Laboratory Analysis of Mudflow Properties

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Abstract: A rotational viscometer has been designed for laboratory measurements of the rheological properties of natural mudflow deposits in Colorado. The mudflow matrices comprised of silt and clay particles are sheared under temperature-controlled conditions at volumetric sediment concentrations ranging from 0.10–0.45. This study stresses the importance of conducting rheological measurements at low rates of shear because: 1) Those are the conditions found in natural channels; and 2) they avoid the slippage problems observed at large sediment concentrations. At low rates of shear, the Bingham model is fitted to the measured rheograms, and both the viscosity and yield stress increase exponentially with the sediment concentration of the fluid matrix. Both the yield stress and the viscosity increase by three orders of magnitude as the volumetric concentration of sediments in the fluid matrix changes from 0.10 to 0.40. The addition of sand particles does not significantly alter the rheological properties of the matrix unless the volumetric concentration of sands exceeds 0.20.

Introduction

In the United States, losses from landslides, subsidence, and other ground failures exceed the losses from all other natural hazards combined. Indeed, the Committee on Ground Failure Hazards (NRC 1982) reported that landsliding in the U.S. causes $1–$2 billion in economic losses and 25–50 deaths each year. Individual landslides can be widely scattered in space and time, but a substantial portion of the annual landslide loss is associated with a few major catastrophic events such as the mudflows in the San Francisco Bay area and along the Wasatch Front in Utah. Semiarid alpine mudflows and debris flows are triggered by the slumping or slipping of unconsolidated material on steep slopes (Higgins et al. 1983). Such movement usually occurs following soil saturation due to fairly intense and short-duration rainfall events, or as a consequence of rapid snowmelt. Mud and debris flows originate on steep slopes or landslide areas. The zone of sediment transport typically has a steep channel system, at the end of which a sudden break in slope on the valley floor induces deposition to form a conical debris fan.

Several investigations have promulgated various classifications of mudflows and hyperconcentrated flows [e.g., Blackwelder (1928), Sharp and Nobles (1953), Johnson (1965), and O'Brien and Julien (1985)]. An attempt to delineate hyperconcentrated flows and mass wasting processes was initiated by the National Research Council Committee on Methodologies for Predicting Mud Flows (NRC 1982). The committee proposed four main categories: water floods, mud floods, mudflows, and landslides. The

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sediment-water mixtures in water floods and mud floods are both unable to resist shear stress without motion. The large sediment concentrations in mudflows invalidate the use of existing sediment transport equations such as Einstein's and Meyer-Peter and Muller's because the higher viscosity and shear strength of the mixture reduces the fall velocity of sediment particles. Mudflows were defined as a division of landslides where: "the transporting mechanism is that of a flow having sufficient viscosity to support large boulders within a matrix of smaller sized particles." The divisions among hyperconcentrated flows, mudflows, and debris flows are still subject to disagreement, and a comprehensive classification of hyper-concentrated flows is not yet available (Bradley and McCutcheon 1985).

The objective of this study is to provide a better description of the physical properties of mudflow material. Laboratory measurements of the rheological properties of natural mudflow deposits were conducted on several samples from the central Colorado Rocky Mountains. The mud-flow matrix, consisting only of silt and clay particles at volumetric sediment concentrations $0.10 < C_v < 0.45$, was sheared in a rotational viscometer to measure the viscosity and yield stress. The effect of adding sand particles to the fluid matrix was then documented.

RHEOLOGICAL MODELS

The rheology of fluids and water-sediment mixtures can be analyzed from measurements of shear stress at various rates of angular deformation, du/dy. With a fluid having low sediment concentrations, this stress-strain relationship is linear with intercept at the origin. This water-sediment mixture is called a Newtonian fluid. The viscosity of the mixture, defined as the slope of the stress-strain relationship, increases with sediment concentration (Thomas 1963; Happel and Brenner 1965). At higher con-centrations, the fluid matrix can resist shear stress without motion, owing to the shear strength provided by cohesion between sediment particles. A threshold value of shear stress called yield stress τ_y must be exceeded prior to fluid motion. A mixture with a finite yield-stress value is a non-Newtonian fluid. According to the experiments of Fei (1981), the critical volumetric concentration at which the water-sediment mixture turns into a non-Newtonian fluid is closely related to the content of fine sediments (0.01 mm). In this study, the fluid matrix refers to a suspension of fine sediments with sizes smaller than 0.072 mm (silt and clay particles). A mixture can behave as a non-Newtonian fluid at a low concentration, provided the proportion of fine particles is high.

Rheological models for non-Newtonian fluids include the Bingham plastic model and the yield-pseudoplastic model. Bingham fluids exhibit a linear stress-strain relationship at shear stresses in excess of the yield stress. The equation describing Bingham fluids is

$$\tau = \tau_y + \eta \frac{du}{dy} \quad \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \quad (1)$$

Hyperconcentrated suspensions of clay and quartz particles in water under low rates of shear behave as Bingham fluids (Govier and Aziz 1982).

Other materials exhibit a yield stress, as in the case of Bingham fluids, but the stress-strain relationship is not linear. Commonly, the relationship

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shows convexity to the shear stress, and this behavior is referred to as yield-pseudoplastic. There is no theoretically based equation for yield-pseudoplastics, but any empirical equation such as the power-law equation can be used:

$$\tau = \tau_y + a\left(\frac{du}{dy}\right)^n \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (2)$$

in which a and n = empirical parameters. This model, first proposed by Herschel and Bulkley (1926), describes the behavior of clay-water suspensions reasonably well at high rates of shear (Govier and Aziz 1982).

Although several investigators have applied the Bingham model to water-sediment mixtures, most available data were collected for dilute mixtures of bentonite and kaolin clays under very high shear rates, well in excess of 100 s^{-1} (Thomas 1963; Plessis and Ansley 1967; Valentik and Whitmore 1965; Mills et al. 1983). When compared to measurements under low rates of shear, these analyses led to larger values of yield stress and lower values of viscosity. It must be considered that typical shear rates for hyperconcentrated sediment flows in the field are on the order of 5–50 s^{-1}. Data from Johnson (1970) show this value to be of a magnitude of 10 s^{-1} or less. Yano and Daido (1965) report shear rates less than 10 s^{-1} for open-channel mudflows with concentrations up to 35% by weight. Therefore, rates of shear in excess of 50 s^{-1} appear to be uncommon in open-channel mudflows. This corroborates the findings of Qian and Wan (1986) in that the rate of shear in hyperconcentrated flows rarely exceeds 100 s^{-1}. Thus, not only must the viscometer experiments be conducted at low shear rates, but the fluid properties must be evaluated at lower shear rates as well.

MEASUREMENT OF MUDFLOW PROPERTIES

The measurement and interpretation of the physical properties of mudflow mixtures is more complex than the viscosity measurements of Newtonian fluids. Three different types of apparatus are in common use for measuring the rheological properties of non-Newtonian fluids; (1) The capillary viscometer; (2) the rotational viscometer; and (3) the cone-and-plate viscometer.

A capillary viscometer measures the rate of flow of a fluid in a capillary tube under a given pressure gradient. The rate of shear varies across the capillary section; this viscometer is not suitable for time-dependent fluids. Due to its simplicity, this viscometer can be invaluable at large rates of shear.

In rotational viscometers, the fluid is sheared at a nearly constant rate between a stationary and a rotating cylinder. The shear stress is obtained from the torque measured on the stationary cylinder. Precautions must be taken to ensure laminar flow and constant temperature; end-effect corrections may also be required. Its suitability to a wide range of shear stresses makes it a versatile and useful instrument to analyze non-Newtonian fluids.

The cone-and-plate viscometer shears the fluid in the narrow space between the flat circular rotating plate and an inverted cone. This viscometer is ideal to study the properties of non-Newtonian fluids at low and

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moderate shear rates. Isothermal conditions and an absence of secondary flows are required.

After considering existing commercial viscometers, a rotational viscometer was designed especially (O'Brien 1986) to investigate the rheological properties of natural mudflow material. The design of the concentric cylindrical viscometer was constrained by low shear rates, sediment size within the mixture, and stability criteria for laminar flow without secondary flow. The flow annulus is sized by the criteria specified by Van Wazer et al. (1963), and the gap size is at least ten times larger than the coarsest particle size in the fluid matrix. The stability criteria suggested in Schlichting (1968) must be satisfied to prevent the formation of Taylor vortices in the annulus. The shear stress contribution at the end of the rotating cylinder is found to be negligible. Temperature is controlled by inserting the whole apparatus into a water bath. The torque exerted on the viscometer bob is measured with strain gages calibrated to provide a torque versus voltage relationship covering the full range of torque measurements encountered during the test program. The resulting accuracy of the device was checked using glycerol solutions with viscosities ranging from 0.1–10 poises.

LABORATORY ANALYSIS OF MUDFLOW SAMPLES

A variety of samples were collected from natural mudflows deposits in the Colorado Rocky Mountains near the towns of Aspen and Glenwood Springs. The properties of the mudflow samples in terms of sediment size distribution and content of clay are given in Table 1. No detailed information on clay mineralogy is available; however, the samples with large clay content were tested to determine the liquid limit and the plasticity index. The plasticity chart indicates inorganic clays with low to medium plasticity. A fluid matrix comprising fine sediments (only silts and clays) was prepared for testing in the new viscometer; 10–15 measurements of shear stress versus shear rates were made for each concentration, as shown in Fig. 1. The volumetric concentration was varied by adding water after each test. In some tests with very large sediment concentrations, slippage was observed around the annulus at rates of shear as low as

TABLE 1. Properties of Mudflow Matrices (Silts and Clays Only)

Sample (1)	Sediment Size Distribution				Liquid limit (6)	Plasticity index (7)
	Clay (%) (2)	D_{16} (mm) (3)	D_{50} (mm) (4)	D_{84} (mm) (5)		
Glenwood original	4.8	0.010	0.034	0.062	—	—
Glenwood sample 1	6.8	0.009	0.023	0.050	—	—
Glenwood sample 2	3.0	0.016	0.035	0.061	—	—
Glenwood sample 3	4.8	0.011	0.025	0.053	—	—
Glenwood sample 4	7.6	0.001	0.018	0.032	—	—
Aspen pit 1	31.3	0.001	0.011	0.032	0.32	0.11
Aspen natural soil	27.0	0.001[a]	0.012	0.028	0.25	0.06
Aspen mine fill	27.8	0.001[a]	0.013	0.030	0.24	0.06
Aspen natural soil source	31.6	0.001[a]	0.016	0.039	—	—
Aspen mine fill source	25.2	0.001[a]	0.018	0.061	—	—

[a]These values were extrapolated from sieve analysis graphs.
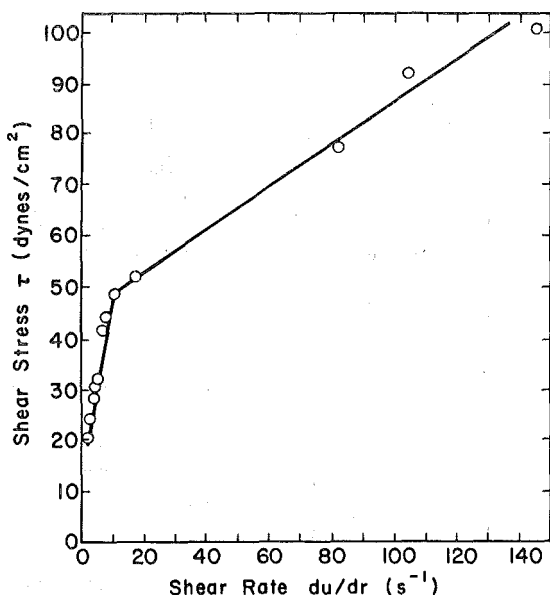
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FIG. 1. Aspen Natural Soil Rheogram (C_v = 34.2%; Silts and Clays)

10 s^{-1}, as shown in Fig.1. For this reason, the evaluation of viscosity and yield stress from the Bingham plastic model was based on the measurements taken at lower shear rates. Of course, when compared to measurements at high rates of shear, this analysis gives slightly lower values of yield stress and larger viscosity measurements.

In hyperconcentrated flows, the Bingham plastic model (Eq. 1) has been used by many researchers, e.g., Cao et al. (1983), Hou and Yang (1983), Higgins et al. (1983), Street (1958), Thomas (1963), Qian et al. (1980), Govier and Aziz (1982), and Dai et al. (1980). It has been generally accepted that both the viscosity η and the yield stress τ_y increase exponentially with the volumetric concentration of fine sediments C_v:

$$\eta = \alpha_1 e^{\beta_1 C_v} \quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad (3)$$

and

$$\tau_y = \alpha_2 e^{\beta_2 C_v} \quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad (4)$$

The values of the four empirical coefficients α_1, α_2, β_1, and β_2 obtained by regression analysis for each mudflow sample are presented in Table 2; the results are in reasonable agreement with those found in the literature. Particularly, the experimental values of the yield stress fall within the range of values defined by Fei (1981). The dispersion of the points at a given concentration certainly calls for more fundamental research to examine possible effects of thixotropy and clay mineralogy. Nevertheless, the open points (Glenwood) indicating lower percentages of clay in Fig. 2 have lower values of yield stress when compared with the samples with larger clay contents (Aspen). This trend is not quite apparent when

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TABLE 2. Yield Stress and Viscosity of Mudflow Matrices

Source (1)	$\tau_y = \alpha_2 e^{\beta_2 C_v}$		$\eta = \alpha_1 e^{\beta_1 C_v}$	
	α_2 (dynes/cm^2) (2)	β_2 (3)	α_1 (poises) (4)	β_1 (5)
(a) Relationships Found in Field				
Aspen pit 1	1.81×10^{-1}	25.7	3.60×10^{-2}	22.1
Aspen pit 4	2.72	10.4	5.38×10^{-2}	14.5
Aspen natural soil	1.52×10^{-1}	18.7	1.36×10^{-3}	28.4
Aspen mine fill	4.73×10^{-2}	21.1	1.28×10^{-1}	12.0
Aspen natural soil source	3.83×10^{-2}	19.6	4.95×10^{-4}	27.1
Aspen mine fill source	2.91×10^{-1}	14.3	2.01×10^{-4}	33.1
Glenwood 1	3.45×10^{-2}	20.1	2.83×10^{-3}	23.0
Glenwood 2	7.65×10^{-2}	16.9	6.48×10^{-1}	6.2
Glenwood 3	7.07×10^{-4}	29.8	6.32×10^{-3}	19.9
Glenwood 4	1.72×10^{-3}	29.5	6.02×10^{-4}	33.1
(b) Relationships Found in Literature				
Iida (1938)	—	—	3.73×10^{-5}	36.6
Dai et al. (1980)	2.60	17.48	7.5×10^{-3}	14.39
Kang and Zhang (1980)	1.75	7.82	4.05×10^{-2}	8.29
Qian et al. (1980)	1.36×10^{-3} ~5.0×10^{-2}	21.2 ~15.48	— —	— —
Chien and Ma (1958)	5.88×10^{-2}	19.1~32.7	—	—
Fei (1981)	1.66×10^{-1} ~4.7×10^{-3}	25.6 ~22.2	— —	— —

viscosity measurements are considered as shown in Fig. 3. It is clearly shown, however, that both the yield stress and viscosity increase by three orders of magnitude as the volumetric concentration increases from 0.10–0.40.

Since the laboratory analysis of the mudflow deposits dealt primarily with the finer fractions of the mudflow material, additional tests were undertaken (O'Brien and Julien 1986) to determine the influence of adding concentrations of sands to be bentonite clay suspensions. At large concentrations, slippage between particle layers occurred at shear rates exceeding 5 s^{-1}, as shown in Fig. 4. Thus, roughness elements consisting of sand particles ranging from 1–1.6 mm in size were glued to the stainless steel bob cylinder of the viscometer. These elements did not alter the viscosity and yield stress measurements at low rates of shear but prevented slippage at higher shear rates. The results shown in Fig. 5 reveal that with increasing sand concentration, the viscosity remains comparable to that given from the clay content alone until the sand concentration exceeds about 20% by volume. Note that with bentonite clay content of 5–6%, the dynamic viscosity shown in Fig. 5 is two orders of magnitude larger than the viscosity of clear water ($\eta_{water} = 0.01$ poise). Further experiments were made with natural mudflow deposits at a larger concentration (shown as dark points on Fig. 5). Similar conclusions were
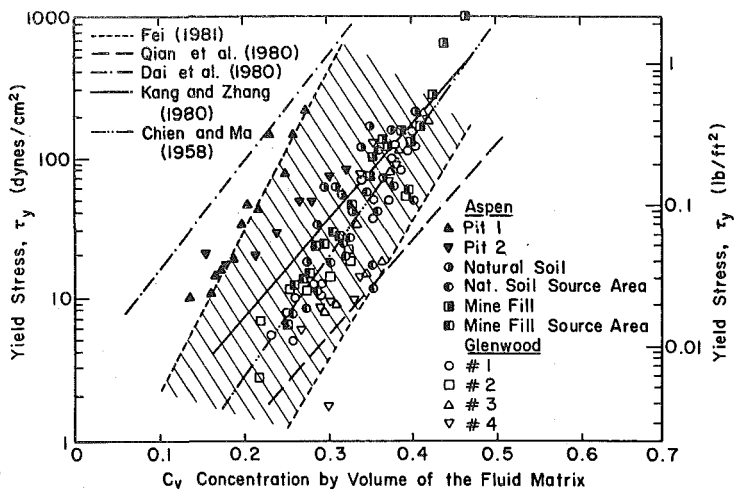
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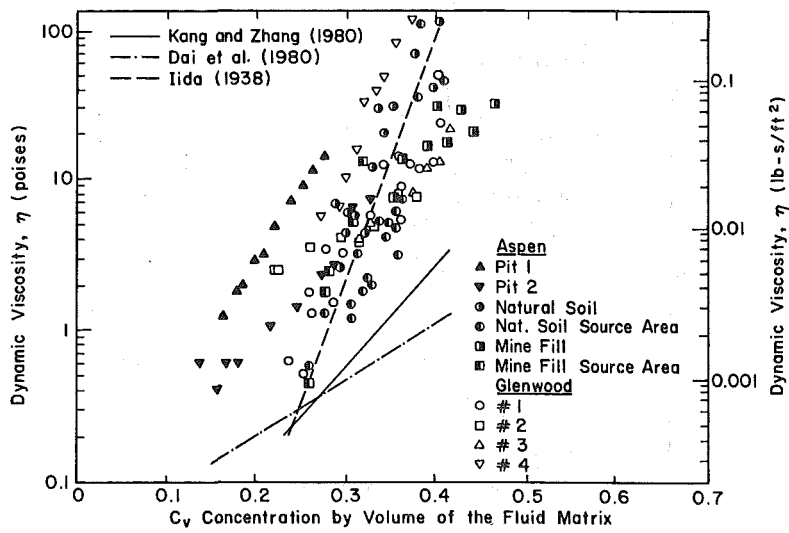**FIG. 2. Yield Stress of Mudflow Samples versus Volumetric Concentration**

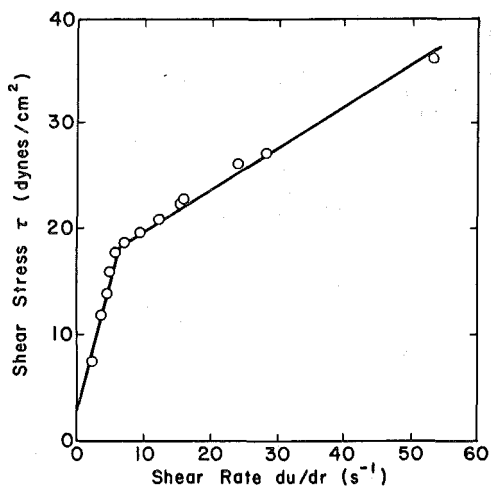**FIG. 3. Dynamic Viscosity of Mudflow Samples versus Volumetric Concentration**

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FIG. 4. Rheogram for Aspen Natural Soil (C_v = 30% Silts and Clays) with Added Sand Concentration C_v = 14%; C_{total} = 44%)
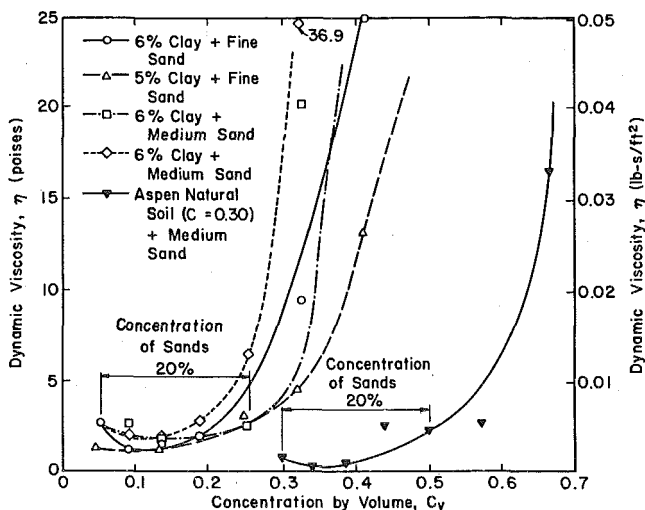

FIG. 5. Dynamic Viscosity of Mixtures with Added Sand Particles versus Total Volumetric Concentration

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obtained, which indicates that large concentrations of sand particles are required in order to significantly alter the physical properties of the mudflow matrix. The viscosity of the fluid matrix increases very rapidly at volumetric concentrations of sand in excess of 20%. Further investigation is needed with coarser grained slurries.

SUMMARY AND CONCLUSION

Two physical properties of the fluid matrix of natural mudflow deposits in the central Colorado Rocky Mountains have been investigated at concentrations ranging from 10–45% by volume. The fluid matrix comprised of particles finer than 0.07 mm (silts and clays) was sheared in a special viscometer designed for the analysis of mudflow samples under temperature-controlled conditions. The viscometer gap size was determined to provide laboratory measurements of the fluid matrix properties under laminar flow conditions at low rates of shear without secondary flows. This study stresses the importance of conducting measurements at low rates of shear because: (1) those are the conditions found in natural channels; and (2) they avoid the slippage problems observed at large sediment concentrations. The Bingham rheological model was applied to the measured rheograms at low rates of shear. Both the yield stress and viscosity are shown in Figs. 2 and 3 to increase by three orders of magnitude as the volumetric concentration of sediments in the fluid matrix changes from 10–40%. The effect of adding sand particles to either a bentonite clay suspension or natural mudflow matrix of silts and clays is negligible, provided that the sand concentration remains less than 20% by volume. The viscosity of mudflow material with volumetric sand concentrations less than 20% simply corresponds to the viscosity of the silt-clay mixture. The viscosity of the mixture, however, increases rapidly with volumetric sand concentrations beyond 20%.

ACKNOWLEDGMENTS

APPENDIX I. REFERENCES

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Appendix II. Notation

The following symbols are used in this paper:

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\begin{aligned}
a, n &= \text{empirical parameters for pseudo-plastic fluids;}\\
C_v &= \text{volumetric concentration of fluid matrix;}\\
D &= \text{sediment size;}\\
du/dy &= \text{velocity gradient;}\\
\alpha_1, \alpha_2, \beta_1, \beta_2 &= \text{coefficients;}\\
\eta &= \text{dynamic viscosity of fluid matrix;}\\
\tau &= \text{total shear stress; and}\\
\tau_y &= \text{yield stress.}
\end{aligned}
$$