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Correlation between the slump parameters and rheological parameters of debris-flow

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Abstract

Rheological characteristics are important information for understanding or simulating debris-flow movement. Debris-flow movements involves complex and heterogeneous material with grain size distributions ranging from silt to large rocks. Conventional rheometers are usually limited to measure the rheological parameters of debris-flow of fine particles. Slump-tests has been used to evaluate the flow behaviour of fresh concretes which allow the tested concrete slurries to have larger particles. In this study, the relationship between the parameters obtained from rheometer measurements and slump tests for debris-flow slurries with/without big particles were investigated. At the initial stage, we used fine-sediment slurries to conduct rheological experiments to find the relationship between the parameters obtained from the rheometer measurements and slump tests. The rheological parameters of slurries were measured using the 'Brookfield DV-III rheometer'. The rheological behavior of the slurry samples used in this study follow the Bingham fluid model. Rheological parameters (i.e., yield stress and viscosity) are affected by the concentration of slurry, indicating that the higher the concentration, the greater the value of the rheological parameters. Slump test was then conducted using the same material samples prepared for rheometer test and the slumped height and spreading diameter of the tested sample were measured. The result shows that the slump height ratio and spreading ratio of the tested slurry decrease with the increase of slurry sediment concentration. Experimental sediment slurry samples were prepared by mixing coarse sands of about 1 mm in diameter. Our results show that the parameters obtained by rheometer measurements are closely related with those by slump tests for the slurries used in this study, indicating that there is a high potential to evaluate rheological parameters of debris-flow using a slump test as an alternative method.

Keywords: Slump test; Bingham model; rheological parameters; and slump parameters.

1. Introduction

Rheology is a science that deals with the study of fluid and deformation behavior of fluid. When an external force is applied to a body (solid, liquid or gas), it leads to the movement of the body from its original position towards the down slopes or cause a change in its original shape (Malkin and Isayev, 2006). The study of rheology is important in debris-flow as well as in many industries such as paints, polymers, printing inks, paper coatings, ceramics, cosmetics, food systems, pharmaceutical and agrochemical formulation, concrete related constructions company, and liquid detergents (Tadros, 2010). The researchers have been suggested numerous techniques to measure the rheology of concrete, concentrated suspensions, thickened tailings and paste fill, which behave as viscoplastic fluids (Bird et al., 1983; Utracki, 1988; Nguyen and Boger, 1992; Schramm, 2000). Nguyen and Boger (1992) mentioned two main methods of rheology measurements; namely direct and indirect methods. In the indirect methods, yield stress can be obtained from the shear stress vs. shear rate graph by extrapolating and in the direct methods the yield stress can be obtained under static conditions (which also known as true yield stress). Debris-flow is usually treated as the movement of a continuum for simplicity, in spite of the existence of solid particles in it. To simulate the debris-flow both in field and in laboratory, we use partial differential equations with some rheological parameters. Selecting suitable rheological model and its associated parameters are very important in debris-flow simulation (Arattano et al., 2006, Jan and Shen, 1997). Iverson (2003) observed that the debris-flow behavior can changes with the changes of

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particle concentration in the mixtures. He also mentioned that Coulomb mixture theory is a good alternative which can represent the inconstant solid-fluid interaction in a heterogeneous mixture.

The rheological behaviors of sediment-slurry mixtures are depended on sediment concentration, sediment type, and particle size distribution. Many researchers have shown that the high concentration slurry mixture could be treated as a Bingham fluid having yield stress and viscosity parameters (Chu, 1983; Fei, 1981 and 1983; Iverson, 2003; Jan et al., 2009, 2011, & 2018; Major and Iverson, 1999; Wu, 1981). Most poorly sorted, naturally debris-flow mixtures are composed of a fluid phase of water and fines (clay and silt), and a granular phase of sand and gravel (Rodine, 1974; Hampton, 1975; Pierson, 1981). The clay and much of the silt are considered to be an intrinsic part of the fluid because they usually will not settle out of suspension during a natural flow event (Tan, 1985; Davies, 1986); sand and gravel, on the other hand, might or might not be carried in suspension by a particular flow. With increasing amounts of silt or clay, sediment-slurry mixtures may acquire a yield strength. Mixtures that contain largely silt acquire a yield strength in the range of 30-35% of volume concentration (Qian et al., 1980). Clay-rich mixtures may exhibit yield strength at volume concentrations as low as 10% or less (Hampton, 1975; Wan, 1982; Yang and Zhao, 1983). Conventional rheometers are usually limited to measure the rheological behavior parameters of debris-flow with fine particles.

The slump measurement using slump test is widely used for measuring the workability of concrete due to its simplicity. In this test, the concrete will collapse or flow if the yield stress is exceeded and will stop when the stress is below the yield stress. Therefore, the slump test is associated to the measurement of yield stress (Ferraris and Larrard, 1998) and spreading distance. Some researchers have used the finite element method to simulate the slump test (Mori and Tanigawa, 1992) assuming that concrete follows the Bingham model. The slump heights were used to measure the viscosity and workability of the mixtures. When the slump height is large, the mixtures holds a small yield stress, and small slump height specifies a large yield stress of the mixture. In this paper, efforts were given on the potential of application of slump test to measure the rheology of sediment-slurry mixtures.

The applicability of slump test to measure rheological parameters of kaolin slurry, slurry with added coarse particles were studied and found a linear relation between rheological parameters and slump parameters (Jan et al., 2009, 2011, 2018). In the present study, the experiments were conducted in two phase: firstly, sediment mixture was used as the tested material and a traditional rheometer was used to measure its rheology. In the second stage, the same sediment mixture was used as the testing materials and its flow behavior were measured by a slump cone instead of a rheometer. The main objective of this study objective is to find the correlation between the rheological parameters and slump parameters, so as to evaluate the potential of using slump test to assess the rheological parameters.

2. Materials and methods

In this study, the tested slurries were the mixtures of fine sediments taken from a reservoir deposition. The sediments have a median diameter of 0.0036 mm and the particle size distribution is shown in Fig. 1. We proportioned those sediment materials into five kinds of slurries having sediment concentrations of 25%, 27.5%, 30%, 32.5% and 35%, respectively. The slurry of sediment concentration 30% was used to mix with different amounts of coarse particles having diameter approximately 1 mm to form five kinds of slurry-gravel mixtures having total sediment concentration of 30%, 40.5%, 44%, 47.5% and 51%, respectively. Those fine-sediment slurries and the slurries with coarse particles (simply named slurry-gravel mixtures herein) were used in the rheological experiments and slump tests.

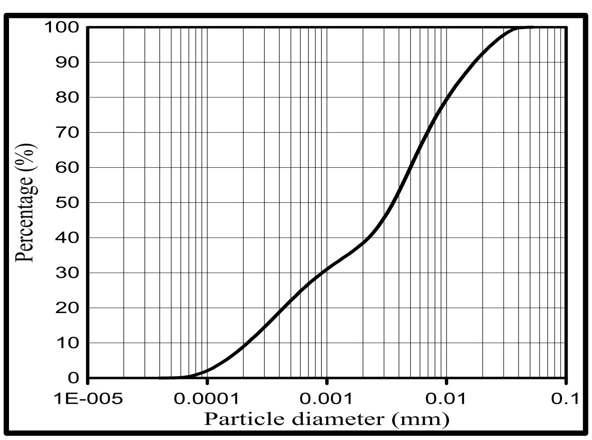


Fig. 1. Particle size distribution of fine-sediment slurry

Rheological experiments in this study were conducted to understand the variation of shear stress of sediment-slurry mixtures with different volume concentration under low shear rates (i.e., < 20 s^{-1}). Based on the measured shear stress, the yield stress and viscosity coefficient of sediment material were calculated to investigate the relationship between the yield stress and viscosity coefficient under the varying concentration of sediment-slurry mixtures. The details experimental procedure and considerations has been described elaborately by Jan *et al.* (2011 and 2018)

3. **Methodology**

In this study, the Bingham fluid model, having two parameters (i.e., the yield stress and viscosity), was used to simulate the rheological behavior of the slurries and the slurry-gravel mixtures,

$$\tau = \tau_B + \mu_B \dot{\gamma} \tag{1}$$

where τ_B is the yield stress and μ_B is the Bingham viscosity, and $\dot{\gamma}$ is the shear rate. The rheological curves of slurries were measured using the 'Brookfield DV-III rheometer' and were shown in Fig. 2b.

The slope of each trend line in the shear stress vs shear rate graph represents the coefficient of viscosity. The plots of Bingham viscosity vs volume concentration and the yield stress vs volume concentration have been constructed as shown in Figs. 3a & b. Later on the rheological parameters will be compared with slump parameters obtained from the slump tests to find the correlation.

A self-made cylindrical slump cone (mould) having top inner diameter of 50 mm, bottom inner diameter of D_0=100 mm, and height of H_0=150 mm was used in the slump tests and slump heights and spreading diameters under different conditions of slurries were measured. The experimental setup is shown in Fig 2c. The slump height and spreading diameter were normalized as the ratio of the slump height to the initial height of tested sample (it equals the height of slump cone), and the ratio of the spreading diameter to the bottom inner diameter of the mould. The normalized terms are known as slump height ratio (H_r) and spreading diameter ratio (D_r), which are shown in equations 2 & 3.

$$H_r = \Delta H / H_0 \tag{2}$$

$$D_r = \Delta D / D_0 \tag{3}$$

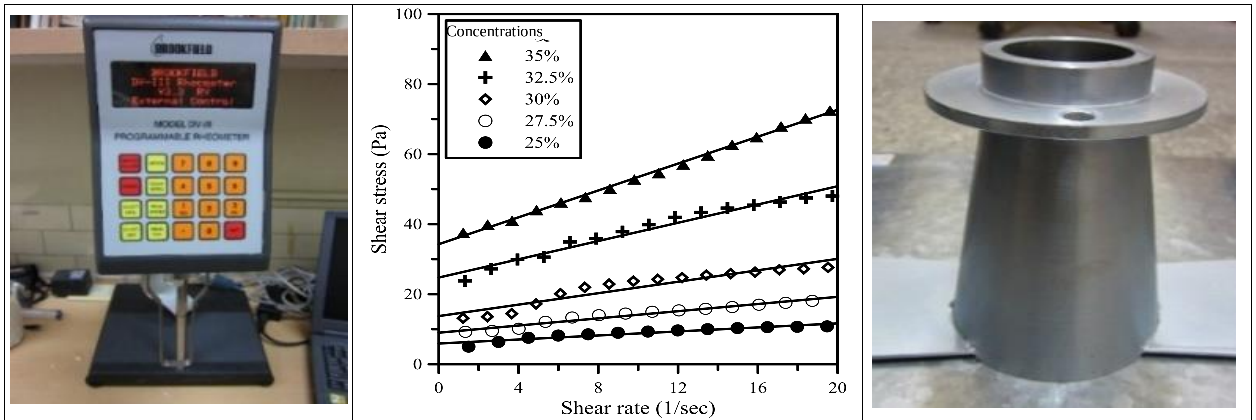
Using the above calculated values the correlations of shear stress and viscosity with the slump height ratio and spreading diameter ratio were determined, respectively. After having the rheological parameters and slump parameters from the experimental results, the plots between the rheological parameters (the yield stress and viscosity) and slump parameters (the slump height ratio and spreading diameter ratio) were compared to assess their relationships.

4. **Results and discussion**

4.1. Rheological parameters

As shown in Fig. 2b, it is clear that the shear stress is linearly related with the shear rate, and this phenomenon indicates that the slurries used in the present study can be treated as Bingham fluids. The shear rate of the reservoir sediments is 20 s^{-1} or less than 20 s^{-1} (Fig. 2b) and the shear stress is about 7.5 to 10 Pa for sediment volume concentration of 25%. Similarly, the range of shear stress at volume concentrations of 27.5%, 30%, 32.5% and 35% are 14~19.1 Pa, 21.9~28.9 Pa, 35.9~50.9 Pa, and 47.4~85.3 Pa, respectively, as shown in Fig. 2b.

The experimental results in Fig 3a, explain that when coarse particles are present in the fine sediment slurry, the yield stress of that slurry become less compared to that mixtures of only fine sediment under same sediment concentration. This phenomenon was also observed by Philips and Davies (1991) and Major and Pierson (1992). The viscosity coefficient of slurry gravel mixtures also shows the similar trend as shown in Fig 3b. The reason behind this characteristic could be the development of stress and viscosity in sediment slurry containing coarse particles is much slower than the development in fine sediment slurry due to high frictional resistance (Major and Iverson, 1999). Therefore, the rheology of the sediment slurry could vary widely depending on the particle size present in the slurry.



a). The Brookfield DV-Ⅲ rheometer setup

b). Shear stress vs shear rate

c). Cylindrical slump cone

Fig. 2: Rheometer and cylindrical mould used in this study

4.2. Slump test

The slump height ratios and spreading diameter ratios of the results of slump tests under different slurry conditions were presented in Figs. 4a & b. As shown in these figures, the slump height ratio and spreading diameter ratio sharply decreases with the increase of slurry sediment concentration. When different amounts of coarse particles mixed with the fine-sediment slurry of concentration 30% to form slurry-gravel mixtures, the decreasing rates of both ratios of slump height and spreading diameter against total sediment concentrations of the slurry-gravel mixtures are much smaller than those obtained from the fine sediment slurries. This indicates that fine sediments (clays) and coarse particles (sands or gravels) play different roles in the rheology of sediment slurries. The former provides friction and cohesion, while the latter majorly provides friction only. The content of fine sediments plays more sensitive roles in the rheological behavior of slurry due to cohesions between fine particles.

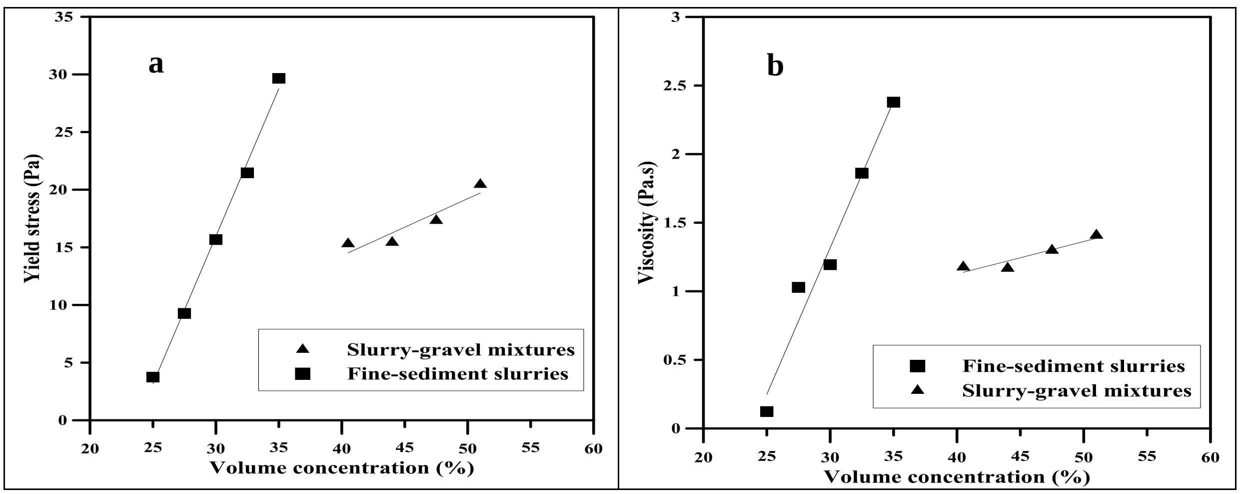


Fig. 3: Relationships of rheological parameters and sediment concentrations of slurries

4.3 Correlation between rheological and slump parameters

The rheological parameters (the yield stress and viscosity) obtained from rheometer measurements, slump parameters (slump height ratio and spreading diameter ratio) obtained from slump tests for fine-sediment slurries, and slurry-gravel mixtures used in this study were compared as shown in Fig. 5. In the above rheological and slump parameters models analysis, the values of R^2 for the relation of parameters of fine-sediment slurries ranges from 0.85 to 0.99. The R^2 values greater than 0.7 are considered as strongly correlated (Moore et al. 2013), as a result it implies that the rheological parameters are strongly related to slump parameters.

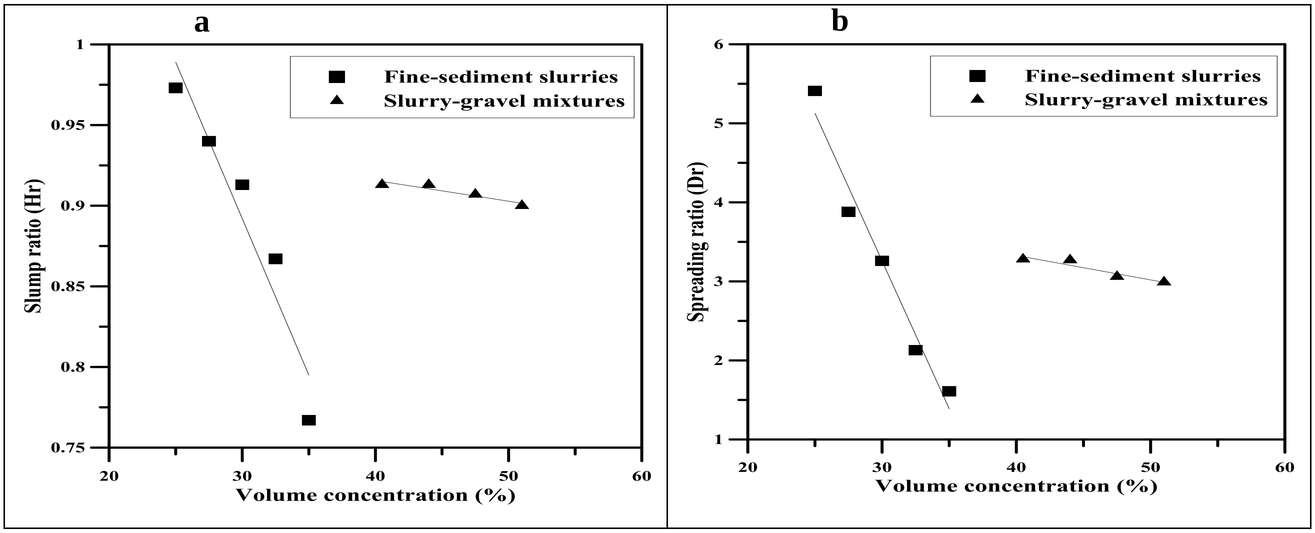


Fig. 4. (a) Slump height ratio vs. concentrations; (b) Spreading ratio vs. concentrations

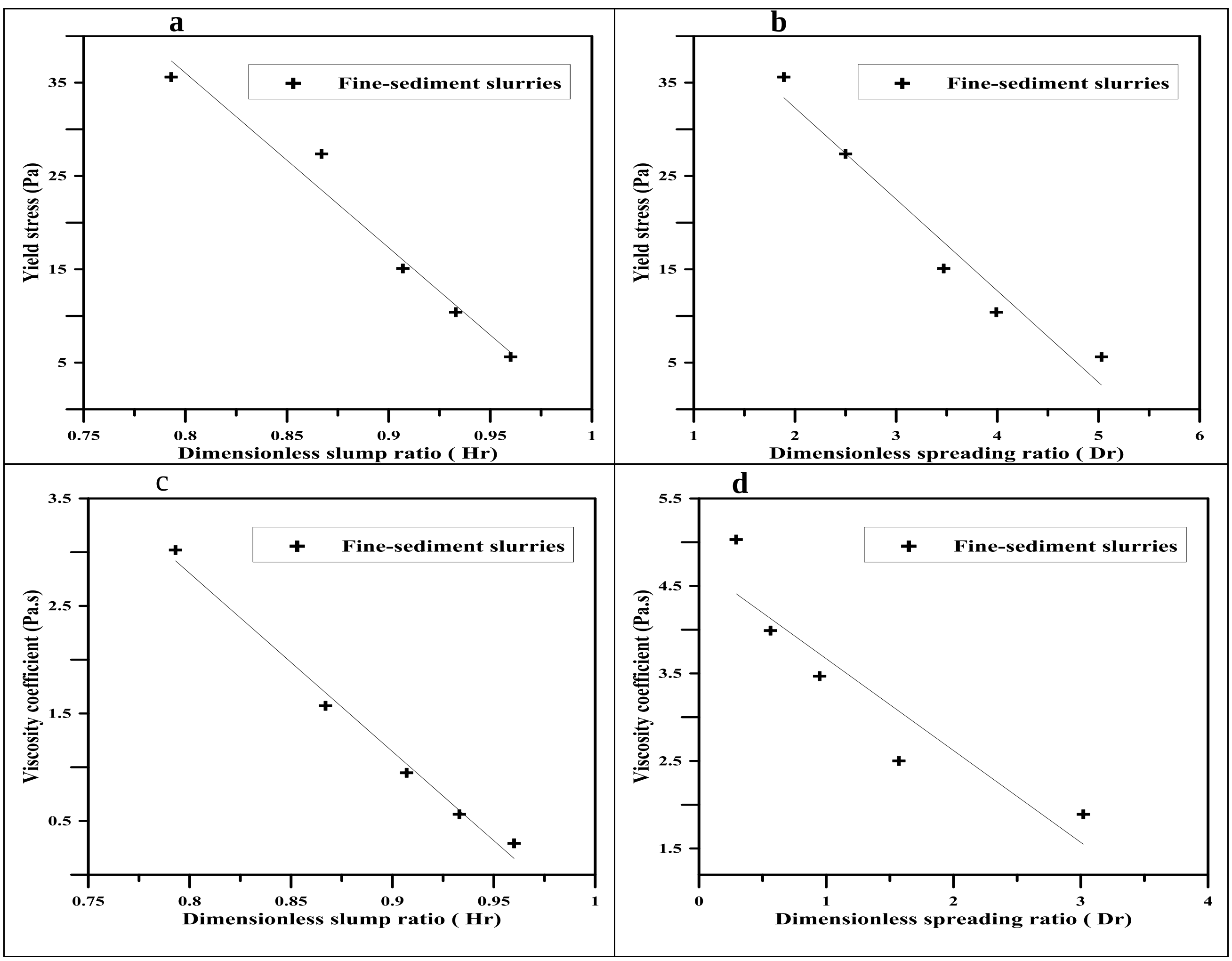


Fig. 5. (a) Yield stress vs. slump height ratio; (b) Yield stress vs. spreading diameter ratio; (c) Viscosity coefficient vs. slump height ratio; (d) Viscosity coefficient vs. spreading diameter ratio.

Table 1: Relations among the rheological and slump parameters of fine-sediment slurries

Relation model	Model coefficients (a, b)	Coefficient of determination R^2
$\tau_B = a + bH_r$	185.78, -187.18	0.97
$\tau_B = a + bD_r$	51.92, -9.8	0.96
$\mu_B = a + bH_r$	16.07, -16.58	0.99
$\mu_B = a + bD_r$	4.71, -1.05	0.85

5. Conclusions:

This study conducted rheological experiments and slump tests of sediment slurries that have Bingham fluid behaviour, to explore the correlation between the rheological parameters and slump parameters. Looking at the experimental results, we conclude:

1. The slurry-gravel mixtures and fine-sediment slurry mixtures at low shear rates (< 20 s^{-1}) exhibit the characteristics of Bingham fluid.
2. The rheological parameters (the yield stress and Bingham viscosity) are affected by the sediment concentration in the slurry as well as by sediment size distribution. The higher the concentration, the greater the value of rheological parameters.
3. With increasing the sediment concentration of the tested slurry using slump test, the values of slump height ratio and spreading diameter ratio are gradually decreasing. Under the same total concentration, the slurry mixed with coarse particles spread slower and shorter than fine sediment slurry.
4. Among the slump parameters, spreading of slump or slump diameter is more sensitive to rheology measurement.
5. The rheological parameters are well related with slump parameters, and this indicates that there is a high potential to evaluate rheological parameters of debris-flow using a slump test as an alternative method.

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