HERSCEL-BULKLEY GENERALIZED MODELING OF REAL DEBRIS FLOW: SET-UP OF RHEOLOGICAL PARAMETERS ACCOUNTING FOR SEDIMENT CONCENTRATION

***Anna Maria Pellegrino* [1] *& Leonardo Schippa* [1*]**

(1) Department of Engineering, University of Ferrara

**email: leonardo.schippa@unife.it*

KEY POINTS

- *Debris flow rheology.*
- *Rheometer tests on the influence of bulk sediment concentration on the debris-flow rheology.*
- *Herschel-Bulkley generalized model accounting for sediment volume concentration.*

1 INTRODUCTION

Natural flows as mud, debris and hyper-concentrated flows are fast-flow phenomena typically characterized by the rapid motion of a large amount of soil mixed with water, and the study of these events is particularly important with reference to their catastrophic and destructive capability worldwide. In this perspective, a complete and appropriate knowledge of the rheological properties of these kinds of granular flows could be an effective support to the assessment of invasion's areas, travel distance and flow velocity (*Schippa & Pavan*, 2011). For such materials, the bulk flow properties (related to failure, propagation and spreading phase) can be extrapolated from the study of the involved soil-liquid mixture paying particular attention to the influence of solid volumetric concentration and grain size distribution (*Coussot et al.*, 1998*; Pellegrino & Schippa, 2013; Pellegrino, Scotto et al.* 2015). We refer to the Herschel-Bulkely rheological model, which is widely used in hydrodynamic modeling of mud and debris-flows (*Laigle & Coussot*, 1997; *Fraccarollo & Papa*, 2000; *Schippa & Pavan*, 2011). Generally speaking, the flow-like behaviour of slurries appears dominated by the rheological properties of the interstitial fluid phase composed by water and finer sediment fraction, whereas yield stress are greatly affected also by coarser fraction (*Major & Pierson*, 1992). The experimental activity herein presented focuses on the former of these aspects, and puts in evidence the effect associated with the granular bulk concentration of the mixture in terms of rheological properties of the mixture. It was carried out using a standard rheometer equipped with vane rotor system on natural soils collected from the source area of two real events of debris flow occurred in Campania region (Italy).

2 EXPERIMENTS.

The tested samples come from the source area of two real debris flows event occurred in Campania region (southern Italy) which involved the pyroclastic terrains covering the mountains of that region. The collapsed soils (i.e. soil A and soil B) are both pyroclastic, and belong to the most recent deposits originated by the volcanic activity of Somma/Vesuvio mount. The soils are sandy silt with small clay fraction, having specific gravity G_S=2.56-2.62, dry weight of soil per unit volume γ_d=9.08-7.11 KNm^{-3}, total weight of soil per unit volume γ=11.35-12.11 KNm^{-3}, and porosity p=0.66-0.71 respectively. *Scotto di Santolo et al*. (2010) reports the extensive description of the geological and geotechnical soils characteristics.

Laboratory activity consists of 9 tests (Tests #0-8 listed in Table 1). involving fine-grained suspensions with particle diameter less than 0.5 mm, which corresponds to the limiting value of medium sand (according to Wentworth scale). This value not only represents the fine-grained limit, but also it is consistent with the geometrical dimension of the used rheometer. Before starting each test, a sample of distilled water and soils having a volume of about 0.030 10^{-3} m^3 was prepared using an electronic mixer (30 rev/min), and the suspension was incessantly mixed for 15 minutes at uniform velocity in order to homogenise the mixture. The experimental program was carried out at constant temperature of about 23°C. The testing samples is prepared mixing the dry soils, with an appropriate amount of distilled water in order to have a desired bulk volume concentration Φ_T:

$$\Phi_T = \frac{V_s}{V_s + V_w} \tag{1}$$

where V_S is the volume of solids and V_w the volume of water. The tested samples have a bulk concentration ranging from 32% to 42%. Fig.1 shows the whole set of sweep test results, for material A and material B

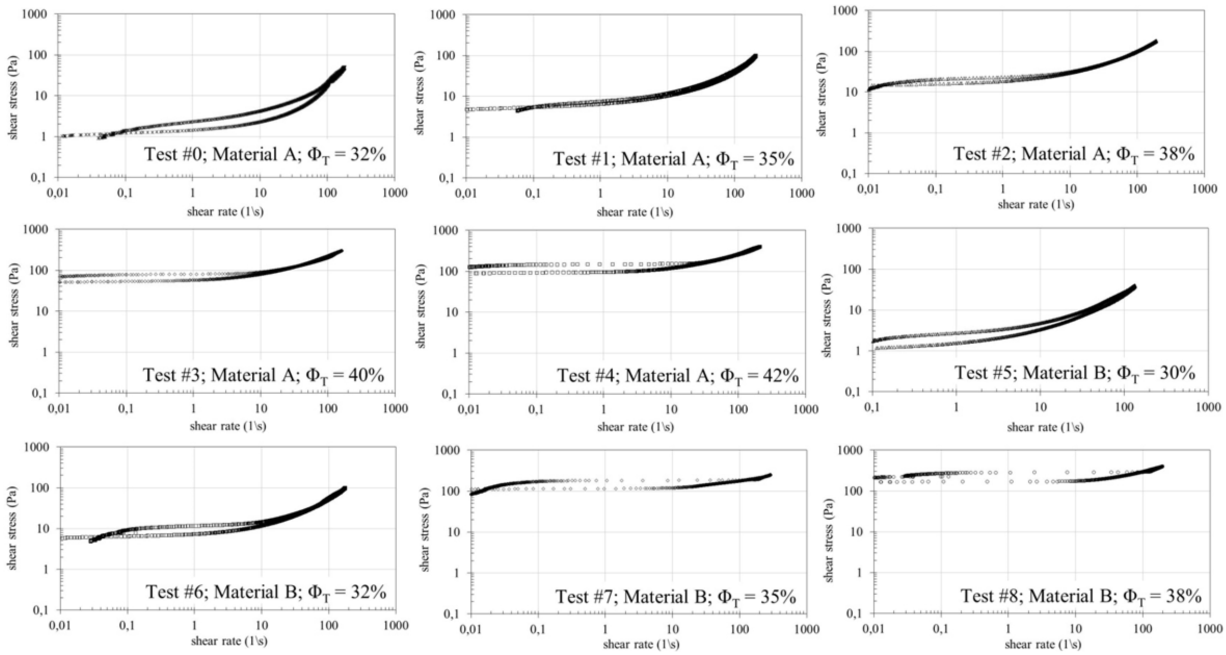

Figure 1. Soil A and B: sweep test results

In order to illustrate the representative behaviour of the fine-grained mixtures, let us consider experimental results for representative soil A mixtures (Φ_T=38 % and Φ_T=40 %) depicted in fig. 2(a). Referring to the increasing ramp of applied shear-stress, the flow curve is composed of two parts: a transition phase, corresponding to the rapid increase of shear rate (stress plateau) above some critical values of stress, which evolution is associated with the liquid regime, and steady flow of material, corresponding to the stress larger than a threshold value, which exhibits an increasing slope of the stress-strain curve associated with a liquid-like behaviour. The stress plateau in the increasing part of the flow curve represents the value of the static yield stress (i.e., τ_{c1} the value of stress at which the material ultimately flows in a liquid regime.). Once the maximum applicable value of shear stress has been reached, the decreasing shear stress ramp is applied. Hysteresis occurs and the shear-strain curve initially overlaps the increasing one, and eventually follows approximately a stress plateau until flow stoppage. The stress plateau associated with the stress-decreasing ramp represents a measurement of the dynamic yield stress (i.e., τ_{c2}). The stress plateau occurred for any test involving material A and B, despite bulk volume concentration (see fig.1). Increasing the stress level around a critical value (i.e. the static yield stress τ_{c1}), leads to a large increasing of the resulting shear rate, until it reaches the value associated with the end of the stress plateau. It may be considered as a critical value ($\dot{\gamma}_{cr}$), which represents the transition of the material mixture from a yielding to a steady state flow behaviour; in fact, no steady flows can be obtained below the critical shear rate value (*Ovarlez et al.*, 2009). The critical shear rate increases similarly to the yield stress, and it implies that the material strength increases with the amount of solid particles in the mixture, but the apparent velocity of the mixture, when it starts to flow, increases almost proportionally. Fig.2 also reports he experimental results in terms of non-dimensional shear stress as a function of the non-dimensional shear rate, to the whole set of tested mixtures. The flow curves related to the material A and B (i.e., the decreasing part of the flow curves plotted in fig.1) collapse to a single curve for each material, and it is evident an asymptotic trend for the higher values of shear rate, corresponding to the apparent viscosity of the mixtures.

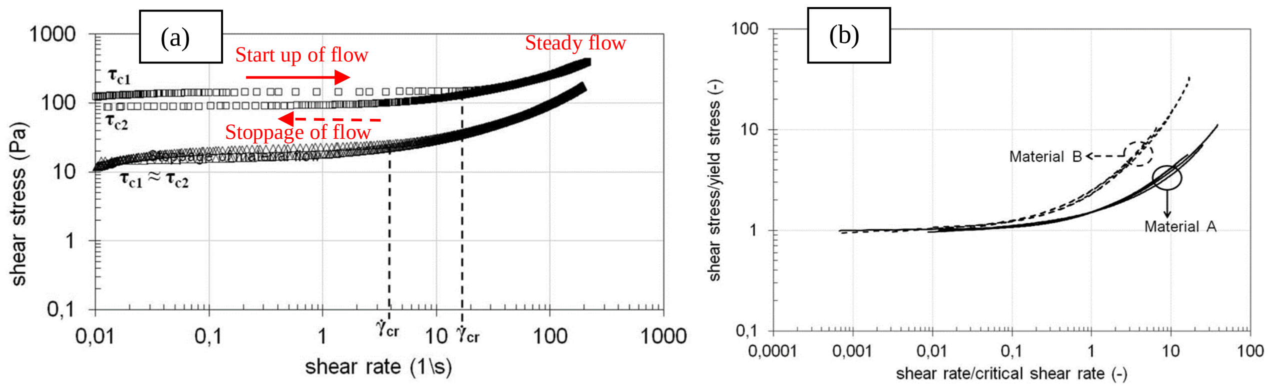

Figure 2. (a) Soil A: representative sweep test Φ_T=38% (empty triangles) and Φ_T=42% (empty square). increasing ramp, decreasing ramp. (b) dimensionless flow curves for soil A and soil B.

3 RHEOLOGICAL MODEL ACCOUNTING FOR THE BULK SOLID VOLUME CONCENTRATION

A Herschel–Bulkley generalized rheological model is used in order to put in evidence the relevance of the effects of the total solid volumetric concentration on the rheological behaviour of the mixture.

$$\tau = \tau_{c2} + k\dot{\gamma}^n \quad (2)$$

where k [Pa·s^n] is the consistent coefficient, and the dimensionless pseudoplastic index n measures the degree to which the fluid is shear-thinning or shear-thickening. Previous work on same debris flow mixtures (*Scotto di Santolo et al.*, 2010) demonstrated that the total solid concentration strongly influences the Herschel-Bulkley generalized model parameters, in terms of consistent coefficient k and yields stress τ_{c2}, which increase, increasing the solid fraction of the mixture. Similarly total solid concentration affects pseudoplastic index n, and the mixture experience shear-thinning or shear-thickening behaviour depending on grain contents (see table 1).

Test-soil	Φ_T (%)	τ_{c2} (Pa)	n (-)	k (Pa s^n)
0-A	32	1.4	1.777	0.004
1-A	35	5.0	1.217	0.126
2-A	38	15.0	0.879	1.504
3-A	40	53.5	0.812	4.008
4-A	42	90.0	0.794	4.431
5-B	30	1.2	1.243	0.076
6-B	32	6.3	1.082	0.319
8-B	38	160.0	0.888	2.231

Table 1 Soil A and B: Herschel & Bulkley model's parameters

In order to put in evidence the influence of the solid volumetric concentration on the consistent coefficient k, and on the pseudoplastic index n, the void ratio of the bulk volume $e_0 = (1-\Phi_T)/\Phi_T$ was considered. Fig. 3 shows the parameters k and n as function of the void ratio e_0:

$$k = \alpha \cdot e^{-4 \cdot e_0} \qquad n = n_{\min} \cdot e^{\beta (e_0 - e_{\min})^{2.5}} \quad (3)$$

where α and β are fitting parameters depending on the material characteristics, reported in table 2. Minimum value (n_{min}=0.7) of pseudoplastic index has been extrapolated from experimental results and minimum void index (e_{min}=0.6) has been set according to *Chang et al.* (2016).

Soil	α	β
A	1215	0.37
B	1522	0.20

Table 2 Soil A and B: Herschel & Bulkley generalized model's fitting parameters (see eq. 3).

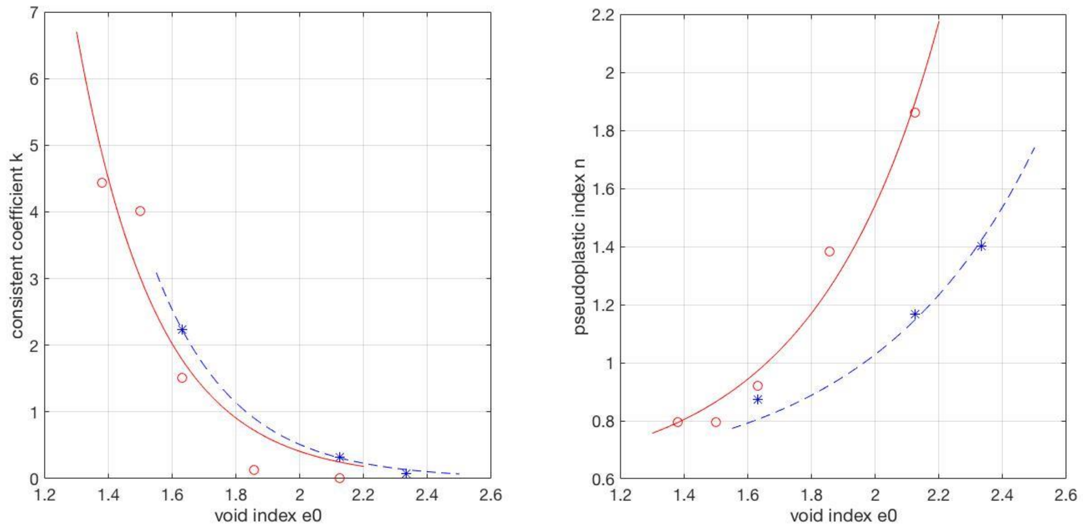

Figure 3. Soil A (o) and B (*): parameters *n* and *k* (see Eq. 3 and table 2) as a function of void ratio.

4 CONCLUSION

The pyroclastic soils analysed in the present study, usually present a very small clay fraction, and sometimes even absent. Consequently, the mixtures behave as homogeneous fluids in a very small range of solid volumetric concentration, typically less than 10%. The solid content greatly affects the behaviour of these mixtures during the flow, as it is evident studying the influence of the solid volumetric concentration on the rheological parameters of the mixtures. The Hershel-Bulkley generalized model (see eq. 2) applies quite satisfactorily to the experimental data, and for any material herein considered it shows a relevant variability of rheological parameter with the concentration, which may be modelled accounting for the void ratio index referred to the bulk volume concentration (see eq.3).

REFERENCES

Chang C.S., Wang J.Y., Ge L. Maximum and minimum void ratios for sand-silt mixtures. Engineering Geology, 2016, 211, pp.7-18

Coussot, P., Laigle, D., Arratano, M., Deganutti, A., & Marchi, L. Direct determination of rheological characteristics of debris flow. Journal of Hydraulic Engineering, 1998, 124, pp. 865–868.

Fraccarollo L. & Papa M. Numerical simulation of real debris flow events, Phys. and chem. of the earth, 2000, 25(9), pp. 757-763.

Laigle, D. & Coussot P. Numerical modeling of mud-flows, Journal of hydraulic engineering, 1997, 123(7), pp.617-623.

Major J. J., Pierson T. C., Debris flow rheology: experimental analysis of fine grained slurries, 1992, Water Resources Research, 28(3), pp. 841-857

Ovarlez, G., Rodts, S., Chateau, X., & Coussot, P. Phenomenology and physical origin of shear localization of the shear banding in complex fluids. Rheologica Acta, 2009, 4, pp. 831-844.

Pellegrino, A. M., Scotto di Santolo, A. & Schippa, L. An integrated procedure to evaluate rheological parameters to model debris flows. Engineering Geology, 2015, 196, pp. 88-98

Pellegrino, A. M., & Schippa, L. Macro Viscous Regime of Natural Dense Granular Mixtures. International Journal of GEOMATE, 2013, 4, pp.482-489.

Schippa, L., & Pavan, S. Numerical modelling of catastrophic events produced by mud or debris flows. Int. J. of Safety and Security Engineering, 2011, 1, pp. 403-422.

Scotto di Santolo, A., Pellegrino, A. M., & Evangelista, A. Experimental study on the rheological behaviour of debris flow. Natural Hazards and Earth System Science, 2010, 10, pp. 2507–2514.