

Critical issues in the determination of the bentonite cation exchange capacity

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**Critical issues in the determination of the bentonite cation exchange capacity for the assessment of the macroscopic density of the solid electric charge**

By

Dominijanni A.\*, Fratalocchi, E., Guarena N., Manassero M., Mazzieri F.

- **Abstract**

The swelling pressure and transport properties of bentonites are controlled by the electric charge density of solid particles, which is commonly estimated from the laboratory measurement of the cation exchange capacity (CEC). However, the standard ammonium displacement method for CEC determination does not take into account the fabric changes that occur in bentonites under exposure to high salt concentration solutions. A series of laboratory tests was conducted to assess the relevance of such a critical issue, by varying the concentration of the extracting KCl solution with respect to that of the standard test. The obtained results show that the release of the adsorbed ammonium cations depends on the bentonite fabric, which is controlled by the KCl concentration. As a consequence, the ammonium displacement method may provide an unrepresentative estimate of the CEC of bentonites. The methylene blue titration method, despite its apparently more limited accuracy, instead seems to provide a more reliable estimation of the CEC, as the bentonite fabric is maintained dispersed during the test.

**Keywords chosen from the ICE Publishing list**

Geosynthetic application, Landfills, Waste management & disposal

**List of notations**

$\alpha$	empirical coefficient of the fabric boundary surface equation
$\beta$	empirical coefficient of the fabric boundary surface equation
$\rho_{sk}$	solid-phase density
$b_n$	average half-distance between the platelets in the tactoid
$c_0$	reference molar concentration in the fabric boundary surface equation
$c_s$	salt molar concentration
$\bar{c}_{sk,0}$	molar concentration per unit solid volume of the solid skeleton electric charge
CEC	cation exchange capacity
$d_d$	$d_{stern}/b_n$
$d_{stern}$	thickness of the Stern Layer around the external surface of the tactoid
$e$	total void ratio
$e_m$	micro-void ratio
$f_{stern}$	fraction of cations adsorbed in the Stern layer
$H$	height of the bentonite layer in the filtration apparatus of the ammonium displacement method
$k$	hydraulic conductivity of the bentonite layer in the filtration apparatus of the ammonium displacement method
$N_{i,AV}$	average number of lamellae per tactoid
$N_{i,AV0}$	empirical coefficient of the fabric boundary surface equation

S total specific surface of bentonite  
u<sub>sw</sub> swelling pressure

## 1 Introduction

2 The transport properties and mechanical behaviour of clay soils with a high specific surface,  
3 such as bentonites, are governed by the microscopic interactions that occur between the  
4 electrically charged solid particles and the ions that are contained in the pore solution (Lambe,  
5 1960; Groenevelt and Bolt, 1969; Sridharan and Rao, 1973; Mitchell, 1991; Moyne and Murad,  
6 2002; Mitchell and Soga, 2005; Guimarães et al., 2013; Musso et al., 2017; Revil, 2017a,  
7 2017b; Delage, 2019).

8 Bentonites can have either a dispersed fabric, in which clay particles are present as well  
9 separated montmorillonite units, or an aggregated structure that consists of packets of particles,  
10 or tactoids, within which several clay platelets are in a parallel array. The formation of tactoids is  
11 determined by a reduction in the electrical repulsive forces among the clay particles, which is  
12 mainly induced by an increase in the salt concentration or a decrease in the solvent dielectric  
13 constant of the pore solution.

14 The expected performances of bentonites can be assessed in field applications through  
15 physics-based models, which relate the macroscopic constitutive parameters, including  
16 hydraulic conductivity, chemico-osmotic efficiency, diffusion coefficient and swelling pressure, to  
17 microscopic fabric parameters, such as the average number of montmorillonite lamellae per  
18 tactoid,  $N_{i,AV}$  (Dominijanni and Manassero, 2012; Shackelford et al., 2019).

19 Manassero (2017) described a physics-based model that was obtained by volume averaging the  
20 equations that govern the electric potential distribution, the water flow and the ion transport at  
21 the pore scale, and by imposing the condition of macroscopic thermodynamic equilibrium  
22 between the pore solution and the external bulk solutions in contact with the bentonite at its  
23 boundaries (Dominijanni and Manassero, 2005, 2012; Dominijanni et al., 2006, 2013, 2018).

24 On the basis of such a theoretical approach, the microscopic (pore scale) properties of  
25 bentonites are taken into account through a single fundamental parameter, that is the molar  
26 concentration per unit solid volume of the solid skeleton electric charge,  $\bar{c}_{sk,0}$ . This parameter is  
27 related to the cation exchange capacity, CEC, as follows (Dominijanni and Manassero, 2012):

28

$$29 \quad \bar{c}_{sk,0} = \frac{1 - f_{Stern}}{N_{i,AV}} \cdot CEC \cdot \rho_{sk} \quad (1)$$

30

31 where  $\rho_{sk}$  is the solid-phase density ( $\approx 2700 \text{ kg/m}^3$ ) and  $f_{\text{Stern}}$  is the fraction of cations  
32 immobilized in the so-called Stern layer ( $\approx 0.75\text{--}0.95$ ).

33 Although CEC determination alone is not sufficient to allow an evaluation of  $\bar{c}_{sk,0}$ , it plays a  
34 fundamental role in relating the physical and chemical properties of bentonite at the pore scale  
35 to the macroscopic constitutive parameters. For this reason, a series of experimental tests has  
36 been conducted to assess the reliability of the most commonly used CEC measurement  
37 methods, including the ammonium displacement method and the methylene blue titration (MB)  
38 method.

39

## 40 **2. Materials and methods**

41

### 42 **2.1 Bentonite**

43 The powdered bentonite used in this study comes from the same lot and was subjected to the  
44 same cyclic-squeezing procedure as in Puma et al. (2015) to remove soluble salts prior to  
45 further testing. The main properties of the bentonite are listed in Table 1.

46

### 47 **2.2 Testing procedures**

48 As far as the ammonium displacement method is concerned, the CEC was determined  
49 according to the ASTM D7503-18 procedure, except for the KCl solutions that were used in the  
50 final extraction step: in addition to the 1 M KCl solution (standard procedure), extracting  
51 solutions with different KCl concentrations (4.5 M, 0.1 M, 0.05 M, 0.025 M, 0.01 M, 0.0025 M,  
52 0.001 M) were used together with distilled water (DW) to investigate the effect of changes in the  
53 bentonite fabric on the CEC results. The tests were generally performed in duplicate for each  
54 extracting solution.

55 The MB test was carried out following the procedure outlined in EUBA (2002). The method is a  
56 rapid qualitative procedure that is used in industry for routine quality controls, which provides a  
57 measure of the accessible anionic sites in a condition of enhanced dispersion of the clay. This

58 dispersion is obtained by bringing the bentonite suspension to the boil and subsequently titrating  
59 the suspension with an anionic dye (methylene blue).

60

### 61 **3. Test results**

62 The CEC measurement results are listed in Table 2 and plotted in Figure 1. The solid symbols  
63 in Figure 1 represent the CEC values obtained from the ammonium release measurements. The  
64 values obtained using DW are plotted at 0.0001 M KCl concentration. Considering the average  
65 of the measurements for each extracting solution concentration, the maximum value of CEC  
66 measured with ammonium was 75.3 meq/100g, which was obtained for the 0.1 M KCl solution  
67 (the value of 103 meq/100g for the third replicate at 0.1 M KCl was considered to be an outlier  
68 of the dataset and, therefore, neglected). As a result, the maximum CEC value obtained with  
69 ammonium was lower than the values obtained with the MB tests (97 and 104 meq/100g; for the  
70 sake of simplicity the mean value is plotted in Figure 1). The results suggest that the measured  
71 CEC depends on the aggregation state of the bentonite particles. The MB test seems to provide  
72 an upper bound of the measured CEC due to the disperse state of the bentonite, which  
73 enhances the accessibility of exchange sites with respect to the state of aggregation obtained in  
74 the standard test. Despite some scatter in the results, the average CEC versus KCl  
75 concentration tends to be practically constant for  $KCl > 0.1$  M, thus suggesting a similar  
76 aggregation state of bentonite particles. As the KCl concentration decreased ( $< 0.1$  M), the CEC  
77 calculated from the released ammonium also decreased. It should be considered that the  
78 amount of K cations available for exchange also decreased. The maximum theoretically  
79 measurable CEC, as calculated from the available potassium, is also shown in Figure 1. The  
80 measured CEC values for low ( $< 0.02$  M) to practically zero (DW) KCl concentrations are in the  
81 13.9 - 23.9 meq/100g range, that is higher than the theoretically predicted values based on the  
82 available potassium. A blank test (performed without soil and using a 1 M KCl solution) showed  
83 that the ammonium residue in the apparatus at most accounts for 1.3 meq/100g. Therefore, the  
84 measured CEC suggests a release of ammonium from the clay that is not related to the  
85 adsorption of potassium. According to the test method, washing the clay with isopropanol  
86 should remove the excess unbound ammonium acetate; however, the test results suggest that  
87 some residual ammonium remains in the clay. A replicate test was performed using 0.0025 M

88 KCl solution and a double wash with isopropanol (240 ml instead of 120 ml), but no significant  
 89 difference in the measured CEC was observed (Table 2). Therefore, the test results suggest  
 90 that, even after washing with isopropanol, some unbound ammonium remains entrapped in the  
 91 bentonite layer. Filtration with low concentration (< 0.02 M KCl) solutions induces a change in  
 92 bentonite fabric during the test, namely swelling and reorganisation, whereby the release of  
 93 ammonium is favoured. This is reflected, at the macroscopic scale, by an increase in the  
 94 average height of the bentonite film that forms in the filtration apparatus, H, at the end of the  
 95 tests, and a corresponding decrease in the hydraulic conductivity, k. The k value was estimated  
 96 from the observed flow rate of the filtrate during the addition of the final 50 ml of the extracting  
 97 solution and from the hydraulic gradient that was established across the bentonite film during  
 98 filtration. H was equal to 2.5 mm and the average k was estimated to be about  $10^{-7}$  m/s with the  
 99 1 M KCl solution (standard procedure), whereas H was 8 mm and k was about  $10^{-9}$  m/s with  
 100 DW.

101

#### 102 4. Discussion

103 The observed changes in the hydraulic conductivity of bentonite suggest that the CEC variation,  
 104 as a function of the extracting KCl solution concentration, can be related to fabric modifications.  
 105 Manassero et al. (2016, 2018), Dominijanni et al. (2017) and Manassero (2017) modelled  
 106 bentonite fabric modifications through a fabric boundary surface (FBS), whereby the average  
 107 number of lamellae per tactoid,  $N_{i,AV}$ , is related to the salt concentration,  $c_s$ , and the micro-void  
 108 ratio,  $e_m$ , which in turn is obtained by subtracting the void space between the platelets of the  
 109 tactoids from the total void space.

110 A first phenomenological formulation of FBS was proposed by Manassero et al. (2016):

111

$$112 \quad N_{i,AV} = N_{i,AV0} + \frac{\alpha}{e_m} \cdot \left( \frac{c_s}{c_0} + 1 \right) + \beta \cdot e_m \cdot \left[ 1 - \exp\left( -\frac{c_s}{c_0} \right) \right] \quad (2)$$

113

114 where  $c_0$  represents the reference molar concentration (= 1 M) and  $N_{i,AV0}$ ,  $\alpha$  and  $\beta$  are non-  
 115 dimensional empirical parameters.

116 The micro-void ratio,  $e_m$ , in Eq. 2 can be derived from the total void ratio,  $e$ , through the  
117 following equation:

118

$$119 \quad e_m = \frac{e \cdot N_{i,AV} - S \cdot \rho_{sk} \cdot b_n (N_{i,AV} + d_d - 1)}{N_{i,AV}} \quad (3)$$

120

121 where  $b_n$  is the average half-distance between the platelets in the tactoid ( $\approx 0.4$  nm),  $S$  is the  
122 total specific surface ( $\approx 700$  m<sup>2</sup>/g) and  $d_d$  is the thickness of the Stern Layer divided by  $b_n$  ( $\approx 4$ ).

123 Inserting Eq. 3 into Eq. 2 the number of lamellae per tactoid is related to the total void ratio and  
124 the salt concentration through a cubic equation, which can be solved analytically or numerically  
125 for given values of the parameters  $N_{i,AV0}$ ,  $\alpha$ ,  $\beta$ ,  $S$ ,  $\rho_{sk}$ ,  $b_n$  and  $d_d$ .

126 Although a sufficient number of experimental data is not available for the tested bentonite to  
127 determine the FBS parameters, a qualitative analysis was conducted by using the calibration  
128 performed by Manassero (2017) on the hydraulic conductivity experimental results obtained by  
129 Petrov and Rowe (1997) on a needle-punched geosynthetic clay liner (GCL), which provided  
130  $N_{i,AV0} = 1.56$ ,  $\alpha = 8.82$ ,  $\beta = 10.01$ . A plot of the corresponding FBS in the space of the variables  
131  $N_{i,AV}$ ,  $e_m$  and  $c_s$  is shown in Figure 2. Such an FBS can be regarded as suitable for the analysis  
132 of the obtained laboratory data, as the features of the bentonite in the GCL are similar to the  
133 ones of the tested bentonite (Table 1) and the GCL hydraulic conductivity is not expected to be  
134 influenced by the presence of needle-punched fibres, at least in the range of low salt  
135 concentrations ( $< 0.1$  M KCl solution) (Puma et al., 2015).

136 The ability of the proposed FBS to accurately model microstructural changes was verified using  
137 a series of experimental results from the literature that included direct measurements of  $N_{i,AV}$ , on  
138 bentonites with similar properties to the ones of the bentonite tested in the present study (Table  
139 1). The values of  $N_{i,AV}$ , which were estimated directly from the ratio of the intra-tactoid to the  
140 inter-tactoid pore-space by means of Small Angle X-Ray Scattering Spectroscopy (Muurinen et  
141 al., 2013) and Nuclear Magnetic Resonance techniques (Muurinen et al., 2013; Ohkubo et al.,  
142 2016), are shown to be in good agreement with the FBS predictions in Figure 3, for a salt  
143 concentration  $c_s = 0.1$  M.

144 The total void ratio was estimated, during the washing phase with isopropanol, from the  
145 measurement of the bentonite layer thickness to be about 4 and, as a result,  $N_{i,AV}$  is calculated  
146 through the FBS equation to be about 4.74, assuming  $c_s = 0$  as a consequence of the complete  
147 removal of the pore aqueous solution.

148 The relation between  $N_{i,AV}$  and the KCl concentration,  $c_s$ , provided by the FBS for the values of  
149 the bentonite void ratio that were estimated at the end of the ammonium displacement tests  
150 (Table 2) is shown in Figure 4. The value of the KCl concentration corresponding to  $N_{i,AV} = 4.74$   
151 is equal to about 0.027 M. As a result, the bentonite is expected to swell during the KCl solution  
152 filtration phase and assume a more dispersed fabric when the KCl concentration is lower than  
153 0.027 M, while it is expected to flocculate and assume a more aggregated fabric when the KCl  
154 concentration is higher than 0.027 M. Such a theoretical threshold value of the KCl  
155 concentration is very close to the experimentally found value of 0.02 M, below which the  
156 released ammonium overcomes the available potassium.

157 This qualitative result suggests an interpretation of the CEC data that were obtained from the  
158 ammonium release measurements. After the washing phase with isopropanol, a portion of  
159 mobile ammonium was not removed because of the presence of pores that are less accessible  
160 to the advection flux. When the KCl concentration of the extracting solution was lower than  
161 about 0.02 M, the dispersion of the bentonite allowed the mobile ammonium ions to be released  
162 by opening such pores. Instead, when the KCl concentration of the extracting solution was  
163 higher than about 0.02 M, the bentonite flocculated and created additional less accessible pore  
164 voids. The potassium cations only had access to a limited portion of the available pores for the  
165 highest values of the KCl concentration ( $\geq 1$  M), and, as a result, the exchanged ammonium ion  
166 measurements underestimated the effective bentonite CEC.

167

## 168 **5. Conclusions**

169 The tests performed by varying the KCl solution concentrations showed that the CEC  
170 measurements based on ammonium release are influenced by bentonite fabric modifications  
171 and may provide an unreliable estimation of the effective density of the exchangeable sites of  
172 the bentonite. For this reason, the ammonium displacement method does not seem to be

173 sufficiently accurate to assess the fundamental fabric parameters of coupled hydro-chemo-  
174 mechanical models, such as the one proposed by Manassero et al. (2016). The experimental  
175 swelling pressure data obtained by Dominijanni et al. (2013) for a saturated sodium bentonite at  
176 a void ratio of 4.26 are compared in Figure 5, by way of example, with the theoretical predictions  
177 that are obtained by determining  $\bar{c}_{sk,0}$  from the measurement of CEC through Eq. 1, with a  
178 constant  $N_{i,AV}$  value ( $N_{i,AV} = 3$ ) for the investigated range of low salt concentrations (Manassero,  
179 2017). The theoretical curve derived from the average CEC provided by the standard  
180 ammonium displacement method underestimates the experimental data to a great extent,  
181 whereas an acceptable fitting is obtained when the average CEC value provided by the  
182 methylene blue titration method is used. As a result, the methylene blue titration method, which  
183 is used in industry for routine quality controls, seems to be able to provide a more reliable  
184 estimation of CEC, despite its apparently more limited accuracy, as the bentonite fabric is  
185 maintained dispersed during the test.  
186

187 **References**

- 188 ASTM D7503-18 Standard Test Method for Measuring the Exchange Complex and Cation  
189 Exchange Capacity of Inorganic Fine-Grained Soils.
- 190 Delage P (2019) Micro-macro effects in bentonite engineered barriers for radioactive waste  
191 disposal. In: Zhan L, Chen Y and Bouazza A (Eds.) Proceedings of the 8th International  
192 Congress on Environmental Geotechnics, Hangzhou, China; 28 October - 1 November 2018.  
193 Springer, Singapore, pp. 61-80.
- 194 Dominijanni A and Manassero M (2005) Modelling osmosis and solute transport through clay  
195 membrane barriers. In: Alshawabkeh A, Benson CH, Culligan PJ, Evans JC, Gross BA,  
196 Narejo D, Reddy KR, Shackelford CD and Zornberg JG (Eds) Proceedings of the Geo-  
197 Frontiers Congress, Austin, Texas (USA), 24-26 January 2005. American Society of Civil  
198 Engineers, Reston, Virginia (USA), pp. 349-360.
- 199 Dominijanni A and Manassero M (2012) Modelling the swelling and osmotic properties of clay  
200 soils. Part II: The physical approach. *International Journal of Engineering Science* 51: 51-73.
- 201 Dominijanni A, Guarena N and Manassero M (2018) Laboratory assessment of semi-permeable  
202 properties of a natural sodium bentonite. *Canadian Geotechnical Journal* 55(11): 1611-1631.
- 203 Dominijanni A, Manassero M and Puma S (2013) Coupled chemical-hydraulic-mechanical  
204 behaviour of bentonites. *Géotechnique* 63(3): 191-205.
- 205 Dominijanni A, Manassero M and Vanni D (2006) Micro/macro modeling of electrolyte transport  
206 through semipermeable bentonite layers. In: Thomas HR (Ed.) Proceedings of the 5th  
207 International Congress on Environmental Geotechnics, Cardiff, Wales (UK), 26-30 June  
208 2006. Thomas Telford, London, England (UK), vol. 2, pp. 1123-1130.
- 209 Dominijanni A, Manassero M, Boffa G and Puma S (2017) Intrinsic and state parameters  
210 governing the efficiency of bentonite barriers for contaminant control. In: Ferrari A and Laloui  
211 L (Eds.) Proceedings of the International Workshop on Advances in Laboratory Testing and  
212 Modelling of Soils and Shales, Villars-sur-Ollon, Switzerland, 18-20 January 2017. Springer  
213 International Publishing AG, Cham, Switzerland, pp. 45-56.
- 214 EUBA - European Bentonite Association (2002) Methodology for the determination of the  
215 methylene blue value of bentonite.

216 Groenevelt PH and Bolt GH (1969) Non-equilibrium thermodynamics of the soil-water system.  
217 Journal of Hydrology 7(4): 358-388.

218 Guimarães LDN, Gens A, Sánchez M and Olivella S (2013) A chemo-mechanical constitutive  
219 model accounting for cation exchange in expansive clays. Géotechnique 63(3): 221-234.

220 Lambe TW (1960) A mechanistic picture of shear strength in clay. In Proceedings of the  
221 Research Conference on Shear Strength of Cohesive Soil, Boulder, Colorado (USA), June  
222 1960. American Society of Civil Engineers, New York (USA), pp. 555–580.

223 Manassero M, Dominijanni A and Guarena N (2018) Modelling hydro-chemo-mechanical  
224 behaviour of active clays through the fabric boundary surface. In: Proceedings of China-  
225 Europe Conference on Geotechnical Engineering, Vienna, Austria, 13-16 August 2018.  
226 Springer, Cham, Switzerland, pp. 1618-1626.

227 Manassero M, Dominijanni A, Fratolocchi E, Mazzieri F, Pasqualini E and Boffa G (2016) About  
228 state parameters of the active clays. In: Proceedings of the Special symposium honoring  
229 D.E. Daniel, Geo-Chicago 2016, 14-18 August 2016, Chicago, Illinois (USA), pp. 99-110.

230 Manassero M. (2017) On the fabric and state parameters of active clays for contaminant control  
231 (2<sup>nd</sup> ISSMGE Kerry Rowe Lecture). In: Lee W and Lee J-S, Kim H-K and Kim D-S (Eds.)  
232 Proceedings of the 19th International Conference of Soil Mechanics and Geotechnical  
233 Engineering, Seoul, Korea, 17-22 September 2017, pp. 167-189.

234 Mitchell JK (1991) Conduction phenomena: from theory to geotechnical practice. Géotechnique  
235 41(3): 299-340.

236 Mitchell JK and Soga K (2005) Fundamentals of soil behavior (3rd Edition). John Wiley & Sons,  
237 New York (USA).

238 Moyne C and Murad MA (2002). Electro-chemo-mechanical couplings in swelling clays derived  
239 from a micro/macro-homogenization procedure. International Journal of Solids and  
240 Structures 39(25): 6159-6190.

241 Musso G, Cosentini, RM, Dominijanni A., Guarena N and Manassero M (2017) Laboratory  
242 characterization of the chemo-hydro-mechanical behaviour of chemically sensitive clays.  
243 Rivista Italiana di Geotecnica, vol. 2017 (3): 22-47.

244 Muurinen A, Carlsson T and Root A (2013) Bentonite pore distribution based on SAXS, chloride  
245 exclusion and NMR studies. Clay Minerals 48 (2): 251-266.

246 Ohkubo T, Ibaraki M, Tachi Y and Iwadate Y (2016) Pore distribution of water-saturated  
247 compacted clay using NMR relaxometry and freezing temperature depression; effects of  
248 density and salt concentration. *Applied Clay Science* 123: 148-155.

249 Petrov RJ and Rowe RK (1997) Geosynthetic clay liner (GCL) - chemical compatibility by  
250 hydraulic conductivity testing and factors impacting its performance. *Canadian Geotechnical*  
251 *Journal* 34: 863-885.

252 Puma S, Dominijanni A, Manassero M and Zaninetta L (2015) The role of physical  
253 pretreatments on the hydraulic conductivity of natural sodium bentonites. *Geotextiles and*  
254 *Geomembranes* 43: 263-271.

255 Revil A (2017a) Transport of water and ions in partially water-saturated porous media. Part 1.  
256 Constitutive equations. *Advances in Water Resources* 103: 119-138.

257 Revil A (2017b) Transport of water and ions in partially water-saturated porous media. Part 2.  
258 Filtration effects. *Advances in Water Resources* 103: 139-152.

259 Shackelford CD, Lu N and Malusis MA (2019) Research challenges involving coupled flows in  
260 geotechnical engineering. In: Lu N and Mitchell JK (Eds.) *Geotechnical Fundamentals for*  
261 *Addressing New World Challenges*. Springer.

262 Sridharan A and Rao VG (1973) Mechanisms controlling volume change of saturated clays and  
263 the role of the effective stress concept. *Géotechnique* 23(3): 359-382.

264

265

266 **Table captions**

267

268 Table 1. Main properties of the bentonite used in this study and comparison with the data of  
269 similar bentonites from the literature (Petrov and Rowe, 1997; Muurinen et al., 2013; Ohkubo et  
270 al., 2016) (DW = distilled water).

271

272 Table 2. CEC values obtained in the study.

273

274

275 **Figure captions**

276

277 Figure 1. CEC values determined with the ammonium acetate method using different KCl  
278 solutions in the final stage of the test and comparison with MB results.

279

280 Figure 2. Plot of the fabric boundary surface (FBS) in the three-dimensional space of the  
281 variables: average number of lamellae per tactoid,  $N_{i,AV}$ , micro-void ratio,  $e_m$ , and salt molar  
282 concentration,  $c_s$ .

283

284 Figure 3. Comparison between the average number of lamellae per tactoid provided by the  
285 Fabric Boundary Surface (continuous line) and the experimental results taken from the  
286 literature.

287

288 Figure 4. Average number of lamellae per tactoid of the bentonite as a function of the  
289 concentration of the extracting KCl solution. The arrows indicate the KCl concentration ( $c_s =$   
290  $0.027$  M) that corresponds to  $N_{i,AV} = 4.74$ , i.e. the average number of lamellae per tactoid after  
291 the washing phase with isopropanol ( $c_s = 0$ ).

292

293 Figure 5. Comparison between the swelling pressure of bentonite, as theoretically predicted on  
294 the basis of the average CEC value derived from the methylene blue titration method [curve (a)  
295 –  $CEC = (97.4 + 104)/2 = 100.7$  meq/100g] and the standard ammonium displacement method  
296 [curve (b) –  $CEC = (73.2 + 60.7)/2 = 66.9$  meq/100g], and the experimental data obtained by  
297 Dominijanni et al. (2013) (closed circles).

1 Table 1. Main properties of the bentonite used in this study and comparison with the data of  
 2 similar bentonites from the literature (Petrov and Rowe, 1997; Muurinen et al., 2013; Ohkubo et  
 3 al., 2016) (DW = distilled water).

Property	This Study	Petrov and Rowe (1997)	Muurinen et al. (2013)	Ohkubo et al. (2016)
Smectite content (%)	> 98	91	84	> 98
Prevalent adsorbed cation	Na <sup>+</sup>	Na <sup>+</sup>	Na <sup>+</sup>	Na <sup>+</sup>
Liquid Limit to DW (%)	525	530	-	-
CEC (meq/100g)	97 - 104 <sup>(a)</sup>	85.8 <sup>(b)</sup>	80 - 88 <sup>(c)</sup>	-
Hydraulic conductivity to DW (m/s)	8.0×10 <sup>-12</sup> <sup>(d)</sup>	1.2×10 <sup>-11</sup> <sup>(e)</sup>	5.0×10 <sup>-12</sup> <sup>(f)</sup>	-

4 <sup>(a)</sup> measured through the methylene blue titration method

5 <sup>(b)</sup> measured through the Ag-Thiourea exchange for Na<sup>+</sup> and K<sup>+</sup>, the KCl exchange for Mg<sup>2+</sup> and  
 6 Ca<sup>2+</sup>

7 <sup>(c)</sup> measured through the Cu(II)-Triethyltetramine exchange method

8 <sup>(d)</sup> measured at a 27.5 kPa confining effective stress

9 <sup>(e)</sup> measured at a 35 kPa confining effective stress

10 <sup>(f)</sup> measured at a bulk dry density equal to 517 kg/m<sup>3</sup>

11

12

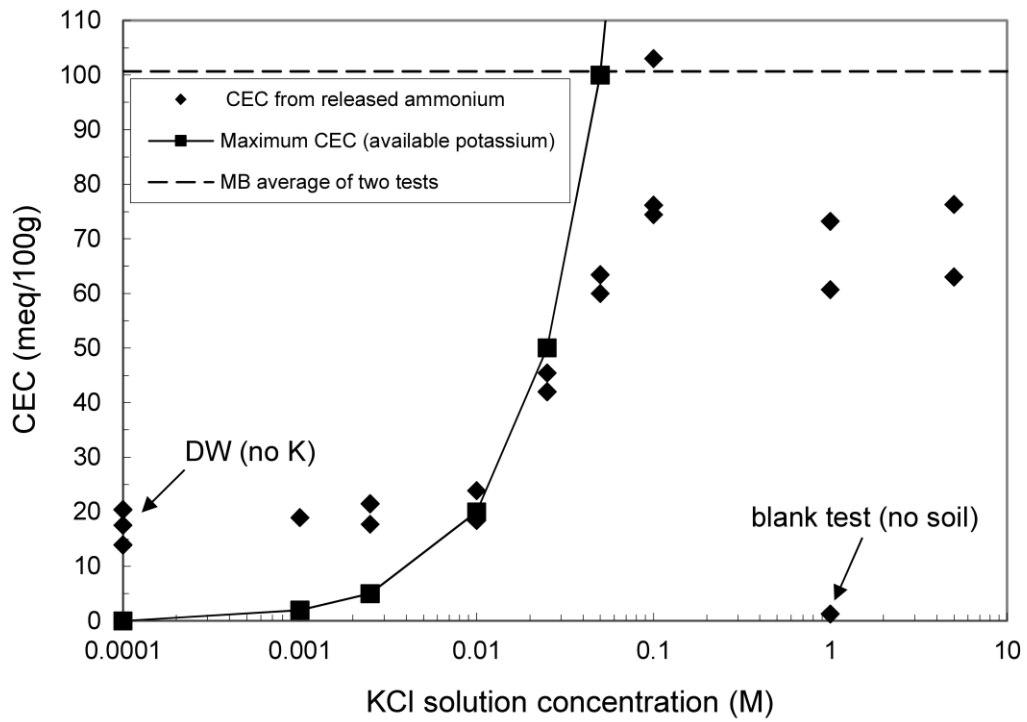
13 Table 2. CEC values obtained in this study.

		Test 1 (meq/100 g)	Test 2 (meq/100 g)	Test 3 (meq/100 g)	Note
<u>ASTM D7035</u> (standard and modified procedure)	Estimated bentonite void ratio, e <sup>(*)</sup>				
DW	14	17.5	20.4	13.9	
0.001 M	12	18.9	-	-	
0.0025 M	12	21.4	17.7	-	
0.0025 M	12	21.5	-	-	Double wash with isopropanol
0.01 M	10	23.9	18.4	-	
0.025 M	8	42.0	45.4	-	
0.05 M	7	60.0	63.4	-	
0.1 M	6	76.2	74.4	103	
1 M (standard)	4	73.2	60.7	-	
1 M (standard)	-	1.3	-	-	Blank test (no soil)
4.5 M	3	63.0	76.3	-	
<u>Methylene Blue</u> (EUBA)	-	97.4	104	-	

14 (\*) total void ratio estimated from the detection of the bentonite layer thickness within the filtration  
 15 apparatus at the end of the ammonium displacement tests

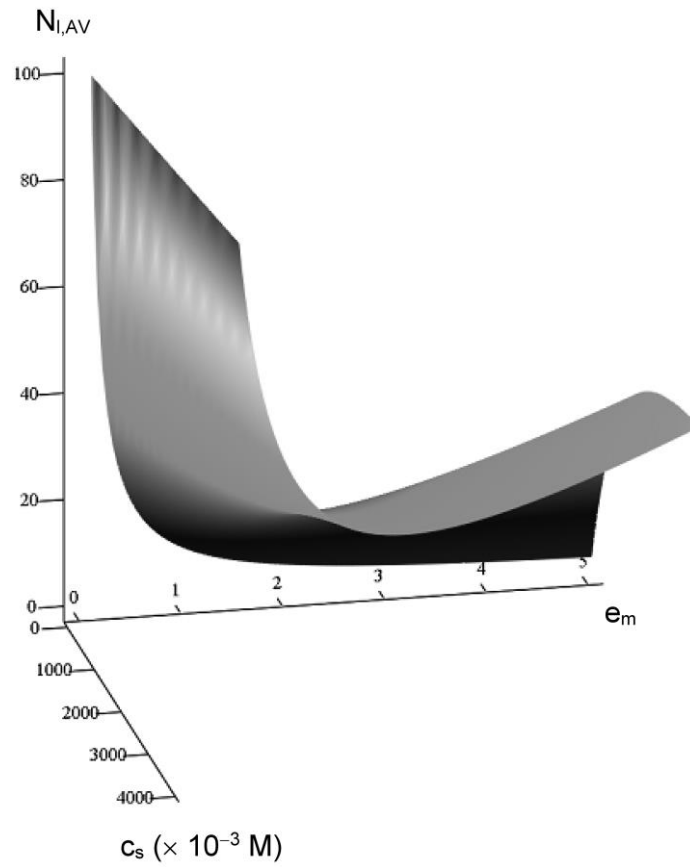
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Figure 1. CEC values determined with the ammonium acetate method using different KCl solutions in the final stage of the test and comparison with MB results.

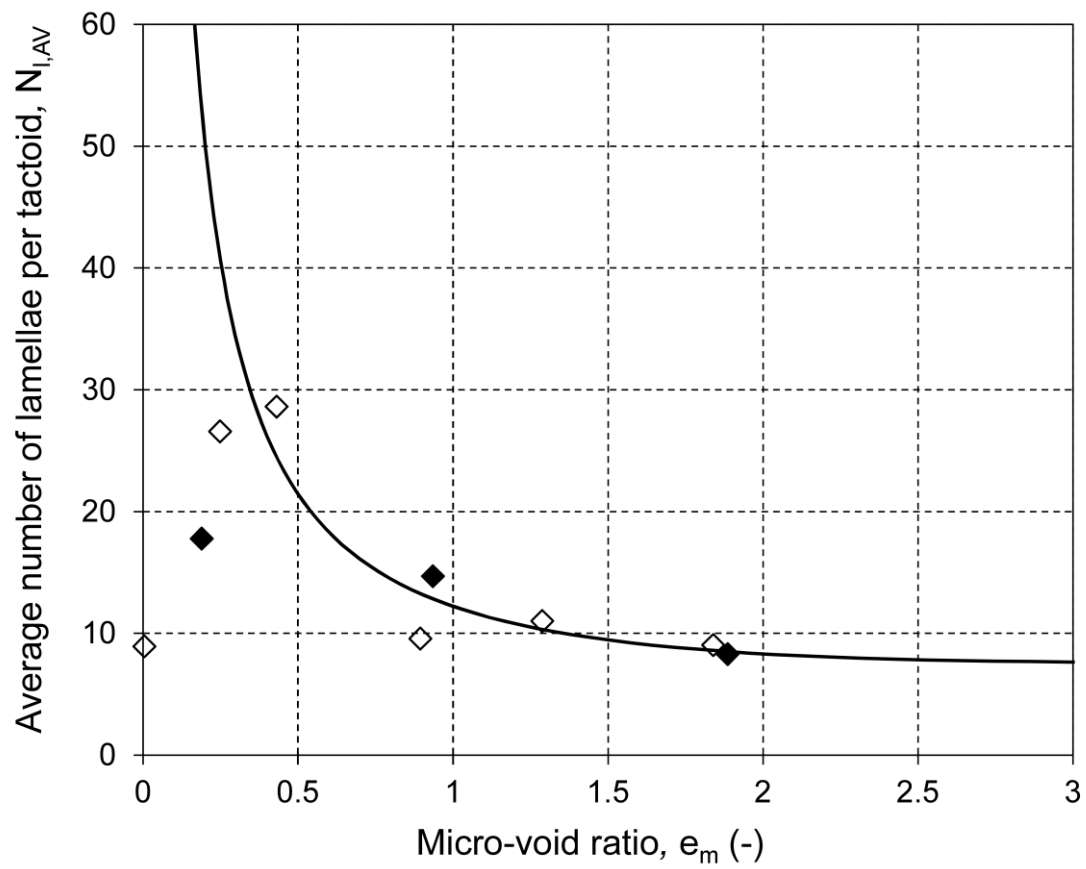


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11 Figure 2. Plot of the fabric boundary surface (FBS) in the three-dimensional space of the  
 12 variables: average number of lamellae per tactoid,  $N_{l,AV}$ , micro-void ratio,  $e_m$ , and salt molar  
 13 concentration,  $c_s$ .

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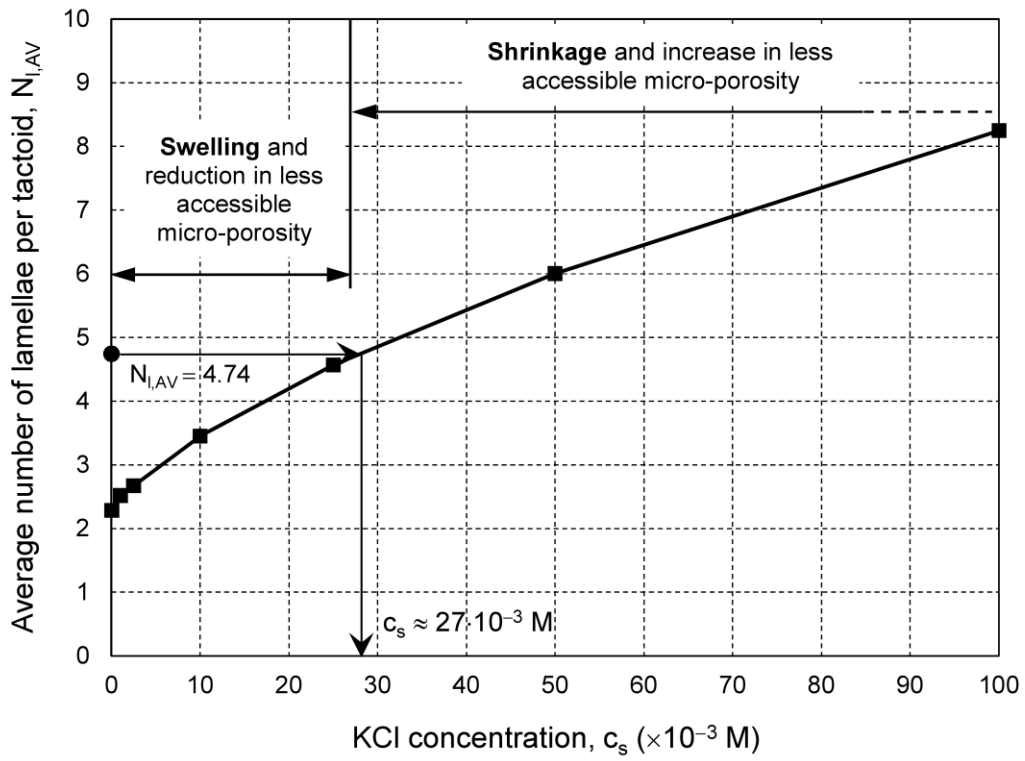


- ◇  $c_s = 0.1$  M - NMR measurements (Data from Muurinen et al., 2013; Ohkubo et al., 2016)
- ◆  $c_s = 0.1$  M - SAXS measurements (Data from Muurinen et al., 2013)

17

18 Figure 3. Comparison between the average number of lamellae per tactoid provided by the  
 19 Fabric Boundary Surface (continuous line) and the experimental results taken from the  
 20 literature.

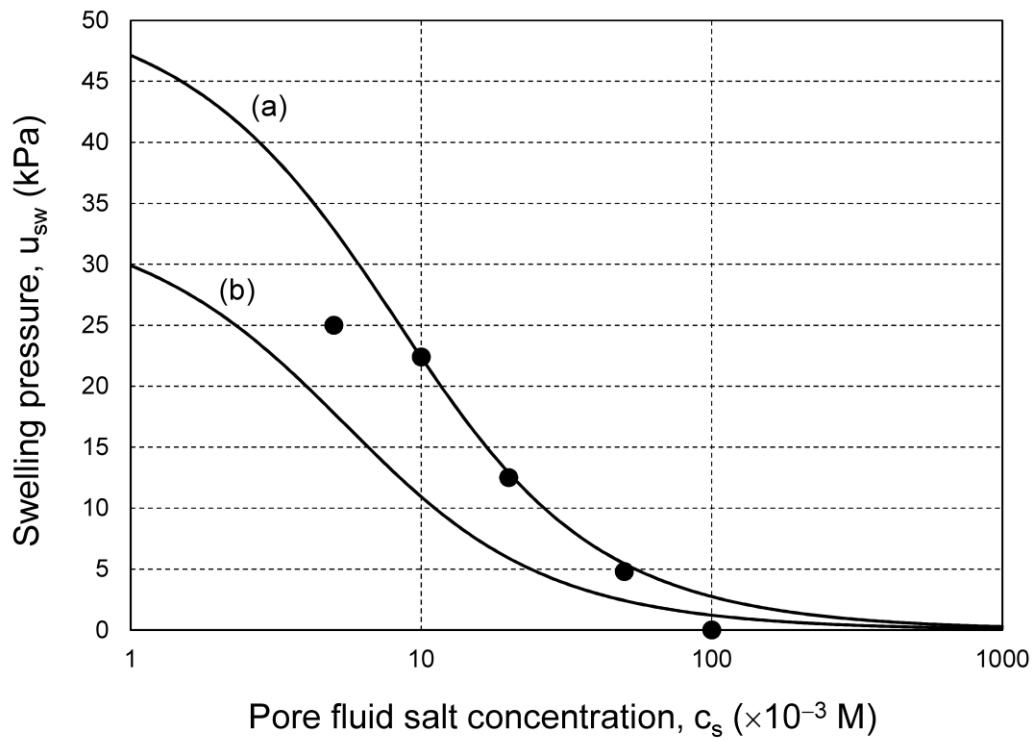
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24 Figure 4. Average number of lamellae per tactoid of the bentonite as a function of the  
 25 concentration of the extracting KCl solution. The arrows indicate the KCl concentration ( $c_s =$   
 26  $0.027$  M) that corresponds to  $N_{i,AV} = 4.74$ , i.e. the average number of lamellae per tactoid after  
 27 the washing phase with isopropanol ( $c_s = 0$ ).

28



29

30 Figure 5. Comparison between the swelling pressure of bentonite, as theoretically predicted on  
 31 the basis of the average CEC value derived from the methylene blue titration method [curve (a)  
 32 –  $CEC = (97.4 + 104)/2 = 100.7$  meq/100 g] and the standard ammonium displacement method  
 33 [curve (b) –  $CEC = (73.2 + 60.7)/2 = 66.9$  meq/100 g], and the experimental data obtained by  
 34 Dominijanni et al. (2013) (closed circles).

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