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Effects of pore water chemical composition on the hydro-mechanical behavior of natural stiff clays

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ABSTRACT

Boom Clay and Ypresian Clays have been considered as potential geological host formations for radioactive waste disposal in Belgium. Considering the significant differences in pore water chemical composition between several sites involving these two formations as well as the possible evolution of the chemical composition during the large lifespan of a radioactive waste disposal, it appeared important to investigate the effects of pore water chemical composition on the hydro-mechanical behaviors of these two potential host formations. In this study, these effects were investigated by carrying out specific œdometer tests. Different compositions were considered for this purpose: distilled water, synthetic site water, and Sodium Chloride solutions at concentrations of 15 and 30 g/L. Clear effects of pore water chemical composition on the hydro-mechanical behavior were observed: increasing pore water salt concentration gave rise to (i) increase of œdometric modulus $E_{œd}$, permeability K and consolidation coefficient C_v; and (ii) decrease of compression slope c'_c, swelling slope c'_s and secondary compression coefficient $C_{\alpha e}$, which is in agreement with the diffuse double layer theory and the clay particle aggregation as identified by microstructural analyses. Furthermore, the pore water chemical composition effects were found to be mineralogy, stress state and salt concentration dependent: (i) Ypresian Clays with higher smectite content showed clearer chemical effect on the coefficient of consolidation C_v; (ii) the chemical effects on compressibility and swelling capacity parameters were found to be attenuated with increasing vertical stress; and (iii) the increase of chemical effect with increasing pore water salinity was limited to a certain salt concentration. The competition between the physico-chemical and mechanical effects was identified: the pore water chemical composition effect is clear only in the low-stress range where the hydro-mechanical behavior is dominated by the physico-chemical effect.

1. Introduction

Two clay formations, Boom and Ypresian, have been considered as potential geological host formations for high-level and/or long-lived radioactive waste disposal in Belgium. Several sites have been investigated, such as Mol and Essen for Boom Clay, Doel and Kallo for Ypresian Clays. Significant variations in pore water salinity between these sites have been reported (De Craen et al., 2004, 2006; van Marcke and Laenen, 2005; van Marcke, 2009). In addition, the pore water salinity at each site may also evolve at the time scale of radioactive waste disposal. This can substantially affect the hydro-mechanical behavior of the host formations. Therefore, it is essential to evaluate the sensitivity of the hydro-mechanical behavior of the host formations to changes in pore water chemical composition.

Most of studies involving chemical effects on the hydro-mechanical behaviors of soils were conducted on reconstituted soils and natural soft soils. Various preparation methods were developed in the laboratory for this purpose: i) mixing the soil powder with a desired solution; ii) immersing a soil sample in a solution; and iii) percolating a soil sample by a solution. Di Maio and Fenelli (1994), Di Maio (1996, 1998), Loret et al. (2002), Di Maio et al. (2004), Gajo and Loret (2007), Rao and Thyagaraj (2007), and Yukselen-Aksoy et al. (2008) showed significant effects of pore water saline concentration on the hydro-mechanical behavior of reconstituted expansive clays with wide ranges of concentrations: i) changes in salt concentration and ion-type result in reversible or irreversible volume changes of soil, mainly by osmotic consolidation or osmotic swelling; ii) increasing vertical stress reduces the extent of chemically-induced volume change; and iii) the compressibility and swelling capacity are reduced by increasing salt concentration. These effects have commonly been explained with the Gouy–Chapman's theory of diffuse double layer (Mitchell and Soga, 2005).

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Table 1
Mineralogical compositions in Boom (BE83) and Ypresian (YK74) Clays.

Minerals (wt.%)	BE83[a]	YK74[b]
Clays	40	57
Illite	10	5
Kaolinite	30	3
Smectite		33
Illite/smectite		12
Chlorite (or others)		4
Non-clays	60	43
Quartz	60	31
Dolomite		0.8
Pyrite	Trace	0.4
K-feldspar	Trace	6
Plagioclase		5

[a] Deng et al. (2011a, 2011b, 2011c, 2012) and Nguyen (2013).
[b] Vandenberghe (2011).

Table 2
Mineralogical composition in the clay fractions (fraction < 2 μm).

Minerals (wt.%)	BE83[a]	YK74[b]
Illite	20	10
Smectite	20	63
Illite/smectite	20	22
Kaolinite	35	2
Others	5	3

[a] Deng et al. (2011a, 2011b, 2011c, 2012) and Nguyen (2013).
[b] Vandenberghe (2011).

For the non-active clays, Olson and Mesri (1970), Sridharan and Rao (1973), Chen et al. (2000), and Wahid et al. (2011a, 2011b) found that they are relatively inert with respect to changes in pore water salt concentration, but sensitive to changes in *pH* (due to the mineral dissolution and the degradation of particle edges) and dielectric constant (due to the van de Waals attractive force).

For the natural stiff clays, the pore water chemical composition effect has been rarely studied. Swelling tests were carried out on the Callovo-Oxfordian claystone with distilled water and several saline solutions under different stress levels by Daupley (1997) and Wakim (2005). It was observed that the higher the salt concentration, the lower the swelling capacity. The same conclusion was drawn by Coll et al. (2008) for the natural Boom Clay (Mol site, 223 m depth). For the unsaturated compacted Boom Clay, Mokni et al. (2012) observed a significant effect of salt concentration on the water retention property but a negligible effect on the compressibility. On the other hand, only a slight pore water chemical composition effect was identified by Deng et al. (2011a) on the hydro-mechanical behavior of Boom Clay at Essen (227 m depth). The reason is probably the slight difference between the two solutions considered, distilled water and synthetic Boom Clay water (SBCW — water prepared with similar chemistry as *in situ* pore water), as well as the limited amount of smectite in Boom Clay. Comparison with reconstituted expansive clays shows that natural stiff clays respond to changes in pore water salt concentration in the same fashion, but to a lesser extent. This is probably due to the fact that only the active clay fraction (smectite for example) in natural stiff clays is sensitive to changes in pore water chemical composition. Moreover, the natural clay structure, *i.e.* particle arrangement and inter-particle bonding (Burland, 1990), developed at great depths since several millions years may also attenuate the effect of pore water salinity changes.

In the present work, the effects of pore water chemical composition on the swelling capacity, compressibility, permeability, consolidation and secondary compression/swelling of Boom Clay and Ypresian Clays were investigated by means of specific œdometer tests. Intact samples with Sodium Chloride solutions at 15 and 30 g/L-concentrations were tested. Data from two similar tests on Boom Clay with distilled water and SBCW (Deng et al., 2011a; Nguyen, 2013) will be incorporated for further analysis. Microstructure analyses were also performed on samples in both intact and after-test states, providing further insight into the mechanisms of chemical impact on the hydro-mechanical behavior of natural stiff clays.

2. Materials and methods

2.1. Boom Clay

Boom formation was deposited in the Rupelian stage, about 36–30 millions years ago, in the Southern part of the North Sea basin (ONDRAF, 2001). In Belgium, Boom Clay is located in the Northeast, in the Campine region. This Tertiary formation outcrops near the Antwerpen city, gently dips and thickens toward the Northeast direction. It corresponds to a marine sediment sequence of silty clays and clayey silts, and is subdivided into four members from bottom to top with depths at the Essen site: Belsele-Waas (260–280 m), Terhagen (237–260 m), Putte (200–237 m), and Boeretang (154–200 m). The soil studied (BE83) was vertically cored in a borehole at the Essen site, from 226.65 m to 227.75 m depth, in the lower part of Putte member. This member is the most clayey one, dark gray in color, rich in organic matters and with low carbonate content (ONDRAF, 2001). Note that the

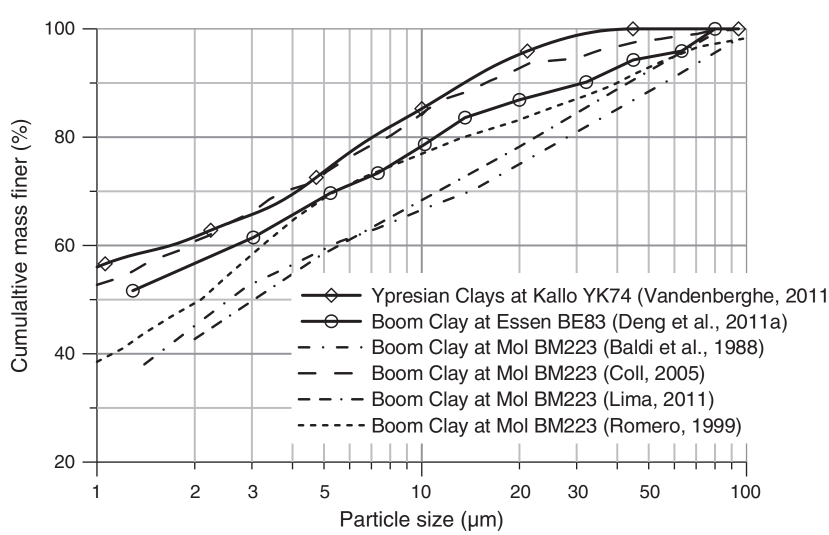

Fig. 1. Particle-size distribution curves of Boom and Ypresian Clays.