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Research paper

Pore fluid salinity effects on physicochemical-compressive behaviour of reconstituted marine clays

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ABSTRACT

It has been well recognized that pore fluid salinity significantly affects physical and mechanical properties of clays. However, how to correlate the pore fluid salinity effects on mechanical behaviour with physicochemical variations induced by pore fluid salinity changes is still pending. This study investigates the changes in liquid limit, oxide compositions and compressibility with pore fluid salinity, based on experimental data obtained from reconstituted specimens of two marine clays in China. It is found that oxide compositions vary little with the change in pore fluid salinity, indicating that no chemical reaction occurs during pore salt changing for the investigated clays. Such a finding means that the pore fluid salinity effects on compression behaviour of reconstituted clays can be attributed to the variations in physical properties. For the investigated marine clays with illite as predominant clay mineral, the void ratio at liquid limit is the crucial physical index of assessing the pore fluid salinity effects on the compression behaviour. The intrinsic compression concept is also introduced to compare the compression behaviour of reconstituted clays with and without pore salt. A quantitative approach is proposed to assess the pore fluid salinity effects on the compression behaviour of marine clays reconstituted at different initial water contents.

1. Introduction

Natural marine clays deposited in the seawater environments are often subjected to salt leaching durings their long post-depositional processes (e.g., Torrance, 1979; Quigley, 1980; Mitchell and Soga, 2005). It has been well reported that salt leaching is the key factor responsible for the development of quick clays in Scandimania and eastern Canada (e.g., Bjerrum, 1967; Crawford, 1968; Torrance, 1974). Torrance (1983) defined the quick clays as the marine clays with the sensitivity larger than 30 and the remoulded shear strength < 0.5 kPa. The sensitivity is defined as the ratio of shear strengths between undisturbed and remoulded specimens of natural clays (Bjerrum, 1967; Torrance, 1974; Mitchell and Soga, 2005). Note that the high sensitivity of quick clays is mainly attributed to the low strength of salt leached natural marine clays reconstituted at their in-situ water contents (e.g., Torrance, 1983; Geertsema and Torrance, 2005). Hence, the pore fluid salinity effects on physical properties and mechanical behaviour of reconstituted clays is an important issue in research and practical application.

It is well documented that salt leaching significantly affects physical properties (e.g., Locat and Lefebvre, 1985; Sridharan et al., 2002; Yukselen-Aksoy et al., 2008) and compression behaviour (e.g., Bjerrum, 1967; Torrance, 1974; Moore et al., 1977; Locat and Lefebvre, 1985). Note that the compression behaviour of reconstituted clays without pore salt has been correlated well with physical parameters as reported by several researchers (e.g., Nagaraj and Murthy, 1986; Alawaji, 1999; Dolinar, 2009; Cui et al., 2013; Gurtug, 2011). However, how to assess the pore fluid salinity effects on compression behaviour of reconstituted clays using physical parameters is still open.

This study firstly investigates the physical properties and the mineralogical compositions of two marine clays in China. Then, the original clays are mixed with distilled water or salting liquors at different

Abbreviations: C_c^*, intrinsic compression index of reconstituted clays, equal to ($e_{100}^* - e^*_{1000}$); e, void ratio; e_L, void ratio at the liquid limit; e_0, initial void ratio; e_{100}^*, void ratio of reconstituted clays at $\sigma'_v = 100$ kPa; e_{1000}^*, void ratio of reconstituted clays at $\sigma'_v = 1000$ kPa; EICL, extended intrinsic compression line; ICL, intrinsic compression line; I_v, void index; m_f, mass of pore fluid; m_s, mass of soil particles of clays; m_{sa}, mass of dissolved salt in pore fluid; m_w, mass of pore water of clays; S_{PL}, pore fluid salinity; w, water content; w_f, fluid content of clays containing dissolved salt; w_L, liquid limit; w_n, natural water content; w_p, plastic limit; w_0, initial water content; XRD, X-ray diffractometry; ε_v, volumetric strain; ρ_s, particle density; σ'_{yr}, remoulded yield stress; σ'_v, effective vertical stress; θ, diffraction angle

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Table 1
Basic physical properties of two investigated marine clays.

Clays	Lianyungang clay	Wenzhou clay
Pore fluid salinity, S_{PL} (g/L)	23.7	4.4
Particle density, ρ_s (Mg/m^3)	2.75	2.71
Liquid limit, w_L (%)	87	66
Plastic limit, w_P (%)	32	30
Sand (0.06–2 mm) (%)	1	1
Silt (0.002–0.06 mm) (%)	39	58
Clay (< 0.002 mm) (%)	60	41

salinities to prepare specimens with different pore fluid salinities (S_{PL}). Experimental studies are carried out to investigate the pore fluid salinity effects on liquid limit (w_L), plastic limit (w_P), oxide compositions and compression behaviour. The relationships between oxide compositions and pore fluid salinities are discussed for understanding whether chemical reaction occurs during pore salt changing. Next, pore fluid salinity effects on compression curves of reconstituted clays are studied and the compression behaviour of reconstituted clays with pore salt is correlated with physical indices. Finally, the intrinsic compression concept proposed by Burland (1990) is adopted for discussing similarities and differences in compression behaviour of reconstituted clays with and without pore salt.

2. Materials and clay minerals

Table 1 shows basic physical properties of two marine clays in China named after Wenzhou clay and Lianyungang clay respectively. These two clays are typical marine clays deposited in China which were formed during the Holocene transgression (e.g., Wang et al., 1981; Wu et al., 2015a). The samples of Wenzhou clay were obtained from the depth of 10 m–15 m below the ground surface at a construction site at Lucheng district of Wenzhou city, Zhejiang province of China. The samples of Lianyungang clay were obtained from the depth of about 4 m below the ground surface at the construction site of the Xin-Xu highway located at the Lianyungang city of the Jiangsu province of China.

The liquid limit (w_L) and plastic limit (w_P) were determined according to ASTM D4318-10e1, 2014. The particle size distribution was measured by the hydrometer test according to ASTM D422-63, 2007, using clay samples treated with desalination. The particle density (ρ_s) was determined in accordance with BS 1377: Part2: 1990: 8.3, as suggested by Head (1992). The pore fluid salinity (S_{PL}) was measured by the oven-drying method using the pore fluid extracted directly from the investigated clays with centrifugation. It can be seen that the in-situ values of S_{PL} are lower than the seawater salinity being about 35 g/L, indicating salt leaching occurs during the post-depositional process for the two marine clays investigated.

X-ray diffractometry (XRD) tests were conducted to determine the mineralogical compositions and clay minerals of the investigated clays. The mineralogical compositions were analyzed by performing XRD tests on powder specimens in a 2θ range of 5–35°, and the oriented slides method was used to specify the clay minerals of particle sizes smaller than 2 μm in a 2θ range of 2–25°. The term θ presents diffraction angle.

The specimens of oriented slides for XRD tests were prepared following the methods described in Whittig and Allardice (1986). Field-moist samples were firstly mixed with distilled water, stirred evenly, and then centrifuged. These operations were conducted repeatedly to remove the dissolved pore salt. Then, they were treated successively with 6% H_2O_2 to remove the organic matter, and 4% $(NaPO_3)_6$ to disperse soil particles. The samples of clay fraction (< 2 μm) were collected by centrifugal separation. Then 2–3 mL distilled water was added, and the mixture was stirred evenly. Afterwards, the suspension containing about 30 mg clay was dropped onto a glass slide (20 mm × 80 mm) by pipette. After air-drying, the specimens were X-rayed with and without solvation by ethylene glycol respectively.

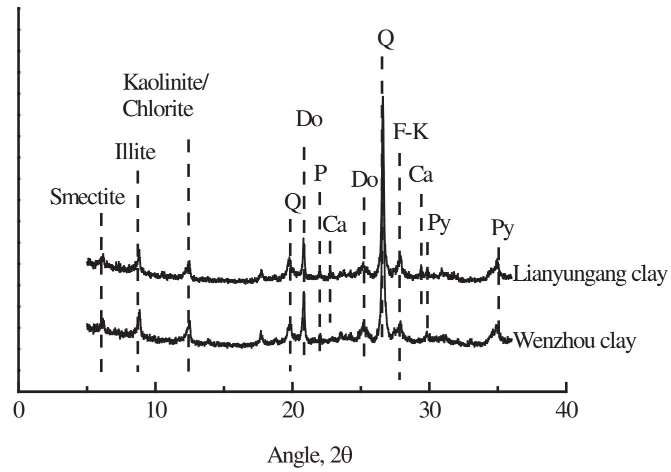

Fig. 1. Random powder XRD patterns of two marine clays.

The X-ray power diffractions of investigated clays are shown in Fig. 1. It can be seen that the main nonclay minerals are quartz and plagioclase, with the presence of others like k-feldspar, calcite, dolomite and pyrite. The X-ray diffraction patterns of the air-dried specimens and the specimens saturated with ethylene glycol for the clay fraction (< 2 μm) are illustrated respectively in Fig. 2(a) and (b). According to the X-ray diffraction patterns of air-dried specimens, the main clay minerals are identified to be illite (basal order reflection = 10.0 Å, 5.0 Å, 3.3 Å), kaolinite (basal order reflection = 7.25 Å, 3.58 Å). For smectite, its basal order reflection changes from 14.2 Å to 17.0 Å after treated with ethylene glycol saturation, as shown in Fig. 2.

Following Mitchell and Soga (2005) and Sridharan et al. (2002), a semi-quantitative method by comparing the reflection areas of the X-ray diffraction patterns was adopted to determine the clay minerals. The results are given in Table 2. The predominant clay mineral for both the two marine clays is illite, being 68% for Lianyungang clay and 76% for Wenzhou clay. For Lianyungang clay, the amount of chlorite, kaolinite, and smectite are 11%, 8% and 13% respectively. For Wenzhou clay, the amount of chlorite and kaolinite are 11% and 13% respectively, but smectite is not detected.

3. Pore fluid salinity effect on oxide compositions

Since the main components in seawater are sodium and chloride ions, NaCl solution was adopted in this study to prepare the specimens with different pore fluid salinities. The dissolved salt in the original marine clays was firstly removed by adding distilled water and centrifugation to avoid the interference of other trace cations such as K^+, Mg^{2+}, Ca^{2+} appeared in the pore fluid of original clays. These operations were conducted repeatedly until the original pore fluid salinity becomes < 1.0 g/L for ensuring the removal of the other trace cations. Then, the NaCl solution was added and mixed with the treated original clays by removing the original pore dissolved salt to prepare test specimens with different values of S_{PL}.

The oxide compositions of the two marine clays with different pore fluid salinities were determined by X-ray fluorescence spectrometer tests. The results of oxide compositions for Lianyungang clay at S_{PL} = 1.8 g/L and 23.3 g/L and for Wenzhou clay at S_{PL} = 0.8 g/L and 36.5 g/L are presented in Table 3. The main oxide compositions are SiO_2 and Al_2O_3 for both two marine clays investigated. The quantity of SiO_2 changes from 53.4% to 49.9% when S_{PL} varies from 1.8 g/L to 23.3 g/L for Lianyungang clay. For Wenzhou clay, it varies from 57.1% to 53.3% responsible for the variation of S_{PL} from 0.8 g/L to 36.5 g/L. The amount of Al_2O_3 changes from 21.2% to 20.2% for Lianyungang clay and 21.2% to 19.9% for Wenzhou clay at different values of S_{PL}.