Research paper

Rheology of concentrated bentonite dispersions treated with sodium pyrophosphate for application in mitigating earthquake-induced liquefaction

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ABSTRACT

The paper investigates the effectiveness of sodium pyrophosphate (SPP) to engineer the rheology of concentrated bentonite dispersions for their use in treating sands susceptible to earthquake-induced liquefaction. This application requires that on the short term the rheological properties of the dispersion allow its permeation inside a porous medium, but that once inside the sand pores, the dispersion regains its gel structure.

The testing program focuses on 10% bentonite dispersions (expressed in terms of mass of bentonite by total mass of the dispersion) prepared using a commercial Wyoming sodium-bentonite, pure water and SPP at dosages ranging from 0% to 2% by mass of the bentonite. Rheological tests are conducted using a Physica MCR 301 rotational rheometer to probe the flow and viscoelastic properties of the dispersions over time. Tests conducted at early ages suggest that dispersions with SPP ≥ 0.5% are likely to be suitable permeation materials. Tests conducted over a period of two years show a significant evolution of the rheology, with all dispersions returning to exhibit response typical of gel-like materials, including thixotropic behavior; the greater the SPP%, the more delayed the formation of the gel. Custom rheological tests establish the independence of the behavior of the SPP dispersions on the frequency of the applied load. These results suggest the ability of these dispersions to mitigate liquefaction during subsequent seismic events, and further support their use in the application considered.

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1. Introduction

Bentonite, a clay composed primarily of montmorillonite, is used in many industries due to the thixotropic properties of water bentonite dispersions. In the geotechnical engineering field, bentonite dispersions are used as drilling fluids, for underground sealing, for excavation support, in slurry cut-off walls to form impermeable barriers, and for grouting. Control of their rheological properties is critical in all these applications. It is well established that a number of factors, including clay concentration, pH, water ionic strength, type of cation and anion affect the rheology of bentonite dispersions (e.g. Bekkour et al., 2005; Durán et al., 2000; Harvey and Lagaly, 2013; Kelessidis et al., 2007; Laribi et al., 2006; Luckham and Rossi, 1999; Malfoy et al., 2003; Penner and Lagaly, 2001; Tombácz and Szekeres, 2004; Yildiz et al., 1999), which, as a result of changes in these parameters, exist in different "states":

sol, repulsive gel, attractive gel, and sediment (Abend and Lagaly, 2000; Lagaly and Dekany, 2013; Michot et al., 2004).

Recent research by El Mohtar et al. (2013, 2014) has explored the use of bentonite for treatment of sand deposits susceptible to earthquake-induced liquefaction. Soil liquefaction, which occurs in saturated loose-medium granular deposits, is caused by the pore pressure increase, and associated effective stress loss, produced by rapid loading (e.g. see Ishihara, 1993; Seed and Lee, 1966). Liquefaction is an important cause of damage to civil infrastructures during earthquakes, and examples of its occurrence have been documented in all recent earthquakes, including the 2007 Pisco, Peru, the 2011 Tohoku, Japan, the 2010 Maule, Chile, and the 2010 and 2011 Christchurch, New Zealand earthquakes (e.g. see Bray and Frost, 2010; O'Connor et al., 2007; Cubrinovski et al., 2011; PEER, 2011). Thus, there continues to be interest in the geotechnical community to identify improved methods to mitigate liquefaction, particularly in proximity of existing structures, where traditional approaches relying on densification of the soil cannot be always implemented.

Both field observations and laboratory measurements indicate that the presence of plastic fines increases the liquefaction resistance of sands (e.g. Ishihara, 1993; Sancio et al., 2002; Tang et al., 2013; Yasuda

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et al., 1994; Yilmaz et al., 2004) and work by El Mohtar et al. (2013) demonstrates that if approximately 3% bentonite by dry mass of the sand can be delivered in the sand pore space, the liquefaction resistance of the sand is greatly enhanced. This effect is ascribed to the rheology of the gel-like pore fluid formed in the presence of bentonite inside the sand pores, which effectively limits the mobility of the sand grains, reducing the generation of pore pressure during cyclic loading (El Mohtar et al., 2014). However, a soil treatment method that is based on the delivery of this amount of bentonite into the sand pore space in dispersion form is faced with significant practical challenges, as 3% bentonite by mass of the sand corresponds to a concentration of clay in the pore fluid of approximately 10%. At this concentration, bentonite dispersions exhibit a gel-like structure and rheological properties (e.g. the presence of a yield stress), which do not permit their permeation in a porous medium. Thus, modification of the rheology of the dispersion is required. This modification, however, has to be reversible so that once inside the sand, the bentonite dispersion can recover the gel structure and properties that ensure its effectiveness in mitigating liquefaction.

This paper presents the results of a study that explored the use of sodium pyro-phosphate decahydrate (herein referred to as SPP) to engineer concentrated bentonite dispersions to be used in treating liquefiable soils. Phosphates are known to be effective in dispersing clays, and previous work (e.g. Goh et al., 2011; Lagaly, 1989; Lagaly and Dekany, 2013; Penner and Lagaly, 2001; Shankar et al., 2010) has shown that, through the neutralization of the positively charged sites of the clay particles, the adsorption of pyrophosphate decreases the yield stress of clay dispersions, permitting in some cases to reach Newtonian behavior. It is also established that the addition of pyrophosphate can retard the gelation process of Laponite (e.g. Martin et al., 2002; Mongondry et al., 2004), which like montmorillonite is a smectite. Results obtained by Clarke (2008) demonstrate that this occurs also in bentonite, with dosages much smaller than those required for Laponite.

The study presented in the paper relies on rheological tests that probed both the at rest and flow properties of concentrated (10% clay by total mass of the dispersion) bentonite dispersions prepared with dosages of SPP ranging from 0 to 2% by mass of the bentonite, and that were conducted from immediately after mixing to after approximately two years of aging. The tests, performed under well-controlled conditions using a state of the art rheometer, provide rheological data that are directly relevant to the performance of the bentonite dispersions in the application of interest. In particular, the data presented describe:

i) the initial structural breakdown of the dispersions due to the addition of sodium pyrophosphate that is required for the "delivery" of the bentonite in a porous medium;

ii) the ability of the dispersions to recover gel structure and "solid" like properties over time, that is critical for the bentonite to inhibit liquefaction;

iii) the small strain frequency independent response of the dispersions after the recovery of the gel structure that is relevant to the performance under earthquake loading;

iv) the effectiveness of the dispersions to resist more than one seismic event.

2. Experimental methods

2.1. Materials

Volclay CP-200, a Wyoming Na-bentonite commercialized by CETCO and intended for geotechnical applications, was used to prepare all the dispersions used in the rheological tests. While impurities present in raw bentonite are known to potentially affect rheological results, the clay was not pre-treated, with the exception of being sieved through a #200 sieve to eliminate all non clay material coarser than 75 μm that could cause blockage of the rheometer when using the cone-plate geometry (see below). The decision to test a commercial bentonite and to avoid pre-treatment procedures stemmed from the desire to use a material that was representative of one that could ultimately be used in the field.

Sodium pyrophosphate decahydrate ($Na_4P_2O_7 \cdot 10H_2O$) or SPP, with molecular weight of 446.06 g/mol was purchased from the Sigma-Aldrich Chemical Company.

Pure water with resistivity ranging between 17.8 and 18 MΩ was used to prepare all clay dispersions. This was done to ensure that the only variables controlling the rheological behavior were SPP percentage and aging time.

2.2. Sample preparation and storage

A Hamilton Beach Model 936 mixer was used to prepare all bentonite dispersions. Half the amount of water needed for the dispersions was first poured into the mixer's cup, and then bentonite was added, followed by the remaining mixing water. In the case of dispersions with SPP, the mixing water was prepared appropriately diluting concentrated solutions of SPP. The lowest speed (~11,000 RPM) available was selected for mixing the dispersions for a total duration of 20 min. Mixing was interrupted every 5 min to fold in the material adhering to the sides of the vessel and promote homogeneity of the samples. Following mixing, the dispersions were either tested or poured into 250 ml plastic containers that were sealed and stored in a cooler at 23 °C. This storage method was found to be effective in avoiding drying of the sample, as demonstrated by measurements of the clay content conducted on all samples used for the tests after two years of storage. For all dispersions these measurements show that the average values of the clay content fall between 9.4% and 10%, with no trend with SPP%, and within the range of values determined at earlier ages.

2.3. Rheological tests

All rheological tests were conducted using the Physica MCR 301 rotational rheometer, an air bearing, stress-controlled device manufactured by Anton Paar GmbH, which can also operate in strain rate controlled mode through a feedback control loop. The Physica MCR 301 is equipped with a permanent magnet synchronous drive (minimum torque = 0.1 μN m, torque resolution = 0.001 μN m), and an optical incremental encoder for measuring the shear strain (resolution < 1 μrad). It can be used to perform a variety of oscillatory and monotonic, stress-controlled, and strain-rate controlled tests including amplitude sweeps, frequency sweeps, time sweeps, rate ramps, stress ramps and creep and recovery tests. The rheometer is equipped with a Peltier temperature control system that can control the temperature in the −40 to 200 °C range. An automated computer software system is used to program the testing variables and to compute and store the experimental results.

Two different geometries (Fig. 1) were used for the tests: the coaxial cylinder geometry for the low viscosity dispersions and the cone-plate geometry for the higher viscosity dispersions (see Table 1). When using the first geometry, the dispersion was poured in the cup, and the bob was then automatically lowered into the cup to the gap position (8 mm from the bottom of the cup). When performing tests with aging up to 30 min the dispersion was poured into the coaxial cylinder cup immediately after mixing, and a thin layer of vegetable oil was poured on top of the dispersion to avoid exposure of the dispersion to the atmosphere and minimize sample evaporation. It was established through preliminary testing that the addition of the vegetable oil did not affect the rheological results. For testing at all other aging times, the dispersion was kept in the storage container until immediately before testing. No oil was used in this case. The dispersions were not stirred prior to testing to minimize disturbance, as one of the main objectives of the