



# The effective viscosity of slurries laden with vegetative ash

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## ABSTRACT

After a forest fire, ash can blanket the soil surface to depths of tens of centimeters. It has been proposed that the incorporation of vegetative ash into hillslope runoff can, by increasing the flow's effective viscosity, reduce the settling velocity of entrained particles and lead to the development of runoff-generated debris flows. To investigate how the addition of this material might affect the rheology of runoff in burned areas, we measured and compared the effective viscosity of slurries composed of varying concentrations of ash and similarly sized mineral particles (i.e., silt). All the slurries were pseudoplastic (i.e., shear-thinning) and, at low weight concentrations ( $\leq 0.3 \text{ g g}^{-1}$ ), the rheologies of ash and silt slurries were nearly identical. At higher concentrations, however, their rheologies diverged significantly. For example, whereas the viscosity of the silt slurries increased monotonically with concentration, the viscosity of the ash slurries decreased. Ash incorporated into silt slurries induced this same complex behavior, indicating that ash alters the rheological properties of runoff in ways that would not be predicted simply based on its size. In addition, we found that, at high concentrations, the intensity of shear-thinning in the ash slurries was greater than in the silt slurries. Finally, we compared the settling velocities of small particles in clear water and ash slurries and conclude that the rheological characteristics of ashy runoff could promote runoff-generated debris flows in burned landscapes.

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## 1. Introduction

In mountainous terrain, debris flows are a common response to the physical and hydrological changes driven by fire (e.g., Cannon and Gartner, 2005; Cannon and Reneau, 2000; Meyer and Wells, 1997; Shakesby and Doerr, 2006). Although fire-related debris flows may represent hazards to life and property, they can also be an important mechanism for delivering coarse sediment and large woody debris to fluvial environments, thereby increasing habitat complexity (Hoffman and Gabet, 2007). In contrast to debris flows that initiate through the fluidization of a failing landslide mass (e.g., Gabet and Mudd, 2006; Iverson et al., 1997), debris flows in recently burned landscapes appear to initiate primarily by the progressive bulking of surface runoff (e.g., Cannon, 2001; Cannon et al., 2003; Meyer and Wells, 1997), a process that is still poorly understood.

Although the mechanisms for the initiation of runoff-generated debris flows have not been fully elucidated, two ingredients appear necessary, abundant water and abundant fine sediment (e.g., Cannon, 2001; Cannon et al., 2001b; Coe et al., 2008), and both can be found in burned landscapes. After fires, surface runoff can be amplified by the development of soil hydrophobicity (DeBano, 1981) and the loss of canopy cover that intercepts rainfall. A layer of vegetative ash can also modulate a burned landscape's hydrological response by slowing infiltration into

the underlying soil (Gabet and Bookter, 2008, 2011; Mallik et al., 1984) and storing water at the soil surface (e.g., Balfour and Woods, 2006; Ebel et al., 2012). The ash layer, therefore, may act as a reservoir of water that can be mobilized by oncoming flows. The second ingredient for runoff-generated debris flows, fine sediment, has two potential sources in burned landscapes. First, high temperatures may reduce soil cohesion and increase the availability of easily erodible soil particles (Cannon and Reneau, 2000; DeBano, 1981). The second source of fine-grained material after a fire is, of course, the ash. The passage of a fire can leave vast quantities of this material mantling a landscape. Furthermore, wind can re-distribute the ash, preferentially depositing it in hillslope hollows, likely areas of runoff-generation. Substantial amounts of ash in the deposits of post-fire debris flows (e.g., Cannon, 2001; Cannon et al., 2001a; Meyer and Wells, 1997; Parrett, 1987) attest to its potential role in generating these events. Moreover, Cannon et al. (2001a,b) noted the absence of debris flows from burnt slopes lacking ash and concluded that ash-laden runoff had been a precursor to runoff-generated debris flows.

Our study was motivated by a series of runoff-generated debris flows generated in the Sleeping Child Creek watershed in Montana (USA). The basin burned in the summer of 2000; a year later, a convective storm passed over the area, delivering 16 mm of rain in 1 h (~2 year recurrence interval) and triggering numerous debris flows (Cannon et al., 2003; Gabet and Bookter, 2008; Hyde et al., 2007). Most of the debris flows issued from steep, unchanneled zero-order valleys filled with colluvial soils. The morphological evidence for the progressive

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bulking of these flows was strong: small rills with heads near the ridge-line became wider and deeper downslope, eventually growing into gullies that were up to 3-m deep and 10-m wide and lined by debris flow levees (Gabet and Bookter, 2008). Ash in the debris flow deposits indicated an abundance of this material in the watershed, even a year after the fire.

On the basis of these observations, it was proposed that ashy hillslope runoff can help trigger a positive feedback between sediment entrainment, bulk density, and effective viscosity that leads to the progressive bulking of these flows (Gabet and Bookter, 2008; Gabet and Sternberg, 2008). Specifically, it was hypothesized that runoff generated high in the catchments incorporates easily erodible ash, which has particle sizes in the silt range (Balfour and Woods, 2013; Gabet and Bookter, 2011). An ashy slurry would be more erosive than clear water because (1) its higher bulk density exerts a greater boundary shear stress (Gabet and Sternberg, 2008), and (2) its higher effective viscosity slows the settling velocity of particles in suspension. Therefore, as the flow progresses downslope, it begins to cut into the soil surface more effectively than clear water would, incorporating soil as well as more ash, which further increases the boundary shear stress and viscosity and, consequently, the flow's erosivity. This positive feedback leads to the entrainment of progressively more mineral material, resulting in an increase in solids concentration with distance downslope (Gabet and Bookter, 2008). A similar process has been proposed for hyperconcentrated flows laden with loess (Xu, 1999a; Xu, 1999b), debris flows on hillslopes in dry environments (Welcker, 2011), and lahars (e.g., Doyle et al., 2011).

According to this proposed mechanism for the initiation of runoff-generated debris flows, both the erosivity and the viscosity of the runoff must increase with ash concentration. Laboratory experiments have confirmed that ash-laden flows are more erosive than clear-water flows and that the difference is likely due to the increase in bulk density (Gabet and Sternberg, 2008). Although Major and Pierson (1992) and Julien and Lan (1991) found that the effective viscosity of slurries increased with the concentration of fine-grained sediment, these studies only included mineral material. Here, we investigate the rheology of ashy slurries. In particular, we answer two questions. Does the effective viscosity of a slurry increase with ash concentration? And does the incorporation of ash into a slurry affect its rheology in the same way as silt?

## 2. Materials and methods

### 2.1. Ash

The ash used in this study was created by burning woody fuels representative of forests in the northwestern US. The fuels were procured from fresh slash piles in logged areas near Missoula, Montana and consisted of Ponderosa pine, Douglas fir and Lodgepole pine. These materials were combusted in a burn barrel made from a 114-l galvanized steel garbage can. Ventilation holes were drilled below a burning grate to allow for greater airflow and more complete combustion. Prior to combustion, all woody fuels were thoroughly cleaned with distilled water to remove soil and then dried in an oven for 48 h at 40 °C. A layer of dried fuels approximately 5-cm thick was placed on the burning grate and ignited with a propane torch. Once a majority of the fuel was combusted (after approximately 30 min) and fell through the grate, another layer of fuel was added. This process was repeated until the entire fuel sample had burned. After the ash had cooled in the base of the burn barrel, the sample was removed and sifted through a 2 mm sieve to remove large pieces of charcoal. The ash was then oven-dried for 24 h at 40 °C and placed in airtight plastic bins. The median grain size of ash generated in this manner varies from 83 to 34  $\mu\text{m}$ , approximately similar to wildfire ash, and the particle density is 2500  $\text{kg m}^{-3}$  (Gabet and Bookter, 2011). The color of the ash was primarily black.

**Table 1**

Conversion of mass concentrations to mass fractions.

| Concentration <sup>a</sup> | Mass fraction <sup>b</sup> |
|----------------------------|----------------------------|
| 0.05                       | 0.05                       |
| 0.10                       | 0.09                       |
| 0.15                       | 0.13                       |
| 0.20                       | 0.17                       |
| 0.25                       | 0.20                       |
| 0.30                       | 0.23                       |
| 0.35                       | 0.26                       |
| 0.40                       | 0.29                       |
| 0.45                       | 0.31                       |
| 0.50                       | 0.33                       |
| 0.55                       | 0.35                       |
| 0.60                       | 0.38                       |

<sup>a</sup> Calculated as: sediment mass/water mass.

<sup>b</sup> Calculated as: sediment mass/(sediment mass + water mass).

Eight batches of ash were used in the viscosity measurements. To ensure that ash created in the different batches was similar in composition, the carbon content of each was determined with the loss-on-ignition technique. A small sample of each batch of ash was dried in an oven for 24 h at 105 °C and weighed. The samples were then heated in a muffle furnace at 400 °C for 15 h, allowed to cool, and re-weighed. The change in weight was used to calculate the percent carbon of the ash sample. The carbon content of the eight ash samples ranged from 47% to 66% with a mean of  $49.4\% \pm 6.1\%$ . These values are similar to those of ash formed under natural conditions with these fuel types (Vicki Balfour, personal communication) and are consistent with burn temperatures of ~300 °C (Balfour and Woods, 2013).

### 2.2. Silt

The silt used in this study was provided by Omnni Engineering (Appleton, Wisconsin). Omnni Engineering used a Gilson shaker to ensure that the grain size was within 0.02% of the reported mean of 55  $\mu\text{m}$ .

### 2.3. Sediment combinations and concentrations

Homogeneous slurries of ash and silt were tested. In addition, different mixtures were tested in which ash and silt were used in identical proportions (i.e., 1:1) by weight. Total sediment concentrations (weight sediment:weight water) ranged from 0.05 to 0.6, in increments of 0.05. The rotating sleeve of the viscometer could not rotate through slurries with concentrations above 0.6 and, therefore, our thickest slurries are at the low end of debris flow concentrations for fine-grained material (Qian et al., 1981 in Pierson, 2005). Note that concentrations of debris flow mixtures are often given as mass fractions (e.g., Major and Pierson, 1992); the measures of concentration reported here are converted to mass fractions in Table 1 to facilitate comparisons with other studies.

Sample volumes were ~350 ml. To control for the effects of temperature on viscosity, distilled water at a temperature of  $20\text{ °C} \pm 1\text{ °C}$  was used in all the slurries.

### 2.4. Viscosity measurements

The Grace Instruments (Houston, Texas) M3500pH rotational viscometer consisted of a rotor bob and a rotating sleeve suspended vertically in the testing material. The rotating sleeve spins at a specified shear rate which induces fluid shear sensed by the rotor bob. The shear gap is 0.61 cm. The viscometer recorded the shear rate and shear stress every 5 s and calculated the effective viscosity. Temperature and pH were also monitored and recorded. Each test ran for 5 min.

O'Brien and Julien (1988) determined that shear rates in natural debris flows are typically  $<20\text{ s}^{-1}$  (although experimental debris flows can have shear rates as high as  $50\text{ s}^{-1}$  (Iverson, 1997)). Thirteen shear

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