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A laboratory experience on the effect of grains concentration and coarse sediment on the rheology of natural debris-flows

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Abstract

Not only solid volumetric concentration, but also coarse particle content play a relevant role on the rheology of soil mixtures involved in mud, debris, hyper-concentrated and earth flows. This paper is devoted to investigating the influence of bulk solid volume concentration and of coarse fraction on the rheological behavior of granular slurries. Laboratory activity is carried out involving different soils from the source area of real debris flows (from the Campania region in Italy). Experimental results demonstrate that the flowing behavior is the same as yield stress fluids with a static yield stress value larger than the dynamic one. A generalized Herschel–Bulkley model is considered, accounting for a consistent index which is a function of solid volume concentration. Experimental evidence demonstrates that the viscous characteristics (i.e., yield stresses and bulk viscosity) are very sensitive to coarse grain content, and the flow characteristics are deeply affected by small variations of both solid content and particle size. In effect, the tested materials show increasing yield stress (both static and dynamic) with solid concentration and decreasing yield stress for an increment of coarser solid fraction. To the contrary, assuming a constant fine grain relative content, the higher the coarse grain fraction is, the lower the yield stress results. Moreover, the typical transition from solid-like to fluid-like behavior, and vice versa, is strongly influenced by solid concentration and grain size distribution.

AQ1

AQ2

Keywords

Debris flow
Fine and coarse-grained mixtures
Rheometer test
Yield stress

Introduction

Natural flows—such as mud, debris, hyper-concentrated flows and earth flows—are fast-flow phenomena typically characterized by the rapid motion of a large amount of soil mixed with water. The study of these events is particularly important considering their catastrophic and destructive capability that has led to the death of thousands of people and to the destruction of service infrastructure worldwide. In this perspective, a complete and appropriate knowledge of the rheological properties of these kinds of granular flows effectively aids the assessment of invasion areas, travel distance and flow velocity (Schippa and Pavan 2011). Natural flows—such as mud, debris hyper-concentrated and earth flows—can be considered as a slope movement in which the collapsing mass moves as a viscous fluid (Cruden and Varnes 1996; Hungr et al. 2014). Indeed, during the flow (Takahashi 1991), the involved mass of soil and water behaves, to all effects, like a concentrated suspension of variously assorted particles. For such materials, the bulk flow properties (related to failure, propagation and spreading phases) can be extrapolated from the study of the involved soil-liquid mixture, paying particular attention to the influence of particle size distribution and solid volumetric concentration (Coussot et al. 1998; Ancey 2003; Schatzmannet al. 2009; Scotto di Santolo et al. 2010; Scotto di Santolo et al. 2012; Pellegrino and Schippa 2013a, b). The experimental activity presented herein is based on this approach and contributes to the theoretical and experimental knowledge of debris flow suspensions behavior.

AQ3

Several previous works on the flowing behavior of viscous suspensions involved in natural flows have already demonstrated that their rheological features are strictly related to both solid volumetric concentration and particle size distribution (O'Brien and Julien 1988; Coussot and Piau 1995; Coussot 1997; Ancey and Jorrot 2001; Schatzmann et al. 2009; Scotto di Santolo et al. 2010; Scotto di Santolo et al. 2012; Pellegrino and Schippa 2013b; Pellegrino et al. 2015a, b). Such viscous suspensions are characterized by a wide grain size distribution (ranging from silt to boulders), and it is not surprising that the interaction between solid and liquid phases causes different behavior. In fact the effects of Brownian motion and colloidal forces control the finest solid fraction, whereas frictional and collisional contacts and hydrodynamic forces govern the coarser particles content. Therefore, the bulk behavior of viscous suspensions is very complex and the effects of many parameters (e.g., solid volumetric concentration, particle size and shape, nature of the interstitial fluid, etc.) must be taken into consideration when analyzing their hydrodynamic behavior.

AQ4

Several authors have extensively studied the flowing characteristics of debris flow mixtures. Sengun and Probstein (1989a, b) ~~(1989)~~ carried out experimental investigations and theoretical analysis on coal slurries. They observed that, on the one hand, the fine (colloidal) fraction seems to perform independently of the coarse fraction and that the fluid matrix, composed of both the interstitial liquid and the finest fraction, confers most of its rheological characteristics to the bulk mixture. On the other hand, the coarser particles significantly contribute to the viscosity variation via processes of hydrodynamic dissipation. The experimental work performed by Coussot and Piau (1995) on natural debris flow mixtures confirmed that the amount of finest fraction influences the main rheological parameters of the entire suspensions, and that the yield stresses strongly vary with the amount of coarse particles. The work of Coussot and Piau (1995) agrees with the laboratory observations of Ancey and Jorrot (2001) in their study of coarse particles dispersed in a clay suspension, conducted with a conventional rheometer. Ancey and Jorrot (2001) emphasized once again that, when the large particle fraction is small in comparison with the amount of fine particles, the finest fraction determines the rheological behavior of the bulk mixture. The same paper also illustrated that the grain size distribution has relevant effects on the yield stress value, which increases proportionally to the solid concentration of coarse fraction if the amount of large particles is high compared to the total solid concentration of the mixture. The observed trend also supports several results reported from studies by Wildemuth and Williams (1985) on coal–glycerin slurries, Banfill (1994) on mortars, Mansoutre et al. (1999) on cement, Contreras and Davies (2000) on natural mud flow, Schatzmann et al. (2009) and Scotto di Santolo et al. (2010) and Pellegrino et al. (2015a, b) on debris flow mixtures.

The definition of the main rheological properties of debris and earth flows is fundamental for modeling the dynamic behavior of these phenomena and for designing mitigation measures. In this perspective, the experimental measuring of viscosity and yield stress constitute valuable tools for estimating mass velocity, flow depth, the critical thickness at which a debris flow will stop moving, as well as deposition and run-out distance.

The present work aims to widen knowledge of the contribution of solid volumetric concentration and grain size distribution (referring to the coarser particle content) on the rheological behavior of debris, mud and earth flow mixtures, paying particular attention to the transition process from a solid-like to fluid-like flow behavior. With this objective, an extensive laboratory activity was performed using a standard rheometer and an inclined plane to investigate natural soils collected from the source areas of two real events of debris flow that occurred in the Campania region (Southern Italy). The conventional rheometer was used to deduce the rheological behavior of mixtures containing particles of limited size (up to 0.5 mm), whereas the inclined plane tested the bulk rheology of the debris-flow mixtures involving particles of larger size (up to 10 mm), in keeping with previous studies regarding these selected soil samples (Scotto di Santolo et al. 2010; Scotto di Santolo et al. 2012; Pellegrino and Schippa 2013a, b; Pellegrino et al. 2015b).

Materials

The tested samples come from the source areas of two real debris flow events that occurred in Campania (Southern Italy), involving the pyroclastic terrains covering the mountains of that region. Several preliminary investigations have been performed on the chosen material mixtures (Scotto di Santolo 2000; Scotto di Santolo et al. 2009, 2010, 2012; Pellegrino 2011; Pellegrino and Schippa 2013a, b; Pellegrino et al. 2015a, b), while the geotechnical properties of the soils are well referenced in literature (e.g., Picarelli et al. 2007). The first (soil A) derives from the source area of the Nocera debris flow (Salerno city) that happened in March 2005. The second (soil B) derives from the source area of the Monteforte Irpino debris flow (close to the city of Avellino) that occurred in May 1998. Both the collapsed soils are pyroclastic and belong to the most recent deposits generated by the volcanic activity of Mount Somma-Vesuvius. Recent studies in this area (Picarelli et al. 2007) have focused on the role of volcanic events and depositional mechanisms, grain size, and the deposits' constitution. Dependent also on relative location with regards to the eruptive centers, the processes of generation and formation of the deposits strongly affect the soil properties and behavior.

The soils are sandy silt with small clay fraction (see Fig. 1). Table 1 depicts the mean physical properties of the sampled soils (where G_S is the specific gravity of soil particles, γ_d and γ are the dry weight of soil per unit volume and the total weight of soil per unit volume respectively, p is the porosity and S_r is the degree of saturation). Scotto di Santolo et al. (2010, 2012) extensively describes the geological and geotechnical characteristics of the soils.

Fig. 1

Grain size distribution of the original soil A and B (black lines), and of the reconstituted fine-grained mixtures (red lines—d_{max} < 0.5 mm)

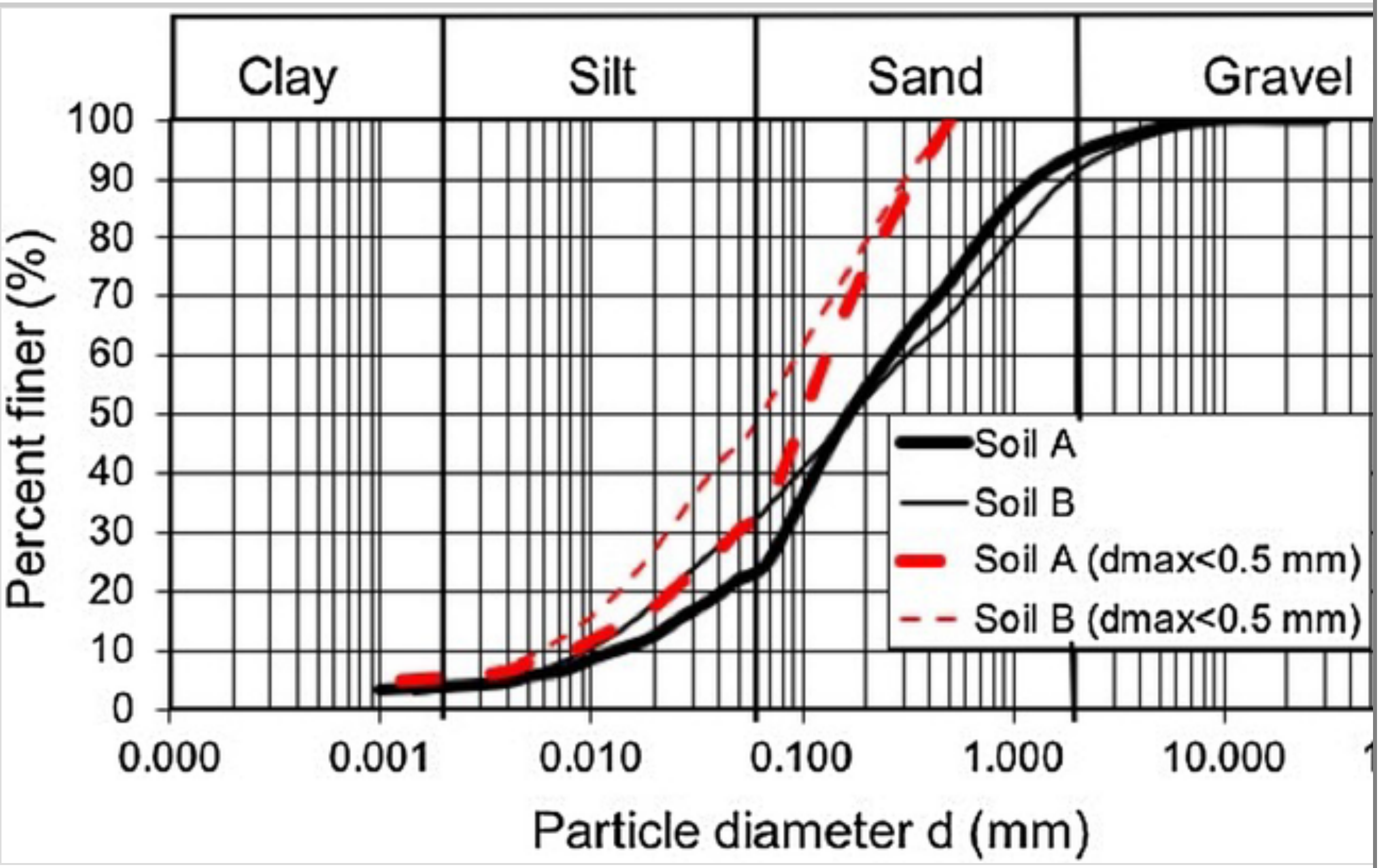


Table 1

Main physical properties of the tested materials

Events	Substratum	Material	G_s	γ_d (kN m^{-3})	γ (kN m^{-3})	p	S_r
Nocera (Salerno, 2005)	Carbonatic	A	2.62	9.08	11.35	0.66	0.35
Montefiorino Irpinio (Avellino, 1998)	Carbonatic	B	2.57	7.11	12.11	0.71	0.71

Organic elements are removed from the sampled soils and they are dried out in an oven at 104 °C for a day. Then a mixture of desired total volumetric concentration Φ_T is prepared by mixing the dry soils, duly cooled, with an appropriate amount of distilled water to give the desired total bulk volume concentration Φ_T:

$$\Phi_T = \frac{V_s}{V_s + V_w}, \quad (1)$$

where V_s is the volume of solids and V_w the volume of water.

Experimental set-up and procedures

Laboratory activity consists of 22 tests (Tests #0–21 listed in Table 2), which refer to fine-grained suspensions (i.e., mixtures composed of soil fraction with a particle diameter less than 0.5 mm) as well as to coarse-grained suspensions (i.e., mixtures composed of soil fraction with a particle diameter ranging between 0.5 and 10 mm).

Table 2

Experimental program

Test	Group	Material	Φ_T (%)	Φ_f (%)	Φ_g (%)	d_{max} (mm)
0[a]	I	A	32	32	–	0.5
1[a]	I	A	35	35	–	0.5
2[a]	I	A	38	38	–	0.5
3[a]	I	A	40	40	–	0.5
4[a]	I	A	42	42	–	0.5
5[a]	I	B	30	30	–	0.5
6[a]	I	B	32	32	–	0.5
7[a]	I	B	35	35	–	0.5
8[a]	I	B	38	38	–	0.5
9[b]	IIa	B	30	22	8	1.0
10[b]	IIa	B	30	17	13	2.0
11[b]	IIa	B	30	15	15	3.0
12[b]	IIa	B	30	14	16	10.0
13[b]	IIb	B	32	24	8	1.0
14[b]	IIb	B	32	19	13	2.0
15[b]	IIb	B	32	16	16	5.0
16[b]	IIb	B	32	15	17	10.0
17[b]	III	B	25	25	–	0.5

18[b]	III	A	33	25	8	1.0
19[b]	III	B	38	25	13	2.0
20[b]	III	B	40	25	15	5.0
21[b]	III	B	41	25	16	10.0
[a]Rotational rheometer test						
[b]Inclined plane test						

The two materials exhibit a similar grain size distribution (see Fig. 1) and so, the representative threshold was assumed for both at a value of 0.5 mm, which corresponds to the limiting range of medium sand (according to the Wentworth scale). This value is not only representative of the fine-grained limit, but is also consistent with the geometrical dimension of the used rheometer. The fine-grained moistures obtained from the original soil A (see Fig. 1) presents a large content of finer fraction (i.e., silt content larger than 50%), whereas soil B reconstituted moisture presents mostly sandy portion (i.e., sand fraction larger than 70%).

According to the grain size distribution, the coarser fraction (i.e., having sediment diameter $d > 0.5$ mm) is subdivided into 4 classes: the first two correspond to coarse sand (0.5 mm $< d <$ 1.0 mm) and very coarse sand (1.0 mm $< d <$ 2.0 mm). The latter two (2.0 mm $< d <$ 5.0 mm and 5.0 mm $< d <$ 10.0 mm) account for the maximum grain size diameter of the collected samples.

Considering the continuum assumption (i.e., the sample must be much thicker than the mean particle size; Coussot 1997), the standard rheometer is only used for fine-grained mixtures, whereas several inclined plane tests are carried out on both fine and coarse-grained mixtures.

The total solid volumetric concentration Φ_T refers to the bulk volume:

$$\Phi_{\mathrm{T}} = \Phi_{\mathrm{f}} + \Phi_{\mathrm{g}}, \tag{2}$$

where Φ_{f} and Φ_{g} are the solid volumetric concentration referring to both the fine and coarse-grained mixtures, respectively:

$$\Phi_{\mathrm{f}} = \frac{V_{\mathrm{sf}}}{V_{\mathrm{sf}} + V_{\mathrm{gf}} + V_{\mathrm{w}}}, \tag{3}$$

$$\Phi_{\mathrm{g}} = \frac{V_{\mathrm{gf}}}{V_{\mathrm{sf}} + V_{\mathrm{gf}} + V_{\mathrm{w}}}. \tag{4}$$

In the Eqs. (3) and (4) the subscripts f, g and w refer, respectively, to the fine-grained and coarse-grained materials and water.

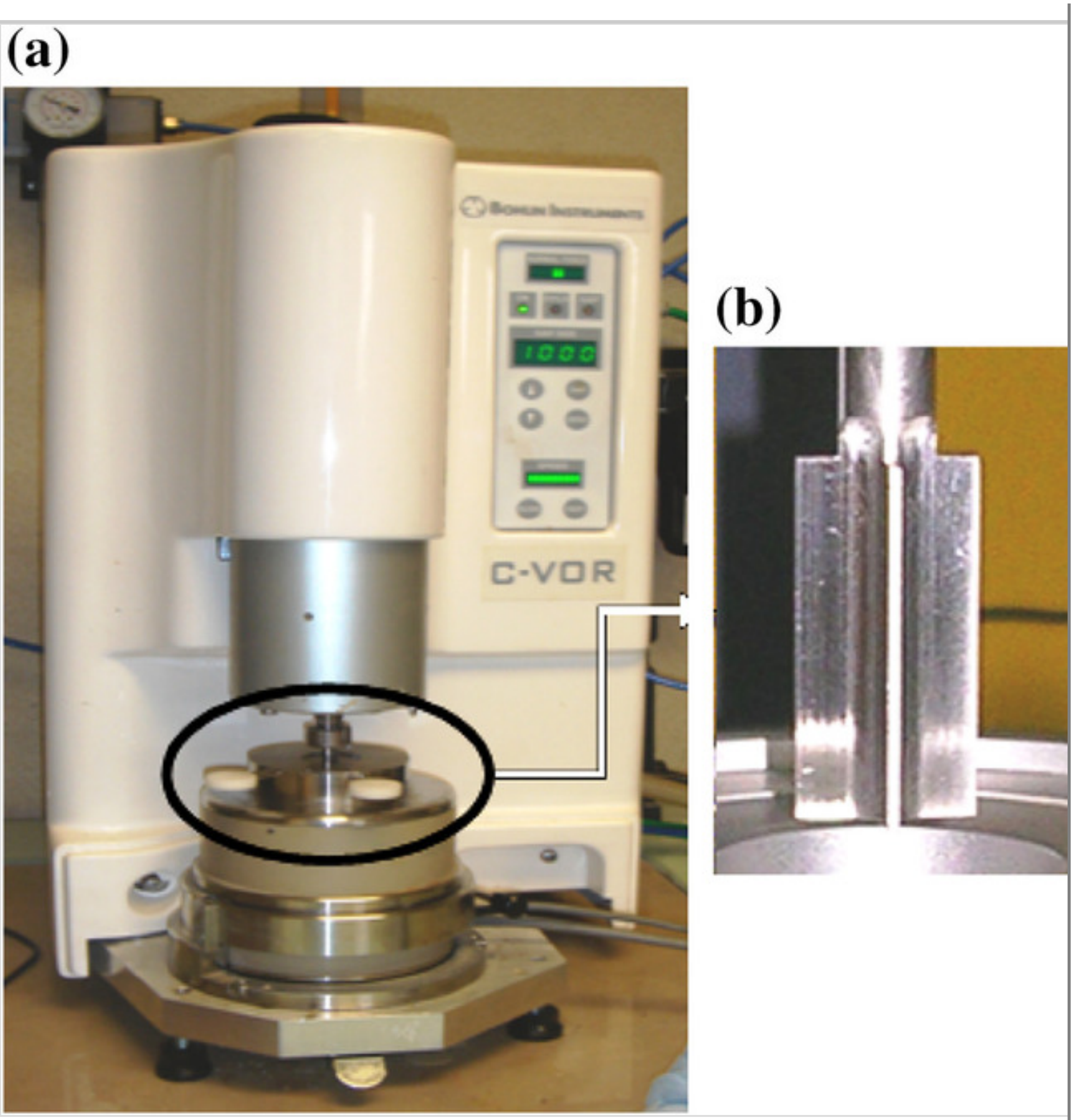
Before starting each test, a sample of distilled water and soils is prepared using an electronic mixer (30 rev/min). To homogenize the mixture, the suspension is constantly mixed for 15 min at uniform velocity. Inclined plane tests use a mixture sample of about 0.5×10^{-3} m^3, whereas rotational rheometer tests refer to a reduced-volume sample of about 0.030×10^{-3} m^3. The experimental program is carried out at a constant temperature of about 23 °C.

Rheometric test

The rheometric tests were performed via a C-VOR (Bohlin Instruments Ltd., UK) rotational rheometer equipped with a vane rotor system (see Fig. 2). The vane consists of four thin blades arranged at equal angles around a small cylindrical shaft; the blades radius R_1 is equal to 13 mm, and the blade height L is equal to 48 mm; the cup radius is $R_2 = 18.5$ mm. Considering that, during the experiments, a portion of the sample was trapped in the blades, then, as a first approximation, the flow was similar to that between two solid coaxial cylinders, having the inner radius equal to the radius of the blade (Nguyen and Boger 1985).

Fig. 2

a Conventional rheometer; **b** vane rotor



Under usual assumptions (i.e., no inertia effects and negligible normal stress differences), the shear stress (τ) and the shear rate ($\dot{\gamma}$) derive from the following formulae:

$$\tau = \frac{T}{2\pi R_1^2 L}; \quad \dot{\gamma} = \frac{\Omega R_1}{R_2 - R_1}, \qquad 5$$

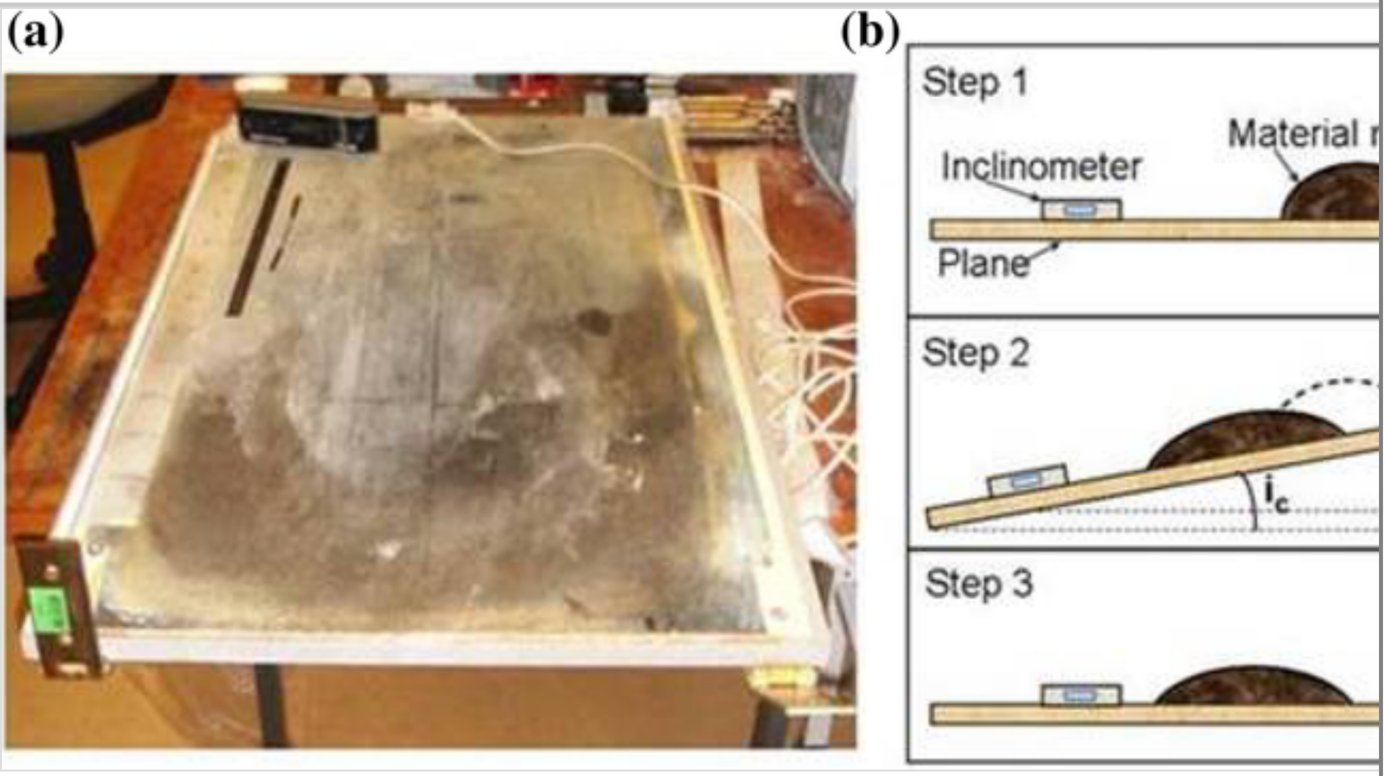
where T is the torque applied to the vane and Ω is the angular velocity of the vane rotor. The experiments with rotational rheometer referred to the stress sweep test, which consists of measuring the apparent flow curves via an increasing–decreasing shear stress ramp. First each mixture was tested to determine the maximum stress value to be applied to the suspensions without any spillage of the mixture from the measuring gap. At the very beginning of the test, a pre-shear was imposed at the maximum stress value for 30 s to ensure the complete homogenization of the mixture. Then the test was started by increasing the shear stress ramp, starting from 0.1 Pa to the maximum stress value (by step of 0.001 Pa); subsequently the decreasing shear stress ramp was implemented and the shear stress value was decreased to its initial level following exactly the same stress-steps. The sweep test lasted 120 s, and during the test the measured shear rate was recorded.

Inclined plane test

The inclined plane consists of a small rectangular plywood board (2 m long and 1 m wide) with a rough plane surface equipped with an inclinometer. Figure 3 shows the set-up and test procedures.

Fig. 3

a Inclined plane; **b** schematic of a representative run: step 1-initial volume of suspension at rest (horizontal); step 2: flowing and stopping suspension (inclined); step 3: measuring characteristic parameters



A typical inclined plane test consists of splitting the suspension on the horizontal rough plane to obtain a wide layer of material. Initially, the sample thickness (h_0) is measured in different points in the central area of the mixture at a distance from the mixture edges that is greater than three times the maximum mixture thickness. Subsequently, the board is progressively inclined to reach a critical angle value (i_c) corresponding to a notable motion of the mass front, and the test continues until full stoppage of the mass is achieved. Lastly the final thickness (h_f) of the mixture is measured with the same procedure used to define the initial sample. On average, each test lasted about 10 s, from the initial spreading to the complete stoppage of the mixture.

According to the lubrication assumption (i.e., material thickness h_0 is much smaller than its longitudinal extent; Coussot 2005), a uniform flow condition may be assumed for the flow mixture and, disregarding inertial effects, momentum balance provides shear stress distribution within the mixture (Coussot 2005; Scotto di Santolo et al. 2012):

$$\tau = \rho g h \sin(i), \tag{6}$$

where ϱ is the soil mixture density, i the inclined plane angle and g the acceleration of gravity.

The static yield stress τ_{c1}, at the critical slope angle i_c results:

$$\tau_{c1} = \rho g h_0 \sin(i_c), \tag{7}$$

where i_c corresponds to the initiation of motion, and the dynamic yield stress, τ_{c2}, corresponding to flow stoppage, is:

$$\tau_{c2} = \rho g h_f \sin(i_c). \tag{8}$$

Experimental results

Sweep test on fine-grained mixtures: the influence of the total solid volumetric concentration on the static and dynamic friction angle

Figure 4 shows the whole set of sweep test results, for materials A and B (i.e., tests #0–8; $\Phi_T = \Phi_f = [30–42\%]$, see Table 2). To illustrate the representative behavior of the fine-grained mixtures, let us consider the experimental results for the material A mixture (test #3 $\Phi_T = 40\%$) depicted in Fig. 5. With regard to the increasing ramp of applied shear stress, the flow curve is composed of two parts: firstly a transition phase is identified in the rapid increment of the shear rate (stress plateau) above some critical stress values, an evolution associated with the liquid regime (start-up of material flow in Fig. 5); and, secondly, the steady flow of material (steady state of material flow in Fig. 5) corresponds to the stress larger than a threshold value, which exhibits an increasing slope of the stress–strain curve associated with a liquid-like behavior. 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).

Fig. 4

Fine-grained mixtures: sweep test (test #0–8; test group I, see Table 2)

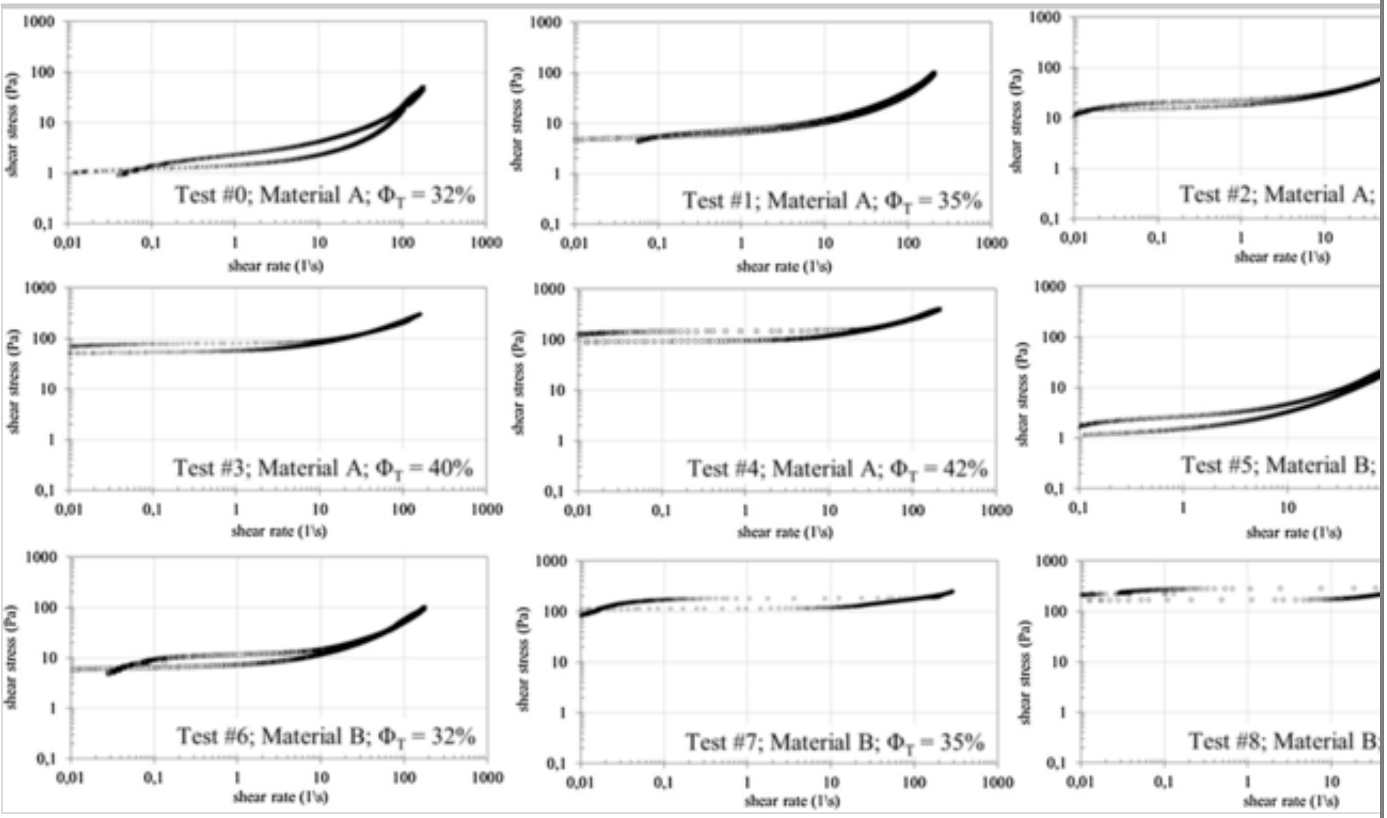
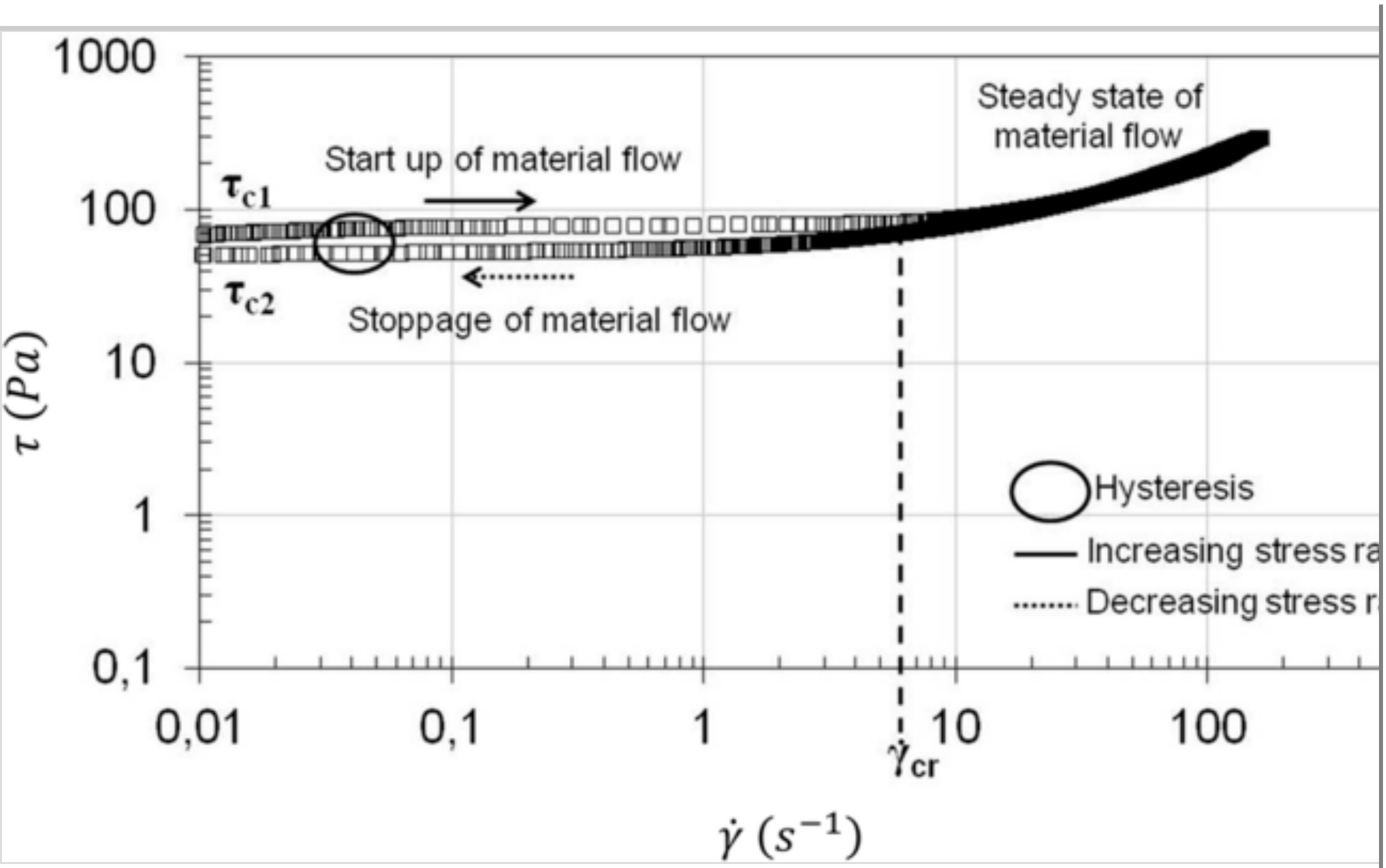


Fig. 5

Fine-grained material A mixture: sweep test at total solid volumetric concentration $\Phi_T = 40\%$ (test #3)



Once the maximum applicable value of shear stress has been reached, the decreasing shear stress ramp is applied. A representative test result, illustrated in Fig. 5, demonstrates hysteresis occurrence: the shear-strain curve, after initially overlapping the increasing one, approximately follows a stress plateau until flow stoppage is achieved (i.e., stoppage of material flow in Fig. 5). The stress plateau associated with the stress-decreasing ramp represents a measurement of the dynamic yield stress (i.e., τ_{c2}).

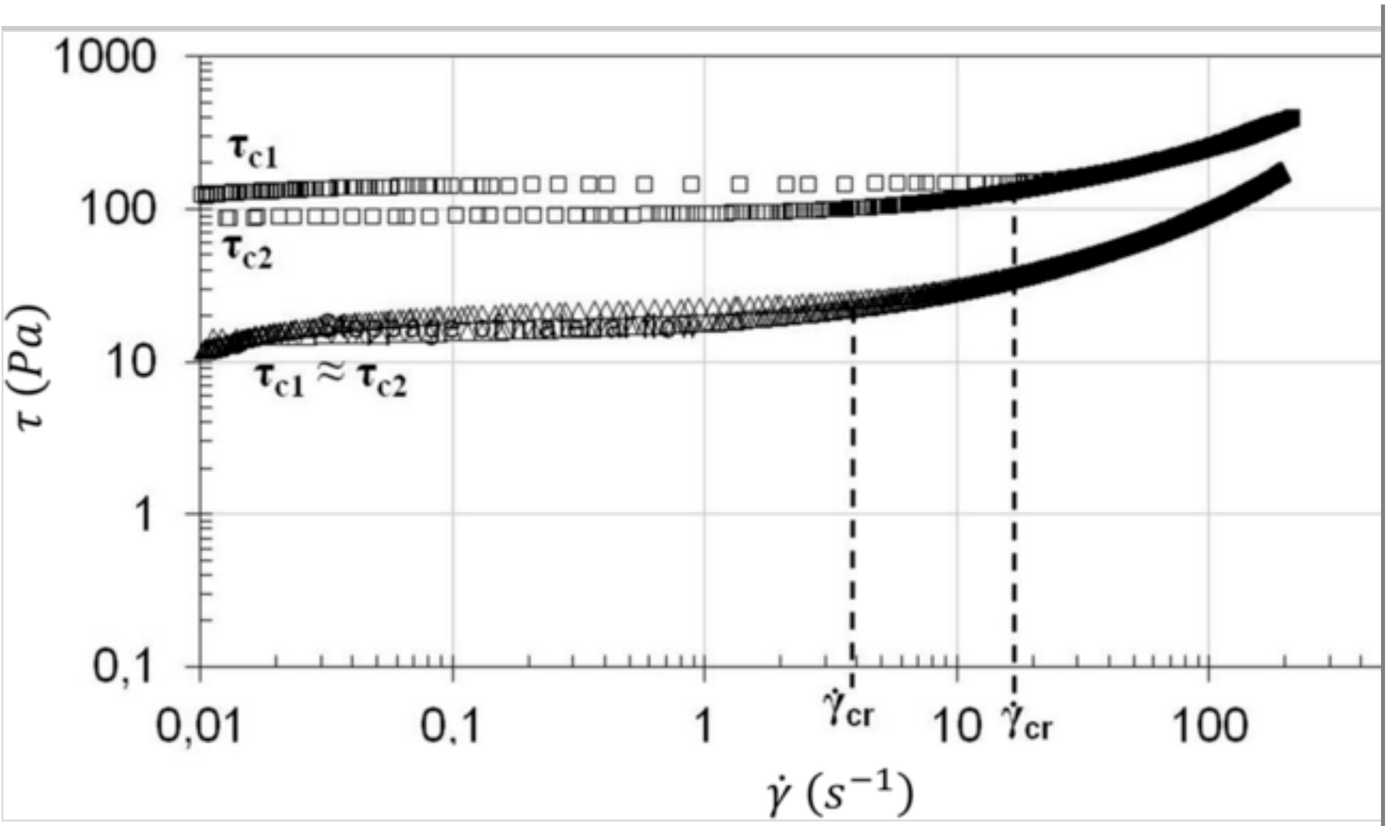
When a material exhibits a smooth solid–liquid transition, the increasing and decreasing stress–strain curves demonstrate a more ample overlapping. In this case, the static yield stress value is comparable to the dynamic yield stress.

As observed in previous work on the same debris flow mixtures (Scotto di Santolo et al. 2012), it may be assumed the suspension was initially broken and later liquefied. In this condition, the stress level required to maintain the flowing regime is lower than the stress level needed to destroy the initial structure, leading to hysteresis on the shear stress curve; this behavior is associated with an abrupt solid–liquid transition (Scotto di Santolo et al. 2012).

Figure 4 shows the stress plateau occurrence for any test involving material A and material B, despite bulk volume concentration. Increasing the stress level around a critical value (i.e., the static yield stress τ_{c1}), leads to a progressive increment of the resulting shear rate until it reaches the value associated with the end of the stress plateau. The threshold value ($\dot{\gamma}_{cr}$) represents the transition of the material mixture from a yielding to a steady state flow behavior; in fact, no steady flows can be obtained below the critical shear rate value (Coussot 2005; Ovarlez et al. 2009). The critical shear rate increases similarly to the yield stress, thus implying that the material strength grows with the concentration of solid particles in the mixture. However, when the mixture starts to flow, its apparent velocity increases almost proportionally. When solid volumetric concentrations are modified, stress–strain curves related to material A (i.e., fine-grained mixture) show some significant variations. Figure 6 demonstrates the influence of total solid concentration Φ_T on the static and dynamic yield stress for fine-grained mixtures. According to Scotto di Santolo et al. (2012), the yield stresses increase by one order of magnitude over the considered range of solid concentration (i.e., less than 10%) in which these debris flow mixtures behave as homogeneous fluids. This experimental evidence points to continuity between the range of solid fraction, in which the material is apparently a simple fluid (i.e., just after homogenization), and the range within which the material exists in a solid state.

Fig. 6

Fine-grained material A mixtures: sweep tests at solid volumetric concentration $\Phi_T = 38\%$ (empty triangles, test #2; see Table 2) and solid volumetric concentration $\Phi_T = 42\%$ (empty square, test #4, see Table 2)



At higher solid concentrations ($\Phi_T = \Phi_f = [40\%, 42\%]$; tests #3 and #4; see Table 2; Fig. 4), the stress–strain curve shows a stress plateau (i.e., constant stress value over a large range of shear rate) associated with the solid–liquid transition, and the increasing and decreasing parts of the stress–strain curve superimpose a range of shear rates, which starts at the very end of the stress plateau. For lower solid content ($\Phi_T = \Phi_f = [30\%, 32\%, 35\%, 38\%]$; tests #0, #1, #2 and #5; see Table 2; Fig. 4) the stress plateau is less evident and the liquid regime is characterized by slightly different stress–strain curves associated with increasing and decreasing stress levels; as a consequence, static and dynamic yield stress slightly differ from one another.

Rheological model accounting for the bulk solid volume concentration

A Herschel–Bulkley generalized rheological model is used to highlight the relevant effects of the total solid volumetric concentration on the rheological behavior of the mixture:

$$\tau = \tau_{c2} + k\dot{\gamma}^n, \tag{11}$$

where k [Pa s^n] is the consistent coefficient, and the dimensionless pseudoplastic n measures the degree to which the fluid is shear-thinning or shear-thickening (Coussot 1997). 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, incrementing the solid fraction of the mixture. Conversely, the authors assumed the pseudoplastic index n does not depend on the solid fraction but is constant for each tested material, with very close values for the two tested materials see (Table 3).

Table 3

Fine grained mixtures: Herschel–Bulkley model parameters

Test	**Material**	Φ_T **(%)**	d_{max} **(mm)**	Φ_{c2} **(Pa)**	n	k **(Pa s^n)**
0	A	32	0.5	1.4	0.7962	0.40
1	A	35	0.5	5.3	0.7962	0.80
2	A	38	0.5	15.9	0.7962	2.10
3	A	40	0.5	53.2	0.7962	4.01
4	A	42	0.5	88.9	0.7962	4.70
5	B	30	0.5	1.2	0.8270	0.34
6	B	32	0.5	6.3	0.8270	0.89
7	B	35	0.5	114.0	0.8270	1.60
8	B	38	0.5	148.0	0.8270	2.20

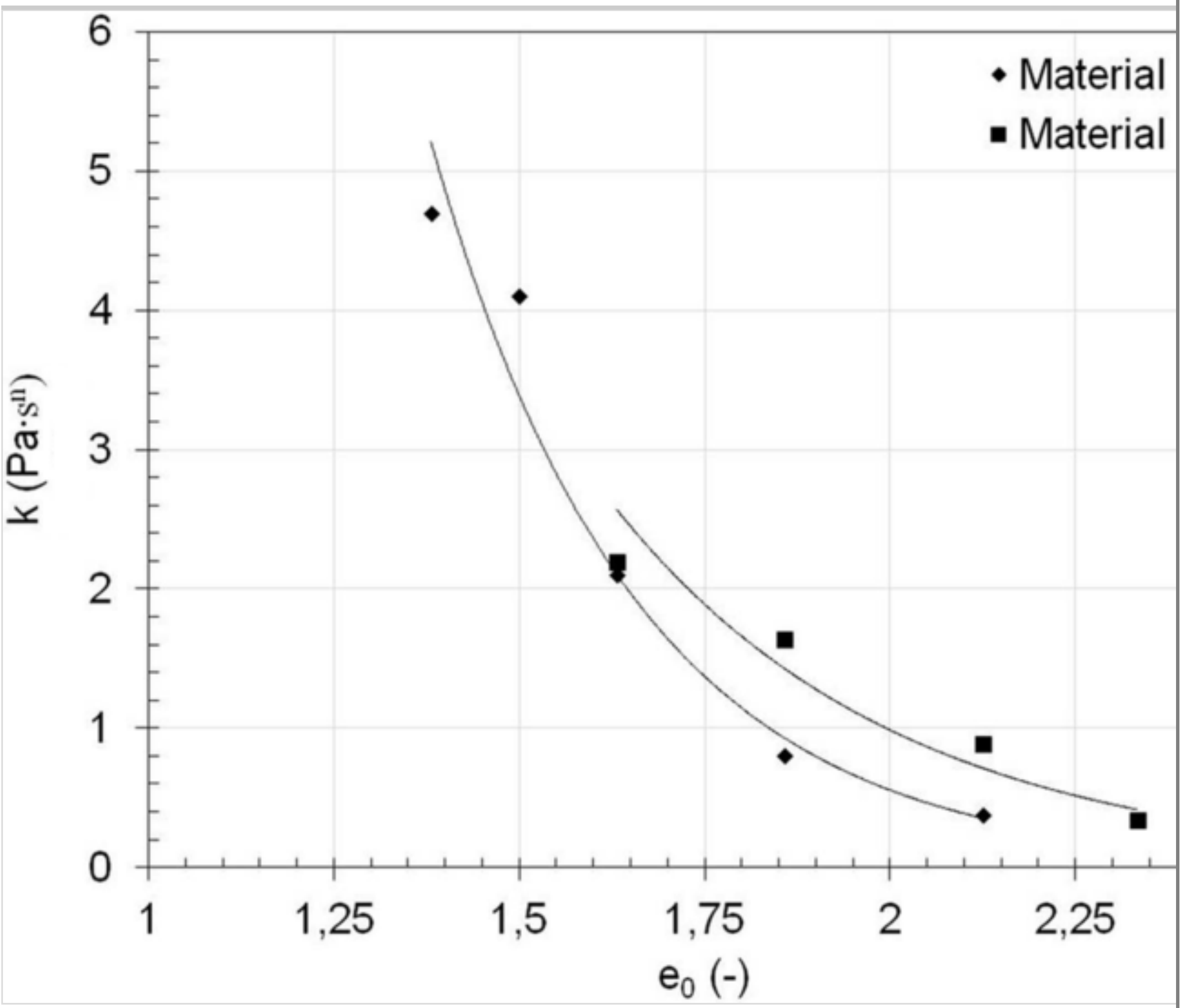
To demonstrate the influence of the solid volumetric concentration on the consistent coefficient k, the void ratio e_0 of the bulk volume (i.e., the ratio of the volume of void to the volume of solid) was considered:

$$e_0 = \frac{1 - \Phi_T}{\Phi_T}. \tag{12}$$

Figure 7 shows the consistent coefficient k as a function of the void ratio e_0, which may be assumed as an exponential function:

Fig. 7

Fine-grained mixtures: the consistent coefficient k (see Eq. 11) as a function of void ratio (tests #0–8; test group I, see Table 2)



$$k = \alpha \cdot e^{\beta \cdot e_0}, \tag{13}$$

where α and β are fitting parameters depending on the material characteristics. The most appropriate results are:

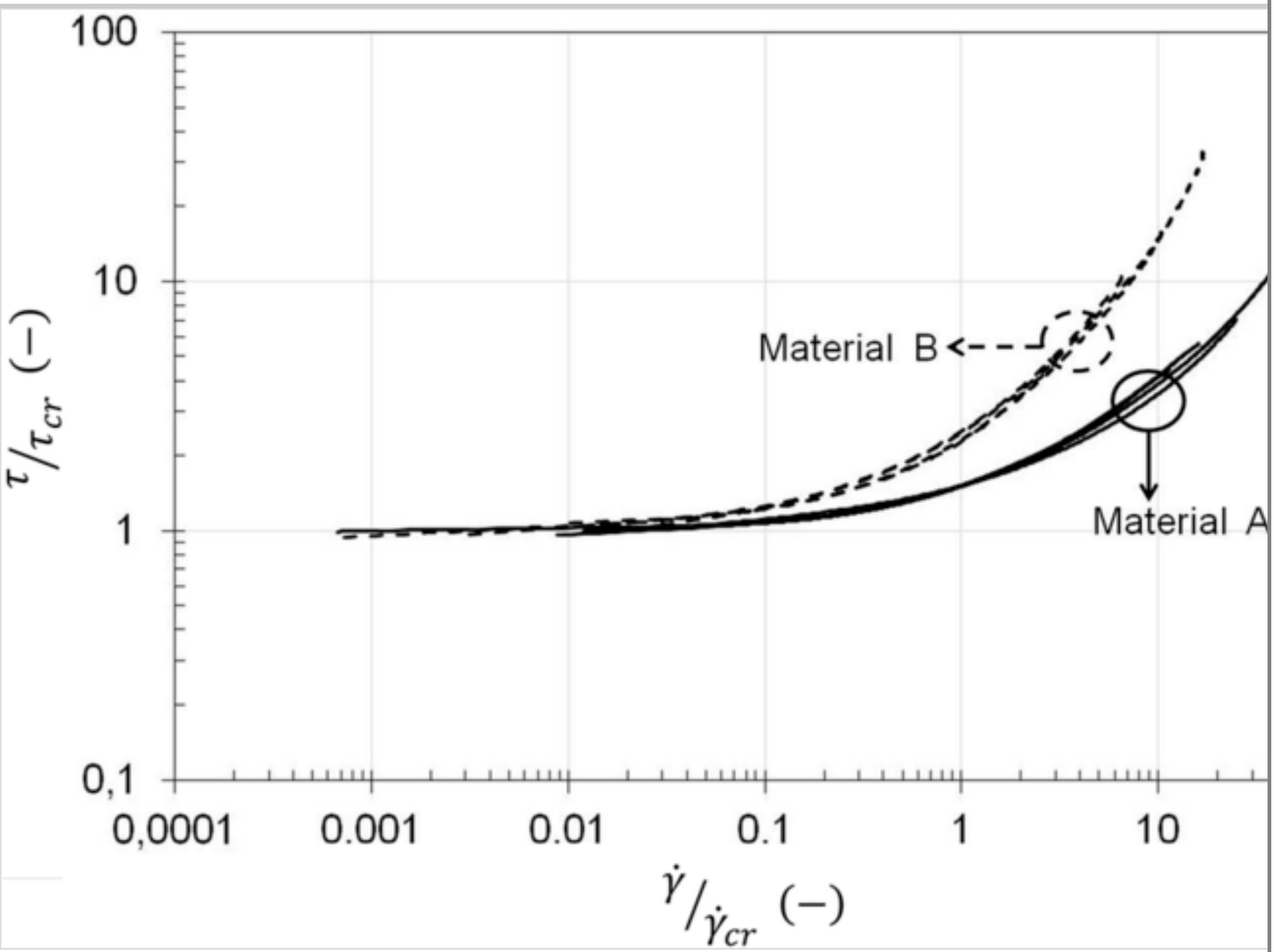
$$\text{Material } A \; k = 770 \cdot e^{-3{,}61 e_0}, \tag{14}$$

$$\text{Material } B \; k = 178{,}6 \cdot e^{-2{,}599 e_0}. \tag{15}$$

Figure 8 shows the experimental results in terms of non-dimensional shear stress as a function of the non-dimensional shear rate, applying the proposed Herschel–Bulkley generalized model (Eqs. 11–15) to the whole set of fine-grained sample mixtures. The flow curves related to materials A and B (i.e., the decreasing part of the flow curves plotted in Fig. 4) collapse to a single curve for each material, while an asymptotic trend can be seen for the higher values of shear rate, corresponding to the apparent viscosity of the mixtures.

Fig. 8

Fine-grained mixtures: dimensionless flow curves of the tested mixtures (tests #0–8; group I, see Table 2)



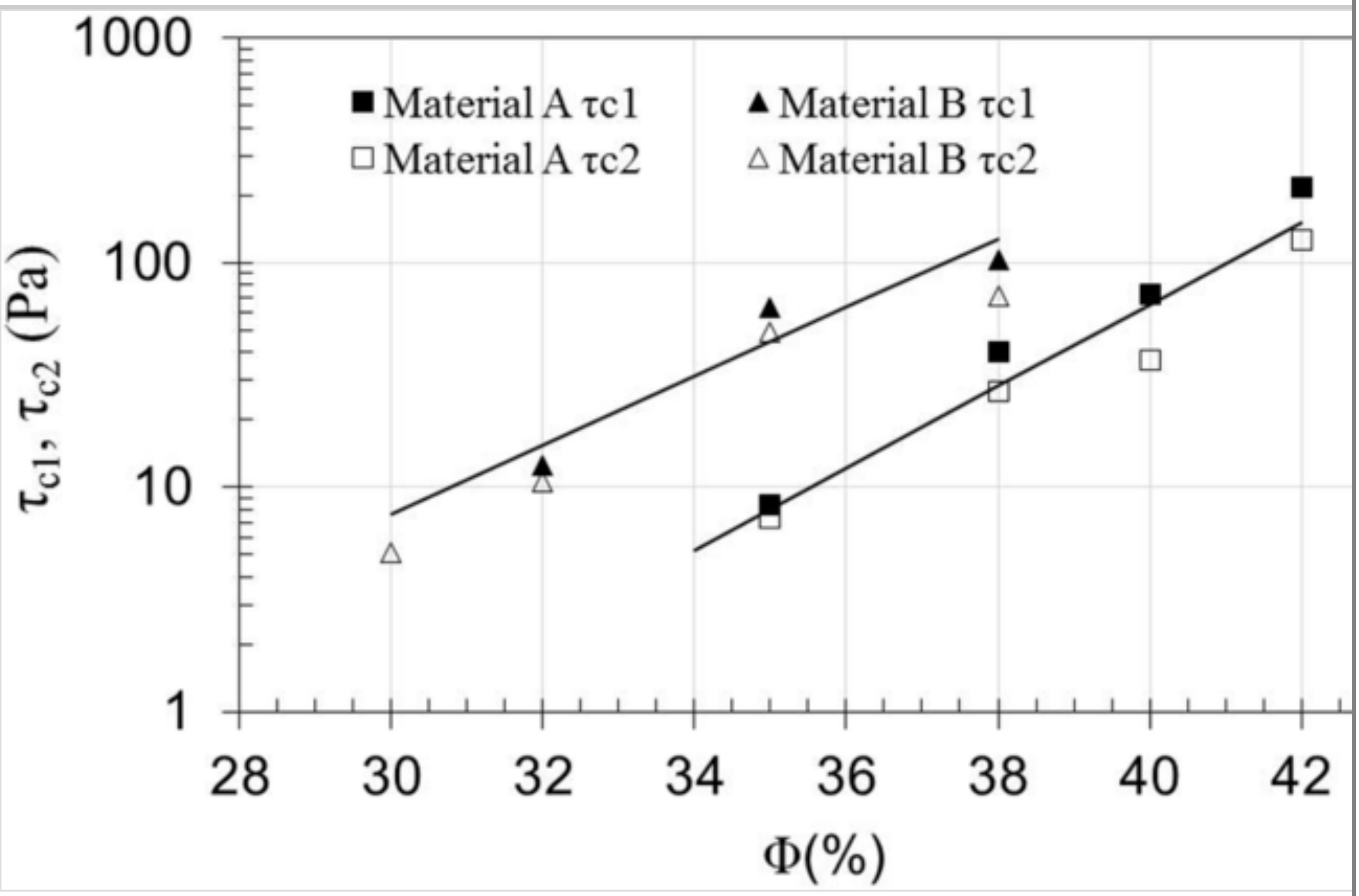
Preliminary sweep test on the influence of grain size dimension with regard to yield stress

To evaluate the influence of particle dimension on the rheological behavior of the mixtures, a rotational rheometer test was performed on two different samples of material B having the same bulk concentration $\Phi_T = 30\%$ (see Fig. 9). The first sample is a coarser grained mixture (i.e., $\Phi_T = 30\%$, $\Phi_f = 20\%$ and $\Phi_g = 10\%$) having particles with maximum diameter $d_{max} = 0.5$ mm. The second sample is a finer graded mixture (i.e., $\Phi_T = \Phi_f = 30\%$ and $\Phi_g = 0\%$)

having maximum diameter $d_{max} = 0.1$ mm.

Fig. 9

Fine-grained mixtures: inclined plane results (tests #1–8; group I, see Table 2)



The presence of coarse particles leads to a decreasing value of the yield stress, and is thus in agreement with prior experimental results on viscous suspension with similar particles tested by different rheometric equipment (Ancey and Jorrot 2001; Scotto di Santolo et al. 2010; Pellegrino and Schippa 2013a, b; Pellegrino et al. 2015b). Since the solid fraction of coarse particles is relatively small in comparison with that of fine particles, it confirms that the coarser solid content mainly affects the rheological behavior of the whole mixture in terms of yield stress (Coussot and Piau 1995; Contreras and Davies 2000; Schatzmann et al. 2009).

Therefore, some doubt surrounds the rheological behavior of natural debris flow when measured by means of a conventional rheometer; indeed, because of geometrical limits the standard apparatus is appropriate only for testing finer fraction of debris. The inclined plane test may overcome this limit, since there is no strict limitation on the grain dimension. Inclined plane test on fine-grained mixtures: comparison with sweep test.

Preliminarily performed to compare the yield stress results with those obtained via the sweep test, inclined plane tests refer to the same total solid volumetric concentration Φ_{T} analyzed by the rheometric tests on fine-grained materials A and B, as illustrated in the experimental program listed in Table 2 (i.e., tests# 1–8).

Figure 10 shows the relationship between the values of yield stresses (static and dynamic) and the total solid volumetric concentration. According to the results obtained with rotational rheometer tests, the dynamic and static yield stresses increase with the solid volumetric concentration, and the static yield stress is higher than the dynamic one. Figure 11 shows that yield stress values obtained from inclined plane versus sweep tests are consistent, even though the former leads to a slight overestimation of yield stress values according to previous observations (Scotto di Santolo et al. 2012; Pellegrino and Schippa 2013a, b; Pellegrino et al. 2015a, b).

Fig. 10

Fine-grained mixtures: comparison between static (filled symbols) and dynamic (empty symbols) yield stresses resulting from inclined plane and rheometric test for material A (squares, tests #1–4, see Table 2) and material B (triangles, tests #5–8, see Table 2)

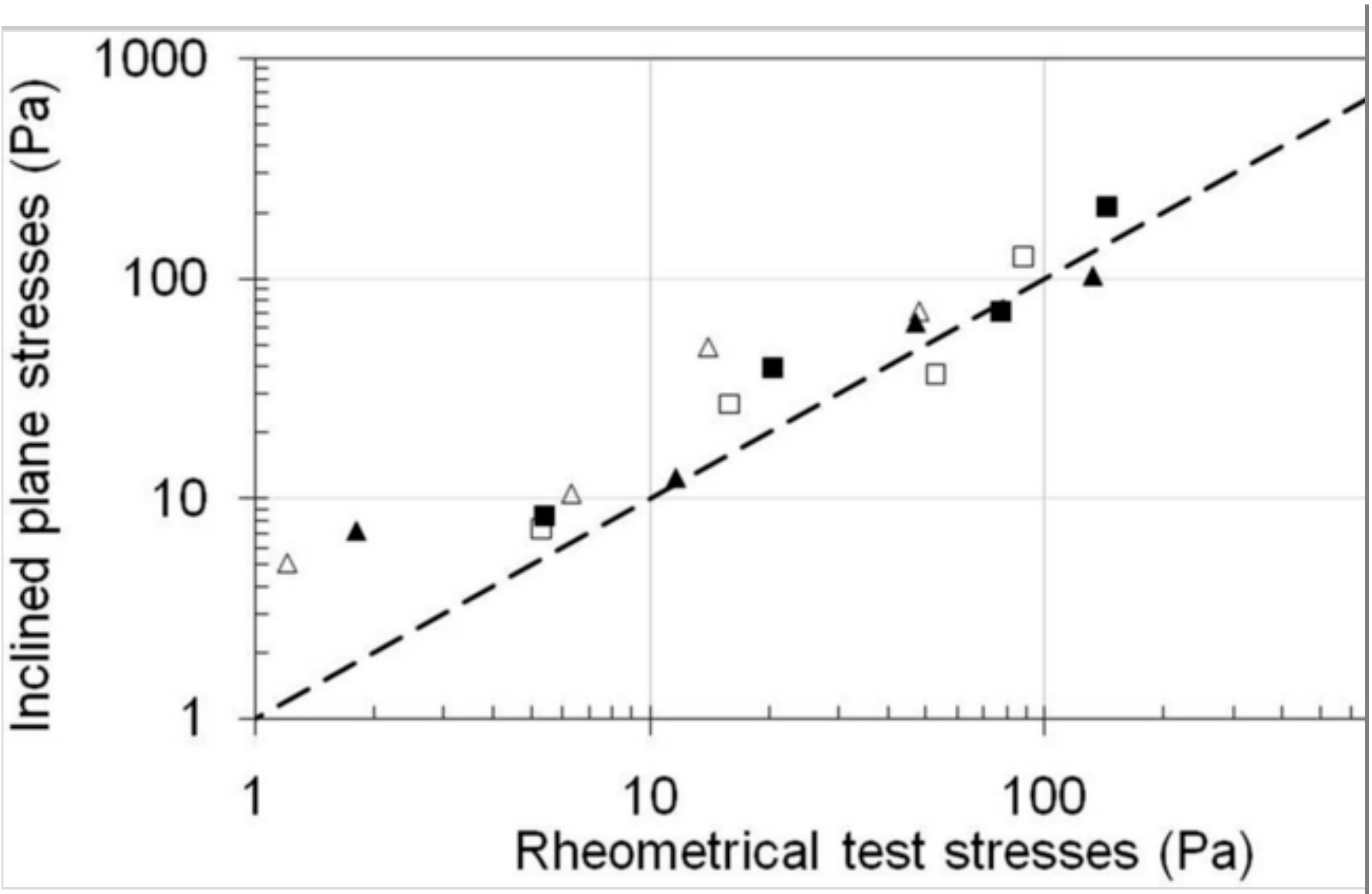
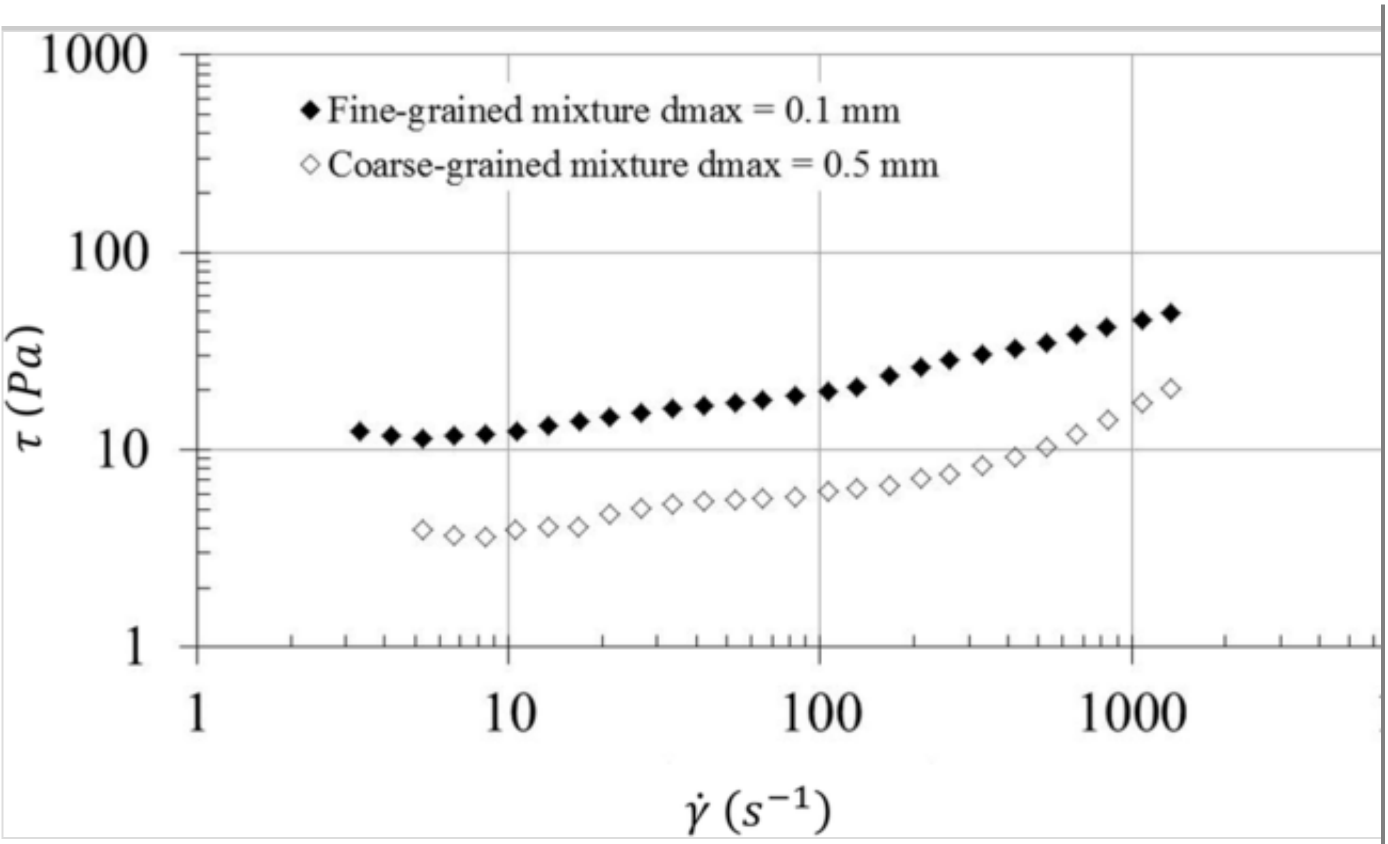


Fig. 11

Material B ($\Phi_T = 30\%$). Flow curves of two mixtures: fine-grained mixture ($\Phi_T = \Phi_f = 30\%$, full symbols); coarse-grained mixture ($\Phi_T = 30\%$, $\Phi_f = 20\%$ and $\Phi_g = 10\%$, empty symbols)



Inclined plane test: the influence of coarse particles on the yield stress

The experimental results achieved using the inclined plane test on coarse-grained mixtures illustrate the rheological behavior of the suspensions as a function of the relative content of fine and coarse grains.

The first set of tests was carried out using several mixtures having the total solid volumetric concentration $\Phi_T = 30\%$, (tests IIa in Table 2) and $\Phi_T = 32\%$, (tests IIb in Table 2), varying the relative content of fine and coarse grains. Test #5 (i.e., $\Phi_T = \Phi_f = 30\%$ and $\Phi_g = 0\%$) and test #6 (i.e., $\Phi_T = \Phi_f = 32\%$ and $\Phi_g = 0\%$) are considered as reference tests.

To investigate the effects of increasing coarse particle content, the second set of tests (i.e., group III in Table 2) was performed on mixtures presenting a constant content of fine particles $\Phi_f = 25\%$, and a different concentration of coarse particles Φ_g. Table 4 reports the experimental program and the results regarding calculated yield stress (Eqs. 7, 8).

Table 4

Inclined plane test on coarse-grained mixtures (material B): experimental program an results

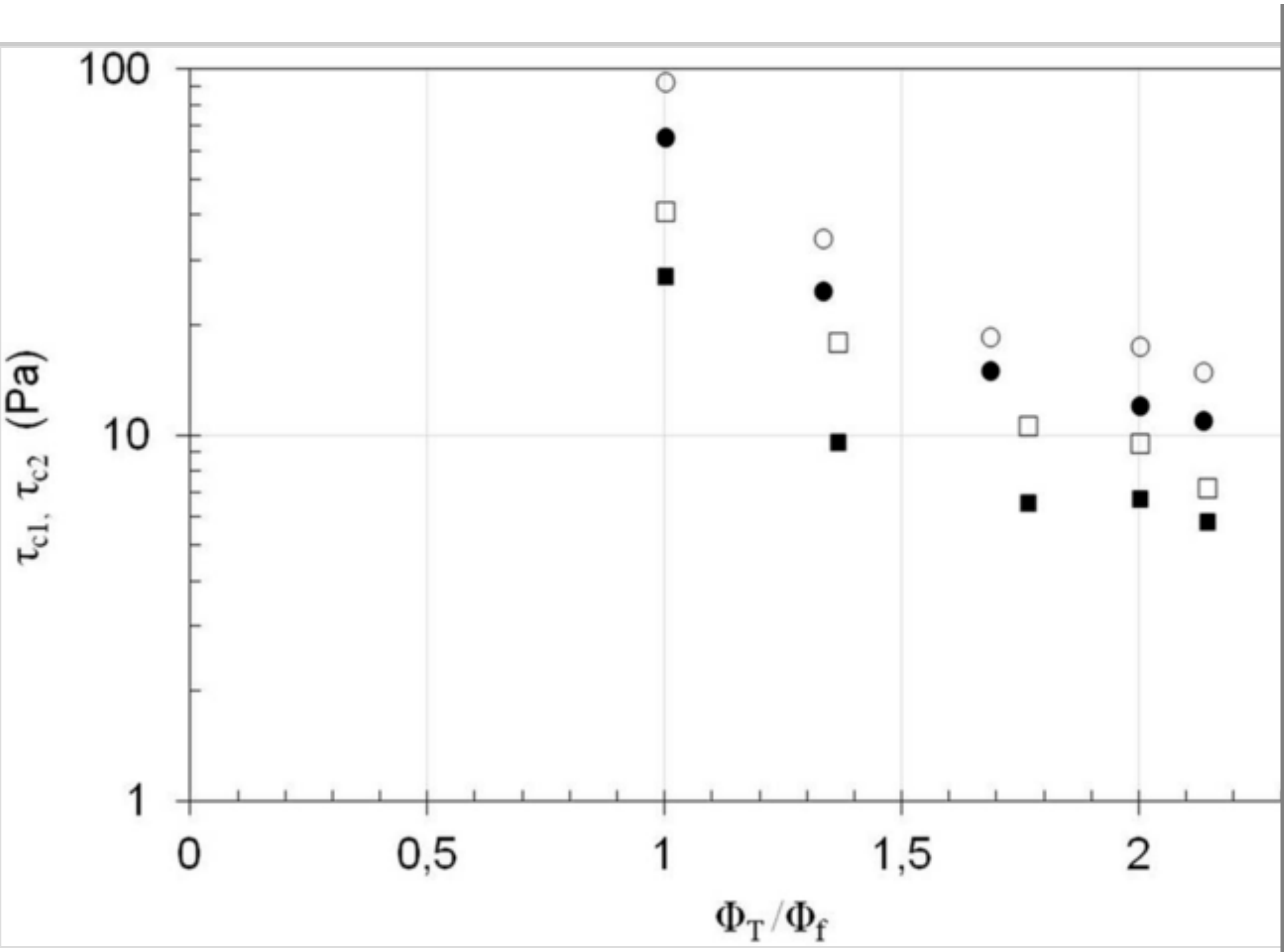
Test	Group	Φ_T (%)	Φ_f [a] (%)	Φ_g (%)				Φ_g (%)	τ_{c1} (Pa)	τ_{c2} (Pa)
				$d <$ 1 mm	$d <$ 2 mm	$d <$ 5 mm	$d <$ 10 mm			
5	I	30	30	-	-	-	-	-	40.74	27.16
6	III	32	32	-	-	-	-	-	92.32	75.51
9	IIa	30	22	8	-	-	-	8	17.89	9.61
10	IIa	30	17	8	5	-	-	13	10.56	6.52
11	IIa	30	15	8	5	2	-	15	9.51	6.70
12	IIa	30	14	8	5	2	1	16	7.20	5.81
13	IIb	32	24	8	-	-	-	8	34.42	24.76
14	IIb	32	19	8	5	-	-	13	17.57	10.65
15	IIb	32	16	8	5	3	-	16	17.44	8.95
16	IIb	32	15	8	5	3	1	17	14.94	7.47
17	III	25	25	-	-	-	-	-	9.50	7.24
18	III	33	25	8	-	-	-	8	17.88	14.72
19	III	38	25	8	5	-	-	13	34.12	23.10
20	III	40	25	8	5	2	-	15	55.11	30.18
21	III	41	25	8	5	2	1	16	77.88	43.59

[a] $d < 0.5$ mm

Figure 12 shows the relation between the measured values of the static and dynamic yield stresses, and the ratio between the total solid volumetric concentration Φ_T and fine particle solid volumetric concentration Φ_f (i.e., $\Phi_T/\Phi_f = 1 + \Phi_g/\Phi_f = 1 + V_{sg}/V_{sf}$), for the first set of tests described above.

Fig. 12

Material B ($\Phi_T = 30\%$—squares—and $\Phi_T = 32\%$—circles). Static (empty symbols) and dynamic (full symbols) yield stress as a function of the ratio between total solid volumetric concentration Φ_T and solid volumetric concentration of fine particles Φ_f (tests #5, #6 and #9–16, see Table 2)

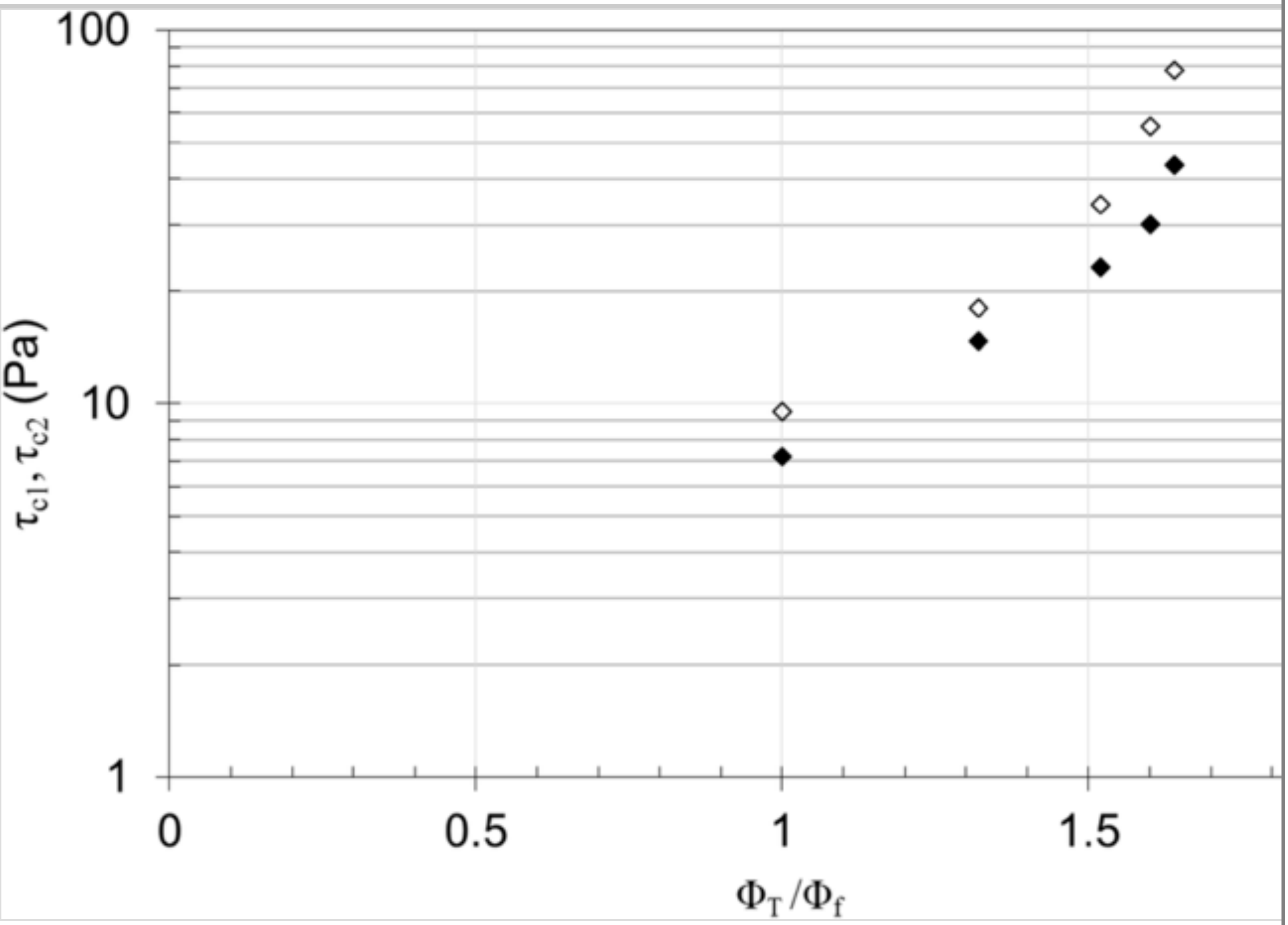


At constant total solid volumetric concentration, the lesser the fine grains content, the smaller the yield stress values (both static and dynamic) are, regardless of the coarse particles fraction in the mixtures (see test #5, #6 and tests #9–16 in Table 4). The static and dynamic yield stresses, meaningfully decrease (by almost one order of magnitude) if the solid volumetric concentration of coarse particles is smaller than that of fine particles (tests #10, #9, #5, #13 and #14). Conversely, the values of the rheological parameters slightly decrease when the concentration of coarse particles in the mixture is comparable with that of fine grains (tests #11, #12, #15 and #16).

Figure 13 reports the experimental results related to the second set of tests (i.e., group III see Tables 2, 4). In this case of constant fine particles fraction, the increment of coarse grains concentration (from 8 to 16%) leads to a significant increasing of the value of rheological parameters (by almost one order of magnitude), according to the experimental evidence gathered using the rotational rheometer. The addition of coarse particles (albeit in small quantity) leads to a decrease in the values of the rheological parameters, regardless of the total solid volumetric concentration of the mixtures. To the contrary, increasing the volumetric fraction of coarse grains leads to a consistent increasing of the values of the rheological parameters of the mixtures.

Fig. 13

Material B ($\Phi_f = \text{constant} = 25\%$). Static (empty symbols) and dynamic (filled symbols) yield stress as a function of the ratio between total solid volumetric concentration Φ_T and solid volumetric concentration of fine particles Φ_f (test #5 and tests #17–21, see Table 2)



Discussion

The experimental results show that the rheological behavior of these suspensions is typical of non-Newtonian fluids exhibiting yield stress; while the gathered data indicates that a general power law model may represent the stress–strain relationship within the range of the sediment concentration examined herein. In this sense, the experimental results are consistent with the conclusions of various authors who performed similar laboratory tests (Coussot 1997; Schatzmann et al. 2009; Scotto di Santolo et al. 2012), showing that yield strength and plastic viscosity are very sensitive to granular concentration and coarse grain content (see Tables 3, 4).

The pyroclastic soils analyzed in our study usually present a very small clay fraction—sometimes it is even absent—consequently, the mixtures behave as homogeneous fluids in a very small range of solid volumetric concentration, typically less than 10% (Picarelli et al. 2007). The measured yield stress for fine-grained mixtures reflects the lack of significant clay fraction content in the tested soils. In fact, the yield stress increases with the amount of clay, since the interactions between the clay particles are stronger than the hydrodynamic interactions among the grains (Coussot and Piau 1995). On the other hand, mixtures characterized by low clay content (generally less than 40%) like the soils examined here, show limited yield stress values (Malet et al. 2003). On the contrary, the experiments of Sosio and Crosta (2009), involving reconstituted debris-flow samples having a clay-silt fraction ranging from 50 to 90% of the total sediment content, show yield strength ranging from 70 Pa to nearly 2000 Pa, respectively, thus one order of magnitude larger than we obtained in our experiments.

Examining the influence of the solid volumetric concentration on the rheological parameters of the fine-grained mixtures demonstrates that solid content greatly affects the behavior of these mixtures during the flow. In particular, in the range of solid volumetric concentration tested here, the yield stress grows very rapidly with the increasing of the solid fraction. The tests carried out on the inclined plane confirmed this trend and provided an acceptable approximation of the values of the static and dynamic yield stresses, whereas the difference between the yield stresses (both static and dynamic) measured via the inclined plane and those determined via the sweep test (i.e., rheometer test) does not seem relevant. Therefore, it may be assumed that for concentrated suspensions, conventional rheometer tests provide an adequate assessment of material behavior during the flow (i.e., flow curve), whereas tests with the inclined plane method are most suitable for estimating the effective yield stress (Coussot et al. 1998; Maletet al. 2003; Schatzmann et al. 2003).

Ancey and Jorrot (2001) experimented unimodal mixtures of poorly sorted sand having mean diameter of 0.3 mm and 1.2 mm in kaolin-water suspension. The mixtures had solid concentration varying from about 29–57%, and the resulting yield stress ranged over one order of magnitude (i.e., from about 70 to 700 Pa). In the range of sediment concentration lower than 45%, the yield stress increased regularly in the range of about 60–200 Pa. Their results are confirmed by our experiments related to fine-grained mixtures (i.e., sand finer than 0.5 mm), which showed a consistent and regular variation of yield stress between 5 and 200 Pa in the range of the tested sediment concentration (i.e., from 30 to 42%, see Fig. 9). The variations in yield stress values between our and their experiments are partly due to the different interstitial fluid, which is clear water and kaolin-water suspension respectively, and to the different experimental procedures, since they used the "slump test" method to determine the yield stress.

Major and Pierson (1992) carried out experiments involving reconstituted debris-flow mixtures from samples of volcanic deposit of the same debris. Among this whole set of data, our interest focuses on the tested mixtures composed of clay-silt ($< 63\ \mu$m) and sand (63 μm to 2 mm) in relative ratio of 1:1 and 1:4.5, respectively, and having total sediment concentration ranging from 56 to 66%, which corresponds to the maximum limit allowing a quasi-fluid behavior. In keeping with the constant clay-silt to sand ratio, the yield stress increases with greater sediment concentration, a finding that is consistent with our experimental results on fine-grained mixture (see Table 3). Among their reconstituted samples, those presenting relative content clay-silt to sand 1:1 and lower sediment concentration are the more comparable to our own laboratory conditions; in these cases, their yield strength values (i.e., 44 Pa and 72 Pa corresponding to grain concentration of 56% and 57%, respectively) are comparable to those obtained in our experiments.

The Hershel-Bulkley generalized model (Eq. 11) applies quite satisfactorily to our experimental data and, for any material considered herein, it shows a relevant variability of consistent index with the concentration, ranging from 0.4 Pa s^n to 4.7 Pa s^n (see Table 3). Major and Pearson (1992) observed a similar behavior and highlighted consistent coefficient variability with regard to the concentration and relative content of clay-silt to sand. In particular, their samples presenting a ratio of clay-silt to sand equal 1:1 and 1:4.5 showed a wide variability of the consistent coefficient between 0.4 Pa s^n to 4.1 Pa s^n.

The influence of particle size on the rheology of such a mixture is a fundamental feature in defining the flowing behavior of materials involved in rapid landslide phenomena. The presence of coarse particles strongly affects the rheological properties of concentrated suspensions (Coussot and Piau 1995; Ancey and Jorrot 2001; Schatzmann et al. 2009), since it possibly refers to the interaction between coarse particles and the matrix composed of finer particles and water. Sand particles present in the tested fine-grained mixtures makes the shear strength independent from the shear rate in the range of shear rate lower than 1–10 s^{-1} depending on sediment concentration and on the relative content of clay-silt and sand in the two considered soil samples. In fact, the higher the relative sand content is, the higher the threshold shear rate results (see Figs. 4, 6). Moreover the sand fraction affects the pseudoviscosity of slurries in the fluid-like regime (i.e., $s_r > 10$ s^{-1}) as can be seen in Fig. 1. This behavior is consistent with observations by Sosio and Crosta (2009), who made experiments with reconstituted debris-flow mixtures obtained from collected samples at the source and deposit areas of real debris flow. The tested samples were obtained by mixing clay-silt fraction and water and adding differing amounts of sand ranging from 10 to 50% in volume with respect to the total sediment content, having different maximum diameter (from 0.150 to 0.425 mm). The range of yield strength occurs for shear rate less than 5 s^{-1}, depending on the percentage of added sand and on the maximum grain diameter.

Considering the coarse-grained mixture tested here, the increase of coarse fraction’s relative content (d_s>0.5 mm) from 27 to 57% leads to a systematic decrease of the yield strength in the range of 18 – 7 Pa and 34–15 Pa, in the presence of a total sediment concentration of 30% and 32%, respectively (see Table 4, test 9–16). The effect of large particle content on rheological behavior is a result of the interaction between the coarse particles and the matrix composed by finer particles and water. Indeed, in coarse-grained mixtures, the yield stress mainly depends on interparticle friction-type contacts. Therefore, the increasing of larger particle content may lead to incremental yield stress values. It is worth noting that this behavior corresponds to a threshold value of coarser particle content (about 15%), which is consistent with other observed results and previous works (Banfill 1994~~1999~~; Coussot and Piau 1995; Coussot et al. 1998; Mansoutre 1999; Ancey and Jorrot 2001).

Conclusion

The present work focuses on the effect of grain size distribution and solid concentration on rheological behavior of reconstituted debris-flow mixtures. The considered viscous suspensions behave like a homogeneous fluid in the tested range of solid volumetric concentration, and their rheological behavior is typical of viscous suspensions with yield stress, exhibiting a static yield stress larger than a dynamic one. The flow of such materials is unstable: the suspension starts to flow at a critical value of shear stress and rapidly reaches high shear rate linked to high flowing velocity. The rheological behavior of these kinds of mixtures is mainly influenced by the solid content and particles size, since yield stresses vary with both the total solid volumetric concentration, and the relative concentration of fine and coarse particles. The different mechanical properties of the original collected soils, due to the variations in the distances of the deposits from the eruptive center and to the mechanisms of deposition, such as the different grain size distribution of the fine-grained reconstituted soil samples A and B (i.e., the former presents a large silty component, and the latter exhibits a relatively sandy content), leads to a significant scatter on the rheological parameter values of the two tested moisture samples. Taking into account the fine-grained mixtures the yield stress widely increases (by orders of magnitude) and is very sensitive to the total grain content by volume. The experimental results show that a general power law model may represent the stress–strain relationship in the examined range of sediment concentration. Therefore, a Herschel–Bulkley generalized rheological model is proposed assuming a consistent coefficient as a function of the void ratio of the bulk mixture and of the material characteristics (Eqs. 13–15). Inclined plane tests performed on coarse-grained mixtures demonstrated the effect of grain size distribution on rheological behavior, also showing that a moderate content of coarse grain may dramatically modify the yield stress value. The relative concentration of coarse and fine particles seems to be discriminant in rheological behavior. In the presence of dominant fine grain fraction, a slight increasing of the coarse grain fraction leads to a relevant decrease of both static and dynamic yield stress values. When the concentration of coarse particles in the mixture increases and becomes similar to that of fine particles, the values of the rheological parameters slightly decrease.

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