Rheological properties of fine-grained sediment: the roles of texture and mineralogy

Sueng Won Jeong, Jacques Locat, Serge Leroueil, and Jean-Philippe Malet

Abstract: Rheological properties of fine-grained sediments depending on index properties and salinity were examined. To characterize flow behaviors as a function of soil type, groups were made for convenience: (*i*) low-activity clays (group 1), (*ii*) high-activity clays (group 2), and (*iii*) silt-rich soils (especially for iron tailings; group 3). Low-activity and high-activity clays have characteristics of pseudoplastic (shear thinning) fluids, and exhibit a decrease in viscosity with increasing shear rate. However, in terms of the change in soil structure due to particle–particle interactions, illitic and montmorillonitic clays have opposite responses to salinity. As most of our data were obtained on low-activity clays — mostly illitic mixtures — we implemented a test program to ascertain the influence of montmorillonite on flow behavior. Using the Bingham model, a simple relationship is presented in terms of the possible critical limits of rheological transitions from clay- to silt- to sand-rich soils.

Key words: low-activity clay, high-activity clay, iron tailings, shear thinning fluid, rheological properties, rheological transition.

Résumé : Les propriétés rhéologiques des sédiments fins dépendantes des propriétés indices et de la salinité ont été examinées. Des regroupements ont été faits afin de caractériser les comportements en écoulement en fonction du type de sol : (*i*) argiles à faible activité (groupe 1), (*ii*) argiles à activité élevée (groupe 2) et (*iii*) sols riches en silt (particulièrement pour les résidus de fer; groupe 3). Les argiles à faible et haute activité ont les caractéristiques d'un fluide pseudo-plastique (fluidification par cisaillement), présentant une diminution de leur viscosité avec une augmentation du taux de cisaillement. Cependant, si l'on considère la variation de la structure du sol due aux interactions entre les particules, les argiles illitiques et montmorillonitiques ont une réaction opposée à la salinité. Puisque la majorité de nos données proviennent d'essais sur des argiles à faible activité, principalement des mélanges illitiques, nous avons effectué des essais pour confirmer l'influence de la montmorillonite sur le comportement en écoulement. À l'aide du modèle de Bingham, une relation simple est présentée, qui décrit les limites critiques possibles des transitions rhéologiques d'argiles à silt à sable.

Mots-clés : argile à faible activité, argile à activité élevée, résidus de fer, fluidification par cisaillement, propriétés rhéologiques, transition rhéologique.

[Traduit par la Rédaction]

Introduction

Subaqueous and subaerial mud or debris flows pose a great threat to life and infrastructure while being a major natural mechanism of sediment transport (Hampton et al. 1996; Jakob and Hungr 2005). One important element of risk analysis and mitigation lies in the use of numerical models for prediction of runout distances and impact pressures. Any numerical model of flow mechanics will require input of rheological parameters including yield strength and viscosity. Extensive work has been carried out by various researchers over the last 20 years to provide such parameters for muddy (O'Brien and Julien 1988; Coussot 1997), sandy (Ilstad et al. 2004), and coarse debris flows (Malet et al. 2005), focusing largely on understanding the effect of grain size. In terms of physical properties, these researchers examined primarily the effect of solid concentration with little or no attempt to provide general relationships based on index properties. To that effect, Locat and Demers (1988), Locat (1997), and Locat and Lee (2002) proposed empirical relationships enabling the estimation of rheological properties of mud based on the liquidity index. These relationships were based on observations obtained from a limited number of samples, mostly inorganic and illitic sensitive clays. As part of a major effort to provide useful relationships for a first approximation of viscosity and yield strength, a larger number of soils or sediments with different textures and mineralogies (low-activity versus high-activity clays) were investigated (Jeong 2006). The present paper aims at revisiting the relationships proposed by Locat (1997) by integrating various rheological test results obtained on samples of different natures so that the role of sediment texture (from clay to sand) and mineralogy (low-activity and high-activity

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clays) on the rheological behavior of muds could be considered.

Apart from the effect of the type of rheometer used and the test procedures followed, the behavior of mud mixtures is influenced by soil type (Major and Pierson 1992; Parsons et al. 2001), pH, temperature, and salinity (Bentley 1979; Torrance and Pirnat 1984; Perret et al. 1996). In particular, an understanding of the influence of coarse-grained soils in fine-grained debris flows is essential. As many authors have pointed out, debris flow materials with large-size particles can yield large data scatter, making it more difficult to describe the rheological behavior of such materials and fit an appropriate model. Debris flows and mudflows were considered a mass of viscous material and generally appear to behave as a laminar flow. These sediment–water mixtures are generally characterized by viscoplastic flow behavior. Because even the largest conventional viscometers are limited to analyzing natural or artificial mixtures with maximum particle sizes of ∼20 to 35 mm (Schatzmann et al. 2003), the presence of large-size particles in highly concentrated soil–water mixtures still presents a problem for the determination of rheological properties (Coussot et al. 1998). In many cases, experimental studies of dense suspension rheology as practiced using conventional rheometers cannot reveal the origins of complex flow behavior, nor even provide consistent data for the development of theory (Barnes et al. 1987; Major and Pierson 1992). This is why procedures for large-scale debris flow experiments still have to be developed.

The present study was designed to investigate several key issues:

(1) generalized flow characteristics with particular reference to the three groups of soils: i.e., low-activity clays (group 1: illitic soils), high-activity clays (group 2: montmorillonitic soils), and silt-rich soils (group 3: iron tailings)
(2) how the index properties and salinity of sediments influence the evolution of rheological behavior
(3) the critical limits obtained from the relationship between yield stress and viscosity (i.e., boundary lines from clay- to silt- to sand-rich materials) existing for a variety of soil texture types.

Rheological behaviors of fine-grained sediments and their flow properties in a pseudoplastic regime

Definition of yield stress and plastic viscosity

Natural soft clays and fine slurries display non-Newtonian flow behavior, which is both strain-rate- and time-dependent. This rheological behavior is generally described by the relationship between shear stress, τ, and shear strain rate, $\dot{\gamma}$. The most popular rheological models of viscoplastic fluids are the Bingham (eq. [1]) and Herschel–Bulkley (eq. [2]) models.

$$[1] \qquad \tau = \tau_c + \eta_h \dot{\gamma}$$

$$[2] \qquad \tau - \tau_c = K \dot{\gamma}^n$$

where τ is in Pa, τ_c is the yield stress (Pa), η_h is the plastic viscosity (Pa·s), and $\dot{\gamma}$ is in s^{-1}. In eq. [2], K is the consistency coefficient (Pa·s) and exponent n is the flow behavior index (dimensionless). For $n < 1$, the behavior is pseudoplastic and for $n > 1$, it is dilatant. If $\tau_c = 0$, the Herschel–Bulkley model simplifies to the power law model. For $n = 1$, the power law model reduces to a Newtonian fluid model. A very helpful review of the classical work in determining rheological properties is given by Barnes (1999).

Among various rheological models, the simplest theoretical model that associates fluids to a yield stress is the Bingham model. The shear stress is given as a linear function of shear strain rate, where yield stress, τ_c, and plastic viscosity, η_h, are constant values. The concept of the ideal Bingham model is still convenient in practice because many fluids approximate this type of flow behavior, more or less closely. For example, Fig. 1 shows the general flow curve in a τ–$\dot{\gamma}$ scale for the Mediterranean Sea sample at a liquidity index of 2.1. According to the Bingham model, τ_c would be equal to 166 Pa and η_h would be equal to 0.124 Pa·s (see fitted lines in Fig. 1), but this model overestimates the shear stress at lower shear rates. The simple Bingham model has been expanded into the Herschel–Bulkley (eq. [2]) rheological (sometimes called the generalized Bingham) model. This nonlinear viscoplastic model is most widely used to describe the rheology of laminar mud flows (Coussot 1997; Imran et al. 2001). Rheological investigation has shown that, for most mudflows, $n < 1$, indicating pseudoplastic (shear thinning) behavior.

The bilinear model can be used for modeling debris flows as well (Imran et al. 2001; Remaître et al. 2005), and the one described below is essentially a generalization of the Bingham model. This model uses two viscosities: plastic viscosity, η_h, and pseudo-Newtonian viscosity, η_l. At sufficiently high shear strain rates, the flow behaves as a Bingham fluid with a low viscosity, η_h. At very low shear strain rates, the flow behaves as a Newtonian fluid with a high viscosity, η_l. The formulation of the bilinear model is written as follows:

$$[3] \qquad \tau = \tau_{ya} + \eta_h \dot{\gamma}^n + \left(\frac{\tau_c \dot{\gamma}_o}{\dot{\gamma} + \dot{\gamma}_o} \right)$$

where τ_{ya} is the apparent yield stress (Pa) and $\dot{\gamma}_o$ is the shear rate at the transition from a Newtonian to a Bingham behavior. As shown in Fig. 1, the difference between the yield values obtained from the Bingham (i.e., τ_c = 166 Pa) and the bilinear (i.e., τ_{ya} = 168 Pa) models is very small. Figure 2 shows the flow curve in a log viscosity(η)–log$\dot{\gamma}$ scale for the Mediterranean Sea sample at a liquidity index of 2.1, using the same results as those presented in Fig. 1. When plotted as the logarithm of viscosity against the logarithm of shear stress (or shear rate), the phenomenon may be better illustrated. It can be seen that η_l is about 60 Pa·s at a shear rate of 1 s^{-1}, and η_h will be become about 0.1 Pa·s at a shear rate of 10 000 s^{-1}.

Flow behavior of fine-grained sediments

In nature and industry many materials are generally considered yield stress fluids — for example, mud, lava, snow, cement, mayonnaise, foam, etc. — and it was shown recently that they are able to remain at rest indefinitely when

Fig. 1. Determination of yield stress, plastic viscosity, and pseudo-Newtonian viscosity for the Mediterranean Sea sample at a liquidity index of 2.1: apparent yield stress (1) is determined by the bilinear model and Bingham yield stress (2) is determined by the Bingham model.

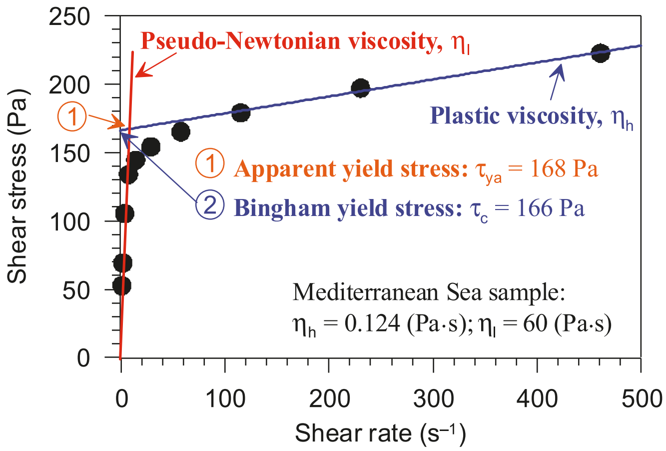
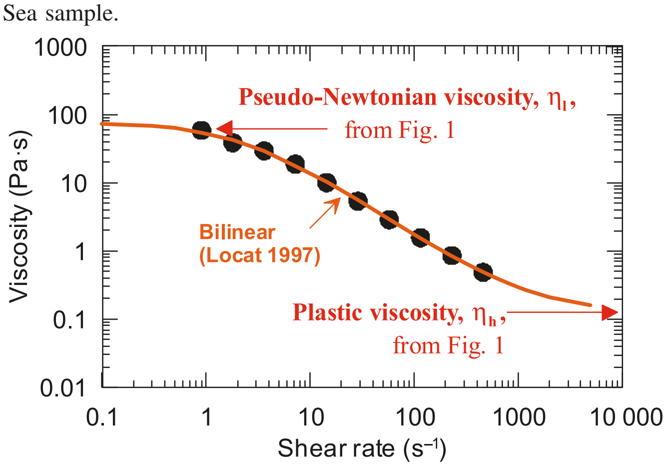


Fig. 2. Plot of log viscosity versus log shear rate: Mediterranean Sea sample.



subjected to insufficient shear stress, but capable of flow under larger stress (Coussot and Piau 1994; Coussot et al. 2005). In rheology these materials, including natural soft clays, present typically thixotropic behavior with yield stress. It should be noted that this will only occur after they have been disturbed, and even then hysteresis is common. Thus, an undisturbed quick clay that is remoulded does not return to its original state, and strength recovery is only a few percent of the strength loss. However, after the quick clay has been thoroughly remoulded, the remoulded clay recovers its original strength at the end of the imposed shear rate change cycle. Such disturbed natural soft clays, which are thixotropic, are included in this study.

Typical viscometric results can be presented in a semi-logarithmic or log–log diagram of rheological and geotechnical parameters with regard to liquidity index. Empirical relationships were presented by Locat (1997) for (*i*) yield stress and plastic viscosity, (*ii*) liquidity index and plastic viscosity, and (*iii*) liquidity index and yield stress. In most cases, the lower limit used for plastic viscosity is 1 mPa·s, i.e., the viscosity of water. Assuming that the flow behaves as a Bingham fluid, there is a relationship between plastic viscosity, η_h (mPa·s), and yield stress, τ_c (Pa). As for natural soft clays in the range of liquidity indices 1–5, the plastic viscosity only represents about 1/1000th of the total shearing resistance of the system. This relationship can be described by the following equation:

$$[4] \qquad \eta_h = 0.52\tau_c^{1.12}$$

Using the liquidity index, I_L, for a variety of soils, plastic viscosity can be written as

$$[5] \qquad \eta_h = \left(\frac{9.27}{I_L}\right)^{3.3}$$

Locat (1997) showed that rheological behavior of sensitive clays could be bounded by two equations, one for very low salinity (~0 g/L, eq. [6]) and one for high salinity (~30 g/L, eq. [7])

$$[6] \qquad \tau_c = \left(\frac{5.81}{I_L}\right)^{4.55}$$

$$[7] \qquad \tau_c = \left(\frac{12.05}{I_L}\right)^{3.13}$$

These equations may be useful for preliminary numerical analyses of subaerial and submarine mass movements (Gauer et al. 2005).

Transitional behavior from viscous to granular flow

Two types of debris flow dynamics can occur: viscous flow (O'Brien and Julien 1988; Coussot 1997) and granular flow (Bagnold 1954; Iverson 1997). In practice, the material properties that determine the rheological transition between viscous (i.e., fines-rich viscoplastic fluid) and granular (i.e., fines-poor material; Bin et al. 2000) are not well defined. Viscous flow assumes that debris flow material behaves as a continuum with an intrinsic yield strength and plastic viscosity (Johnson 1984; Parsons et al. 2001), but granular flow is based on the mechanics of granular media (the physics of grain–grain and grain–fluid interactions). To estimate the flow behavior of a field debris flow, the rheological parameters used in the compatible model must be similar to actual field conditions. Several studies have been carried out to determine the influence of different soil types and solid concentrations on rheological properties, but assessing the dependence of rheological response on soil type is still difficult. Also, the previous work does not provide sufficient information regarding rheological transitions to allow determination of corrections between debris flow mobility and sediment characteristics. According to Major and Pierson (1992), small changes in the clay fraction or proportion of silt and sand particles can strongly modify the flow behavior. They also showed that, with an increase in clay and sand content (for instance, a ratio of silt-to-clay to sand ranged from 11 : 1 to 1 : 4.5), debris flow rheology tends to exhibit a more Bingham-like behavior. As examined preliminarily by Jeong (2006), silt-rich soils have low yield values and an almost linear viscous flow for shear stresses exceeding the yield stress. Thus, the plastic viscosity – shearing resistance relationship can provide much higher correlation for silt-rich soils than for clay-rich material. Based on the empirical relationship (eq. [4]), the ratio of the apparent yield stress, τ_{ya}, to the plastic viscosity, η_h, can extend the possible rheological range of coarse-grained soils in comparison with fine-grained soils. It may be possible to define the conditions for the rheological transition from typical clays (viscous) through silt- or sand-rich soils to granular flow. If so, the plastic viscosity of materials having low plasticity could be described by the following equation, similar to eq. [4], where soil parameter α depends on soil type:

$$[8] \qquad \eta_h = \alpha\tau_{ya}$$

where the apparent yield stress, τ_{ya}, is in Pa and plastic viscosity η_h is in mPa·s. This is the hypothesis that is to be tested with the results presented in this paper.

Materials and methods

Materials

Materials investigated and methods used in this paper are described in Jeong et al. (2009): the soil samples were separated into three groups using Casagrande's plasticity chart (Fig. 3) and activity. The main geotechnical and physicochemical parameters of the studied soils are presented in Table 1. The first group is low-activity clays: Adriatic Sea, Beaufort Sea, Cambridge Fjord, Hudson Apron, Jonquière, Baie des Ha!Ha!, Pointe-du-Fort and Confluence (USAG-86 and USAG-87) near the Cap de l'Est in upper Saguenay Fjord, Mediterranean Sea, and St-Alban clays. For these materials, the liquid limit, w_L, and plasticity index, I_P, ranges are approximately 30%–70% and 16%–36%, respectively. Group 1 can be described as soft clays, i.e., inorganic clays of medium plasticity. Group 2 consists of two montmorillonite-rich Black Sea sediments and the sodium-rich montmorillonite clay supplied by Black Hills Bentonite, LLC (Wyoming, USA). These are highly plastic soils with liquid limits and plasticity indices in the 100% to 360% and 80% to 300% ranges, respectively. The third group is silt-rich soils (flocculated and unflocculated iron tailings taken from Wabush Lake, Newfoundland, Canada). Here the flocculation is achieved by adding a small amount of organic polymer. In group 3, the liquid and plastic limits are <23% and <19%, respectively. They are dark brown and reddish brown in color, and plasticity indices, I_P, are 6.2% and 3.7% for flocculated and unflocculated samples, respectively. They are typically classified as inorganic clayey silts of low plasticity. In short, group 1 has low to medium activities (i.e., $0.3 < A_c < 1.1$), group 2 has high activities (i.e., $1.1 < A_c < 4$), and group 3 is inactive soils (i.e., $0 < A_c < 0.3$).

Sample preparation

Prior to the rheological tests, all the natural sediments tested were thoroughly mixed to ensure complete homogenization for particle size and solid concentrations. Samples were then left to rest for at least 30 to 60 min to allow hydration and dispersion of the sediment particles. For low-activity clays, the pore-water salinity varied from about 0 to 30 g/L, with the salt content measured as NaCl equivalent. Thus, they were maintained (tested) at their natural salinity (Table 1). The solution volume and hence, void ratio can be underestimated by about 5% at 30 g/L salinity unless the volume effect of the salts being dissolved in the water is taken into account (Shimizu 1990). For the Wyoming bentonite, more than 99% of the test samples passed through the No. 200 (0.075 mm) sieve. Because sample preparation has a significant influence on the state of suspension (degree of dispersion) and thus, on rheological behavior (Benna et al. 1999), all the bentonite samples were prepared in the same way. The samples were progressively dispersed in fresh or salt water, for example, 0, 1, 10, and 30 g/L NaCl solution, and shaken intensely for more than 10 min. The sample was then put in a jug and left for 24 h before testing. The index properties of two iron-rich tailings (flocculated and unflocculated samples) showed that the difference in I_p is small. Both tailings materials were stored in small tanks for 24 h after initial collection. For the iron-rich tailings (mostly silt-sized particles), the higher water content samples were made by adding water collected from the tailings at the collection site to ensure there was no change in pore-water chemistry.

Methods

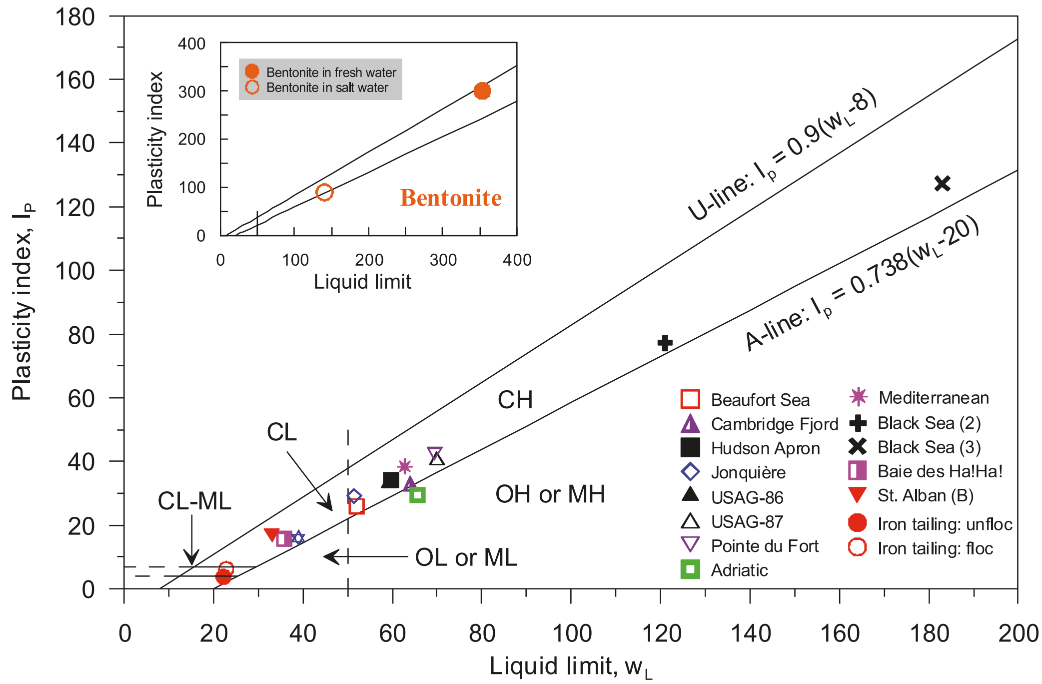
The rheological analyses of low-activity and high-activity clays and iron tailings were carried out using a coaxial cylinder viscometer (Rotovisco RV-12). The detailed procedures followed for viscometric measurements, and the American Society for Testing and Materials (ASTM) and Bureau de normalization du Québec (BNQ) standards used for basic geotechnical tests, are described in Locat and Demers (1988). These procedures include three types of tests: (*i*) constant shear rate, (*ii*) dynamic response, and (*iii*) hysteresis. After sample preparation, the liquidity index was slowly increased at a constant salinity of the pore water by adding water with the same salinity. For each step the required geotechnical parameters, e.g., water content and remoulded undrained shear strength using the Swedish fall cone, were measured whenever possible. For the sediment–water mixtures examined in this study, the rheological response is assumed to be of the Bingham type: the yield stress and plastic viscosity were always calculated by taking the slope of the last three points of the flow curve, despite the fact that even more complex rheological response was expected. The range for measuring viscosity was varied between the portion of the curve between shear rates of 58 and 512 rpm (Torrance 1987; Locat and Demers 1988). Particle settling in the course of tests was assumed to be negligible for the examined sediment concentrations.

Results

Group 1: low-activity clays

The chosen representative material in group 1 is the Mediterranean Sea sample. Figure 4 presents the flow curves in (*a*) $\log\eta$–$\log\dot{\gamma}$ scale and (*b*) τ–$\dot{\gamma}$ scale at the same salinity (29 g/L), but different liquidity indices. The samples exhibited a pseudoplastic (shear thinning) flow character. This tendency is much stronger in low I_L samples than in high ones, but all curves in Fig. 4 appear to exhibit shear thinning. Similar flow behaviors are also observed for the other materials in group 1. However, some samples exhibit close to a Bingham-like flow behavior, mostly at very high liquidity indices. At low liquidity indices, for all materials regard-

Fig. 3. Plasticity charts for classification of fine-grained soils. The A-line on the plasticity chart separates the clays (C) from the silts (M); the U-line represents the approximate upper limit of w_L and I_p combinations for natural soils. CH, inorganic clays of high plasticity; CL, inorganic clays of low to medium plasticity; ML or OL, inorganic silts and very fine sands with very low plasticity and organic silts and silt-clay mixtures of low plasticity; OH or MH, organic silts and clays of medium to high plasticity and inorganic silts; floc, flocculated; unfloc, unflocculated.



less of grain size and clay mineralogy, the difficulty in determining rheological parameters may lead to an overestimation of the value of yield strength at lower strain rates (see also Fig. 1).

Many samples exhibited pseudo-yielding behavior, probably due to slip effects at low shear rates (see Barnes 1999). Barnes et al. (1995) pointed out that because of various wall-depletion (slip) effects, the apparent flow curves of some non-Newtonian systems show a pseudo-Newtonian plateau at low shear rates even though they obviously conform to the simple “Newtonian-through-power-law-to-Newtonian” flow behavior; this can be confirmed with the bilinear model (see Fig. 2). Figure 4 gives a typical example of the type of pseudo-yielding behavior observed in the Mediterranean Sea samples at shear rates lower than 10 s^{-1}. In particular, this behavior, along with wall slip, seems to occur as soon as one makes an attempt to create a homogeneous flow, but such a flow is difficult to create due to shear localization (Raynaud et al. 2002; Møller et al. 2006). Thus, for materials with low liquidity indices, particular care should be taken between the readings of torques during the process of sample preparation and visual observation while the sample is being sheared. The experimental results revealed that these materials exhibit pseudoplastic behavior and have values of n between 0.1 and 0.5. These values are consistent with rheological measurement of fine-grained debris flow material (grain diameter $d \leq$ 0.4 mm), for which n is typically equal to about 0.3 (Coussot et al. 1998; Remaître et al. 2005).

Figure 5 shows the general relationships between liquidity index and rheological properties for these and other low-activity clays: (*a*) yield stress and viscosity, (*b*) viscosity and liquidity index, (*c*) yield stress and liquidity index, and (*d*) pseudo-Newtonian viscosity and liquidity index. The results are compared with the empirical relationships reported by Locat (1997) as a reference (see eqs. [4] to [7]). Figures show some scatter, but the results are close to the empirical relationships. Thus, we can use these relationships as a first approximation to describe muddy debris flows. For this reason, data used in this study are compared with expected values calculated using the relationships presented by Locat (1997). There is also a positive relationship between liquidity index and pseudo-Newtonian viscosity. For low-activity clays, on average, a similar equation can be obtained for the pseudo-Newtonian viscosity (mPa·s)

$$[9] \qquad \eta_1 = \left(\frac{29.1}{I_L}\right)^{4.3}$$

Group 2: high-activity clays

The chosen representative material of group 2 is Wyoming bentonite. Despite the high swelling capacity and high plasticity, the flow curve development in Fig. 6 seems comparable to that for low-activity materials (Fig. 4). According to Jeong (2006), the behavior of bentonite is similar to that observed for illitic natural clays; the flow behavior of all the materials depends not only on the shear rate, but also on the concentration of particles. However, it will be shown below that the behavior of bentonite may differ fundamentally depending on salinity and shearing time. The different behaviors of low-activity and high-activity clays are confirmed in the following paragraphs.

Figure 6 shows the flow curves of bentonite samples in fresh water (*a* and *b*) and bentonite in salt water (i.e., S =

Table 1. Main geotechnical parameters of studied soils (data from Jeong et al. 2009).

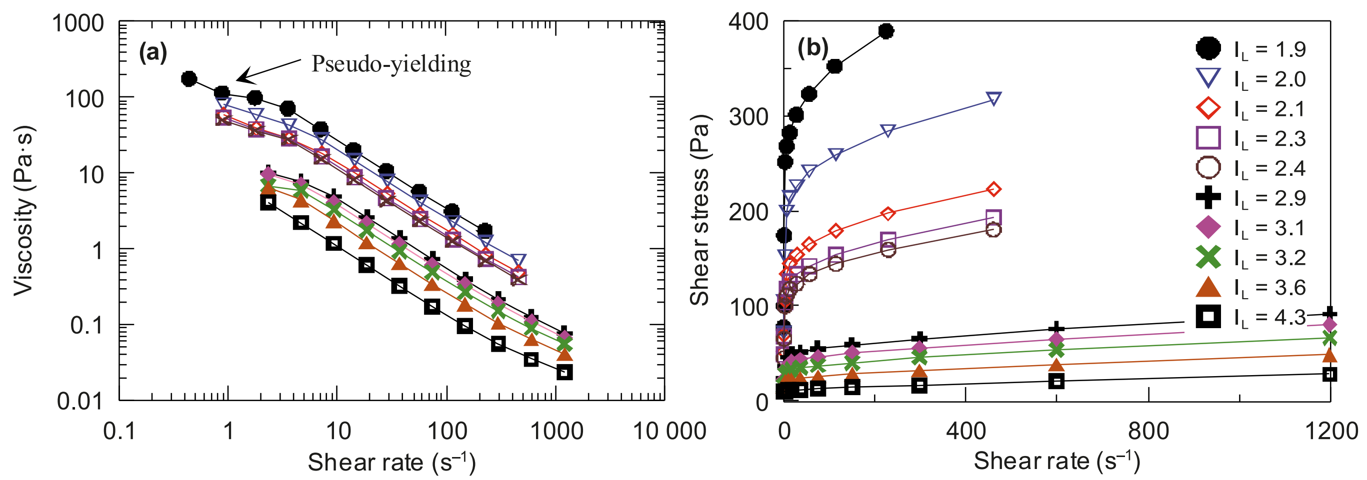
Sample	Water content, w_n (%)	Liquid limit, w_L (%)	Plastic limit, w_p (%)	Plasticity index, I_p (%)	Specific area, SS (m^2/g)	Salinity, S (g/L)	Clay fraction, CF (%)	Activity, A_c[†]	Cation exchange capacity, CEC (meq/100g)
Group 1									
Beaufort Sea	34.6	52	26	26	57	20	30	0.9	—
Cambridge Fjord	76	64	31	33	38	33	40	0.8	—
Hudson Apron	58.6	59.8	25.6	34.2	70^{avg}	30	48.5^{avg}	0.7	7–12
Jonquière	—	51.3	22.3	29.2	65^{avg}	0.1	59.5^{avg}	0.5	7–10
Baie des Ha!Ha! (Saguenay)	—	35.9	20.3	15.6	20.3	21.5	35	0.5	—
USAG 86 (Saguenay)	64	59	26	33	28	27.5	62	0.5	—
USAG 87 (Saguenay)	78	70	29	41	63	23.5	85	0.5	—
Pointe-du-Fort (Saguenay)	—	69.4	27.1	42.3	—	30	45	0.9	—
Adriatic Sea	75.7	65.6	36.1	29.5	52.5^{avg}	30	18^{avg}	1.1	6–12
Mediterranean Sea	67.5	62.8	24.4	38.4	—	29	52	0.7	—
St-Alban	45.0	33.1	16.1	16.9	40.1	0.9	38	0.4	—
Group 2									
Black Sea T1	177.7	121	43.7	77.3	—	23	59	1.3	29.3
Black Sea T2	214.5	183	55.8	127.2	—	22.5	40	3.2	29.3
Bentonite	—	353.4	53.9	299.5	—	0*	77	3.9	—
		140.5	51.3	89.2	—	30	77	1.2	—
Group 3									
Iron tailing	—	22.3 (TU)	18.5	3.7	—	—	≤22	—	—
		22.9 (TF)	16.7	6.2	—	—	≤22	—	—

Note: avg, mean value; TF, iron tailing flocculated; TU, iron tailing unflocculated. Bentonite sample mixtures were prepared using tap water close to zero salinity (see text).

*0 g/L is with bentonite hydrated with fresh water.

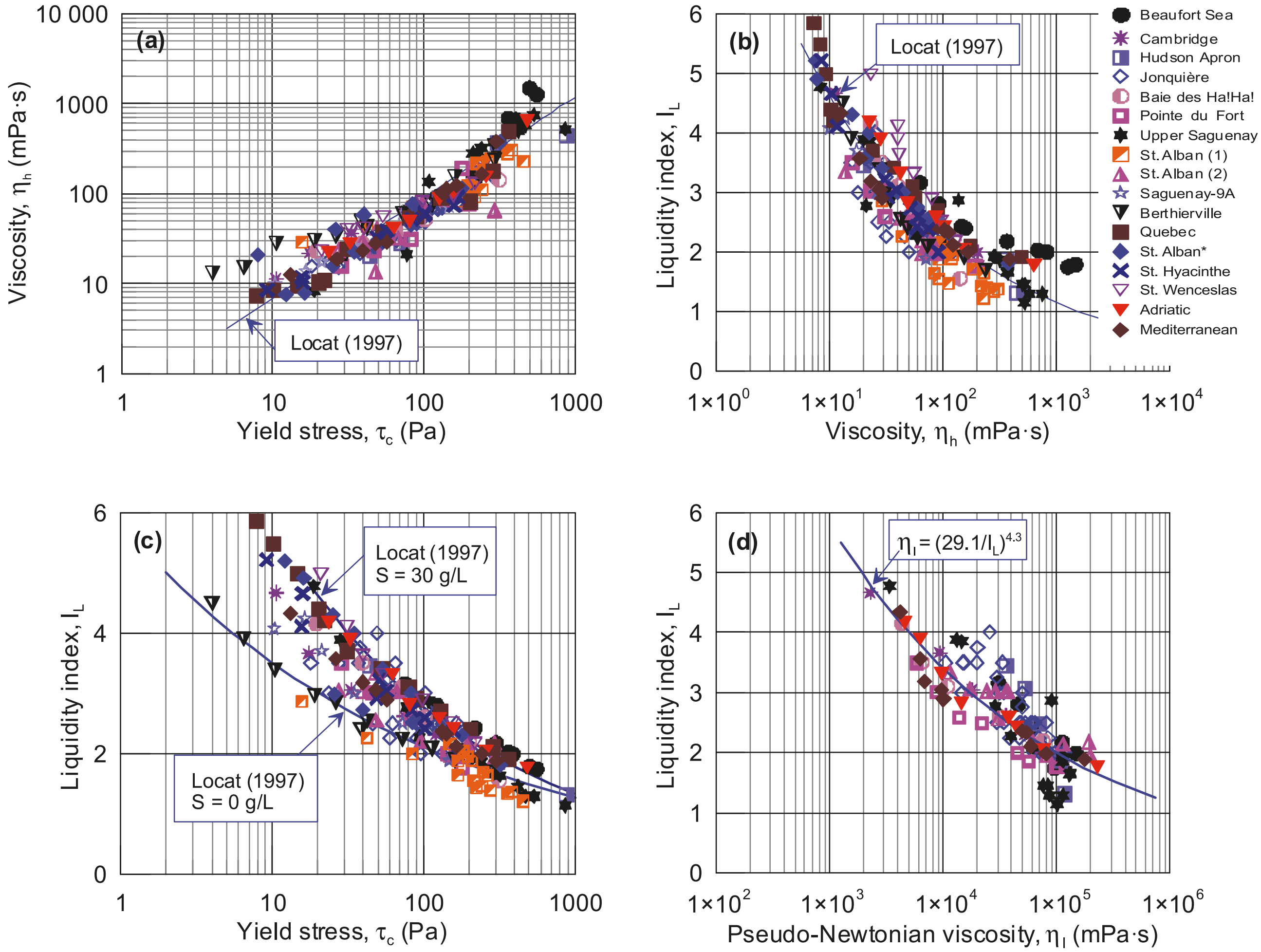
[†]$A_c = I_p$/CF.

Fig. 4. Rheological characteristics of low-activity clays: Mediterranean Sea samples. Flow curves in (*a*) logη–log$\dot{\gamma}$ scale and (*b*) τ–$\dot{\gamma}$ scale.



30 g/L; *c* and *d*). Without any special methods to achieve 0 g/L salinity from bentonite powder, as received, the authors believe that the salinity obtained from the bentonite sample in fresh water is not higher than 1 g/L salinity, thus bentonite samples in fresh water and with 1 g/L salinity show a difference in determining the consistency limit (see first figure presented in section titled "Effect of type of clay mineral and salinity on flow properties"). After the end of shearing, we confirmed the salinity of the bentonite in fresh water to be 0 g/L. However, according to J.K. Torrance (personal communication, 2009), for Wyoming bentonite to which deionized water was added to 652%, with I_L = 2, the salinity of the pore water being pressed out was 0.7%. This indicates that bentonite in fresh water may range between 0 and 1 g/L salinity. For bentonite with 0 g/L salinity, this may not be true salinity, but in this paper, the ben-

Fig. 5. Rheological relationships among the yield stress, viscosity, and liquidity index, for low-activity clays (group 1). (*a*) Yield stress and viscosity; (*b*) viscosity and liquidity index; (*c*) yield stress and liquidity index; (*d*) pseudo-Newtonian viscosity and liquidity index.



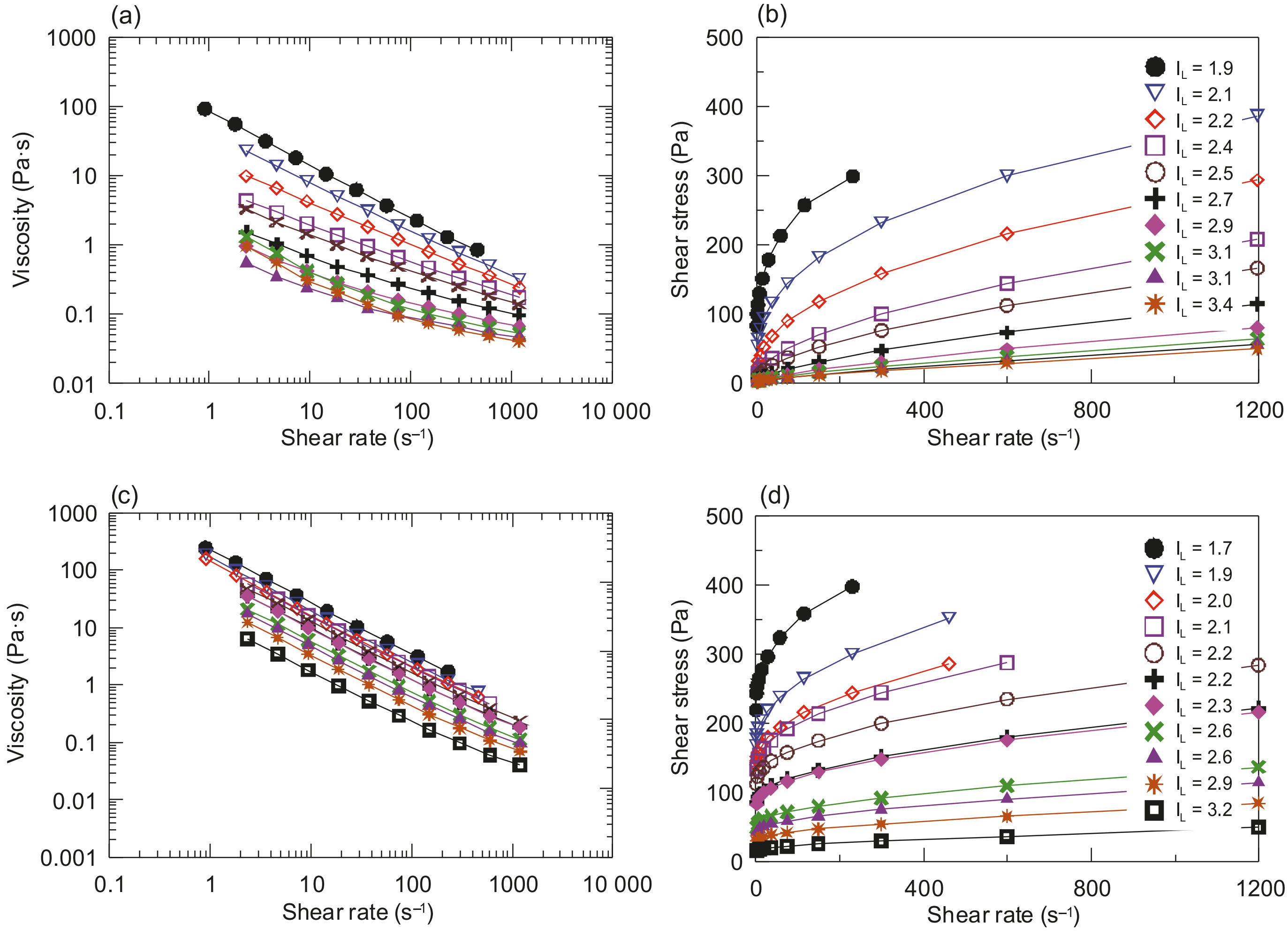
tonite in fresh water is very close to and is considered as 0 g/L.

As shown in Figs. 6*a* and 6*c*, the bentonite exhibits pseudoplastic (shear thinning) behavior. This finding is in good agreement with numerous experimental works (e.g., Luckham and Rossi 1999; Besq et al. 2003). The degree of shear thinning changes with water content. At a given water content, the shear thinning is greater at high salinity. However, it is not clear from Figs. 6*a* and 6*c* that the degree of shear thinning differs when the liquidity index is the same for low-salinity bentonites. For high-salinity bentonites, it is generally observed that the flow behavior of bentonite in salt water is more pseudoplastic than that of bentonite in fresh water. Figure 7 shows the relationships between liquidity index and rheological properties for high-activity clays. Globally, Fig. 7 shows the same trend for high-activity clays as Fig. 5 shows for low-activity clays. However, the relationship between yield stress and pseudo-Newtonian viscosity (Fig. 7*d*) is similar to that of low-activity clays only for bentonite in salt water, but is rather different for bentonite in fresh water. At $I_L = 3$, the difference in viscosity is approximately one order of magnitude.

Group 3: silt-rich soils

The chosen representative material of group 3 is iron tailings (silt-rich) samples. Figure 8 shows the flow curves of flocculated (*a* and *b*) and unflocculated (*c* and *d*) iron tailings at different water contents. Regardless of the structure (flocculated and unflocculated) and shape (flocculation does not change the shape of the particles, but it does create aggregates that will be larger and of a different shape than the individual particles until shear rates break down the aggregates), the iron tailings have characteristics between ideal Bingham and shear thinning at low water content, but generally closer to the former. This may be the case for low shear rates and low water contents. For the materials mainly composed of clay and silt with a variable sand content, rheological behavior can change from shear thinning to shear thickening when particle sizes are increased (Sosio and Crosta 2009). It can be seen from Fig. 8 that samples have a relatively high yield stress and plastic viscosity as water content decreases. It is of interest to note that the flow curves are very sensitive to relatively small changes in water content. For example, for the flocculated samples (Figs. 8*a* and 8*b*), there is almost no difference between 28.3% and

Fig. 6. Rheological characteristics of bentonite in fresh water (*a* and *b*) and bentonite in salt water (*c* and *d*).



29.2%, but there is a large difference between 29.2% and 34.8%. A large difference is observed between unflocculated samples at water contents of 27.9% and 29.3%. However, we do not know how the transition would look if, say, 1.4% water content increments were used. More interestingly, at the same water content (w = 29%), behavior differs greatly between flocculated and unflocculated samples.

In Fig. 8, an unexpected feature is found among the flow curves of the unflocculated sample. The sample having the lowest water content w = 26.2% has a shear stress (not clearly visible in Fig. 8*d*) or viscosity value (readily apparent in Fig. 8*c*) that is between w = 26.9% and 27.9%, particularly at the lower shear rates. Actually, it changes from being the same as that for the 27.9% water content sample at shear rates up to about 10 s^{-1} to that of the 26.9% water content sample at about 100 s^{-1}. The test results (Figs. 8*c* and 8*d*) clearly indicate that the flocculated material is substantially more plastic than the unflocculated one — at 37.3% water content flocculated material the flow curve is about the same as the unflocculated flow curve at 29.3% water content.

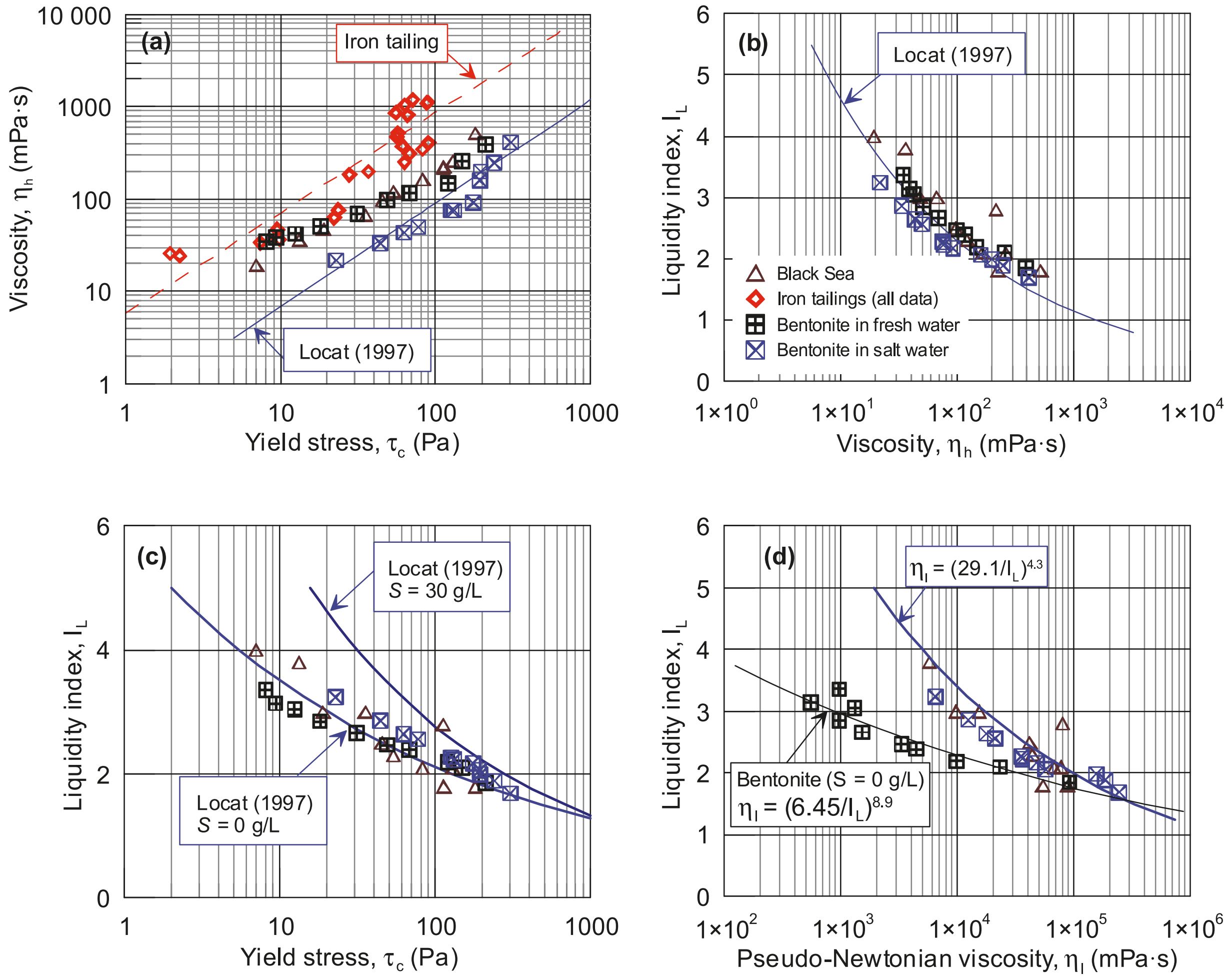
Because of their low plasticity, the measurements of Atterberg limits and rheological properties are difficult and the calculated liquidity index can be meaningless. In this case, it is recommended that the test results be plotted as a function of water content (or solid concentration) as presented by Coussot et al. (1998) and Malet et al. (2003). Except for the τ_c–η_h relationship (the plastic viscosity only represents about 1/100th of the shearing resistance of the sediments, as shown in Fig. 7*a*), the relationships are all soil specific. A relationship between the yield stress, τ_c (Pa), and plastic viscosity, η_h (mPa·s), using the Bingham model can be obtained

$$[10] \qquad \eta_h = 5.77\tau_c^{1.1}$$

Effect of type of clay mineral and salinity on flow properties

Index properties, which are dependent on the type of clay mineral, can be related to various properties, such as friction angle (Terzaghi et al. 1996), coefficient of consolidation, compression index (Sridharan and Nagaraj 2000), and undrained shear strength (Leroueil et al. 1983; Mitchell 1993). Van Olphen (1964) has also shown that the NaCl concentration can influence index properties and rheological properties of bentonite. Therefore, using standard procedures in accordance with BNQ (as described in Locat and Demers (1988)), the liquid limit of various mixtures was determined by the

Fig. 7. Rheological relationships among (*a*) the yield stress and viscosity, (*b*) liquidity index and viscosity, (*c*) liquidity index and yield stress, and (*d*) liquidity index and pseudo-Newtonian viscosity for high-activity clays (group 2) and silt-rich soils (group 3).



Swedish fall cone test. For low-activity and high-activity clays, the salinity-corrected liquid limits, w_{Lc}, are plotted as a function of NaCl concentration in Fig. 9. Locat (1982) showed that the liquid limit of Quebec clays increases slightly with increasing salinity, but the extent of change is small in comparison with bentonite. In this paper, we consider that the Quebec post-glacial marine clays consist of Grande-Baleine, Olga, and St Marcel clays. For Grande-Baleine materials, the rate of change is greater from 0.6 to 2.7 g/L than it is above 2.7 g/L, but a substantial change in w_L occurs above 2.7 g/L as well. The liquid limits of Olga and St Marcel clays with increasing salinity are presented within a boundary zone in Fig. 9. Two major observations were made for Quebec clays: (*i*) they have a substantial range of liquid limit, w_L, associated with textural differences and other factors and (*ii*) the sharp decrease in liquid limit, w_L, at very low salinities (from 2 to 0.1 g/L or less) is not included in this graph. In Table 5 in his paper, Torrance (1974) presented the liquid limit, w_L, for Drammen plastic clay, which changed from 31.6% at 0.25 g/L to 45.1% at 2.15 g/L to 53.1% at 7.8 g/L. The plastic limit, w_p, varied from 24% to 30%, depending on salinity. The plasticity increased from about 16 to 25 as salinity increased above 2% to reach a w_p of 26%. The plasticity index, I_p, increased by about 30% of the liquid limit. The salinity varies for Drammen plastic clay. Similar differences occur for almost all the post-glacial marine sediments of the St. Lawrence River Basin. Contrary to the behavior of kaolinitic and illitic clays (Sridharan and Prakash 1999; Yukselen-Aksoy et al. 2008; and many more), salinity has a significant, but opposite, effect on the liquid limit of bentonite; it decreased from 353% in distilled water to 144% in 30 g/L NaCl solution. This is attributed to double-layer compression and *c*-axis contraction (van Olphen 1963, 1964; Petrov and Rowe 1997; Luckham and Rossi 1999).

A large difference between the behaviors of clay mineral groups is also shown in Fig. 10. A semi-log plot of liquidity index and remoulded shear strength is drawn for low-activity and high-activity clays. For low-activity clays, the remoulded shear strength increases with decreasing liquidity index. At the liquid limit, the remoulded shear strength is equal to 1.6 Pa. This type of behavior is also observed for Champlain Sea clays due to its mineralogy, particle arrangement, and restructuring during specimen preparation (Saihi et al. 2002). At a liquidity index of 3, remoulded shear strength was found to be equal to about 0.13 kPa for low-activity clays and 0.02 kPa for high-activity clays.

Fig. 8. Rheological characteristics of flocculated (*a* and *b*) and unflocculated (*c* and *d*) iron tailings.

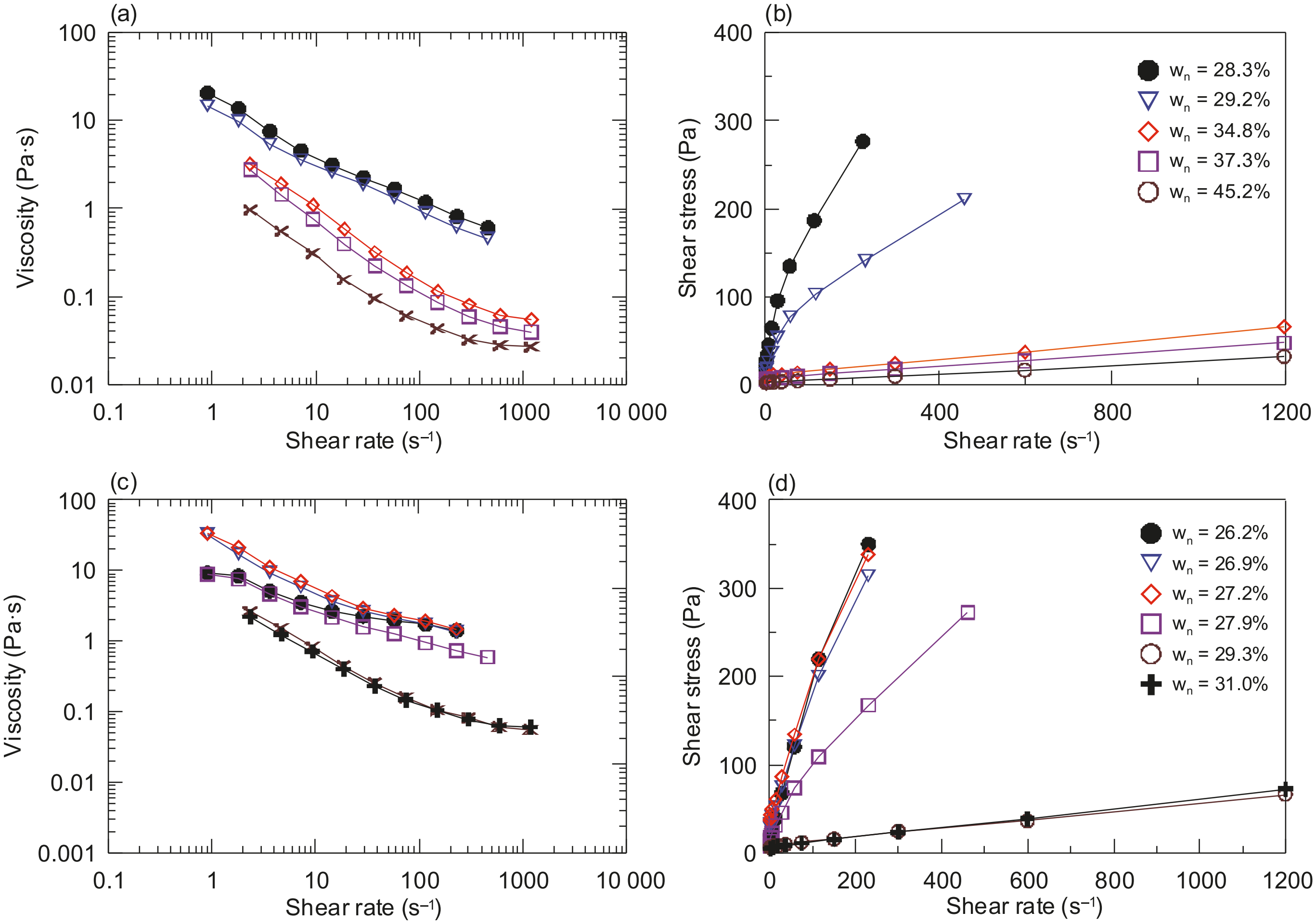
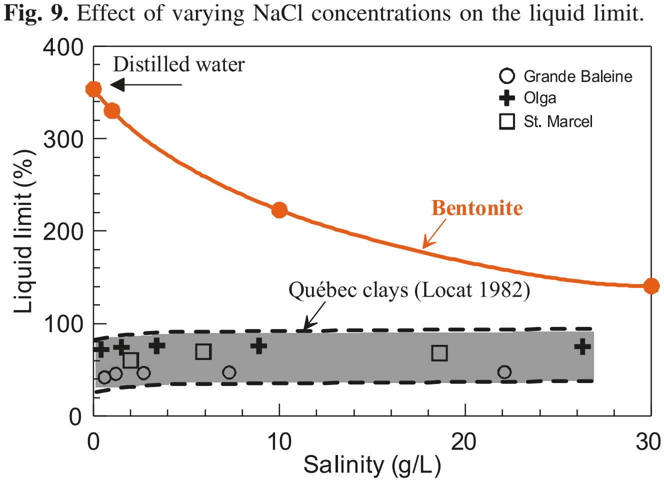


Fig. 9. Effect of varying NaCl concentrations on the liquid limit.



They differ by a factor of about 10. Bentonite in fresh water may be highly flocculated (edge–edge and edge–face contacts), with small flow channels and low permeability (Terzaghi et al. 1996; Luckham and Rossi 1999). At a somewhat higher salinity, face–face contacts (i.e., particle–particle aggregation rather than dispersion) may be predominant with high permeability.

Figure 11 presents the relationship between the flow behavior index, n, computed from the Herschel–Bulkley model (eq. [2]), and the liquidity index to allow examination of change in flow behavior with salinity. All samples studied here exhibited behavior fluidity, as they all have an n value lower than 1. At high salinity (e.g., about 30 g/L), the flow behavior of St-Alban clay is typical of pseudoplastic fluids, while at high water content and at low salinity the flow behavior approaches that of a Bingham-like fluid with the value of n tending toward 1.0. It can also be seen that, for a given salinity, the value of n increases with increasing liquidity index; for the Saguenay Fjord sample n value, n_{Sag}, an example of an exponential curve is shown in Fig. 11. A similar trend is seen for the other materials in group 1. In addition, the flow behaviors of groups 1 and 2 (bentonite) materials differ greatly. Bentonite hydrated with salt water (S = 30 g/L, BHS) has a very narrow range of flow behavior indices (n = 0.4 to 0.6) in comparison with bentonite mixed with fresh water (n = 0.47 to 0.85, BHF). The result of BHF (S = 0 g/L) shows a trend similar to typical flow behavior obtained for low-activity clays, while the behavior of BHS is slightly different. Change in water content is a change in physicochemical properties and BHF is more strongly affected by this (in terms of change in n) than BHS is. In fact, this is the only physicochemical property that changed when water was added to increase the liquidity index. Therefore BHS is not strongly influenced by this change. The Black Sea material responded more like

Fig. 10. Relationship between liquidity index and remoulded shear strength.

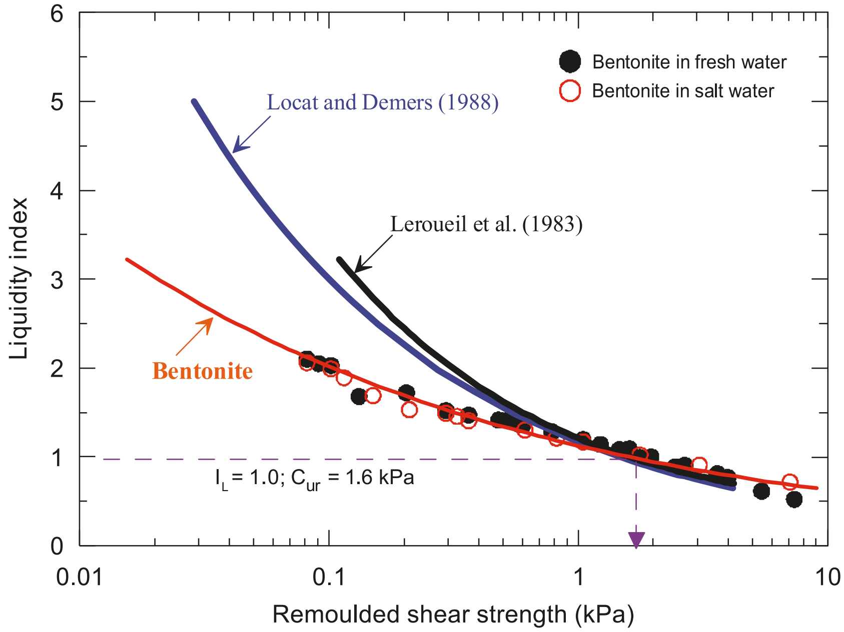
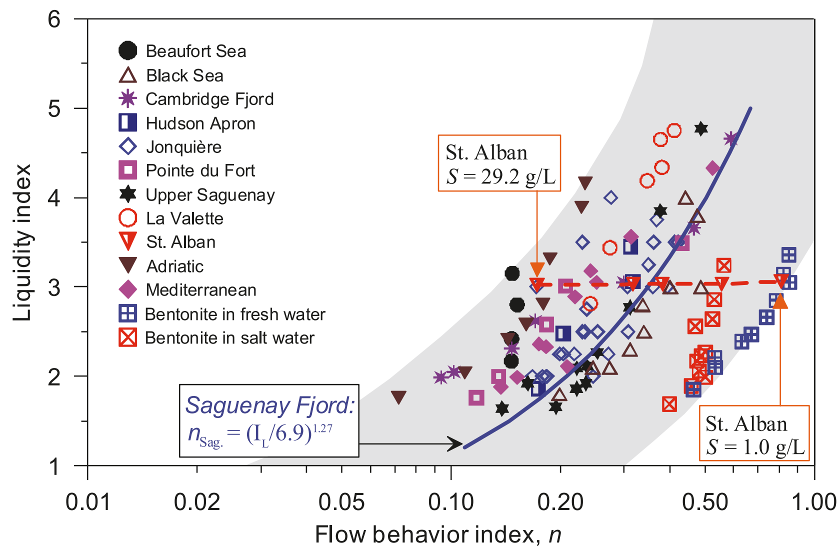


Fig. 11. Flow behavior index, *n*, obtained from the Herschel–Bulkley model versus liquidity index. With a decrease in salinity of St-Alban clay, sediment rheology tended to be more Bingham-like (*n* approximately unity).



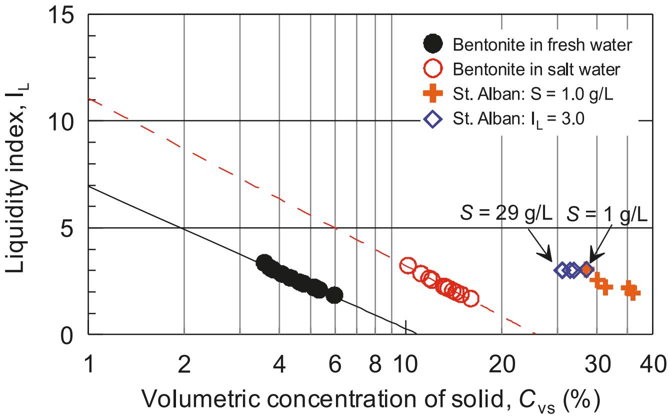
the upper Saguenay Fjord sediments than the Wyoming bentonite. This is undoubtedly due to the fact that all the Black Sea samples (T1 and T2 in Table 1) are not pure bentonite mixtures and that their clay contents are ~50%.

As many authors have pointed out, the general trend is that the yield stress and plastic viscosity of fine-grained sediments increase with increasing volumetric concentration of solid, C_{vs}. These low-activity and high-activity clays, as expected, show a trend similar to that found in the literature (see Coussot 1995; Malet et al. 2003), as shown in Fig. 12, within the given range of solid concentration from 3% to 6% for BHF and 10% to 16% for BHS. The lowest values of rheological parameters were obtained at ~3.5% (water content, w_n = 1030%) for BHF and 10% (w_n = 340%) for BHS. With the same rheological properties, C_{vs} of BHF is up to about three times lower than that of BHS. The samples show quite similar trends, but there is a large difference in C_{vs}. The opposite response to salinity change was observed for the St-Alban sample. This has an important implication related to change of soil structure due to a sufficiently strong particle–particle interaction (i.e., edge–edge, edge–face or face–face mode of particle association); for bentonite, it is clear that the flocculation pattern is different. Most clay specialists would say that swelling in response to salt removal from bentonite samples represents a greater degree of dispersion (the opposite of flocculation).

Discussion

The rheological properties obtained from the low-activity and high-activity clays investigated can be compared with those reported in the literature for silt-rich and coarser de-

Fig. 12. Relationship of log volumetric concentration of solid, C_{vs}, and liquidity index.



bris flow materials (Table 2) from the Tarndale Slip and fines from the Bullock Creek debris flow, New Zealand (Phillips and Davies 1991; Contreras and Davies 2000); the Moscardo debris flow, Friuli Region, Northeastern Italy (Coussot et al. 1998); Barcelonnette Basin, Haute-Alpes, France (Malet et al. 2003); debris flow fans in Owen Valley, California (Whipple and Dunne 1992); and artificial coarse mixtures (Major and Pierson 1992; Parsons et al. 2001; Schatzmann et al. 2003; Ilstad et al. 2004). These materials will serve as a reference group for a comparative consideration of rheological property differences between mudflows and debris flows that were composed, in large part, of coarse sands and boulders, but few silts and fines.

It should be noted that the rheological properties in natural and (or) artificial coarse mixtures were estimated by the Bingham model, assuming that the debris flow material behaves as a viscoplastic fluid. It has been shown above that the rheological behavior of silt mixtures presents a ratio of τ_c/η_h of 0.1, which is significantly different from what has been observed for clays (τ_c/η_h = 1 from Locat 1997). To further explain the effect of texture, rheological test results from studies carried out on coarse-grained fluid mixtures have been assembled in Table 2. As far as time-independent rheological behavior is concerned, a comparison (Fig. 13) of data obtained using the conventional viscometer used in this study and the results for coarse-grained fluid mixtures presented in Table 2 show substantial similarity over a wide range of shear rates. Although there is greater data scattering with increasing grain size, compared with the low-activity clays at the same yield stress, the viscosity increases stepwise with the same slope. As shown in Fig. 13, three lines are presented with boundary lines for clay-rich, silt-rich, and sand-rich soils. These lines are so-called "critical limits" representing the change in rheological properties due to grain size.

Rheological properties presented by Schatzmann et al. (2003) and Ilstad et al. (2004) are similar to those obtained from the test results of iron tailings. It is worth noting here that Ilstad et al. (2004) presented coarser artificial mixtures, for example, water (35%) – clay (28.7%) – sand (36.3%), with rheological properties appearing in the range of given values close to the limit of silt-rich materials. The rheological parameters obtained from Coussot and Piau (1995) compare to the range from sand and clay sizes, while, at a relatively low concentration of solids, those obtained from Coussot et al. (1998) lie close to the behavior obtained from clay-rich materials. However, when increasing with volumetric concentration of solids (i.e., τ_c = 2000 Pa corresponding to C_{vs} = 73%), the critical limits of clay-rich materials go towards that of iron tailings.

The rheological parameters determined in various flow types (e.g., Bingham, shear thinning, and a few shear thickening) on artificial silt- and sand-rich soils presented by Major and Pierson (1992) are also in the range between clay-rich and sand-rich materials, but about half of them plot higher than any of the test results of Coussot and Piau (1995) and Coussot et al. (1998). Except for the parameters obtained from debris flows with large sand and gravel contents (e.g., Phillips and Davies 1991; Whipple and Dunne 1992), the parameters fall well within the defined range between sand-rich and the fine-grained (clay-rich and silt-rich) soils. Consequently, the critical limits identified in Fig. 13 can represent the possible boundary of rheological transition from clay- to sand-sized particles.

Soil texture is one of the most important factors affecting rheological properties of muddy debris flows. From this point of view, it would be interesting to plot the ratio of yield stress (Pa) to plastic viscosity (mPa·s) as a function of grain size. The ratio obtained from Locat (1997) and from the present study is about 1 for clayey soils. The ratio for silt-rich material with a low sand percentage is about 0.1. On the other hand, Phillips and Davies (1991) and Whipple and Dunne (1992) who tested gravelly soils found a ratio in the order of 200–2000 (see Fig. 13). The schematic view of rheological transformation depending on grain size is presented in Fig. 14. It results mostly from the fact that, in cohesionless materials, yield stress, τ_c (Pa), is small compared with plastic viscosity, η_h (mPa·s), and consequently the τ_c/η_h ratio is small. Even if these ratios provided here are mostly indicative, they all provide an estimate of rheological properties for the case where only approximations are possible.

As emphasized for the rheological investigations summarized in Fig. 13, the influence of grain-size distribution on flow behavior is of paramount importance. It is generally accepted that rheological properties were influenced by mineralogy and soil texture. It is a well-known fact that the two extreme types of clays are montmorillonitic soils and kaolinitic soils whose response to physicochemical factors are quite opposite to one another because of different controlling mechanisms. While the diffuse double layer related factors play a dominant role in the rheological behavior of montmorillonitic clays, kaolinitic soils are controlled mainly by the net attractive force and mode of particle arrangement (Sridharan and Prakash 1999). For kaolinitic soils, surface charges are very important to interparticle forces and associated fabric formations (Wang and Siu 2006). Without examining and comparing the flow behavior of kaolinitic soils, the generalization made in this paper has limitations.

Pseudo-Newtonian viscosity, η_l, is also an important parameter in determining flow behavior (Figs. 5 and 7). This viscosity is determined mostly in the lower range of shear rates from 0.1 to 1 s^{-1}, because the viscometer has a limited range of shear rates available from 0.1 to 1200 s^{-1}. However, this range of shear rates in rheological tests is still much higher than in conventional tests, within the range

Table 2. Summary of coarse-grained debris flows: rheological properties and soil descriptions.

Samples	Description	Concentration of solids, C_{vs} (%)	Yield stress, τ_c (Pa)	Plastic viscosity, η_h (Pa·s)	Shear rate, γ (1/s)	Particle size, d (mm)	Fines (%)	Gravels (%)	Source
Debris flow (Tarndale Slip)	Muddy sandy gravels or gravelly muddy sands	70∼90	15∼300	0.4∼104	≤16	≤35	12∼23	—	Phillips and Davies (1991)
Debris flows (Bullock Creek)	Bullock Creek, Mt. Thomas	48∼88	167∼384	—	≤7	≤35	13∼17 (22∼24)	25∼50 (5∼9)	Contreras and Davies (2000)
Debris flows (Italy)	Moscardo debris flow	75.4	80∼1885	0.07∼39.5	≤20	≤25	10	—	Coussot et al. (1998)
Debris flows (France)	Alpine debris flows	60∼80	131∼540	0.3∼10.2	≤60	≤20	—	—	Coussot and Piau (1995)
Debris flows (USA)	Owens Valley, California	—	80∼2150	18∼430	—	—	—	—	Whipple and Dunne (1992)
Sediment mixture	1980 North Fork River volcanic debris flow (clay–silt–sand mixtures)	44∼66	15∼405	0.2∼29.7	≤50	≤2	19∼28	10∼35	Major and Pierson (1992)
Sediment mixture	Artificial mixtures of fine-medium-coarse	—	14∼124	0.71∼4.1	—	—	10∼45	≤5; S = 50∼85	Parsons et al. (2001)
Sediment mixture	Artificial mixtures of fine and large particles	23∼30; C_g = 10∼40	33∼169	0.5∼3.5	≤100	≤10	—	—	Schatzmann et al. (2003)
Sediment mixture	Artificial mixtures of fine-grained soils.	—	9.9∼125	0.08∼0.86	—	—	28.7	S = 36.3	Ilstad et al. (2004)

Note: C_g, concentration of gravel; S, sand content (%).

Fig. 13. Relation of yield stress (τ_c) versus plastic viscosity (η_h): possible rheological transition in a variety of soil types.

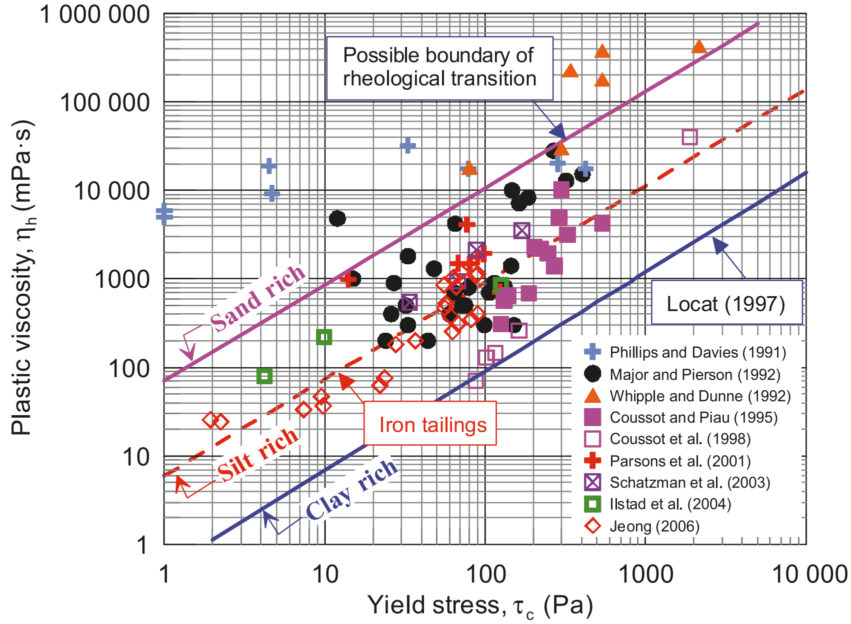
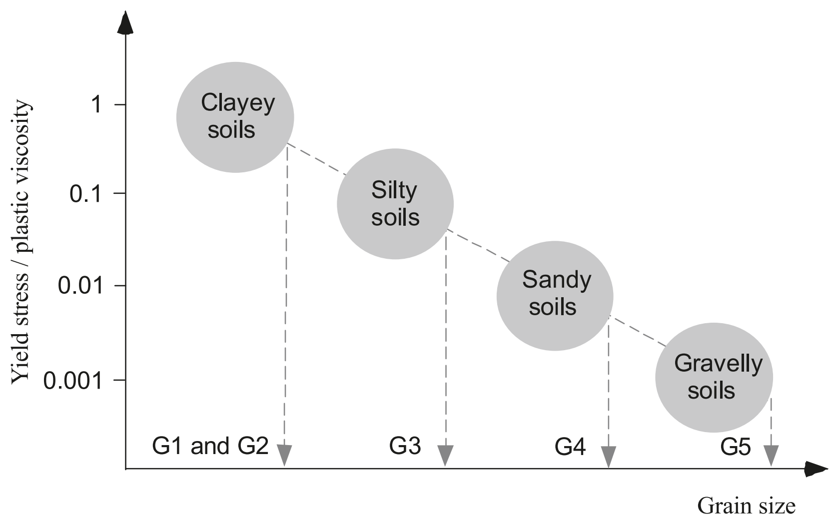


Fig. 14. Ratio of yield stress (Pa) to viscosity (mPa·s) as a function of grain size. G1, low-activity clays; G2, high-activity clays; G3, silt-rich soils; G4, sand-rich soils; G5, gravelly soils ranging in particle size from clay to boulders.



$\dot{\gamma}$ = 10^{-10}–10^{-5} s^{-1}, on intact clays (Leroueil 2006). This is why the transition from solid-like to liquid-like rheological behavior should be examined.

Conclusions

The influence of index properties and salinity of fine-grained sediments on their rheological behavior was examined. In particular, the possible rheological transition between viscous and granular flows was studied. The main conclusions are as follows:

(1) Low-activity (mostly inorganic and illitic soils) and high-activity clays (montmorillonitic soils) have characteristics of a pseudoplastic (shear thinning) fluid even in the case of silt-rich iron tailings. It is interesting to note that the behavior of sediment–water mixtures changed from shear thinning to Bingham type when they had a low solid concentration and low salinity. Pseudo-yielding due to wall slip and shear localization at low shear rates is a commonly observed phenomenon in the rheology of fine-grained sediments.

(2) In terms of the relationships between liquidity index and rheological parameters, high-activity clays show a similar trend to those of low-activity clays, except for pseudo-Newtonian viscosity. Rheological properties of low-activity and high-activity clays are strongly influenced by salinity; however, they show opposite responses in terms of structural formation and strength evolution with physicochemical properties. The flow behavior of iron tailings samples is very sensitive to small changes in water content.

(3) Results suggest that it may be possible to estimate rheological parameters depending on the soil texture. The possible transitional boundaries of rheological properties

implemented by a linear relation of apparent yield stress (Pa) and plastic viscosity (mPa·s) are $\tau_c/\eta_h = 1$ for clays, 0.1 for silts, and 0.01 for sands.

Further studies should be done on the effect of the presence of swelling clays in natural debris flows.

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References

Bagnold, R.A. 1954. Experiments on a gravity-free dispersion of large solid spheres in a Newtonian fluid under shear. Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences, **225**(1160): 49–63.

Barnes, H.A. 1999. The yield stress – a review or 'παντα ρει' – everything flows? Journal of Non-Newtonian Fluid Mechanics, **81**(1–2): 133–178. doi:10.1016/S0377-0257(98)00094-9.

Barnes, H.A., Edwards, M.F., and Woodcock, L.V. 1987. Applications of computer simulations to dense suspension rheology. Chemical Engineering Science, **42**(4): 591–608. doi:10.1016/0009-2509(87)80021-0.

Barnes, H.A., Edwards, M.F., and Woodcock, L.V. 1995. A review of the slip (wall depletion) of polymer solutions, emulsions, and particle suspensions in viscometers: its cause, character, and cure. Journal of Non-Newtonian Fluid Mechanics, **56**(3): 221–251. doi:10.1016/0377-0257(94)01282-M.

Benna, M., Kbir-Ariguib, N., Magnin, A., and Bergaya, F. 1999. Effect of pH on rheological properties of purified sodium bentonite suspensions. Journal of Colloid and Interface Science, **218**(2): 442–455. doi:10.1006/jcis.1999.6420. PMID:10502376.

Bentley, S.P. 1979. Viscometric assessment of remoulded clays. Canadian Geotechnical Journal, **16**(2): 414–419. doi:10.1139/t79-043.

Besq, A., Malfoy, C., Pantet, A., Monnet, P., and Righi, D. 2003. Physicochemical characterisation and flow properties of some bentonite muds. Applied Clay Science, **23**(5–6): 275–286. doi:10.1016/S0169-1317(03)00127-3.

Bin, Y., Huilin, Z., Coussot, P., Laigle, D., Arattano, M., Deganutti, A., and Marchi, L. 2000. Direct determination of rheological characteristics of debris flow. Journal of Hydraulic Engineering, **126**(2): 158–159. doi:10.1061/(ASCE)0733-9429(2000)126:2(158).

Contreras, S.M., and Davies, T.R.H. 2000. Coarse-grained debris-flows: hysteresis and time-dependent rheology. Journal of Hydraulic Engineering, **126**(12): 938–941. doi:10.1061/(ASCE)0733-9429(2000)126:12(938).

Coussot, P. 1995. Structural similarity and transition from Netwonian to non-Newtonian behavior for clay-water suspensions. Physical Review Letters, **74**(20): 3971–3974. doi:10.1103/PhysRevLett.74.3971. PMID:10058380.

Coussot, P. 1997. Mudflow rheology and dynamics. Balkema, Rotterdam, the Netherlands.

Coussot, P., and Piau, J.-M. 1994. On the behavior of fine mud suspensions. Rheologica Acta, **33**(3): 175–184. doi:10.1007/BF00437302.

Coussot, P., and Piau, J.-M. 1995. A large-scale field coaxial cylinder rheometer for the study of the rheology of natural coarse suspensions. Journal of Rheology, **39**(1): 105–124. doi:10.1122/1.550693.

Coussot, P., Laigle, D., Arattano, M., Deganutti, A., and Marchi, L. 1998. Direct determination of rheological characteristics of debris flow. Journal of Hydraulic Engineering, **124**(8): 865–868. doi:10.1061/(ASCE)0733-9429(1998)124:8(865).

Coussot, P., Roussel, N., Jarny, S., and Chanson, H. 2005. Continuous or catastrophic solid–liquid transition in jammed systems. Physics of Fluids, **17**(1). Paper No. 011704. doi:10.1063/1.1823531.

Gauer, P., Kvalstad, T.J., Forsberg, C.F., Bryn, P., and Berg, K. 2005. The last phase of the Storegga Slide: simulation of retrogressive slide dynamics and comparison with slide-scar morphology. Marine and Petroleum Geology, **22**(1–2): 171–178. doi:10.1016/j.marpetgeo.2004.10.004.

Hampton, M.A., Lee, H.J., and Locat, J. 1996. Submarine landslides. Reviews of Geophysics, **34**(1): 33–59. doi:10.1029/95RG03287.

Ilstad, T., Elverhøi, A., Issler, D., and Marr, J.G. 2004. Subaqueous debris flow behavior and its dependence on the sand/clay ratio: a laboratory study using particle tracking. Marine Geology, **213**(1–4): 415–438. doi:10.1016/j.margeo.2004.10.017.

Imran, J., Parker, G., Locat, J., and Lee, H. 2001. 1D numerical model of muddy subaqueous and subaerial debris flows. Journal of Hydraulic Engineering, **127**(11): 959–968. doi:10.1061/(ASCE)0733-9429(2001)127:11(959).

Iverson, R.M. 1997. The physics of debris flow. Reviews of Geophysics, **35**(3): 245–296. doi:10.1029/97RG00426.

Jakob, M., and Hungr, O. 2005. Debris-flow hazards and related phenomena. Praxis Publishing, Chichester, UK.

Jeong, S.W. 2006. Influence of physico-chemical characteristics of fine-grained sediments on their rheological behavior. Ph.D. thesis, Department of Civil Engineering, Laval University, Québec City, Que.

Jeong, S.W., Leroueil, S., and Locat, J. 2009. Applicability of power law for describing the rheology of soils of different origins and characteristics. Canadian Geotechnical Journal, **46**(9): 1011–1023. doi:10.1139/T09-031.

Johnson, A.M. 1984. Debris flows. *In* Slope instability. *Edited by* D. Brunsden and D.B. Prior. John Wiley & Sons, Chichester, UK. pp. 257–361.

Leroueil, S. 2006. The Isotache Approach. Where are we 50 years after its development by Professor Šuklje? 2006 Prof. Šuklje's Memorial Lecture. *In* Proceedings of the XIII Danube–European Conference on Geotechnical Engineering, Ljubljana, Slovenia, 29–31 May 2006. Slovenian Geotechnical Society, Ljubljana, Slovenia. Vol. 1, pp. 55–88.

Leroueil, S., Tavenas, F., and Le Bihan, J.-P. 1983. Propriétés caractéristiques des argiles de l'est du Canada. Canadian Geotechnical Journal, **20**(4): 681–705. doi:10.1139/t83-076.

Locat, J. 1982. Origine de la surconsolidation des argiles sensibles de l'Est du Canada. Ph.D. thesis, Department of Civil Engineering, University of Sherbrooke, Sherbrooke, Que.

Locat, J. 1997. Normalized rheological behaviour of fine muds and their flow properties in a pseudoplastic regime. *In* Debris-flow hazards mitigation: mechanics, prediction, and assessment. Water Resources Engineering Division, American Society of Civil Engineers, New York. pp. 260–269.

Locat, J., and Demers, D. 1988. Viscosity, yield stress, remoulded strength, and liquidity index relationships for sensitive clays. Canadian Geotechnical Journal, **25**(4): 799–806. doi:10.1139/t88-088.

Locat, J., and Lee, H.J. 2002. Submarine landslides: advances and challenges. Canadian Geotechnical Journal, **39**(1): 193–212. doi:10.1139/t01-089.

Luckham, P.F., and Rossi, S. 1999. The colloidal and rheological properties of bentonite suspensions. Advances in Colloid and Interface Science, **82**(1–3): 43–92. doi:10.1016/S0001-8686(99)00005-6.

Major, J.J., and Pierson, T.C. 1992. Debris flow rheology: experimental analysis of fine-grained slurries. Water Resources Research, **28**(3): 841–857. doi:10.1029/91WR02834.

Malet, J.P., Remaître, A., Maquaire, O., Ancey, C., and Locat, J. 2003. Flow susceptibility of heterogeneous marly formations. Implications for torrent hazard control in the Barcelonnette basin (Alpes-de-Haute-Provence, France). *In* Proceedings of the 3rd International Conference on Debris-Flow Hazards Mitigation, Davos, Switzerland, 10–12 September, 2003. *Edited by* D. Rickenmann and C.L. Chen. Millpress, Rotterdam, the Netherlands. pp. 351–362.

Malet, J.P., Laigle, D., Remaître, A., and Maquaire, O. 2005. Triggering conditions and mobility of debris flows associated to complex earthflows. Geomorphology, **66**(1–4): 215–235. doi:10.1016/j.geomorph.2004.09.014.

Mitchell, J.K. 1993. Fundamentals of soil behavior. 2nd ed. John Wiley & Sons Inc., New York.

Møller, P.C.F., Mewis, J., and Bonn, D. 2006. Yield stress and thixotropy: on the difficulty of measuring yield stresses in practice. Soft Matter, **2**(4): 274–283. doi:10.1039/b517840a.

O'Brien, J.S., and Julien, P.Y. 1988. Laboratory analysis of mud flow properties. Journal of Hydraulic Engineering, **114**(8): 877–887. doi:10.1061/(ASCE)0733-9429(1988)114:8(877).

Parsons, J., Whipple, K., and Simoni, A. 2001. Experimental study of the grain flow, fluid-mud transition in debris flow. The Journal of Geology, **109**(4): 427–447. doi:10.1086/320798.

Perret, D., Locat, J., and Martignoni, P. 1996. Thixotropic behavior during shear of a fine-grained mud from Eastern Canada. Engineering Geology, **43**(1): 31–44. doi:10.1016/0013-7952(96)00031-2.

Petrov, R.J., and Rowe, R.K. 1997. Geosynthetic clay liner (GCL) – chemical compatibility by hydraulic conductivity testing and factors impacting its performance. Canadian Geotechnical Journal, **34**(6): 863–885. doi:10.1139/cgj-34-6-863.

Phillips, C.J., and Davies, T.R.H. 1991. Determining rheological parameters of debris flow material. Geomorphology, **4**(2): 101–110. doi:10.1016/0169-555X(91)90022-3.

Raynaud, J.S., Moucheront, P., Baudez, J.C., Bertrand, F., Guilbaud, J.P., and Coussot, P. 2002. Direct determination by nuclear magnetic resonance of the thixotropic and yielding behavior of suspensions. Journal of Rheology, **46**(3): 709–732. doi:10.1122/1.1463420.

Remaître, A., Malet, J.-P., Maquaire, O., Ancey, C., and Locat, J. 2005. Flow behavior and runout modelling of a complex debris flow in a clay–shale basin. Earth Surface Processes and Landforms, **30**(4): 479–488. doi:10.1002/esp.1162.

Saihi, F., Leroueil, S., Rochelle, P.L., and French, I. 2002. Behavior of the stiff and sensitive Saint-Jean-Vianney clay in intact, destructured, and remoulded conditions. Canadian Geotechnical Journal, **39**(5): 1075–1087. doi:10.1139/t02-053.

Schatzmann, M., Fischer, P., and Bezzola, G.R. 2003. Rheological behavior of fine and large particle suspensions. Journal of Hydraulic Engineering, **129**(10): 796–803. doi:10.1061/(ASCE)0733-9429(2003)129:10(796).

Shimizu, M. 1990. Pore fluid content and void ratio for marine sediments. Soils and Foundations, **30**(3): 124–128.

Sosio, R., and Crosta, G.B. 2009. Rheology of concentrated granular suspensions and possible implications for debris flow modeling. Water Resources Research, **45**(3): W03412.1–W03412.16. doi:10.1029/2008WR006920.

Sridharan, A., and Nagaraj, H.B. 2000. Compressibility behavior of remoulded, fine-grained soils and correlation with index properties. Canadian Geotechnical Journal, **37**(3): 712–722. doi:10.1139/cgj-37-3-712.

Sridharan, A., and Prakash, K. 1999. Mechanisms controlling the undrained shear strength behaviour of clays. Canadian Geotechnical Journal, **36**(6): 1030–1038. doi:10.1139/cgj-36-6-1030.

Terzaghi, K., Peck, R.B., and Mesri, G. 1996. Soil mechanics in engineering practice. 3rd ed. John Wiley & Sons Inc., New York.

Torrance, J.K. 1974. A laboratory investigation of the effect of leaching on the compressibility and shear strength of Norwegian marine clays. Géotechnique, **24**(2): 155–173. doi:10.1680/geot.1974.24.2.155.

Torrance, J.K. 1987. Shear resistance of remoulded soils by viscometric and fall-cone methods: a comparison for the Canadian sensitive marine clays. Canadian Geotechnical Journal, **24**(2): 318–322. doi:10.1139/t87-037.

Torrance, J.K., and Pirnat, M. 1984. Effect of pH on the rheology of marine clay from the site of the South Nation river, Canada, landslide of 1971. Clays and Clay Minerals, **32**(5): 384–390. doi:10.1346/CCMN.1984.0320506.

van Olphen, H. 1963. An introduction to clay colloid chemistry. John Wiley & Sons Inc., New York.

van Olphen, H. 1964. Internal mutual flocculation in clay suspension. Journal of Colloid Science, **19**(4): 313–322. doi:10.1016/0095-8522(64)90033-9.

Wang, Y.H., and Siu, W.K. 2006. Structure characteristics and mechanical properties of kaolinite soils. I. Surface charges and structural characterizations. Canadian Geotechnical Journal, **43**(6): 587–600. doi:10.1139/T06-026.

Whipple, K., and Dunne, T. 1992. The influence of debris flow rheology on fan morphology, Owens Valley, California. Geological Society of America Bulletin, **104**(7): 887–900. doi:10.1130/0016-7606(1992)104<0887:TIODFR>2.3.CO;2.

Yukselen-Aksoy, Y., Kaya, A., and Ören, A.H. 2008. Seawater effect on consistency limits and compressibility characteristics of clays. Engineering Geology, **102**(1–2): 54–61. doi:10.1016/j.enggeo.2008.07.005.