



Salinity and Clay Mineralogy Effects on Consolidation Behavior of Pure Clays

Tongwei Zhang¹(✉), Yongfeng Deng², Haocheng Xue²,
Xingjun Zhang³, and Shijun Wang⁴

¹ Key Laboratory of Mechanics on Disaster and Environment in Western China,
College of Civil Engineering and Mechanics, Lanzhou University,
Lanzhou 730000, China

z t w @ L z u . e d u . c n

² Institute of Geotechnical Engineering, Transportation College,
Southeast University, Nanjing, China

³ Gansu Henlu Transportation Survey and Design Co., Ltd., Lanzhou, China

⁴ Economy and Technology Research Institute,

State Grid Gansu Electric Power Company, Lanzhou, China

Abstract. Pure clays or sand-clay mixtures with different clay mineral are widely used in liners or vertical barriers of waste landfill, and the pore water was characterized by its high salinity in coastal area. Thus, it is essential to understand the salinity effects on their consolidation behavior. In this study, oedometer and SEM tests were conducted on four pure clays with different mineralogy. Several aspects of soil behavior, such as compression index, the end of primary consolidation stage and micro-structure, were investigated in view of pore water salinity effect. The results show that higher ionic concentration significantly decreases the compression index C_c and liquid limits (LL) for clays containing montmorillonite. While the period of primary consolidation was shorten under the impact of water salinity. For kaolinite with or without sodium chloride, a similar C_c , LL and the ending time of primary consolidation stage t_p were observed. In view of flocculation, the salinity effect on consolidation behavior was interpreted. Increasing in salinity allows a flocculation and particle readjustment at constant water content for montmorillonitic clay. Then, larger inter-particle spaces and effective void ratio increased the permeability and decreased the drainage period, and larger internal frictions decreased the compression index C_c and LL .

Keywords: Pure clays · Water salinity · Clay minerals
Consolidation behaviour · Micro-structure

1 Introduction

Previous studies revealed that changing of pore water chemistry (such as cation concentration, cation valence and dielectric constant etc.) has significant influences on physical and mechanical behaviour of clays, especially on swelling clays (Yukselen-Aksoy et al. 2008; Abdullah et al. 1997; Bolt 1956; Di Maio et al. 2004; Kaya and Fang 2000; Oren and Kaya 2003). Bolt (1956) firstly stated that the compressibility of

pure clay suspensions could be accounted well by considering the interaction between double electric layers around clay particles. Di Maio et al. (2004) presented that an increase in pore solution concentration may cause a reduction in compressibility of compacted bentonite. Gajo and Maines (2007) investigated the mechanical behaviour of active clays affected by pore fluid acidity and alkalinity. Zhang et al. (2016) and Ye et al. (2017) systematically investigated the influences of infiltrating solutions on volume change behaviour and hydraulic conductivity of highly compacted GMZ bentonite. However, the salinity and clay mineral effect on their consolidation behaviour of pure clays is still few concerned.

This paper focuses on the pore water salinity and clay mineral effect on the consolidation behaviour and micro-structure of four soils at high initial water contents (0.6–1.5 times liquid limits). To simulate this variety of mineral composition and porewater salinity, a mixture of commercial kaolin, bentonite and NaCl solution was employed in this investigation. The salinity effect on the compression index C_c and the ending time of primary consolidation were examined. With the help of micro-structure observations, a reasonable mechanism of salinity effect on macro consolidation behaviour was suggested.

2 Experimental Programs

2.1 Materials

To prepare specimens in laboratory, commercial kaolin and bentonite from Jiangsu province in China, were mixed with different proportions based on the dry weight ratio. It should be noted that the composition of mixtures was selected based on the typical marine clay deposited in Lianyungang area in Jiangsu Province. The basic physical properties of materials are shown in Table 1. Liquid limit (LL) and plastic limit (PL) was determined using Casagrande method according to British standard BS1377-2 (1990). Besides, the specific surface area (SSA) was determined using the Ethylene Glycol Monoethyl Ether (EGME) method (Cerato and Lutenegeger 2002; Fan et al. 2014). By the X-ray diffraction analysis, the mineral compositions were presented in Table 2.

Table 1. Physical properties of the considered materials

Soil types	Specific gravity G_s	LL (%)	PL (%)	PI (%)	SSA (m ² /g)
Kaolinite	2.66	33	16	17	46
Bentonite	2.73	301	95	206	378.5

Table 2. Mineral composition of the kaolinite and bentonite

Materials	Mineral composition (%)								
	Primary mineral (%)						Clay mineral (%)		
	Quartz	K-feldspar	Plagioclase	Calcite	Dolomite	Siderite	Illite	Kaolinite	Smectite
Kaolinite	4.0	5.1	17.1	3.5	2.1	0		68.2	
Bentonite	1.3	0.3	0	0.1	0	2.0	3.9	1.9	90.5

2.2 Specimen Preparation

The pure kaolin or mixed clays were added with distilled water or sodium chloride solutions at a mass concentration of 1%, 3%, 5% and 10% (equal to 0.17 mol/L, 0.51 mol/L, 0.86 mol/L and 1.7 mol/L). For the artificial mixed clays, three mass ratios of kaolin to bentonite at 19/1, 9/1 and 4/1 were designed. A preset mass of dry powder and solutions were thoroughly stirred for at least 10 min using a paddle mixer. Thereafter, the slurries were cured in a sealed plastic chamber for a minimum of 24 h to homogenize the distribution of the pore liquid. The indexes of mixtures were summarized in Table 3. The selected water contents were set as 0.6 to 1.2 times of LL . Hereafter, for K5%B95% as an example, ‘B’ and ‘K’ in sample identification is shorted for ‘bentonite’ and ‘kaolin’ clay, and the value represents the percentage of bentonite and kaolin clay in the mixture.

Table 3. Initial state of samples

Sample ID	Bentonite content (%)	G_s	w_0 (%)	LL (%)	e_0	w_0/LL
K	0	2.66	41 ± 1	33	1.08 ± 0.01	1.2
B5%K95%	5	2.664	42 ± 1	35	1.10 ± 0.02	1.2
B10%K90%	10	2.667	43 ± 1	42	1.13 ± 0.02	1.0
B20%K80%	20	2.674	33 ± 1	52	0.92 ± 0.01	0.6
B20%K80%Micro	20	2.674	63 ± 1	52	1.78 ± 0.02	1.2
KMicro	0	2.66	43 ± 1%	33	1.24	1.3

2.3 Oedometer Test

A total of 24 specimens were prepared by mixing kaolin and bentonite at different proportions. These mixtures were divided into 6 groups: K, B5%K95%, B10%K90%, B20%K80%, B20%K80%Micro and KMicro. The first 4 groups were used to conduct oedometer tests, and each specimen was mixed with NaCl solution at concentrations 0%, 1%, 3%, 5% and 10%. The mixtures were carefully installed to the oedometer ring. Then, samples were first saturated by soaking with the equivalent concentrations of sodium chloride for 48 h. For the slurry samples ($w_0 > LL$), vertical loads 1 kPa, 1.8 kPa, 3.2 kPa and 5.8 kPa were supplied step by step in order to avoid squeezing the soil from the ring (Hong et al. 2010). For sample B20%K80% ($w_0 < LL$), an initial load 12.5 kPa was applied avoiding the swelling influence. Each load was kept for at

least 24 h until the displacement satisfied the standard requirement (ASTM-D2435 2011). Additionally, the organic plastic oedometer cell was applied in order to keep the concentration in the cell and prevent the cell erosion.

2.4 Micro-structural Investigation

As mentioned above, the last 2 groups (B20%K80%Micro and KMicro) were used to perform SEM (Scanning electronic microscopy) tests, aiming to clarify the mechanism of salinity effect on the intrinsic compression behavior of soft clay. Samples were consolidated by stepwise applying the vertical load from 1 kPa to 100 kPa, and then removed from oedometer cells. Thereafter, all samples were carefully trimmed to appropriate sizes and then immersed in liquid nitrogen for instant freezing (Zhang et al. 2014). Finally, they were lyophilized and vacuum coated with a layer of gold to conduct SEM tests.

3 Results and Discussions

3.1 Salinity Effects on Compression Index C_c

As a common knowledge, the compression index C_c was defined by the slope of straight portion of compression curve. The Evolutions of compression curves, LL and C_c changing with concentrations of NaCl solution were presented in Fig. 1(a)–(b). It shows that the LL and C_c of B5%K95%, B10%K90% and B20%K80% all decrease with pore water salinity, whilst those of kaolinic clay are relatively stable. Note that the variation trend of LL shown in Fig. 1(b) is consistent with the results in previous publications (Abdullah et al. 1997; Di Maio et al. 2004; Kaya and Fang 2000; Oren and Kaya 2003; Sridharan and Rao 1975; Yukselen-Aksoy et al. 2008). Among them, Sridharan and Rao (1975) proposed a mechanism on the LL of the clay, i.e., for montmorillonite, LL is predominantly controlled by the thickness of double diffusion layer. Thickness suppression of the double diffusion layer caused by increasing the salt concentration, leads to LL 's reduction. The similar variation trends of Fig. 1(a) and (b) indicate that the mechanism accounting for pore water salinity effect on compression behavior of clays is probably related to the suppression of double diffusion layer.

3.2 Salinity Effects on Consolidation Behavior

The primary consolidation stage is defined in terms of the change in effective vertical stress. In the absence of pore water pressure measurements, the end of primary consolidation stage is defined using settlement observations. The elapsed time t_p represents the time required for the completion of primary consolidation. The typical relationships between void ratio e and elapse time t of four clays are shown in Fig. 2(a)–(d). As illustrated in Fig. 2(a), the primary consolidation ended in 10 min for kaolinite mixed with distilled water and 10% NaCl solutions, and the ending point of primary consolidation t_p were not significantly affected by pore water salinity and applied stresses. In contrary, the results as shown in Fig. 2(b)–(d) indicate that the period of primary

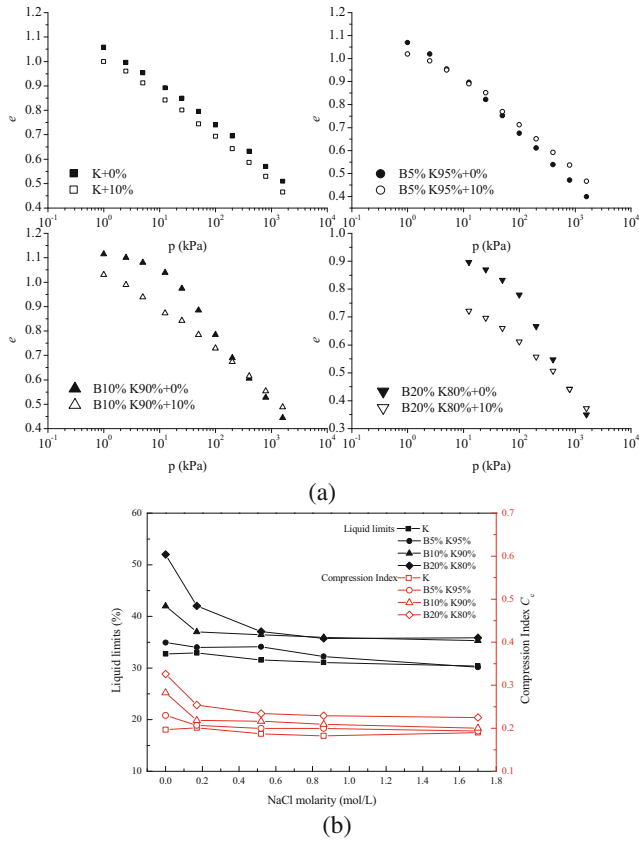


Fig. 1. Liquid limits LL and compression index C_c vs. NaCl molarity: (a) Compression curves; (b) C_c vs. NaCl molarity and LL vs. NaCl molarity

consolidation behavior of clays containing montmorillonite are apparently influenced by water salinity. The t_p of B5%K95%, B10%K90% and B20%K80% decreased by nearly an order of magnitude when the saline concentration increased to 10%. According to Terzaghi's one-dimensional consolidation theory, the decreasing of t_p represents a shorter drainage time and a higher consolidation coefficient. The permeability coefficient k is directly proportional to consolidation coefficient C_v , and it can be concluded that the permeability of pure clays containing montmorillonite increased with pore water salinity increasing. The mechanism attributed to the above findings was further discussed by micro-structure observations.

3.3 Microstructure and Mechanism

The salinity effect on microstructures was examined by binary SEM images (magnified 5000 times) as shown in Fig. 3. The fabric element of specimen B20%K80% Micro-01 hydrated with distilled water (Fig. 3a) exists a shape of thin platelet; whilst that of

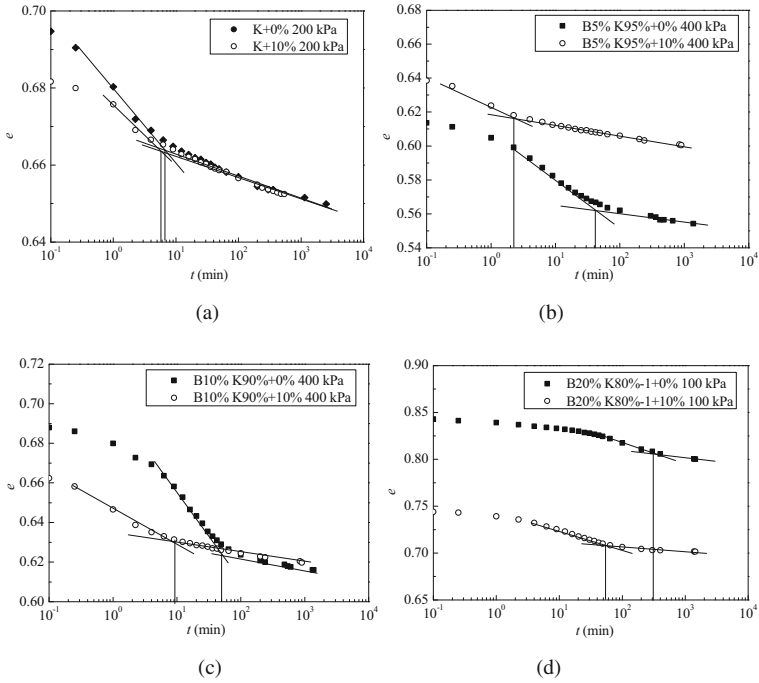


Fig. 2. The e - lgt curves of specimens: (a) K with 0% and 10% under 200 kPa; (b) B5%K95% with 0% and 10% under 400 kPa; (c) B10%K90% with 0% and 10% under 400 kPa; (d) B20% K80% with 0% and 10% under 100 kPa

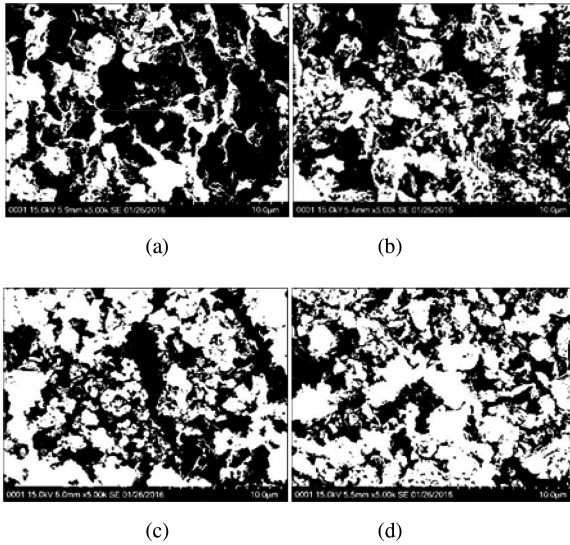


Fig. 3. SEM photos (magnified 5000 times): (a) B20%K80%Micro-01; (b) B20%K80%Micro-02; (c) KMico-01; (d) KMico-02;

specimen B20%K80%Micro-02 salinized with 0.86 mol/L NaCl solution (Fig. 3b) presents a shape of bulky pellet. On the other hand, for specimens only composed of kaolin (Fig. 3c and d), the similar arrangement and shape of bulky pellet are identified whatever with or without porewater salinity. Hence flocculation mechanism could be introduced to interpret the salinity effect on normalized compression behavior for reconstituted clay, especially for that with rich montmorillonite.

4 Conclusions

To better understand the salinity and clay mineral effects on the consolidation behaviour of clays, oedometer tests and SEM tests were conducted on four artificial clays. The main conclusions can be drawn as follows:

- (1) It shows that the LL and C_c of pure clays containing bentonite all decreased with pore water salinity, whilst those of kaolinic clay are relatively stable.
- (2) The ending points of primary consolidation of kaolinite were not significantly affected by pore water salinity. In contrary, the period of primary consolidation for clays containing montmorillonite decreased with pore water salinity.
- (3) The SEM observation shows that the fabric element of B20%K80% with a shape of thin platelet tend to be flocculated when the water salinity increased, whilst the micro-structure of kaolinite were not influenced by the water salinity.

Acknowledgements. This study is supported by Fundamental Research Funds for the Central Universities (Grant lzujbky-2018-8), and the National Natural Science Foundation of China (General Program, Grant Nos. 51378117; 41572280, 41790443, 41525010) and Postgraduate Research & Practice Innovation Program of Jiangsu Province (Grant No. KYCX17-0131).

References

- Abdullah WS, Alzoubi MS, Alshibli KA (1997) On the physicochemical aspects of compacted clay compressibility. *Can Geotech J* 34(4):551–559
- Bolt GH (1956) Physico-chemical analysis of the compressibility of pure clays. *Géotechnique* 2 (6):86–93
- Cerato AB, Lutenege AJ (2002) Determination of surface area of fine-grained soils by the ethylene (EGME) method. *Geotech Test J* 25(3):315–321
- Di Maio C, Santoli L, Schiavone P (2004) Volume change behaviour of clays: the influence of mineral composition, pore fluid composition and stress state. *Mech Mater* 36(5–6):435–451
- Fan RD, Du YJ, Reddy KR, Liu SY, Yang YL (2014) Compressibility and hydraulic conductivity of clayey soil mixed with calcium bentonite for slurry wall backfill: Initial assessment. *Appl Clay Sci* 101:119–127
- Gajo A, Maines M (2007) Mechanical effects of aqueous solutions of inorganic acids and bases on a natural active clay. *Géotechnique* 57(8):687–699
- Kaya A, Fang HY (2000) The effects of organic fluids on physicochemical parameters of fine-grained soils. *Can Geotech J* 37(5):943–950

- Oren AH, Kaya A (2003) Some engineering aspects of homoionized mixed clay minerals. *Environ Monit Assess* 84(1–2):85–98
- Sridharan A, Rao GV (1975) Mechanisms controlling the liquid limit of clays. In: *Proceeding of the Istanbul conference on soil mechanics and foundation engineering*, pp 75–84
- Ye W-M, Zhang F, Chen Y-G, Chen B, Cui Y-J (2017) Influences of salt solutions and salinization-desalinization processes on the volume change of compacted GMZ01 bentonite. *Eng Geol* 222:140–145
- Yukselen-Aksoy Y, Kaya A, Oren AH (2008) Seawater effect on consistency limits and compressibility characteristics of clays. *Eng Geol* 102(1–2):54–61
- Zhang F, Ye W-M, Chen Y-G, Chen B, Jun Cui, Yu (2016) Influences of salt solution concentration and vertical stress during saturation on the volume change behavior of compacted GMZ01 bentonite. *Eng Geol* 207:48–55
- Zhang T, Yue X, Deng Y, Zhang D, Liu S (2014) Mechanical behaviour and micro-structure of cement-stabilised marine clay with a metakaolin agent. *Constr Build Mater* 73:51–57