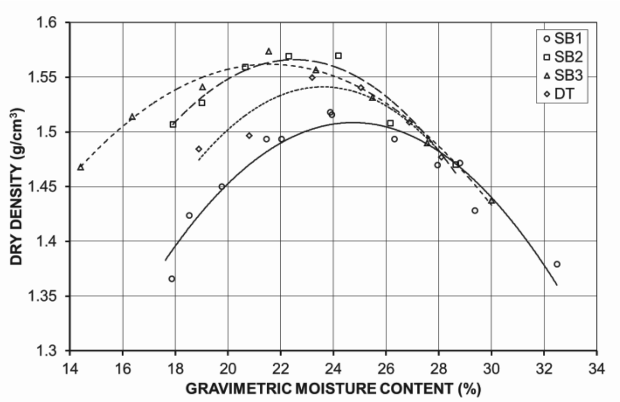

Figure 1. Compaction curves for clay samples.

Table 2. Chemistry of saline CSG water.

Cl^- (mg/l)	Na^+ (mg/l)	Mg^{2+} (mg/l)	Ca^{2+} (mg/l)	K^+ (mg/l)	EC (dS/m)	pH
789	1484	11	8	8	5.8	9.6

3 HYDRAULIC CONDUCTIVITY TESTING

3.1 *Compaction mould testing*

Specimens were compacted to the specified dry density at the specified moisture content in a 144 mm diameter by 130 mm high modified compaction mould permeameter. The initial height of each compacted specimen was limited to 50 mm, to allow space for the specimen to swell to its maximum capacity, as would occur in the field. Prior to a test, no attempt was made to saturate the specimen, simulating the field condition in which a clay liner will not be fully saturated prior to the ponding of CSG water. A 100 kPa constant water pressure was gradually applied to top of the specimen to simulate a 10 m deep pond of CSG water.

To minimise bypass flow along the wall of the permeameter under the high applied hydraulic gradient of 200, a well-graded sand was glued to the wall to roughen its surface. The effectiveness of the sand coating in preventing bypass flow was verified by conducting hydraulic conductivity tests under a 100 kPa constant water pressure using CW applied to SB1 mixed with CW and compacted to 90% of the MDD at OMC, and 95% of MDD wet of OMC. A 101.9 mm diameter by 5 mm thick sharp-edged divider ring was installed centrally on top of the base plate, on which a 3 mm thick medium sand layer was placed to act as a drainage layer. The divider ring had an area of about 50% of the open permeameter area and penetrated about 2 mm into the base of the compacted clay specimen. In addition to an outlet located at the centre of the base plate, two outer outlets between the permeameter wall and the edge of divider ring were provided. The flow rates from each of the outlets were calculated assuming vertical only flow. The measured flow rates from each of the outlets for the 90% MDD at OMC specimen are shown in Figure 2, in which there are no appreciable differences between the central and outer flow rates, indicating that the roughened permeameter wall was effective in minimising bypass flow. A similar result was obtained for the 95% MDD wet of OMC specimen.

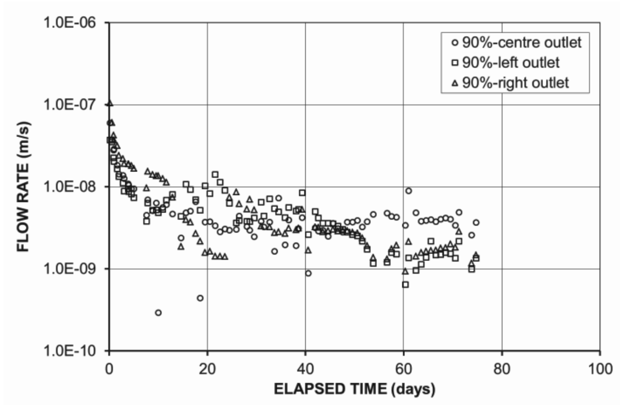

Figure 2. Flow rates from centre and outer outlets during testing of 90% MDD at OMC specimen with roughened permeameter wall.

A set of hydraulic conductivity tests was conducted on SB3 compacted to 90% of the MDD at the OMC, 95% of MDD at OMC and wet of OMC, 98% of MDD at OMC and wet of OMC, and 100% of MDD at OMC, to study the effects of dry density and moulding moisture content on hydraulic conductivity. Another set of hydraulic conductivity tests was conducted on all samples compacted to 95% of MDD wet of OMC, and mixed and permeated with DW and CW, to investigate the effects of moulding and permeating water type on hydraulic conductivity. These dry densities and moisture contents were selected because the clays in the field are usually compacted to 95% of MDD wet of OMC.

It was expected that moisture conditioning wet of the OMC would show significant differences in the compacted hydraulic conductivity compared to that following moisture conditioning to the OMC, since additional water would be available to fill the initially air-dried voids. The permeameter tests were terminated once a relatively constant flow rate and salt concentration of the outflow had been achieved. The EC and pH values of the outflows were measured using a portable EC-pH meter, while concentrations of major anions (Cl^-) and cations (Na^+, Mg^{2+}, Ca^{2+} and K^+) were measured using inductively-coupled plasma and inductively-coupled plasma-optical emission spectrometry methods, respectively.

3.2 *Oedometer testing*

Oedometer tests were conducted on standard 76 mm diameter by 20 mm thick compacted specimens mixed with and in a water bath of CW or DW. Each specimen was subjected to incremental applied stresses of 10 kPa, 50 kPa, 100 kPa and 150 kPa, from which data the coefficients of consolidation and coefficients of volume decrease, and hence hydraulic conductivities, were calculated. During the tests, the oedometer cells were covered with Glad wrap to prevent any change in the salt concentration or pH of the water bath due to evaporation.

4 TEST RESULTS AND DISCUSSION

4.1 *Compaction mould hydraulic conductivity*

The measured hydraulic conductivities of all compacted SB3 specimens are shown in Figure 3. Figure 3 shows that specimens compacted to 90% of MDD at OMC tend to have the highest hydraulic conductivities, while specimens compacted to 100% of MDD at OMC and 98% of MDD wet of OMC tend to have the lowest hydraulic conductivities. Comparing the data for specimens compacted at 98% and 95% of MDD, it appears that those compacted wet of OMC tend to have lower hydraulic conductivities than those compacted at OMC.

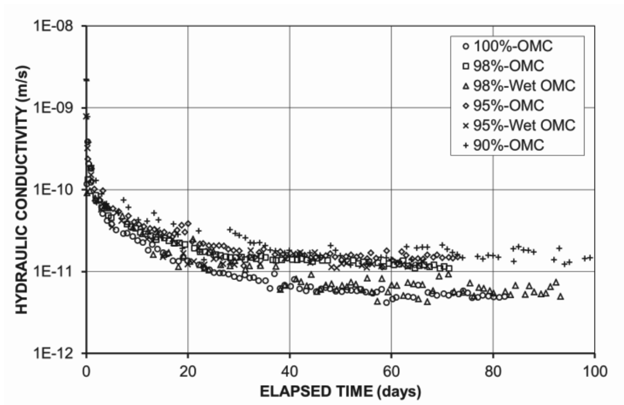

Figure 3. Hydraulic conductivity of SB3 specimens compacted to various dry densities at various moisture contents.

The change in the EC of the outflow from the SB3 specimens during the hydraulic conductivity tests is shown in Figure 4. The samples were originally saline, with an EC at their natural moisture content much higher than that of the CW. As the ponded CW infiltrated the compacted specimens, ionic exchange occurred between the infiltrating CW and the original pore water. This caused the EC of the outflow to decrease with time and eventually approach that of the CW, as salts in the compacted specimens were washed out, as shown in Figure 5.

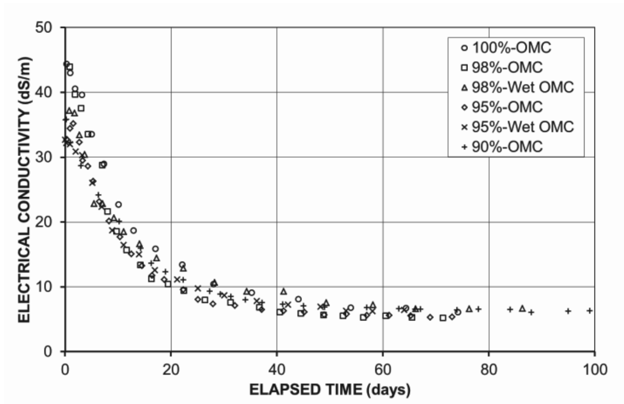

Figure 4. Electrical conductivity of SB3 specimens compacted to various dry densities at various moisture contents.

The pH of the pore water squeezed from SB3 mixed with CW to a gravimetric moisture content of 29% was 5.7, and at the OMC (21.8%) the pH was expected to be lower. Figure 6 shows that the pH of the outflow from SB3 specimens compacted to various dry densities at different moisture contents increased with time, exceeding the pH at the point of zero charge (PZC) at the edges (E) of the kaolinite particles, in the pH range 5 to 7 (Kretzschmar et al. 1998, Wang and Siu 2006). Below the PZC, the edges of kaolinite particles carry positive charges, while above the PZC, the edges carry negative charges. The faces (F) of kaolinite particles are always negatively-charged, resulting in a lower pH than at the edges (Wang and Siu 2006). Below the PZC, kaolinite particles tend to develop an E-F flocculated structure. When the pH is greater than that at the PZC, E-F interaction is prevented, since both E and F are negatively-charged, and kaolinite particles tend to have a dispersed structure.

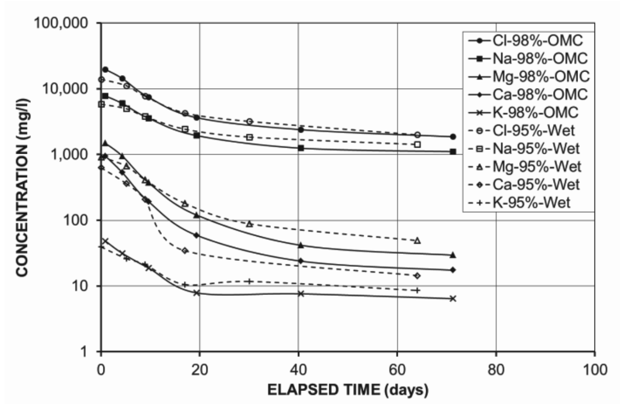

Figure 5. Concentrations of major ions in outflow from SB3 specimens compacted to 98% and 95% of MDD.

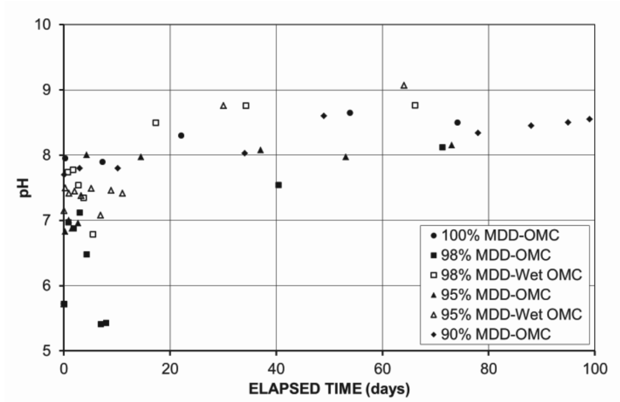

Figure 6. pH of SB3 specimens compacted to various dry densities at various moisture contents.

The hydraulic conductivity was initially high due to a flocculated clay structure, and decreased with time as the kaolinite particles became aligned and developed a dispersed structure. In addition, high clay dispersion was observed in the upper 3 to 5 mm layer of the compacted specimens. Clay dispersion is likely to clog the compacted pores and hence contribute to the observed decrease in hydraulic conductivity.

Similar to the compacted specimens permeated with CW, the hydraulic conductivity of all compacted specimens permeated with DW also decreased with time, as shown in Figure 7. Again, the kaolinite particles tend to develop a dispersed structure when the PZC of the edges is exceeded. As the pH of DW is 7, slightly above the PZC of the edges of kaolinite particles, the infiltration of DW eventually raises the pH of the outflow to 7, resulting in a dispersed structure and the decrease in the hydraulic conductivity with time observed in Figure 7.

Table 3 shows that there is no a clear trend of hydraulic conductivity of specimens moisture-conditioned and permeated with DW and CW in the compaction mould permeameter tests. The differences are considered to be within the accuracy of outflow measurements at these low hydraulic conductivities, due to susceptibility to environmental conditions such as evaporation. Moisture-conditioning with CW and DW is likely to affect the kaolinite structures only after mixing, or at the beginning of the hydraulic conductivity tests. Rearrangement of the kaolinite particles as the tests proceeded resulted in their eventual exposure to permeating CW.

4.2 *Oedometer hydraulic conductivity*

Despite the reduced reliability of the oedometer test for determining the hydraulic conductivity of a compacted clay, the values obtained from the oedometer test data under an applied stress of 100 kPa were reasonably comparable to, or a little higher than, those measured using the compaction mould permeameter under a 100 kPa applied water pressure, as seen in Table 3. However, it is important to note that the underlying flow mechanisms in the compaction mould permeameter and oedometer tests are quite different.

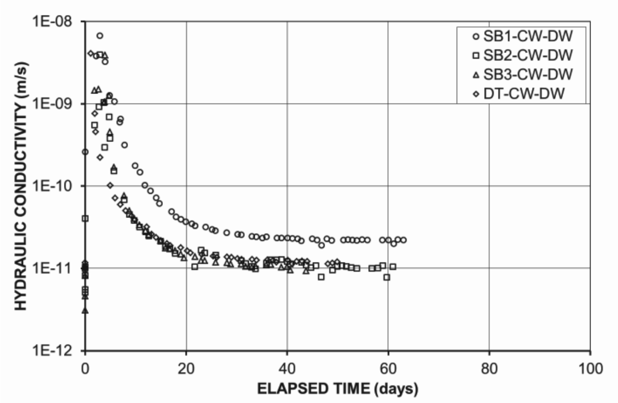

Figure 7. Hydraulic conductivity of all specimens moisture-conditioned with CW, compacted, and permeated with DW.

Table 3. Compaction mould permeameter and oedometer hydraulic conductivities of specimens compacted to 95% of MDD wet of OMC.

Sample	Hydraulic conductivity under 100 kPa	
	Compaction mould	Oedometer
SB1-DW-CW	1.2E-11	3.0E-11
SB1-CW-CW	6.5E-12	7.0E-12
SB1-CW-DW	2.2E-11	1.1E-11
SB2-DW-CW	1.2E-11	1.3E-11
SB2-CW-CW	1.8E-11	1.2E-11
SB2-CW-DW	1.1E-11	7.2E-11
SB3-DW-CW	1.0E-11	1.5E-11
SB3-CW-CW	1.2E-11	1.2E-11
SB3-CW-DW	1.0E-11	1.9E-11
DT-CW-CW	1.1E-11	5.9E-11
DT-CW-DW	1.2E-11	-
Averages	1.2E-11	2.5E-11

In the compaction mould permeameter, ponded water is forced under a pressure of 100 kPa to flow into the compacted specimens, causing their moisture content to increase significantly and the specimens to swell by about 70% of their initial height, with the upper 3 to 5 mm layer reaching a final gravimetric moisture content of about 70%. Swelling allowed the rearrangement of the clay particles from flocculated to dispersed.

In the oedometer specimens, matric suctions of 40 to 50 kPa were measured using tensiometers, and swelling pressures were likely to be greater than 10 kPa. As a result, under an applied stress of 10 kPa bath water was adsorbed and the compacted specimens swelled, allowing the rearrangement of the clay particles. At applied stresses of 50 kPa and greater, water is forced to flow out of the specimens, as indicated by the reduction in vertical strain with increasing applied stress shown in Figure 8. Since the amount of pore water is reducing, physico-chemical interaction between the pore water and the clay particles is likely to be limited. The main mechanism is therefore consolidation, a reduction in the void ratio, and a consequent reduction in the hydraulic conductivity.

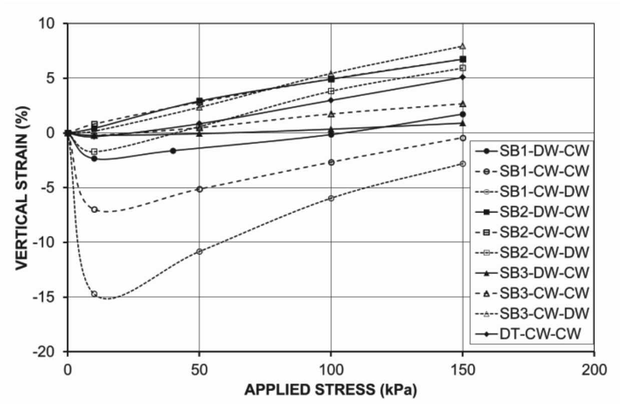

Figure 8. Vertical strains measured during oedometer tests.

5 CONCLUSION

The hydraulic conductivity of clays moisture-conditioned, compacted and permeated with saline CSG water was found to be similar to that of the same clays moisture-conditioned, compacted and permeated with deionised water. The hydraulic conductivity of the clay specimens decreased with increasing compaction from 90% to 100% of MDD, achieving a low value at 100% of MDD. The clays *in situ* would have a high dry density of at least 100% of their MDD, and hence would be suitable as a liner for a CSG water storage pond.

In both CSG and deionised waters, the compacted clay particles dispersed and the hydraulic conductivity decreased to a very low value of about 1E-11 m/s. The hydraulic conductivities measured using a compaction mould permeameter were found to be comparable to, and a little higher than, those calculated from oedometer test data for the same compacted clays.

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