Engineering Geology 125 (2012) 26–34

Contents lists available at SciVerse ScienceDirect

Engineering Geology

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

Mineral dissolution effects on mechanical strength

M. Khoa Tran [a], Hosung Shin [b], Yong-Hoon Byun [a], Jong-Sub Lee [a,*]

[a] School of Civil, Environmental and Architectural Engineering, Korea University, Seoul 136-701, Republic of Korea
[b] Department of Civil, Environmental Engineering, University of Ulsan, Ulsan 680-749, Republic of Korea

ARTICLE INFO

Article history:
Received 20 June 2011
Received in revised form 21 October 2011
Accepted 22 October 2011
Available online 9 November 2011

Keywords:
Soluble mixtures
Mineral dissolution
Direct shear test
Shear strength
Fabric
DEM

ABSTRACT

The fabric of soil media may change due to certain factors such as the dissolution of soluble mineral particles, desiccation, and cementation. The fabric changes lead to mechanical behaviour changes. The purpose of this study is to investigate the effects of mineral dissolution on mechanical strength. Experimental studies and numerical simulations are performed by using conventional direct shear and discrete element methods. The dissolution specimens are prepared with different volumetric soluble particle fractions in sandy soils. The dissolution of the specimens is implemented by saturating the salt–sand mixtures at the different confining stresses in the experimental study and reducing the sizes of soluble particles in the numerical simulations. Experimental results show that after the particle dissolution as the soluble particle fraction increases, the peak shear strength decreases, the void ratio increases, and the vertical displacement behaviour during shearing changes from dilative to contractive behaviour. The numerical simulations exhibit that the macro-behaviours match well with the experimental results. In addition, the micro-scale observation shows that the reduction in the shear strength of the soluble particle mixtures after the particle dissolution results from the reductions of the coordination number, the stability of the fabric, the ability to develop the anisotropy of the fabric, and the increases in the local voids and anisotropy. This study reveals that the particle dissolution has a significant effect on the shear strength, deformation, and fabric change.

1. Introduction

In granular materials, the initial fabric significantly influences the mechanical behaviours such as the shear strength, the deformation and the stiffness. A significant reduction in the shear strength due to the differences in the fabrics of steel ball assemblies was observed, even though the assemblies had the same densities (O'Sullivan et al., 2004). The fabric effects on sandy soils were investigated by triaxial compression and extension simulations with different initial contact normals (Yimsiri and Soga, 2010): the specimens sheared in the contact normal direction had higher strengths, and were stiffer and exhibited greater dilative responses than the specimens sheared perpendicular to the contact normal direction.

Soils may generally contain soluble minerals such as halite, calcite, dolomite, gypsum, anhydrite, magnesite, and carnalite, especially in arid regions (Bell, 2007). Soluble minerals can be easily found in the foundation or abutments of dams (Mikheev and Petrukhin, 1973; Craft, 2005). The dissolution of soluble minerals increases the void ratio, and thus the soil media become looser and more compressible (Al-Amoudi and Abduljauwad, 1995; Truong et al., 2010). The changes of the void ratio and the vertical strain are proportional to the initial soluble mineral contents (Truong et al., 2010). After mineral dissolution, the fabric of the soil media becomes a honeycomb-like fabric (Shin and Santamarina, 2009), and thus the stiffness decreases (Fam et al., 2002; Truong et al., 2010). The soluble minerals in the granular soil media also play a crucial role in the stability of geotechnical structures. The mineral dissolution rendered the failures of the Macmillan reservoir (Blyth and de Freitas, 1984), the Clubbiedean Dam (Blyth and de Freitas, 1984), and the St. Francis Dam (Craft, 2005). The mineral dissolution effects of the granular media on the mechanical strength from the macro and micro points of view have not been discussed.

The direct shear test, which is specified in ASTM D3080, has been commonly used in geotechnical engineering for the characterisation of the strength and the friction angle (Jewell, 1989). As the shearing process starts, at the split plane level, multiple shear bands propagate from the edge of the shear box towards the middle of the specimen (Scarpelli and Wood, 1982; Wang et al., 2007), and the fabrics of the soil media become anisotropic (Masson and Martinez, 2001; Cui and O'Sullivan, 2006; Wang et al., 2007; Zhang and Thornton, 2007). The stresses and strains within the failure zone are quite uniform (Jewell and Wroth, 1987; Potts et al., 1987). The peak shear strength determined by the direct shear test is very similar to that obtained in an ideal simple shear condition (Potts et al., 1987; Wang et al., 2007).The vertical behaviour of the top boundary measured in the dense sample results in the dilation inside the shear band (Masson and Martinez, 2001).

The discrete element method (DEM) introduced by Cundall (1971) has been used for particle level studies, the validation of constitutive

* Corresponding author. Tel.: +82 2 3290 3325.
E-mail address: jongsub@korea.ac.kr (J. S. Lee).

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doi:10.1016/j.enggeo.2011.10.014

models, and the analyses of dynamic as well as static soil behaviour (Ting et al., 1989). In the DEM, the soil is treated as an assembly of separated particles; contact forces between particles and movements of particles are calculated at each time step by adopting a force–displacement law at each contact and the application of Newton's 2nd law to each particle (Cundall and Strack, 1979; PFC2D, 2006). Data obtained from the particle level are used to obtain continuum level information such as stress and strain. In addition, the DEM has been widely used for analysing the macro- and micro-behaviours of granular materials inside a shear box in both two- and three-dimensional models (Masson and Martinez, 2001; Cui and O'Sullivan, 2006; Wang et al., 2007; Zhang and Thornton, 2007).

This study addresses the mineral dissolution effects on the mechanical strength. Experimental and numerical tests were conducted by using mixtures of soluble particles with various soluble particle fractions. First, the experimental programme and experimental results are presented. Then, the detailed descriptions of the DEM simulation for the direct shear test, the particle dissolution process and the numerical results are introduced. Finally, the micro characteristics including the coordination number, the fabric and contact forces, and the anisotropy coefficients are discussed.

2. Experimental study

2.1. Materials

The soluble particle mixtures were prepared by using sand and salt particles, which are commonly used for the investigation of the mechanical behaviours of soluble mixtures (Fam et al., 2002; Shin and Santamarina, 2009; Truong et al., 2010). Jumunjin 30/40 sand, which passed through sieve no. 30 and remained on sieve no. 40, was uniform size with a medium angular shape. The maximum and minimum void ratios of the sand were 0.927 and 0.612, respectively. The table salts, which were also sieved in 30/40, were uniform size and cubic in shape. The specific gravities of the sand and salt were 2.62 and 2.16, respectively. The mean grain sizes of the sand and salt particles were 0.5 mm.

2.2. Specimen preparation

The soluble particle mixtures were prepared by mixing the sand with the salt particles at different salt contents based on the volumetric salt fraction (% of salt $= V_{salt}/V_{sand} \times 100\%$, where the V_{salt} and V_{sand} denote the volumes of salt and sand, respectively). The salt fractions (soluble particle fraction) prepared were 0 (pure sand), 2, 5, and 10%. For the preparation of the well mixed specimens, the sieved table salt particles and clean, dried and sieved sand particles were mixed for more than 10 min in a container. The well mixed salt–sand mixtures were funnelled into a cylindrical direct shear cell in four layers. Each layer was compacted by using a tamping foot with the same tamping numbers. Because the size of the salt particles is the same as the size of sand particles, the initial void ratios of all mixtures were same under the same tamping energy. The initial void ratio of all specimens was $e_0 = 0.707$. Note that the size of the specimens is 60 mm in diameter and 21 mm in height.

2.3. Test procedure

After the salt–sand mixture specimens were prepared in the direct shear cell, the pre-determined vertical stresses of 50 kPa, 100 kPa, and 150 kPa were applied on the top of the specimens. When the vertical settlement of the specimens did not occur, the water was slowly poured into the water reservoir in which the direct shear cell was located. When the water level reached the level of the top cap, the water supply was stopped. Thus, the water flowing from the bottom to the top of the specimens dissolved the soluble particles. The volume of the water reservoir was 868.2 cm^3 excluding the volume of the specimen and the direct shear cell. Because the solubility of sodium chloride is 360 g/l (Craft, 2005), the water volume of 868.2 cm^3 can dissolve 312.6 g of salt. Because the maximum amount of salt in this study was 7.03 g, all soluble particles in the specimens could be dissolved completely. During the dissolution of the soluble particles, the vertical displacement was continuously recorded.

After the particles were completely dissolved and no more vertical settlement occurred, the specimens were sheared by the direct shear device at the rate of 1 mm/min. During the shearing tests, the vertical deformations, horizontal deformations, and shear forces of the specimens were continuously recorded. The direct shear tests were completed at the horizontal displacement of 6 mm.

2.4. Results

2.4.1. Vertical settlement during dissolution

The vertical settlement during particle dissolution under the normal stress of 100 kPa is plotted in Fig. 1. Fig. 1 shows that the vertical settlement was completed within 1 min for the 2% salt fraction specimen, 2 min for the 5% salt fraction specimen, and 10 min for the 10% salt fraction specimen. No settlement occurred during saturation process for the 0% salt fraction specimen. The final vertical settlement is proportional to the initial soluble mineral content. Note that the specimen was sheared 30 min later after particles were dissolved.

2.4.2. Stress–displacement

The shear stresses versus horizontal displacements and vertical displacements versus horizontal displacements behaviours of soluble mixtures under the normal stress of 100 kPa are plotted in Fig. 2(a) and (b), respectively. The shear stress of the 0% salt fraction specimen increases with the horizontal displacement, obtains the peak shear strength and then decreases to the residual shear strength. The specimens with 2% and 5% salt fraction show the peak strengths. No clear peak strength, however, is observed for the specimen with the 10% salt fraction. Note that the strength decreases with the increase in the salt contents. However, the residual shear strengths of all mixtures are almost the same. The clear dilative behaviour is observed for the specimens of the 0% and 2% salt fraction during shearing, as shown in Fig. 2(b). The minor dilative behaviour is shown in the 5% salt fraction specimen. However, no dilative behaviour is observed for the 10% salt fraction specimen. As the salt fraction increases, the vertical displacement shows more contractive behaviour.

2.4.3. Void ratio

The void ratio of specimens before shearing (which is the void ratio after particle dissolution) and after shearing versus soluble particle contents is plotted in Fig. 3. Fig. 3 shows that the void ratio of the specimens before shearing increases with an increase in the salt content and with a decrease in the normal stress. The increase in void ratios results from particle dissolution and arching effects (Truong et al.,

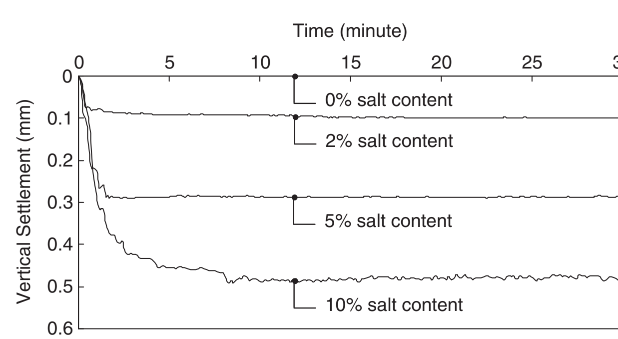

Fig. 1. Vertical settlement during soluble particle dissolution under 100 kPa normal stress.