Experimental investigation on viscoplastic parameters of conditioned sands in earth pressure balance shield tunneling

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1. Introduction

The earth pressure balance (EPB) shield tunneling machine is the most common mechanized tunneling equipment in soft ground. However, natural soils do not usually have ideal properties (e.g., low inner friction, good plastic flow characteristics, low penetrability, and compressibility [1, 2]) when excavated, especially, under unfavorable geological conditions, (e.g., sand ground). To improve the operation of EPB shield machines by modifying the properties of the excavated soils, conditioning agents such as foams, bentonite slurry, and polymers should be injected ahead of the cutterhead, into the working chamber, and along the screw conveyor, to mix with the original soil during the excavating process [3]. Satisfactory conditioning treatment is very important for the pressure balance control between the working chamber and the ground at the excavation face, which is the key factor of efficient excavation.

Soil viscoplastic behavior has been reported in several studies (Day and Holmgren [4]; McMurdie and Day [5]; Ghavami et al. [6]; Ghezzehei [7]). The soil flow behavior is governed by general theory of rheology [8].

Viscoplastic fluid is a non-Newtonian fluid. A non-

Newtonian fluid is any fluid that does not obey the Newtonian relationship (shear stress is linearly proportional to shear strain rate) between the shear stress and shear rate [9]. Viscoplastic fluids behave similarly to solids when the shear stress is less than the yield stress; however, it will flow similarly to a regular fluid when yield stress is exceeded [10].

Three models are commonly used for viscoplastic fluids: Bingham, Herschel-Bulkley, and Casson. Bingham fluids combine the behaviors of rigid solids and non-Newtonian viscous liquids by differentiating between physical regions where these descriptions hold according to criteria based on the stress level of the material. Here, regions of rigid solid and plastic fluid behavior are separated by von Mises’ yield criteria [11]. The Bingham model is expressed as

\[
\tau = \tau_y + \mu \dot{\gamma} \quad \text{for} \quad |\dot{\gamma}| < \tau_y \\
\dot{\gamma} = 0 \quad \text{for} \quad |\dot{\gamma}| > \tau_y
\]

where \(\tau\) is shear stress (Pa), \(\dot{\gamma}\) is shear rate (s\(^{-1}\)), \(\tau_y\) is yield stress (Pa), and \(\mu\) is the viscosity coefficient or plastic viscosity (Pa·s).

Thus, to optimize the working efficiency of an EPB shield machine and compare various conditioning products, quantifying the plastic flow characteristics of the conditioned soil is necessary. Despite its great importance, very little progress on soil conditioning has been achieved, particularly for cohe-
The conditioning criterion is usually defined on the basis of a trial-and-error procedure directly developed on job sites. Most previously reported studies on the plastic flow characteristics of conditioned soil are based on the slump tests [1, 12-17] or the scale models for EPB excavation systems [2, 15, 20-24].

The slump test, which determines the rheological behavior of fresh concrete, has been widely used to evaluate the conditioned soil quality (Quebaud et al. [1]; Williamson et al. [12]; Jancséc et al. [13]; Boone et al. [14]; Vinai et al. [15]; Peila et al. [16]; Thewes et al. [17]). Several authors have suggested that a slump value in the range of 100–200 mm is necessary to provide a mixture with the optimum plastic flow characteristics in an EPB shield machine. This type of test has some advantages, such as operating easily and giving an overall index on the behavior of the conditioned soil. The slump value is well correlated with the yield stress; however, it is not a very good response to the effect of the stain rate on the stress–strain behavior of the conditioned soil [18, 19]. The slump test can usually only be carried out at atmospheric pressure. However, in practice, the soils at the face and in the working chamber are under variable pressures, depending on circumstance. Therefore, this cannot always accurately simulate the flow behavior of the conditioned soil under confining pressure in the working chamber.

Furthermore, a laboratory device that simulates the extraction of the conditioned soil from a pressurized tank with a screw conveyor has been used by several authors to study the plastic flow characteristics of the conditioned soil (Merritt and Mair [2], Vinai et al. [15], Bezuijen and Schaminee [20, 21], Yoshikawa [22], Mair et al. [23], Peila et al. [24]). This method is able to check the ability of soil to control the pressure both in the bulk chamber and along the screw conveyor. Moreover, it can obtain the screw torque and the ratio between the mass of the material extracted from the screw conveyor and the theoretical mass. Although the effects of the dynamic process and confining pressure could be considered in this method, the plastic flow characteristics of conditioned soils are not quantified from the fluid mechanism. Due to the complex experimental process and much experimental work, this method is not convenient for comparisons among the various conditioning schemes.

However, the studies mentioned above suffer from some limitations that mainly concern the inadequate interpretation of rate effect and effect of confining pressure on soil flow characteristics. According to extensive tunneling studies, soils at the face and in the working chamber undergo variable pressures depending on circumstance. In addition, the excavating process is dynamic. The flow characteristics of conditioned soil could be affected by rate effect and by confining pressure. Furthermore, studies on soil flow characteristics based on the viewpoint of non-Newtonian fluid have already been conducted in other fields (e.g., tillage, fresh concrete, and debris flow, among others) [25-27]. The rheological models and parameters obtained were used to simulate soil flow and obtain flow field distributions using computational fluid dynamics (CFD). Improving EPB technology and the real tunneling procedure with quantification research based on the rheology theory for the plastic flow characteristics of the conditioned soils is very significant.

The main motive of the current study is to develop a soil rheometer, and to determine the viscoplastic parameters of conditioned soil. This quantitative method, which would be a valuable tool for defining the soil conditioning parameters in EPB shield tunneling, could be used to compare various conditioning products and determine the optimal amount of conditioning agents. Moreover, by simulating the soil flow in working chambers and along the screw conveyor with the CFD program, the results could provide requisite data to obtain distributions of the velocity field and the pressure field, as well as the torques of cutterhead and screw conveyor.

2. Description of the experimental device

To evaluate the viscoplastic parameters of conditioned soil, a motorized soil rotational viscometer was developed. The device is able measure the viscosity coefficient and yield stress of the conditioned soils. Considering two main factors (shearing gap and wall-slip effect [28]), the vane type was chosen. The device works on the principle of torsional shear applied to a standard vane with controlled strain rate. Moreover, considering circumstances wherein the soil was conditioned during the EPBS excavation process, the device must be capable of achieving undrained conditions and different confining pressure levels in the measurement process.

2.1 Design criteria

The final form of the soil failure surface would be a cylinder that depends on the length and diameter of the vane. The distribution of shear stress around the soil failure surface is assumed to be uniform on the top, bottom, and lateral surfaces. The geometric size of the vane is standardized in terms of ASTM (D2573–72) [29]. Thus, the expression of shear stress is written as

\[ \tau = \frac{0.86M}{\pi d^3} \]  

(3)

where M is the maximum torque (Nm), and d is the vane blade diameter (m).

The confining pressure is applied to soil by the gasbag at the bottom of the test container. Due to anisotropy of soil, the normal pressures of soil are unequal between the vertical and the horizontal. The relationship is given as

\[ \sigma_{\text{top}} = \sigma_{\text{bottom}} = \frac{\sigma_{\text{normal}}}{k} \]

(4)
where $\sigma_{\text{top}}$ is the soil’s normal pressure on the top surface of the failure cylinder (Pa), $\sigma_{\text{bottom}}$ is the soil’s normal pressure on the bottom surface of the failure cylinder (Pa), $\sigma_{\text{lateral}}$ is the soil’s normal pressure on the lateral surface of the failure cylinder (Pa), and $k$ is the lateral pressure coefficient.

The relationship between normal pressure and shear stress is known by Coulomb’s law:

$$\tau = \sigma \tan \varphi + c$$

(5)

where cohesion $c$ could be neglected for the sand.

$$\tau_{\text{top}} = \tau_{\text{bottom}} = \frac{\tau_{\text{lateral}}}{k}$$

(6)

Eq. (3) could be modified; thus, the equivalent shear stress is obtained as

$$\tau = \frac{M}{\left(\frac{1}{6k} + 1\right)\pi d^3}.$$  

(7)

The expression of the shear rate is written as

$$\dot{\gamma} = \frac{2\pi n_{\text{vane}}}{60} \times \frac{D^2}{D^2 - d^2}$$

(8)

where $n_{\text{vane}}$ is the vane’s rotational speed (RPM), and $d$ is the internal diameter of the container (m).

### 2.2 Description of the device

The laboratory device (Figs. 1 and 2) consists of a test container, a driveline, a torque sensor, a shearing vane, a loading system, an earth pressure sensor, and a data acquisition system.

The test container consists of an upper cover and a bottom container. The diameter of the upper cover is 395 mm and the thickness is 26 mm. The driveline is supported, and a setting hole for the earth pressure sensor is on the upper cover. The outer diameter of the bottom container is 273 mm and the thickness is 8 mm. The volume of the bottom container is 10 L. The upper cover and the bottom container are connected by 12 bolts, and sealed by an O-ring.

The driveline consists of a motor (JSCC Automation Co., Ltd., Model 80GK180RT), two speed reducers (SHLP Precision Machinery Co., Ltd., Model AB90-25-S2-P2), a torque sensor, a coupler, and a shearing vane. The driveline is mounted on the upper cover of the pressure container. Two speed reducers reduce the motor speed close to the required vane speed, and transmit the rotary motion of the motor to the shearing vane. A speed governor controls the speed of the motor for driving the vane at different shear rates.

Reducer 1 has a speed ratio of 1:180 and Reducer 2 has speed ratio of 1:25. The motor, Reducer 1, and Reducer 2 are connected directly in sequence. Thus, the speed reduction from the motor to the vane is shown as

$$n_{\text{vane}} = \frac{1}{4500} n_{\text{motor}}$$

(9)

where $n_{\text{vane}}$ is the vane speed (RPM), and $n_{\text{motor}}$ is the motor speed (RPM).

For the recommended range of vane rotation of 6° to 12° per minute, the RPM of the vane should be in the range of 1/50 to 1/33. Thus, for a motor speed of 150 RPM, the vane speed obtained in the designed driveline is as follows:

$$n_{\text{vane}} = 150 \times \frac{1}{4500} = 1/30.$$  

(10)

The required torque when vane shears the soil is measured by a torque sensor with four rings (GB-DTS100). One end of the torque sensor is connected to an output shaft of Reducer2 by a coupler. The other end is connected to the vane spindle. The vane spindle and the upper cover of the test container are sealed by a lip seal.
The shearing vane is made in accordance with a standard size specified by ASTM standards. The diameter of the vane spindle is 12.5 mm and its length is 114.3 mm. The end of the spindle is protruded to keep the vanes in the slots.

The loading system is made up of a gasbag, an air compressor (Leopard Air Compressor Manufacturing Co., Ltd., Model ZB-0.10/8-LBDF), and two earth pressure sensors (Kyowa Electronic Instruments Co., Ltd., Model BER-A-17S). The gasbag is placed at the bottom of the test container, and is inflated by an air compressor. The maximum inflated volume of the gasbag is 1 L. The maximum pressure provided by the air compressor is 800 kPa. The measuring range of earth pressure sensor is 0–500 kPa. One sensor is mounted on the upper cover, whereas the other is mounted on the lateral wall of the bottom container. An O-ring seals the opening between the earth pressure sensor and the setting hole.

The data acquisition (DAQ) system consists of an industry scopemeter (Fluke Co., Ltd., Model Fluke 123) and a computer. The data is collected by an industry scopemeter and monitored on the computer screen.

2.3 Working features

The working conditions of conditioned soil in the working chamber and the screw conveyor of EPB shield machines are considered in the design of the device. In addition, the test method in other fields can also be used as a reference. The function and characteristic are summarized as follows:

1. The device can measure viscoplastic parameters of the tested material under undrained condition by sealing;
2. The device is capable of investigating the effect of the confining pressure on viscoplastic parameters of the tested material by loading system;
3. The confining pressure of the tested material and the lateral pressure coefficient can be determined by the measured values of earth pressure sensors and the inflated pressure of gasbag. Thus, more accurate shear stress can be obtained.

3. Sample preparation and test procedure

3.1 Sample preparation

Sand ground commonly belongs to an unfavorable geological condition in EPB tunneling. Better plastic flow characteristics obtained by appropriate conditioning treatment are subjects of extensive concern. Thus, conditioned sand of EPB shield machine has been chosen as the research object in the current paper. Conditioned sand is a multiphase material composed of sand particles, water, and additives such as foam and bentonite slurry. For comparison in the laboratory, three tested samples were prepared in accordance with different conditioning treatments commonly used in practical EPB tunneling. In the current research, the difference between the conditioning treatments is mainly the different foam injection ratio (FIR, the volume ratio of mixing foam with Soil) values of the conditioned sands under the same precompression pressure.

3.1.1 Characteristics of tested sand

The untreated sand came from a section of the metro. The moisture content (gravimetric) was between 4.6% and 20.4%. The average natural density was 1.55 g/cm³. The grain size distribution of the original sand is shown in Fig. 3. The tested samples were prepared in accordance with an initial moisture content of 7% and an initial bulk density of 1.55 g/cm³.

3.1.2 Use of foaming device

The function of the foam is to reduce the surface contact tension of soil particles, weaken the connected force of water between soil particles, and lubricate the soil. The foam was generated by impacting foaming additive with a concentration of 5% (the ratio of the mass of additive to the mass of foaming solution) with the compressed air of 200 kPa. The expansion ratio (the ratio of the measured volume of foam to the volume of the liquid required for its production) was 6. The drainage time (the time required to drain out 50% volume of the foam) of the foam was 40 min. The foam property depends on the time; hence, the foam should be immediately placed into the reproduced sand. The foaming device is shown in Fig. 4.

3.1.3 Bentonite slurry

Bentonite is a very important and commonly used soil-conditioning agent. The bentonite used is a sodium montmorillonite-type that is capable of swelling to approximately ten times its original volume. Greater surface area is provided, into which water molecules may be absorbed. In tunneling applications, the bentonite slurry dosage should be sufficient to fill the theoretical porosity of the sand more than once to create the impermeable “filter cake” [30]. In addition, it
should enhance the cohesion of the conditioned sand. The water was treated with caustic soda (NaOH) to achieve pH 8 for better mixing. The bentonite powder and water with a volume ratio of 1:6 were mixed to produce the slurry. The slurry should be used after 24 h.

3.1.4 Mixing and precompression

Referring to the practical tunneling of the EPB shield machine, the volume of the additives was calculated according to the volume of the untreated sand. The sand and the additives were mixed to a homogeneous plastic soil paste. Three samples of conditioned sands were prepared based on different FIR values, with the same value of the bentonite slurry injection ratio. Slump test was performed for each sample. The final slumped shapes of the three samples are shown in Fig. 5. The correlated parameters of all samples are listed in Table 1.

3.2 Test procedure

Due to the mixing of additives in the working chamber, the excavated soil became a viscoplastic in the EPB shield tunneling. The mixture was discharged by the screw conveyor from the working chamber to the discharge outlet. In this process, the pressure dissipated from earth pressure to atmospheric pressure. Due to the viscoplastic properties of conditioned sands, the sand had different characteristics between loading and unloading. Thus, this should be considered in the test procedure. First, pre-compression pressure of 400 kPa was applied to each tested sample for approximately 10 min. Second, the different test conditions were performed by changing different pressure levels of the gasbag and the vane speeds. The gasbag had five pressure levels: 0, 100, 200, 300, and 400 kPa. The confining pressure level decreased from 400 to 0 kPa. Under each pressure level, seven vane speeds were predetermined: 1/3.4, 1/4.1, 1/5, 1/6.4, 1/9, 1/15, and 1/30 RPM. The data logger recorded the time history curve of the vane torque and the confining pressure.

4. Results and discussion

4.1 Viscoplastic parameters of conditioned sands

The test device was able to obtain the time history curve of vane torque under different test conditions. This curve was converted into time history curve of shear stress by Eq. (5). Fig. 6 shows the typical time history curve of shear stress for tested sample F3 with a confining pressure of 400 kPa and vane speed of 1/3.4 RPM. The steadily increasing displacement applied increasing shear force on the soil at the peripheral region of the vane. Soil sustained the applied torque until the induced stress reached its maximum value. The shear stress at the moment of soil failure is defined as the peak shear strength. Typically, a loss of strength with continuous shear displacement was observed. Strength with no further strength loss and with continuous displacement is called the residual strength. The conditioned soil in the working chamber and along the screw conveyor of EPB shield machine was in a continuous-flow state; hence, the residual strength was selected for shearing curve.

Fig. 8 shows that the apparent viscosity (the ratio of shear stress to shear rate) of the conditioned sands decreased with the increase of the shear rate at different confining pressure levels for the three tested samples. This illustrates the shear-thinning properties of non-Newtonian fluid. The relationship between the apparent viscosity and the shear rate was influ-

| Table 1. Characteristics of test samples. |
|-------------------------------|---|---|---|
| Sample number | F1 | F2 | F3 |
| Initial moisture content (%) | 7 | 7 | 7 |
| Initial bulk density (g/cm³) | 1.55 | 1.55 | 1.55 |
| Foam injection ratio (%) | 27 | 23 | 19 |
| Bentonite slurry injection ratio (%) | 14.3 | 14.3 | 14.3 |
| Final bulk density (g/cm³) | 1.65 | 1.69 | 1.74 |
| Final moisture content (%) | 15.3 | 15 | 14.6 |
| Slump value (cm) | 15 | 12 | 9 |

(a)                  (b)                 (c)
Fig. 5. Final shapes of all samples in slump test: (a) F1; (b) F2; (c) F3.

Fig. 6. Time history curve of shear stress.

Under each pressure level, seven vane speeds were predetermined: 1/3.4, 1/4.1, 1/5, 1/6.4, 1/9, 1/15, and 1/30 RPM. The data logger recorded the time history curve of the vane torque and the confining pressure.
enced by confining pressure. In the same shear rate, the apparent viscosity increased with the increase of the confining pressure. Similar trends were found in the results when comparing the three samples, except for slight differences.

The relationships between shear stress and shear rate under different confining pressure levels for all tested samples were fitted to the Bingham fluid model (Eq. (1)) using professional statistical software Origin version 8.0. Using this method, the viscosity coefficient and yield stress could be obtained for different test conditions (Table 2). The values of viscosity coefficient and yield stress for all test conditions were found to be 9.1–53.5 kPa·s and 1.5–10.2 kPa, respectively.

4.2 Effect of confining pressure and FIR on viscoplastic parameters of conditioned sands

From the above results, the viscosity coefficient and yield stress of conditioned sands were clearly affected by the con-
fining pressure and FIR. The effects of the confining pressure and FIR on the viscosity coefficient are illustrated in Fig. 9. Notably, the viscosity coefficient increases linearly with the increase of the confining pressure for all tested samples. At the microscopic scale, this increase is due to the fact that the volume of pore spaces would reduce with an increasing confining pressure and the relative increasing content of fine particles would enhance cohesion effect between soil particles.

In addition, the increasing FIR is accompanied by a decreasing viscosity coefficient. The increasing FIR would increase the volume of pore spaces between soil particles on account of the swelling effect and reduce the solid–solid interactions, thereby decreasing the viscosity coefficient.

Fig. 10 illustrates the effects of the confining pressure and FIR on yield stress. Yield stress was found to increase linearly with the increase of the confining pressure, and to decrease slightly with the increase of FIR. This may be due to the fact that the increasing confining pressure would reduce the volume of pore spaces between soil particles. This would then cause more solid–solid contact and a greater solid–solid friction when the relative motion between the soils particles occurs. Hence, the yield stress increases. Moreover, the increasing FIR would enhance lubrication between soil particles and reduce the solid–solid interactions.

5. Conclusions
The following conclusions can be drawn from the experiments on conditioned sands by EPB shield tunneling:

(1) Conditioned sands in the working chamber and the screw conveyor of the EPB shield machine exhibited the characteristics of viscoplastic fluid and corresponded with the Bingham fluid model. The values of the viscosity coefficient and yield stress of conditioned sands were found to be in the range of 9.1–53.5 kPa·s and 1.5–10.2 kPa, respectively.

(2) Conditioned sands showed shear-thinning properties of non-Newtonian fluid. In the same shear rate, the apparent viscosity increased with the increase of confining pressure.

(3) The viscosity coefficient and the yield stress of conditioned sands increased with the increase of confining pressure and decreased with the increase of FIR.

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References
[8] C. P. Gupta and A. C. Pandya, Rheological behavior of soil...


Qinglin Meng is currently a Ph.D candidate at the School of Mechanical Engineering, Dalian University of Technology, China. He is currently working on the numerical simulation of tunneling.