

Experimental study on the rheological behaviour of debris flow

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Abstract. A model able to describe all the processes involved in a debris flow can be very complex owing to the sudden changing of the material that turns from solid into liquid state. The two phases of the phenomenon are analysed separately referring to soil mechanics procedures with regard to the trigger phase, and to an equivalent fluid for the post-failure phase. The present paper is devoted to show the experimental results carried out to evaluate the behaviour assumed by a pyroclastic-derived soil during the flow. A traditional fluid tool has been utilized: a standard rotational rheometer equipped with two different geometries. The soils tested belong to deposits that cover the slopes of the Campania region, Italy, often affected by debris flows. The influence of solid concentration C_v and grain size distribution was tested: the soils were destructured, sieved and mixed with water starting from the in situ porosity. All material mixtures showed a non-Newtonian fluid behaviour with a yield stress τ_y that increases with a solid volumetric concentration and decreases for an increase of sand fraction. The experimental data were fitted with standard model for fluids. A simple relation between C_v and τ_y was obtained. The yield stress seems to be a key parameter for describing and predicting the post-failure behaviour of debris flows. These results suggest that in the field a small change in solid fraction, due to rainfall, will cause a slight decrease of the static yield stress, readily inducing a rapid flow which will stop only when the dynamic yield stress is reached, namely on a much smoother slope. This can explain the in situ observed post-failure behaviour of debris flows, which are able to flow over very long distances even on smooth slopes.

1 Introduction

Debris flows represent serious hazards on the slopes of the North-western Campania region (southern Italy). Therefore, the evaluation of constitutive laws for the material involved represents a key requirement for the hazard mitigation. Traditionally, debris flows have been regarded as homogeneous fluids and flow behaviour has been considered to be controlled by the properties of the “matrix”, a mixture of fine sediment and water in which coarse particles are dispersed (Costa and Williams, 1984; Johnson, 1984). Existing physical theories to describe flow and depositional process of debris flows are mainly divided into theories which are based on the treatment of the material as one single phase (rheological approaches) (O’Brien and Julien, 1984; Phillips and Davies, 1991; Major and Pierson, 1992; Coussot and Piau, 1994) or as two or more phases (Coulomb mixture approaches) (Savage and Hutter, 1989; Iverson, 1997). The Coulomb mixture approach specifies distinct constitutive equations for the solid phase, the liquid phase and the interaction forces phase. Conversely, using a rheological approach, the bulk mixture behaviour can be characterised by a limited number of parameters, relating shear stress and viscosity to shear rate. The present study focuses on the results obtained by means of a rheological point of view.

1.1 Debris flow rheology

Natural debris flows are often classified on the relative concentration of fine and coarse sediments that are used to characterize the main flow regime behaviour (Takahashi, 2007). Above a critical solid concentration C_v^* , a particle-friction-collision regime dominates the flow process. Models based on the work of Bagnold (1954) are used to describe the flow behaviour of such mixtures. If the solid concentration is less than the critical one, the flow behaves like a Non-Newtonian



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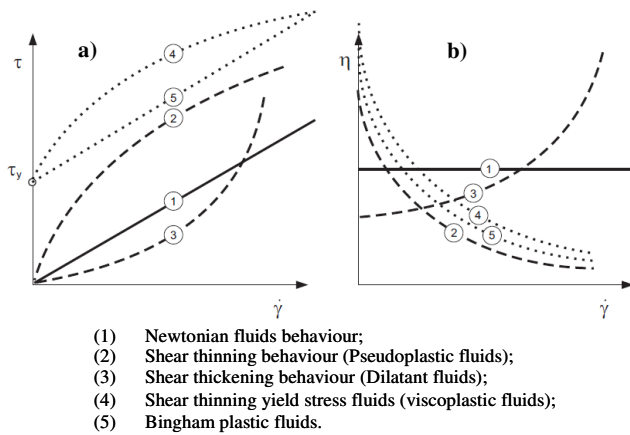


Fig. 1. (a) Flow curves; (b) Viscosity curves.

fluid. They are also called time-independent fluids and are subdivided into several groups (Fig. 1). Generally, the debris flow mixtures behave like viscoplastic fluids, as indicated in curve (4), Fig. 1. It is considered that, for such a fluid, an abrupt change in flow behaviour exists around a given shear stress value, the yield stress τ_y , which needs to be overcome before flow takes place. The viscoplastic character of debris flow mixtures has often been reported in literature (O'Brien and Julien, 1984, 1988; Phillips and Davies, 1991; Major and Pierson, 1992; Coussot and Piau, 1995; Contreras and Davies, 2000; Ancey and Jorrot, 2001; Schatzmann, 2005; Kaitna et al., 2007). Phenomenological laws like the Bingham generalized model (or Herschel & Bulkley model) are usually used to describe the rheological behaviour of such mixtures (Major and Pierson, 1992; Nguyen and Boger, 1992; Coussot, 1997). The mathematical expression can be written as:

$$\tau = \tau_y + k \cdot \dot{\gamma}^n \quad (1)$$

In Eq. (1), τ_y is the yield stress, $\dot{\gamma}$ is the shear rate, k is the consistent coefficient [Pa s^n] and n is the pseudoplastic index. When the index n is equal to the unity, the Eq. (1) becomes the Bingham model and the coefficient k becomes the Bingham viscosity η_B (curve (5) in Fig. 1).

2 Experimental setup and procedures

2.1 Rheometer apparatus

In order to ensure the validity of rheometrical measurements and to reduce the risk of misinterpretation, the rotational rheometer AR 2000ex (TA Instruments) equipped with two different geometry systems (parallel plates – PP, and vane rotor – VR) has been utilized (Fig. 2). The parallel plates geometry is composed of a lower stationary steel plate and an upper rotational one with a 4 mm diameter. The distance between two plates (the gap H) must be at least ten times the



Fig. 2. The rotational rheometer AR 2000ex (TA Instruments) and the two rheometrical system used: parallel plates and vane rotor system.

maximum particles diameter, d_{\max} (Chhabra and Richardson, 1999). Because of the variability in the grain size distribution of the material, the gap has been fixed (H equal to 1 mm) and the maximum diameter has been established according to the previous relation ($d_{\max} \leq 0.1 \text{ mm}$). The shear rate and the shear stress are evaluated with the following equations:

$$\dot{\gamma}_R = \dot{\gamma}(R) = \frac{\Omega \cdot R}{H} \quad (2)$$

$$\tau(\dot{\gamma}_R) = \frac{3T}{2\pi R^3} + \frac{\dot{\gamma}_R}{2\pi R^3} \cdot \frac{dT}{d\dot{\gamma}_R} \quad (3)$$

where R is the upper plate radius, H is the gap, Ω is the rotation velocity (rad/s) and T is the torque (Coussot, 1997).

The vane rotor geometry consists of four thin blades arranged at equal angles around a small cylindrical shaft: the blades radius is 14 mm and the blades height is 42 mm. It is immersed in the sample contained in a cylindrical cup with 15 mm in radius. The vane is rotated around its axis at a given rotational speed Ω , and the torque T is measured. During the test the material is trapped in the blades and the shear is achieved around a fictitious cylinder within the mixture. The shear stress and shear rate are:

$$\dot{\gamma} = \frac{\Omega \cdot R_1}{R_2 - R_1} \quad (4)$$

$$\tau = \frac{3 \cdot T}{2 \cdot \pi \cdot R_1^2 \cdot L} \quad (5)$$

where R_1 and R_2 are, respectively, the blades radius and the cup radius, L is the material depth. The Eqs. (4) and (5) are usually applied when the ratio R_1/R_2 is close to the unity (Coussot, 1997); in our case R_1/R_2 is equal to 0.933.

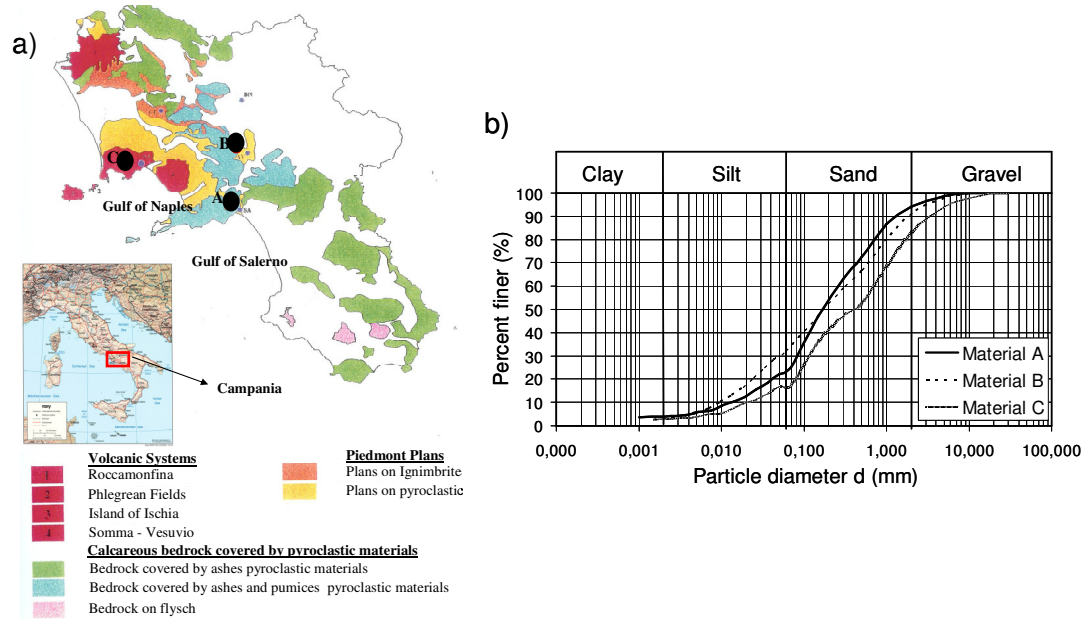


Fig. 3. (a) Location of the studied debris flows and distribution of the main deposits (Modified from di Gennaro et al., 1998); (b) Grain size distribution of the tested debris flow materials.

2.2 Materials

The materials tested have been collected from the source area of three debris flows, which are originated in pyroclastic-derived terrains, occurred in Campania region (southern Italy), Fig. 3a. Material A has been sampled in Nocera, Salerno (event of March 2005); material B in Monteforte Irpino, Avellino (event of May 1998); material C in Astroni, Naples (event of December 2005). The soil type derived from the most recent deposits produced by the volcanic activity of mount Somma/Vesuvius for materials A and B and by the volcanic activity of the Phlegrean Fields for material C. The grain size distributions of the undisturbed samples are reported in Fig. 3b. Soil A and soil B are sandy silt with a small clay fraction, while soil C is gravely silty sand. The clay part is slightly plastic though only in the Vesuvian deposits. The gravel part mainly consists of pumices and, to a minor extent, of scoriae and lapilli. The particles are mainly siliceous. Their structure is amorphous and porous; there is a double porosity system inter- and intra-particle (the latter not connected to the surface). Porosity exceeds 70% for Vesuvian deposits while it is lower for the Phlegrean deposits. The cover is partially saturated; the level of saturation varies according to weather conditions. Mean physical properties are reported in Table 1 (G_s is the specific gravity of soil particles, γ_d and γ are the dry and total weight of soil per unit volume, respectively, n is the porosity and S_r is the degree of saturation). The geotechnical properties of such materials are well documented in literature (e.g. Scotto di Santolo, 2000a, b; Ruopolo, 2006; Papa, 2007; Picarelli et al., 2007). The nature of the substratum underlying the soil is volcanic for material C, and carbonatic for materials A and B (Fig. 3a).

2.3 Laboratory procedures

The analysed debris flow mixtures have been tested in rate-controlled mode at a constant temperature ($20 \pm 0.5^\circ\text{C}$). The flow curves (τ , $\dot{\gamma}$) have been determined by applying a successive shear rate level, ranging from 0.014 to 1400 1/s.

For each level of shear rate the duration of the experiment has been imposed long enough to obtain a simple shear steady regime. In order to certify the reproducibility of the experiment, each test has been repeated at least three times and the averaged values of the experimental results have been considered. Due to the geometry dimension of the used rheometer, only the flow curves of fine material with grain sizes smaller than 0.1 mm have been derived. The experiments have been carried out with mixtures of different water content. The solid volumetric concentration C_v , i.e., the ratio of the amount of solids to the total mixture, has been considered. The total solid volumetric concentration C_v is defined as:

$$C_v = \frac{V_s}{V_s + V_w} \quad (6)$$

where V_w and V_s are, respectively, the volumes of water and solid in the sample. In order to consider a significant range of the sediment concentration for the material tested, mixtures with C_v changing from 20% to 40% have been prepared. These values correspond to the variation of porosity in situ (n ranging from 60 ÷ 80%). Two grain size distributions were analysed for each material: the first with a maximum particle diameter equal to 0.1 mm, and the second with a maximum diameter equal to 0.5 mm, respectively, defined

Table 1. Main physical properties of the tested debris flow materials.

Debris flow	Substratum	Material	G_S (1)	γ_d (kN/m ³)	γ (kN/m ³)	n (1)	S_r (1)
Nocera	Carbonatic	A	2.62	9.08	11.35	0.66	0.35
Monteforte Irpino	Carbonatic	B	2.57	7.11	12.11	0.71	0.71
Astroni	Pyroclastic	C	2.54	8.99	9.84	0.67	0.24

Table 2. Experimental program.

#	Material	Mixture	Test	C_v	Geometry system	
					Parallel plate	Vane rotor
1	A	FP	A-FP-20	20	A-FP-20-PP	A-FP-20-VR
2			A-FP-30	30	A-FP-30-PP	
3			A-FP-40	40	A-FP-40-PP	
4		LP	A-LP-20	20	A-LP-20-PP	A-LP-20-VR
5			A-LP-30	30	A-LP-30-PP	
6			A-LP-40	40	A-LP-40-PP	
7	B	FP	B-FP-20	20	B-FP-20-PP	B-FP-20-VR
8			B-FP-30	30	B-FP-30-PP	B-FP-30-VR
9			B-FP-40	40	B-FP-40-PP	B-FP-40-VR
10		LP	B-LP-20	20	B-LP-20-PP	B-LP-20-VR
11			B-LP-30	30	B-LP-30-PP	B-LP-30-VR
12			B-LP-40	40	B-LP-40-PP	B-LP-40-VR
13	C	FP	C-FP-20	20		C-FP-20-VR
14			C-FP-30	30		C-FP-30-VR
15			C-FP-40	40		C-FP-40-VR
16		LP	C-LP-20			
17			C-LP-30			
18			C-LP-40			

(FP maximum diameter 0.1 mm; LP maximum diameter 0.5 mm; – = not investigated.)

fine (FP) and coarse (LP) in the following. The experimental programme performed is shown in Table 2.

3 Experimental results

3.1 Preliminary evaluations

The choice of the measurement geometry depends on the expected rheological properties of the mixture. Because the rheological properties are unknown a priori, preliminary measurements are absolutely necessary.

Disturbing effects due to material properties and rheometrical geometry features could lead to erroneous data interpretation (Major and Pierson, 1992; Coussot and Piau, 1995; Coussot, 1997; Kaitna et al., 2007). Depending on the geometry apparatus, shear conditions (related to samples volume) and disturbing effects (related to geometry features and fluid types) change in a different way. Data obtained by dif-

ferent facilities should be in agreement only if the material tested has been homogeneously sheared as predicted by theory (Major and Pierson, 1992; Coussot, 1997).

In order to understand how the geometry system influences the experimental results, preliminary tests on a typical Newtonian fluid ($\tau = \eta \cdot \dot{\gamma}$ in which η is the viscosity), liquid paraffin on sale with η equal to 0.01 Pa s, have been carried out with parallel plates and vane rotor. Figure 4 reports the flow curves of the liquid paraffin obtained using the mentioned geometries. A quantitative difference, between the experimental results obtained using the parallel plates system and the experimental data obtained using the vane rotor system, has always been noted. Comparing the theoretical and the measured viscosity values, an overestimate of the rheological parameters has been observed when the parallel plates geometry has been used. A scale factor from the results obtained with the parallel plates system to the results obtained with the vane rotor system has been evaluated, by considering the Newtonian behaviour of the liquid paraffin.

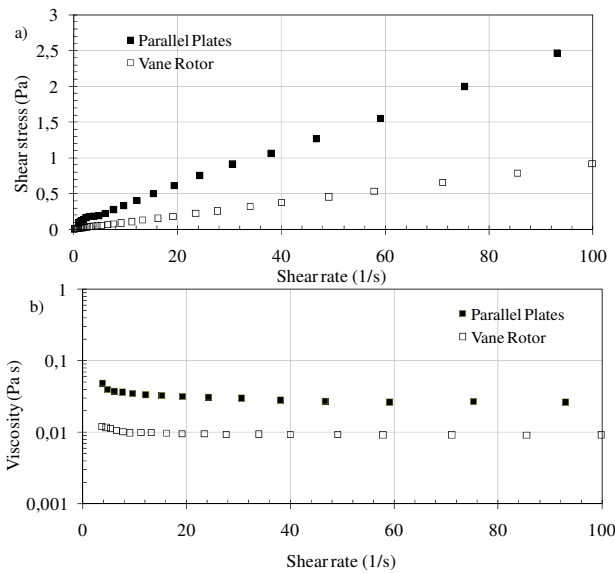


Fig. 4. Liquid paraffin on sale. Comparison of parallel plates results and vane rotor results.

For a Non-Newtonian fluid, like the mixtures tested, quantitative and qualitative differences have been observed. In Fig. 5 for material A with C_v equal to 20%, the flow curves obtained with the two geometric facilities have been reported. At a small shear rate, a minimum in the flow curves attained by the tests carried out using the vane rotor system has been noted: the shear stress decreases with shear rate, followed by a subsequent increase at larger shear rate values. Such behaviour for concentrated suspensions, with a minimum to low shear rate, has been reported by several authors (Nguyen and Boger, 1985; Alderman et al., 1991; Major and Pierson, 1992; Pignon et al., 1996; Coussot, 1997; Ancey and Jorrot, 2001; Kaitna et al., 2007) and only the increasing part of the flow curves has been considered. Moreover, the vane rotor response is higher than the parallel plates response after a shear rate value equal to 50 1/s. Regardless of the solid volumetric concentrations considered, after this value of shear rate the mixtures analysed behave like a Non-Newtonian fluid. In the following, only these experimental results have been analysed.

Probably, some disturbing effects have occurred during the tests like the changing of the material free surface, edge/crack effects, heterogeneities in particle distribution (particle settling and migration due to particle inertia and secondary flow) and the phenomenon of wall slip. The occurrence of some disturbing effects has been evaluated. In static experiments gravity forces are in competition with the Brownian forces. To estimate the sedimentation of the samples of spherical particles, the ratio between gravity (settling) and Brownian forces (thermal) should be greater than 1 (Macosko, 1994):

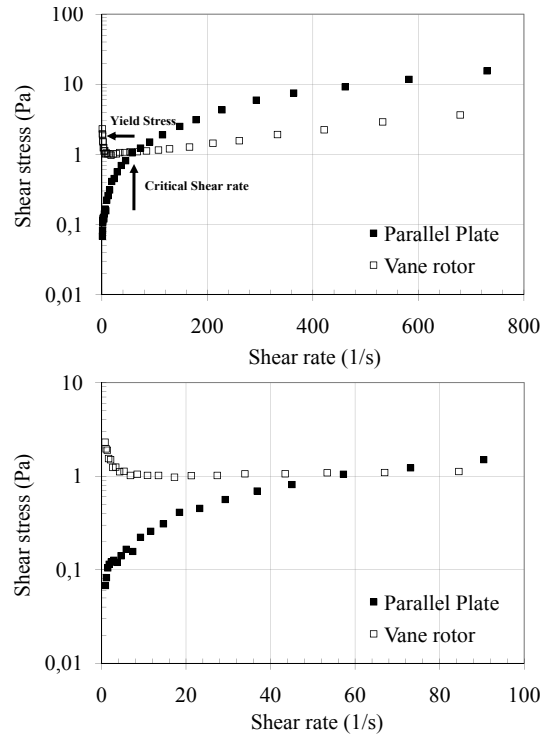


Fig. 5. Material A, $C_v = 20\%$. Comparison between the experimental results obtained with the parallel plates and the vane rotor system.

$$\frac{\text{gravity} \cdot \text{force}}{\text{Brownian} \cdot \text{force}} = \frac{(\rho_d - \rho_c) \cdot g \cdot a^3}{k_B \cdot T/a} \tag{7}$$

where ρ_d and ρ_c are the densities of the disperse and continuous phase, g is the acceleration of gravity, a is the particle radius, k_B is the Boltzmann's constant, T is the absolute temperature.

As shown by Larson (1999) sedimentation certainly occurred for $\Delta\rho$, difference between the densities of the disperse ρ_d and the continuous phase ρ_c , equal to 10^3 kg m^{-3} and particles or aggregates larger than $1 \mu\text{m}$ radius. For our mixtures these differences are equal to 1600; the experimental flow condition should be adjusted so that during the experimental time the sedimentation does not play an important role. It is possible to estimate the influence of settling through the calculation of the experimental time t_{exp} required for a single sphere of radius a to migrate over a length l (l is equal to H , the gap height) as in the following:

$$t_{\text{exp}} = \frac{9}{2} \cdot \frac{\eta_c \cdot l}{\Delta\rho \cdot g \cdot a^2} \tag{8}$$

where η_c is the viscosity of the continuous phase (for water 10^{-3} Pa s), $\Delta\rho$ is the difference between the densities of the disperse ρ_d and the continuous phase ρ_c , g is the acceleration of gravity and a is the radius of the particle with maximum size in the mixtures (Macosko, 1994). For our mixtures this time is equal to 0.115 s for fine mixtures and equal to 0.005 s for coarse mixtures.

Particle inertia can also influence the results of experiments. With the particle Reynolds number Re_p an estimation of the inertial effects is possible:

$$Re_p = \frac{\rho_c \cdot \dot{\gamma} \cdot a^2}{\eta_c} \quad (9)$$

In this equation $\dot{\gamma}$ and η_c are the shear rate and the viscosity of the continuous phase, respectively. For a maximum diameter used (radius a equal to 0.05 mm and 0.25 mm), and for a shear rate equal to 50 1/s particle inertia occurred because the Re_p is 0.125 and 3.125 greater than 10^{-1} (Macosko, 1994).

In the following, due to the presence of these phenomena, the flow curves for the shear rate more than 50 1/s have been shown and interpreted.

3.2 Experimental results and model fitting

The flow curves for each analysed material have been reported in Fig. 6. It is noted that all the investigated debris flow mixtures behave like a non-Newtonian fluid and, in particular, like yield stress fluids: shear stress non-linearly increases with the increase of shear rate after a yield stress that represents the value of τ required to initiate the flow (value of τ as $\dot{\gamma}$ goes to zero).

The influence of the solid volumetric concentration C_v on the rheological behaviour of fine debris flow material mixtures tested has been evaluated. Proportionally higher values of shear stress with the increasing of the solid volumetric concentration have been noted. Moreover, at equal solid volumetric concentration, the shear stresses of material B are higher than materials A and C. The rheological parameters of C mixtures are the lowest due to the different volcanic particle nature (Phelegrean Field) and the higher grain size (Fig. 3b).

The best fitting model of the experimental data is the Bingham generalized (Eq. 1). The theoretical flow curves are reported as a solid line in Fig. 6. Table 3 shows the relative rheological parameters. The obtained yield stress τ_y is plotted versus the solid volumetric concentration C_v in Fig. 7. It can be observed that the yield stress τ_y exponentially increases with the increase of solid volumetric concentration C_v . According to some previous study (O'Brien and Julien, 1984, 1988; Phillips and Davies, 1991; Major and Pierson, 1992; Coussot and Piau, 1995; Coussot, 1997; Kaitna et al., 2007), the following relation can be used:

$$\tau_y = \alpha \cdot e^{\beta \cdot C_v} \quad (10)$$

where α and β are material parameters. Their values, for all the tested material mixtures, have been reported in Table 4.

In order to evaluate the influence of larger particles, mixtures with the same solid volumetric concentration and with a maximum diameter of 0.5 mm were tested using a vane rotor. Figure 8 shows, for instance, the comparison between fine and coarse particle mixtures of the materials B for a solid volumetric concentration equal to 30%. A decrease of

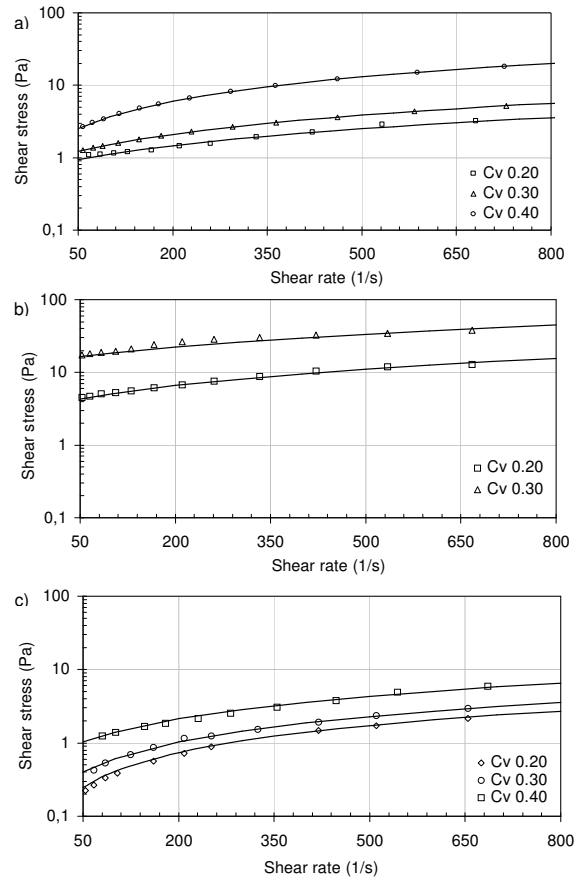


Fig. 6. Experimental data and theoretical flow curves at different volumetric concentration C_v : (a) material A; (b) material B; (c) material C.

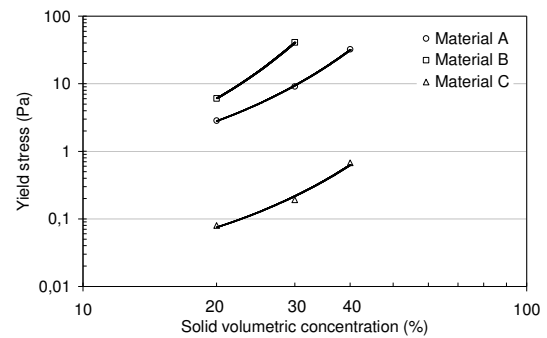


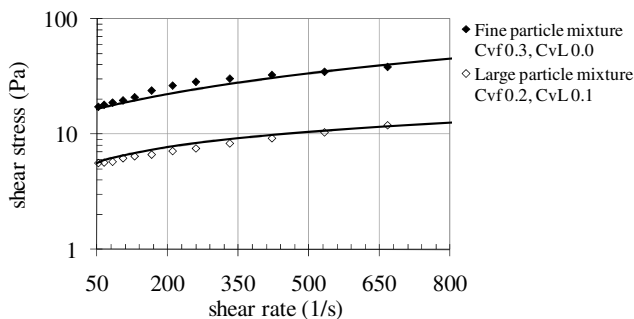
Fig. 7. Yield stress τ_y vs. solid volumetric concentration C_v .

yield stress is observed. This reduction may be justified by a decrement of finer content, the yield stress tends to disappear due to a reduction of the fine fraction (clean water).

This behaviour is in agreement with the experimental results of Ancy and Jorrot (2001) on coarse particles within a clay dispersion with a parallel plates system. When the large particle fraction is small compared to the amount of fine particle fraction, the colloidal fine fraction determines the rheological features of the mixture.

Table 3. Bingham generalized model parameters.

Material	Solid volumetric concentration (%)	Mixture	Yield stress (Pa)	Consistent coefficient (Pa s^n)	Pseudoplastic index (1)	Determination coefficient (1)
A	20	Fine particle	0.4431	0.2756	0.6116	0.988
A	30	Fine particle	0.9169	0.5227	0.6116	0.979
A	40	Fine particle	3.2398	2.9569	0.6116	0.991
B	20	Fine particle	3.5465	1.8708	0.2553	0.999
B	30	Fine particle	14.5960	6.7207	0.2553	0.998
B	30	Coarse particle	5.55	1.7351	0.3653	0.955
C	20	Fine particle	0.080	0.00105	0.6842	
C	30	Fine particle	0.1910	0.0914	0.6842	0.999
C	40	Fine particle	0.6744	0.2302	0.6842	0.999

**Fig. 8.** Material B: effect of maximum particle diameter for C_v equal to 30%.

Instead, as observed in different studies led using non-conventional rheometers on material mixtures, rheological properties are altered by addition of larger particles (up to several centimeters) to the viscous fluid (Coussot and Piau, 1995; Contreras and Davies, 2000; Schatzmann 2005). Thus, rheological parameters determined by debris flow material of limited grain size with a conventional rheometer do not represent the bulk rheological behaviour of the complete natural material. Therefore, further tests are necessary on mixtures including sand and gravel fraction according to the natural grain size distribution. This activity is being undertaken through the development of a new type of equipment that is presently being tested.

4 Conclusions

In order to evaluate the rheological behaviour of debris-flow material, laboratory tests involving soils taken in the source areas of three debris flows occurred in Campania region (southern Italy) were carried out. Mixtures with varying concentration of fine sediment with maximum diameter less than 0.1 mm (fine particle mixture) and less than 0.5 mm (coarse

Table 4. Material parameters.

Material	α	β
A	0.2464	0.1215
B	0.1333	0.1909
C	0.0089	0.1066

particle mixtures), and distilled water were prepared. Such mixtures were investigated in a standard rheometer with two different geometries, the parallel plates system and the vane rotor system, in order to distinguish disturbing effects. The vane geometry seems to be an appropriate rheometrical tool for quantitative evaluation of the rheological behaviour of debris flow materials. Instead, by using the parallel plates system, only some qualitative ideas about their behaviour can be obtained. The comparison between the results of the two geometry configurations allows checking the range of shear rate where there are no disturbing effects and misleading evaluations. In this range of shear rate all the tested debris flow mixtures behave like a non-Newtonian fluid with a yield stress τ_y that increases with solid volumetric concentration C_v and decreases for sand fraction increase. The experimental data were fitted with the theoretical Bingham generalized model, in the range of the evaluated shear rate. A simple relation between C_v and τ_y was obtained.

These results suggest that in the field a small change in solid fraction, due to rainfall, will cause a slight decrease of the yield stress, inducing a flow rapidly reaching a shear rate larger than the critical shear rate associated with a rapid flow. Then, the flow will stop only when the material reaches a much smoother slope. This might explain the in situ observed post-failure behaviour of debris flows, which are able to flow over very long distances even over smooth slopes.

The rheological parameters determined for flows of limited grain size with a conventional rheometer do not represent

the bulk rheological behaviour of the complete natural material. Further tests are necessary on mixtures including sand and gravel fraction reflecting the natural grain size distribution. This activity is being undertaken through the development of a new equipment under test. The yield stress seems to be a key parameter for describing and predicting the post-failure behaviour of debris flows, but further experimental validation is required.

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