Applied Clay Science 135 (2017) 355–361

Contents lists available at ScienceDirect

Applied Clay Science

journal homepage: www.elsevier.com/locate/clay

Research paper

Sand fraction effect on hydro-mechanical behavior of sand-clay mixture

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ARTICLE INFO

Article history:
Received 21 June 2016
Received in revised form 8 October 2016
Accepted 11 October 2016
Available online 17 October 2016

Keywords:
Sand-clay mixture
Sand fraction
Hydro-mechanical behavior
Four-phase model
Sand skeleton formation

ABSTRACT

The sand-clay mixture was prepared to simulate special soils with discontinuous gradations, *e.g.* the residual soils, clinosols or hydraulic filling soils. Incremental loading oedometer tests were conducted to investigate their hydro-mechanical behaviors. The results were first analyzed based on the plots in the semi-logarithmic planes (*i.e.* normalized void ratio by that at liquid limit *versus* vertical effective stress, and *versus* hydraulic conductivity). It appears that the normalized void ratio by that at liquid limit allows valuable and reliable normalization of the compressibility and permeability curves. To investigate the influence of sand fraction, a four-phase model of sand-clay mixture was introduced, enabling the void ratios of clay and sand to be determined. Further analysis showed that the sand void ratio and the normalized clay void ratio by that at liquid limit are also suitable parameters to describe the sand skeleton formation. Moreover, the normalized clay void ratio by that at liquid limit is an appropriate parameter to describe the hydraulic behavior of soils with or without sand fraction. When the sand skeleton was partly formed, the vertical stress was partly supported by the skeleton resulting in a different compression behavior from that of common clays. The partial formation of skeleton was found to depend on the relative dimension of coarse to fine grains as well as the stress state. This implies that during compression the interaction between sand and clay evolves, from non-, partial- to complete sand skeleton, reaching at the end of the maximum void ratio of sand.

1. Introduction

The compression and percolation behaviors of soils are essential when analyzing the foundation deformation, dam seepage, *etc.* Many investigations were conducted in this field, but mostly focusing on cohesive soils with relatively continuous gradations (Mesri and Olson, 1971; Tavenas et al., 1983; Burland, 1990; Sivakumar babu et al., 1993; Sridharan and Nagaraj, 2005; Yukselen-Aksoy et al., 2008; Dolinar, 2009; Hong et al., 2010; Hong et al., 2012; Chapuis, 2012). However, for most naturally formed soils, including residual soils, clinosols and deposit clays, their fractions are composed of clay, silt, sand or gravel. On the other hand, special soils with multi fractions can also be produced by human activities. For instance, during the land reclamation of Ganyu port in Lianyungang, China, the hydraulic filling method was performed by dredging the original sand and clay interbedded layers, leading to the formation of sand-clay mixtures. Note that in this case, the sand content and the ratio of bentonite and kaolinite in clay minerals randomly deposited from 0% to 80%, and 5/5 to 9/1 respectively after site re-investigation (Wu et al., 2015, 2016). For this kind of soils, the hydro-mechanical behavior can strongly depend on the sand fraction, and it is thereby essential to investigate the effect of sand fraction on the compression and percolation behaviors of soils.

The sand-clay mixture is usually adopted to investigate the effect of large grain fraction and the interaction among different fractions (Cabalar and Hasan, 2013). Watabe et al. (2011) reported that the compressibility of compacted sand-clay mixtures was governed by the sand fraction when the sand fraction reaches a threshold to form a sand skeleton. This observation is consistent with the previous results obtained by Fukue et al. (1986) and Boutin et al. (2011). Cabalar and Hasan (2013) further pointed out that the sand size/shape, percentage of sand or clay and stress states are also important factors affecting soil compressibility. For the percolation behavior, Watabe et al. (2011) found that the increase of sand fraction leads to a slight increase of hydraulic conductivity below a threshold, followed by a sharp increase beyond the threshold. Tripathi and Viswanadham (2012) further found that the percolation behavior of sand-bentonite mixtures was both controlled by the initial saturation process, testing method and bentonite content.

Although there have been some investigations on the compressibility and percolation behaviors of sand-clay mixtures, the sand fraction effect on the hydro-mechanical behavior of this kind of soils has not been fully understood yet. In this study, a series of oedometer tests on

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http://dx.doi.org/10.1016/j.clay.2016.10.017
0169-1317/

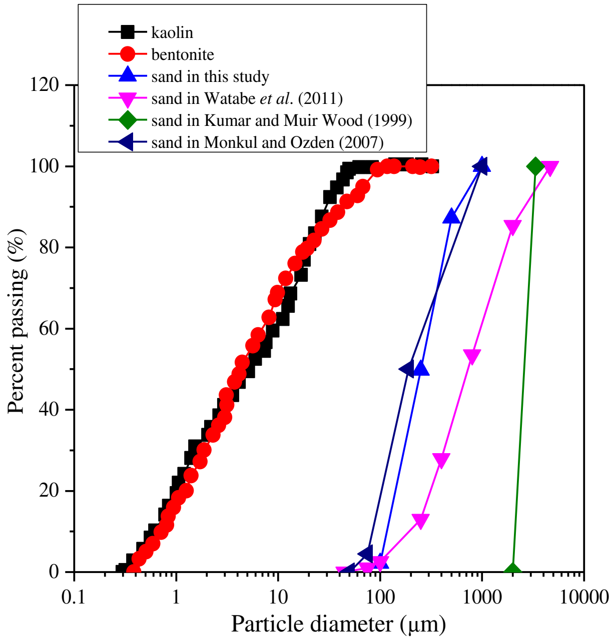

Fig. 1. Particle size distribution of sand, kaolin and bentonite.

sand-clay mixtures with various sand/clay fraction ratios were carried out. The compressibility and the hydraulic conductivity obtained by back analysis (Sivapullaiah et al., 2000; Watabe et al., 2011) were adopted to evidence the effect of sand fraction.

2. Materials and methods

2.1. Materials

The basic materials studied were composed of standard quartz sand, commercial kaolin and bentonite. The standard sand was provided by Fujian Sand Product Company, with the maximum void ratio (e_{max}) of 0.83 and the minimum void ratio (e_{min}) of 0.485 respectively. The particle size distribution curve was shown in Fig. 1. Note that the size distribution of sand in this study was obvious different from that in other literatures, aiming to simulate the sand composition of soils from Ganyu Port, and to investigate the effect of particle size distribution on the hydro-mechanical behaviors.

The commercial kaolin and bentonite were provided by Zhenjiang and Xuzhou Clay Manufacturing Company in China respectively. Their grain size distributions measured by the Marlvern laser particle size analyzer were shown in Fig. 1. It can be observed that the kaolin and bentonite have the similar grain size distributions. The mineralogical compositions of kaolin and bentonite materials were semi-quantitatively determined by X-ray diffractometry method and presented in Table 1. It shows that the minerals of kaolin are composed of quart (4.0%), K-felspar (5.1%), plagioclase (17.1%), calcite (3.5%) and dolomite (2.1%) respectively, and the clay mineral is just kaolinite with a content of 68.2%. On the other hand, the minerals of bentonite are of quart (1.3%), K-felspar (0.3%), calcite (0.1%), and the clay minerals are mostly composed of smectite (90.5%).

Table 2
Properties of bentonite and kaolin used in this study.

Property	Testing method	Materials	
		Kaolin	*Ca*-bentonite
Liquid limit, w_L (%)	ASTM (2010b)	42	301
Plastic limit, w_P (%)	ASTM (2010b)	23	95
Plasticity index *Ip*	—	19	206
Sand (%; >0.075 mm)	*a*	5%	3%
Silt (%; 0.005 mm–0.075 mm)		47%	42%
Clay (%;<0.005 mm)		48	55%
Exchangeable cations (cmol/kg)	ASTM (2010d)		
Na^+		4.75	53.39
K^+		0.34	0.53
Ca^{2+}		1.44	22.74
Mg^+		0.08	1.41
Sum		6.61	78.07
Specific surface area (m^2/g)	*b*	45.7	378.5
pH	ASTM (2007)	8.7	10.0
Classification	ASTM (2010a)	CL	CH

a: Measured using a laser particle analyzer Mastersizer 2000 (Malvern Instruments Ltd., UK).
b: Measured used EGME method according to Cerato and Luteneggerl (2002).

The basic physicochemical properties of studied kaolin and bentonite were listed in Table 2, which shows that the bentonite has the higher values of liquid limit (w_L), plastic limit (w_P), plasticity index (*Ip*), exchangeable cations, specific surface area (*SSA*) and pH, owing to the high smectite content. According to the Unified Soil Classification System (ASTM, 2010a), the kaolin and bentonite are low-plasticity clay (CL) and high-plasticity clay (CH), respectively.

2.2. Methods

Sand-clay mixtures were prepared by mixing the pure clays and sand. To consider the mineralogy influence in the clays, three dry mass ratios of bentonite to kaolin were considered: 9/1, 7/3 and 5/5. The sand fractions (w_s) were preset as 0%, 30%, 40% and 50%, defined by Eq. (1):

$$w_s = \frac{m_s}{m_s + m_c} \quad (1)$$

where m_s and m_c are the dry mass of sand and clay, respectively.

During the sample preparation, a predetermined mass of sand and air-dried clays were thoroughly mixed using a paddle mixer. The basic properties of the mixtures are presented in Table 3, where the liquid limit (w_L) was determined following ASTM D4318 (2010b), the specific gravity (d_{sc}) of clay and that (d_{ss}) of sand were determined following ASTM D854 (2010c), and the specific gravity (d_{sm}) of mixtures was calculated by the weighted average method.

After mixing, distilled water was added until the water content reached the liquid limit (w_L). Then, stirring process was applied to further homogenize the mixtures. Afterwards, the wetting sand-clay pastes were poured into the consolidation rings (61.8 mm in diameter and 20 mm in height) with tapping to minimize entrapped air bubbles in the specimens. The prepared samples were vacuumed in distilled water for 24 h to achieve full saturation. Note that the inside of ring was previously lubricated with silicon grease to minimize skin friction.

The one-dimensional oedometer tests were conducted on the prepared samples following ASTM (2011). The first load applied was

Table 1
Semi-quantitative analysis of the kaolin and bentonite materials.

Materials	Mineral composition (%)								
	Quartz	K-feldspar	Plagioclase	Calcite	Dolomite	Siderite	Illite	Kaolinite	Smectite
Kaolin	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