The Effective Viscosity of Ash-Laden Flows

Kirstin Anne Burns

The University of Montana

Follow this and additional works at: https://scholarworks.umt.edu/etd

Let us know how access to this document benefits you.

Recommended Citation

https://scholarworks.umt.edu/etd/1215

This Thesis is brought to you for free and open access by the Graduate School at ScholarWorks at University of Montana. It has been accepted for inclusion in Graduate Student Theses, Dissertations, & Professional Papers by an authorized administrator of ScholarWorks at University of Montana. For more information, please contact scholarworks@mso.umt.edu.
THE EFFECTIVE VISCOSITY OF ASH-LADEN FLOWS

By

Kirstin Anne Burns

B.S., Michigan Technological University
Houghton, Michigan, 2005

Thesis

presented in partial fulfillment of the requirements
for the degree of

Master of Science
in Geology

The University of Montana
Missoula, MT

Spring 2007

Approved by:

Dr. David A. Strobel, Dean
Graduate School

Dr. Rebecca Bendick
Geosciences

Dr. Emmanuel Gabet
Environmental Sciences, University of California Riverside

Dr. Scott Woods
Ecosystem and Conservation Sciences
Debris flows can drastically alter ecosystems and damage infrastructure, and there is an increased risk of debris flows following a wildfire. In general, runoff and erosion drastically increase following a wildfire as a result of many processes, one of them being debris flows. Large debris flows are common in the months and years after wildfire in mountainous areas throughout the western U.S.A.

The progressive bulking of surface runoff may be the dominant triggering mechanism of these debris flows. Vegetative ash on the hillslope becomes entrained in the flow, along with other fine-grained sediment and increases the effective viscosity of the flow. The increase in effective viscosity decreases the settling velocity of the sediment within the flow, which in turn increases the bulk density of the flow. The increase in bulk density increases the erosivity of the flow. While previous research has shown that the addition of fine-grained particles can increase the effective viscosity of a flow, little research has been done to determine how the addition of ash changes the effective viscosity of the flow.

A viscometer was used to test the effective viscosity of a variety of sediment and water slurries. The tests varied in shear rate, sediment composition (ash, silt, sand) and sediment concentration. These parameters mimicked natural conditions where debris flows occur. Comparisons were made between slurries containing different sediment types and sediment concentrations at various shear rates to form equations that related these parameters.

All of the slurries tested could be classified as a power-law fluid; more specifically, all slurries exhibited pseudoplastic (shear thinning) behavior. Slurries containing only ash behaved differently than slurries containing only silt or sand. Also, in the slurries containing ash, silt and sand, it was found that slurries containing a high percentage of ash behave differently than those containing mainly silt and sand.

Using the data collected, two equations were generated that relate the effective viscosity to shear rate and sediment concentration. One equation is for use with ash-rich slurries, the other ash-poor slurries.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSTRACT</td>
<td>ii</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>v</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>vi</td>
</tr>
<tr>
<td>LIST OF APPENDICES</td>
<td>ix</td>
</tr>
<tr>
<td>INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>METHODS</td>
<td></td>
</tr>
<tr>
<td>Materials Used</td>
<td>10</td>
</tr>
<tr>
<td>Equipment Used</td>
<td>11</td>
</tr>
<tr>
<td>Experimental Procedure</td>
<td>12</td>
</tr>
<tr>
<td>Data Processing</td>
<td>19</td>
</tr>
<tr>
<td>RESULTS</td>
<td></td>
</tr>
<tr>
<td>Carbon Content of Ash</td>
<td>22</td>
</tr>
<tr>
<td>Temperature and pH of Samples Tested</td>
<td>22</td>
</tr>
<tr>
<td>Homogeneous Slurries of Ash, Silt or Sand</td>
<td>25</td>
</tr>
<tr>
<td>Two Sediment Slurries</td>
<td>38</td>
</tr>
<tr>
<td>Ash, Silt and Sand Slurries</td>
<td>50</td>
</tr>
<tr>
<td>Combined Data</td>
<td>54</td>
</tr>
<tr>
<td>DISCUSSION</td>
<td></td>
</tr>
<tr>
<td>Carbon Content of Ash</td>
<td>81</td>
</tr>
<tr>
<td>Temperature and pH of Samples Tested</td>
<td>81</td>
</tr>
<tr>
<td>Average Effective Viscosity Tests</td>
<td>82</td>
</tr>
</tbody>
</table>
CONCLUSION .................................................................................................................. 91

REFERENCES ............................................................................................................... 92
<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Density of sediments used in experiments</td>
<td>11</td>
</tr>
<tr>
<td>2</td>
<td>Amount of ash, silt and sand used in homogeneous slurries</td>
<td>15</td>
</tr>
<tr>
<td>3</td>
<td>Amounts of ash, silt and sand used in 2 sediment slurries</td>
<td>16</td>
</tr>
<tr>
<td>4</td>
<td>Amounts of ash, silt and sand used in 3 sediment slurries</td>
<td>17</td>
</tr>
<tr>
<td>5</td>
<td>Shear rates used in laboratory experiments</td>
<td>17</td>
</tr>
<tr>
<td>6</td>
<td>Carbon content of the ash samples used in experiments</td>
<td>22</td>
</tr>
<tr>
<td>7</td>
<td>$D$, $b$ and $R^2$ values for each concentration of ash slurry tested</td>
<td>30</td>
</tr>
<tr>
<td>8</td>
<td>$D$, $b$ and $R^2$ values for each concentration of silt slurry tested</td>
<td>33</td>
</tr>
<tr>
<td>9</td>
<td>$D$, $b$ and $R^2$ values for each concentration of sand slurry tested</td>
<td>37</td>
</tr>
<tr>
<td>10</td>
<td>$D$, $b$ and $R^2$ values for each concentration of ash + silt slurry tested</td>
<td>41</td>
</tr>
<tr>
<td>11</td>
<td>$D$, $b$ and $R^2$ values for each concentration of ash + sand slurry tested</td>
<td>45</td>
</tr>
<tr>
<td>12</td>
<td>$D$, $b$ and $R^2$ values for each concentration of silt + sand slurry tested</td>
<td>48</td>
</tr>
<tr>
<td>13</td>
<td>$D$, $b$ and $R^2$ values for each concentration of ash + silt + sand slurry tested</td>
<td>52</td>
</tr>
<tr>
<td>14</td>
<td>$D$, $b$ and $R^2$ values for each concentration of the combined data</td>
<td>68</td>
</tr>
<tr>
<td>15</td>
<td>Comparison of $D$ and $b$ values for all slurry types and combined data</td>
<td>71</td>
</tr>
</tbody>
</table>
### LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Schematic diagram of the hypothesized progressive bulking mechanism</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>Photograph of the Grace Instruments M3500pH viscometer</td>
<td>12</td>
</tr>
<tr>
<td>3</td>
<td>Example of data used for calculating mean effective viscosity</td>
<td>20</td>
</tr>
<tr>
<td>4</td>
<td>Effective viscosity and pH of an ash slurry over time with the addition of a pH buffer</td>
<td>24</td>
</tr>
<tr>
<td>5</td>
<td>Average effective viscosity versus concentration for ash slurries</td>
<td>26</td>
</tr>
<tr>
<td>6</td>
<td>Average effective viscosity versus shear rate for ash slurries</td>
<td>27</td>
</tr>
<tr>
<td>7</td>
<td>Comparison of power and exponential trendlines</td>
<td>28</td>
</tr>
<tr>
<td>8</td>
<td>Average effective viscosity versus shear rate for all concentrations of ash</td>
<td>29</td>
</tr>
<tr>
<td>9</td>
<td>$D$ values for varying concentrations of ash</td>
<td>30</td>
</tr>
<tr>
<td>10</td>
<td>$b$ values for varying concentrations of ash</td>
<td>31</td>
</tr>
<tr>
<td>11</td>
<td>Average effective viscosity versus concentration for silt slurries</td>
<td>32</td>
</tr>
<tr>
<td>12</td>
<td>Average effective viscosity versus shear rate for silt slurries</td>
<td>33</td>
</tr>
<tr>
<td>13</td>
<td>$D$ values for varying concentrations of silt</td>
<td>34</td>
</tr>
<tr>
<td>14</td>
<td>$b$ values for varying concentrations of silt</td>
<td>34</td>
</tr>
<tr>
<td>15</td>
<td>Average effective viscosity versus concentration for sand slurries</td>
<td>36</td>
</tr>
<tr>
<td>16</td>
<td>Average effective viscosity versus shear rate for sand slurries</td>
<td>36</td>
</tr>
<tr>
<td>17</td>
<td>$D$ values for varying concentrations of sand</td>
<td>37</td>
</tr>
<tr>
<td>18</td>
<td>$b$ values for varying concentrations of sand</td>
<td>38</td>
</tr>
<tr>
<td>19</td>
<td>Average effective viscosity versus concentration for ash + silt slurries</td>
<td>40</td>
</tr>
<tr>
<td>20</td>
<td>Average effective viscosity versus shear rate for ash + silt slurries</td>
<td>40</td>
</tr>
<tr>
<td>21</td>
<td>$D$ values for varying concentrations of ash + silt</td>
<td>42</td>
</tr>
</tbody>
</table>
b values for varying concentrations of ash + silt ..............................42
Average effective viscosity versus concentration for ash + sand slurries.....43
Average effective viscosity versus shear rate for ash + sand slurries........44
D values for varying concentrations of ash + sand..............................45
b values for varying concentrations of ash + sand...............................46
Average effective viscosity versus concentration for silt + sand slurries....47
Average effective viscosity versus shear rate for silt + sand slurries.......47
D values for varying concentrations of silt + sand..............................49
b values for varying concentrations of silt + sand...............................49
Average effective viscosity versus concentration for ash + silt + sand slurries...51
Average effective viscosity versus shear rate for ash + silt + sand slurries......51
D values for varying concentrations of ash + silt + sand........................53
b values for varying concentrations of ash + silt + sand........................53
Average effective viscosity versus concentration for all slurries at 1 & 3 s^{-1}.....55
Average effective viscosity versus concentration for all slurries at 5 & 7 s^{-1}.....56
Average effective viscosity versus concentration for all slurries at 9 & 12 s^{-1}....57
Average effective viscosity versus concentration for all slurries at 15 & 18s^{-1}....58
Average effective viscosity versus concentration for all slurries at 20 & 25s^{-1}....59
Average effective viscosity versus concentration for all slurries at 30 & 35s^{-1}....60
Average effective viscosity versus concentration for all slurries at 40 s^{-1}.......61
Average effective viscosity versus shear rate for all slurries at concentration of 0.05 and 0.10.................................................................62
Average effective viscosity versus shear rate for all slurries at concentration of 0.15 and 0.20.................................................................63
LIST OF APPENDICES

All appendices can be found on cd that accompanies this thesis

Appendix

A  User’s manual for Grace Instruments M3500pH viscometer
B  Matlab programs used for data analysis
C  Raw lab data as exported by GraceDaq software for trial 1, 2 and 3 for each slurry tested
D  Analyzed viscosity data
E  Movie clip of Figure 74
INTRODUCTION

Debris flows can pose a particular hazard to both natural systems and infrastructure in steep terrain. This risk is increased following a wildfire. Many researchers (Swanson, 1979; Meyer and Pierce, 2003; Shakesby and Doerr, 2006) have observed that runoff and erosion drastically increase following wildfires. Large debris flows are common after wildland fire in mountainous areas in the months and years immediately following a severe forest fire (Parrett, 1987; Meyer and Wells, 1997; Cannon, 2001; Cannon et al., 2001). There are two primary initiation processes identified in the literature for these debris flows occurring in burned areas. The first is an infiltration-triggered failure and mobilization of a discrete landslide mass (Wells, 1987). The second is runoff-dominated erosion by surface overland flow (Cannon et al., 2001; Meyer and Wells, 1997).

The first possible initiation process for debris flows is the failure and mobilization of a landslide mass. Iverson (1997) conducted an extensive study on the mobilization of debris flows from landslides; however, Parrett (1987) and Cannon et al. (2001) both noted the lack of landslide scars in burned areas that had experienced debris flows. Wells (1987) first described debris flow initiation as miniature soil slips in a saturated layer of the soil a few millimeters thick above a subsurface water-repellent zone. During a fire, volatilized organic molecules form a hydrophobic layer that causes an increase in overland flow in the area (DeBano et al., 1981). However, the effect of soil hydrophobicity on post-fire runoff may be limited by the fact that it is generally not continuous in lateral extent or severity across the hillslope (Huffman et al., 2001; Martin and Moody, 2001; Woods et al., 2007)). In addition, once the area burns ash and char
may seal surface pores, further reducing the soil’s infiltration capacity (Etiegni and Campbell, 1991). Martin and Moody (2001) conducted an investigation on the hydrologic and geomorphic response following wildfire in the Colorado Front Range and found that surface sealing did occur and that infiltration rates on burned soils were reduced. Surface sealing is one way that ash may promote debris flow generation in burned areas.

An alternative initiation mechanism of debris flows may be the progressive bulking of surface runoff. Cannon et al. (2001) concluded that ash-laden surface runoff was the dominant triggering mechanism of debris flows in previously burned areas. During an intense storm, rainfall cannot infiltrate down through the soil (due to the ash/char layer and/or hydrophobic layer) at a rate equal to the rainfall rate. This water must then flow overland. It is hypothesized that as the water flows, it begins to entrain ash and sediment that is lying on the surface (Parrett, 1987) increasing the viscosity of the flow. The increase in viscosity decreases the settling velocity of larger particles (Wan, 1985), which in turn increases the bulk density of the flow. An increase in bulk density means more shear stress is being applied to the hillslope as the flow passes over it. This increase in shear stress means that the flow is more erosive and more sediment and ash from the hillslope become entrained in the flow. The process feeds upon itself as the flow travels down the hillslope. Figure 1 below is a graphical representation of the hypothesized progressive bulking process.

While it is hypothesized that a large increase in effective viscosity of the flow may lead to greater hillslope erosion, a flow with a higher viscosity would be a stronger material and may exhibit a slower flow velocity. Conversely, a lower viscosity flow
would be structurally weaker, and therefore, more prone to sliding. Therefore, a balance exists between the flow’s ability to progressively bulk based on a higher effective viscosity and the flow’s strength and ability to travel down the hillslope.

**Figure 1.** Schematic diagram of the hypothesized progressive bulking mechanism within an ash-laden debris flow.

Cannon et al. (2001) suggested that the large size of the materials transported in fire-related debris flows is indicative of the role of availability of wood ash on the hillslopes. Johnson (1984) and Wells (1987) both concluded in their studies conducted in California that debris flows initiated high on the hillslopes from material eroded by surface runoff, and then the debris flows increased in volume by entraining sediment as they traveled down the hillslope. Meyers and Wells (1997), working in Yellowstone National Park, concluded that debris flows were initiated through progressive bulking of surface runoff and erosion in steep upper basin slopes, followed by deep incision as the flows progressed down the hillslope. Cannon and Gartner (2005) noted that debris flow
tracks could be followed upslope from the debris flow deposit through gullies and into small rills. Studies by Cannon et al. (2001) and Meyer and Wells (1997) show that silt, sand and ash make up a significant portion of the post-fire debris deposits. In addition, Cannon et al. (2001) found that there was a lack of ash in runoff from hillslopes that were burned but did not produce a debris flow. These studies suggest that ash may play a critical role in the development of debris flows in burned areas. It is possible that ash within the flow can change the flow’s rheology and can promote flow in situations that may not flow if no ash were present. It is hypothesized that the increase in the viscosity of the flow due to the entrainment of ash and fine-grained sediments may be an essential prerequisite to initiation of debris flows by the progressive bulking process.

Numerous studies have shown that, at the macroscopic scale, a debris flow can behave as a viscoplastic fluid (Major and Pierson, 1992; Whipple and Dunne, 1992; Cannon et al., 2001). Johnson (1970) was the first to adopt the Bingham, or viscoplastic, model for debris flows. Johnson (1970) recognized that debris flows exhibit properties of both viscous fluids and plastic solids. The Bingham model describes a single-phase material that remains rigid or elastic until deviatoric stresses exceed a threshold in plastic yield strength. When stresses exceed the yield strength, the material flows like a viscous fluid. At a stress-free surface of a debris flow, a Bingham material translates like a rigid solid (Iverson, 1997). Mixtures, such as debris flows, that are non-Newtonian fluids have rheological properties that are influenced by a variety of factors such as sediment composition, particle shape and size, particle size distribution, volume concentration of solids, and thermal, chemical and electrical forces (Bird et al., 2006).
The purpose of this study is to determine the effect of the entrainment of ash particles on the effective viscosity of a water-sediment mixture. The effective viscosity is the actual viscosity of the fluid at the particular shear rate which exists in the test conditions (i.e., shear rate). Shear rate is the rate of shear deformation which is usually defined as the velocity gradient within the material (i.e., velocity of the material divided by the depth of the material). A viscometer will be used to measure the effective viscosity of varying concentrations of ash, silt and sand over a range of shear rates. Previous similar experiments were conducted by O’Brien and Julien (1988), Phillips and Davies (1991) and Major and Pierson (1992) focusing on testing slurries that were representative of naturally occurring debris flows. These experiments used two different types of viscometers, a concentric-cylinder rotational viscometer and cone-and-plate viscometer, the former of which will be used in this experiment. The advantages of the rotational viscometer are simplicity, ease of operation and an ability to conduct measurements continuously over an extended period of time. The concentric-cylinder viscometer, like the one used in this experiment, is the most commercially available rotational viscometer.

This study will investigate how the entrainment of ash into a water-sediment mixture affects the effective viscosity of the flow over a variety of shear rates and sediment concentrations. Major and Pierson (1992) found that the addition of fine sediment (less than 2mm size fraction) significantly increased the effective viscosity of a slurry. Julien and Lan (1991) found that slurries containing between 15 percent and 40 percent by volume of fine particles can have effective viscosities that are 150 percent to 400 percent greater than the viscosity of clear water. However, both the Major and
Pierson (1992) and the Julien and Lan (1991) studies only included clastic sediment. This study will build on these previous studies and will include vegetative ash in addition to fine-grained clastic sediments.

During the transition from clear-water overland flow to a debris flow, a flow passes through the hyperconcentrated flow regime (Pierson, 2005). Sediment-water mixtures tested in this experiment fall within both the hyperconcentrated and debris flow concentration regimes (Costa, 1984). However, recent literature (Pierson, 2005; Iverson, 2005) illustrates that debris flows and hyperconcentrated flows cannot be differentiated based on sediment concentration alone. Since no coarse particles were included in the tests performed in this project, it cannot be determined if these coarse particles would be in intermittent (hyperconcentrated flow) or constant (debris flow) dynamic suspension. Naturally occurring flows with sediment compositions that include the fine particles tested in these experiments could be classified as either hyperconcentrated or debris flows. Therefore, mixtures tested in this experiment will be called slurries. Despite the two nomenclatures based on the ability of the flow to suspend coarse particles, Iverson (2005) contends that the flows physically behave in generally the same way.

There are a variety of empirical formulas for the effective viscosity of sheared suspensions that are unrestricted in volume fraction up to a maximum packing (concentration). The varying formulas are the results of many experiments by different authors using different types of viscometers and different types of settling medium (Poletto and Joseph, 1995). None of these experiments to date have included ash particles in the sediment samples. It is hypothesized that entrained ash increases the
effective viscosity of the flow according to the following equation (Poletto and Joseph, 1995):

\[
\mu_m = \frac{\mu_f \phi^2}{(1 - \frac{\phi}{A})}
\]  

(1)

where \(\mu_m\) is the viscosity of the fluid-solid mixture, \(\mu_f\) is the fluid viscosity, \(\phi\) is the volumetric fraction of the solids (volume of sediment divided by total mixture volume), and \(A\) is an empirical constant that varies with sediment size, composition and rounding. This equation is appropriate over the range of solid concentrations (Poletto and Joseph, 1995). For this project, the ash and clastic sediment mixtures will be entrained in water so \(\mu_f\) will be 1.0020 cP (distilled water at 20° C).

Equation 1, however, does not take into account shear rate. Because flows can vary in shear rate, it is important to understand how the effective viscosity of the slurry depends on the shear rate. In these experiments the viscometer will measure the effective viscosity of the fluid-sediment mixture of varying concentration at a variety of shear rates to develop a relationship relating ash concentration and shear rate to the effective viscosity of the slurry over a range of concentrations and shear rates realistic to natural conditions where debris flows occur.

It is further hypothesized that this increase in slurry viscosity then decreases the settling velocity of the particles within the flow -- meaning settling of sediment out of the flow is being hindered by the increase in viscosity and, therefore, concentrating the flow. The increase in effective viscosity reduces the settling velocity \(v_s\) of entrained sediment possibly according to the modified version of Stokes Law presented by Poletto and Joseph (1995):
where $\rho_s$ is the density of the particles, $\rho_m$ is the density of the mixture, $\rho_f$ is the density of the fluid, $C_d$ is the drag coefficient that accounts for particle size and $Re$ is the particle Reynold’s Number.

This reduction in settling velocity leads to an increase in the bulk density of the flow since entrained particles cannot settle out. The increase in bulk density leads to a larger shear stress being exerted on the hillslope by the flow -- assuming that this increase in bulk density is not offset by a decrease of flow depth or water surface slope. The increase in basal shear stress leads to greater erosion. The increase in bulk density of the flow leads to higher basal shear stress ($\tau_b$) following the basal shear stress equation below:

$$\tau_b = \rho_m g h S$$  

where $\rho_m$ is the density of the mixture, $g$ is gravitational acceleration, $h$ is flow depth and $S$ is the water surface slope (roughly equal to the slope of the hill). This larger shear stress allows the flow to entrain more sediment, and the process feeds upon itself in a positive-feedback loop.

Understanding the relationship between sediment concentration and effective viscosity of the flow is integral in predicting the erosivity of the flow. Further work by others involved in this project will determine exact relationships for the effect of increased effective viscosity on the settling velocity of the ash and sediment particles as well as more specific relationships on how concentration of ash and sediment particles changes the erosivity of the flow in a flume setting. In addition, further work is being
done to determine how ash on a hillslope behaves during a rainstorm and what role it plays in the generation of a debris flow.

The processes that initiate and propagate debris flows in burned areas need to be better understood to allow hazard assessment and possible remediation of areas that are at risk of accelerated erosion. Most debris flows in burned areas occur within 18 months of the fire, but some debris flows do occur within weeks of the fire (Tom Deluca, personal communications, December 2005). This short time span makes it critical to assess the danger posed on an area by ash-covered hillslopes. New insights on the viscosity of ash-laden debris flows coupled with previous research could be helpful in creating hazard maps based on ash volume estimated from burn severity and slope. Also, it will be known how much water will be required to generate an ash-laden debris flow (based on concentration measurements in lab and known amounts of ash at a burned site). Warning systems could be implemented to warn people when a storm produces the required amount of rain to potentially produce a debris flow. A better understanding of the mechanics of ash-laden debris flows and their initiation will be gained in this study and will be beneficial to the management and remediation of burned areas.
METHODS

Materials Used

Ash Generation:

The ash used in this study was created by burning woody fuels representative of local forests in a burn barrel. Ash was not collected in the field due to the difficulty of removing mineral soil from the sample, as ash and soil can have the same grain size. The burn barrel was engineered from a 114 liter galvanized steel garbage can. Ventilation holes were drilled below a burning grate to allow for greater airflow and more complete combustion. The fuels were procured from slash piles in logging areas near Missoula, Montana and consisted of Ponderosa Pine, Douglas Fir and Lodgepole pine. No grass, duff or needles were included in the fuel samples. Branches ranging from 2-8 cm in diameter were sawed into 15-30 cm length pieces. Prior to combustion, all woody fuels were thoroughly cleaned with distilled water to remove any soil or other contamination and then dried in an oven for 48 hours at 40 degrees Celsius. 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 minutes) and fell through the grate, another layer of fuel was added. This process was repeated until the entire fuel sample was combusted. Once the ash had cooled in the base of the burn barrel, the sample was removed and sifted through a 2 mm sieve to remove the larger pieces of charcoal. The ash was then oven-dried for 24 hours at 40 degrees Celsius and placed in airtight plastic bins. Previous work by Bookter (2006) showed that the median grain size of ash generated in this manner is 0.127 to 0.136 mm and that the particle density of ash generated in this manner is 2.20 g/cm$^3$ (Table 1). Ash created under these
conditions has a carbon content of approximately 45-60% (Vicki Balfour, personal communication, April 2007). In all, a total of 8 ash samples were created using this process. Whenever ash was used in a test, the batch of ash used was also recorded to check for differences in viscosity resulting from slight differences in ash composition.

Table 1. Density of the sediments used in this experiment.

<table>
<thead>
<tr>
<th>Sediment</th>
<th>Density (g/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ash</td>
<td>2.60</td>
</tr>
<tr>
<td>Silt</td>
<td>2.65</td>
</tr>
<tr>
<td>Sand</td>
<td>2.65</td>
</tr>
</tbody>
</table>

Silt and Sand:

The silt and sand used in this study were provided by Omni Engineering, a geotechnical lab in Appleton, Wisconsin. The sediments provided were concrete testing sands with a specified mean grain size. Omni Engineering further refined the samples using a Gilson shaker to ensure that the grain size was within 0.02% of the mean grain size reported. The mean grain sizes of the silt and sand were 0.055 mm and 0.25 mm respectively.

Equipment Used

A Grace Instruments M3500pH rotational viscometer was used throughout this project. A photo of this rotational viscometer can be seen below in Figure 2. Technical specifications and the users’ manual for this viscometer can be found in Appendix A. This viscometer consists of a rotor bob and a rotating sleeve that are suspended in the fluid and between which the fluid is sheared. The rotating sleeve spins at a specified shear rate which induces fluid shear in turn creating a shear stress sensed by the rotor.
bob. The viscometer records this shear rate and shear stress and calculates effective viscosity. Also, the viscometer measures the pH and temperature of the slurry throughout the test. This viscometer can accommodate a sample volume of up to 350 mL. This particular model has the advantage of a continuous shear rate range from 0.0027 to 3524 s\(^{-1}\). This viscometer measures viscosity in units of centipoise (cP). While this is a CGS unit, it is still the most widely used viscosity unit in industry. One cP is equal to one mPa*s.

**Figure 2.** Photograph of the Grace Instruments M3500pH viscometer used in this project.

**Experimental Procedure**

**Carbon Content of Ash:**

In order to ensure that the ash created in each batch was similar in composition, the carbon content of each batch was determined by the Loss on Ignition technique. A small sample of each batch of ash was dried in an oven for 24 hours at 105°C. The samples were weighed at the end of the 24 hours. The sample was then placed in a
muffle furnace at 400°C for 15 hours to combust any remaining carbon. The samples appeared white when removed from the muffle furnace. The samples were then cooled and weighed again. The weight difference was the amount of carbon within the sample. For each sample this difference was then divided by the pre-muffle furnace weight to determine the percent carbon of the ash sample.

*Sediment Combinations and Concentrations Used:*

Sediment slurries tested varied from a homogeneous sample of ash, silt or sand to the four mixtures listed in Tables 2-4. Sediment concentrations used ranged from 0.05 to 0.6 concentration by mass. Typical natural debris flows have a solid fraction concentration by mass of 0.3 to 0.6 (Iverson and Vallance, 2001). This experiment expanded that range to include lower concentrations. The rotating sleeve of the viscometer could not rotate through slurries with concentrations above 0.6, so that became the upper limit for concentration in this lab experiment.

*Shear Rates Used:*

O’Brien and Julien (1988) stated that rates of shear in open-channel debris flows rarely exceed 20 s⁻¹ and perhaps are more commonly less than 10 s⁻¹. Iverson and Vallance (2001) estimated shear rates between 3 and 50 s⁻¹ for a range of natural and laboratory debris flows. Both of these studies dealt with only non-ash sediments. For this experiment shear rates ranging from 1 - 40 s⁻¹ were used in an attempt to be able to compare to previous research, as well as expand the range of previously tested shear rates.
Viscometer Tests:

Distilled water at a temperature of 20°± 1°C was added to a sample of sediment to reach a desired concentration by mass as seen in Table 2-4 below. The slurry sample needed to have a volume of 320-350 mL in order for the viscometer to register an accurate measurement. The slurry of sediment and water was then poured into the viscometer’s sample cup where it ran for five minutes at a specified shear rate as seen in Table 5 below.
Table 2. The amounts of ash, silt and sand used to create the homogenous slurries used in the viscosity experiments.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(g/g)</td>
<td>(g)</td>
<td>(g)</td>
<td>(g)</td>
<td>(cm^3)</td>
<td>(g)</td>
<td>(cm^3)</td>
<td>(mL)</td>
</tr>
<tr>
<td>100% ash</td>
<td>0.05</td>
<td>16.25</td>
<td></td>
<td></td>
<td>6.25</td>
<td>325.00</td>
<td>325.00</td>
<td>331.25</td>
</tr>
<tr>
<td></td>
<td>0.10</td>
<td>32.50</td>
<td></td>
<td></td>
<td>12.50</td>
<td>325.00</td>
<td>325.00</td>
<td>337.50</td>
</tr>
<tr>
<td></td>
<td>0.15</td>
<td>48.75</td>
<td></td>
<td></td>
<td>18.75</td>
<td>325.00</td>
<td>325.00</td>
<td>343.75</td>
</tr>
<tr>
<td></td>
<td>0.20</td>
<td>65.00</td>
<td></td>
<td></td>
<td>25.00</td>
<td>325.00</td>
<td>325.00</td>
<td>350.00</td>
</tr>
<tr>
<td></td>
<td>0.25</td>
<td>75.00</td>
<td></td>
<td></td>
<td>28.85</td>
<td>300.00</td>
<td>300.00</td>
<td>328.85</td>
</tr>
<tr>
<td></td>
<td>0.30</td>
<td>90.00</td>
<td></td>
<td></td>
<td>34.62</td>
<td>300.00</td>
<td>300.00</td>
<td>334.62</td>
</tr>
<tr>
<td></td>
<td>0.35</td>
<td>105.00</td>
<td></td>
<td></td>
<td>40.38</td>
<td>300.00</td>
<td>300.00</td>
<td>340.38</td>
</tr>
<tr>
<td></td>
<td>0.40</td>
<td>120.00</td>
<td></td>
<td></td>
<td>46.15</td>
<td>300.00</td>
<td>300.00</td>
<td>346.15</td>
</tr>
<tr>
<td></td>
<td>0.45</td>
<td>123.75</td>
<td></td>
<td></td>
<td>47.60</td>
<td>275.00</td>
<td>275.00</td>
<td>322.60</td>
</tr>
<tr>
<td></td>
<td>0.50</td>
<td>137.50</td>
<td></td>
<td></td>
<td>52.88</td>
<td>275.00</td>
<td>275.00</td>
<td>327.88</td>
</tr>
<tr>
<td></td>
<td>0.55</td>
<td>151.25</td>
<td></td>
<td></td>
<td>58.17</td>
<td>275.00</td>
<td>275.00</td>
<td>333.17</td>
</tr>
<tr>
<td></td>
<td>0.60</td>
<td>165.00</td>
<td></td>
<td></td>
<td>63.46</td>
<td>275.00</td>
<td>275.00</td>
<td>338.46</td>
</tr>
<tr>
<td>100% silt</td>
<td>0.05</td>
<td>16.25</td>
<td></td>
<td></td>
<td>6.13</td>
<td>325.00</td>
<td>325.00</td>
<td>331.13</td>
</tr>
<tr>
<td></td>
<td>0.10</td>
<td>32.50</td>
<td></td>
<td></td>
<td>12.26</td>
<td>325.00</td>
<td>325.00</td>
<td>337.26</td>
</tr>
<tr>
<td></td>
<td>0.15</td>
<td>48.75</td>
<td></td>
<td></td>
<td>18.40</td>
<td>325.00</td>
<td>325.00</td>
<td>343.40</td>
</tr>
<tr>
<td></td>
<td>0.20</td>
<td>65.00</td>
<td></td>
<td></td>
<td>24.53</td>
<td>325.00</td>
<td>325.00</td>
<td>349.53</td>
</tr>
<tr>
<td></td>
<td>0.25</td>
<td>75.00</td>
<td></td>
<td></td>
<td>28.30</td>
<td>300.00</td>
<td>300.00</td>
<td>328.30</td>
</tr>
<tr>
<td></td>
<td>0.30</td>
<td>90.00</td>
<td></td>
<td></td>
<td>33.96</td>
<td>300.00</td>
<td>300.00</td>
<td>333.96</td>
</tr>
<tr>
<td></td>
<td>0.35</td>
<td>105.00</td>
<td></td>
<td></td>
<td>39.62</td>
<td>300.00</td>
<td>300.00</td>
<td>339.62</td>
</tr>
<tr>
<td></td>
<td>0.40</td>
<td>120.00</td>
<td></td>
<td></td>
<td>45.28</td>
<td>300.00</td>
<td>300.00</td>
<td>345.28</td>
</tr>
<tr>
<td></td>
<td>0.45</td>
<td>123.75</td>
<td></td>
<td></td>
<td>46.70</td>
<td>275.00</td>
<td>275.00</td>
<td>321.70</td>
</tr>
<tr>
<td></td>
<td>0.50</td>
<td>137.50</td>
<td></td>
<td></td>
<td>51.89</td>
<td>275.00</td>
<td>275.00</td>
<td>326.89</td>
</tr>
<tr>
<td></td>
<td>0.55</td>
<td>151.25</td>
<td></td>
<td></td>
<td>57.08</td>
<td>275.00</td>
<td>275.00</td>
<td>332.08</td>
</tr>
<tr>
<td></td>
<td>0.60</td>
<td>165.00</td>
<td></td>
<td></td>
<td>62.26</td>
<td>275.00</td>
<td>275.00</td>
<td>337.26</td>
</tr>
<tr>
<td>100% sand</td>
<td>0.05</td>
<td>16.25</td>
<td></td>
<td></td>
<td>6.13</td>
<td>325.00</td>
<td>325.00</td>
<td>331.13</td>
</tr>
<tr>
<td></td>
<td>0.10</td>
<td>32.50</td>
<td></td>
<td></td>
<td>12.26</td>
<td>325.00</td>
<td>325.00</td>
<td>337.26</td>
</tr>
<tr>
<td></td>
<td>0.15</td>
<td>48.75</td>
<td></td>
<td></td>
<td>18.40</td>
<td>325.00</td>
<td>325.00</td>
<td>343.40</td>
</tr>
<tr>
<td></td>
<td>0.20</td>
<td>65.00</td>
<td></td>
<td></td>
<td>24.53</td>
<td>325.00</td>
<td>325.00</td>
<td>349.53</td>
</tr>
<tr>
<td></td>
<td>0.25</td>
<td>75.00</td>
<td></td>
<td></td>
<td>28.30</td>
<td>300.00</td>
<td>300.00</td>
<td>328.30</td>
</tr>
<tr>
<td></td>
<td>0.30</td>
<td>90.00</td>
<td></td>
<td></td>
<td>33.96</td>
<td>300.00</td>
<td>300.00</td>
<td>333.96</td>
</tr>
<tr>
<td></td>
<td>0.35</td>
<td>105.00</td>
<td></td>
<td></td>
<td>39.62</td>
<td>300.00</td>
<td>300.00</td>
<td>339.62</td>
</tr>
<tr>
<td></td>
<td>0.40</td>
<td>120.00</td>
<td></td>
<td></td>
<td>45.28</td>
<td>300.00</td>
<td>300.00</td>
<td>345.28</td>
</tr>
<tr>
<td></td>
<td>0.45</td>
<td>123.75</td>
<td></td>
<td></td>
<td>46.70</td>
<td>275.00</td>
<td>275.00</td>
<td>321.70</td>
</tr>
<tr>
<td></td>
<td>0.50</td>
<td>137.50</td>
<td></td>
<td></td>
<td>51.89</td>
<td>275.00</td>
<td>275.00</td>
<td>326.89</td>
</tr>
<tr>
<td></td>
<td>0.55</td>
<td>151.25</td>
<td></td>
<td></td>
<td>57.08</td>
<td>275.00</td>
<td>275.00</td>
<td>332.08</td>
</tr>
<tr>
<td></td>
<td>0.60</td>
<td>165.00</td>
<td></td>
<td></td>
<td>62.26</td>
<td>275.00</td>
<td>275.00</td>
<td>337.26</td>
</tr>
</tbody>
</table>
Table 3. The amounts of ash, silt and sand used to create the two sediment mixture slurries used in the viscosity experiments.

<table>
<thead>
<tr>
<th>Test Name</th>
<th>Conc. By Mass (g/g)</th>
<th>Mass of Ash (g)</th>
<th>Mass of Silt (g)</th>
<th>Volume of Sediment (cm³)</th>
<th>Mass of Water (g)</th>
<th>Volume of Water (cm³)</th>
<th>Volume of Slurry (mL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50% ash + 50% silt</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.05</td>
<td>8.18</td>
<td>8.18</td>
<td>6.23</td>
<td>325.00</td>
<td>325.00</td>
<td>331.23</td>
<td></td>
</tr>
<tr>
<td>0.10</td>
<td>16.25</td>
<td>16.25</td>
<td>12.38</td>
<td>325.00</td>
<td>325.00</td>
<td>337.38</td>
<td></td>
</tr>
<tr>
<td>0.15</td>
<td>24.38</td>
<td>24.38</td>
<td>18.58</td>
<td>325.00</td>
<td>325.00</td>
<td>343.58</td>
<td></td>
</tr>
<tr>
<td>0.20</td>
<td>32.50</td>
<td>32.50</td>
<td>24.76</td>
<td>325.00</td>
<td>325.00</td>
<td>349.76</td>
<td></td>
</tr>
<tr>
<td>0.25</td>
<td>37.50</td>
<td>37.50</td>
<td>28.57</td>
<td>300.00</td>
<td>300.00</td>
<td>328.57</td>
<td></td>
</tr>
<tr>
<td>0.30</td>
<td>45.00</td>
<td>45.00</td>
<td>34.29</td>
<td>300.00</td>
<td>300.00</td>
<td>334.29</td>
<td></td>
</tr>
<tr>
<td>0.35</td>
<td>52.50</td>
<td>52.50</td>
<td>40.00</td>
<td>300.00</td>
<td>300.00</td>
<td>340.00</td>
<td></td>
</tr>
<tr>
<td>0.40</td>
<td>60.00</td>
<td>60.00</td>
<td>45.72</td>
<td>300.00</td>
<td>300.00</td>
<td>345.72</td>
<td></td>
</tr>
<tr>
<td>0.45</td>
<td>61.86</td>
<td>61.86</td>
<td>47.14</td>
<td>275.00</td>
<td>275.00</td>
<td>322.14</td>
<td></td>
</tr>
<tr>
<td>0.50</td>
<td>68.75</td>
<td>68.75</td>
<td>52.39</td>
<td>275.00</td>
<td>275.00</td>
<td>327.39</td>
<td></td>
</tr>
<tr>
<td>0.55</td>
<td>75.63</td>
<td>75.63</td>
<td>57.63</td>
<td>275.00</td>
<td>275.00</td>
<td>332.63</td>
<td></td>
</tr>
<tr>
<td>0.60</td>
<td>82.50</td>
<td>82.50</td>
<td>62.86</td>
<td>275.00</td>
<td>275.00</td>
<td>337.86</td>
<td></td>
</tr>
<tr>
<td>50% ash + 50% sand</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.05</td>
<td>8.18</td>
<td>8.18</td>
<td>6.23</td>
<td>325.00</td>
<td>325.00</td>
<td>331.23</td>
<td></td>
</tr>
<tr>
<td>0.10</td>
<td>16.25</td>
<td>16.25</td>
<td>12.38</td>
<td>325.00</td>
<td>325.00</td>
<td>337.38</td>
<td></td>
</tr>
<tr>
<td>0.15</td>
<td>24.38</td>
<td>24.38</td>
<td>18.58</td>
<td>325.00</td>
<td>325.00</td>
<td>343.58</td>
<td></td>
</tr>
<tr>
<td>0.20</td>
<td>32.50</td>
<td>32.50</td>
<td>24.76</td>
<td>325.00</td>
<td>325.00</td>
<td>349.76</td>
<td></td>
</tr>
<tr>
<td>0.25</td>
<td>37.50</td>
<td>37.50</td>
<td>28.57</td>
<td>300.00</td>
<td>300.00</td>
<td>328.57</td>
<td></td>
</tr>
<tr>
<td>0.30</td>
<td>45.00</td>
<td>45.00</td>
<td>34.29</td>
<td>300.00</td>
<td>300.00</td>
<td>334.29</td>
<td></td>
</tr>
<tr>
<td>0.35</td>
<td>52.50</td>
<td>52.50</td>
<td>40.00</td>
<td>300.00</td>
<td>300.00</td>
<td>340.00</td>
<td></td>
</tr>
<tr>
<td>0.40</td>
<td>60.00</td>
<td>60.00</td>
<td>45.72</td>
<td>300.00</td>
<td>300.00</td>
<td>345.72</td>
<td></td>
</tr>
<tr>
<td>0.45</td>
<td>61.86</td>
<td>61.86</td>
<td>47.14</td>
<td>275.00</td>
<td>275.00</td>
<td>322.14</td>
<td></td>
</tr>
<tr>
<td>0.50</td>
<td>68.75</td>
<td>68.75</td>
<td>52.39</td>
<td>275.00</td>
<td>275.00</td>
<td>327.39</td>
<td></td>
</tr>
<tr>
<td>0.55</td>
<td>75.63</td>
<td>75.63</td>
<td>57.63</td>
<td>275.00</td>
<td>275.00</td>
<td>332.63</td>
<td></td>
</tr>
<tr>
<td>0.60</td>
<td>82.50</td>
<td>82.50</td>
<td>62.86</td>
<td>275.00</td>
<td>275.00</td>
<td>337.86</td>
<td></td>
</tr>
<tr>
<td>50% silt + 50% sand</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.05</td>
<td>8.18</td>
<td>8.18</td>
<td>6.17</td>
<td>325.00</td>
<td>325.00</td>
<td>331.17</td>
<td></td>
</tr>
<tr>
<td>0.10</td>
<td>16.25</td>
<td>16.25</td>
<td>12.26</td>
<td>325.00</td>
<td>325.00</td>
<td>337.26</td>
<td></td>
</tr>
<tr>
<td>0.15</td>
<td>24.38</td>
<td>24.38</td>
<td>18.40</td>
<td>325.00</td>
<td>325.00</td>
<td>343.40</td>
<td></td>
</tr>
<tr>
<td>0.20</td>
<td>32.50</td>
<td>32.50</td>
<td>24.53</td>
<td>325.00</td>
<td>325.00</td>
<td>349.53</td>
<td></td>
</tr>
<tr>
<td>0.25</td>
<td>37.50</td>
<td>37.50</td>
<td>28.30</td>
<td>300.00</td>
<td>300.00</td>
<td>328.30</td>
<td></td>
</tr>
<tr>
<td>0.30</td>
<td>45.00</td>
<td>45.00</td>
<td>33.96</td>
<td>300.00</td>
<td>300.00</td>
<td>333.96</td>
<td></td>
</tr>
<tr>
<td>0.35</td>
<td>52.50</td>
<td>52.50</td>
<td>39.62</td>
<td>300.00</td>
<td>300.00</td>
<td>339.62</td>
<td></td>
</tr>
<tr>
<td>0.40</td>
<td>60.00</td>
<td>60.00</td>
<td>45.28</td>
<td>300.00</td>
<td>300.00</td>
<td>345.28</td>
<td></td>
</tr>
<tr>
<td>0.45</td>
<td>61.86</td>
<td>61.86</td>
<td>46.69</td>
<td>275.00</td>
<td>275.00</td>
<td>321.69</td>
<td></td>
</tr>
<tr>
<td>0.50</td>
<td>68.75</td>
<td>68.75</td>
<td>51.89</td>
<td>275.00</td>
<td>275.00</td>
<td>326.89</td>
<td></td>
</tr>
<tr>
<td>0.55</td>
<td>75.63</td>
<td>75.63</td>
<td>57.08</td>
<td>275.00</td>
<td>275.00</td>
<td>332.08</td>
<td></td>
</tr>
<tr>
<td>0.60</td>
<td>82.50</td>
<td>82.50</td>
<td>62.26</td>
<td>275.00</td>
<td>275.00</td>
<td>337.26</td>
<td></td>
</tr>
</tbody>
</table>
Table 4. The amounts of ash, silt and sand used to create the three sediment mixture slurries used in the viscosity experiments.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(g/g)</td>
<td>(g)</td>
<td>(g)</td>
<td>(g)</td>
<td>(cm³)</td>
<td>(g)</td>
<td>(cm³)</td>
<td>(mL)</td>
</tr>
<tr>
<td>33% ash +</td>
<td>0.05</td>
<td>5.42</td>
<td>5.42</td>
<td>5.42</td>
<td>6.17</td>
<td>325.00</td>
<td>325.00</td>
<td>331.17</td>
</tr>
<tr>
<td>33% silt +</td>
<td>0.10</td>
<td>10.83</td>
<td>10.83</td>
<td>10.83</td>
<td>12.34</td>
<td>325.00</td>
<td>325.00</td>
<td>337.34</td>
</tr>
<tr>
<td>33% sand</td>
<td>0.15</td>
<td>16.25</td>
<td>16.25</td>
<td>16.25</td>
<td>18.51</td>
<td>325.00</td>
<td>325.00</td>
<td>343.51</td>
</tr>
<tr>
<td></td>
<td>0.20</td>
<td>21.67</td>
<td>21.67</td>
<td>21.67</td>
<td>24.69</td>
<td>300.00</td>
<td>300.00</td>
<td>324.69</td>
</tr>
<tr>
<td></td>
<td>0.25</td>
<td>25.00</td>
<td>25.00</td>
<td>25.00</td>
<td>28.48</td>
<td>300.00</td>
<td>300.00</td>
<td>328.48</td>
</tr>
<tr>
<td></td>
<td>0.30</td>
<td>30.00</td>
<td>30.00</td>
<td>30.00</td>
<td>34.18</td>
<td>300.00</td>
<td>300.00</td>
<td>334.18</td>
</tr>
<tr>
<td></td>
<td>0.35</td>
<td>35.00</td>
<td>35.00</td>
<td>35.00</td>
<td>39.88</td>
<td>300.00</td>
<td>300.00</td>
<td>339.88</td>
</tr>
<tr>
<td></td>
<td>0.40</td>
<td>40.00</td>
<td>40.00</td>
<td>40.00</td>
<td>45.57</td>
<td>275.00</td>
<td>275.00</td>
<td>320.57</td>
</tr>
<tr>
<td></td>
<td>0.45</td>
<td>41.25</td>
<td>41.25</td>
<td>41.25</td>
<td>47.00</td>
<td>275.00</td>
<td>275.00</td>
<td>322.00</td>
</tr>
<tr>
<td></td>
<td>0.50</td>
<td>45.83</td>
<td>45.83</td>
<td>45.83</td>
<td>52.22</td>
<td>275.00</td>
<td>275.00</td>
<td>327.22</td>
</tr>
<tr>
<td></td>
<td>0.55</td>
<td>50.42</td>
<td>50.42</td>
<td>50.42</td>
<td>57.44</td>
<td>275.00</td>
<td>275.00</td>
<td>332.44</td>
</tr>
<tr>
<td></td>
<td>0.60</td>
<td>55.00</td>
<td>55.00</td>
<td>55.00</td>
<td>62.66</td>
<td>275.00</td>
<td>275.00</td>
<td>337.66</td>
</tr>
</tbody>
</table>

Table 5. Shear rates used in each suite of viscosity experiments. Sediment was remixed between each individual test. The sample interval was 5 seconds.

<table>
<thead>
<tr>
<th>Test #1</th>
<th>Shear Rate (1/s)</th>
<th>Test Time (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>300</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>300</td>
</tr>
<tr>
<td>3</td>
<td>5</td>
<td>300</td>
</tr>
<tr>
<td>4</td>
<td>7</td>
<td>300</td>
</tr>
<tr>
<td>5</td>
<td>9</td>
<td>300</td>
</tr>
<tr>
<td>6</td>
<td>12</td>
<td>300</td>
</tr>
<tr>
<td>7</td>
<td>15</td>
<td>300</td>
</tr>
<tr>
<td>8</td>
<td>18</td>
<td>300</td>
</tr>
<tr>
<td>9</td>
<td>20</td>
<td>300</td>
</tr>
<tr>
<td>10</td>
<td>25</td>
<td>300</td>
</tr>
<tr>
<td>11</td>
<td>30</td>
<td>300</td>
</tr>
<tr>
<td>12</td>
<td>35</td>
<td>300</td>
</tr>
<tr>
<td>13</td>
<td>40</td>
<td>300</td>
</tr>
</tbody>
</table>
GraceDaq software, supplied with the viscometer, continually collected shear rate, viscosity, temperature, and pH data at a rate of one measurement every five seconds. The data from each individual test was exported from GraceDaq into a Microsoft Excel spreadsheet.

Major and Pierson (1992) found no significant difference in viscosity between the tests where the sediment was remixed before the test and those tests where the sediment was allowed to settle over multiple tests. However, Major and Pierson’s (1992) experiments included only clastic sediment. Being unsure of the settling behavior of ash in this experiment, at the end of each five minute test, the sample was removed from the viscometer, stirred briskly to remix the sediment, then replaced in the viscometer and the experiment was repeated at the next shear rate. This process was repeated for each of the thirteen shear rates. At the end of the suite of thirteen tests, the sample was discarded.

To increase the size of the data set and test for repeatability, each suite of tests was repeated three times, each time using a fresh sediment slurry. In most cases the ash used in each suite came from different batches of ash in order to ensure that a specific batch of ash was not greatly different than the others. This procedure was used for all of the sediment combinations listed in Tables 2-4. Occasionally the viscometer would register an anomalously high viscosity for one or two readings during the test. These peaks were most likely due to a clump of sediment becoming lodged between the sleeve and the rotor bob of the viscometer. If this were to happen in the first 120 seconds or the last 30 seconds, the data from that test was still able to be processed. However if a sharp peak occurred in the middle of a test, the entire test was discarded and repeated.
Ash is extremely alkaline compared to the clastic sediments used in these experiments. Therefore, to test if the increased pH caused by the addition of ash was affecting the effective viscosity of a slurry, three individual tests were run where the pH of the slurry was buffered using a pH 4 buffer. Since slurries containing only ash at high concentrations had the highest pH, a 0.60 concentration ash-only slurry was chosen for these tests. Effective viscosity and pH data were collected over a period of five minutes at three shear rates (5, 18 and 40s\(^{-1}\)). Data from the first 120 seconds were not analyzed due to the variation in effective viscosity caused by the viscometer ramping up to the proper shear rate (further discussed in Data Processing). Between 120 and 180 seconds, effective viscosity and pH of the slurry were collected, prior to the addition of the pH buffer. At 180 seconds, the buffer (pH 4) began to be slowly added until the pH of the slurry became nearly 7 towards the end of the test. The viscometer recorded the effective viscosity and pH of the slurry every five seconds. These data were later analyzed to determine if the pH of a slurry could affect the effective viscosity.

**Data Processing**

The main goal of this experiment was to determine the mean effective viscosity of each of the slurries at each shear rate. The first step in this calculation was determining which of the test’s sixty data points were usable. The first 80 to 120 seconds of measurements were not included in this average due to the recording of false extremely high viscosities as the viscometer ramped up to its full shear rate. Similarly, Major and Pierson (1992) did not include the first 150 seconds of data collected in their experiment. Also, as previously mentioned, if a clump of sediment became lodged in the viscometer and caused an anomalously high viscosity near the end of the test, those false high
viscosities needed to be removed from the average calculation. A Matlab program was written to average the effective viscosity of the slurry over a user-specified range of time. This program, called `averager.m` (Appendix B), allows the user to determine the starting and ending time over which the data are averaged. The program displays the test data as a graph and allows the user to choose a starting and ending time by clicking on the graph at the desired start or end point. The program then averages the data over the time interval chosen and reports the mean and standard deviation. The start and end times chosen, mean effective viscosity and standard deviation were recorded in a spreadsheet for later analysis. An example graph of this process is shown in Figure 3. This data processing resulted in a mean effective viscosity for a slurry of a certain concentration at a specified shear rate.

![Figure 3. Example of data used for calculating mean effective viscosity. Effective viscosity data points were excluded from the beginning of the test when the viscometer was ramping up to the designated shear rate and also from any anomalous points near the end of the experiment that were caused by clumps of sediment lodging in the viscometer.](image-url)
In order to increase the size of the data set and test repeatability, data from the three tests of a suite were combined into a larger data set to calculate the mean effective viscosity of the entire suite of tests run on a slurry. Another Matlab program was written to accomplish this task. This program, called `combiner.m` (Appendix B), is similar to `averager.m` in that it allows the user to select the start and end time for the desired data window. However, instead of averaging the data, `combiner.m` outputs the effective viscosity of data points in the desired data range into a new spreadsheet. The same start and end times for the data window were used for both `averager.m` and `combiner.m`. This is done for all three tests within the suite. The mean effective viscosity and standard deviation for the entire suite is then calculated in Excel. The mean effective viscosity for the suite can then be compared to the effective viscosity of the individual test to determine if any of the individual tests were significantly different for each other. This analysis resulted in a mean effective viscosity for a suite of tests of a specific mixture and concentration at one shear rate.
RESULTS

Carbon Content of Ash

The carbon content of the eight ash samples ranged from 47% to 66% with a mean carbon content of 49.4 ± 6.1% (Table 6).

Table 6. Carbon content of the eight ash samples created in the burn barrel.

<table>
<thead>
<tr>
<th>Ash Sample</th>
<th>Carbon Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan 2006</td>
<td>49%</td>
</tr>
<tr>
<td>Feb 2006</td>
<td>66%</td>
</tr>
<tr>
<td>Feb 2006</td>
<td>47%</td>
</tr>
<tr>
<td>April 2006</td>
<td>52%</td>
</tr>
<tr>
<td>May 2006</td>
<td>56%</td>
</tr>
<tr>
<td>July 2006</td>
<td>53%</td>
</tr>
<tr>
<td>Sept 2006</td>
<td>50%</td>
</tr>
<tr>
<td>Sept 2006</td>
<td>52%</td>
</tr>
</tbody>
</table>

Temperature and pH of Samples Tested

The temperature of the sample did not change during any of the tests. Therefore, the sample always remained at the temperature of the distilled water that was used to make the slurry. The mean temperature of the slurries was 20°±0.8°C. Temperature was continuously recorded throughout the tests, these data can be seen in the raw data for each test in Appendix C. Because the temperature was constant, no additional analysis was performed on the temperature data.

Similarly, the pH of the sample did not change throughout any test. Any change in pH of the slurry occurred immediately after the addition of sediment to the distilled water. Slurries containing ash had a higher pH than those containing only clastic sediments. The pH of the slurries containing only clastic sediments remained approximately 7, regardless of sediment concentration. The pH of the ash slurries depended on ash concentration, ranging from 7.9 at ash concentrations of 0.05 to 11.1 at
ash concentrations of 0.60. Slurries containing a mixture of ash and clastic sediments did show a slight increase in pH although not to the extent of the ash-only slurries. These data containing the pH can be seen in Appendix C in each of the raw test data sheets.

To determine if the effective viscosity of a slurry could be affected by the alkaline nature of the ash, the data from the test where the pH buffer was introduced were analyzed. Figure 4 shows the effective viscosity and pH of a 0.60 concentration ash slurry being sheared at three different rates, before and after the buffer was added. At all three shear rates, the effective viscosity does not change when the buffer is added and after the slurry returns to a neutral pH. The 0.60 concentration ash-only slurries tested had the greatest pH compared to all other slurries tested. Therefore, it can be assumed that if pH has no affect on this slurry, the effective viscosity of the other slurries used in this project should not changed based on pH either.
Figure 4. The effective viscosity and pH of a 0.60 concentration ash slurry over time with the addition of a pH buffer at 180 seconds tested at a shear rate of (a) 5s⁻¹, (b) 18s⁻¹ and (c) 40s⁻¹.
**Homogenous Slurries of Ash, Silt of Sand**

The first tests conducted consisted of homogenous slurries of ash, silt or sand ranging in concentration from 0.05 to 0.6 grams of sediment per grams of water tested at shear rates ranging from 1 to 40s$^{-1}$. Three trials of each test were conducted as previously mentioned, however the data presented is the combination of the three trials into one data set for each test. There was no significant difference between any single trial and the combined data. The data for the three separate trials, as well as the combination of the three, can be seen in the appropriate spreadsheet in Appendix D. The raw lab data as exported from GraceDaq can be seen in Appendix C which is sorted by trial number. It should also be noted that, for clarity, error bars are not presented on most of the graphs in this section, standard deviations of the average effective viscosities can be seen in the data in Appendix D. All standard deviations were within 10% of the average value reported.

*Ash Slurries*

The average effective viscosity of ash slurries varied from 2.8cP to 294.4cP over the range of concentrations and shear rates tested. Numerical data for these tests can be seen in Appendix D in a spreadsheet named “Ash_only.xls”. Figure 5, below, is a graphical representation of how the average effective viscosity of an ash slurry changes with increasing concentration by mass when tested at multiple shear rates. It is evident that there is not a simple relationship between concentration by mass of the slurry and average effective viscosity that would hold true over the entire range of shear rates. Also, it can be seen that the slurries as a whole have a lower average effective viscosity as the shear rate increases. This phenomenon is more evident in Figure 6, which clearly shows
that these ash slurries exhibit shear thinning behavior. Figure 6 is a graphical representation of how the average effective viscosity changes according to the shear rate over the range of concentrations tested. Ash slurries, even at low concentrations, are extremely viscous at low shear rates relative to higher shear rates.

**Figure 5.** The average effective viscosity of an ash slurry with increasing concentration by mass of ash at the shear rates tested in the experiment.
Figure 6. The average effective viscosity of an ash slurry with increasing shear rates at all of the concentrations by mass tested in the experiment.

Because the goal of this project was to determine an empirical relationship between shear rate, sediment and ash concentrations and average effective viscosity, trendlines were calculated for each of the concentration trends seen in Figure 6. A power law equation was chosen to fit these data. The power law function provides a reasonable $R^2$ value for the majority of the concentrations, however in some cases, an exponential equation provided a better $R^2$ value as shown below in Figure 7. Despite the exponential equation sometimes having a better fit to the data, a power law equation was chosen over an exponential equation. A power law equation yields an infinite average effective viscosity at very small shear rates, whereas, an exponential equation yields a maximum average effective viscosity at a shear rate of zero as seen below in Figure 7. Because effective viscosity depends on shear rate, if a slurry were not being sheared at all, it would have an infinitely high effective viscosity. Therefore, a power law equation is more appropriate.
A comparison of (a) a power and (b) an exponential trendlines for two example sets of ash slurry data. The green trendline and equation correspond to the power fit, and the red trendline and equation correspond to the exponential fit.

A power law equation trendline was fitted to the data for all concentrations to determine if one equation could be used to calculate the effective viscosity based on the shear rate. As shown in Figure 8 below, a power law equation was fit to the data, however, the $R^2$ value is only 0.632 and the trendline does not fit all of the data well. Therefore, the effective viscosity of an ash slurry does not solely depend on shear rate and that parameterization of the ash equation is not complete.
Trendlines were then fitted to each of the concentration data sets presented in Figure 6 to determine how both sediment concentration and shear rate affected the effective viscosity of the slurry. The general form of the equation relating shear rate and effective viscosity for each concentration is as follows:

$$
\mu_m = D\gamma^b
$$

where $\mu_m$ is the effective viscosity of the slurry in cP, $D$ is an empirical constant that depends on concentration in cP*s, $\gamma$ is the shear rate in s$^{-1}$, and $b$ is another empirical constant that is unitless. For each concentration’s trendline, $D$ and $b$ values were recorded and can be seen below in Table 7 and Figures 9 and 10.
Table 7. $D$, $b$ and $R^2$ values for each concentration of ash slurry tested.

<table>
<thead>
<tr>
<th>Concentration</th>
<th>$D$</th>
<th>$b$</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.60</td>
<td>411.77</td>
<td>-0.9665</td>
<td>0.832</td>
</tr>
<tr>
<td>0.55</td>
<td>346.8</td>
<td>-0.9087</td>
<td>0.818</td>
</tr>
<tr>
<td>0.50</td>
<td>271.7</td>
<td>-0.7609</td>
<td>0.9332</td>
</tr>
<tr>
<td>0.45</td>
<td>199.33</td>
<td>-0.6546</td>
<td>0.9725</td>
</tr>
<tr>
<td>0.40</td>
<td>207.8</td>
<td>-0.6034</td>
<td>0.8557</td>
</tr>
<tr>
<td>0.35</td>
<td>155.93</td>
<td>-0.5876</td>
<td>0.9022</td>
</tr>
<tr>
<td>0.30</td>
<td>144.77</td>
<td>-0.5764</td>
<td>0.8865</td>
</tr>
<tr>
<td>0.25</td>
<td>117.02</td>
<td>-0.5256</td>
<td>0.905</td>
</tr>
<tr>
<td>0.20</td>
<td>89.24</td>
<td>-0.4607</td>
<td>0.912</td>
</tr>
<tr>
<td>0.15</td>
<td>74.835</td>
<td>-0.5003</td>
<td>0.9528</td>
</tr>
<tr>
<td>0.10</td>
<td>61.137</td>
<td>-0.542</td>
<td>0.8727</td>
</tr>
<tr>
<td>0.05</td>
<td>35.58</td>
<td>-0.6278</td>
<td>0.7711</td>
</tr>
</tbody>
</table>

Figure 9. $D$ values for varying concentrations of ash. The equation given on the chart can be used to determine the $D$ value at any concentration.
Given an estimate of the shear rate, the effective viscosity of an ash-only slurry can be calculated as follows:

$$\mu_m = (547.9\psi + 5.3)\gamma^b$$  \hfill (5)

where $\mu_m$ is the effective viscosity of the slurry (cP), $\psi$ is the concentration by mass of ash in the slurry (unitless), $\gamma$ is the shear rate (s$^{-1}$), and $b$ is empirical constant (unitless) that changes with concentration of ash and can be found in Figure 10.

**Silt Slurries**

The average effective viscosity of silt slurries varied between 7.8cP and 197.6cP over the range of concentrations and shear rates tested. Numerical data for these tests can be seen in Appendix D in a spreadsheet named “Silt_only.xls”. Figure 11, below, is a graphical representation of how the average effective viscosity of a silt slurry changes...
with increasing concentration by mass when tested at multiple shear rates. Again, as with ash, there is not a simple relationship between concentration by mass of the slurry and average effective viscosity that would hold true over the entire range of shear rates. Like ash, silt appears to shear thin as seen in Figure 12. Figure 12 is a graphical representation of how the average effective viscosity of a silt slurry changes according to the shear rate over the range of concentrations tested.

Figure 11. The average effective viscosity of a silt slurry with increasing concentration by mass of silt at the shear rates tested in the experiment.
Figure 12. The average effective viscosity of a silt slurry with increasing shear rates at all of the concentrations by mass tested in the experiment.

Again, power law equation trendlines were fitted to each of the concentration data series in Figure 12. The $D$, $b$ and $R^2$ values were again recorded and are shown in Table 8 and Figures 13 and 14. The general equation remains identical to Equation 4.

Table 8. $D$, $b$ and $R^2$ values for each concentration of silt slurry tested.

<table>
<thead>
<tr>
<th>Concentration</th>
<th>$D$</th>
<th>$b$</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.60</td>
<td>227.08</td>
<td>-0.451</td>
<td>0.8845</td>
</tr>
<tr>
<td>0.55</td>
<td>227.17</td>
<td>-0.4843</td>
<td>0.8739</td>
</tr>
<tr>
<td>0.50</td>
<td>206.11</td>
<td>-0.4997</td>
<td>0.8542</td>
</tr>
<tr>
<td>0.45</td>
<td>168.62</td>
<td>-0.4097</td>
<td>0.7959</td>
</tr>
<tr>
<td>0.40</td>
<td>146.01</td>
<td>-0.4225</td>
<td>0.7708</td>
</tr>
<tr>
<td>0.35</td>
<td>140.32</td>
<td>-0.4552</td>
<td>0.7624</td>
</tr>
<tr>
<td>0.30</td>
<td>119.67</td>
<td>-0.4472</td>
<td>0.808</td>
</tr>
<tr>
<td>0.25</td>
<td>95.546</td>
<td>-0.4314</td>
<td>0.854</td>
</tr>
<tr>
<td>0.20</td>
<td>96.925</td>
<td>-0.5381</td>
<td>0.8972</td>
</tr>
<tr>
<td>0.15</td>
<td>83.217</td>
<td>-0.5682</td>
<td>0.8851</td>
</tr>
<tr>
<td>0.10</td>
<td>47.64</td>
<td>-0.4673</td>
<td>0.9233</td>
</tr>
<tr>
<td>0.05</td>
<td>26.31</td>
<td>-0.389</td>
<td>0.7727</td>
</tr>
</tbody>
</table>
Figure 13. $D$ values for varying concentrations of silt. The equation given on the chart can be used to determine the $D$ value at any concentration.

Figure 14. $b$ values for varying concentrations of silt. Error bars represent two standard deviations.
Unlike ash slurries, where there was greater variability of $b$ with concentration, silt slurries have a consistent $b$ value over the range of concentrations tested. Within two standard deviations, the value of $b$ for a silt slurry is -0.5. Therefore, given an estimate of the shear rate, the effective viscosity of a silt-only slurry can be calculated as follows:

$$\mu_m = (364.7\psi + 13.5)\gamma^{-0.5}$$

where $\mu_m$ is the effective viscosity of the slurry (cP), $\psi$ is the concentration by mass of silt in the slurry (unitless), $\gamma$ is the shear rate ($s^{-1}$), and $b$ is an empirical constant (unitless).

**Sand Slurries**

The average effective viscosity of sand slurries varied between 1.9cP and 149.8cP over the range of experimental conditions tested. The data for tests can be seen in Appendix D in a spreadsheet named “Sand_only.xls”. Figure 15, below, shows how the average effective viscosity of a sand slurry changes as the concentration of sand by mass increases. Similar to ash and silt slurries, there is not one single type of mathematical expression that would fit well with all of shear rates series. Figure 16 shows how sand slurries do appear to shear thin similarly to ash and silt slurries. Figure 16 is a graphical representation of how the average effective viscosity of a sand slurry changes with shear rate over the range of concentrations tested.
Figure 15. The average effective viscosity of a silt slurry with increasing concentration by mass of silt at the shear rates tested in the experiment.

Figure 16. The average effective viscosity of a silt slurry with increasing shear rates at all of the concentrations by mass tested in the experiment.
Power law equation trendlines were then fitted to each of the concentration data series shown in Figure 15. Table 9 and Figures 17 and 18 show the $D$, $b$ and $R^2$ values for the fitted trendlines. The general equation remains Equation 4.

**Table 9.** $D$, $b$ and $R^2$ values for each concentration of sand slurry tested.

<table>
<thead>
<tr>
<th>Concentration</th>
<th>$D$</th>
<th>$b$</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.60</td>
<td>187.62</td>
<td>-0.5378</td>
<td>0.8752</td>
</tr>
<tr>
<td>0.55</td>
<td>175.21</td>
<td>-0.5476</td>
<td>0.8638</td>
</tr>
<tr>
<td>0.50</td>
<td>151.6</td>
<td>-0.5422</td>
<td>0.8504</td>
</tr>
<tr>
<td>0.45</td>
<td>115.98</td>
<td>-0.431</td>
<td>0.8606</td>
</tr>
<tr>
<td>0.40</td>
<td>98.335</td>
<td>-0.4033</td>
<td>0.8544</td>
</tr>
<tr>
<td>0.35</td>
<td>84.593</td>
<td>-0.3856</td>
<td>0.7947</td>
</tr>
<tr>
<td>0.30</td>
<td>70.633</td>
<td>-0.397</td>
<td>0.7649</td>
</tr>
<tr>
<td>0.25</td>
<td>54.511</td>
<td>-0.3991</td>
<td>0.8079</td>
</tr>
<tr>
<td>0.20</td>
<td>48.134</td>
<td>-0.4391</td>
<td>0.8595</td>
</tr>
<tr>
<td>0.15</td>
<td>42.491</td>
<td>-0.4945</td>
<td>0.778</td>
</tr>
<tr>
<td>0.10</td>
<td>38.358</td>
<td>-0.56</td>
<td>0.6981</td>
</tr>
<tr>
<td>0.05</td>
<td>34.013</td>
<td>-0.566</td>
<td>0.7233</td>
</tr>
</tbody>
</table>

**Figure 17.** $D$ values for varying concentrations of sand. The equation given on the chart can be used to determine the $D$ value at any concentration.
Again, like silt, a $b$ value of -0.5 always falls within two standard deviations of measurements over the concentration range. Therefore, given an estimate of shear rate, the effective viscosity of a sand-only slurry can be calculated as follows:

$$
\mu_m = (269.2\psi + 6.4)\gamma^{-0.5}
$$

(7)

where $\mu_m$ is the effective viscosity of the slurry (cP), $\psi$ is the concentration by mass of sand in the slurry (unitless), $\gamma$ is the shear rate ($s^{-1}$), and $b$ is an empirical constant (unitless).

**Two Sediment Slurries**

The second set of tests performed involved slurries with two different sediment components, ash and silt slurries, ash and sand slurries, and silt and sand slurries. The range of concentrations by mass of sediment remained the same (0.05 to 0.6 g$_{\text{sed}}$ per g$_{\text{water}}$) as did the shear rate range (1 to 40 s$^{-1}$). The total mass of sediment in each slurry
sample was the same as for the homogenous slurries, but in these tests that sediment mass was split equally between two types of sediment. Again, the data presented in this results section is the data combined from the three individual trials. The data for the three separate trials, as well as the combined data, can be seen in the appropriate spreadsheet in Appendix D. In addition, the raw laboratory data as exported from GraceDaq can be seen in Appendix C. The procedure for analyzing the data is identical for these two sediment mixtures as the homogenous mixtures presented above.

_Ash and Silt Slurries_

The average effective viscosity of ash and silt slurries ranged from 3.7cP to 251.9cP. Analyzed lab data for these tests can be seen in Appendix D in a spreadsheet named “Ash+Silt.xls”. Figure 18 shows how the average effective viscosity of an ash and silt slurry changes with increasing concentration by mass when tested at multiple shear rates. As with the other slurries, there is a large variation in the slopes of the lines and one single equation type could not be used to accurately describe the trend in the data. The ash and silt slurry does appear to exhibit the same shear thinning behavior as the other slurries tested in the lab, as seen in Figure 20. Figure 20 shows how the average effective viscosity of an ash and silt slurry changes according to the shear rate for each concentration tested.
**Figure 19.** The average effective viscosity of an ash and silt slurry with increasing concentration by mass of silt at the shear rates tested in the experiment.

**Figure 20.** The average effective viscosity of an ash and silt slurry with increasing shear rates at all of the concentrations by mass tested in the experiment.
Power law trendlines were fitted to each of the concentration data series in Figure 20. The general equation remains Equation 4. The $D$, $b$ and $R^2$ values for each concentration series can be seen in Table 10 and are plotted in Figures 21 and 22. The $b$ value is nearly -0.5 until a concentration of 0.40. Ash may begin to play a more dominate role at these high concentrations, and therefore, one value for $b$ is not appropriate for all concentrations of ash+silt slurries. The effective viscosity of an ash and silt slurry can be calculated given an estimate of shear rate and concentration by mass of the slurry using the following equation:

$$\mu_m = (502.1\psi + 2.4)\gamma^b \tag{8}$$

where $\mu_m$ is the effective viscosity of the slurry (cP), $\psi$ is the concentration by mass of ash and silt in the slurry (unitless), $\gamma$ is the shear rate ($s^{-1}$), and $b$ is an empirical constant (unitless) that varies with concentration and can be chosen from Figure 22.

<table>
<thead>
<tr>
<th>Concentration</th>
<th>$D$</th>
<th>$b$</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.60</td>
<td>342.28</td>
<td>-0.6656</td>
<td>0.9536</td>
</tr>
<tr>
<td>0.55</td>
<td>316.53</td>
<td>-0.6565</td>
<td>0.9526</td>
</tr>
<tr>
<td>0.50</td>
<td>250.56</td>
<td>-0.6067</td>
<td>0.9511</td>
</tr>
<tr>
<td>0.45</td>
<td>208.95</td>
<td>-0.5721</td>
<td>0.932</td>
</tr>
<tr>
<td>0.40</td>
<td>178.67</td>
<td>-0.5479</td>
<td>0.8799</td>
</tr>
<tr>
<td>0.35</td>
<td>149.07</td>
<td>-0.521</td>
<td>0.8476</td>
</tr>
<tr>
<td>0.30</td>
<td>126.85</td>
<td>-0.5058</td>
<td>0.8472</td>
</tr>
<tr>
<td>0.25</td>
<td>107.65</td>
<td>-0.4934</td>
<td>0.8812</td>
</tr>
<tr>
<td>0.20</td>
<td>91.05</td>
<td>-0.4957</td>
<td>0.9025</td>
</tr>
<tr>
<td>0.15</td>
<td>79.546</td>
<td>-0.5273</td>
<td>0.9169</td>
</tr>
<tr>
<td>0.10</td>
<td>56.567</td>
<td>-0.5185</td>
<td>0.895</td>
</tr>
<tr>
<td>0.05</td>
<td>37.958</td>
<td>-0.5047</td>
<td>0.7537</td>
</tr>
</tbody>
</table>

Table 10. $D$, $b$ and $R^2$ values for each concentration of ash and silt slurry tested.
**Figure 21.** $D$ values for varying concentrations of ash and silt. The equation given on the chart can be used to determine the $D$ value at any concentration.

**Figure 22.** $b$ values for varying concentrations of ash and silt. For concentrations between those used in this experiment, interpolation must be used to determine the $b$ value. Error bars represent two standard deviations.
**Ash and Sand Slurries**

The average effective viscosity of ash and sand slurries varied between 2.4 cP and 202.1 cP over the range of concentrations of sediment and shear rates tested in the experiments. Analyzed experimental data can be seen in Appendix D in a spreadsheet named “Ash+Sand.xls”. Figure 23 illustrates how the average effective viscosity of an ash and sand slurry varies when the concentration by mass of sediment in the slurry is increased over the range of shear rates tested. There appears to be a difference in the rate at which the effective viscosity increases with concentration at different shear rates. Therefore, it is useful to look at how the average effective viscosity changes according to shear rate at the range on concentrations tested, as shown in Figure 24. Again, the ash and sand slurry appears to shear thin dramatically, especially at the highest concentrations.

![Average Effective Viscosity over a Range of Shear Rates of Slurries Containing Varying Concentrations of Ash and Sand](image)

**Figure 23.** The average effective viscosity of an ash and sand slurry with increasing concentration by mass of silt at the shear rates tested in the experiment.
Figure 24. The average effective viscosity of an ash and sand slurry with increasing shear rates at all of the concentrations by mass tested in the experiment.

Again, Equation 4 remained a viable general equation for ash and sand slurries. Power law equation trendlines were fitted to each concentration by mass series in Figure 24. The $D$, $b$ and $R^2$ values for these trendlines can be seen in Table 11 and Figures 25 and 26. The $b$ value is nearly (within two standard deviations) -0.5 for all concentrations of ash+sand slurry tested. The effective viscosity of an ash and sand slurry can be calculated given an estimate of shear rate and concentration by mass of the slurry using the following equation:

$$
\mu_m = (371.3\psi + 3.2)\gamma^{-0.5}
$$

(9)

where $\mu_m$ is the effective viscosity of the slurry (cP), $\psi$ is the concentration by mass of ash and sand in the slurry (unitless), $\gamma$ is the shear rate (s$^{-1}$), and $b$ is empirical constant (unitless).
Table 11. $D$, $b$ and $R^2$ values for each concentration of ash and sand slurry tested.

<table>
<thead>
<tr>
<th>Concentration</th>
<th>$D$</th>
<th>$b$</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.60</td>
<td>264.68</td>
<td>-0.6257</td>
<td>0.8877</td>
</tr>
<tr>
<td>0.55</td>
<td>240.12</td>
<td>-0.6145</td>
<td>0.8904</td>
</tr>
<tr>
<td>0.50</td>
<td>183.99</td>
<td>-0.5533</td>
<td>0.8692</td>
</tr>
<tr>
<td>0.45</td>
<td>153.94</td>
<td>-0.5097</td>
<td>0.872</td>
</tr>
<tr>
<td>0.40</td>
<td>128.11</td>
<td>-0.4613</td>
<td>0.8464</td>
</tr>
<tr>
<td>0.35</td>
<td>110.32</td>
<td>-0.4517</td>
<td>0.8383</td>
</tr>
<tr>
<td>0.30</td>
<td>95.128</td>
<td>-0.4534</td>
<td>0.8656</td>
</tr>
<tr>
<td>0.25</td>
<td>77.106</td>
<td>-0.4392</td>
<td>0.8763</td>
</tr>
<tr>
<td>0.20</td>
<td>62.651</td>
<td>-0.4204</td>
<td>0.9093</td>
</tr>
<tr>
<td>0.15</td>
<td>51.727</td>
<td>-0.4532</td>
<td>0.9183</td>
</tr>
<tr>
<td>0.10</td>
<td>43.582</td>
<td>-0.4899</td>
<td>0.8175</td>
</tr>
<tr>
<td>0.05</td>
<td>39.226</td>
<td>-0.5543</td>
<td>0.7248</td>
</tr>
</tbody>
</table>

**Figure 25.** $D$ values for varying concentrations of ash and sand. The equation given on the chart can be used to determine the $D$ value at any concentration.
**Values for Varying Concentrations of Ash and Sand**

Figure 26. $b$ values for varying concentrations of ash and sand. Error bars represent two standard deviations.

**Silt and Sand Slurries**

The average effective viscosity of silt and sand slurries ranged from 4.1 cP to 178.9 cP. Analyzed experimental data for these tests can be found in Appendix D in a spreadsheet called “Silt+Sand.xls”. Figure 27 again shows that, like the ash and sand slurries, there appears to be different rates of increase in the effective viscosity of the slurry with increasing concentration by mass depending on the shear rate. Also, as seen in Figure 28, Equation 4 is still the most reasonable trendline for the data series, although at shear rates of 7 to 15 s$^{-1}$ the effective viscosity does not change significantly at any of the concentrations tested.
Figure 27. The average effective viscosity of a silt and sand slurry with increasing concentration by mass of silt at the shear rates tested in the experiment.

Figure 28. The average effective viscosity of a silt and sand slurry with increasing shear rates at all of the concentrations by mass tested in the experiment.
Trendlines were again fitted to all of the concentration data series shown in Figure 28; Equation 4 remains the general form of the equation. $D$, $b$ and $R^2$ values for the trendlines can be found in Table 12 and Figures 29 and 30. While the $R^2$ values for the silt and sand slurries are not as high as for some of the other slurries, they are higher than other trendline types tried (linear, exponential, moving average, etc.). The anomaly that occurs between the shear rates of 7 and 15 s$^{-1}$ is the cause of the poorer fit of the trendline. Again, a value of -0.5 can be used to approximate $b$ over the range of concentrations tested. The effective viscosity of a silt and sand slurry can be calculated given an estimate of shear rate and concentration by mass of the slurry according to:

$$\mu_m = (333.0 \psi + 7.9)\gamma^{-0.5}$$

(10)

where $\mu_m$ is the effective viscosity of the slurry (cP), $\psi$ is the concentration by mass of silt and sand in the slurry (unitless), $\gamma$ is the shear rate (s$^{-1}$), and $b$ is an empirical constant (unitless).

Table 12. $D$, $b$ and $R^2$ values for each concentration of silt and sand slurry tested.

<table>
<thead>
<tr>
<th>Concentration</th>
<th>$D$</th>
<th>$b$</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.60</td>
<td>216.63</td>
<td>-0.4954</td>
<td>0.8652</td>
</tr>
<tr>
<td>0.55</td>
<td>209.97</td>
<td>-0.5157</td>
<td>0.8677</td>
</tr>
<tr>
<td>0.50</td>
<td>170.24</td>
<td>-0.4701</td>
<td>0.8204</td>
</tr>
<tr>
<td>0.45</td>
<td>149.8</td>
<td>-0.4305</td>
<td>0.8314</td>
</tr>
<tr>
<td>0.40</td>
<td>128.91</td>
<td>-0.425</td>
<td>0.7863</td>
</tr>
<tr>
<td>0.35</td>
<td>115.73</td>
<td>-0.4258</td>
<td>0.7735</td>
</tr>
<tr>
<td>0.30</td>
<td>101.24</td>
<td>-0.4283</td>
<td>0.7744</td>
</tr>
<tr>
<td>0.25</td>
<td>80.44</td>
<td>-0.4221</td>
<td>0.7853</td>
</tr>
<tr>
<td>0.20</td>
<td>76.14</td>
<td>-0.4947</td>
<td>0.8433</td>
</tr>
<tr>
<td>0.15</td>
<td>67.2</td>
<td>-0.5457</td>
<td>0.8045</td>
</tr>
<tr>
<td>0.10</td>
<td>46.347</td>
<td>-0.5033</td>
<td>0.7766</td>
</tr>
<tr>
<td>0.05</td>
<td>31.176</td>
<td>-0.466</td>
<td>0.6977</td>
</tr>
</tbody>
</table>
Figure 29. $D$ values for varying concentrations of silt and sand. The equation given on the chart can be used to determine the $D$ value at any concentration.

Figure 30. $b$ values for varying concentrations of silt and sand. Error bars represent two standard deviations.
Ash, Silt and Sand Slurries

The last group of tests run involved slurries comprised of ash, silt, sand and water. The range of concentrations by mass of sediment remained the same (0.05 to 0.6 g<sub>sed</sub> per g<sub>water</sub>) as did the shear rate range (1 to 40 s<sup>-1</sup>). The total mass of sediment in each slurry sample was the same as for the homogenous slurries, but in these tests that sediment mass was split equally between ash, silt and sand. Again, the data presented here is the data combined from the three individual trials for each concentration and shear rate combination. The data for the three separate trials, as well as the combined data, can be seen in the appropriate spreadsheet in Appendix D. In addition, the raw laboratory data as exported from GraceDaq can be seen in Appendix C. The procedure for analyzing the data is identical for these three sediment mixtures as all the slurries previously mentioned.

The average effective viscosity of ash, silt and sand slurries varied from 3.2 cP to 218.9 cP over the range of concentrations and shear rates tested in the lab. Analyzed data for these experiments can be seen in Appendix D in a spreadsheet named “Ash+Silt+Sand.xls”. Figure 31 is a graphical representation of how the average effective viscosity of an ash, silt and sand slurry increases with increasing concentration of sediment for the range of shear rates tested. Ash, silt and sand slurries do shear thin as well, as seen in Figure 32. Figure 32 shows how increasing the shear rate decreases the average effective viscosity of an ash, silt and sand slurry over the range of concentrations tested.
Figure 31. The average effective viscosity of an ash, silt and sand slurry with increasing concentration by mass of silt at the shear rates tested in the experiment.

Figure 32. The average effective viscosity of an ash, silt and sand slurry with increasing shear rates at all of the concentrations by mass tested in the experiment.
A power law equation was again fitted to all of the concentration data series shown above in Figure 32; the general form of the equation was again Equation 4. The $D$, $b$ and $R^2$ values are shown in Table 13 and Figures 33 and 34. The $b$ value is nearly (within two standard deviations) -0.5 for all concentrations of ash+silt+sand slurry tested. The effective viscosity of an ash, silt and sand slurry can be calculated given an estimate of shear rate and concentration by mass of the slurry using the following equation

$$\mu_m = (391.4\psi + 2.4)\gamma^{-0.5}$$

where $\mu_m$ is the effective viscosity of the slurry (cP), $\psi$ is the concentration by mass of ash, silt and sand in the slurry (unitless), $\gamma$ is the shear rate (s$^{-1}$), and $b$ is an empirical constant (unitless).

Table 13. $D$, $b$ and $R^2$ values for each concentration of ash, silt and sand slurry tested.

<table>
<thead>
<tr>
<th>Concentration</th>
<th>D</th>
<th>b</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.60</td>
<td>262.98</td>
<td>-0.5427</td>
<td>0.9589</td>
</tr>
<tr>
<td>0.55</td>
<td>231.73</td>
<td>-0.5254</td>
<td>0.963</td>
</tr>
<tr>
<td>0.50</td>
<td>191.13</td>
<td>-0.4946</td>
<td>0.9431</td>
</tr>
<tr>
<td>0.45</td>
<td>167.53</td>
<td>-0.4746</td>
<td>0.9301</td>
</tr>
<tr>
<td>0.40</td>
<td>145.61</td>
<td>-0.4525</td>
<td>0.8981</td>
</tr>
<tr>
<td>0.35</td>
<td>122.03</td>
<td>-0.4283</td>
<td>0.8787</td>
</tr>
<tr>
<td>0.30</td>
<td>110.24</td>
<td>-0.4449</td>
<td>0.8547</td>
</tr>
<tr>
<td>0.25</td>
<td>91.679</td>
<td>-0.4443</td>
<td>0.8726</td>
</tr>
<tr>
<td>0.20</td>
<td>77.837</td>
<td>-0.4581</td>
<td>0.9118</td>
</tr>
<tr>
<td>0.15</td>
<td>64.864</td>
<td>-0.4736</td>
<td>0.9102</td>
</tr>
<tr>
<td>0.10</td>
<td>52.179</td>
<td>-0.4942</td>
<td>0.8515</td>
</tr>
<tr>
<td>0.05</td>
<td>37.961</td>
<td>-0.4879</td>
<td>0.765</td>
</tr>
</tbody>
</table>
Figure 33. $D$ values for varying concentrations of ash, silt and sand. The equation given on the chart can be used to determine the $D$ value at any concentration.

Figure 34. $b$ values for varying concentrations of ash, silt and sand. Error bars represent two standard deviations.
Combined Data

The data presented above was then split up into two datasets, one dataset separated based on shear rate and the other concentration by mass. This was done to determine how each of the slurry types behaved relative to the others at varying shear rates and concentrations. The data for both of these datasets can be found in Appendix D in a spreadsheet named “Comparison by Shear Rate and Concentration.xls”.

In an attempt to determine how the various slurries behaved relative to each other at each shear rate, the data presented above for each slurry type is re-displayed below in Figures 35-41. Each chart in Figures 35-41 shows how the effective viscosity of each type of slurry (ash, silt, sand, ash+silt, ash+sand, silt+sand, and ash+silt+sand) varies with concentration by mass of sediment at each individual shear rate tested. In these charts it is easy to see how each type of slurry of varying concentrations behaves relative to other slurries of the same concentration at each shear rate that was tested in the lab. These data could be used to determine if at certain shear rates any of the slurries behave identically and could be modeled using the same equation.
Figure 35. The average effective viscosity of all types of slurries with increasing concentration by mass at a shear rate of (a) $1\text{s}^{-1}$ and (b) $3\text{s}^{-1}$. 
Figure 36. The average effective viscosity of all types of slurries with increasing concentration by mass at a shear rate of (a) $5\text{s}^{-1}$ and (b) $7\text{s}^{-1}$. 
Figure 37. The average effective viscosity of all types of slurries with increasing concentration by mass at a shear rate of (a) $9\text{s}^{-1}$ and (b) $12\text{s}^{-1}$. 

57
Figure 38. The average effective viscosity of all types of slurries with increasing concentration by mass at a shear rate of (a) 15 s⁻¹ and (b) 18 s⁻¹.
Figure 39. The average effective viscosity of all types of slurries with increasing concentration by mass at a shear rate of (a) 20 s\(^{-1}\) and (b) 25 s\(^{-1}\).
Figure 40. The average effective viscosity of all types of slurries with increasing concentration by mass at a shear rate of (a) 30 s\(^{-1}\) and (b) 35 s\(^{-1}\).
Figure 41. The average effective viscosity of all types of slurries with increasing concentration by mass at a shear rate of $40 s^{-1}$.

In “real-world” cases, sometimes the exact proportion of ash to silt to sand may not be known or may not exactly match one of the slurries tested in these experiments. Therefore it would be useful to have a set of $D$ and $b$ values that could be used in Equation 4 in the case where the exact composition of the slurry is either unknown or does not match one of the cases tested in the lab. In order to determine if one set of $D$ and $b$ values could be found for each concentration, regardless of slurry composition, the data from all seven slurry types were plotted together on Figures 42-47. These figures show how the effective viscosity of each of the slurry types changes as the shear rate increases at each individual concentration tested.
Figure 42. The average effective viscosity of all types of slurries with increasing shear rate at a concentration by mass of (a) 0.05 and (b) 0.10.
Figure 43. The average effective viscosity of all types of slurries with increasing shear rate at a concentration by mass of (a) 0.15 and (b) 0.20.
Figure 44. The average effective viscosity of all types of slurries with increasing shear rate at a concentration by mass of (a) 0.25 and (b) 0.30.
Figure 45. The average effective viscosity of all types of slurries with increasing shear rate at a concentration by mass of (a) 0.35 and (b) 0.40.
Figure 46. The average effective viscosity of all types of slurries with increasing shear rate at a concentration by mass of (a) 0.45 and (b) 0.50.
Figure 47. The average effective viscosity of all types of slurries with increasing shear rate at a concentration by mass of (a) 0.55 and (b) 0.60.
A power trendline was fitted to all of the data in each of the charts in Figures 42-47 above to determine a $D$ and $b$ value for each concentration for all of the slurry compositions combined and to determine the fit of those trendlines ($R^2$). These trendlines approximate the effective viscosity response to a decrease in shear rate for a slurry of unknown proportions of ash, sand and silt. The general equation remained Equation 4. The charts with the fitted trendlines can be seen in Appendix D, “Comparison by Shear Rate and Concentration”, tab entitled “D, b dataset”. The $D$, $b$ and $R^2$ values can be seen in Table 14 and Figures 48 and 49.

**Table 14.** $D$, $b$ and $R^2$ values for each concentration of the data combined from all slurry types tested.

<table>
<thead>
<tr>
<th>Concentration</th>
<th>$D$</th>
<th>$b$</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.60</td>
<td>266.64</td>
<td>-0.6143</td>
<td>0.7512</td>
</tr>
<tr>
<td>0.55</td>
<td>245.91</td>
<td>-0.61</td>
<td>0.7653</td>
</tr>
<tr>
<td>0.50</td>
<td>199.86</td>
<td>-0.561</td>
<td>0.8244</td>
</tr>
<tr>
<td>0.45</td>
<td>163.67</td>
<td>-0.4975</td>
<td>0.8148</td>
</tr>
<tr>
<td>0.40</td>
<td>143.97</td>
<td>-0.4737</td>
<td>0.7964</td>
</tr>
<tr>
<td>0.35</td>
<td>122.83</td>
<td>-0.4646</td>
<td>0.7912</td>
</tr>
<tr>
<td>0.30</td>
<td>107.4</td>
<td>-0.4847</td>
<td>0.7799</td>
</tr>
<tr>
<td>0.25</td>
<td>87.174</td>
<td>-0.5518</td>
<td>0.7752</td>
</tr>
<tr>
<td>0.20</td>
<td>75.278</td>
<td>-0.4712</td>
<td>0.7951</td>
</tr>
<tr>
<td>0.15</td>
<td>64.7</td>
<td>-0.509</td>
<td>0.7864</td>
</tr>
<tr>
<td>0.10</td>
<td>48.874</td>
<td>-0.5107</td>
<td>0.7569</td>
</tr>
<tr>
<td>0.05</td>
<td>36.792</td>
<td>-0.5135</td>
<td>0.7067</td>
</tr>
</tbody>
</table>

Average = -0.52183
St. Dev = 0.061558
2 St. Dev = 0.123116

68
D Values For Varying Concentrations of All Slurry Types Combined

\[ D = 400.7(concentration) + 0.962 \]

\[ R^2 = 0.9536 \]

Figure 48.  \(D\) values for varying concentrations of data combined from all slurry types tested. The equation given on the chart can be used to determine the \(D\) value at any concentration.

b Values for Varying Concentrations of All Slurry Types Combined

Figure 49.  \(b\) values for varying concentrations of data combined from all slurry types tested. For concentrations between those used in this experiment, interpolation must be used to determine the \(b\) value. Error bars represent two standard deviations.
Figure 49 shows that for all concentrations, the value of $b$ is approximately -0.5. Therefore, for a slurry containing unknown proportions of ash, silt and sand, the effective viscosity of the slurry can be calculated given an estimate of shear rate and concentration by mass of the slurry using the following equation:

$$\mu_m = (400.7\psi + 1.0)\gamma^{-0.5}$$

(12)

where $\mu_m$ is the effective viscosity of the slurry (cP), $\psi$ is the concentration by mass of sediment in the slurry (unitless), and $\gamma$ is the shear rate ($s^{-1}$).

Table 15 shows the $D$, $b$ values for this combined data set, as well as for all the other slurry types as a means of comparison. Figures 50 and 51 allow for a comparison of this combined dataset’s $D$ and $b$ values with those from each of the slurry types tested. Figures 50 and 51 were used to test if this combined dataset and its resultant $D$ and $b$ values could be used if the exact proportion of ash to silt to sand was not known.
Table 15. $D$, $b$ and $R^2$ values for each concentration of the data combined from all slurry types tested.

<table>
<thead>
<tr>
<th>Conc.</th>
<th>$D_{\text{combined}}$</th>
<th>$D_{\text{ash}}$</th>
<th>$D_{\text{silt}}$</th>
<th>$D_{\text{sand}}$</th>
<th>$D_{\text{ash + silt}}$</th>
<th>$D_{\text{ash + sand}}$</th>
<th>$D_{\text{silt + sand}}$</th>
<th>$D_{\text{ash + silt + sand}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.60</td>
<td>266.64</td>
<td>411.77</td>
<td>227.08</td>
<td>187.62</td>
<td>342.28</td>
<td>264.68</td>
<td>216.63</td>
<td>262.98</td>
</tr>
<tr>
<td>0.55</td>
<td>245.91</td>
<td>346.83</td>
<td>227.17</td>
<td>175.21</td>
<td>316.53</td>
<td>240.12</td>
<td>209.97</td>
<td>231.73</td>
</tr>
<tr>
<td>0.50</td>
<td>199.86</td>
<td>271.74</td>
<td>206.11</td>
<td>151.64</td>
<td>250.56</td>
<td>183.99</td>
<td>170.24</td>
<td>191.13</td>
</tr>
<tr>
<td>0.45</td>
<td>163.67</td>
<td>199.33</td>
<td>168.62</td>
<td>115.98</td>
<td>208.95</td>
<td>153.94</td>
<td>149.89</td>
<td>167.53</td>
</tr>
<tr>
<td>0.40</td>
<td>143.97</td>
<td>207.83</td>
<td>146.01</td>
<td>98.33</td>
<td>178.67</td>
<td>128.11</td>
<td>128.91</td>
<td>145.61</td>
</tr>
<tr>
<td>0.35</td>
<td>122.83</td>
<td>155.93</td>
<td>140.32</td>
<td>84.59</td>
<td>149.07</td>
<td>110.32</td>
<td>115.73</td>
<td>122.03</td>
</tr>
<tr>
<td>0.30</td>
<td>107.40</td>
<td>144.77</td>
<td>119.67</td>
<td>70.63</td>
<td>126.85</td>
<td>95.128</td>
<td>101.24</td>
<td>110.24</td>
</tr>
<tr>
<td>0.25</td>
<td>87.174</td>
<td>117.02</td>
<td>95.546</td>
<td>54.51</td>
<td>107.65</td>
<td>77.106</td>
<td>80.44</td>
<td>91.679</td>
</tr>
<tr>
<td>0.20</td>
<td>75.278</td>
<td>89.24</td>
<td>96.925</td>
<td>48.134</td>
<td>91.05</td>
<td>62.651</td>
<td>76.14</td>
<td>77.837</td>
</tr>
<tr>
<td>0.15</td>
<td>64.70</td>
<td>74.835</td>
<td>83.217</td>
<td>42.491</td>
<td>79.546</td>
<td>51.727</td>
<td>67.2</td>
<td>64.864</td>
</tr>
<tr>
<td>0.10</td>
<td>48.874</td>
<td>61.137</td>
<td>47.64</td>
<td>38.358</td>
<td>56.567</td>
<td>43.582</td>
<td>46.347</td>
<td>52.179</td>
</tr>
<tr>
<td>0.05</td>
<td>36.792</td>
<td>35.58</td>
<td>26.31</td>
<td>34.013</td>
<td>37.958</td>
<td>29.226</td>
<td>31.176</td>
<td>37.961</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Conc.</th>
<th>$b_{\text{combined}}$</th>
<th>$b_{\text{ash}}$</th>
<th>$b_{\text{silt}}$</th>
<th>$b_{\text{sand}}$</th>
<th>$b_{\text{ash + silt}}$</th>
<th>$b_{\text{ash + sand}}$</th>
<th>$b_{\text{silt + sand}}$</th>
<th>$b_{\text{ash + silt + sand}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.60</td>
<td>-0.6143</td>
<td>-0.9665</td>
<td>-0.451</td>
<td>-0.5378</td>
<td>-0.6656</td>
<td>-0.6257</td>
<td>-0.4954</td>
<td>-0.5427</td>
</tr>
<tr>
<td>0.55</td>
<td>-0.61</td>
<td>-0.9087</td>
<td>-0.4843</td>
<td>-0.5476</td>
<td>-0.6566</td>
<td>-0.6145</td>
<td>-0.5157</td>
<td>-0.5254</td>
</tr>
<tr>
<td>0.50</td>
<td>-0.561</td>
<td>-0.7609</td>
<td>-0.4997</td>
<td>-0.5422</td>
<td>-0.6067</td>
<td>-0.5533</td>
<td>-0.4701</td>
<td>-0.4946</td>
</tr>
<tr>
<td>0.45</td>
<td>-0.4975</td>
<td>-0.6546</td>
<td>-0.4097</td>
<td>-0.431</td>
<td>-0.5721</td>
<td>-0.5097</td>
<td>-0.4305</td>
<td>-0.4746</td>
</tr>
<tr>
<td>0.40</td>
<td>-0.4737</td>
<td>-0.6034</td>
<td>-0.4225</td>
<td>-0.4033</td>
<td>-0.5479</td>
<td>-0.4613</td>
<td>-0.425</td>
<td>-0.4525</td>
</tr>
<tr>
<td>0.35</td>
<td>-0.4646</td>
<td>-0.5876</td>
<td>-0.4552</td>
<td>-0.3856</td>
<td>-0.521</td>
<td>-0.4517</td>
<td>-0.4258</td>
<td>-0.4283</td>
</tr>
<tr>
<td>0.30</td>
<td>-0.4847</td>
<td>-0.5764</td>
<td>-0.4472</td>
<td>-0.397</td>
<td>-0.5058</td>
<td>-0.4534</td>
<td>-0.4283</td>
<td>-0.4449</td>
</tr>
<tr>
<td>0.25</td>
<td>-0.5518</td>
<td>-0.5266</td>
<td>-0.4314</td>
<td>-0.3991</td>
<td>-0.4934</td>
<td>-0.4392</td>
<td>-0.4221</td>
<td>-0.4443</td>
</tr>
<tr>
<td>0.20</td>
<td>-0.4712</td>
<td>-0.4607</td>
<td>-0.5381</td>
<td>-0.4391</td>
<td>-0.4957</td>
<td>-0.4204</td>
<td>-0.4947</td>
<td>-0.4581</td>
</tr>
<tr>
<td>0.15</td>
<td>-0.509</td>
<td>-0.5003</td>
<td>-0.5682</td>
<td>-0.4945</td>
<td>-0.5273</td>
<td>-0.4532</td>
<td>-0.5457</td>
<td>-0.4736</td>
</tr>
<tr>
<td>0.10</td>
<td>-0.5107</td>
<td>-0.542</td>
<td>-0.4673</td>
<td>-0.56</td>
<td>-0.5185</td>
<td>-0.4899</td>
<td>-0.5033</td>
<td>-0.4942</td>
</tr>
<tr>
<td>0.05</td>
<td>-0.5135</td>
<td>-0.6278</td>
<td>-0.389</td>
<td>-0.566</td>
<td>-0.5047</td>
<td>-0.5543</td>
<td>-0.466</td>
<td>-0.4879</td>
</tr>
</tbody>
</table>
Figure 50. $D$ values for varying concentrations of each type of slurry tested and the data combined from all the data sets. The equation given on the chart can be used to determine the $D$ value at any concentration.

Figure 51. $b$ values for varying concentrations of each type of slurry tested and the data combined from all the data sets. For concentrations between those used in this experiment, interpolation must be used to determine the $b$ value.
Table 15 and Figure 51 show that the $b$ value for most slurries is approximately -0.5. As seen in the previous charts of $b$ values versus concentration for each slurry type, -0.5 is encapsulated within two standard deviations of the $b$ value reported with the exception of 100% ash slurries. Therefore, the effective viscosity of most hyperconcentrated flows and debris flows (except those containing a high percentage of ash) can be modeled using Equation 12 ($\mu_m = (400.7\psi + 1.0)\gamma^{-0.5}$). Figure 52 shows the effective viscosity of a slurry containing less than 50% ash relative to clastic sediments calculated by Equation 12 over a range of concentrations and shear rates, overlain by the effective viscosity measured in the lab for six slurry types (silt-only, sand-only, ash+silt, ash+sand, silt+sand, ash+silt+sand). This figure illustrates how well the data from these six slurry types fit the model created by Equation 12 especially at shear rates that may be naturally occurring. A movie clip of this figure rotating can be seen in Appendix E.
Figure 52. Modeled effective viscosity calculated by Equation 12 versus measured experimental effective viscosity of slurries containing no more than 50% ash.
Ash-only slurries are unique in that at high concentrations these slurries tend to have significantly lower $b$ values than the clastic sediment slurries tested. This demonstrates that ash slurries do not behave similarly to the clastic sediments tested in this project, especially at high concentrations. Also, this means that the effective viscosity of hyperconcentrated flows or debris flows that contain a large proportion of ash cannot be modeled using Equation 12 and should be modeled using Equation 5 ($\mu_m = (547.9\psi + 5.3)\gamma^b$), where the $b$ value is not constant and needs to be chosen from Figure 10 based on concentration. Figures 53-55 show the comparison between the effective viscosity of an ash-laden slurry calculated using Equation 5 with six different $b$ values (-0.4, -0.5, -0.6, -0.7, -0.8, and -0.9) and the effective viscosity data collected in the lab over a range of concentration and shear rates. Visually, based on Figures 53-55, there is no $b$ value that perfectly fits all of the data, but using a $b$-value of -0.8 in Equation 5 provides the best fit of the modeled effective viscosity to the laboratory data over most conditions. However, at high sediment concentrations, a $b$ value of -0.8 causes the calculated effective viscosity to be much greater than the effective viscosity measured in the lab under the same conditions. Figure 56 and 57 illustrate the predictive power of Equation 5 at two different $b$ values. Figure 56 shows the effective viscosity predicted by Equation 5 with a $b$ value of -0.8 and the average effective viscosity measured in the lab for an ash slurry with a concentration of 0.05 and 0.60. Based on this figure, it can be seen that using a $b$ value of -0.8 is appropriate at all shear rates for a 0.60 concentration ash slurry, but is not appropriate for a 0.05 concentration ash slurry. Figure 57 shows the effective viscosity predicted by Equation 5 using a $b$ value of -0.5 and the average effective viscosity measured in the lab for ash slurries with concentrations of 0.05 and
0.60. This figure shows that for a 0.05 concentration slurry, the calculated effective viscosity given by Equation 5 using a $b$ value of -0.5 closely approximates the effective viscosity measurements made in the lab. However, the same is not true for the higher concentration slurry. Therefore, to most accurately model hyperconcentrated flows or debris flows containing mostly ash, Equation 5 should be used with the appropriate $b$ value chosen from Figure 10.

Also, it can be seen in Figures 53-55 that using a lower (more negative) $b$ in Equation 5 results in a steeper relationship between shear rate and effective viscosity at high concentrations of ash. Therefore, at lower strain rates (i.e., when the flow is first mobilizing) the slurry is extra viscous and can “bulk” as proposed. However, at higher strain rates, the slurry has a much lower viscosity, and, therefore, is much weaker than at lower shear rates. This lower viscosity at higher shear rates could result in more catastrophic debris flows since the flow itself is weaker.
Figure 53. Modeled effective viscosity calculated by Equation 5 (blue plane) versus measured experimental effective viscosity (red dots) of slurries containing greater than 50% ash using a $b$ value of (a) -0.4 and (b) -0.5.
Figure 54. Modeled effective viscosity calculated by Equation 5 versus measured experimental effective viscosity of slurries containing greater than 50% ash using a $b$ value of (a) -0.6 and (b) -0.7.
Figure 55. Modeled effective viscosity calculated by Equation 5 versus measured experimental effective viscosity of slurries containing greater than 50% ash using a $b$ value of (a) -0.8 and (b) -0.9.
Figure 56. Effective viscosity measured in the lab versus effective viscosity calculated with Equation 5 using a $b$ value of -0.8 for the end member concentrations of ash slurry.

Figure 57. Effective viscosity measured in the lab versus effective viscosity calculated with Equation 5 using a $b$ value of -0.5 for the end member concentrations of ash slurry.
DISCUSSION

Carbon Content of Ash

The main concern in using ash created in a burn barrel was that the ash created would not be similar to ash created in a natural fire situation. Carbon content analysis was chosen to judge if the ash created in the burn barrel was similar to naturally created ash. Loss on Ignition is a relatively simple and inexpensive method to determine carbon content and therefore was chosen to determine the carbon content of the various ash batches. The carbon content of each ash batch was within the range seen in real fire situations (Vicki Balfour, personal communication, April 2007), with the exception of the Feb 2006 batch which was slightly higher. The Feb 2006 ash was created on a day when the air temperature was -10°C and there was a strong wind. All of the other batches were made when the air temperature was above 0°C and the wind was calm. These cold and windy conditions may have caused the temperature in the burn barrel to be slightly lower than during the other batches’ creations. However, when trials using ash from the Feb 2006 batch are compared to trials using the same concentration and shear rate conditions with another batch of ash, there is no statistical difference between the two trials. There is no change in the effective viscosity of a slurry based on the carbon content of the ash. However, it is important to note that the ash used in these experiments had a similar carbon content to ash that results from a wildfire.

Temperature and pH of Samples Tested

It is assumed that if a chemical reaction were taking place between the ash and the water or other sediments, there would be a change in either the temperature or the pH of the slurry itself. The temperature and pH data both show that no change in either
property occurs once a shear rate is applied to the slurry. Therefore, no obvious chemical reaction is occurring in the slurry while it was being tested. There had been a reaction between the ash and the water since the pH of the ash slurries was always greater than 7.0, however, that reaction took place immediately upon mixing and the slurry reached equilibrium before the test began. Applying a shear rate to the slurry did not restart the reaction.

Also Figure 4 clearly illustrates that the pH of the ash-laden slurry did not affect the slurry viscosity. The greatest pH measured in the lab occurred in a 0.60 concentration ash slurry which is what was tested in the experiment shown in Figure 4. If effective viscosity was a function of pH, the viscosity measured in this experiment should have changed when the buffer was added. No change in viscosity occurred as the pH changed at any of the three shear rates tested.

**Average Effective Viscosity Tests**

The slurries tested did behave similarly at most shear rates, as seen in Figures 35 to 41. At shear rates of 1 and 3s\(^{-1}\), all of the slurries showed a steady increase in effective viscosity as the sediment concentration increased though the rate of increase depended on the sediment type in the slurry. That trend generally continued at a shear rate of 5s\(^{-1}\), with the exception of the ash slurry. The ash slurry showed an anomalously low effective viscosity at a concentration of 0.45 g\(_{\text{sed}}/\text{g}_{\text{water}}\). This low effective viscosity was seen in all three trials run at this shear rate. At a shear rate of 7, 9, 12, and 15s\(^{-1}\), a similar trend occurs with the ash slurries. At both shear rates, the effective viscosity of the ash slurry peaks at a concentration of 0.40 g\(_{\text{sed}}/\text{g}_{\text{water}}\) and then drops dramatically at a concentration of 0.45 g\(_{\text{sed}}/\text{g}_{\text{water}}\) and then increases again. None of the other slurries exhibit this
behavior at those shear rates. One possible explanation for this would be the breakup of the ash particles into smaller particles. Ash particles do decrease in size when first sheared, however, the grain size does not appreciably change after the initial shearing (Andy Bookter, personal communications, April 2006). Also, if the ash were broken up into smaller particles (clay-sized), the effective viscosity should increase due to the increase in finer grained particles (Major and Pierson, 1992). Therefore, another process must be at work in these ash slurries. The ash particles are platy and angular, making it possible for them to align within the slurry, thereby reducing the viscosity of the slurry.

The most distinct example of this behavior occurs at a shear rate of 12, 15 and 18 s\(^{-1}\). These three shear rates see a dramatic drop in effective viscosity of an ash slurry as the concentration of ash increases. In these cases, the effective viscosity at a concentration of 0.60 g\(_{\text{sed}}\)/g\(_{\text{water}}\) is less than that of 0.05 concentration slurry. This behavior of the viscosity peaking at a concentration of 0.40 and then dropping back down at 0.45 is evident in all but the lowest three shear rates tested. Generally the greatest effective viscosity of an ash slurry occurs at a concentration of 0.40 g\(_{\text{sed}}\)/g\(_{\text{water}}\).

This dramatic drop in effective viscosities of ash slurries at higher concentrations is particularly important because it occurs at shear rates that have been observed in naturally occurring debris flows. This reduction in viscosity weakens the slurry and makes it more likely to slide. If the hypothesis that an increase in effective viscosity of the debris flow leads to a reduction in settling velocity and in turn an increase in bulk density of the flow holds true, then in the case of an ash-only debris flow, the most erosion would occur at low to moderate (0.30 to 0.45) concentrations and shear rates ranging from to 7 to 20 s\(^{-1}\). However, this may not be the case when the effective
viscosity of a high concentration ash slurry drops significantly at higher shear rates. An ash slurry under these conditions would be very structurally weak and prone to instability. High concentration ash slurries must be capable of creating a fabric of some type that reduces their effective viscosity at shear rates greater than 5s\(^{-1}\). Regardless of the physical cause of this decrease in effective viscosity, ash slurries behave fundamentally different than the clastic sediment slurries tested in these experiments.

Silt and sand slurries also have a few peculiar behaviors at various shear rates. At intermediate shear rates (18 to 35s\(^{-1}\)) silt slurries appear to always have a peak effective viscosity at a concentration of 0.45 \(\text{g}_{\text{sed}}/\text{g}_{\text{water}}\). At low shear rates, the effective viscosity of the slurry steadily increases as the concentration increases. The effective viscosity of sand slurries also steadily increases as concentration increases for shear rates up to 18s\(^{-1}\). At higher shear rates the effective viscosity of sand slurries steadily increases with the exception of a lower viscosity at a concentration of 0.50. However, after the low at 0.50 the effective viscosity then continues to increase.

Combining sediments into the four different mixed slurries tested appears to remove some of the particular behavior of the separate slurry types. With a few minor exceptions, the mixed slurries have an effective viscosity that increases steadily with increasing concentration of the slurry. The combination of different grain sizes and grain shapes in the slurry does may not allow particles to align which would reduce the effective viscosity of the slurry. In all cases, the effective viscosity of the slurry containing ash, silt and sand fell between the silt and sand slurries which tend to form the upper and lower limits of the effective viscosity data as seen in Figures 35 to 41.
All slurries, regardless of sediment composition and sediment concentration, had lower effective viscosities as the shear rate increased. In some cases there was as much as a 10-fold decrease in the viscosity of the slurry from a shear rate of $1\text{s}^{-1}$ to $40\text{s}^{-1}$. Shear thinning behavior implies that once a flow begins on a hillslope and the shear rate increases as the flow speeds up, the flow will continue to weaken and will not stop. This is consistent with field observations that flows only stop when the slope decreases or the flow hits some sort of barrier (topographic, slope break, stream, etc). Ash-only slurries exhibited the most drastic shear thinning due to their extremely high effective viscosities at very low shear rates. Ash-only slurries appear to be the most dependent on shear rate of all the slurries tested. This is most likely because they are more likely than sand and silt to align while being sheared, thus reducing their viscosity.

Silt slurries exhibited another interesting phenomenon; the effective viscosity of a silt slurry of any concentration was very similar over shear rates of 7 to $15\text{s}^{-1}$. This can be seen by the flat lines for all concentration series in Figure 12. This implies that at shear rates of 7 to $15\text{s}^{-1}$, the effective viscosity of a silt slurry does not depend on shear rate. This also means that if Equation 12 is used to model silt slurries, it must be noted that over these shear rates, the equation will not give an accurate estimate of effective viscosity. Natural debris flows can have shear rates within this range, so this “flat” area in the effective viscosity versus shear rate graphs may allow future researchers to apply a single effective viscosity to a silty debris flow that has shear rates within this range. Silt particles may be able to align in some way that makes them immune to changes in shear rate between 7 and $15\text{s}^{-1}$. However, when ash and silt are mixed, this phenomenon no longer occurs. An ash+silt slurry exhibits very similar behavior to ash slurries. The ash
appears to overpower the silt’s tendency to have the same effective viscosity at those shear rates and the slurry as a whole behaves similarly to an ash slurry. The combination of ash and silt also fits the power law equation to a much better degree than ash-only slurries.

Sand slurries also exhibited similar effective viscosities at each concentration over shear rates of 7 to 15s$^{-1}$. The effective viscosity of sand slurries appears to be independent of shear rate for this range of shear rates. Even when ash and sand are combined to form a slurry, this behavior persists. The ash is unable to overcome sand’s tendency to have the same effective viscosity over this range of shear rates, unlike when ash is combined with silt. Also, when silt and sand are combined, the effective viscosity of a slurry of any concentration is independent of shear rate at shear rates of 7 to 15s$^{-1}$. Silt and sand both must have one or more intrinsic properties which allow slurries of silt and sand to have an effective viscosity which is independent of shear rate between 7 and 15s$^{-1}$. Further investigation is needed to determine what makes silt and sand behave in this manner, as the shear rates over which this behavior occurs are within the range of naturally occurring debris flow shear rates.

In slurries where all three types of sediment are present, there are no shear rates where the effective viscosity is the same. As seen by the $R^2$ values in Table 13, there is a distinct shear thinning that occurs according to the power law equation seen in Equation 12. Again, the ash behavior dominates over the silt and sand.

In Figures 42-47 it can be seen, that while the shape of the curves for each slurry type may be similar, none of the slurry types tested behaved identically. This illustrates the importance of field research to determine what types of sediment are mobile on a
hillslope and likely to form a debris flow. For example, an ash-only slurry with a concentration of $0.6 \, \text{g}_{\text{sed}}/\text{g}_{\text{water}}$ has an effective viscosity of nearly 300cP at a shear rate of $1s^{-1}$ whereas a sand only slurry has an effective viscosity of about 150cP at the same conditions. This two-fold difference in viscosity could have important implications on the slurry’s ability to erode a hillslope.

Due to the high degree to which the effective viscosity depends on shear rate, it becomes essential to have a way to relate the viscosity of the slurry to the shear rate at which it is being exposed. It is clear from these experiments that ash slurries do not behave the same as clastic sediment slurries, therefore it becomes necessary to have two equations to calculate the effective viscosity of a debris flow, one for ash flows and one for clastic sediment mixtures. Equation 12, shown again below, can be used to model the effective viscosity of debris flows with a small ash component:

$$\mu_m = (400.7\psi + 1.0)\gamma^{-0.5}$$

where $\mu_m$ is the effective viscosity of the slurry (cP), $\psi$ is the concentration by mass of sediment in the slurry (unitless), and $\gamma$ is the shear rate ($s^{-1}$). To model the effective viscosity of a debris flow with a large ash component of sediment, Equation 5 must be used and the appropriate $b$ value must be chosen from Figure 10:

$$\mu_m = (547.9\psi + 5.3)\gamma^b$$

where $\mu_m$ is the effective viscosity of the slurry (cP), $\psi$ is the concentration by mass of sediment in the slurry (unitless), $\gamma$ is the shear rate ($s^{-1}$), and $b$ is an empirical constant (unitless) that depends on concentration and can be chosen from Figure 9. Despite the limitations of these equations previously mentioned, these two equations allow one to estimate the effective viscosity of a debris flow if three items are known or estimated: the
composition of the sediment in the flow, the concentration of the flow, and the shear rate of the flow.

There is a critical transition between an ash-poor and ash-rich slurry that results in the necessity of the two equations. Figure 58 below is a stability analysis in concentration space of the slurries tested in this experiment. For slurries containing less than 50% ash, Equation 12 can be used to solve for the effective viscosity of the flow given the shear rate and concentration of sediment. Equation 12 also holds true for ash and sand mixtures, which these experiments showed behaved similarly to ash-poor flows. It is hypothesized that ash and sand mixtures may continue to act as an ash-poor slurry until the ash makes up more than 66% of the sediment within the slurry. For ash and ash+silt slurries, however, the \( b \) value does not remain constant in Equation 5, so there are a series of equations with differing \( b \) values that need to be used based on the concentration of ash. As the \( b \) value becomes more negative in Equation 5, the slurry shear thins more rapidly, meaning that at moderate shear rates the slurry is not as viscous and, therefore, weaker and more prone to sliding. This is most likely why debris flows are more likely to occur when ash is present on the hillslope. It becomes necessary to change the hypothesized ash-laden flow model to include this critical transition from a strict progressively bulked flow to one where ash is dominant, as seen in Figure 59 below.
Figure 58. Stability diagram of sediment-water slurries in concentration space.

\[ \mu_m = (400.7 \psi + 1.0) \gamma^{0.5} \]

\[ \mu_m = (547.9 \psi + 5.3) \gamma^{0.5} \]
Figure 59. Modified hypothesis for a progressively bulked debris flow which has a high percentage of ash particles relative to clastic sediments.

A $b$ value of -0.5 in the case of slurries containing less than 50% ash means that effective viscosity is related to the inverse square root of shear rate. This could be the result of perfectly elastic collisions between the clastic particles (Bird et al., 2006). In the case of a slurry containing more than 50% ash, the $b$ value is not always -0.5, an indication that there are not perfectly elastic collisions occurring between ash particles. This could be a result of ash’s inconsistent particle size and irregular shape.

These experiments confirmed Poletto and Joseph’s (1994) results, showing that the addition of fine sediment generally increased the viscosity of the flow. Poletto and Joseph’s (1995) equation (Equation 1) related the effective viscosity of a mixture to the effective viscosity of the fluid and the volumetric fraction of the solid particles, along with an empirical constant that depended on particle size, composition and rounding.
This equation did not take shear rate into account. Because all of the slurries tested showed that, with few exceptions, viscosity was almost equally dependent on shear rate and concentration, a new equation had to be developed to account for this dependence on shear rate (Equations 5 and 12).

A Bingham model describes a material that flows like a viscous fluid once stresses applied exceed the yield strength of the material (Bird et al., 2006). Johnson (1970) proposed that debris flows fell within this model. The slurries tested in this experiment can be classified as a Bingham model material since the yield strength of the material was surpassed by the shear applied by the viscometer and the slurries began to flow. More specifically, the slurries exhibited power-law fluid behavior once they began to flow. A power-law fluid can be described by the Ostwald-de Waele power law (Bird et al., 2006):

\[
\mu_{\text{eff}} = K \left( \frac{\delta u}{\delta y} \right)^{n-1}
\]

where \( \mu_{\text{eff}} \) is the effective viscosity (Pa*s) of the mixture, \( K \) is the flow consistency index (Pa*s^n), \( \delta u/\delta y \) is the shear rate (s^-1), and \( n \) is the flow behavior index (unitless). If \( n<1 \), the fluid can be classified as pseudoplastic. While there are a number of other models that better describe the entire flow behavior of shear-dependent fluids, they are more mathematically complicated and difficult to exactly determine without the use of time-lapse photography (Bird et al., 2006). In most instances, the power law in Equation 13 is still used to describe fluid behavior, permit mathematical predictions and correlate experimental data (Bird et al., 2006).
Equations 5 and 12 developed in this experiment are similar to those of a pseudoplastic fluid (Equation 13). For ash- and fine-sediment-laden slurries, $K$ becomes a function of concentration. The $b$ constant in Equation 5 and 12 can be substituted for $n-1$ in Equation 13, clearly showing that $n$ is less than one for the slurries tested. Therefore, the slurries tested can be classified as pseudoplastic.

A pseudoplastic, or shear thinning, fluid has a lower effective viscosity at higher shear rates (Bird et al., 2006). It is generally supposed that the solid particles tumble at random and cause a high effective viscosity at low shear rates but gradually align themselves in the direction of increasing shear and produce less resistance at higher shear rates. This alignment of particles results in the distinct shear thinning behavior that is seen throughout these experiments (i.e. Figure 6). If more than one particle size and shape are present in the mixture, alignment of particles cannot occur to such a great degree as in single particle type mixtures (Bird et al., 2006). The slurries containing a combination of sediment types did not shear thin as distinctly as the single sediment mixtures did, most likely a result of the interference between grains that prohibited the alignment of particles in the slurry.

This project is limited in that for the slurries that contained multiple sediment types, the amount of sediment in the slurry was split evenly among the sediment types. This additional work would be helpful in determining at what percentage of ash it becomes necessary to use Equation 5 instead of Equation 12. Currently, it is known that Equation 5 is required to calculate the effective viscosity of 100% ash slurries, but that Equation 12 is appropriate for slurries with 50% ash. More research could be done testing more combinations of sediment, for example, a slurry that was 70% ash, 20% silt
and 10% sand to determine if this slurry would behave similarly to the ash-only slurry and therefore required the use of Equation 5.

For hazard assessment, it can be useful to determine the best and worst case scenarios. Because of the hypothesis that effective viscosity of the debris flow is related to the erosivity of the flow, determining those flows with the lowest and highest viscosity provide upper and lower bounds on the erosive potential of a debris flow. Debris flows in burned areas are not likely to contain only ash. So even though the effective viscosity of an ash slurry is greatly decreased at high concentrations at moderate shear rates, this phenomenon would most likely not be seen on a hillslope. More likely, effective viscosities of a debris flow in a burned area would fall in the range of one of the mixtures tested in the lab. Therefore, the highest effective viscosities (and most likely erosion) would occur at high concentrations of sediment, a higher percentage of ash and low shear rates. Because shear rate can be calculated as flow velocity divided by flow depth (Bird et al., 2006), these conditions would occur in a natural setting as a deep, dense (highly concentrated) flow moved slowly down a hillslope. Conversely, the least erosion will take place at low sediment concentrations with a higher percentage of sand and high shear rates. This would be the case of shallow, slightly-sedimented overland flow moving quickly down a hillslope. Work is on-going to relate the changes in effective viscosity caused by a variety of sediment types and concentration into the change in settling velocity, bulk density and increased shear stress of the hillslope. This work is integral in connecting the change in viscosity caused by the addition of sediment to overland flow and the erosivity of a debris flow in a previously burned area.
CONCLUSION

Debris flows in burned areas may propagate through a combination of progressive bulking and shear thinning. The first step in the progressive bulking sequence is the increase in effective viscosity of the flow that results from sediment being entrained in overland flow. Identifying the conditions that result in the greatest change in effective viscosity is important in determining which areas may be most at risk of a debris flow following a forest fire. Also, ash on the hillslope will become entrained in these flows as well as clastic sediments which may have been present prior to the fire. Little research has been done to determine how the addition of ash into a debris flow changes its rheological properties. This study determined that ash behaved differently than clastic sediments when acting alone in a flow. However, these behaviors particular to ash become less pronounced when silt or sand are added to the mixture.

Flows containing a high percentage of ash behave differently than flows that contain mainly silt and sand. Therefore it was necessary to develop two different equations to calculate the effective viscosity of either an ash-rich or ash-poor debris flow (Equation 5 and 12 respectively). These two equations allow for the calculation of the effective viscosity of the flow when the sediment concentration of the flow and the flow’s shear rate is known.

Ash plays a critical role in the propagation and travel downslope of debris flows due to its unusual properties. An ash-laden slurry does become more viscous with the addition of ash particles until a threshold concentration (usually 0.5) is reached and the slurry exhibits a decrease in effective viscosity. This increase is effective viscosity with increasing concentration fits the hypothesis of progressive bulking presented. The
increase in effective viscosity could lead to a reduction in settling velocity of the particles within the slurry, causing the flow to become more dense and exert a greater shear stress on the hillslope. However, ash plays a roll in keeping the flow moving downslope. The decrease in viscosity at higher concentrations causes the slurry to become weaker and, on a slope, more likely to slide or keep sliding. Ash within a flow may cause the flow to bulk initially and, later, as concentration increases, to weaken.

If existing debris flow models are used in areas that have been burned by wildfire, it is important to note that they may not accurately predict or model the debris flow because they do not take into account the ash on the hillslope.
REFERENCES


