KSCE Journal of Civil Engineering (2020) 24(6):1914-1923
DOI 10.1007/s12205-020-2035-5

pISSN 1226-7988, eISSN 1976-3808
www.springer.com/12205

Tunnel Engineering

Experimental Investigation on Rheological Behaviors of Bentonite- and CMC-Conditioned Sands

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ARTICLE HISTORY

Received 11 November 2019
Revised 2 February 2020
Accepted 2 March 2020
Published Online 28 April 2020

KEYWORDS

EPB shield
Conditioned sand
Rheological models
Thixotropy
Flow curve
Rheological transition

ABSTRACT

The rheological properties of sands conditioned with different conditioners and injection ratios were examined. The conditioned sands were prepared with a 40% and 60% volume injection ratio of a bentonite slurry or a carboxymethyl cellulose (CMC) solution. The experiment results show that the tested bentonite-conditioned sand exhibits the characteristics of a Herschel-Bulkley fluid at shear rates in the range of 0-10 s^{-1}, while the CMC-conditioned sand conforms to the power law model. The flow curves of all of the samples show a marked shear-thinning behavior. They also indicated that the existence of a yield stress (τ_0) depends only on the rheological behavior of the conditioner and that the yield stress (τ_0, if present) and the plastic viscosity (μ_p) increase with an increase in the volumetric concentration of the sand. Furthermore, to characterize the thixotropy of the conditioned sand, experiments were carried out by using three loading histories with shear rate accelerations of 0.1, 0.2 and 0.4 s^{-1}/s. In the measured results, the thixotropy of the conditioned sand is heavily dependent on the recent flow history. Based on the experimental data, a simple thixotropic prediction model was developed to analyze and predict the transient flow curves of bentonite-conditioned sands.

1. Introduction

Earth pressure balanced (EPB) shield tunneling has become the first choice for urban tunneling in recent years due to its high adaptability for different ground conditions. The main challenges faced by EPB shield machines in cohesionless soils are, on the one hand, how to balance the pressure of the shield-tunneling face, and on the other hand how to reduce the frictional forces, tool wear and power consumption. This is a common phenomenon in shield tunneling, for example, in the subway construction in Shenzhen, China, the shield is completely driven in the sand layer with cohesion of 0 (Jin et al., 2018). Soil conditioning is an effective way to cope with these challenges by injecting conditioners (foam, polymers, bentonite slurry and/or water) into the tunnel face, the bulk chamber and the screw conveyor to transform the excavated sand into a plastic and "pulpy" medium. Usually, the choice of conditioner type and the optimal conditioning depends heavily on laboratory tests, including the slump test (Vinai et al., 2008; Peila et al., 2009; Thewes and Budach, 2010), the shear test (Zumsteg et al., 2012; Mori et al., 2018; Yang et al., 2018), the penetration test (Borio and Peila, 2010; Huang et al., 2019; Kim et al., 2019) and the screw conveyor test (Merritt and Mair, 2006; Rivas et al., 2009). Although a great deal of work has been done to explore the feasibility and applicability of conditioned sand, few studies have been found on the rheological behavior of this plastic paste, which is soft, consistent and flowable (Galli and Thewes, 2019). Therefore, an investigation into this type of behavior of conditioned sand with indoor tests is very urgently needed, and a quantitative description of the flow behavior of the muck is of great engineering significance.

The two main conditioners for sand layers, bentonite slurries and polymer solutions, are also widely used in other industries such as agriculture, light industry, cosmetics and pharmaceuticals due to their swelling, colloidal and rheological properties. Kök et al. (2000) found that the rheology of bentonite suspensions was well fitted with the yield pseudoplastic behavior represented by the Herschel-Bulkley and Robertson-Stiff models. In engineering practice, a bentonite slurry is also often simplified using a Bingham model for ease of calculations (Merrill et al., 2017). Benyounes and Benmounah (2015) indicate that rheological

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parameters of bentonite slurry vary as a function of the concentration of electrolyte due to the structural change of the material. Pinho and Whitelaw (1990) performed rheological testing of sodium carboxymethyl cellulose (CMC) solutions with four concentrations and found that the solutions were non-Newtonian and best fit a power law model over Reynolds numbers domain of 240 – 111,000. As a typical representative of high-molecular-weight polymer conditioners, CMC solutions have been reported by other authors that exhibit a power law behavior over a shear rate range of 0 – 1,000 s^{-1} (Benchabane and Bekkour, 2008). Furthermore, some studies have explored the rheological behavior of the mixed solution of the two materials. It has been shown that the presence of CMC in the bentonite slurry has helped to remove the yield stress and to increase the viscosity of the mixture (Benyounes et al., 2010). Mesboua et al. (2018) study the influence of bentonite contents on the physical and rheological parameters on the cement grouts. For non-Newtonian fluids like bentonite slurries and polymer solutions, the relationship between shear stress $\boldsymbol{\tau}$ and strain rate $\boldsymbol{D}$ can be written as:

$$\boldsymbol{\tau} = \mu(\dot{\gamma})\boldsymbol{D} \quad (1)$$

$$\boldsymbol{D} = \frac{1}{2}(\nabla \boldsymbol{u} + \nabla \boldsymbol{u}^T) \quad (2)$$

where viscosity μ is a function of shear rate $\dot{\gamma}$, and $\boldsymbol{u}$ is velocity tensor. If a material can be regarded as a Herschel-Bulkley fluid, the numerical modeling process for it will be easy by using Eq. (3):

$$\begin{cases} \boldsymbol{\tau} = \left(\frac{\tau_0}{|\dot{\gamma}|} + \mu_p|\dot{\gamma}|^{n-1}\right)\boldsymbol{D} & \tau > \tau_0 \\ \dot{\gamma} = 0 & \tau \leq \tau_0 \end{cases} \quad (3)$$

Where,

n = Flow index

τ_0 = Yield stress

μ_p = A Parameter related to viscosity

Power law model is a special case of Herschel-Bulkley model when τ_0 is 0.

As a solid-fluid two-phase body in which most of the volume is occupied by insoluble solids, it is not known whether the conditioned sand can conform to a liquid rheological model due to its currently unclear rheological behavior. Some rheological tests have been carried out on viscous bodies containing coarse particles similar to the muck. First, the rheological behaviors of some naturally occurring viscous materials, such as silt, mudflows and sediment, have been noted and tested for some engineering purposes. Jeong et al. (2010) stated that the rheological properties of fine-grained sediments depend on index properties and salinity. Both the Herschel-Bulkley model and the Carreau model were able to describe the rheological behaviors of dense cohesive sediments that were collected from the mouth of the Yangtze River, the shoal of the Hangzhou Bay, and Yangcheng Lake in China (Yang et al., 2014). Xu and Huhe (2016) conducted experimental research on the Lianyungang mudflows with a mud volume concentration (i.e., the ratio of mud mass concentration to sediment grains density) range of 0.058 to 0.179, and a Dual-Herschel-Bulkley model described by six parameters base on two different regions of the shear rates was developed for flow curve analysis. In addition, some studies have focused on the rheological behaviors of artificial materials, such as mortar and self-compacting concrete, to develop a deeper understanding. Kaci et al. (2011), using a stress-controlled shear rheometer, found that bentonite can enhance mortar creep resistance, including an increase in the yield stress recovered after shear, and a reduction in the characteristic time for yield stress recovery. Cordeiro et al. (2016) reported that the Herschel-Bulkley model adequately fits the rheological data of concrete made with crushed granite fine aggregate. Hong et al. (2016) found that the Herschel-Bulkley model can be used to effectively predict the rheological behavior of kaolin-sand mixtures over a pH range of 4 – 11, a temperature range of 20 – 50ºC, and a solids concentration range of 5 – 50%. The kaolin-sand mixtures exhibited a shear thickening behavior, with higher concentrations leading to greater viscosity and shear stress values. In addition, the accuracy of the model predictions is reduced when the solid concentrations (i.e., the ratio of solid mass to total mass of mixture) are greater than 50%.

Thus, there is still a lack of research on the rheological behavior of conditioned sand with a volume fraction of solid particles (i.e. the ratio of solid particle volume to total volume of conditioned sand) exceeding 50%. Moreover, it is also urgent to find a reliable rheological testing method for "plastic paste" muck materials that are similar to conditioned sand. To identify a rheological model of conditioned sand, rheological tests were performed on a rheometer (R/S+, Brookfield, USA) with stress-controlled and strain-controlled modes. The rheological behaviors of the two typical conditioners (a Na-bentonite slurry and a CMC solution) and sand were investigated based on multiple sets of different injection ratios. Furthermore, based on the test results, the intrinsic reasons for the thixotropy of the conditioned sands were discussed as well, and a simple thixotropic prediction model was established. Thixotropy is a reversible phenomenon, representing the time dependency of fluid viscosity or shear stress.

2. Materials and Methods

2.1 Experimental Materials

In this study, China's ISO standard sand was chosen as the soil sample to be conditioned. As depicted in Fig. 1, the grain size of the ISO standard sand is between 0.075 mm and 2 mm, which precisely meets the particle size requirements of the rheological test. The silica (SiO_2) content of the sand is more than 96%, and the clay content (including the soluble salts) does not exceed 0.2%.

A Na-bentonite slurry and a carboxymethyl cellulose (CMC) aqueous solution were selected as the two kinds of conditioners. These are commonly used for water shutoff in earth pressure balance (EPB) shield tunneling. The Na-bentonite used in this

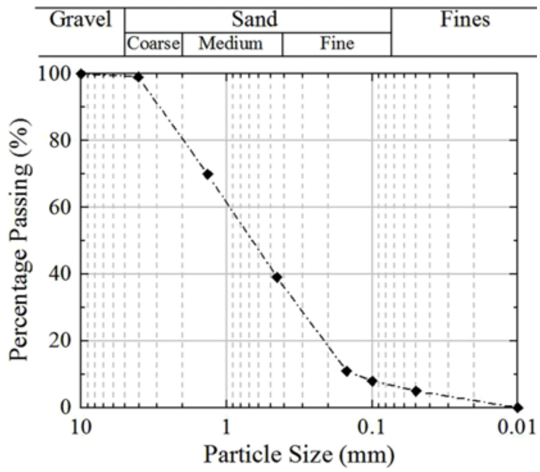

Fig. 1. Grain Size Distributions of the ISO Standard Sand

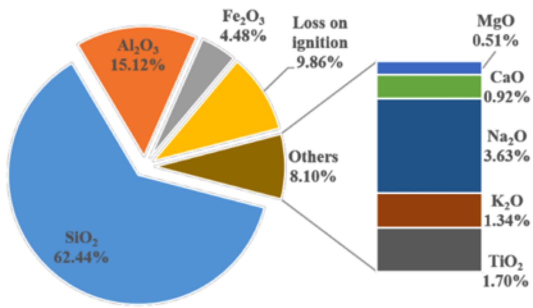

Fig. 2. Chemical Composition (w/w%) of the Bentonite Sample

test was produced in Henan Province, China. It contains approximately 57% Na-montmorillonite, 21% illite-kaolinite, and small amounts of quartz, calcite and plagioclase. The chemical composition of bentonite sample is shown in Fig. 2. Furthermore, it has an expansion index (EI) of approximately 22 ml/g, a pH value of 9.1, and a two-hour water absorption value of 270%. As a representative cellulosic polymer, CMC is widely used as a binder and thickener in industry. In EPB shield tunneling, CMC is used as a conditioner to deal with the water in a water-rich sand layer due to its high viscosity. This high viscosity allows the CMC to have the ability to bind sand grains together and improve the flow of the sand, thus ensuring good water-plugging in water-rich sands. To meet the engineering construction requirements as much as possible, an industrial grade product with a purity of 85%, a 0.6 degree of substitution, and an aqueous solution pH of 6.0 to 8.5 at 25°C was prepared as the CMC material. The CMC used has a degree of substitution varying between 0.4 and 0.6, and its molecular weight is about 200,000 g/mol.

In actual operation, both the bentonite and the CMC need to be preformed into a slurry or an aqueous solution. The bentonite slurry was prepared in a mass ratio of bentonite to deionized water of 1:4, which is a suitable ratio for sand conditioning according to the viscosity test results. Similarly, a CMC amount of 1.5% of the solution mass is a suitable ratio. A 5 min agitation at 100 rpm was applied to the mixtures of bentonite or CMC and deionized water that was followed by a 48 h dissolution period for complete homogenization.

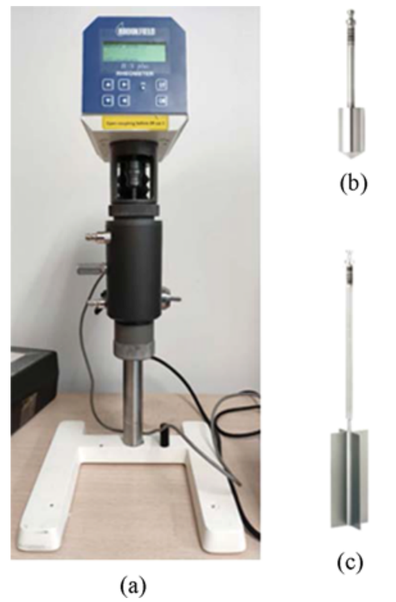

Fig. 3. R/S+ Rheometer and Two Kinds of Measuring System Used in This Study: (a) R/S+ Rheometer, (b) CCT-40, (c) VT-40-20

2.2 Equipment for the Rheological Tests

The R/S+ Rheometer manufactured by Brookfield, USA, as shown in Fig. 3, was selected to measure the rheology of the conditioners and the conditioned sands by using a CCT-40 coaxial cylinder measuring system and a VT-40-20 vane spindles measuring system, respectively. To ensure the effectiveness of the rheological measurements and to reduce misunderstandings of test results, the appropriate measurement system must be selected according to the type of sample. Fig. 4 shows the four different rheological measurement systems that were used for the different types of samples. The CCT-40 and VT-40-20 belong to the measuring systems shown in Figs. 4(a) and 4(b), respectively. Taking the CCT and VT measuring system as examples, the apparent viscosity coefficient μ of a sample can be obtained by Eq. (4):

$$\mu = \frac{\tau}{\dot{\gamma}} \tag{4}$$

Where,

$\tau =$ Shear stress
$\dot{\gamma} =$ Shear rate

τ and $\dot{\gamma}$ are given by Eqs. (5) and (6):

$$\tau = \frac{T}{2\pi R_2^2 L + 4\pi R_2^3/3} \tag{5}$$

where T is the torque, R_2 is the outer radius of the vane, and L is the working height of the vane.

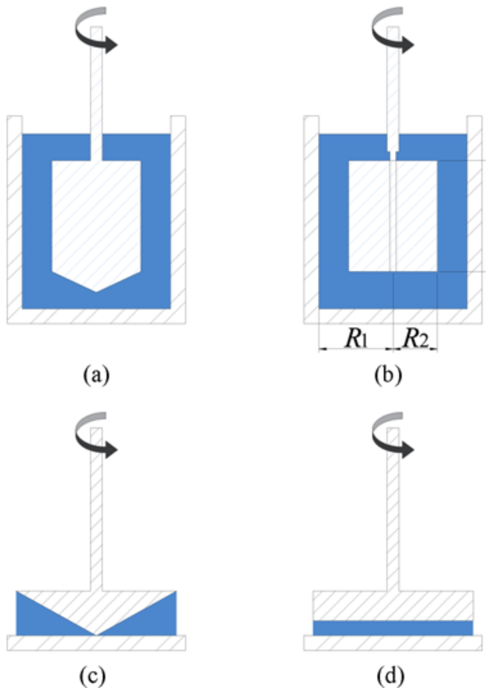

Fig. 4. Different Measuring Systems for a R/S+ Rheometer: (a) The Coaxial Cylinder Measuring System, (b) The Vane Measuring System, (c) The Cone Spindle/plane Measuring System, (d) The Plane Spindle/plane Measuring System

$$\dot{\gamma} = \frac{2R_1^2}{R_1^2 - R_2^2}\omega \tag{6}$$

where R_1 is the inner radius of outer cylinder, and ω is the rotating speed.

When making the selection of the measurement system, it is necessary to estimate not only the torque generated but also the size of the particles in the sample and, more importantly, the needed reliability of the measurement data. Scotto et al. (2010) studied the rheological behavior of a debris flow by using a rotational rheometer, model AR 2000ex, with two measurement systems, a vane rotor system and a parallel plate system (which are similar to Figs. 4(b) and 4(d)). In addition, the results show that the vane rotor system seems to be more suitable for the quantitative evaluation of the debris flow materials. For the conditioned sands studied in this paper, the disturbing effects that occur in the measurements mainly come from the heterogeneities in the particle size distribution, the wall slip phenomenon and the edge/crack effect. The cone/plate (Fig. 4(c)) and plate/plate (Fig. 4(d)) measurement systems are not suitable for fluid-solid two-phase bodies such as conditioned sand, due to the particle settling and migration caused by gravity and secondary flow during the test. Compared to coaxial cylinder measuring systems, the vane measuring system can better drive the central zone of the sample and reduce the wall slip, which means that the vane measuring system is the best choice for conditioned sands. For the conditioner solution, cylinder measurement system is the most suitable choice according to previous study (Min et al., 2018). In order to make a comparison of different measurement systems, cylinder and vane measurement systems were used for conditioner solution.

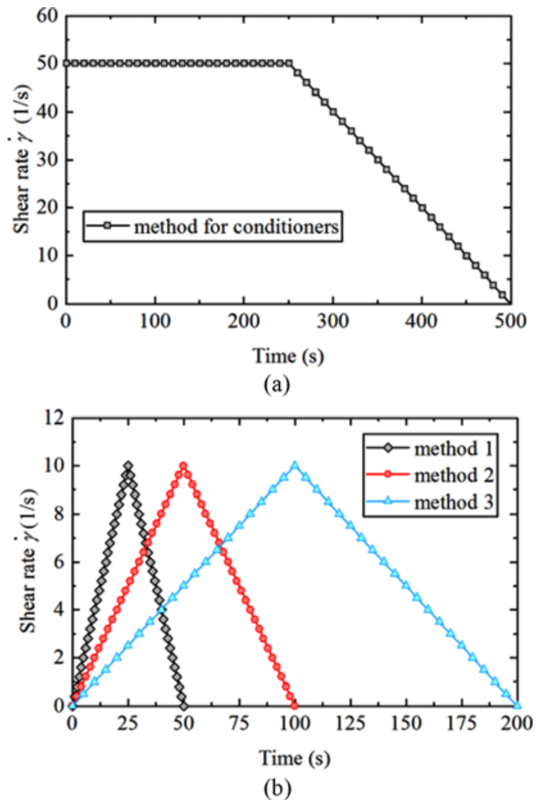

Fig. 5. Loading History That Was Set in the Brookfield R/S+ Rheometer: (a) Loading History Used for Conditioners, (b) Loading History Used for Conditioned Sands (The shear rates of method 1, method 2 and method 3 vary with accelerations of 0.4, 0.2, and 0.1 s^{-1}/s, respectively.)

2.3 Mixing and Testing Method

The two conditioners were formulated as described in Section 2.1 for rheological testing and for testing with conditioned sand. One conditioner was a slurry having a bentonite mass of 25%, and the other was an aqueous solution having a CMC concentration of 1.5%. The loading history shown in Fig. 5(a) was adapted to test the rheological behavior of two conditioners, and consisted of a preshear with a shear rate of 50 s^{-1} for 250 s, followed by a descending ramp from 50 s^{-1} to 0 s^{-1} for 250 s. The purpose of preshear is to keep the conditioner in a steady stage flow, in other words, to eliminate the influence of loading history on the flow curve. Table 1 shows the mixture proportions of all of the conditioned sands, as well as the injection rate, which is the value of the volume of conditioner/water divided by the cumulative volume of sand, often represented as a percentage. The sand and conditioner were originally mixed by hand for 60 s and, sequentially, with a three-blade stirrer at 30 rpm for 3 min. After homogenization, a 500 ml sample was placed in the measurement system and the rheological characterization was conducted using a loading history that was preset in the

Table 1. Percentage (by mass) of the Conditioned Sands

Identity of conditioned sand	Sand (%)	Bentonite slurry (%)	CMC solution (%)	Deionized water (%)	Conditioner injection ratio (%)	Water injection ratio (%)	Loading method
CS1	79	21	-	-	40	0	1,2,3
CS2	71	29	-	-	60	0	2
CS3	72	20	-	8	40	20	2
CS4	81	-	19	-	40	0	1,2,3
CS5	74	-	26	-	60	0	2
CS6	74	-	17	9	40	20	2

Brookfield R/S+ rheometer. Roussel (2006) reported that concrete is most frequently studied over a shear rate range of 0-10 s^{-1}. Since the conditioned sand is similar to concrete in terms of its flowability, three loading histories were adapted as shown in Fig. 5(b) that consisted of an ascending ramp from 0 to 10 s^{-1} and a descending curve from 10 to 0 s^{-1}.

3. Experimental Results and Analysis

3.1 Rheological Properties of the Conditioners

The rheological curves of the bentonite slurry and polymer solution that were obtained from two measurement systems at 20°C are shown in Figs. 6 and 7, respectively. In Fig. 6, two similar rheological curves of the bentonite slurry were obtained by using the coaxial cylinder measuring system CCT-40 and the vane measuring system VT-40-20. The test data of both groups were well fitted using the Herschel-Bulkley model, although the absolute values of the model parameters are slightly different. Min et al. (2018) found that the slurry (mainly bentonite) used in a slurry shield is more in line with the Herschel-Bulkley model than the Bingham model while using a NXS-11A rotational viscometer, especially in a low shear rate range. Goh et al. (2011) attributed this phenomenon to the shear dilution characteristics of the slurry as a solid-liquid two-phase fluid. Similarly, the rheology experimental data of the CMC aqueous solution

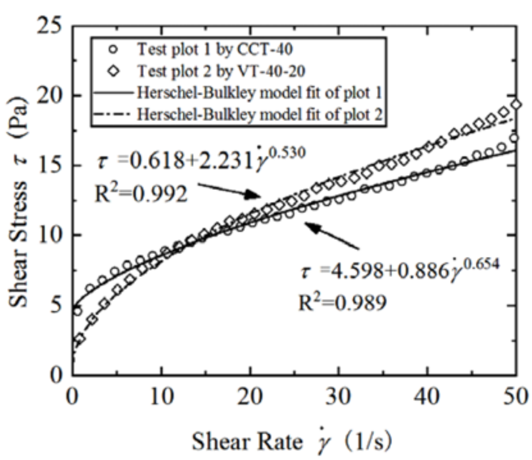

Fig. 6. Rheological Curves of the Bentonite Slurry Used as a Conditioner in This Study

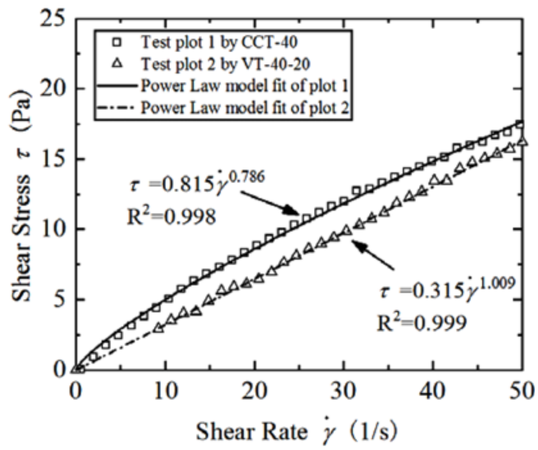

Fig. 7. Rheological Curves of the CMC Solution Used as a Conditioner in This Study

measured by using two measurement systems and the fitting curve are given in Fig. 7. Unlike the bentonite slurry, the power law model can more accurately describe the flow behavior of the CMC aqueous solutions. The difference between the Herschel-Bulkley model and the power law model is whether there is a yield stress at the beginning of the sample flow that passes through the origin point. Rheometers are required to have excellent performance in low shear rate zone to accurately capture yield stress values, while differences in measurement systems can also result in different rheological parameter values. For fluids such as these conditioners with lower shear stress (compared to conditioned sand), the coaxial cylinder measuring system is a more precise choice. According to the previous understanding, CMC solution should follow the power law model with $n < 1$ (Benchabane and Bekkour, 2008). However, as shown in Fig. 7, the n value of CMC solution obtained by VT-40-20 measurement system is 1.009. This proved that there is an error during the measurement of CMC solution by VT-40-20 system, which leads to a smaller shear stress τ. The calculation method described in Eqs. (5) and (6) is based on the assumption that the shear plane is cylindrical. It is difficult for a vane measuring system to ensure that shearing occurs in accordance with the designed cylindrical shear plane due to the high fluidity of these low viscosity fluids, which results in the difference of rheological parameters of the same material in Figs. 6 and 7. In conclusion, it is necessary to select a suitable measurement

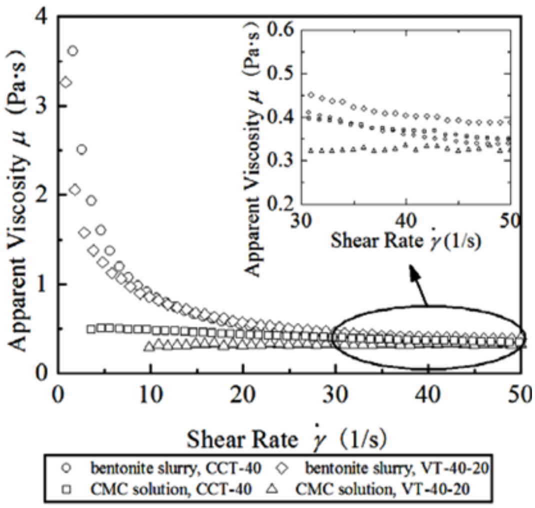

Fig. 8. Flow Curves of the Two Conditioners in $\mu-\dot{\gamma}$ - Scale

system according to the characteristics of materials in order to get accurate and reliable data.

Figure 8 presents the flow curves of the two conditioners in apparent viscosity μ-shear rate $\dot{\gamma}$ scale that were found by using the different measuring systems. Both sets of bentonite slurry exhibited shear thinning (pseudoplastic) flow characteristics, that is, the apparent viscosity μ decreases with the increase of shear rate $\dot{\gamma}$. Conversely, the CMC solution did not exhibit this pattern significantly, and the CMC solution is closer to a Newtonian fluid. The differences in flow curves between the two conditioners are mainly concentrated in the low shear rate zone ($\dot{\gamma} < 30$ s–¹), and the apparent viscosity values of the two conditioners in the high shear rate zone ($\dot{\gamma} > 30$ s^{-1}) are very close (between 300 – 450 mPa·s). The differences in performances of the conditioners in the low shear rate zone determine the differences in their conditioning effects, as shown by the rheological behavior of the conditioned sands that will be described below. As a non-Newtonian fluid, a conditioner cannot be evaluated simply by a certain apparent viscosity value. As confirmed, the bentonite slurry and CMC solution exhibited similar viscosity values in the high shear rate zone but presented completely different rheological curves.

3.2 Rheological and Thixotropic Properties of Bentonite-Conditioned Sands

Considering the effect that consolidation may have on the rheological properties of a conditioned sand, an extra one-minute agitation was performed for consistency after the sample had been put in the rheometer tool. After agitation, the test procedure was started within two minutes to reduce the effects of consolidation. The flow curves of sample CS1, as described in Table 1, that were obtained by the three loading histories given in Fig. 5(b) are presented in Fig. 9. The flow curves exhibit a two-part loop shape at the first the shear rate rise followed by a shear rate drop. In the stage of descending shear rate, the curves obtained by the three methods, all of which can be better described by the Herschel-Bulkley model, are basically the same, and this stage is called steady-state flow. However, in the stage of ascending shear rate, the shear stress τ first increases linearly with the shear rate $\dot{\gamma}$, and then, as the shear rate $\dot{\gamma}$ continues to increase, the rheological curve approaches steady-state flow. The period between the stationary state and the steady state flow is called transient flow.

As long as steady-state flow is reached, the behavior of the bentonite-conditioned sand can be described by a yield stress model such as the Herschel-Bulkley model. This delay in material response before reaching steady state flow is called thixotropic behavior. The transient flow and the steady-state flow together constitute a complete "thixotropic loop". Steady-state flow can be described simply by a yield stress model. In comparison, transient flow is more difficult to describe and predict. The conceptual form of a thixotropic material model was originally defined by Cheng and Evans (1965), and the

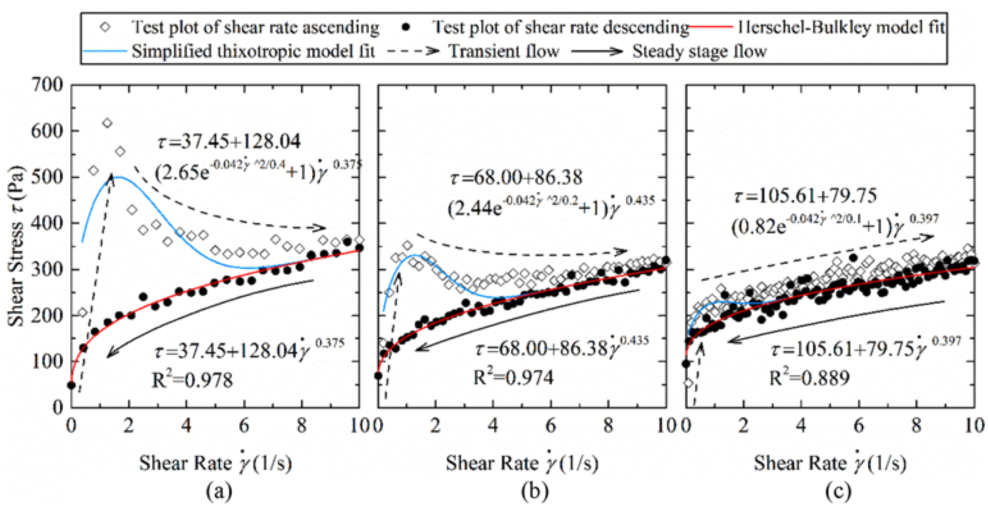

Fig. 9. Flow Curves of Sample CS1 in $\tau-\dot{\gamma}$ Scale Obtained by the Three Loading Histories: (a) Method 1, (b) Method 2, (c) Method 3

relationship between the shear stress τ and the shear rate $\dot{\gamma}$ is expressed as:

$$\tau = \eta(\lambda, \dot{\gamma})\dot{\gamma} \quad (7)$$

where λ is a structural parameter related to the flocculation level of the material structure, and it evolves with the following equation as:

$$\frac{d\lambda}{dt} = f(\lambda, \dot{\gamma}) \quad (8)$$

Over the years, a number of thixotropic models, with varying levels of sophistication, have been developed. The thixotropy of a fluid depends on the extent of the structure in the material, or more generally, its "degree of jamming" (Coussot et al., 2002b). As suggested by Coussot et al. (2002a) and Roussel et al. (2004), λ was introduced to represent the sum of the structural rebuilding due to flocculation and the structural breakdown caused by the flow. This model was written as:

$$\tau = \mu_0(1+\lambda^n)\dot{\gamma} \quad (9)$$

$$\frac{\partial\lambda}{\partial t} = \frac{1}{T} - \alpha\lambda\dot{\gamma} \quad (10)$$

where μ_0 is the viscosity at an infinite shear rate when the fluid is flowing stably, n is a constant with a positive value, $1/T$ represents the rate of the material "natural" restructuration due to flocculation, $\alpha\lambda\dot{\gamma}$ represents the rate of destructuration of the material due to flow (i.e., the rate of deflocculation) and this is considered to be proportional to the shear rate.

Based on the basic model given in Eqs. (9) and (10), combined with the test data of the bentonite-conditioned sand under the loading history of a constant shear rate acceleration obtained in this paper, a simplified version of the thixotropic model is established. First, the Herschel-Bulkley model is assumed to be reasonable and highly consistent for describing the steady-state flow of bentonite-conditioned sand. Second, the plastic viscosity μ_p is assumed to vary with the degree of jamming, and the effect of flocculation can be ignored because the time required for flocculation is much longer than the test time, so the $1/T$ in Eq. (10) can be ignored. Thus, the model can be written as:

$$\tau = \tau_0 + \mu_p(1+\lambda)\dot{\gamma}^n \quad (11)$$

$$\frac{\partial\lambda}{\partial t} = -\alpha\lambda\dot{\gamma} \quad (12)$$

Under the loading histories of this study, the shear rate $\dot{\gamma}$ is proportional to time t ($\dot{\gamma}=at$, where a is the acceleration of the shear rate). For a constant acceleration a of the shear rate, Eq. (12) can be integrated as:

$$\lambda = \lambda_0 e^{-0.5a\alpha t^2} = \lambda_0 e^{-0.5\alpha\dot{\gamma}^2/a} \quad (13)$$

Then, Eq. (11) can be written as:

$$\tau = \tau_0 + \mu_p(1+\lambda_0 e^{-0.5a\alpha t^2})\dot{\gamma}^n = \tau_0 + \mu_p(1+\lambda_0 e^{-0.5\alpha\dot{\gamma}^2/a})\dot{\gamma}^n \quad (14)$$

where τ_0, and μ_p are the Herschel-Bulkley model parameters that can be obtained from the steady-state flow, a is the test loading parameter, which was set artificially during the experiment, and λ_0 and α are parameters waiting to be identified from the experimental results.

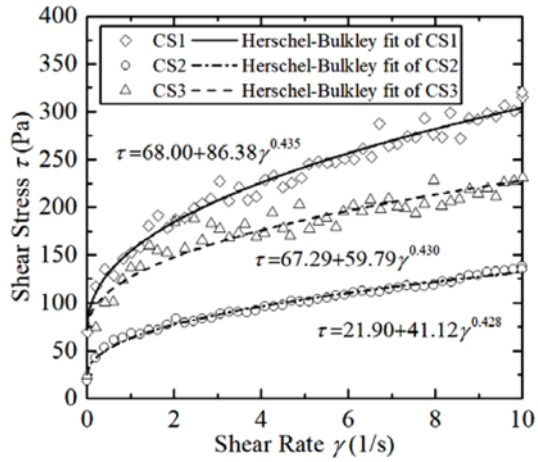

Fig. 10. Flow Curves of the Bentonite-Conditioned Sand in τ–$\dot{\gamma}$ Scale Obtained by Using Loading Method 2

Using this model, the data points of the ascending shear rate shown in Fig. 9 can be better explained and predicted, especially in the range of shear rates from 0 to 4 s^{-1}. It is of interest to note that α can be considered as a material parameter because the three sets of test point data can be described by the same α value. In contrast, λ_0 is not only a material parameter but is also related to the loading history (acceleration of shear rate). The delay in material response due to thixotropy is heavily dependent on the recent flow history of the material.

When only the data of steady stage flow are retained, the rheological curves of bentonite-conditioned sand with different proportions by using loading method 2 are shown in Fig. 10. In the experiments shown in Fig. 10, the fitted flow curves of all the bentonite-conditioned sands did not pass through the origin; in other words, there was a yield stress to be overcome before the flow started. This characteristic of bentonite-conditioned sand is consistent with bentonite slurry, except that the addition of the sand greatly increases the yield stress value. The shear strength value decreases as the slurry injection rate increases, indicating that the bentonite slurry acts as a lubricant during the conditioning process. The rheological results presented in Fig. 10 indicate that the injection of the slurry is responsible for a decrease in both of the Herschel-Bulkley parameters, τ_0 and μ_p.

3.3 Rheological and Thixotropic Properties of the CMC-Conditioned Sand

The rheological and thixotropic behaviors of the CMC-conditioned sands was tested by using the same test preparation as described in Section 3.2, which is the same as that used for the bentonite-conditioned sands. It can be seen from a comparison of Figs. 9 and 11 that the test plot of the CMC-conditioned sand does not

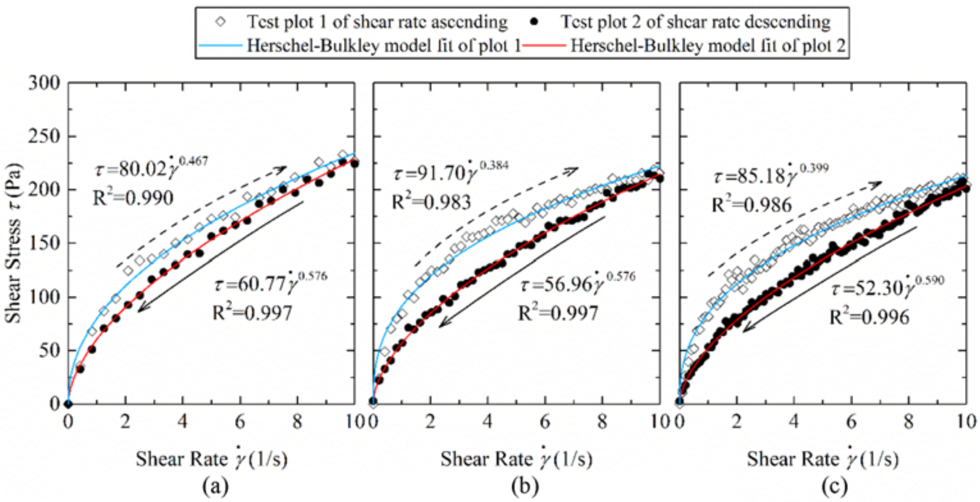

Fig. 11. Flow Curves of Sample CS4 in $\tau-\dot{\gamma}$ Scale Obtained by the Three Loading Histories: (a) Method 1, (b) Method 2, (c) Method 3

exhibit a yield stress such as that of the bentonite-conditioned sand. Based on the findings determined from Fig. 11, a power law fluid model was used to describe CMC-conditioned sand. In addition, it can be considered a pseudoplastic fluid (shear thinning) and is highly consistent with the power law model (all R-square values are above 0.98). The solid particles in the conditioned sand are mainly composed of hard and insoluble quartz, with no characteristics of shear thinning. So the rheological behavior of shear thinning mainly comes from the conditioner, i.e., the CMC solution. This is basically in agreement with the fact that the shear thinning behavior of the polymer solution is caused by the untangling of the polymer coils in a solution or an increased orientation of the polymer coils in the flow direction (Dunstan et al., 2004). Lizarraga et al. (2006) pointed out that the disentanglement-entanglement process of polymer chains and the alignment of polymer chains along the shear direction are the intrinsic reasons for the thixotropic behavior of CMC solutions. In Fig. 11, a similar thixotropic loop (hysteresis loop) is obtained by using the three different methods, indicating that the loading history does not have a significant effect on its thixotropic behavior, which is advantageous for the numerical simulations of CMC-conditioned sands.

The steady flow curves of the CMC-conditioned sand in the τ-$\dot{\gamma}$ scale by using loading method 2 are presented in Fig. 12. All of the samples can be fitted with a power law model in which all of the n values are less than 1. Regarding the effect of the conditioner injection ratio on the shear stress, the general trend is that the plastic viscosity decreases with decreasing volumetric sand concentration. Comparing samples CS5 and CS6, the volumetric sand concentrations were similar, but the net content of the conditioner of sample CS5 was higher, resulting in the higher shear stress and plastic viscosity values of CS5. It is puzzling that the opposite rule was observed in the comparison of samples CS2 and CS3. It can only be guessed that the particle structures of the two types of conditioned sand are different, which leads to their different rheological and thixotropic behaviors.

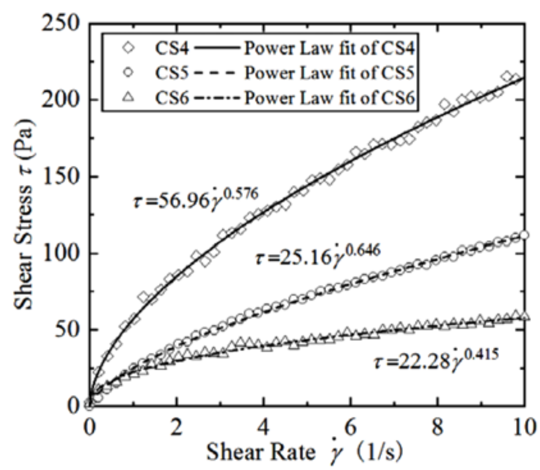

Fig. 12. Flow Curves of the CMC-Conditioned Sand in $\tau-\dot{\gamma}$ Scale by Using Loading Method 2

4. Discussion

All the Herschel-Bulkley rheological model parameters of conditioner and conditioned sand are listed in Table 2. As discovered from Table 2, the type of rheological model for conditioned sand (with or without yield stress) depends on the conditioner, while the volumetric concentration of the sand and the water have only an effect on the rheological model parameters. This rule is confirmed by all of the test results that were determined in this study. As shown in Figs. 9 and 11, the thixotropic behavior of conditioned sand is heavily dependent upon the performance of the conditioner and is also affected by its recent rheological history. For the bentonite-conditioned sand with typical and apparent thixotropic behavior, a simple thixotropic model was found to describe and predict the flow curve of a sample at constant shear rate acceleration, but it seems that the results are not very satisfactory. The factors that influence the test results are attributed to many aspects, the most

Table 2. Herschel-Bulkley Model Parameters of Conditioner and Conditioned Sand

Conditioner	τ_0 (Pa)	μ_p (Pa·s^n)	n	Conditioned sand	τ_0 (Pa)	μ_p (Pa·s^n)	n
Na-bentonite slurry	4.598	0.886	0.654	CS1	68.00	86.38	0.435
				CS2	67.29	59.79	0.430
				CS3	21.90	41.12	0.428
CMC solution	0	0.815	0.786	CS4	0	56.96	0.576
				CS5	0	25.16	0.646
				CS6	0	22.28	0.415

important of which is its flow history, such as manual or mechanical placement. In general, at the same injection rate, the CMC-conditioned sand has a lower shear stress, which is more advantageous for reducing the friction coefficient of the muck and reducing the wear on the tools. Although both bentonite- and CMC-conditioned sand exhibit pseudoplasticity, their internal structures are different. The bentonite-conditioned sand can be regarded as a suspension containing coarse particles (sand) and fine particles (bentonite), and its pseudoplasticity is a result of the jamming and unjamming of the microstructure between fine particles and fine particles, as well as between fine particles and coarse particles. The pseudoplasticity of the CMC-conditioned sand depends essentially upon the entanglement-detanglement process of the polymer chain. In comparison, a simulation of CMC-conditioned sand is easier to achieve because it has no yield stress, which means that there are no mathematical discontinuities in the calculations.

Considering the complex structure of shield cutter head and screw conveyor, it seems impossible to establish an analytical solution of muck flow considering the movement of shield equipment. However, based on the constitutive model in this paper, it is easy to establish a numerical analytical model of conditioned sand flow, which is beneficial for estimating power consumption of shield equipment and improving material flow in EPB tunneling. Conditioned sand is a typical non-Newtonian fluid with high plastic viscosity μ_p and yield stress τ_0. Therefore, the transportation of conditioned sand under the action of cutter head and screw conveyor should belongs to the laminar flow, which makes it possible to use computational fluid dynamics (CFD) method to calculate and analyze the movement of conditioned sand. By using the parameters in Table 2, a finite element model for calculating the flow of conditioned sand can be easily established, which can be used to analyze the transportation law of conditioned sand in excavation chamber and screw conveyor.

5. Conclusions

1. At low shear rates (0 – 10 s^{-1}), bentonite-conditioned sand meets the characteristics of the Herschel-Bulkley model, and CMC-conditioned sand meets the characteristics of the power law model. A bentonite-conditioned sand needs to overcome its yield stress before flowing, while a CMC-conditioned sand does not need to do this, a fact that is related to the rheological behavior of the conditioner.
2. In general, the yield stress (if any) and plastic viscosity increase with increasing sand content. At the same volume injection rate, a CMC solution has a greater effect on lubrication and wear reduction than a bentonite slurry because the CMC-conditioned sand exhibits a lower shear stress.
3. The thixotropy of conditioned sand is heavily dependent on its recent flow history. A simple thixotropic model, as given in Eq. (14), can be used to describe and predict the flow curves in a τ-$\dot{\gamma}$ scale of bentonite-conditioned sand at constant shear rate acceleration.
4. For computing applications, CMC-conditioned sand is easier to simulate. Since it has no yield stress and due to its simpler thixotropic behavior, there are no mathematical discontinuities in the calculations.

Acknowledgements

The authors would like to acknowledge the National Basic Research Program of China ("973" Program, 2015CB057802) and the National Natural Science Foundation of China (No. 51978040) for supporting this research.

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