Engineering Geology 243 (2018) 84–100

Contents lists available at ScienceDirect

Engineering Geology

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

A study on the mechanical interaction between soil and colloidal silica gel for ground improvement

Christopher Wong, Matteo Pedrotti*, Gráinne El Mountassir, Rebecca J. Lunn

Department of Civil and Environmental Engineering, University of Strathclyde, UK

ARTICLE INFO

Keywords:
Ground stabilisation
Colloidal silica grout
Soil shear strength
Soil compressibility

ABSTRACT

In this paper, we explore the mechanical performance of colloidal silica grout to assess its potential for ground stabilisation and hydraulic barrier formation during decommissioning of major industrially contaminated sites. We consider two colloidal silica -soil systems: sand grouted with colloidal silica and kaolin clay mixed with colloidal silica. The aims of the paper are to evaluate the drained stress-strain behaviour (1-D compression and shear resistance) of colloidal silica-soil systems and to determine the particle interactions between soil and colloidal silica at a micron-scale so as to provide an understanding of the macroscopic mechanical behaviour. Two different colloidal silica-soil interaction mechanisms have been found: formation of a solid, cohesive matrix for the case of grouted sand, and increase of the clustering of clay particles for the case of clay mixtures. This paper illustrates for the first time that even under drained conditions colloidal silica can provide mechanical improvement. Colloidal silica-grouted sand showed an increased stiffness and enhanced peak friction angle, while still having a very low hydraulic conductivity (~10^{-10} m/s), typical of intact clay. Similarly, clay-colloidal silica mixtures showed reduced volumetric deformation, increased stiffness for low values of stress (~100 kPa), and increases in both the peak and the ultimate shear strength. Our results show that colloidal silica could be deployed in environments where not only hydraulic containment is critical, but where reduced deformation and enhanced resistance to shearing would be beneficial, for example in landfill capping or in the outer fill layers of embankments designed to minimise internal seepage and infiltration.

1. Introduction

Over the last thirty years, Colloidal Silica (CS) has been investigated, and more recently deployed, as a low viscosity grout for permeation grouting in soils and for grouting fractured rock. CS has a number of properties that make it attractive. It has an initially low viscosity (close to water) which means that very low injection pressures are required (Moridis et al., 1995). The gel time of CS can be controlled from minutes to several days (Iler, 1979; Yates, 1990) and, once gelled, it has a hydraulic conductivity in the order of 10^{-9} m/s (Moridis et al., 1996a). In addition, it is considered to be environmentally inert (Moridis et al., 1995) and withparticle sizes < 100 nm, it has high penetrability (Iler, 1979; Yates, 1990; Persoff et al., 1995; Moridis et al., 1995).

The key material property that makes CS attractive for use in ground engineering is undoubtedly its low hydraulic conductivity. As such it has been investigated for (i) controlling fluid flow around wellbores within the petroleum industry (Jurinak and Summers, 1991), (ii) as a permeation grout for barrier systems for contaminated sites (Persoff et al., 1995; Moridis et al., 1995; Moridis et al., 1996a; Moridis et al., 1996b; Hakem et al., 1997; Moridis et al., 1999; Persoff et al., 1999; Manchester et al., 2001),and (iii) for preventing water ingress in the tunnelling and underground construction industry (Bahadur et al. (2007), Butrón et al. (2010).

However, CS also provides some level of mechanical improvement. Indeed, a field test by (Moridis et al., 1995) showed that "CS imparted sufficient structural strength to the matrix to permit 10ft high vertical sections of the matrix (characterized by very loose, friable, and heterogeneous materials) to stand without collapsing". CS has also been investigated as a means of increasing resistance to liquefaction in loose sands (Gallagher and Mitchell, 2002; Gallagher and Finsterle, 2004; Gallagher et al., 2007; Gallagher and Lin, 2009; Huang and Wang, 2016), and as stabilizer for collapsible clayey soils (Iranpour, 2016).

Despite its consideration for use in a range of different applications, limited data exist which characterise the mechanical behaviour of grouted soils. The behaviour of pure CS silica has been investigated (Axelsson, 2006; Funehag and Fransson, 2006; Funehag and Gustafson, 2008; Butrón et al., 2009) indicating the fragile nature of the gel. To

* Corresponding author at: Department of Civil and Environmental Engineering, University of Strathclyde, James Weir Building - Level 5, 75 Montrose Street, Glasgow G1 1XJ, Scotland, UK.
E-mail address: matteo.pedrotti@strath.ac.uk (M. Pedrotti).

https://doi.org/10.1016/j.enggeo.2018.06.011
Received 23 December 2017; Received in revised form 12 May 2018; Accepted 19 June 2018
Available online 26 June 2018
0013-7952/

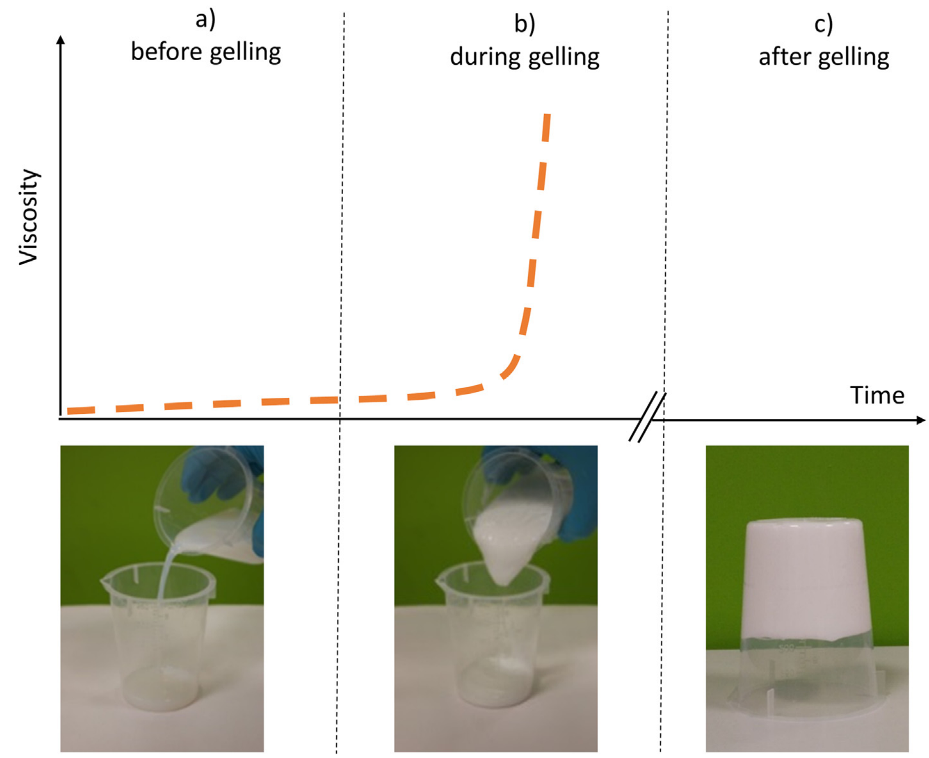

Fig. 1. Gelling of CS: a) CS before gelling, b) CS close to the gel time, c) CS after gelling.

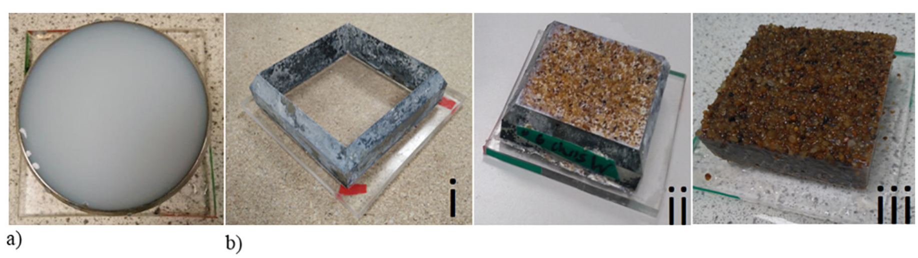

Fig. 2. Specimen preparation: (a) colloidal silica specimen during curing in oedometer mould, (b) shearbox specimen *i.* mould, *ii.* sand grouted with CS in mould and *iii.*Grouted sand specimen after curing and removal from mould.

date the mechanical behaviour of grouted soils which has been reported has been largely limited to the undrained behaviour of grouted sand. Unconfined compressive strength (UCS) tests of grouted soil samples have been reported which demonstrate that grouted-sand specimens have UCS values up to several hundreds of kPas and that increasing the concentration of silica in the colloidal suspension increases the UCS and that UCS increases with curing time (Persoff et al., 1999; Gallagher and Mitchell, 2002; Liao et al., 2003; Mollamahmutoglu and Yilmaz, 2010; Changizi and Haddad, 2017). Undrained triaxial tests have also been conducted which demonstrate the reduced deformation of grouted sand specimens (and hence reduced loss of strength) when subjected to cyclic loading (to simulate earthquake loading) as a means of assessing its potential to mitigate against liquefaction (Gallagher and Mitchell, 2002). A reduction in compressibility and reduced strain at failure has also been observed for clayey soil when mixed with a small amount of colloidal silica ($< 1\%$ by weight) (Changizi and Haddad, 2017).

The small increase in the mechanical resistance (an increase in the cohesion and a decrease in the compressibility) coupled with the well-documented large reduction in hydraulic conductivity (and hence increase in consolidation time) makes CS grouting or CS soil mixtures a promising technique for a range of soil stabilisation applications. In particular, the undrained results reported to date in the literature indicate its potential for short-term stability problems e.g. for temporary excavations, cuttings immediately after excavation, tunnelling and construction in earthquake prone areas. In this paper, we explore the drained behaviour of CS-soil systems to assess its potential for use in other ground improvement applications. The drained behaviour of CS-soil systems has not been investigated until now.

In this research we consider two CS-soil systems: sand grouted with CS and kaolin clay mixed with CS. The former is to simulate soil grouted via permeation grouting and the latter to investigate a potential new material for ground engineering. The aims of the paper are (1) to evaluate the drained stress-strain behaviour (1-D compression and shear resistance) of CS-soil systems and (2) to determine the particle interactions between soil and colloidal silica at a micron-scale so as to provide an understanding of the macroscopic mechanical behaviour.

2. Materials and specimen preparation

Five different materials were used during this experimental campaign: CS gel only, Leighton Buzzard sand only, Leighton Buzzard sand grouted with CS, kaolin clay only and kaolin clay mixed with CS. The preparation methods for these materials are each described in-turn.