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Changes of Atterberg limits and electrochemical behaviors of clays with dispersants as conditioning agents for EPB shield tunnelling

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ABSTRACT

Clay clogging frequently happens during tunnelling with an earth pressure balance (EPB) shield in clayey ground and results in local disk cutter housings. It could even completely clog shield chambers with a blocked cutterhead. Dispersants are commonly adopted as conditioning agents to reduce clay stickiness, which is related to clay consistency determined based on the Atterberg limits. This paper investigates changes of Atterberg limits of clays with dispersant content and their electrochemical mechanism on evaluating clay conditioning approach for EPB shield tunnelling. Soils consisting of bentonite, kaolin and their mixtures were conditioned respectively with two different dispersants including sodium hexametaphosphate and sodium polyacrylate. They were then tested for determining their Atterberg limits, Zeta potential and repulsive energy. The results show that the liquid limit and plasticity index decreased significantly due to the addition of the dispersants, but these decreases became less obvious with a higher dispersant content. The effect of sodium hexametaphosphate was more significant than that of sodium polyacrylate on the clays at the same dispersant content, but the latter had quicker conditioning effect. The amount of the negative charge of the clayey particles increased and the Zeta potential decreased with an increase of dispersant content. The reduction of Zeta potential induced by the sodium hexametaphosphate was greater than that induced by the sodium polyacrylate at the identical dispersant content. The decrease of Zeta potential increased the peak value of the total repulsive energy, leading to reductions of the Atterberg limits of the clays. The reduction of plasticity index leads to less water required to transform clay from "soft" to "very soft" or "liquid" region and shorter time required for the response of clay to dispersant.

1. Introduction

Earth Pressure Balance (EPB) shields have been widely adopted due to its high tunnelling efficiency and safety. However, in clayey ground, the muck easily sticks to the working parts such as cutter head, chamber bulkhead and screw conveyer, resulting in low tunnelling rate and high energy consumption. The usual approach to avoid clay clogging is to decrease the consistency by adding water and/or injecting soil conditioners into the clayey muck. Several researchers have worked on soil conditioning for EPB shield tunnelling in clayey ground. Milligan (2000) stated that dispersants, which increase the overall negative surface charge on solid particles, should be applied in clayey soils. Messerklinger et al. (2011), Zumsteg and Puzrin (2012) determined the shear strength and adhesion of clay paste conditioned with foam and dispersant through a pressurized vane shear apparatus, Hobart mortar mixer and shear plate apparatus, where an enhanced interaction mechanism was proposed by Zumsteg et al. (2013) later on. Peila et al. (2015) determined the conditioning parameters by slump tests, and the dynamic and static lateral adhesion tests were carried out to evaluate the adhesion of the conditioned soil. Heuser et al. (2012) proposed that the electro-osmosis method could be applied to reduce the adhesion of clays on the tunnel boring machines. Using a large vane device, Merritt (2005) measured the undrained shear strength of clayey paste before and after being conditioned, presenting that they were not different significantly with those obtained from the normal shear vane apparatus. Qiao (2009) studied the permeability, plastic flow, shear strength and compression of red clay conditioned with foam and analyzed the micro-mechanism of foam improving clay. These methods were much more scientific approaches than the slump testing scheme which cannot represent soil stickiness. They were also helpful to promote the

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understanding of clay conditioning from the soil mechanics standpoint. However, they have not been standardized for engineering application. Moreover, it is not convenient to conduct the tests, which leads to the result that the selection of conditioning agents and their dosage in the field remain empirical.

Clay stickiness is related to clay consistency determined from Atterberg limits (Hollmann and Thewes, 2013), which can be obtained easily with standard testing apparatus including fall cone and Casagrande cup. The liquid limit represents the water content limit of clay between flowable and plastic states, while the plastic limit defines the water content limit of clay between plastic and hard states. With the actual water content, the soil consistency can be evaluated. Additionally, the liquid and plastic limits can indirectly show the shear strength of clay. Undrained shear strengths of a soil at the liquid limit and plastic limit can be considered to be about 1.7 kPa and 110 kPa, respectively (e.g. Sherwood and Ryley, 1970; Zhou and Zhang, 1985). So Atterberg limits determined by fall cone method reflect the undrained shear strength of soil (Feng, 2002). The reduction of liquid limit and plastic limit represents that the water content of soil with undrained shear strength of 1.7 kPa and 110 kPa reduces. With identical water contents, the soil with lower liquid and plastic limits has lower undrained shear strength. In other words, the reductions of liquid and plastic limits indicate the reduction of undrained shear strength, and vice versa.

So far, few researchers have studied the effect of conditioning agent on the Atterberg limits of conditioned soil. Merritt (2005) investigated the variation of liquid and plastic limits of kaolin due to the addition of partially hydrolysed polyacrylamide (PHPA) polymer, indicating that the liquid and plastic limits of clays increased when being reconstituted with PHPA polymer solutions. Spagnoli (2011) studied the effect of fluid dielectric constant on liquid limit, showing a decrease in the liquid limit for Na-smectite and no change of the liquid limit for the illite and kaolinite with a decrease in the dielectric constant of the pore medium. Maines and Gajo (2007) investigated the influence of solution concentration on the liquid limit of natural clay, indicating that the liquid limit decreased with the increase of solution concentration. Ye et al. (2017) determined the effect of foam injection ratio on the Atterberg limits of the muck developed from the EPB shield passing through the argillaceous siltstone. The study shows that the Atterberg limits decreased after the muck was conditioned with foam. Although some findings on the variation of Atterberg limits due to soil conditioning have been presented, there are not comprehensive research results revealing the effects of dispersant on Atterberg limits and their electrochemical mechanism.

This paper studies changes of the Atterberg limits of clays due to addition of dispersants and their electrochemical mechanism. For investigating the electrochemical mechanism of dispersants, the Zeta potential was tested on the solutions of the clays respectively conditioned with the dispersants, and the repulsive energy among soil particles was calculated based on the DLVO (Derjaguin-Landau-Verwey-Overbee) theory.

2. Testing material and approaches

2.1. Soils and dispersants tested

The tested soils included sodium bentonite, kaolin and their mixtures. The effect of soil conditioners are mainly based on the predominant clay minerals. The minerals of sodium bentonite and kaolin were tested by X-ray diffraction (XRD), listed in Tables 1 and 2. The sodium bentonite includes Na-montmorillonite, Ca-montmorillonite, soda feldspar and a small amount of microcline, quartz and calcite. The minerals of kaolin are kaolinite, muscovite and quartz. The dispersants used are sodium hexametaphosphate and sodium polyacrylate. The major component of granular sodium hexametaphosphate is sodium meta polyphosphate. Liquid sodium polyacrylate and distilled water were used in these tests. The solution concentrations were made up 10% and 25%, respectively for sodium hexametaphosphate and sodium polyacrylate. The dispersant content was defined as the ratio of dispersant mass to dry soil mass. A summary of the tested specimens can be found in Table 3.

Table 1
Mineral composition of the sodium bentonite.

Mineral name	Chemical formula	Mass percentage (%)
Na-montmorillonite	$Na_{0.3}(Al,Mg)_2Si_4O_{10}(OH)_2$	48.8
Ca-montmorillonite	$Ca_{0.2}(Al,Mg)_2Si_4O_{10}(OH)_2$	14.1
Soda feldspar	$NaAlSi_3O_8$	28.3
Microcline	$(K_{0.95}Na_{0.05})\ (AlSi_3O_8)$	5.5
Quartz	SiO_2	2.5
Calcite	$CaCO_3$	0.8

Table 2
Mineral composition of the kaolin.

Mineral name	Chemical formula	Mass percentage (%)
Kaolinite	$Al_2(Si_2O_5)(OH)_4$	83.7
Muscovite	$KAl_{2.2}(Si_3Al)_{0.975}O_{10}((OH)_{1.72}O_{0.28})$	14.0
Quartz	SiO_2	2.3

2.2. Testing approaches

2.2.1. Determination of the Atterberg limits

The fall cone approach was adopted herein to measure the Atterberg limits of the soils with dispersants. The soils were mixed with a certain amount of distilled water and then stored in a sealed bag for 24 h. The Atterberg limits were determined after the wet soil specimens were mixed respectively with each of the two dispersants. The shield machine may stay in tunnelling state or be stopped for construction need in the field. Each tunnelling cycle of the EPB shield normally requires a time span ranging from several tens of minutes to several hours, depending on the tunnelling efficiency, and engineering geologies, etc. The soil muck mixed with soil conditioner may stay in the shield chamber for about 30 min per tunnelling cycle. Moreover, the soil muck mixed with conditioning agent will stay for a longer time, if the EPB shield is stopped for handling field problems. To study the time effect of soil conditioning, the Atterberg limits of the sodium bentonite mixed with the sodium hexametaphosphate and sodium polyacrylate were tested respectively after remaining there for 0 h, 5 h, 10 h, 24 h and 48 h.

2.2.2. Determination of the Zeta potential

The negatively charged clay particles attract metal cations on their surface through Van der Waals force and electrostatic attraction force to keep charge in balance. There are double absorption layers including Stern and diffusion ones (Fig. 1). Only metal cations exist in the Stern layer while both metal cations and anions distribute in the diffusion layer. The metal cation concentration decreases with the increasing distance away from the particle surface. When the clay particle moves in the electric field, a shear plane will appear in the double layers, and the potential there is called as the Zeta potential. The Zeta potentials of the clay particles were measured by the Malvern Zetasizer Nano ZS90. Owing to the poor light transmittance of soil at the liquid limit and plastic limit, it is difficult to measure its Zeta potential at those water contents. Therefore, the clay pastes of different soil materials were diluted with the distilled water and the water contents of all soil specimens were kept to be same, which included the water in the soil and that using for making the dispersant solutions. For each testing specimen, the ratio of the soil mass to the total of the water mass was 1:1000. The specimens were mixed completely and kept there for 5 min.