Rheological investigation of natural mudflow at Lian-yun Harbor in China

Xu Jing-yu[1*], Zhang Jian[1], Tang Chi[1], Huhe Aode[1]

(1. Institute of Mechanics, Chinese Academy of Sciences, Beijing, China
*Corresponding Author: Tel.: +86 10 8254 4179; Fax: +86 10 6256 1284
E-mail: xujingyu@imech.ac.cn (Dr. J-y Xu))

Abstract: An experimental study of the rheological properties of natural mudflow at Lian-yu Harbor in China has been carried out in this work by using the RS6000 rheometer, including steady and dynamic (oscillatory) measurements. Based on the experimental results and analysis, it is found that in the steady measurement, a Dual-Herschel-Bulkley model, base on two different regions of the shear rate, are developed for analyzing the flow curve and interpolating the values of both static and dynamic yield stresses. After the sample put in the rheometer, consolidation time and system temperature do not seem to significantly influence on the results of steady measurement, especially for the sample with high sediment volume concentration. Under a shear stress sweep, there are two plateau intervals showing the viscosity and the elastic behaviors, respectively. In the elastic region, complex viscosity, elastic modulus and loss modulus are several orders of magnitude lager than those in the viscosity region. Furthermore, our analysis also shows that both steady and dynamic rheological properties can be expressed as appropriate exponential functions of sediment volume concentration.

Keywords: Rheology, Natural mud, Herschel-Bulkley model, Oscillatory viscoelastic properties

1 Introduction

Natural mud is a complex mixture of saline water, cohesive sediments, organic matter and a certain amounts of sand and silt. Dilute mud suspensions can demonstrate nearly the complex behavior rheology, such as yield stress, shear-thinning, thixotropy and viscoelastic. Knowledge of these properties is important to assess the sensitivity to fluidization and erodibility, damping of turbulence and the prediction of density currents and fluid mudflow. The rheology of sediment and water mixtures was discussed in detail by Berlamont et al. (1993)[1] for the marine sediment transport and by Coussot (1997, 2007)[2][3] for the mudflows, respectively. Overall, at low sediment concentrations, the mixtures usually exhibit Newtonian fluid behavior, while at high sediment concentration the mixtures become non-Newtonian shear-thinning or viscoelastic behaviors. Furthermore, the rheological behavior of the mixtures is affected strongly by the sediment concentration and physic-chemical factors (flocculation).

Rheological measurements of natural mud usually include the steady and dynamic (oscillatory) measurements. In the steady measurement of mudflow, the value of the yield stress plays a central role in the interpretation and correlation of experimental results on mudflow. The definition of yield stress is the critical stress below which the shear rate is exactly zero. In most cases, stress-strain data are extrapolated to zero-shear rate, and the intercept on the ordinate is taken to be the yield stress. Although there is a debate in the literature on the existence of a "true" yield stress, in the present study the existence of the yield stress is assumed for natural mud. In practice, it is difficult to ascribe a value to the yield stress in that the great scatter observed in the published data of yield stress is due to the different rheological model selected and the segment of the flow curve for extrapolation (James et al., 1987[4]; Julien and Lan, 1991[5]; Chhabra, 2006[6]). Therefore, the yield stresses obtained by the different models should not be directly compared with each other and the extrapolation beyond the range of experimental conditions must be treated with reserve.

In the last half century, a number of rheology models have been used to study the mixtures of sediment and water. These models, which describe the sediment response to fluid loading, can generally be grouped into three main categories, namely liner model (Newtonian and Bigham fluids), power function model (Power-law and Herschel- Bulkley fluids) and viscoelastic model (Kelvin-Voigt fluid). The results show that both apparent viscosity and yield stress, which are obtained by using these models, are largely dependent on the shear rate and increases exponentially with increase of the sediment concentration (O'Brien and Julien, 1988[7]; Huhe and Huang, 1994[8]).

Unlike the steady measurement, until now few experimental work has been published on the oscillatory measurements of natural mud (Jiang and Metha, 1995[9]; Kessel and Blom, 1998[10]; Babatope et al., 2008[11]; Huhe and Huang, 2009[12]), although the tests provide information on elastic properties of the mud, which is of importance to study the wave forcing in shallow waters (Williams and Williams, 1989[13]). Thus, the purpose of the present study is to investigate on the rheological behavior of natural mud and contribute a valuable data set of the dynamic rheology for the natural mud at the Lian-yun Harbor.

2 Experimental

2.1 **Materials**

In this study natural mud samples were taken from Lian-yun Harbor in China. Sediment grains were characterized by an average density of 2713 kg/m3 and a median grain diameter of 6.2μm (D50). Size distribution of the sediment grains measured by two different methods is shown in Figure.1. A good agreement was obtained.

2.2 Samples preparation

To get the desired volume concentrations the natural mud samples were diluted by using the different amounts of salty water with 15‰ salinity. Five mud samples with different sediment volume concentrations were studied. Several basic properties of the mudflow samples were summarized in Table 1. During the experiments, the samples were prepared in batches of 300 ml and pre-heated to a fixed test temperature, and then the homogenization was achieved by using the hree-blade stirrer at a fixed low speed. After homogenization, the rheological characterization of the samples was measured by exploiting the performance of the rheometer (Rheometric Scientific Haake RheoStress 6000, Germany).

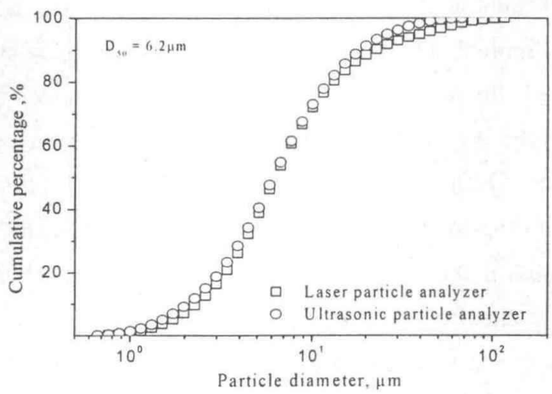


Figure 1: Sediment size distribution measured by two different methods

Table 1: Several basic properties of the mudflow samples

Sample No.	Mud volume concentration, C_V	Mud density, ρ_c (kg/m^3)	Mud mass concentration, S (kg/m^3)	Sediment grains density, ρ_s (kg/m^3)
Sample 1	0.058	1098	157	
Sample 2	0.086	1146	233	
Sample 3	0.118	1200	320	2706~2720
Sample 4	0.152	1256	412	
Sample 5	0.179	1305	486	

2.3 Rheological measurements

Rheological measurements were carried out on a HAAKE RS6000 Rheometer with a coaxial cylinder sensor system (Z38 DIN, gap width = 2.5 mm and sample volume of 30.8 cm^3). A variety of temperature control units was available to reliably and accurately handle temperatures ranging from –40 to 140°C. After two minutes from positioning the sample on the sensor system, the corresponding measurement was started. Three replicates of each test were performed and repeatability was good. Furthermore, this rheometer had a range of shear rate from 10^{-3} s^{-1} to 1000 s^{-1} and a range of viscosity from 0.001 Pa·s to 1000 Pa·s. In oscillatory measurements, an amplitude sweep at a fixed frequency of 1 Hz was performed prior to the following frequency sweep in order to ensure the selected stress keeping in the linear viscoelastic region. Experimental data were obtained by recording the complex viscosity (η*), the elastic modulus (G') and the loss modulus (G"). Frequency ranged was from 0.01 to 100 rad/s. Furthermore, a vane-type rotor (FL22) was also used to measure the static yield stress of the samples according to the suggestion by Schramm (2000)[14].

3 Results and discussions

3.1 Steady mudflow

3.1.1 Flow curves

The flow behavior of mud at Lian-yun harbor is investigated over a wide range of shear rates from 0.001s-1 to 200s-1. Figure.2 shows the variation of the flow curve with the shear rate. At low shear rates, the shear stress increases with the shear rate and passes through a maximum and thereafter decreases gradually. When the shear rate further increasing τ reaches to a lowest point and then quickly increases again. During this process of the increases, τ passes through a turning point and then slightly go up with the shear rate. Overall, it is observed that the shear stress of the sample increases with the increases of the volume concentration. This occurs is due to the fact that the internal frictional forces in the flowing fluid become greater with the increases of the sediment quantity so that the shear stress will has to be increased at a fixed shear rate (Macial, 2009[15]). Furthermore, the mud sample shows a strong shear-shinning rheological behavior.

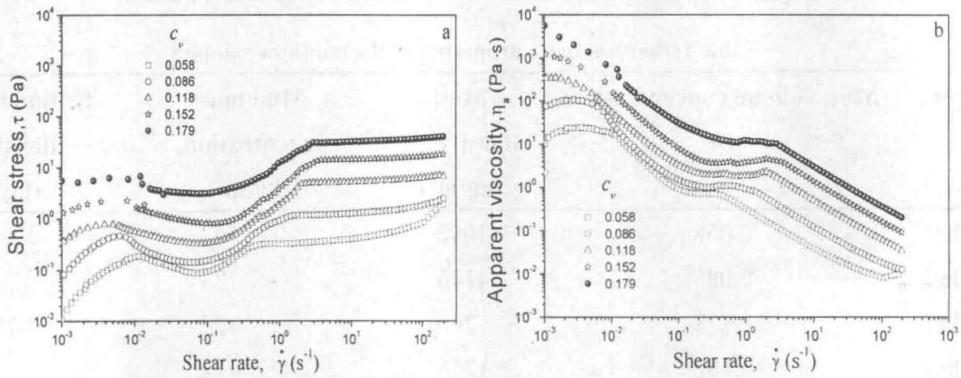


Figure.2: Rheograms of the samples with different volume concentrations at 20°C

3.1.2 Model prediction and yield stress

To predict the flow characteristics of mud, one of the best methods is to exploit a theoretical model to reveal the experimental data and obtain the yield stress. The simplest theoretical model for yield stress fluid is the Bingham model, which exhibits a linear stress-strain relationship at shear stress in excess of the yield stress. In most cases, fitting the experimental data with satisfactory accuracy is not good over the low range of shear rates by using this simple model (Julien and Lan, 1991[5]; Kessel and Blom, 1998[10]; Toorman, 1994[16]; Coussot et al., 1996[17]; Maciel et al., 2009[15]). Kessel and Blom (1998) investigated the applicability of rheological models to a natural and an artificial mud. Their results showed that the Bingham model is only suitable for describing the measurements at shear rates in excess of 20 s^{-1}. To overcome this problem, Huang and Huhe (2009[12]) developed a Dual-Bingham model to predict the flow curve over the entire range of 0.001 s^{-1} to 200 s^{-1} base on two different ranges of shear rates. However, it can found in Fig.2a that over the range of low shear rates, the materials in this work exhibit that the stress-strain relationship is not linear and yet shows a convexity to the shear stress. This behavior is referred to as yield-pseudo-plastic. The Herschel-Bulkley model is proposed to fit the experimental data with this behavior (Govier and Aziz, 1982[18]; Mitsoulis, 2007[19]; Maciel et al., 2009[15]). Therefore, in the following study we extend the Dual-Bingham model as the Dual-Herschel-Bulkley model to study the rheological characteristic of mudflow at Lian-yun Harbor. The Dual-Herschel-Bulkley model is described by six parameters base on two different regions of the shear rate in the following equation:

In the region (1):

$$\tau = \tau_{o1} + \eta_{o1}(\dot{\gamma})^{n_1} \quad \dot{\gamma} > \dot{\gamma}_c \tag{1}$$

In the region (2):

$$\tau = \tau_{o2} + \eta_{o2}(\dot{\gamma})^{n_2} \quad \dot{\gamma} \le \dot{\gamma}_c \tag{2}$$

here, τo are the yield stress in Pa. ηo and n are the consistency index in Pa·sn (defined as the apparent viscosity of Herschel-Bulkley model in this work) and the flow behavior index, respectively. The subscript 1 and 2 refer to the region (1) and region (2), respectively. γc' is the critical shear rate defined as (Huang and Huhe, 2009)[12]:

$$\dot{\gamma}_c = \frac{\tau_{o1} - \tau_{o2}}{\eta_{02} - \eta_{01}} \tag{3}$$

Six parameters of the Dual-Herschel-Bulkley model simulated for five samples are listed in Table 2. Figure.3 gives a comparison of experimental data with the flow curve predicted for the sample 2 in a rectangular coordinate system. It can be observed that the shear stress predicted by the model is good over the entire range of shear rates, especially for the high shear rates (i.e. in the region (1), R2 > 0.99). In Figure.3, the two yield stresses obtained from the model can be interpreted as the upper limit of solid-like behavior and the lower limit of liquid-like behavior, representing the static yield stress and the dynamic yield stress (Uhlherr et al., 2005)[20].

In hyper-concentrated flows, it has been generally accepted that the yield stress (τ_o) and the consistency index (η_o) increase exponentially with the sediment volume concentration (CV) as:

$$\tau_{o1} = \alpha_{11} * e^{b_{11}C_v} \quad \dot{\gamma} > \dot{\gamma}_c \tag{4}$$

$$\tau_{o2} = \alpha_{12} * e^{b_{12}C_v} \quad \dot{\gamma} \le \dot{\gamma}_c \tag{5}$$

$$\eta_{o1} = \alpha_{21} * e^{b_{21}C_v} \quad \dot{\gamma} > \dot{\gamma}_c \tag{6}$$

$$\eta_{o2} = \alpha_{22} * e^{b_{21}C_v} \quad \dot{\gamma} \le \dot{\gamma}_c \tag{7}$$

here, the values of the eight empirical coefficients a11, a12, a21, a22, b11, b12, b21 and b22 obtained by regression analysis for each mudflow sample, according to the two regions respectively, are presented in Figures. 4 and 5. A good agreement can be obtained between data and predication.

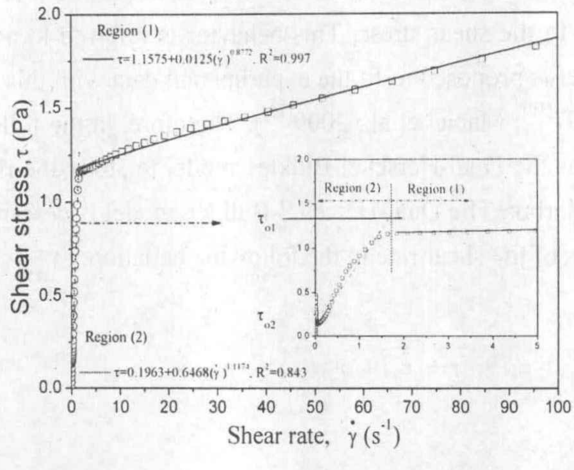


Figure.3: A comparison of experimental data with the flow curve predicted by Dual-Herschel-Bulkley model for the sample 2 in a rectangular coordinate system

In this work a vane-type rotor is used to measure the traditional value of yield stress of the static samples at a fixed shear rate (Schramm, 2000[14]). The shear stress on the flow curve corresponding to a shear rate of about 0.01 s^{-1} is generally very close to the real yield stress (Mas and Magnin, 1994[21]; Maciel et al., 2009[15]). In Figure.2a, it can be also found that there is a maximum value of shear stress around the shear rate of 0.01 s^{-1}. Consequently, the yield stress has been measured around this point by using the vane-type rotor. The results are shown in Figure.4 by using the triangular symbol. It is observed that the measured yield stress is very close to those extrapolated in the region (1) with the higher value of the static yield stress. These findings further prove the validity of the model.

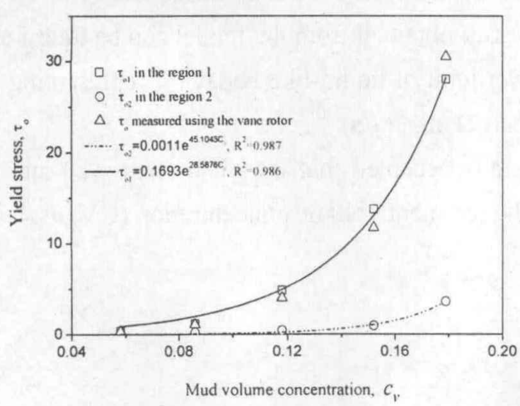


Figure.4: Yield stresses, extrapolated by the Dual-Herschel-Bulkley model and the measured by the vane- type rotor, as a function of mud volume concentration at 20°C

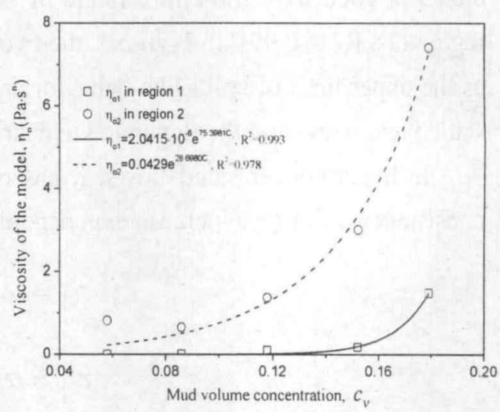


Figure.5: Viscosity of the Dual-Herschel-Bulkley model as a function of mud volume concentration the model at 20°C

Table 2: Parameters extrapolated by the Dual-Herschel-Bulkley model for mudflow samples

Mud No.	τ_o (Pa)		η_o (Pa·s^n)		*n*		R^2	
	Region1	Region2	Region1	Region2	Region1	Region2	Region1	Region2
	τ_{o1}	τ_{o2}	η_{o1}	η_{o2}	n_1	n_2	R_1^2	R_2^2
Sample 1	0.3583	0.0977	0.0008	0.8155	1.4392	1.7572	0.986	0.521
Sample 2	1.1575	0.1963	0.0125	0.6568	0.8772	1.1174	0.997	0.843
Sample 3	4.8348	0.4293	0.1015	1.3785	0.5980	1.5734	0.998	0.971
Sample 4	13.7360	0.9314	0.1782	3.0091	0.6155	1.2341	0.999	0.968
Sample 5	28.0287	3.6036	1.4830	7.4070	0.4049	1.2643	0.998	0.967

3.1.3 Effect of consolidation time

Consolidation process of the sediment and water materials could influence the microstructure of mud sample. After the sample materials are mixed, the microstructure in mud sample has already been changed, thus certain consolidation time is needed for the mud to restore its microstructure (Berlamont et al., 1993[1]; Whitehouse et al., 2000[22]). In order to study this influence on the results of measurement, a small device is designed to simulate the consolidation process of sample materials in the rheometer. The device consists of a measuring cylinder and cylinder rotor with the gap width of 2.5mm, which is the same width with the coaxial cylinder sensor system used in this work. The sample is put into the device and then the consolidation process investigated during two hours. Figure.6 represents the photos of results for the samples with two sediment concentrations (CV=0.058, 0.118). It can be seen that for the sample with CV=0.058, the natural phase separation of samples is observed clearly due to the hydrodynamic interactions (flocculation) and the density difference between water and clay (settling). And yet for the sample with CV=0.118 it does not seem to significantly influence the phase separation base on visual observation. The reason might be that a small gap width 2.5mm restricts the deposition of high concentrations of sediment. Figure.7 gives the water volume fraction separated of the sample with Cv=0.058 against the consolidation time, corresponding to the results of Figure.6a. It can be found that the water volume fraction separated from the sample increases with the consolidation time, and a liner relationship can be obtained.

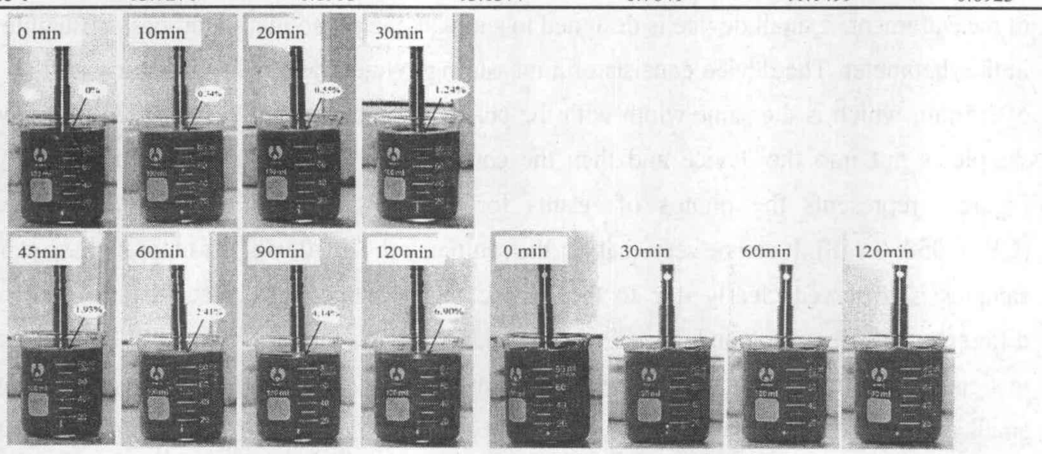
Figure.8 shows the effect of the consolidation time on the measured flow curves. Three consolidation times (0, 30 and 60 minutes) are examined and observed by using the samples1, 2, 3 and 4. Obviously, the consolidation time of the sample put in the coaxial cylinder sensor system has a few effects on the rheograms with low sediment concentrations. The effects have been gradually weakened with sediment volume concentration increasing. These findings are consistent with the results of Figure.6. Table 3 gives the yield stresses extrapolated by the Dual Herschel-Bulkley model corresponding to the Figure.8. As be shown in the table 3, in the steady measurement the consolidation time after the sample put in the rheometer does not change greatly the extrapolated yield stress.

3.1.4 Effect of system temperature

Figure.9 depicts the variation of flow curves in the function of temperature for samples 1 and 3, respectively, in a range from 5oC to 50oC. Generally, the increases of temperance slightly reduce the shear stress, especially for the sample 1 with low volume concentration. In Figure.9a, the effect of temperature on the flow curve becomes larger in the low shear rates (region 2) than those in the high shear rates (regions 1). However, with increases of volume concentration, this discrepancy caused by the system temperature becomes smaller (see the Figure.9b). The results are consistent with the findings of Maciel et al. (2009)[15]. Figure.10 gives the yield stresses, extrapolated by the Dual-Herschel-Bulkley model, corresponding to the Figure.9. It can be found that an increase of temperature only causes a slight reduction in the yield stress of the region (2), τo2. On the contrary, the yield stress in the region(1) show a few increases with the temperature.

Table 3: The yield stresses extrapolated by the Dual-Herschel-Bulkley model corresponding to Figure.8

	Settling time, 0 min		Settling time, 30 min		Settling time, 60 min	
	τ_{o1}	τ_{o2}	τ_{o3}	τ_{o4}	τ_{o5}	τ_{o6}
Sample 1	0.3586	0.0996	0.3636	0.0695	0.4299	0.0901
Sample 2	1.1575	0.2019	1.2232	0.1511	0.5857	0.1211
Sample 3	4.8761	0.4012	4.5753	0.3409	4.8549	0.4266
Sample 4	13.7270	0.8953	13.0377	0.7641	11.1499	0.6923



a, Sample with Cv=0.058　　　　b, Sample with Cv=0.118

Figure.6: Photos of natural phase separation of samples between a measuring cup and a cylinder rotor (gap width = 2.5mm) during two hours.

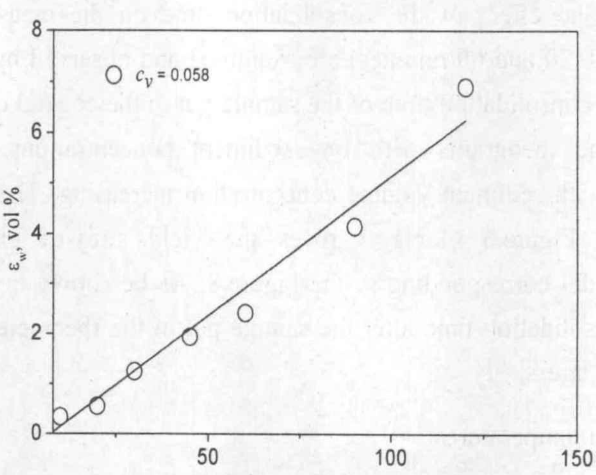


Figure.7: Water volume fraction separated from the sample with C_v=0.058 against consolidation time

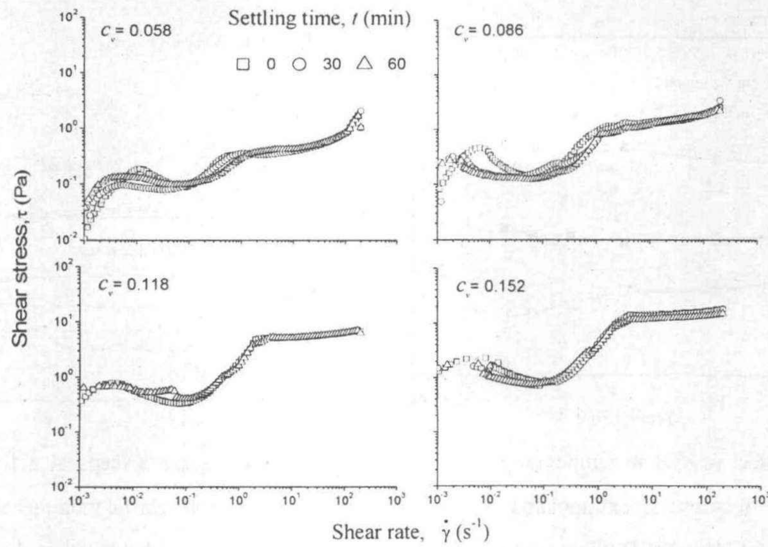


Figure.8: Effect of consolidation time on the rheograms for four different samples at 20°C

3.2 Oscillatory mudflow

In oscillatory measurements of mudflow, a shear stress sweep at a fixed frequency is performed prior to the following frequency sweep in order that the selected stress is in the linear viscoelastic region. Figure.11 shows the variations of the elastic modulus and the loss modulus with the shear stress at a fixed frequency (f=1 Hz) for the sample 2. Here, they are displayed in linear coordinate and logarithmic coordinate systems, respectively. It can be found that a solid-like behavior is observed at lower shear stress (G'<G") and a liquid-like behavior observed at higher shear stress (G'>G"). The crossover shear stress (G'=G") is found to be around 0.5 Pa. As be shown in Figure.11, there appears to be two approximate plateau intervals in the range of low and high shear stresses, respectively. Thus, in the following study, the measurements are carried out including these two regions, which are defined as the viscosity region and elastic region.

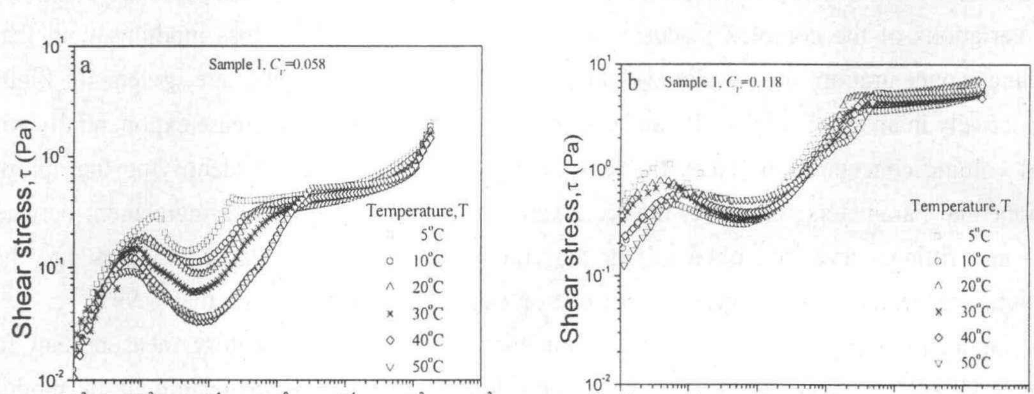


Figure.9: Flow curves of shear rate against shear stress at different system temperatures for samples 1 and 3, respectively

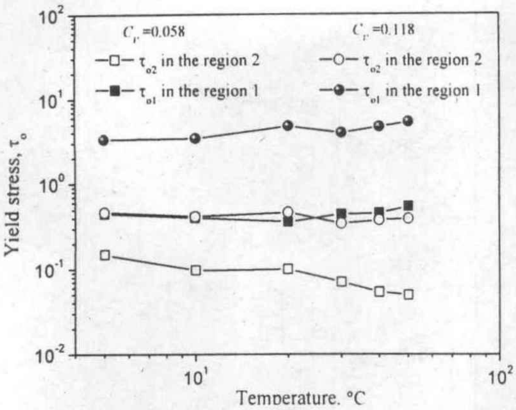


Figure.10: Effect of system temperature on the yield stresses, extrapolated by the Dual-Herschel-Bulkley model, for samples 1 and 3, respectively

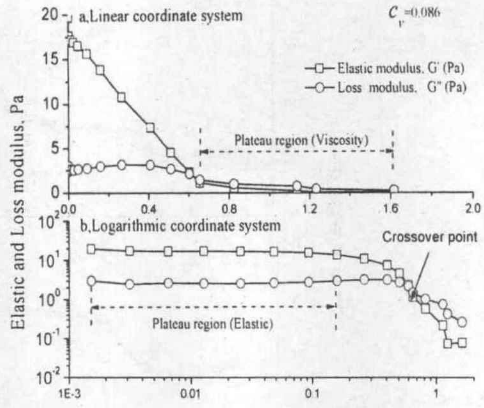


Figure.11: Shear stress sweeps at a fixed frequency (f=1 Hz): variations of the elastic modulus and the loss modulus with the shear stress, displayed in linear coordinate and logarithmic coordinate systems, respectively

3.2.1 Frequency sweep in the elastic region

Figure.12 plots that the variations of the complex viscosity, the elastic modulus and the loss modulus with the frequency for four samples. An important point to note is that the elastic modulus is greater than the loss modules over the entire frequency range measured, indicating these samples are predominantly elastic. With the mud volume concentration increasing theses parameters are increased. Moreover, the Figure.12 also demonstrates that the frequency dependence of the loss modulus and the elastic modulus are rather weak over the range of low frequency and but the complex viscosity sharply decreases with the increases of the frequency.

Ocean waves near shore normally have a period about 3-8s, i.e. an angular velocity from 0.7 to 1.5 rad/s. The effects of the muddy seabed on water waves above will become weaker when waves become shorter or water gets deeper (Huang and Huhe, 2009). Thus, from a practice point of view, the variations of the complex viscosity, the elastic modulus and the loss modulus with the mud volume concentration at angular velocities ω=0.68 and 1.47 rad/s are given in Figure.13, respectively in an elastic region. It can be seen that experimental data increase exponentially with the mud volume concentration. Thus, the least squares method is used in identifying the appropriate exponential parameters. These results are given in Figure.13. A very good agreement between the data and fitting curves are obtained for the complex viscosity, the elastic modulus and the loss modulus, respectively. The regression correlation coefficient (R2) is larger than 0.997.

Figure.14 depicts that effect of consolidation time on the oscillatory measurement for the sample CV=0.058. Clearly, the longer the consolidation time is, the greater the elastic modulus is. However, the loss modulus shows a low sensitivity to the variation of the consolidation time, which is similar to the measured results of steady mudflow as shown in Figure.8. Combined with the discussion of 3.1.3 section, the consolidation time of sample put in the rheometer strongly changes the elastic, while play few impacts on the viscosity.

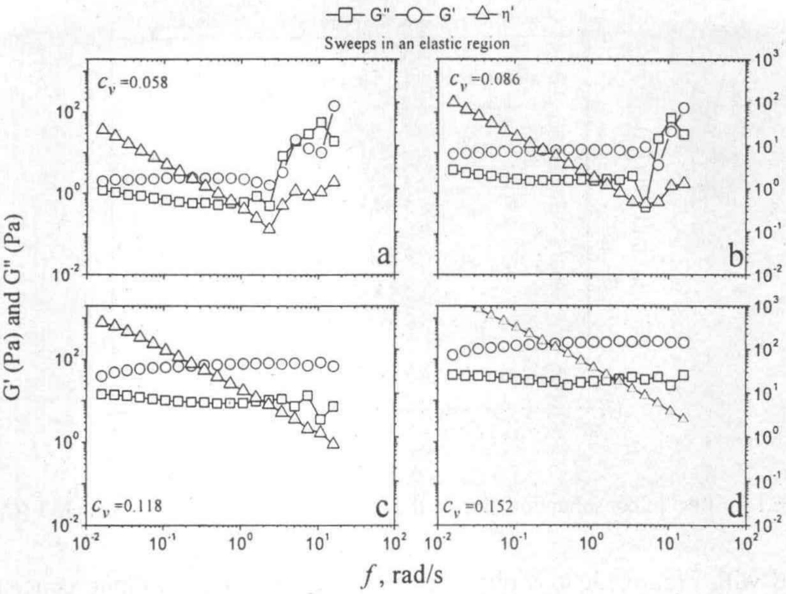


Figure.12: Frequency sweeps for four samples in an elastic region: variations of the complex viscosity, the elastic modulus and the loss modulus with the frequency

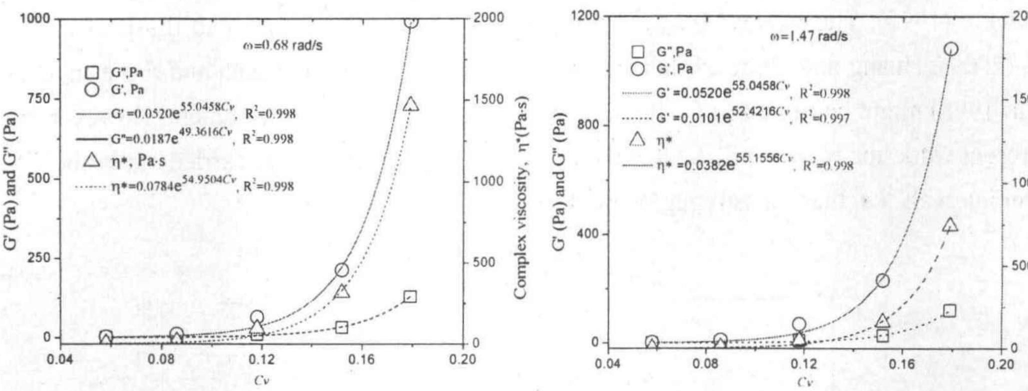


Figure.13: Variations of the complex viscosity, the elastic modulus and the loss modulus with the mud volume concentration at angular velocity ω=0.68 and 1.47 rad/s, respectively, in an elastic region

3.2.2 Frequency sweep in the viscosity region

Figure.15 gives the results of frequency sweeps for four samples in the viscosity region. Unlike the results of sweeps in the elastic region, the curve shows a strong dependence on the frequency. Overall, a liquid-like behavior is observed over the range of frequency measured (G'<G"). With the increases of the frequency, the elastic modulus and the loss modulus maintain a continuous increase, and the complex viscosity firstly decreases and then increases. Figure.16 shows the variations of the complex viscosity, the elastic modulus and the loss modulus with the mud volume concentration at angular velocities ω=0.68 and 1.47 rad/s in the viscosity region, respectively. The exponential relationships are also used to fit the curves and the results given in the Figure. As be seen, the agreement between the data with the predictions is also acceptable.

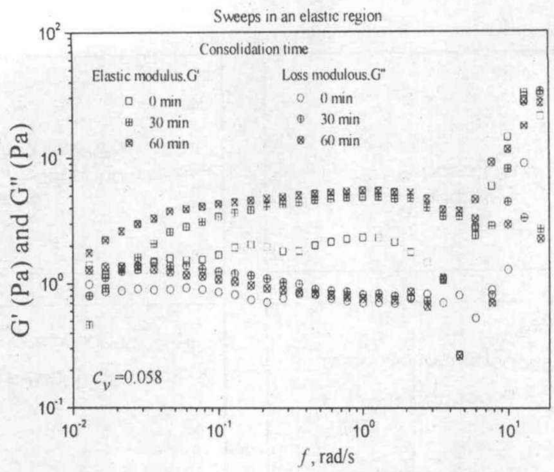
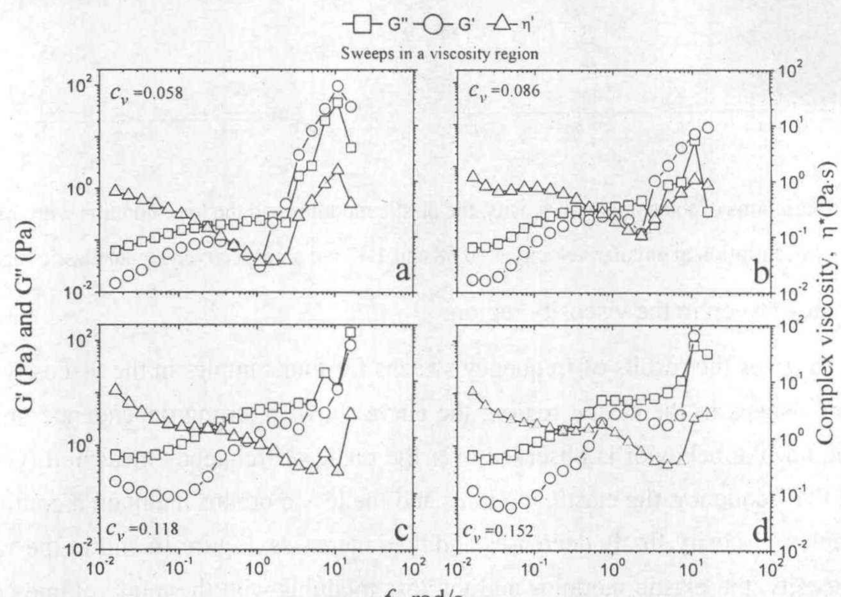


Figure.14: Effect of consolidation time on the oscillatory mudflow for the sample 1 (C_V=0.058)

Compared with Figure.13, it is observed that at a fixed mud volume concentration, all three parameters in the elastic region are several orders of magnitude lager than those in the viscosity region. Table 4 shows a comparison of the elastic modulus and the complex viscosity in this work with those in the literature. As shown, our results in the elastic region are similar to those of Jiang and Mehta (1995). The values obtained in the viscosity region are similar to those of Huang and Huhe (2009). Huang and Huhe explained this difference between their data and those in Jiang and Mehta (1995) might be because of different median gain size and organic content. However, base on the present work, the reason may be that the oscillatory measurements are carried out in the different plateau intervals, i.e. the viscosity region or elastic region, respectively.



Figre.15: Frequency sweeps for four samples in a viscosity region: variations of the complex viscosity, the elastic modulus and the loss modulus with the frequency

Table 4: Comparison of the elastic modulus and viscosity in this work with those in the literature

Mud source	Lian-yun Harbor in elastic region	Lian-yun Harbor in viscosity region	Hangzhou Bay (Huang and Huhe, 2009)	Okeechobee (Jiang and Mehta, 1995)
D50 (μm)	6.2	6.2	10.35	9
C_V	0.118	0.118	0.12	0.11
G' (Pa)	70	0.247	0.074	399
η^*/η' (Pa·s)	48	1.426	0.129	71

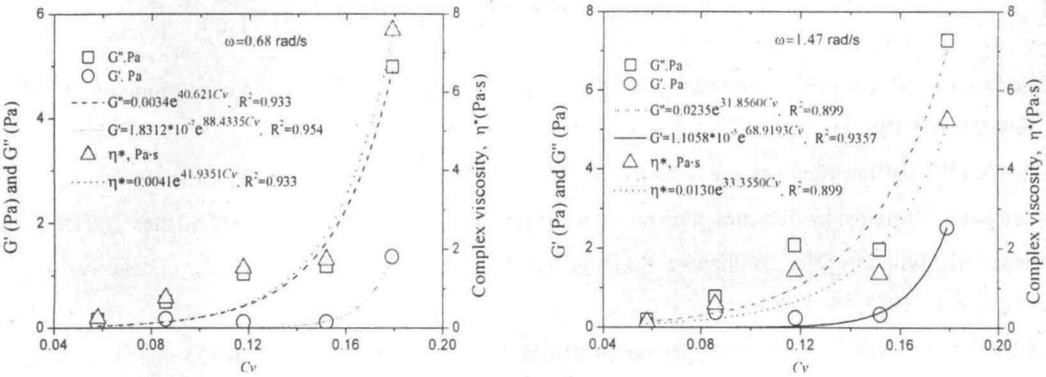


Figure.16: Variations of the complex viscosity, the elastic modulus and the loss modulus with the mud volume concentration at angular velocity ω=0.68 and 1.47 rad/s, respectively, in an viscosity region

4 Conclusions

The rheological properties of steady and oscillatory mudflow at Lian-yun Harbor in China have been studied by using the RS6000 rheometer. Based on the experimental results and analysis, the following conclusions can be obtained:

(1) In the steady flow, the Dual-Herschel-Bulkley model, base on two different regions of the shear rate, can be used to describe the flow curve and obtain both the static yield stress and dynamic yield stress. The higher value of static yield stress is in good agreement with the traditional value of yield stress measured by using the vane torsion. After the sample put in the rheometer, consolidation time and system temperature show a few influences on the results of steady measurement, especially for the sample with high sediment volume concentration.

(2) In the dynamic (oscillatory) measurements, at a shear stress sweep there are two approximate plateau intervals, which are defined as the viscosity region and elastic region, respectively. The complex viscosity, the elastic modulus and the loss modulus in the elastic region are several orders of magnitude lager than those in the viscosity region. Thus, in the oscillatory measurements, the researchers should be careful to choose the stress plateau intervals as the frequency sweep according to the actual conditions.

(3) Our analysis also shows that both steady and dynamic rheological properties can be expressed as appropriate exponential functions of sediment volume concentration. The consolidation

time in the rheometer shows a major impact on the elastic modulus. However, the loss modulus shows low sensitivity to the variation of the consolidation time.

Acknowledgement

The financial support by 300 thousand tons channel construction project at Lian-yun Harbor (20100714-30HDK Y008-2) is partially responsible for the conduct of this research.

Reference

1 Berlamont J, Ockenden M, Toorman E, et al. The characterisation of cohesive sediment properties, Coastal Eng., 1993,21: 105-128

2 Coussot P, Mudflow rheology and dynamics, Rotterdam, The Netherlands : A.A. Balkema,1997

3 Coussot P, Rheophysics of pastes: a review of microscopic modelling approaches, Soft Matter, 2007,3: 528-540

4 James AE, Williams DJA., Williams P.R., Direct measurement of static yield properties of cohesive suspensions, Rheol. Acta, 1987, 26: 437-446

5 Julien PY, Lan YQ, Rheology of hyperconcentrations, J. Hydraul. Eng., 1991,3: 346-353

6 Chhabra RP, Bubbles, drops, and particles in non-Newtonian fluids (2nd Edition), Boca Raton, FL : CRC/Taylor & Francis, 2006

7 O'Brien JS, Julien PY, Laboratory analysis of mudflow properties, J. Hydraul. Eng., 1988, 114: 877-887

8 Huhe A, Huang Z H, Zhang Y B, et al. Rheology of mudflow in Lian-yun-gang Port, Mech. Prac., 1994, 16: 21-24 (in Chinese)

9 Jiang F, Mehta AJ, Mudbanks of the southwest coast of India IV: Mud viscoelastic properties, J. Coastal Res., 1995, 11: 918-926

10 Kessel TV, Blom C, Rheology of cohesive sediments: comparison between a natural and an artificial mud, J. Hydraul. Res., 1998, 36: 591-612

11 Babatope B, Williams PR, Williams DJA., Cohesive sediment characterization by combined sedimentation and rheological measurements, J. Hydraul. Eng., 2008, 134: 1333-1336

12 Huang Z, Huhe A, A laboratory study of rheological properties of mudflows in Hangzhou Bay, China, Int. J. Sediment Res., 2009, 24: 410-424

13 Williams PR, Williams DJA, Rheometry for concentrated cohesive suspensions, J. Coastal Res., 1989, Spec. Issue 5: 151-164

14 Schramm G, A practical approach to rheology and rheometry (2nd Edition), Gebrueder HAAKE GmbH, Germany, Chapter 8, 2000

15 Maciel GF, Santos HK, Ferreira FO, Rheological analysis of water clay compositions in order to investigate mudflows developing in canals, J. of the Braz. Soc. of Mech. Sci. & Eng., 2009, 31: 64-74

16 Toorman EA, An analytical solution for the velocity and shear rate distribution of non-ideal Bingham fluids in concentric cylinder viscometers, Rheol. Acta, 1994, 33: 193-202

17 Coussot PS, Proust, Ancey C, Rheological interpretation of deposits of yield stress fluids, J. Non-Newtonian Fluid Mech., 1996, 66: 55-70

18 Govier GW, Aziz K, The flow of complex mixtures in pipes, Van Nostrand Reinhold Co, 1982

19 Mitsoulis E, Flows of viscoplastic materials: models and computations, Rheol. Reviews, 2007, 135-178

20 Uhlherr PHT., Guo J, Tiu C, et al. The shear-induced solid-liquid transition in yield stress materials with chemically different structures, J. Non-Newtonian Fluid Mech., 2005, 125: 101–119

21 Mas R, Magnin A, Rheology of colloidal suspensions: Case of lubrificating greases, J. Rheol., 1994, 38: 889-908

22 Whitehouse R, Soulsby R, Roberts W, et al. Dynamics of estuarine muds: a manual for practical applications, Thomas Telford, USA, Chapter 3, 2000