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Rheological study of mudflows at Lianyungang in China

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ABSTRACT

An experimental study of the rheological properties of mudflows at Lianyungang in China was carried out by the RS6000 rheometer, including steady and dynamic measurements. Five samples with the range of mud volume concentration from 0.058 to 0.179 were investigated. Based on the experimental data, a Dual-Herschel–Bulkley model was developed to analyze the flow curve and interpolate the static and dynamic yield stresses. The results show that in the steady measurement, the consolidation time and the system temperature show some effects on the rheogram and the yield stress for the sample with low sediment volume concentration, and the effects are strengthened gradually with the sediment volume concentration increasing. Under a shear stress sweep, two linear visco-elastic regions, showing the viscous and the elastic behaviors respectively, were discovered. Complex viscosity, elastic modulus and loss modulus in the elastic region are several orders of magnitude larger than those in the viscous region. Furthermore, the analysis of experimental data show that both steady and dynamic rheological properties can be expressed as appropriate exponential functions of the sediment volume concentration.

1. Introduction

Natural mud is a complex mixture of saline water, cohesive sediment, 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, the 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) for the marine sediment transport and by Coussot (1997, 2007) for the mudflow, respectively. Overall, at low sediment concentrations, the mixtures usually exhibit Newtonian fluid behavior, while at high sediment concentrations the mixtures become non-Newtonian shear-thinning or viscoelastic behaviors. Furthermore, the rheological behaviors of the mixtures are also affected strongly by the physic-chemical factors (flocculation).

Rheological experiments 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 the 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 both the different rheological model selected and the flow curve segmented for extrapolation lead to a wide distribution in the published data of yield stress (James et al., 1987; Julien & Lan, 1991; Chhabra, 2006). Therefore, the yield stress obtained by different models should not be directly compared with each other and the extrapolation beyond the range of experimental conditions must be treated with caution.

In the last half-century, a number of rheological 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 these models, are largely dependent on the shear rate and increases exponentially with the sediment volume concentration increasing (O’Brien & Julien, 1988; Huhe et al., 1994).

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Unlike the steady measurement, until now few experimental data has been published on the oscillatory measurement of natural mud (Jiang & Metha, 1995; Kessel & Blom, 1998; Babatope et al., 2008; Huang & Huhe, 2009), although the test provides information on the elastic properties of the mud, which is of importance to study the wave forcing in shallow waters (Williams & Williams, 1989). Thus, the present study focuses on the rheological behaviors of natural mud and contributes a valuable data set of the steady and dynamic rheology for the natural mud at Lianyungang.

2. Experimental methods

In this study, natural mud samples were taken from Lianyungang in China. They were packaged in a sealed container and shipped to the laboratory. Sediment grains are characterized by an average density of 2713 kg/m^3 and a median grain diameter of 6.2 μm (D50). Size distribution of the sediment grains measured by two different methods is shown in Fig. 1.

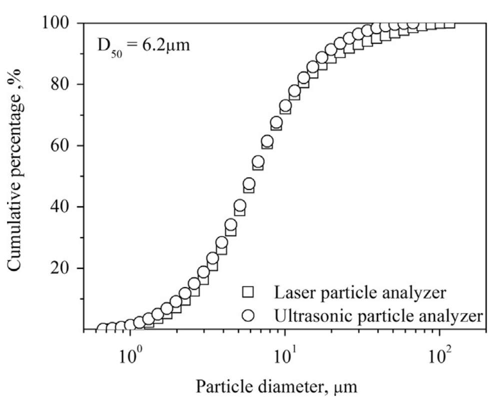

Fig. 1. Sediment size distribution measured by two different methods.

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	2713
Sample 2	0.086	1146	233	
Sample 3	0.118	1200	320	
Sample 4	0.152	1256	412	
Sample 5	0.179	1305	486	

To get the desired sediment volume concentration, 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 are summarized in Table 1. In the table, the mud volume concentration is equal to the ratio of the mud mass concentration to the sediment grains density (s/ρ_s) (Whitehouse et al., 2000). During the tests, 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 three-blade stirrer at a fixed low speed. After homogenization, the rheological characterization of the samples was measured by exploiting the performance of the rheometer (Haake RheoStress 6000, Germany).

Rheological measurements were carried out on the RS6000 rheometer with a coaxial cylinder sensor system (Z38 DIN, gap width=2.5 mm and sample volume of 30.8 cm^3). In the rheometer, a temperature control system for cone and plate measuring geometries and two units with different coaxial cylinder diameters is available. Liquid temperature-controlled units can make the sensor system reach to a fixed temperature and maintain this temperature throughout the experiment. 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 has a range of shear rates from 10^{-3} s^{-1} to 1000 s^{-1} and a range of viscosity from 0.001 Pa s to 1000 Pa s. In the oscillatory measurement, an amplitude sweep at a fixed frequency of 1 Hz was performed prior to the following measurement of oscillatory frequency in order to ensure the selected stress keeping in the linear visco-elastic region. Experimental data were obtained by recording the complex viscosity ($\eta*$), the elastic modulus (G') and the loss modulus (G''). Frequency ranged was from 0.01 rad/s to 100 rad/s. Furthermore, a vane-type rotor (FL22) was also used to measure the yield stress of the samples according to the suggestion by Schramm (2000).

3. Results and discussion

3.1. Steady mudflow

The flow behaviors of mud at Lianyungang are investigated over a wide range of shear rates from 0.001 s^{-1} to 100 s^{-1}. Fig. 2a shows the variation of the flow curve with the shear rates. At low shear rates, the shear stress increases quickly with the shear rate and passes through a turning point and thereafter goes up slightly. Overall, it is observed that the shear stress of the sample increases with the volume concentration increasing. Due to the fact that the internal frictional forces become greater with the sediment

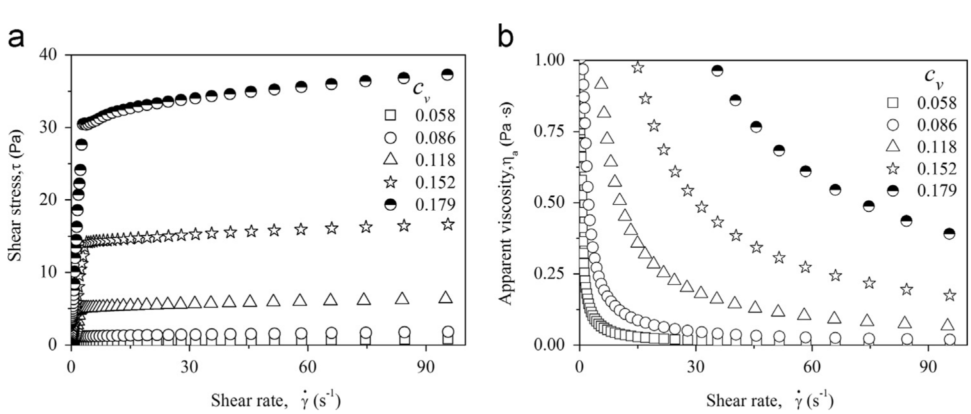

Fig. 2. Rheograms of the samples with different volume concentrations at 20 °C.