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Internal Structure and Rheology of Post-Wildfire Debris Flows

A Dissertation submitted in partial satisfaction of the requirements
for the degree Doctor of Philosophy

in

Structural Engineering

by

Wenpei Ma

Committee in charge:

Professor Ingrid Tomac, Chair
Professor John Scott McCartney
Professor Oliver Schmidt
Professor Qiang Zhu

2024

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University of California San Diego

2024

DEDICATION

To my mom, Yuan Wang, for her love and support,
and to my late dad, Chunlong Ma, for being my inspiration and motivation

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FIELD OF STUDY

Major Field: Geotechnical Engineering
Studies in Post-Wildfire Debris Flow
Professor Ingrid Tomac

ABSTRACT OF THE DISSERTATION

Internal Structure and Rheology of Post-Wildfire Debris Flows

by

Wenpei Ma

Doctor of Philosophy in Structural Engineering

University of California San Diego, 2024

Professor Ingrid Tomac, Chair

This work provides a novel understanding of the internal structure and the rheological behavior of post-wildfire debris flows. During the wildfire process, the topsoil layer becomes hydrophobic due to the condensation of chemicals that are released from burning vegetation and organic matter. Hydrophobic soil causes problems such as reducing water infiltration rate, prolonging the wetting process, increasing soil erosion, forming preferential flow paths, changing hydrological characteristics of the watershed, and inducing severe mudflow, debris flows, or mudslides. This work hypothesizes that air, intermixed into a flowing mudflow, plays a critical role in modifying post-wildfire mudflow behavior compared to regular mudflows. Liquid marbles

form because mudflows can entrap hydrophobic soil particles. Liquid marbles have air bubbles in the center, covered by hydrophobic soil particles. Existing investigations and research include many different rheological models for post-wildfire mudflow slurries, ignoring the role of entrapped air bubbles. This research provides new insights to explore the air entrapment mechanism and to incorporate entrapped air into the rheological responses of post-wildfire mudflow. For example, preliminary findings reveal that fully covered liquid marbles (i.e., air bubbles with the entire surface covered with hydrophobic sand particles) will replace all partially covered liquid marbles (i.e., air bubbles with part of the surface vacant of sand particles) after 50 seconds of mixing. Micromechanical analysis of submerged hydrophobic particle to air bubble attaching and detaching forces in the particle-bubble interaction reveals conditions that lead to stable liquid marbles in post-wildfire mudflows. The amount of new liquid marbles depends on mixing speed, mixing time, and sand particle diameter. Larger sand particles and higher air entrapment lead to a collision-dominated flow regime. In addition, what has not yet been understood is the role of hydrophobic particles and air entrapment in the case where only a portion of material enrolled into a mudflow is hydrophobic. This work also investigates the flow of such complex mixture in an open channel using the GeoPIV method. Overall, this work provides a greater understanding of the internal structure and rheological behavior of post-wildfire mudflows and contributes to better analysis of future debris flow runoff and sediment transport events.

Chapter 1 Introduction

1.1 Research Motivation

Severe and destructive wildfires are more frequent, and they have caught people's concerns in recent years in the United States and around the world. Some of them have been repeatedly reported within a certain time range in mass media and social media and induce severe public fears: the 2023 Canadian wildfires, the 2022 European and Mediterranean wildfires, the 2020 California wildfires, the 2020 Brazil rainforest (Amazon) wildfires, and the 2019-2020 Australian bushfire season ("Black summer"). Wildfires erase surface vegetation and alter the hydrological and ecological characteristics of local regions. A hydrophobic soil layer forms at the top due to the condensation of chemicals during the burning of organic matter (DeBano et al., 1979; DeBano, 1981, 1991, 2000; Neary et al., 2005) (**Figure 1.1b**). During the rainstorm event, the surface rain water runoff erodes the top hydrophobic soil and entraps air bubbles, developing into devastating post-wildfire debris flows (**Figure 1.1c**). As a result, local communities face severe damage in the aftermath (**Figure 1.1d**).

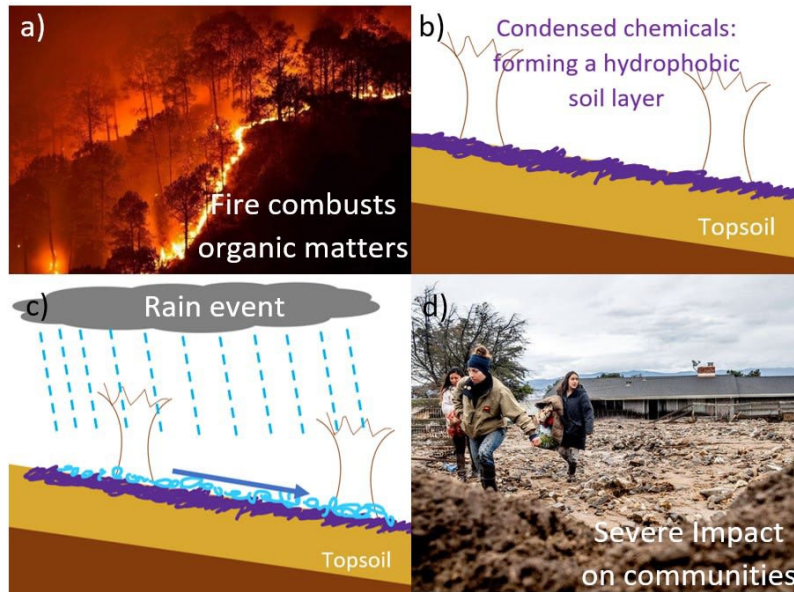


Figure 1.1. Formation of Post-Wildfire Debris Flow: a) Wildfire Combusts Organic Matters, b) Top Hydrophobic Soil Layer Forms after Fire, c) Storm Rain Water Erodes Surface Soil, and d) Local Communities Undergoes Huge Damage. Image Courtesy to NY Times.

Soil hydrophobicity plays an active role in the above disaster. Debris flow can easily entrap massive air bubbles and form liquid marbles due to soil hydrophobicity. Those liquid marbles make it different from general debris flows. This research includes a series of fundamental studies that intend to understand how liquid marbles form, how the presence of liquid marbles affects the internal structure of the debris flow, how the presence of liquid marble affects the rheological behavior of debris flow, how different levels of hydrophobicity affect the formation of liquid marbles, how different levels of hydrophobicity affect the rheological behavior of the debris flow, and how the debris flows with liquid marble flow differently from general debris flow in an open channel. Besides, this research also has a side project that investigates environmentally friendly methods to reduce soil hydrophobicity and slope erosion.

1.2 Research Objectives

This research aims to understand better the mechanism of the air entrapment process in the post-wildfire debris flow and the role of air entrapment in the rheological behavior of such a complex mixture. There are five specific objectives:

- Objective 1: To quantify the forces that cause the liquid marble formation to be made of completely hydrophobic solids on water under post-wildfire debris flow-like conditions like soil types and shear rates.
- Objective 2: Based on Objective 1, to develop novel rheological laws for complex mixtures that contain liquid marbles in water under different shear rates, volumetric concentrations, and sand types.
- Objective 3: Based on Objectives 1 and 2, quantify the air entrapment due to different levels of solid hydrophobicity. Besides, to establish the relationship between levels of solid hydrophobicity and rheological behavior of the post-wildfire debris flow-like material.
- Objective 4: Based on Objectives 1, 2, and 3, to validate the rheological relationships of post-wildfire debris flow-like material in a laboratory condition under the effects of levels of solid hydrophobicity and slope inclination angle.
- Objective 5: To advance erosion remediation techniques by investigating different covers like Xanthan Gum and Sodium Cocoyl Isethionate as surface tension modifiers for hydrophobic sand surfaces. The effectiveness of surface modifiers will be assessed by quantifying the contact angle and waterdrop penetration time reduction due to the selected modifiers. In addition, this objective aims to quantify erosion reduction and to develop a theoretical prediction of infiltration due to selected modifiers.

1.3 Dissertation Structure

This dissertation is prepared as a paper-based dissertation. The contents from each chapter are partially or completely adopted from the paper drafts that are prepared to be submitted to peer-reviewed journals. Some contents are adopted from published materials from conferences. The organization of chapters for this dissertation is summarized as follows:

Chapter 2 presents the fundamental background and literature reviews relevant to wildfire severity and post-wildfire debris flow, air-water-solid interactions, rheological models considered in the literature, open channel experiments done by previous researchers, the PIV method, and the GeoPIV analysis.

Chapter 3 presents the materials and methodology that this research uses. This chapter shows what type of sand particles are used in the study and how they are treated hydrophobic. After sand material, this chapter also includes experimental designs for each of the objectives.

Chapter 4 presents the results of the air entrapment mechanism experiment. This chapter shows how air bubbles get entrapped and what factors have an impact on the formation of liquid marbles. In addition, density reduction estimation due to entrapped air bubbles is summarized.

Chapter 5 presents the results of the rheological behavior experiment. Bagnold number is a powerful indicator for distinguishing flow regimes from viscous fluid regimes and collision-dominated regimes. Based on the Bagnold number, this chapter summarizes how the rheological behaviors are different in each regime at different shear rate ranges.

Chapter 6 presents the results of the mixed hydrophobicity experiment. This chapter studies how air entrapment and the mixture's rheological behavior differ as the levels of hydrophobicity of the sand solids are different.

Chapter 7 presents the results of the open-channel experiment. GeoPIV analysis helps to provide velocity profiles for debris flows along the open channel. This chapter investigates how the hydrophobicity can alter the flow behavior of the mixture. This chapter also tries to answer the influence of levels of hydrophobicity and slope inclination on flow profiles.

Chapter 8 presents the results of the soil hydrophobicity remediation experiment. Xanthan Gum (XG) and Sodium Cocoyl Isethionate (CSI) are used to explore the ability to reduce soil hydrophobicity. This study also investigates how CSI behaves during erosion control tests under different environmental conditions.

Chapter 9 concludes and summarizes all the findings of this research.

Chapter 2 Background and Literature Review

2.1 Wildfire and Post-Wildfire Debris Flow Severity

Postfire mudflows are devastating natural disasters whose frequency increases with climate change and wildfire events worldwide, including California (CALFIRE, 2017, 2018, 2020, 2021) and the Western US, the Pacific West, Canada, Europe, and the Mediterranean. In addition, the severity of fire events is likely to increase in the future for most areas due to an increase in regional temperature and dryness (Fried et al., 2004; Westerling & Bryant, 2008; Westerling et al., 2011; Abatzoglou & Williams, 2016; Lozano et al., 2017; Wotton et al., 2017; Williams et al., 2019; Dupuy et al., 2020; Goss et al., 2020; Halofsky et al., 2020). Postfire mud- and debris flow differ from most natural mudflows because of fire-induced soil wettability modifications. Wildfires combust organic fuel-like plant parts in soil and generate hydrophobic substances that precipitate and coat granular soil particles (DeBano et al., 1979; DeBano, 1981, 1991, 2000a; Neary et al., 2005). The fire-induced hydrophobic soil layer averages between 0.5 cm to 5 cm (Parsons et al., 2010) and can be up to 16 cm (Huffman et al., 2001) reported on burned chaparral lands in southern California in the 1960s (DeBano et al., 1967; Savage, 1974; DeBano et al., 1976; DeBano, 2000a, 2000b; Neary et al., 2005), and has been regularly classified in Burned Area Response (BAER) reports (USDA Forest Service, 2021a, 2021b, 2021c). According to Morell et al. (2021), in collected sediments from nearby channels around the 2018 Montecito debris flow event that are 90% aerial coincident with the 2017 Thomas Wildfire, at least 550,000 m³ of sediments are captured in a watershed of 25.5 km². Thus, the rough estimate of scour depth would be 2.5 cm. Assuming the hydrophobic layer is on the order of 1 cm, the collected sediments contain roughly 40% hydrophobic particles. Considering the time factor of the flooding process, this percentage must be higher at the beginning of an erosion event. Nevertheless, debris flow material has various

resources, and the hydrophobic particles have uncertain concentrations. Some of the collectible debris mainly comes from the hydrophobic hillslopes (Staley et al., 2014), while some of the collectible debris mainly comes from the general channels and gullies (Santi et al., 2008; Rengers et al., 2023). There are also scenarios that the collectible debris comes from a combination of hillslopes and channels (Tang et al., 2019). Currently, it is very hard to estimate how much of the sediments contain hydrophobic material. Although wildfires can also reduce the long-term soil hydrophobicity in rare, naturally highly water-repellent areas (Tessler et al., 2013), this research applies to regions with naturally wettable soil that becomes hydrophobic after wildfire, like the USA's arid southwest.

Postfire debris and mudflows initiate from shallow slopes, as well as channels, bank failures, and shallow landslides several years after the fire, when rain erodes burned scars' loose surficial soil layers and subsequently carries debris downhill, endangering lives and properties (Cannon et al., 2001; Cannon et al., 2008; Kean et al., 2019; Tang et al., 2019; Thomas et al., 2021). Different initiation processes will lead to different compositions in the general debris and mudflows. The internal structure and composition of postfire mudflows in real life are difficult to quantify due to their short duration and fast flows, up to 30 km/h (Hamilton & Serna, 2018, as cited in Cui et al., 2018). Limited studies have reported postfire sediment yield, hydraulic recovery, hydrophobic bed role, entrainment into mudflows, and erosion patterns (Kean et al., 2011; Lamb et al., 2011; Gartner et al., 2014; Staley et al., 2014; Ebel, 2020; Morell et al., 2021; Thomas et al., 2021; Ng et al., 2022; Perkins et al., 2022). For example, the solid volumetric concentration varies and can be as high as 60% in postfire mudflows and debris flows (Conedera et al., 2003; Cannon et al., 2001; Cannon et al., 2008; Kean et al., 2011; Cui et al., 2018; Lee & Widjaja, 2013). In addition to solids and water, Bull (1963) described for the first time how air entrapment occurs in

mudflows. Mudflow traps air from the atmosphere while flowing down the tributary ravines and channels, and existing air from pores in the soil deposits can roll into the mudflow. Bull (1963) postulated that part of the air becomes trapped by mudflow and forms bubble cavities that are qualitatively shown in mudflow deposit images and have different shapes and sizes based on sediment material. Furthermore, mudflows can entrap air when obstacles impact the flow (Song et al., 2021; Garoosi et al., 2022). In addition, the air entrapment rate in a granular flow depends on the gradient of solid velocity and flow thickness (Sheng et al., 2013), enhanced by particle hydrophobicity (Cervantes-Álvarez et al., 2020).

2.2 Hydrophobicity and Air Entrapment

Since wildfires turn surficial soil hydrophobic and hydrophobized granular materials, likely contain excess air, this paper investigates micromechanics of hydrophobic particle-air-water mixtures to understand better postfire internal composition, air entrapment mechanisms, and density modifications. While previous research highlighted the importance of solids availability on total air entrapment when grains enter the water, further enhanced by hydrophobicity (Cervantes-Álvarez et al., 2020; Ong et al., 2021), the air entrapment dynamics has not been fully quantified for flowing mixtures. Wang et al. (2016) observed submerged three particle-air bubble detachment mechanisms: centrifugal force on particles due to the rotation of the air bubble about its axis in a vortex, irregular trajectories of the particle-bubble complex under motion, strong oscillation of the bubble surface, which expels the particles. Furthermore, although many studies investigate the formation and stability of a single liquid marble, which is an air bubble whose surface is covered with a layer of hydrophobic particles (Bormaschenko, 2011; McHale and Newton, 2011, 2015), as further explained in section 2.3 to 2.5, the macro-level effects of particle-

bubble interactions and dynamics of liquid marbles formation in a flowing mixture with numerous particles and bubbles are poorly understood. In addition to mudflows, air entrapment into particle-water slurries is relevant in engineering applications (Suhr et al., 1984; Römken et al., 1997; Sheng et al., 2013; Tanaka et al., 2019; Cervantes-Álvarez et al., 2020; Dunkerley, 2020; Ong et al., 2021; Garoosi et al., 2022).

2.3 Forces Involved in Particle Bubble Interaction

The internal structure of the multiphase system, which consists of hydrophobic solid particles and air bubbles submerged in water, depends on an interphase force balance. Particle-bubble interaction involves attractive and repulsive forces, including capillary, hydrostatic pressure, hydrodynamic drag, net weight, centrifuge, local turbulence, and van der Waals forces (Schulze, 1982; Preuss & Butt, 1998; Ralston & Dukhin, 1999; Nguyen & Evans, 2002a, 2002b; Phan et al., 2003; Pyke et al., 2003; Gillies et al., 2005; Tao, 2005; Johnson et al., 2006; Wang et al., 2016a; Ekanlou et al., 2019). Gravity mainly contributes to particle-bubble detachment (Phan et al., 2003). For example, when a particle passes a bubble during falling (Verrelli et al., 2011) and slides towards the lower bubble hemisphere (Maxwell et al., 2012) or detaches (Gao et al., 2014). Gravity promotes attachment when a particle penetrates an air bubble at a certain grazing trajectory collision angle (Schulze, 1989). Van der Waals force (Lu, 1991) and electrostatic forces from Derjaguin-Landau-Verwey-Overbeek (DLVO) theory are only crucial for nanoparticles and not mm-scale sand particles. Capillary force (F_c) at the particle-bubble-liquid interface is:

$$F_c = \frac{\pi D_p \sigma (1 - \cos \theta)}{2} \quad (2.1)$$

where, D_p is particle diameter (m), σ is the fluid surface tension (N/m), and θ is the contact angle at the interface between particle-fluid-bubble interface ($^\circ$). The particle diameter is assumed to be much smaller than the bubble diameter. Therefore, the sand particle roughness effect is minimized at the bubble-particle contact point. According to Movasat et al. (2023), the contact angle of a smooth sand particle surface can be assumed to be 91° .

The net excess force (F_{es}) for the bubble (Tao, 2005) is the difference between two parts: the excess pressure in the bubble (favoring particle-bubble attachment) and the hydrostatic force (favoring particle-bubble detachment):

$$F_{es} = \frac{\pi}{4} D_p^2 (1 - \cos\theta) \left(\frac{2\sigma}{D_b} - \frac{\rho_w g D_b}{2} \right) \quad (2.2)$$

where ρ_w is water density (kg/m^3), D_b is the bubble diameter (m), and g is the acceleration due to gravity (9.8 m/s^2). The same contact angle is applied here. The bubble diameter should be less than 5.5 mm to maintain the attaching effect on particle-bubble interaction (Tao, 2005).

The net weight force of a sand particle (F_w), which is the difference between particle weight and buoyance force, shows the real weight of a particle partially immersed in the water due to attachment to a bubble (Drzymala, 1994). The net weight is generally a repulsive force (Tao, 2005):

$$F_w = \frac{\pi}{6} D_p^3 \rho_p g - \frac{\pi}{8} D_p^3 \rho_w g \left[\frac{2}{3} + \cos\left(\frac{\theta}{2}\right) - \frac{1}{3} \cos^3\left(\frac{\theta}{2}\right) \right] \quad (2.3)$$

where, ρ_p is particle density (kg/m^3).

The hydrodynamic drag force (F_{hd}) includes far-field flow conditions and short-range particle-bubble hydrodynamic force (Nguyen & Evans, 2002b) and is:

$$F_{hd} = -3\pi\mu D_p V f_1 + 3\pi\mu D_p W f_2 \quad (2.4)$$

where, μ is the dynamic viscosity of fluid (kg/m-s), V is the particle slip velocity (m/s), W is the undisturbed velocity of liquid (m/s), h , f_1 , and f_2 are correction factors (Nguyen & Evans, 2002b):

$$f_1 = \left[1 + \left(\frac{D_p}{2H} \right)^{0.719} \right]^{\frac{1}{0.719}} \quad (2.5)$$

$$f_2 = \frac{f_2' - h f_2''}{1 - h} \quad (2.6)$$

$$f_2' = \frac{1.707 + 2H/D_p}{0.836 + 2H/D_p} \quad (2.7)$$

$$f_2'' = \frac{2.656 + 2H/D_p}{1.440 + 2H/D_p} \quad (2.8)$$

$$h = \frac{H + 0.5D_p}{0.5d_b} \quad (2.9)$$

where, H is particle-bubble separation (m, for short-range distance, $H = 0.05 \cdot D_p$). Drag reduction due to surface hydrophobicity can be between 19% and 38% from the observed literature (Balasubramanian et al., 2004; Geraldi et al., 2017; Shi et al., 2019).

Finally, when particles move at high speed, there is a local turbulence force (F_t) in the particle-bubble interaction process (Phan et al., 2003; Schulze, 1982). The local turbulence force is:

$$F_t = \frac{4\pi R_p^3}{3} \Delta \rho b_m \quad (2.10)$$

$$b_m \approx \frac{1.9 \epsilon^{\frac{2}{3}}}{D_b^{\frac{1}{3}}} \quad (2.11)$$

where, ϵ is the fluid energy dissipation per unit volume (kW/m^3 , range 1-100).

The liquid film between an approaching particle and an air bubble ruptures as the particle hydrophobicity increases so that it thins until critical and breaks during the collision (Ishida, 2007). Then, a three-point contact develops into a three-phase contact line (TPCL) (Nguyen et al., 1997). The bubble spreads over the particle surface until an equilibrium contact angle occurs (Fornasiero & Filippov, 2017). Hydrostatic pressure enhances the hydrophobic-particle-bubble adhesion (Phan et al., 2003). For example, Fielden et al. (1996) show that hydrophobicity treatment of silica sand leads to a "jump" from repulsive to attractive interactions. Compared to regular sand, the distance between the hydrophobic particle and bubble reduces due to a hydrophobicity-promoted adhesion, which leads to faster TPCL formation and is consistent with the capillary force mechanism at contact angles above 85° . However, despite hydrophobic surface alterations, repulsive forces remain present, and the original electrical properties remain unchanged (Fielden et al., 1996).

2.4 Liquid Marble Stability (Modified Bond Number)

The modified Bond Number (Bo^*) assesses the stability of liquid marble shape in a moving multiphase solid-water-air phase system (Schulze, 1982). Bo^* is the ratio of all detaching forces to the attaching forces of a submerged liquid marble. If Bo^* is less than one, particles will likely stay attached to the bubble; if Bo^* otherwise, particles will detach from the bubble. Bo^* is defined as (Schulze, 1982):

$$Bo^* = \frac{-D_p^2(g\Delta\rho + \rho_p b_m) - D_p\sigma'\sin^2\left(180^\circ - \frac{\theta}{2}\right)}{6\sigma\sin\left(180^\circ - \frac{\theta}{2}\right)\sin\left(180^\circ + \frac{\theta}{2}\right)} \quad (2.12)$$

The parameter b_m is (Wang et al., 2016b):

$$b_m = \frac{\bar{u}^2}{r} \quad (2.13)$$

where, $\Delta\rho$ is the density difference between particle and liquid (kg/m^3), b_m is the eddy turbulent acceleration (m/s^2), σ' is the modified fluid surface tension (N/m^2) $= 4\sigma/D_b - D_b\rho_f g$, $\bar{u}^2$ is the root mean square of the velocities under turbulent condition (m/s), and r is the rotating length scale (m) which a single particle's travel path is the circle circumference that the blade sweeps through.

When the mixture that contains liquid marbles and a smaller amount of free-flowing sand particles submerged in water starts to flow, different flow regimes and internal structure perturbations can occur governed by slope steepness, initial and boundary conditions, and the mixture composition. As a result, the mixture's internal composition changes, including liquid marble modifications, occur. Specifically, the particle presence in water can generally enhance or

decrease turbulence (Gai et al., 2020). Turbulent flow regimes affect fluid drag, particle-bubble relative velocity, and particle dispersion rates, increase collision frequency, and diminish the stability of hydrophobic particle-bubble attachment (Pyke et al., 2003; Liu & Schwarz, 2009). The submerged bubble surface oscillates and loses sphericity at $Re > 700$ (Schulze, 1989). As a result, an air bubble can rotate about the axis and induce a centrifugal force on particles or have an irregular trajectory or oscillate. In contrast, the particles fail to follow the bubble due to inertia in high-velocity fluid (Wang et al., 2016a). Furthermore, the detachment of some hydrophobic particles from the air-bubble bottom surface occurs due to the viscous drag force from the counter-current fluid motion (Eskanolou et al., 2019) or lower localized particle surface-to-volume ratio at higher particle surface roughness and larger sizes (Fornasiero & Filippov, 2017). Additionally, gravity is insignificant relative to inertia for particles with a density like carrying fluid. However, if the particle density is larger than the fluid, the gravity effect surpasses the inertia effect (Brabcová et al., 2015).

2.5 Liquid Marble Size Estimation

The diameter of liquid marbles or particle-stabilized air bubbles depends on liquid density, air density, particle density, particle radius, dispersed liquid phase volumetric concentration, and particle volumetric concentration (Binks and Lumsdon, 2001; Frith et al., 2008; Haney et al., 2019). Frith et al. (2008) theoretically estimated the liquid marble diameter:

$$d_{lm} = 2 r_p \alpha_m \frac{\rho_p - \rho_{cont}}{\rho_{cont} - \rho_{disp}} \quad (2.14)$$

where r_p is the radius of a solid particle; α_m is the packing fraction of solid particles at the droplet interface equal to 0.907 for a closely packed droplet; ρ_p is the density of the solid particle, ρ_{cont} is the density of water or continuous phase liquid, ρ_{disp} is the density of gas or dispersed liquid phase.

Besides, Haney et al. (2019) estimated the diameter of liquid marble (d_{lm}) as:

$$d_{lm} = 0.9 \frac{24\rho_s}{\rho_{\text{cont}}} \beta \frac{V_p}{\pi D_p^2} \quad (2.15)$$

where d_{lm} is the diameter of a droplet; 0.9 is the packing fraction (same as α_m in **Eqn. 2.14**); β is the mass ratio of dispersed phase to particles; V_p is the average volume of a single solid particle.

In addition, the liquid marble diameter (d_{lm}) can also be estimated by Binks and Lumsdon (2001):

$$d_{lm} = \frac{2 \varphi_{\text{disp}} r_p}{\varphi_p} \quad (2.16)$$

where, φ_{disp} is the volume fraction of the dispersed liquid phase to the continuous liquid phase; φ_p is the volume fraction of the particle to the dispersed phase. According to Sutherland (1948), the collision efficiency (E_c) between a particle and a bubble is:

$$E_c = 3 \frac{D_p}{D_b} \quad (2.17)$$

2.6 Common Rheological Models for General Debris Flows

General debris flows are widely studied, and many rheological models have been developed. The linear Newtonian model is the simplest rheological model to describe general debris flow behavior. In the Newtonian model, shear stress is linearly proportional to shear rate. The slope is a constant, which is the viscosity of the fluid. Although inaccurate when the solid volumetric concentration is high, simplifying general debris flow as Newtonian fluid is possible when the solid volumetric concentration is less than 5% (Floyd et al., 2019b). Gorr et al. (2022) use the Newtonian model to approximate the Bingham model at high flow velocities and low yield stress conditions. Bingham fluid model is the Newtonian model with an additional yield shear stress term. The Bingham model can describe various conditions: Hungr (1995) develops a continuum model and applies the Bingham model to simulate landslides, debris flow, avalanches, rockslides, liquefaction failure, and slides of fill and mining wastes. Bingham model is a common model for general debris flows in research (Iverson, 1997; Dai et al., 2002; McDougall & Hungr, 2004; Naef et al., 2006; Bertolo & Bottino, 2007; Medina et al., 2007; Dahl et al., 2012; Travis et al., 2012; Gregoret et al., 2019; Lee et al., 2022; Floyd et al., 2019a, 2019b). Bingham model can fit many different conditions: rapid flow slides (McDougall & Hungr, 2004), steep channel and stopping conditions (Naef et al., 2006), 2-D shallow water approximation (Medina et al., 2007), bulking effects and water discharge change (Travis et al., 2012) and erosion-entrainment condition (Lee et al., 2022).

Herschel-Bulkley (HB) model is another studied nonlinear model for general debris flows (Rickenmann et al., 2006; Medina et al., 2007; Sosio et al., 2007). HB model expands the Bingham model so that the model can describe fluids from shear-thinning to shear-thinning. Rickenmann et al. (2006) compare simulation results with field events using the HB model. Medina et al. (2007)

compare the accuracy of the Bingham model and HB model. Sosio et al. (2007) confirm that shear-thinning HB behavior is suitable if general debris flow has a shear rate of smaller than 5 s^{-1} .

O'Brien & Julien (1988) and O'Brien et al. (1993) models try to incorporate the effect of solid concentration into the rheological behavior of general debris flows. The second model is commonly referred to as the quadratic model. O'Brien & Julien (1988) model is accurate when the solid concentration is between 10% and 45%. O'Brien et al. (1993) model is applicable if the solid concentration is higher than 10%. Naef et al. (2006) use the O'Brien et al. (1993) model to conduct 2D debris flow numerical simulation in FLO-2D software. Pirulli (2010) applies the quadratic model to a case study in Hong Kong where a massive debris flow occurs and predicts the behavior of a potentially even larger debris flow. Travis et al. (2012) uses quadratic model in HEC-RAS software. Chen et al. (2016) simulate the interaction among multiple debris flows.

As solid particle content increases, the internal solid-solid or solid-fluid interaction dominates the shear flow behavior instead of simple viscous fluid inertial forces. Coulomb friction provides all resistance to motion (Iverson, 1997). However, Mohr-Coulomb frictional rheology does not include the velocity-dependent shear stress (Pirulli, 2010). The Coulomb-Viscous model combines Mohr-Coulomb frictional rheology and the Bingham model. McDougall & Hungr (2004) use the Coulomb-Viscous model to simulate a rapid flow slide problem such as a dam break problem. Lee et al. (2022) use the Coulomb-Viscous model to conduct numerical simulations for a landslide event in Korea.

The Voellmy (1955) model was initially applied to simulate snow avalanches and incorporates the effect of turbulence; it was later used to model turbulent cohesionless landslides with granular materials, with or without fluids (Hungr, 1995; Hürlimann et al., 2003; van Asch et al., 2013). The use of the Voellmy mode in general debris flow studies is more common than in

Coulomb models (Hungr, 1995; McDougall & Hungr, 2004; Naef et al., 2006; Rickenmann et al., 2006; Pirulli, 2010; Lee et al., 2022).

2.7 Rheological Models for Post-Wildfire Debris Flows

Post-fire debris flow is a relatively new topic. Most rheological models for post-fire debris flows evolve from the models for general debris flows. Floyd et al. (2019b) point out that simplifying post-fire debris flow as Newtonian fluid is the same as simplifying general debris flow as long as the solid volumetric concentration is lower than 5%. Gibson et al. (2021) confirm that a 5% concentration is a threshold between Newtonian and non-Newtonian behavior for post-fire debris flows in a numerical analysis of flume experiments. Bingham model and its variation are widely used to model post-fire debris flows. O'Brien et al. (1993) used the Bingham model to develop the well-known FLO-2D model. Note that the Bingham model is mostly applicable if the debris flows are hyper-concentrated sediment flows of fine sediments (O'Brien et al., 1993). Bingham model behaves better if the debris flows are visco-plastic under a laminar environment (Melo et al., 2018). Bingham model is also better if the debris flows are under a low shear rate of less than 5 s^{-1} (Wasklewicz & Scheinert, 2016). Gibson et al. (2021) point out that the Bingham model is better than the Newtonian model if the solid concentration is larger than 5%. Prochaska et al. (2008) developed a database of Bingham properties to investigate the feasibility of using laboratory measurements for both general and post-fire debris flow velocity predictions. Gao & Choi (2023) observe a Bingham behavior in the rheometer measurement of artificially heated soil samples.

Kostynick et al. (2020) fit rheometer measurement results with the HB model for soil samples from burned sites, considering the effects of fine components, jamming, and critical strain.

Gibson et al. (2021) verify the HB model numerical simulation with experimental data. Later, Kostynick et al. (2022) fit the flow curves of post-fire soil sample slurries by HB model with clay portions. Liu et al. (2024) consider the HB model in the probabilistic assessment of post-fire debris flow inundation. KC et al. (2024) use the HB model to simulate post-fire debris flow in Montecito, CA.

O'Brien & Julien's (1988) model and the O'Brien et al. (1993) model also apply to post-fire debris flows. Elliott et al. (2005) conducted post-fire flood hazard, post-fire debris flow hazard, and post-fire hydrologic hazard analyses for the 2002 Hayman wildfire. Stevens et al. (2011) estimate the probabilities, volumes, and inundation area depth in a burned area if a rainstorm occurs. Bessette-Kirton et al. (2019) apply the quadratic model in a numerical simulation study for the post-fire debris flow event in Montecito, CA. Similarly, Floyd et al. (2019a) apply a quadratic model in a numerical simulation study for the post-fire debris flow due to the Las Conchas wildfire in New Mexico.

The use of Mohr-Coulomb frictional rheology in post-fire debris flow simulation is new and unpopular (Melo et al., 2018; Floyd et al., 2019b). The use of the Coulomb-Viscous model is very rare in post-fire debris flow simulation. So far, only Melo et al. (2018) consider this model to simulate two debris flows in a burned area in Portugal. Similarly, the use of the Voellmy model in post-fire debris flow studies is also very rare (Melo et al., 2018; Barnhart et al., 2021). Imran et al. (2001) model incorporates the HB model with the bi-linear rheology of viscoplastic fluid behavior (Floyd et al., 2019a, 2019b). Jin & Fread's (1997) model incorporates Coulomb and Bingham models with Saint-Venant unsteady flow conditions (Floyd et al., 2019a, 2019b). Bagnold's (1954) model includes particle-particle interaction in a granular-clastic environment (Floyd et al., 2019a, 2019b). Takahashi's (1978) model expands Bagnold's (1954) model and considers the critical

slope angle for debris flows, stationary and nonstationary beds, and concentration in the bore fronts (Floyd et al., 2019a, 2019b).

2.8 Air Entrapment with Mixed Hydrophobic and Hydrophilic Solids

Research with air entrapment in mixed hydrophobic and hydrophilic particles is rare. Pinchasik et al. (2014) studied the Janus particle-bubble hydrophobic-hydrophilic interaction by making particles partially hydrophobic. Froth flotation uses hydrophobic-particle-bubble stability to extract hydrophobic particles in minerals, and the effect decreases as more hydrophilic particles present in minerals (Pawlik, 2022). Parkes et al. (2024) investigate the bubble-particle interaction in the froth flotation process with different ratios of hydrophilic to hydrophobic particles using a commercial product, showing that the existence of hydrophilic particles hinders the hydrophobic-particle-bubble adhesion kinetics.

2.9 Open Channel Investigations of Debris Flows

Debris Flows are complex to study because they include air, water, sandy soil, clayey soil, sediments, vegetation parts, and many other potential materials that might be carried due to gravity-driven flows down the hillslopes. The interaction among those phases and components is still not well understood yet. Large solid particles and a wide distribution particle diameter can induce very complex interactions between the solid phase and liquid phase in the debris flow body. Excluding large particles and other sediments, fine contents can be well mixed with carrying fluid so that the overall behavior of the slurry can be considered as a homogenous, viscous, and perhaps non-Newtonian fluid (Armanini et al., 2003). However, due to the presence of large particles, the

solid phase and surrounding fluid phase cannot be well mixed, so the instantaneous velocities of the particle itself and the fluid are different (Tubino & Lanzoni, 1993).

Although debris flow hazards have a long history, the systematic and organized scientific investigation of debris flows is relatively new (Takahashi, 1978, 1980, 1981, 1991). Takahashi applied geotechnical approaches and granular flow theories to the debris flow problems. Prior to Takahashi, most of the existing experimental studies were focused on dry granular flows or non-Newtonian single-phase flows. Takahashi started experimental works on debris flows, specifically with water and highly concentrated solids (Berzi et al., 2010). Since then, researchers began to experimentally investigate steady, uniform debris flows (Davies, 1988; Takahashi, 1991; Tubino & Lanzoni, 1993; Capart et al., 2002; Spinewine et al., 2003; Armanini et al., 2005; Larcher et al., 2007; Fraccarollo et al., 2007; Fraccarollo & Rosatti, 2009). At the same time, researchers also investigated steady, non-uniform debris flows experimentally (Davies, 1988; Davies, 1990). During past decades, more experimental works have been done to understand the flow and deposit behavior of debris flows done in an open channel (Hu et al., 2013; Scheidl et al., 2015; Haas & Woerkom, 2016; Lanzoni et al., 2017; Wang et al., 2017; Chen et al., 2018; Song et al., 2021; Yu et al., 2022; Wang et al., 2022b).

2.10 PIV and GeoPIV

Particle Image Velocimetry (PIV) is a sophisticated measurement technique used to capture, measure, and analyze fluid flow velocities. PIV tracks the movement of particles inside a fluid flow. In mudflow and mudslide experiments, PIV must be used to examine and quantify the dynamic and intricate flow dynamics, which is crucial to understanding what occurs during these hazardous natural events. The first step of the PIV process is inserting tracer particles into the mud

that are small enough to move with the flow but large enough to be detected by imaging equipment (Adrian & Westerweel, 2011). High-speed cameras are used to capture the images of the fluid with the tracers inside in short intervals. The images are then put into a unique software that identifies the displacement of the particles between each frame. From this, the software calculates the velocity vectors of the particles (Adrian & Westerweel, 2011). From here, a detailed vector field can be represented, showing a comprehensive map of the flow dynamics. From this data, important characteristics of the flow can be found, such as flow velocity, direction, turbulence, and shear stress of the mudflow. In mudflow and mudslide experiments, PIV is crucial for several different reasons. First, it helps researchers understand the mechanisms of the flow. With this, velocity vectors can be analyzed over time, and space researchers can find the patterns and conditions that lead to mudflow acceleration (Raffel et al., 2018). Second, it helps the calibration and validation of numerical models and can be used to predict mudflow behavior. Accurate data can create more reliable models and, with this, give researchers a better understanding of how to make predictions. Thus, PIV is used to study the impact of various environmental and material properties on how mudflow behaves. There are many variables, such as size distribution, water content, and slope gradient, that can significantly influence flow dynamics. PIV helps isolate the effects of each of these variables (Raffel et al., 2018). This data and information are crucial to understanding how to design effective mitigation and preventive barriers like retaining walls or other barriers that may be used as early warning systems.

GeoPIV is a more advanced and specialized extension of regular PIV designed to assist geotechnical engineers. Regular PIV analysis of tracer particles and how they move with the flow. Differing from this slightly, GeoPIV analyzes granular materials such as soil, sand, and sediments. The GeoPIV is extremely valuable for investigating soil mechanics, sediment, transport, and other

geotechnical phenomena (White et al., 2003). A defining characteristic of GeoPIV is its ability to handle large deformations and non-uniform strain fields that are very frequent in geotechnical contexts. Soil, like other granular materials, demonstrates complex behavior under stress, including displacement, rotation, and deformation. This can be localized or vary significantly across the sample size. GeoPIV catches high-resolution images of a soil sample at different phases of loading and deformation. These images can then be analyzed using specialized image correlation technology to determine the movement and deformation of the soil and the different particles at the time (White et al., 2003). GeoPIV uses digital image correlation or DIC methodology. This involves the dividing of images into smaller regions and windows. By tracking this movement of such a small window, detailed displacement vectors can be drawn to describe how each part of the soil sample moved. This analysis can reveal patterns of strain localization, such as shear bands, and it is able to provide insights into what causes soil to fail and how to prevent that type of loading. Again, compared to regular PIV, GeoPIV is analyzed using more advanced image processing algorithms to manage the irregular and complex texture of soil samples (Iverson & LaHusen, 1993). Soil varies in shape, size, color, and many more, which creates a complex visual field that requires robust techniques to track particle movements accurately. GeoPIV also deals with changes in soil surface texture due to deformation. This adds just another level of complexity to the image analysis process. GeoPIV is imperative for several geotechnical applications. It is used to study soil-structure interaction, where understanding how soil deforms around foundations, retaining walls, or other structures is crucial for design and safety. It can also be used to assess slope stability, analyze slip conditions, and provide mitigation strategies to prevent landslides (Iverson & LaHusen, 1993). In addition, it can be used to analyze geotechnical materials under cyclic loading, such as earthquake engineering.

GeoPIV is an invaluable tool when it comes to analyzing mudslides and landslide experiments. It offers insights into the behavior of soil and sediment during these natural disasters. The experiments usually have controlled conditions in a laboratory field where the mudflow can be initiated and maintained. It is used to capture high-resolution chronological images of soil surface at different stages of the flow (Poretti et al., 2020). The images are then analyzed with DIC to track the movements and deformation and to develop a conclusion on how the soil acts and how engineers can design it. The first step in using GeoPIV is applying a grid or pattern to the soil surface to demonstrate more visibility and tracking of particles and sediments. As the mudflow is triggered, a high-speed camera captures these images in precise intervals, and they are then analyzed using the software in small windows (Poretti et al., 2020). These windows are then compared to one another frame by frame for analysis. The detailed analysis of GeoPIV provides critical data on the velocity, direction, and magnitude of soil movement. This reveals patterns are essential for understanding the mechanics of mudflows and landslides. It can identify shear zones where significant deformation occurs as well as slip surfaces where soil detaches and moves (Soga & Bogaard, 2014). These detailed insights help researchers understand the conditions that lead to mudflows and landslides like rain and slope saturation. This software also allows for the study of the internal deformation of a soil mass that cannot be visible to the naked eye. This also includes the analysis of strain localization, where deformation is concentrated in narrow bands, and it is able to detect some causes for the mudslide. Going on the data obtained by GeoPIV is critical in validating numerical models that represent mudflows and landslides (Soga & Bogaard, 2014). Thus, GeoPIV gives a comprehensive and detailed way of studying the dynamics of mudflows and landslides.

2.11 Xanthan Gum (XG) and Sodium Cocoyl Isethionate (SCI)

This research investigates two materials for hydrophobicity reduction: Xanthan Gum (XG) powder representing the biopolymer group and Sodium Cocoyl Isethionate (SCI) powder representing the surfactant group. XG is a common commercially available microbial polysaccharide fermented from various carbohydrates by the microorganism *Xanthomonas Campestris* (García-Ochoa et al., 2000; Sworn, 2021), and it has been approved by the FDA in the food industry since 1969 (Katzbauer, 1998). XG is soluble in water, and the XG solution is non-Newtonian and highly pseudoplastic (Katzbauer, 1998; García-Ochoa et al., 2000). XG is fully biodegradable within roughly two days (Katzbauer, 1998). Common applications of XG in food, cosmetics, and pharmaceutical industries include stabilizers and thickeners in salad dressings, rheology and gas entrainment controllers, oil-in-water emulsion stabilizers, stabilizers in toothpaste and creams, preventer of separation of insoluble ingredients in X-ray contrast (Katzbauer, 1998; Habibi & Khosravi-Darani, 2017). Because of XG's ability to stabilize the oil and water phases, this research evaluates its ability to enhance water infiltration in hydrophobic sandy soil conditions.

SCI is a gentle surfactant made from coconut oil and sodium isethionate. Surfactants are chemical compounds that lower the surface tension between two liquids. SCIs are generally amphiphilic because of double agents containing a hydrophilic head and hydrophobic tail. Common uses of surfactants are emulsifiers, wetting agents, and detergents. SCI is widely applied in the cleaning and cosmetics industry as a surfactant-cleaning agent (Burnett et al., 2017). According to FDA regulation, SCI belongs to the Voluntary Cosmetic Ingredient Reporting Program (VCRP) (Burnett et al., 2017). The oral and dermal acute toxicity study also concludes SCI to be a safe ingredient in health and beauty products (Burnett et al., 2017). SCI benefits in

shampoos, liquid soaps, soap bars, skin care products, and baby products because of low skin irritation levels (Petter, 1984; Sun et al., 2003). However, SCI has limited solubility in water, and health products must combine SCI with other ingredients to achieve maximum performance (Sun et al., 2003).

Kavazanjian et al. (2009) used XG to primarily test its effects on wind-induced erosion control; biopolymers provided a cost-effective solution to increase sandy and silty soil particle resistance and reduce the potential for wind-induced soil particle detachment. Chang et al. (2016) also used XG to measure soil erosion resistance on a slope of 20° with a rainfall simulator. The investigation (Chang et al., 2016) found that XG improved vegetation growth by three times and caused less than 2% soil erosion compared to the control treatment. Akin et al. (2021) studied the use of XG and commercial polyacrylamide (PAM) to prevent wind and run-off-dominated erosion. The study (Akin et al., 2021) used a rainfall simulator and sprinkled surfactant to replicate the post-wildfire erosion environment on the treated soil surface. They measured runoff and soil loss and found that XG and PAM decrease soil loss and infiltration (Akin et al., 2021). These recent works have explored XG as a sprinkled surfactant in a large-scale environment with a rainfall simulator.

Chapter 3 Materials and Methodology

3.1 Sand Material

This research mainly focuses on sand mixtures because wildfires do not alter hydrophobicity on cohesive soils like clays but significantly affect sands and gravels in highly erodible areas (Debano, 1981; Huffman et al., 2001). Although post-mudflow reconnaissance typically does not quantify volumes of displaced hydrophobic soils, early-stage mudflows (i.e., when clear excess rainwater initially flows over a fresh burned scar site and starts to pick up hydrophobic soil particles) are composed of eroded hydrophobic particles from burned scar surfaces. Specifically, this paper studies how air entrapped by hydrophobic particles changes internal structure composition and density in controlled laboratory conditions. Since previous research shows that laboratory sands can well represent site soils following standard geotechnical procedures (Movasat & Tomac, 2021), this research uses clean sand with small sieve sizes to better understand sand size's role in air entrapment. Although post-mudflow reconnaissance efforts to date have failed to identify volumes of displaced hydrophobic soils, this study investigates the worst-case scenario and early-stage mudflows as composed of eroded hydrophobic particles from burned scar surfaces.

Experiments consider three types of sand: sieved 10/16 coarse sand (mean particle diameter: 1.33 mm, **Figure 3.1a**), sieved 40/50 medium silica sand (mean particle diameter: 0.27 mm, **Figure 3.1b**), and American Foundry Society (AFS) 50/70 testing Ottawa silica fine sand (mean particle diameter: 0.15 mm, **Figure 3.1c**). Sand is mixed with blades in a 290-ml volume cup with an overall 75-mm height and a 70-mm diameter. After removing fine dust by washing, the sand is oven-dried for 24 hours at 100 °C and then submerged in a mixed solution of 10% Triethoxy-n-octylsilane ($C_{14}H_{32}O_3Si$) and 90% isopropyl alcohol by volume for at least 48 hours

at room temperature, which builds a hydrophobic coating. After the treatment, hydrophobic sand is washed in water and then dried in an oven. **Table 3.1** summarizes the mean contact angles and water drop penetration times for each type of sand after hydrophobicity treatment and includes hydrophobic soil samples from the fire sites and hydrophilic (untreated) sand. Hydrophobicity classification uses the same method in Bisdom et al. (1993) and Leelamanie et al. (2008). The initial volumetric sand-to-water ratio is determined by measuring the sand weight and using the sand's specific gravity (G_s) to obtain the volume of sand solids. Specific gravity is the ratio of the sand grain density to the density of water. The specific gravity for fine, medium, and coarse sand is measured as 2.65, 2.65, and 2.64, respectively.

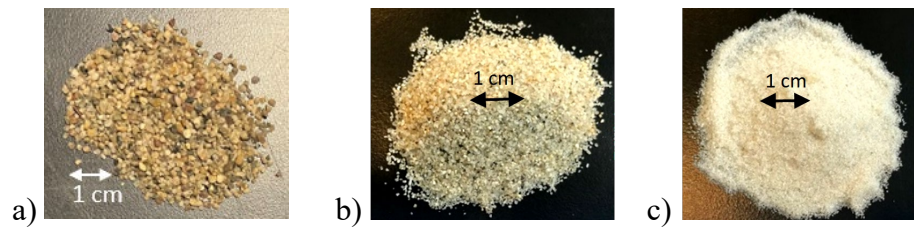


Figure 3.1. Examples of a) coarse, b) medium sand, and c) fine sand in the experiments.

Table 3.1. Mean Contact angles and water drop penetration times for different types of artificial hydrophobic sand, hydrophilic (untreated) sand, and hydrophobic sand from a fire site.

Sand Type	Mean Contact Angle, (°)	Water Drop Penetration Time (s) and Repellency Category
Hydrophobic Soil from Fire Site	112 ± 9.6	> 600 (severely water-repellent)
Artificial Hydrophobic Fine Sand	120 ± 8.1	> 3600 (extremely water-repellent)
Artificial Hydrophobic Medium Sand	112 ± 6.4	> 3600 (extremely water-repellent)
Artificial Hydrophobic Coarse Sand	109 ± 8.9	> 3600 (extremely water-repellent)
Hydrophilic (Normal) Fine Sand	57 ± 2.1	0.08 (Wettable / Non-repellent)
Hydrophilic (Normal) Medium Sand	70 ± 2.8	0.02 (Wettable / Non-repellent)
Hydrophilic (Normal) Coarse Sand	68 ± 3.5	0.02 (Wettable / Non-repellent)

3.2 Air Entrapment Experiment Mixing Design

A comprehensive mixing program is performed in controlled laboratory conditions to investigate the extent and forms of entrapped air after mixing. The custom mixing system uses a 1-HP motor and variable-frequency drive (VFD) that controls the speed of the mixer blade. Multi-purpose Synthetic Grease prevents all possible water or air leakages from gaps around the container. Before mixing, a certain amount of sand sits at the bottom of the container, followed by pouring water above the sand layer. Air exists naturally within the hydrophobic sand layer and above the water layer within the container. Supporting Information S5 shows details of the mixing blade and investigates the effect of mixing blade shape. Mixing in a cup and vane system replicates kinetic energy and shear rates in postfire mudflows. The shear rates in approximately 1 m high mudflows, at 30 km/h (8.3 m/s) average mudflow velocity, produce shear rates in the order of tens of s^{-1} in laminar regimes. Using the equivalent energy principle as an alternative approach ensures mixing equivalence of the highly heterogeneous three-phase mixture due to the flow regime and dynamics being erratic in nature due to changes of downhill slopes, slope lengths, and natural obstacles, and thus to a large extent unknown before the experiment. Therefore, the vane and cup mixing speed relates to a possible downhill mixture velocity using the work-energy principle:

$$KE_{translational} = \frac{1}{2}mv^2 \quad (3.1)$$

where, $KE_{translational}$ is the kinetic energy of the mixture mass at a translational motion; m is the mixture mass; and v is the linear velocity of the mixture during a mudflow event. **Eqn. 3.2** defines the rotational kinetic energy in the experiments using the work-energy principle:

$$KE_{rotational} = \frac{1}{2}I\omega^2 \quad (3.2)$$

where $KE_{rotational}$ is the kinetic energy of the mixture mass at a rotational motion; ω is the angular velocity; and I is the moment of inertia of the mixture. When the mixing blade rotates, the mixture resembles a hollow cylinder shape with a thin boundary layer at the wall edge; thus, I is estimated for a cylindrical container shown in **Fig. 3.2**. By equating $KE_{translational}$ in **Eqn. 3.1** and $KE_{rotational}$ in **Eqn. 3.2**, one can easily obtain the relationship between translational velocity v from the field and angular velocity ω used in experiments as follows:

$$\omega = \sqrt{\frac{mv^2}{I}} \quad (3.3)$$

The following example demonstrates the calculation: a 30.5-g of fine sand and 218.5-g water mixture, rotating at an angular velocity of 314 rad/s, is subjected to a total rotational energy of 3.84 kg-m²/s². However, when the same mixture mass is subjected to equivalent kinetic energy flowing downhill, it reaches the velocity of 5.6 m/s. This experiment considers three levels of mixing speeds: 2.2, 3.9, and 5.6 m/s (corresponding to 311, 544, and 778 s⁻¹). Those selections fall within the estimated velocity range, as reported by Cui et al. (2018). The smallest speed falls within the laminar mixing range, while the largest speed falls within the turbulent mixing range.

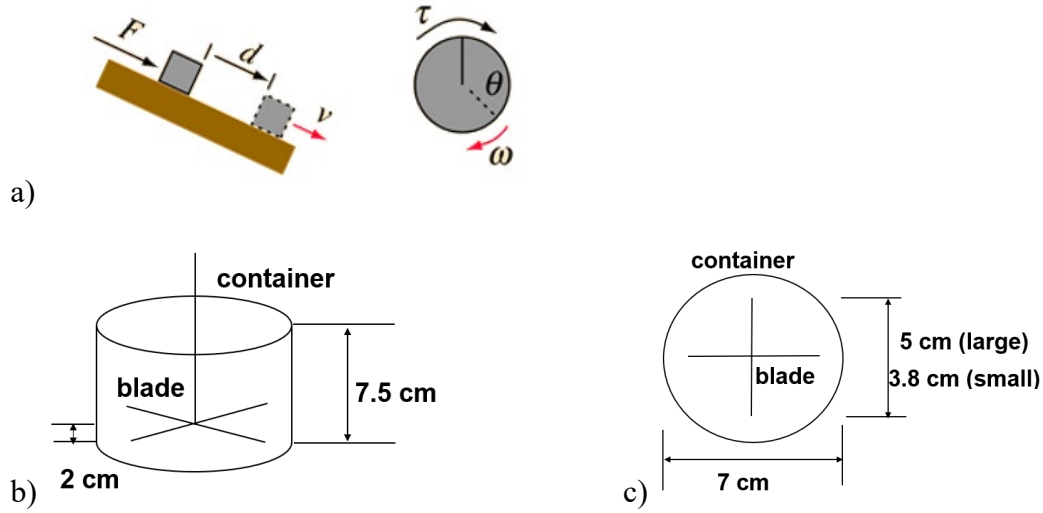


Figure 3.2. a) Relations between downhill velocity and experimental rotational agitation, b) Front view and the dimension of the mixing container, c) Top view and the dimension of the mixing container

Experiments vary fluid mixing speed, mixing time, and initial solid volumetric concentration of sand (V_s) to the water (V_w) across shear rates, and mixing time varies from 10 s to 120 s. Then, the mixing time increases until evident air-entrapment level changes cease. Depending on how many sand particles are available initially and the type of sand particles, the degas process ends at different times. The degassing process does not change significantly after 60 s for fine sand and after 40 s for medium and coarse sand. The mixing duration stops at 120 s for fine sand, 80 s for medium sand, and 90 s for coarse sand. Before and after mixing, water surface levels help determine the volumes of free air, escaped air, free water, sand particles, and entrapped air. Image documentation of side and top views helps visualize the physical presence and sizes of liquid marbles and sediment.

This paper introduces the specific air content (e^*), the main parameter describing how much air gets entrapped during the mixing process. It is the ratio between the total volume of entrapped air (V_a) to the volume of initial sand particles (V_s):

$$e^* = \frac{V_a}{V_s} \quad (3.4)$$

Figs. 3.3a-c shows the pictures of mixing blades used in the experiments. Type I and Type III blades have four leaves, while Type II has three. **Table 3.2** shows a detailed geometric comparison among three types of mixing blades.

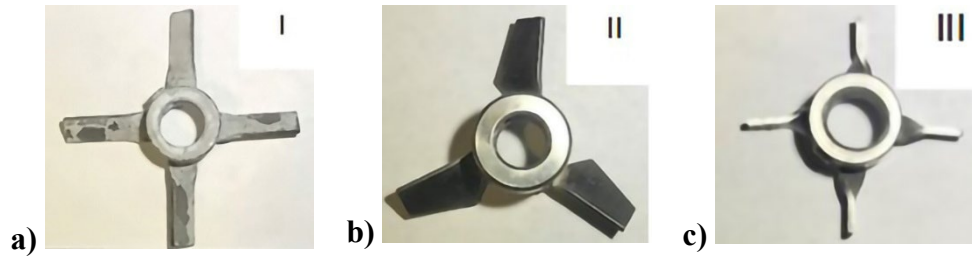


Figure 3.3. Mixing blade geometries considered for the experiments: **a)** Type I with a 5.1-cm span, **b)** Type II with a 5.1-cm span, and **c)** Type III with a 3.8-cm span.

Table 3.2. Detailed geometrical description of each mixing blade type

	Type I	Type II	Type III
Commercial Name	Mixer Direct's 2-inch Lab Hydrofoil Blade	Mixer Direct's 2-inch Lab Axial Flow Turbine Blade	Mixer Direct's 1.5-inch Axial Flow Turbine Blade
Blade Diameter (inch)	2	2	1.5
Blade Diameter (cm)	5.1	5.1	3.8
Number of Leaves	4	3	4
Leaf Separation Angle (°)	90	120	90
Leaf Inclination Angle (°)	45	45	90
Leaf Length (cm)	1.9	1.9	1.3
Leaf Width (cm)	0.5, uniform	1 to 0.5, reducing	0.5, uniform
Leaf Thickness (cm)	0.16	0.16	0.16

3.3 Rheological Behavior Measurement Design

A pre-mixing phase is necessary to create the mixture for rheological behavior measurement tests. Hydrophobic sand particles were poured into a container first, then followed

by water. Therefore, due to the particle surface hydrophobicity, the hydrophobic sand and water layers have a clear boundary. Before the mixing process, the container should be capped and sealed with grease so that there is no air exchange between the inside system and the surrounding environment. **Fig. 3.4a** shows the mixing system. The mixer has a diameter of 5 cm, and the container has a diameter of 7 cm. The height of the container is 7.5 cm. According to the industrial practice of the mixing process, the mixer is about 33% away from the container bottom. Ma & Tomac (2024) investigate the air entrapment mechanism. Therefore, different pre-mixing shear rates and pre-mixing times control the air entrapment of the final mixture for rheology measurements (**Table 3.3**). Selected air entrapment ratios are 20%, 28%, 40%, 51%, and 60% for rheological tests. The shear rate range for rheological tests is from 0.01 to 235 s⁻¹.

Fig. 3.4b shows the setup for rheological tests. This research uses a Brookfield Ametek RSX commercial Rheometer. The vane-shaped spindle can minimize the relative slippery between the spindle itself and sand particles. The vane spindle has a height of 4 cm and a diameter of 2 cm. According to the rheometer instruction, the vane spindle should be at least 1 cm away from the container bottom. In addition, the container diameter should be at least three times the spindle diameter.

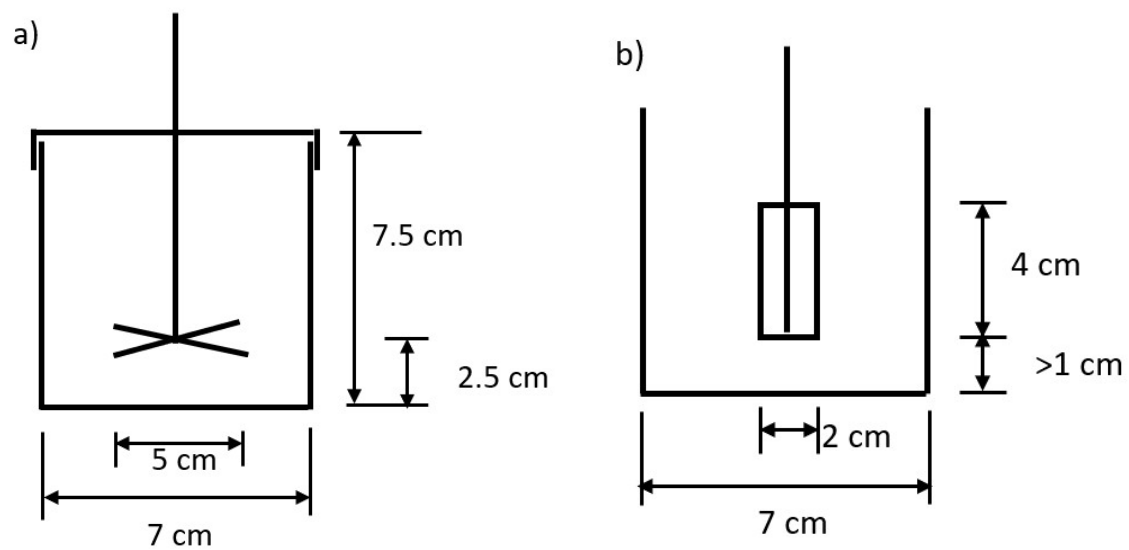


Figure 3.4. Illustrations for a) Mixing Station and b) Rheological Measurement

Table 3.3. Test Conditions for Rheological Behavior Measurements

Test No.	Sand Type	Sand Particle Volumetric Concentration, V_s/V_w	Air Bubble Entrapment Ratio, V_a/V_s	Pre-mixing Time [s]	Pre-mixing Shear Rate [s^{-1}]	Rheometer Shear Rate [s^{-1}]
1	Hydrophobic Fine	70%	28%	240	50	0.01 - 235
2	Hydrophobic Fine	70%	40%	150	50	0.01 - 235
3	Hydrophobic Fine	70%	51%	90	50	0.01 - 235
4	Hydrophobic Fine	70%	60%	60	50	0.01 - 235
5	Hydrophobic Fine	56%	28%	240	50	0.01 - 235
6	Hydrophobic Fine	75%	28%	240	50	0.01 - 235
7	Hydrophobic Fine	75%	40%	180	50	0.01 - 235
8	Hydrophobic Fine	70%	Varying	50	20	0.01 - 235
9	Hydrophobic Fine	70%	Varying	25	20	0.01 - 235
10	Hydrophobic Medium	70%	28%	120	40	0.01 - 235
11	Hydrophobic Medium	70%	40%	90	40	0.01 - 235
12	Hydrophobic Medium	75%	28%	120	40	0.01 - 235
13	Hydrophobic Coarse	70%	20%	90	40	0.01 - 235
14	Hydrophobic Coarse	70%	28%	60	40	0.01 - 235
15	Hydrophobic Coarse	75%	20%	90	40	0.01 - 235
16	Fire Site Samples	N.A.	N.A.	240	50	0.01 - 235

3.4 Experimental Design for Mixed Hydrophobic and Hydrophilic Sand Particles

The level of hydrophobicity is the mass percent of hydrophobic sand particles to total sand particles. For example, 25% hydrophobicity for a total of 100 g of sand particles includes 25 g hydrophobic sand particles and 75 g hydrophilic sand particles. For air entrapment experiments

with fine sand case, the tests include 0%, 5%, 10%, 25%, 35%, 50%, 65%, 70%, 75%, 80%, 85%, 90% and 100% hydrophobicity. However, for air entrapment experiments with medium and coarse sand particles, the tests include 0%, 10%, 25%, 50%, 75%, 90%, and 100% hydrophobicity. The fine sand experiments have more hydrophobicity levels because of their strong ability to entrap more air bubbles. Tests with fine sand and clay composition have a fixed amount of clay portion of 10% mass. For example, a 25% hydrophobicity for a total of 100 g of fine sand and Kaolinite experiment includes 10 g of Kaolinite, 22.5 g of hydrophobic fine sand, and 67.5 g of hydrophilic fine sand.

Fig. 3.5a shows the dimensions of the mixing chamber for air entrapment tests. The mixing blade has a diameter of 5 cm, and the mixing chamber has a diameter of 7 cm. The mixing chamber has a height of 7.5 cm. According to the industrial mixing practice, the mixing blade is placed at about 25% to 30% of the height of the mixing chamber, which is 2 cm for air entrapment tests. The mixing procedure follows the same philosophy as in Ma & Tomac (2024). However, the mixing time and mixing speed have to be large in order to make sure the formed liquid marbles (i.e., a complex multiphase matter in the water domain that contains a core air bubble covered by hydrophobic sand particles) are stable during the air entrapment tests and rheological properties tests. As a result, the mixing time should be at least 60, 80, and 100 seconds for coarse, medium, and fine sand particles, respectively. The mixing speed is at the maximum of 7.78 m/s.

Since the sand particle layer has two parts (hydrophobic layer and hydrophilic layer), water infiltration should not exist in order to be consistent with the results observed in Ma & Tomac (2024). **Fig. 3.5b** shows the proper physical appearance of different phases prior to mixing. Hydrophilic sand particles should be at the bottom of the mixing chamber, then followed by hydrophobic sand particles. The water layer should be at the top. Due to strong hydrophobicity,

water at the top cannot infiltrate down to the sand layer. **Fig. 3.5c** shows examples when water infiltration is observed because hydrophobic and hydrophilic sand layers are pre-mixed prior to the general mixing process.

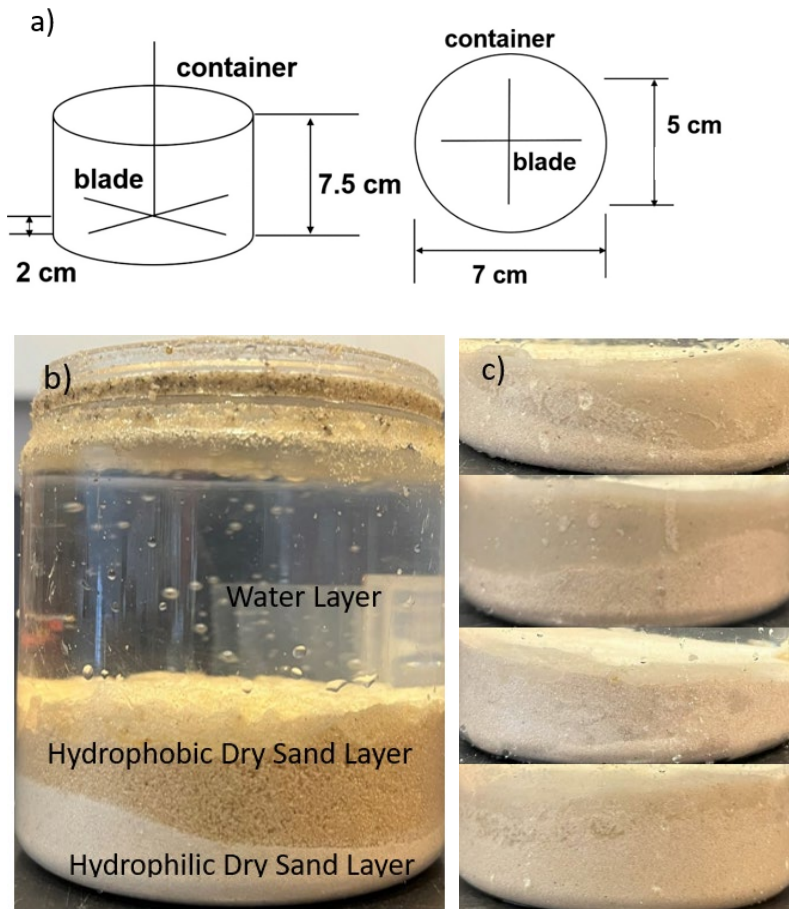


Figure 3.5. Sand material and mixing scheme. a) the geometry of the mixing chamber; b) proper layout of different phases prior to the general mixing process; c) examples of water infiltration problems prior to general mixing process due to poorly-designed experiment configuration.

All rheological tests (i.e., fine, medium, coarse, and fine with Kaolinite cases) only consider five levels of hydrophobicity: 0%, 25%, 50%, 75%, and 100%. All rheological tests are conducted immediately after the mixing procedure during the air entrapment tests. The rheological measurements are conducted with a Brookfield Ametek RSX commercial rheometer. **Fig. 3.6a**

shows the geometric configuration of the rheological measurement. The spindle should be at least 10 mm away from the container bottom. The container diameter should be at least three times the diameter of the spindle. The mixture should be at least 65 mm in height in the container. **Fig. 3.6b** shows the spindle used in the rheological tests. The tests use a vane-shaped spindle instead of a classical cylindrical-shaped spindle because vanes minimize the slip between the spindle and liquid marbles. The vanes are 40 mm long, and the spindle diameter is 20 mm. The shear rate range is from 0.01 to 234 s⁻¹ for all tests.

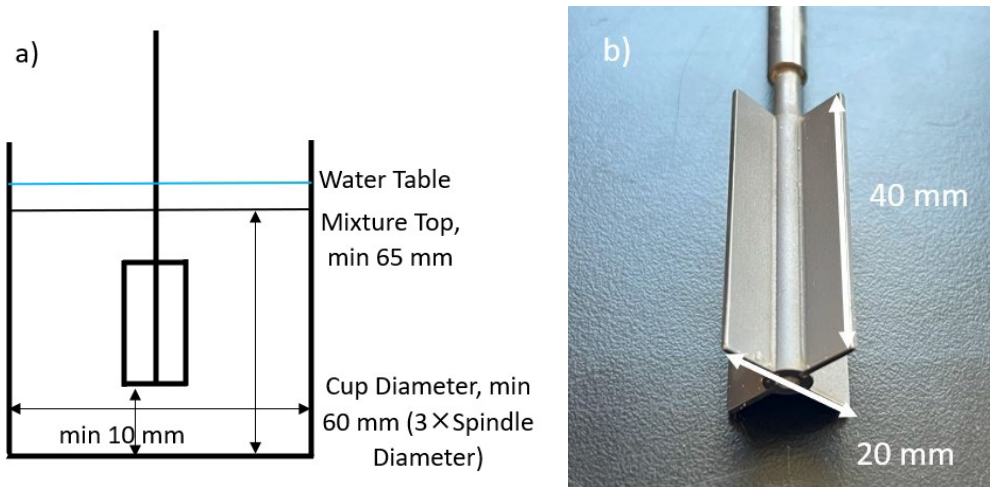


Figure 3.6. Rheological measurement design. a) geometric configuration of measuring spindle and container in rheological tests; b) the dimensions of vane-shaped measuring spindle.

3.5 Open Channel Flow Experimental Design

Due to the extraordinary capability of entrapping air bubbles (Ma & Tomac, 2024), this experiment only uses sieved 50/70 Ottawa hydrophobic fine sand particles (mean particle diameter: 0.15 mm).

For each test, the total mass of fine sand particles is 320 g, and the mass of water is 1200g. Thus, the mass concentration of sand particles in water is 27%. The above condition corresponds

to a total volume of fine sand particles of 120 mL and a volume of water of 1200 mL. Therefore, the volumetric concentration of sand particles in water is 10%. The above concentration is determined after several trials. If the concentration is too low, then not a significant number of liquid marbles can be captured since liquid marble flow is distributed across a definite period of time and along with the channel. If the concentration is too high, most liquid marbles and free sand particles stay in the storage tank and will not flow into the channel easily.

The liquid marble is formed by pre-mixing the hydrophobic fine sand particles and water. This investigation only considers stable liquid marbles after mixing. That means the pre-mixing process should have a long mixing time and fast mixing speed. According to Ma & Tomac (2024), the pre-mixing time shall be longer than 120 s, and the pre-mixing shear rate should be 778 s^{-1} . Therefore, the estimated specific air content is about 0.2. This number means that the volume of total entrapped air bubbles to the total volume of sand particles is 0.2. Given the selected volume of fine sand particles in this open channel experiment, the estimated total volume of entrapped air bubbles is 24 mL.

The channel includes two parts: the storage tank and the open channel. A removable gate separates the two parts. **Figs. 3.7a-b** show the top view and front view of the channel experiment. According to Ma & Tomac (2024), the average diameter of liquid marble is about 0.12 cm. The width of the channel is designed to be at least 50 times the diameter of the liquid marble (i.e., larger than 6 cm). The length of the channel is designed to be at least 10 times the width of the channel (i.e., larger than 60 cm). Due to manufacture defects, the actual channel width is 6.6 cm, and the actual channel length is 60.5 cm. The width and the length of the storage tank are 19.7 cm and 10.9 cm, respectively. The heights of the channel and tank are consistently 18 cm.

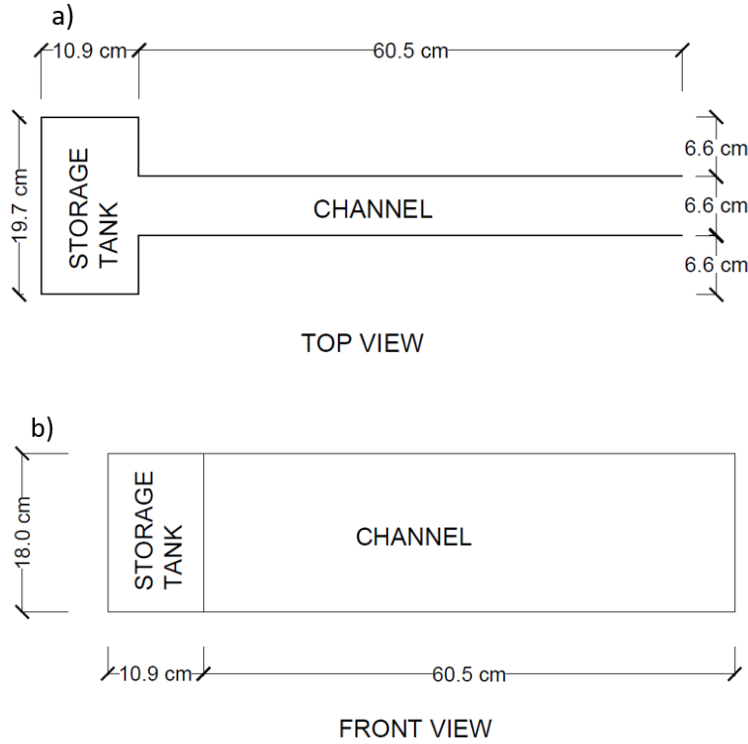


Figure 3.7. The a) top view and b) front view of open channel experiment.

The open channel experiment has two varying parameters: level of sand particle hydrophobicity and channel inclination degree. **Table 3.4** summarizes the test schedule for all recorded tests for the open-channel experiment. Tests 1-3 correspond to 100% hydrophobicity with a channel inclination of 15° . The difference is that each test aims to shoot a different region of the channel. Test 1 is the front window, in which the left boundary of the camera window is aligned with the very beginning of the channel. Test 2 is the middle window in which the left boundary of the camera is aligned 20 cm away from the beginning of the channel. Test 3 is the end window in which the left boundary of the camera is aligned 40 cm away from the beginning of the channel. Similarly, every three tests in the table are grouped together. There are 5 levels of sand particle hydrophobicity at a channel inclination of 15° . In addition, at a 100% level of hydrophobicity, the experiment also considers a comparison of channel inclinations of 15° and 45° . For intermediate

levels of hydrophobicity, the number is defined as the mass ratio of hydrophobic sand particles to total sand particles. For example, at 75% level of hydrophobicity, there are 240 g of hydrophobic fine sand particles and 80 g of regular fine sand particles.

Table 3.4. Test Schedule for Open Channel Experiment

Level of Hydrophobicity	Channel Inclination	Front Window	Middle Window	End Window
100%	15°	Test 1	Test 2	Test 3
75%	15°	Test 4	Test 5	Test 6
50%	15°	Test 7	Test 8	Test 9
25%	15°	Test 10	Test 11	Test 12
0%	15°	Test 13	Test 14	Test 15
100%	45°	Test 16	Test 17	Test 18

The open channel experiment employs a high-speed, high-resolution Phantom C320 camera to record the flow of the mixture with liquid marbles. All general videos and pictures have a resolution of 1920×1080 pixels. For zoomed-in videos and images, the resolution is 1280×800 pixels. All videos, no matter which resolution, are recorded in 700 frames per second (fps). The camera is perpendicular to the channel face. An additional LED light with 12,000 lumens is placed in front of the channel next to the Phantom camera to enhance the room lighting condition.

The Particle Image Velocimetry (PIV) method is a powerful tool for studying the motion of particulate materials. In this experiment, the Geo-Particle Image Velocimetry-Reliability-Guided (GeoPIV-RG) Matlab module investigates the liquid marble flow motion in the open channel recorded by the high-resolution camera. GeoPIV-RG was developed by Stainer et al. (2015), previously named GeoPIV by White & Take (2002). **Fig. 3.8** shows the general process for how to use the GeoPIV-RG module. Before the main process, the user should decide the series of images, the region of interest (ROI), and the mesh size and spacing. The main process compares particle displacement among images by comparing the initial reference and following images at

the point in time of interest. GeoPIV-RG uses both leapfrog and sequential schemes to guarantee an accurate result. The calibration procedure follows Ma & Tomac (2021).

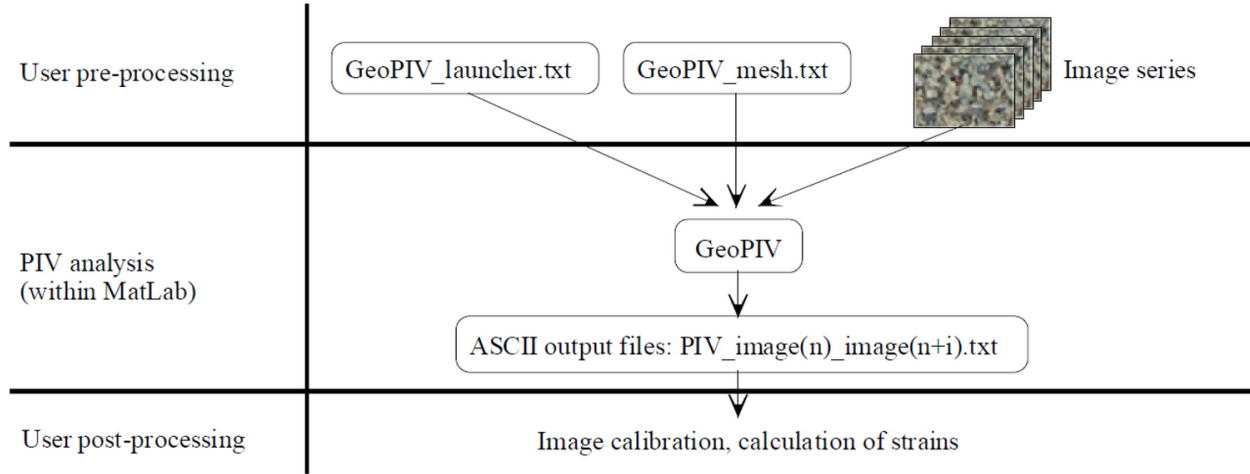


Figure 3.8. GeoPIV-RG software Procedure (White & Take, 2002)

3.6 Experimental Design for Sand Hydrophobicity Remediation

The sand in this study is QUIKRETE® All-Purpose Sand with properties shown in **Fig. 3.9a**. Since the hydrophobic coating is only significant in coarse and not fine-grained sandy soils (Debano, 1981; Huffmann et al., 2001), early preparation washes away all the fine particles and dust. **Fig. 3.9a** shows the gradation curve for washed sand samples from sieve analysis. As a result, the sand sample only satisfies one of the ASTM D2487 standard's "well-graded sand" criteria with a Curvature Coefficient (C_c) greater than 1. However, according to the same standard, the uniformity coefficient (C_u) does not exceed 6 for sand samples. The median and average sand particle sizes are 0.6 and 0.68 mm, respectively. Before making sand samples hydrophobic, the sand is oven-dried for 24 hours at 100 °C. After cooling down to room temperature, the sand samples are submerged in a mixed solution of Triethoxy-n-octylsilane ($C_{14}H_{32}O_3Si$, 10% by volume) and isopropyl alcohol (90% by volume) for at least 48 hours, allowing the formation of

hydrophobic coating outside the particles. After the treatment, hydrophobic sand in the chemical solution is washed in water and oven-dried for 24 hours (Movasat et al., 2023).

Two main measurements for evaluating hydrophobicity severity are contact angle and water drop penetration time (WDPT). The contact angle is the angle between two lines (**Fig. 3.9b**): the horizontal line between the sand layer and the water droplet bottom and the tangent line between the water and air boundary at the toe of the water droplet. The sand is hydrophobic when the contact angle is larger than 90° . The contact angle for the artificial hydrophobic sand sample is $109 \pm 3^\circ$. Bisdom et al. (1993) provide sandy soil classification based on WDPT, see **Table 3.5**. The average WDPT of the artificial hydrophobic sand sample is over 10800 s (or 3 hours). Thus, it is "Extremely Water Repellent." In comparison, the clean hydrophilic sand sample has an average contact angle of $68 \pm 5^\circ$ and a WDPT of less than 0.02 s. The sandy soil sample from a burn scar (3 years) has an average contact angle of $112 \pm 9^\circ$ and a WDPT of roughly 790 s.

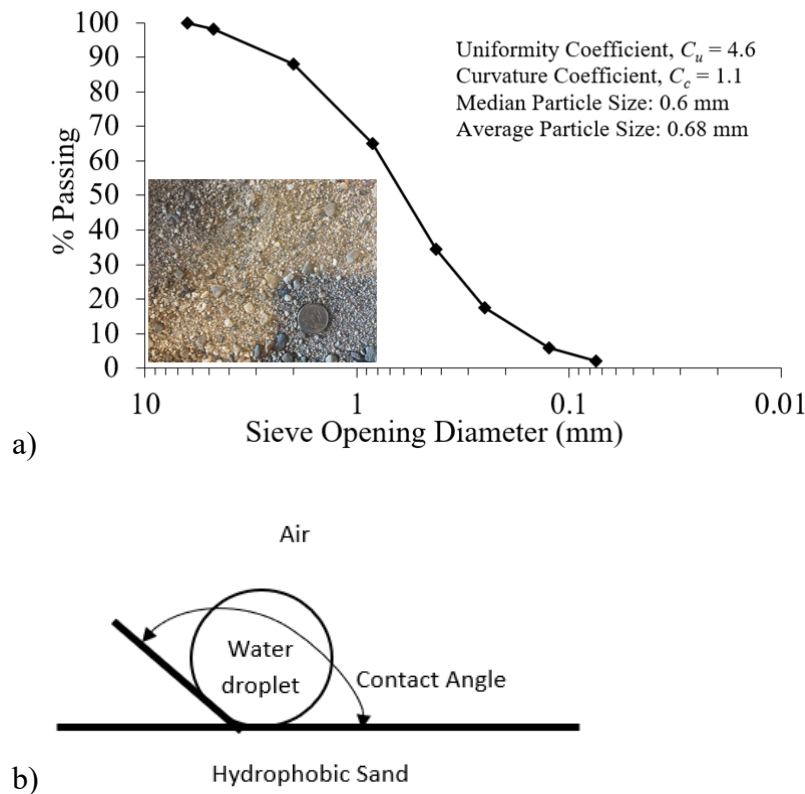


Figure 3.9. a) Physical Appearance of Sand Sample and Gradation Curve for Washed Sand Sample; b) Illustration of the Definition of Contact Angle

Table 3.5. WDPT classification defined by Bisdom et al. (1993)

WDPT (s)	Classification
< 5	Wettable
5 - 60	Slightly Water Repellent
60 - 600	Strongly Water Repellent
600 - 3600	Severely Water Repellent
> 3600	Extremely Water Repellent

Fig. 3.10 shows Two different modifiers XG ($C_{35}H_{49}O_{29}$)_n, in **Fig. 3.10a**, and SCI ($C_{14}H_{27}O_5NaS$) in **Fig. 3.10b**, used to alleviate sand hydrophobicity. XG is a brown-colored fine-grained powder, while SCI is a pale white super fine-grained clay-like powder. **Fig. 3.10c** and **Fig.**

3.10d demonstrate the primary structure of XG (Sworn, 2021) and the chemical structure of SCI (Sakai, 2017).

The research proposes a range of mass concentrations of XG to hydrophobic sand of 0.5%, 1%, 1.5%, 2%, 3%, and 5%. However, additional lower mass concentrations are needed for SCI powders since higher concentrations cannot provide a clear image of the role of modifier concentration on contact angle and WDPT reduction: 0.05%, 0.1%, 0.2%, and 0.5%.

For all contact angle measurements, WDPT measurements, and erosion tests on sloped surfaces of 15°, 30°, and 45°, modifiers mix with well-graded sand material thoroughly in a closed box for at least 5 minutes. Besides, SCI powders are sprinkled evenly onto testing sand surfaces for erosion tests on sloped surfaces due to the feasibility considerations in real applications.

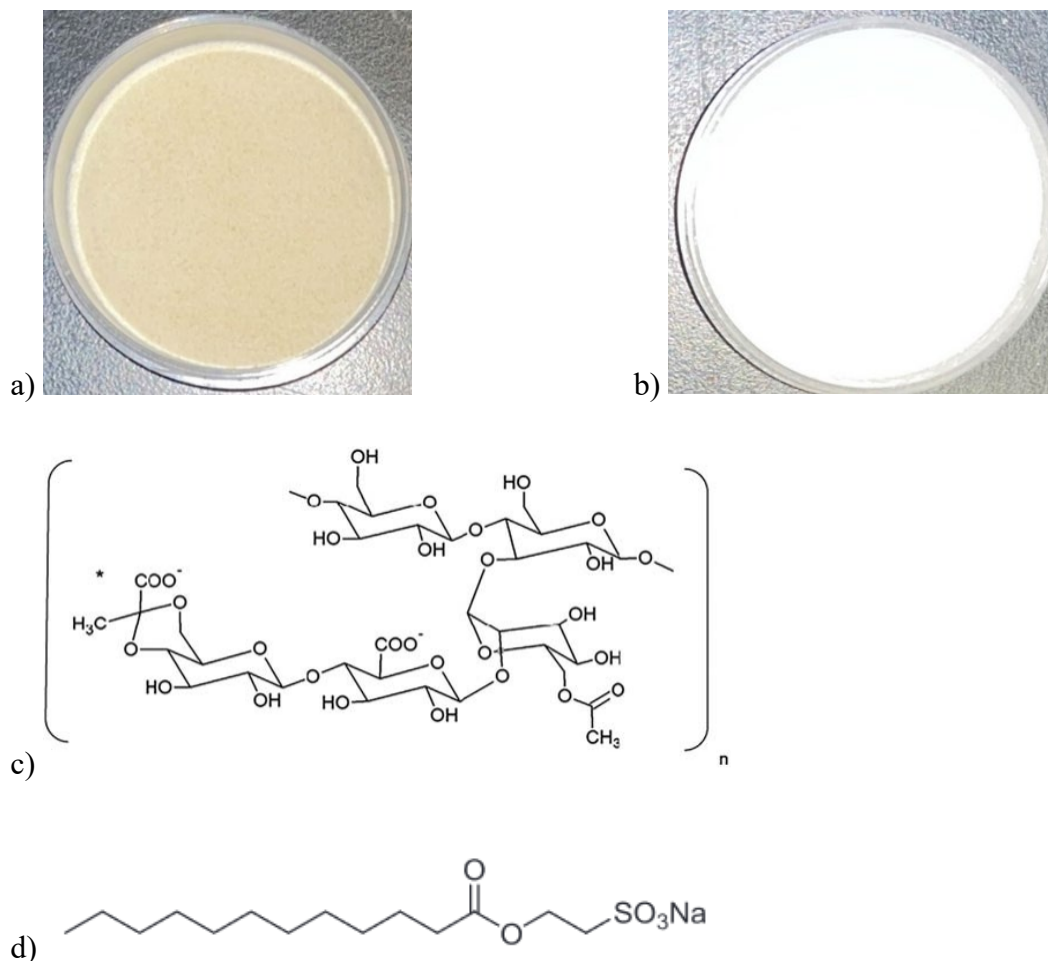


Figure 3.10. a) XG powder; b) SCI powder; c) Chemical Structure of XG (Sworn, 2021); d) Chemical Structure of SCI (Sakai, 2017)

Before contact angle measurements, WDPT measurements, and surface erosion tests, all sand surfaces from Petri dishes and erosion channels are flattened to ensure that local geometric heterogeneity of the testing material surface does not affect the measurement accuracy. Measurements of contact angle and WDPT are the averaged results of three tests. Water drops have an average diameter of 0.62 cm, with a standard deviation of 0.07 cm.

Fig. 3.11a shows the experimental setup of the horizontal surface's contact angle and WDPT measurements. The camera lens is at the same level as the flattened sand sample surface,

perpendicular to the testing material. A high-resolution and high-frame-rate PHANTOM MIRO C320 camera captures the image. Most of the contact angle and WDPT measurements do not require video captures. However, water droplets penetrate the sand body quickly for testing samples with high concentrations of SCI modifiers, and video recordings are necessary. The contact angle is measured based on the first video frame, which shows that water droplets are in full contact with the sand sample surface. In addition, video recordings are crucial for samples at an inclined angle due to the moving nature of the water droplet. All videos have a recording rate of 700 frames per second (FPS). A light-emitting diode (LED) light with 12,000 lumens is placed after and above the camera to provide additional light in the environment.

Fig. 3.11b shows the setup for slope erosion tests on 15°, 30°, and 45° sloped surfaces. Hydrophobic, hydrophilic, 5% modifier mixed, and sprinkled modifier sand are pulvinated from the same distance into the erosion slope with flattened surfaces. A camera is set up perpendicular to the erosion channel to videotape the water-dropping process. The LED light, with the purpose of light enhancement, is placed next to the erosion channel. A MIOPS Splash device drops water droplets 9 cm above the surface at one-second intervals. The water drops from the MIOPS device have an average diameter of 0.50 cm. The error is very small, with only 0.02 cm. Erosion pictures after each droplet record crater diameter and tail length.

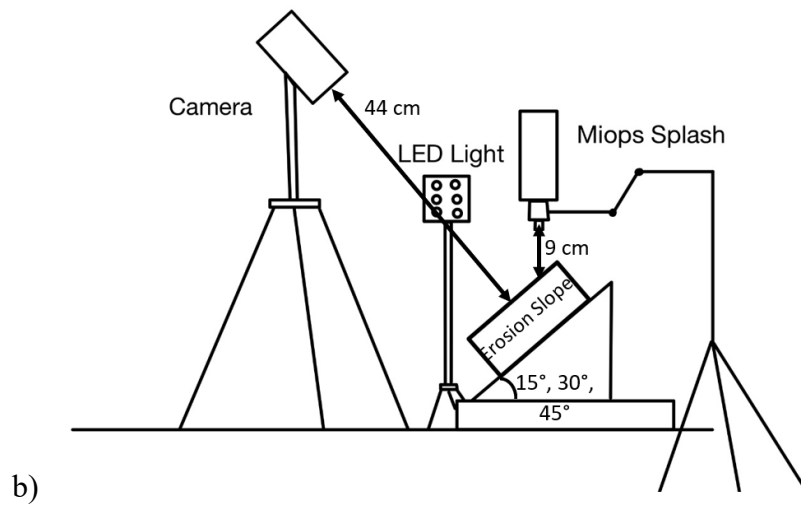
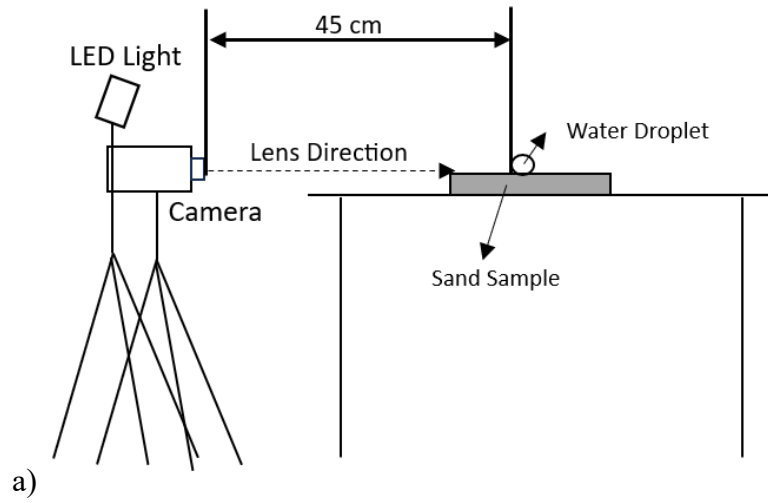


Figure 3.11. Camera setting for a) Contact Angle and WDPT Measurement and b) slope Erosion Test

Chapter 4 Air Entrapment Mechanism Experiment

4.1 Liquid Marble Size and Stability in Experimental Post-Wildfire Debris Flows

On a millimeter scale, hydrophobic sand particles have a strong affinity to bond with air, forming a heterogeneous mixture with liquid marbles or particle-stabilized air bubbles and preventing degasification (Aussillous and Quéré, 2001; Du et al., 2003; Bormaschenko, 2011; McHale and Newton, 2011, 2015; Ong et al., 2021). Particle attachment, detachment, and collision occur during liquid marble formation (**Figs. 4.1a-c**). The camera window only focuses on the near-wall region of the container. The cropped images show the nearest region right to the mixer shaft to avoid image distortion. To better capture the particles and bubbles, the solid concentrations are fixed at only 5% in the images. Higher concentrations will cause the image to be overcrowded with many particles and mature liquid marbles. For example, liquid marbles collide; some merge into larger marbles, and others vanish. For example, **Fig. 4.1a** shows that only a few particles are attached to bubbles within the first 5 s of mixing, and the rest are still floating in the carrying fluid. At 20 s, more sand particles stick to air bubbles (**Fig. 4.1b**). Finally, particle-covered bubbles collide and form super-large marbles. The initially wide marble size distribution reduces and becomes more uniform after 50-s mixing (**Fig. 4.1c**).

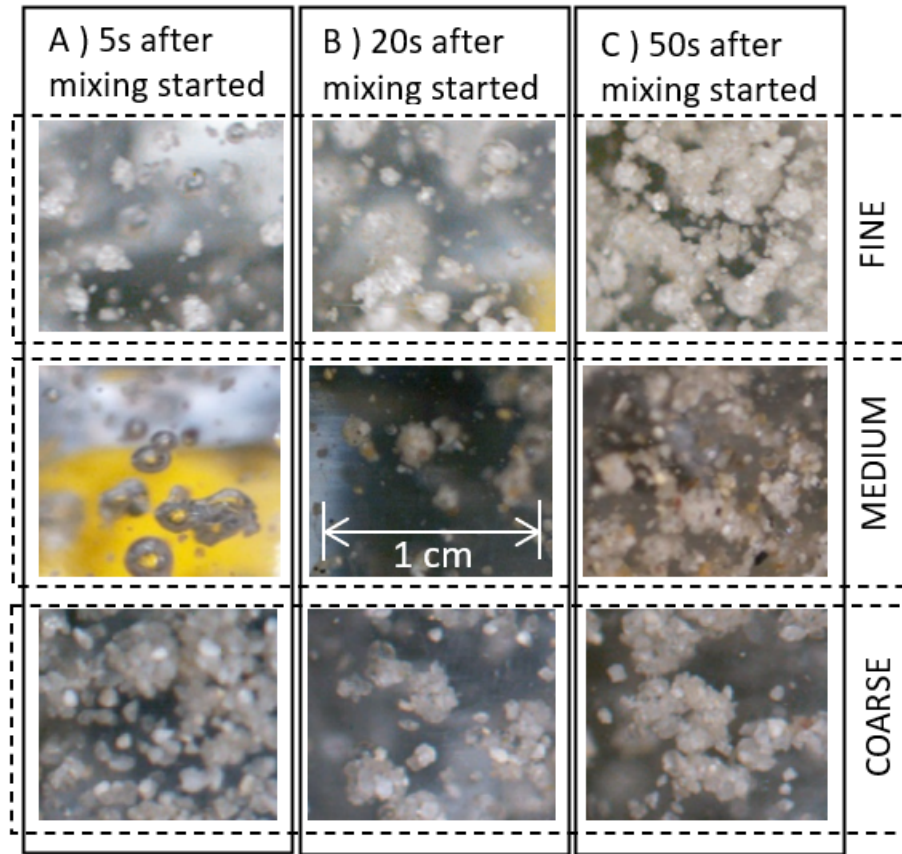


Figure 4.1. Different sub-processes of particle-bubble interaction include particle bubble approaching, attachment, interactions, and detachment **a)** within the first 5 s, showing a diagram of particle-bubble attachment mechanisms; **b)** within 20 s, showing a diagram of marble-marble collision mechanism; and **c)** within 50 s after mixing started, showing marble-marble collision and particle-bubble separation mechanism.

This paper theoretically and experimentally investigates the formation process and stability of submerged liquid marbles composed of fine, medium, and coarse hydrophobic sands to understand conditions leading to mudflow air entrapment via liquid marbles. Modified Bond Number (Bo^*) can predict whether liquid marbles will form or not as stable under a specific set of conditions. **Table 4.1** summarizes the parameters used for calculating Bo^* . Assuming that the

blade edge region has the most turbulent fluid flow condition, the rotation length of a single particle's travel path is taken as the circle circumference that the blade sweeps by. The eddy turbulent accelerations have different values since the equivalent downhill mixing velocities are different. **Fig. 4.2** plots the experimental Bo^* for mean particle diameters of each sand with observed average bubble diameters inside liquid marbles that occurred at different mixing speeds against the theoretical Bo^* line at the value of one as a liquid marble stability criterion. Coarser sand particles and higher equivalent downhill mixing speed lead to $Bo^* > 1$, where liquid marbles become unstable, and particles detach from bubbles more easily.

Table 4.1. Parameters for calculating the modified Bond number of liquid marbles

	Fine Sand			Medium Sand			Coarse Sand		
Particle Diameter (mm)	0.15			0.27			1.33		
Particle Density (kg/m ³)	2600			2600			2600		
Equivalent downhill mixing velocity (m/s)	3.11	5.44	7.78	3.11	5.44	7.78	3.11	5.44	7.78
Rotating Length Scale (m)	0.157								
Eddy Turbulent Acceleration (m/s ²)	62	188	385	62	188	385	62	188	385
Fluid Surface Tension (N/m)	0.07								
Average Contact Angle (°)	91			91			91		
Bo^*	0.09	0.13	0.18	0.13	0.23	0.40	0.67	1.72	3.34

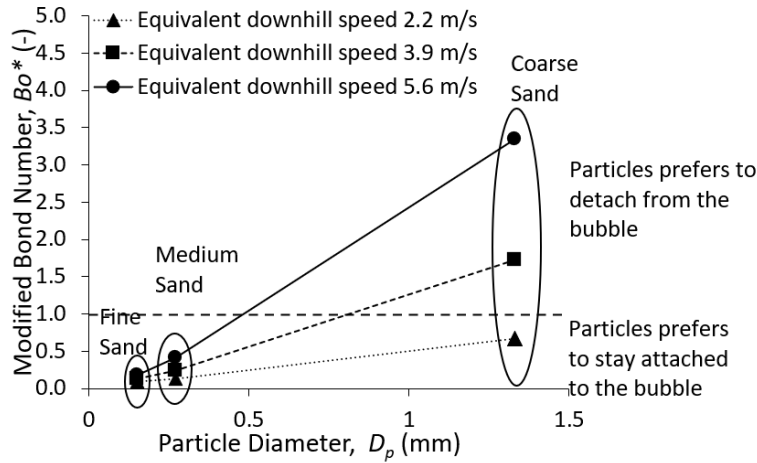


Figure 4.2. The combined effect of particle diameter D_p and equivalent downhill mixing speed on the modified Bo^* .

Although the modified Bo^* serves as an estimate of the likelihood of forming liquid marbles during various flow and transport conditions for different sands, the bubble stability estimation based on modified Bo^* has several limitations. First, the modified Bo^* only considers a particle at the bottom of the bubble. Second, Bo^* does not provide information about the liquid marble's size or shape. Third, air pressure and hydrodynamic pressure on the bubble are neglected, while **Eqn. 2.2** provides a more accurate calculation for balancing air pressure and hydrodynamic pressure. Fourth, the particle buoyancy exists at the partially submerged condition, so the approximation using a fully submerged condition is limited, and **Eqn. 2.3** addresses the issue. Fifth, the particle diameter is relatively restricted to a small range: between 0.15 mm and 0.25 mm for fine sand, between 0.25 mm and 0.425 mm for medium sand, and between 1.18 mm and 1.70 mm for coarse sand. The soil in field conditions has a continuous particle diameter distribution of less than 0.075 mm up to 5 mm or above. Lastly, hydrodynamic drag is omitted. Therefore, a comprehensive analysis should provide a better estimate of liquid marble stability using modified forces and considering multiple particle-bubble locations and a complete set of forces.

Next, the applicability of theoretical **Eqns. 2.14 – 2.16** to mudflow conditions liquid marbles is investigated in **Fig. 4.3**. For fine sand, theoretically-predicted liquid marble diameters are 0.87 mm, 0.75 mm, and 0.45 mm, respectively, based on **Eqns. 2.14 - 2.16**. Similarly, for medium sand particles, the liquid marble diameters are 1.57 mm, 1.36 mm, and 1.49 mm, respectively. Finally, the liquid marble diameters for coarse sand particles are 7.72 mm, 6.69 mm, and 7.30 mm, respectively. **Fig. 4.3** shows positive analysis results for only a high shear rate of 778 s^{-1} where the sand particle size strongly correlates with the final size of liquid marbles, where coarser hydrophobic sand leads to larger marbles. **Fig. 4.3** results are selected among various tested mixing times, equivalent downhill mixing speeds, and initial solid volumetric concentrations. Although the liquid marbles have been generated so that the distribution of diameter is narrow, it should be noted that relatively larger liquid marbles are more likely to float at the top. Therefore, the effect of gravity shall be further considered and investigated.

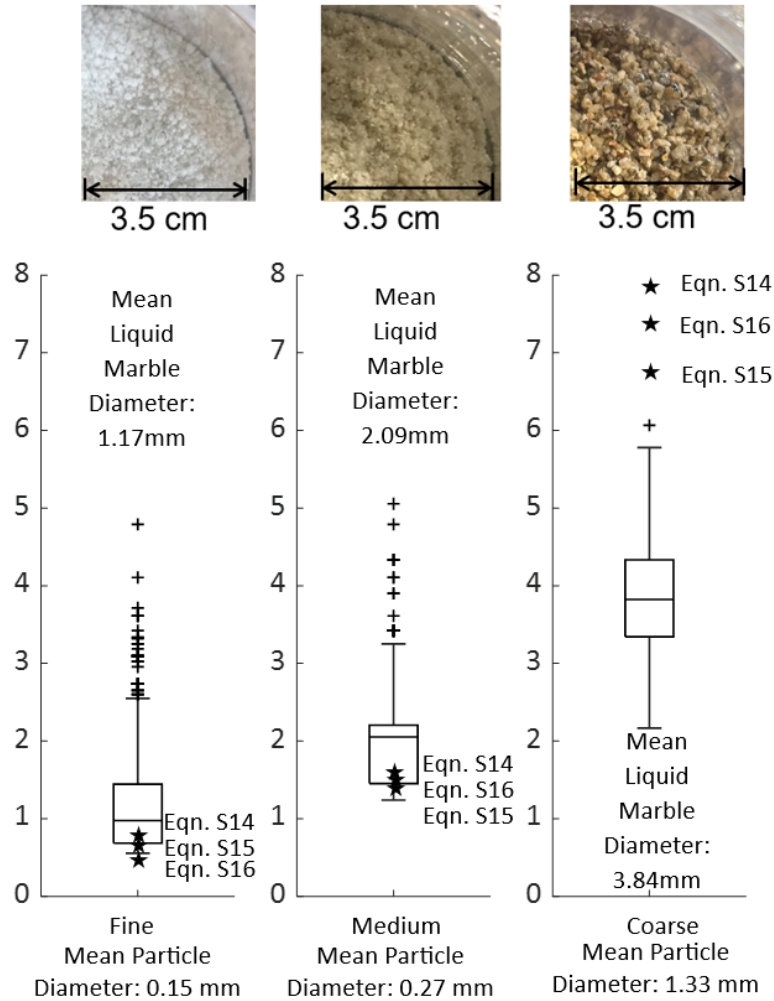


Figure 4.3. Effect of the sand particle size on the liquid marble size. The results include all initial solid concentrations at the high end of 778 s^{-1} , which produces the most stable liquid marbles. The mixing time is cut after the equilibrium condition: $> 60 \text{ s}$ for fine sand and $> 40 \text{ s}$ for medium and coarse sand.

Since Bo^* and **Eqns. 2.14 – 2.16** are limited in the prediction of sizes and stabilities of liquid marbles in mudflows, a comprehensive force analysis is proposed to identify a full set of conditions in liquid marble formations for postfire mudflow-like mixtures. The analysis quantifies the forces that affect liquid marble formation and uses static and dynamic equilibrium to understand better liquid marble stability constrained to postfire mudflow conditions. Since a single hydrophobic sand particle can attach to a bubble anywhere on the surface, different scenarios that

can be used to study force balance are investigated. In **Fig. 4.4a**, a hydrophobic sand particle stays at the top of the bubble; in **Fig. 4.4b**, a particle stays at the left/right side of the bubble, which is the worst-case scenario considering the hydrodynamic effects in horizontal fluid flow; and in **Fig. 4.4c** a particle stays at the bottom of the bubble which is not favorable when gravity dominates over inertial forces.

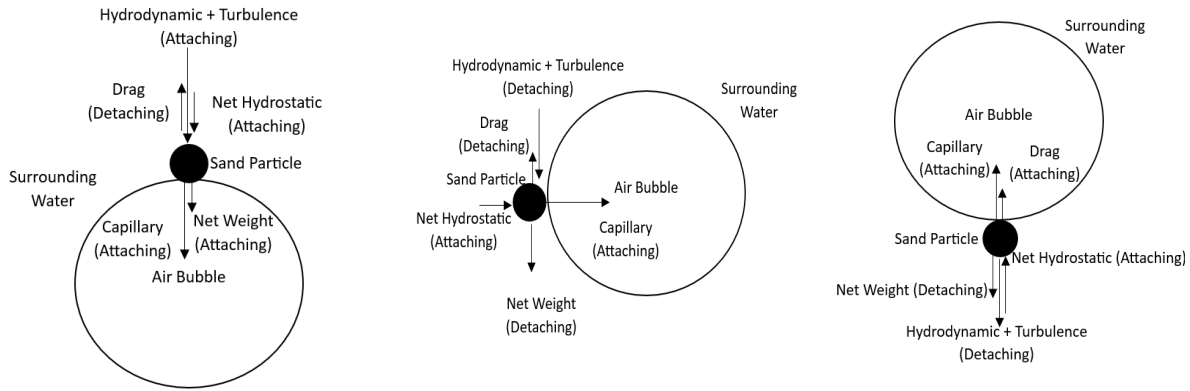


Figure 4.4. Examples of Forces under different scenarios with different particle-bubble relative locations: **a)** sand particle on the top of the bubble, **b)** sand particle to the left of the bubble, and **c)** sand particle at the bottom of the bubble.

Many forces are involved in particle-bubble interaction (see **Eqns. 2.1-2.11**). Three types of static forces dominate in the particle-bubble interaction process (**Fig. 4.5a**): capillary force, excess force, and net weight force. Capillary force favors particle-bubble attraction (Tao, 2005) and linearly depends on the sand particle diameter (**Fig. 4.5a**). The excess force acts as an attractive force when the bubble diameter is smaller than 5.5 mm (Tao, 2005) and is a function of the sand particle diameter squared, as shown by **Eqn. 2.2**. Smaller bubbles experience stronger attractive net hydrostatic forces. The net weight is generally a repulsive force (Tao, 2005). The net weight force (**Fig. 4.5a**) has a cubic relationship with the sand particle diameter since both the weight and buoyancy parts of the equation depend on the sand particle volume. For all three forces, Young's

contact angle applies. Two major hydrodynamic forces exist in the particle-bubble interaction process: hydrodynamic drag force (**Fig. 4.5b**) and local turbulence force (**Figs. 4.5e-g**). In drag calculation here, an estimate of drag reduction of 25% is applied. Hydrodynamic drag force is a repulsive force (Tao, 2005). Drag force is linearly dependent on fluid velocity (**Fig. 4.5b**). The undisturbed fluid flow velocity is assumed to be the same as the velocity provided by the impeller. The particle slip velocity is obtained from Stokes' rule. The drag force is larger on coarser particles.

Reynolds number of the fluid flow during the mixing process is a function of impeller diameter, liquid density, liquid dynamic viscosity, and velocity provided by the impeller (Paul et al., 2004). The mixing process becomes turbulent when the Reynolds number exceeds 10,000 (Paul et al., 2004), which occurs at impeller velocities higher than 4 m/s in this experiment. Therefore, the local turbulence force is only considered in a turbulent flow regime. Flow direction allows hydrodynamic force on particles to attach or detach from the bubble (**Figs. 4.5c-d**). Instead of plotting hydrodynamic force only, this figure plots the ratio between hydrodynamic force and the sum of all other static forces. The calculation takes the air bubble as a fixed reference point. Therefore, the u_{pb} is the relative velocity between the sand particle and the bubble. The particle velocity is induced by surrounding fluid obtained from **Eqns. 2.4 - 2.9**. In case 1 defined in **Fig. 4.4a**, the sand particle is above the air bubble (hydrodynamic force analysis in **Fig. 4.5c**). Therefore, net weight, capillary, and excess forces attach forces in which the overall acting direction is downward. When hydrodynamic impact angle α equals 0 or 2π , the flow direction is parallel to gravity or the overall acting direction of all static forces. When α equals π , the flow direction is perpendicular to gravity. When the hydrodynamic drag force has the same direction as the overall acting direction of all static forces ($0 < \alpha < \pi/2$, or $3\pi/2 < \alpha < 2\pi$), a more attaching particle-bubble interaction will occur. When hydrodynamic drag force is in the opposite direction

of the overall acting direction of all static forces ($\pi/2 < \alpha < 3\pi/2$), a detaching particle-bubble interaction will occur. In case 2 defined in **Fig. 4.4c**, the sand particle is below the air bubble (hydrodynamic force analysis in **Fig. 4.5d**). Therefore, net weight has a detaching effect, while capillary and excess forces have an attaching effect. The overall acting direction of all static forces is still towards the bubble center (upward, favoring attractive interaction). The hydrodynamic effect is opposite to case 1. While the hydrodynamic impact angle is between $3\pi/2$ and 2π , the hydrodynamic drag force has an attaching effect in particle-bubble interaction. Otherwise, the hydrodynamic drag force causes the detaching effect. The analysis considers local turbulence force as an additional enhancement of hydrodynamic drag force. In the force equilibrium analysis, the local turbulence force only applies when the impeller-induced Reynolds number exceeds 10,000. **Figs. 4.5e-g** show how local turbulent force depends on bubble diameter, sand particle diameter, and fluid energy dissipation. As bubble size increases, the local turbulence force decreases. However, local turbulence force increases as sand particle diameter or fluid energy dissipation increases.

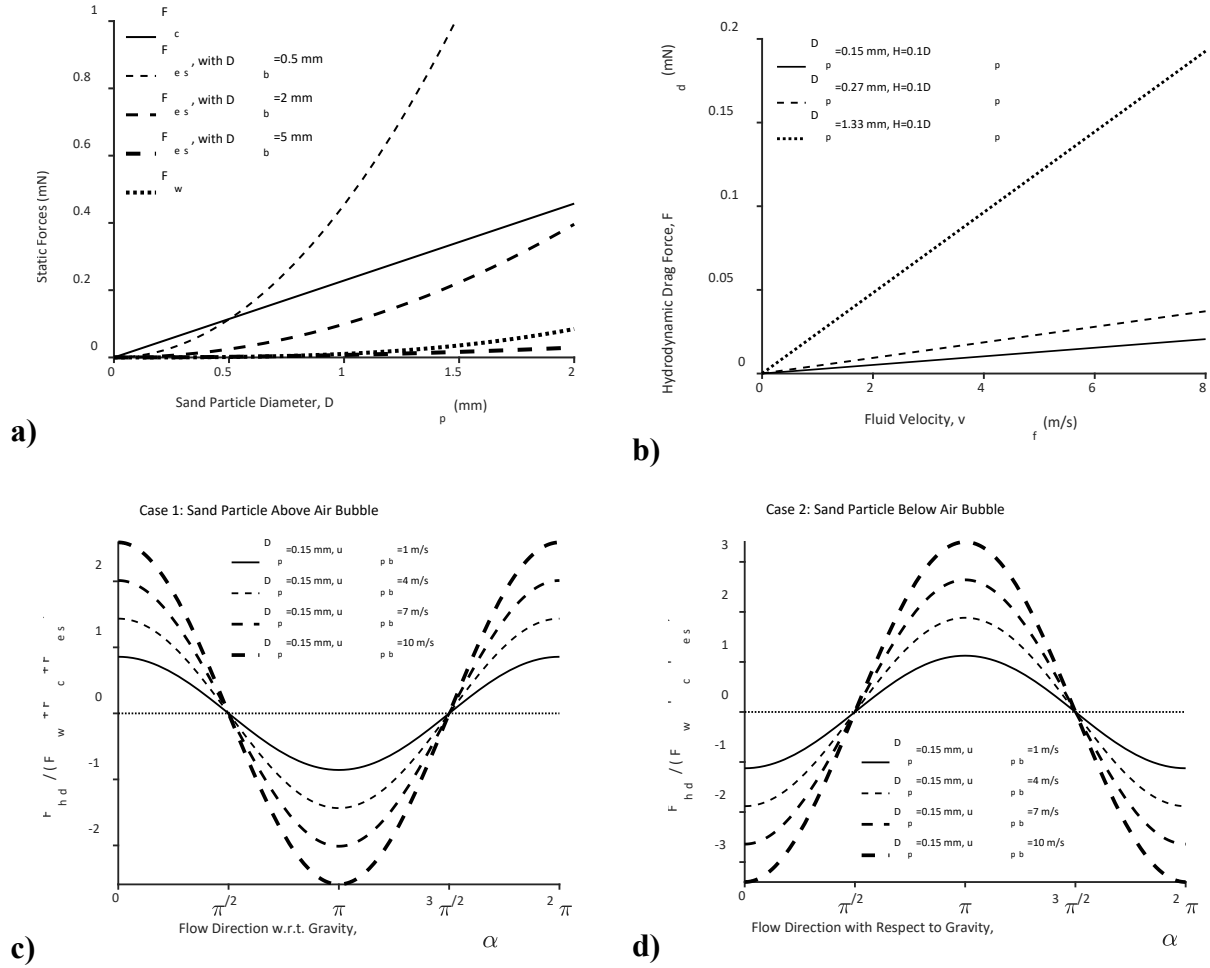


Figure 4.5. Static and Dynamic forces in particle bubble interaction process. **a)** capillary, excess static, and weight forces, where D_b is the bubble diameter. **b)** hydrodynamic drag forces. **c)** effect of hydrodynamic impact angle when the particle is above the bubble, **d)** effect of hydrodynamic impact angle when the particle is below the bubble, **e)** local turbulence force due to the effect of bubble diameter, **f)** local turbulence force due to the effect of sand particle diameter, **g)** local turbulence force due to the effect of fluid energy dissipation.

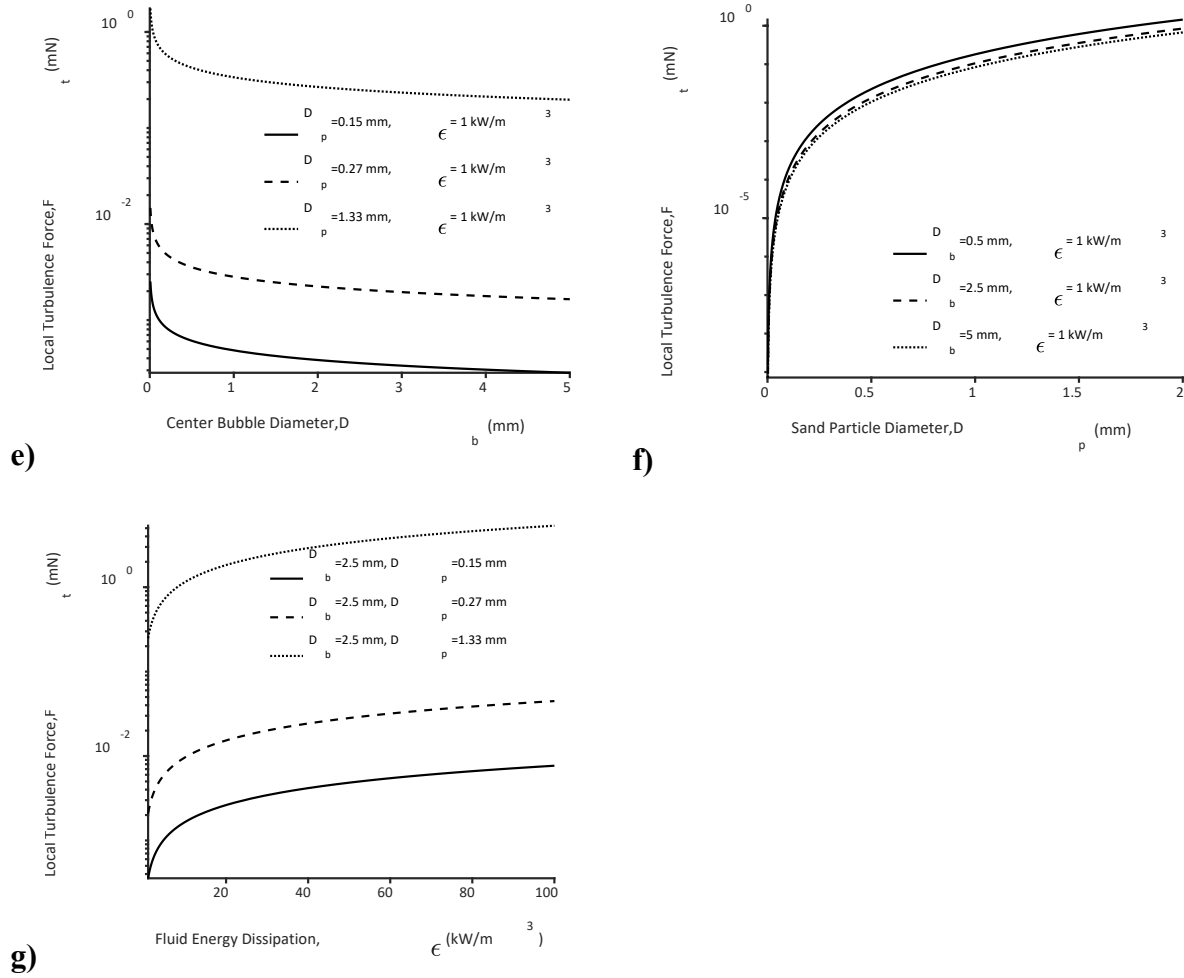
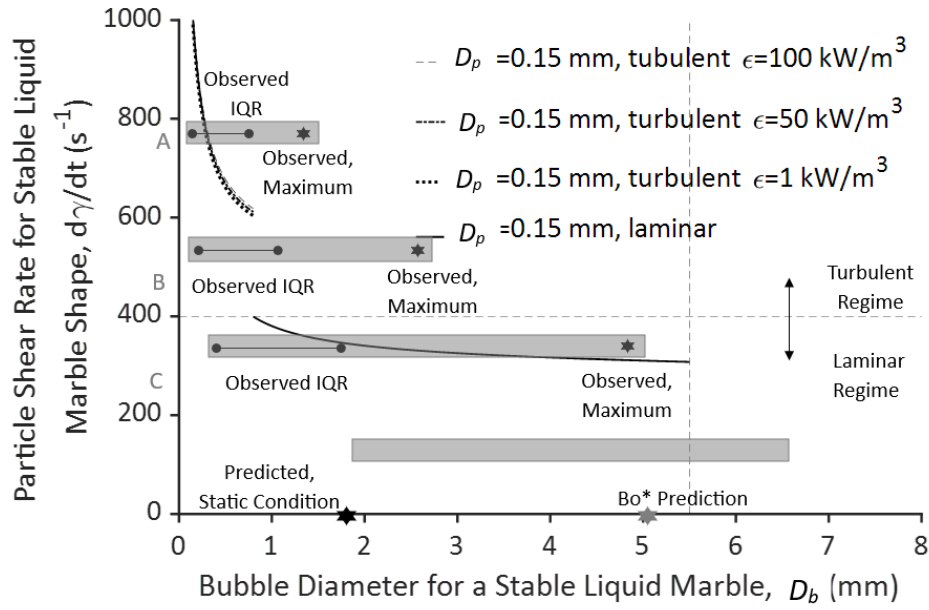
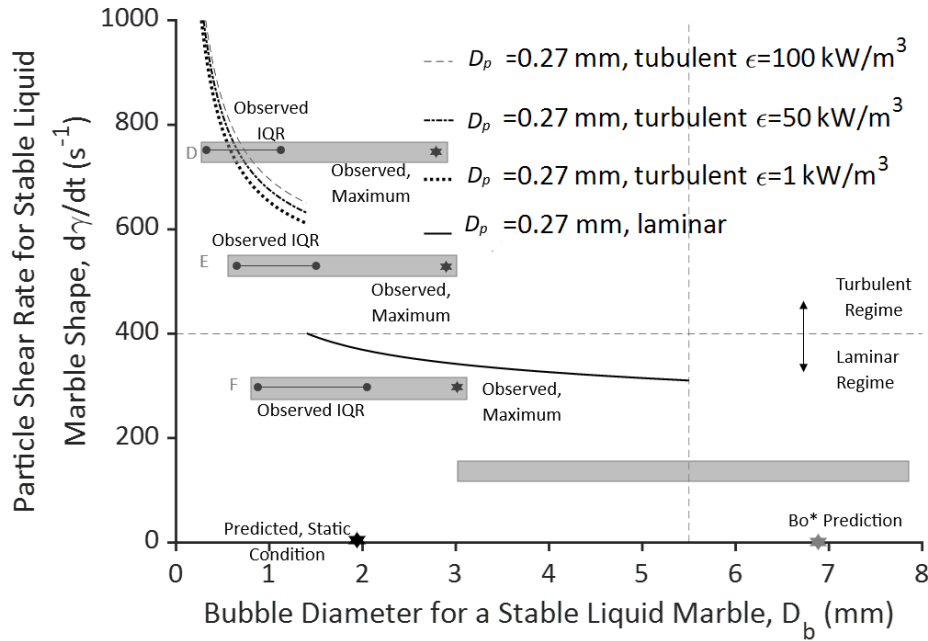


Figure 4.5 (Continued). Static and Dynamic forces in particle bubble interaction process. **a)** capillary, excess static, and weight forces, where D_b is the bubble diameter. **b)** hydrodynamic drag forces. **c)** effect of hydrodynamic impact angle when the particle is above the bubble, **d)** effect of hydrodynamic impact angle when the particle is below the bubble, **e)** local turbulence force due to the effect of bubble diameter, **f)** local turbulence force due to the effect of sand particle diameter, **g)** local turbulence force due to the effect of fluid energy dissipation.

Figs. 4.6a-c quantify results of force balance analysis between capillary, net hydrostatic, hydrodynamic, and local turbulence forces. The shear rate and bubble diameter relationship at a condition of a stable liquid marble, specifically for a single-bubble-single-particle interaction process, is obtained from the force equilibrium. The system is turbulent for all three sand sizes when the particle shear rate exceeds 400 s^{-1} and laminar when the particle shear rate is less than 400 s^{-1} . The cutoff bubble diameter for the analysis is 5.5 mm.



a)



b)

Figure 4.6. Particle shear rate vs. bubble diameter for a stable liquid marble (single-particle-single-bubble interaction) based on force equilibrium analysis: **a)** fine sand particles, **b)** medium sand particles, **c)** coarse sand particles.

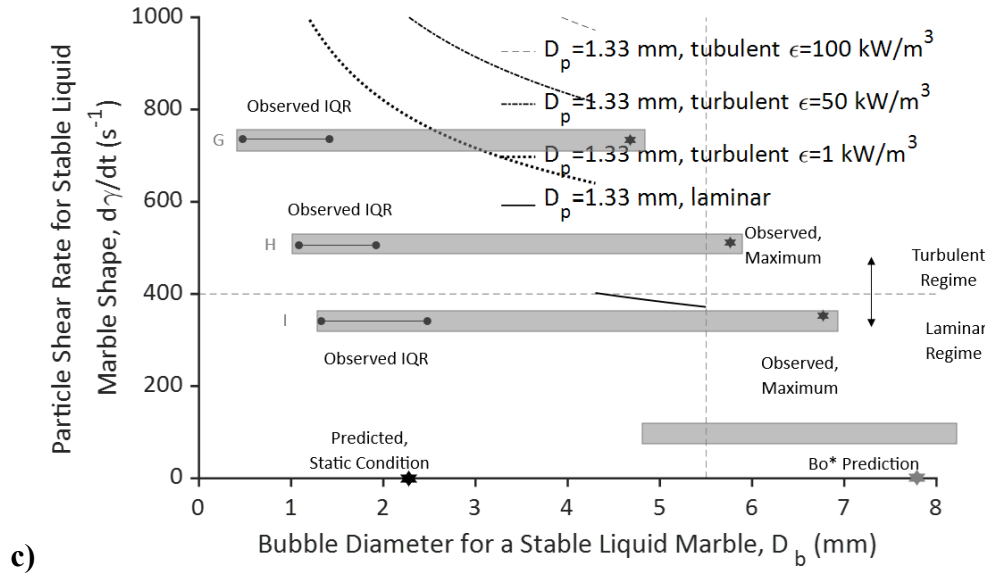


Figure 4.6 (Continued). Particle shear rate vs. bubble diameter for a stable liquid marble (single-particle-single-bubble interaction) based on force equilibrium analysis: **a)** fine sand particles, **b)** medium sand particles, **c)** coarse sand particles.

Liquid marbles covered with fine sand particles (**Fig. 4.6a**) have the largest stable diameter range between 1 and 5.5 mm in a laminar environment among all three types of sand. The analysis (see star dots on the x-axis in Figs. 9a-c) predicts a stable liquid marble diameter of about 1.8 mm using the same forces equations but without the hydrodynamic effect. With a fixed mixing time and a fixed initial solid volumetric concentration ratio, the interquartile range (IQR, or middle 50% and is defined as the difference between the 75% and 25% of the data) of observed liquid marble completely falls below the equilibrium-analysis predicted line for the lowest shear rate of 311 s^{-1} (Cup A, also in **Fig. 4.7a**). However, the maximum observed liquid marble diameter falls to the right side of the prediction curve. For higher shear rates of 544 s^{-1} (Cup B, also in **Fig. 4.7b**) and 778 s^{-1} (Cup C, also in **Fig. 4.7c**), the IQR of observed liquid marbles will cross the prediction curve further away. Note that the maximum observed liquid marble diameters both fall to the right side of the curve. For liquid marbles covered with medium sand particles (**Fig. 4.6b**), the range of stable bubble diameter in a laminar environment is narrower, from 1.5 to 5.5 mm. The stable

bubble diameter range is smaller for medium sand compared with fine sand conditions. Without a hydrodynamic effect, the stable liquid marble has a predicted bubble diameter of about 1.9 mm. The liquid marble diameter under three different shear rates for medium sand particles is similar to the cases for fine sand particles. The only difference is that the maximum observed liquid marble diameter under the shear rate of 311 s^{-1} (Cup D, also in **Fig. 4.7d**) is still within the curve boundary. However, it is very close to the boundary. Observed liquid marble diameters exceed the prediction limit for shear rates at 544 s^{-1} (Cup E, also in **Fig. 4.7e**) and 778 s^{-1} (Cup F, also in **Fig. 4.7f**). For liquid marble covered with coarse sand particles (**Fig. 4.6c**), the range of stable bubble diameter in a laminar environment is the shortest, from 4 to 5.5 mm. The stable bubble diameter range is the smallest for coarse sand. That means the liquid marble stability is the worst for coarse sand among all three types of sand particles. Without hydrodynamic effects, the stable liquid marble has a predicted bubble diameter of about 2.6 mm. The IQR of the observed liquid marble still falls within the prediction limit. However, unlike the other two types of sand particles, the maximum observed liquid marbles all fall to the right side of the prediction curve (Cup G, also in **Fig. 4.7g**; Cup H, also in **Fig. 4.7h**; Cup I, also in **Fig. 4.7i**). Overall force equilibrium analysis and experimental data match well, where experimental data show a range of liquid marble diameters. Roughly 70% of the Interquartile Range (IQR) of observed liquid marbles falls within the prediction, meaning most of the liquid marbles obtained from the experiment still follow the general principle of force balances for single-particle-single-bubble interaction. Multiple-particle-single-bubble interaction (Wang et al., 2022a) and liquid-marble-liquid-marble interaction (Jin et al., 2018), particle diameter discrepancies due to sieve sizes, roundness, and sphericity variances are the possible reasons for the observed ranges.

For fine sand particles with an average diameter of 0.15 mm, the average estimated bubble diameter of the final liquid marble covered by fine sand is about 0.96 mm using the force balance method and the three direct estimation equations (see **Eqns. 2.14-2.16**) mentioned previously in this paper. Therefore, the collision efficiency (see **Eqn. 2.17**) for a single fine sand particle to collide with a bubble is 0.47. Medium sand particles have an average diameter of 0.27 mm. The average estimated bubble diameter of the final liquid marble covered by medium sand is about 1.33 mm. Thus, the collision efficiency for a single medium sand particle to collide with a bubble is 0.61. Coarse sand particles have an average diameter of 1.33 mm. The average estimated bubble diameter of the final liquid marble covered by coarse sand is about 6.12 mm. The collision efficiency for a single coarse sand particle to collide with a bubble is 0.65.

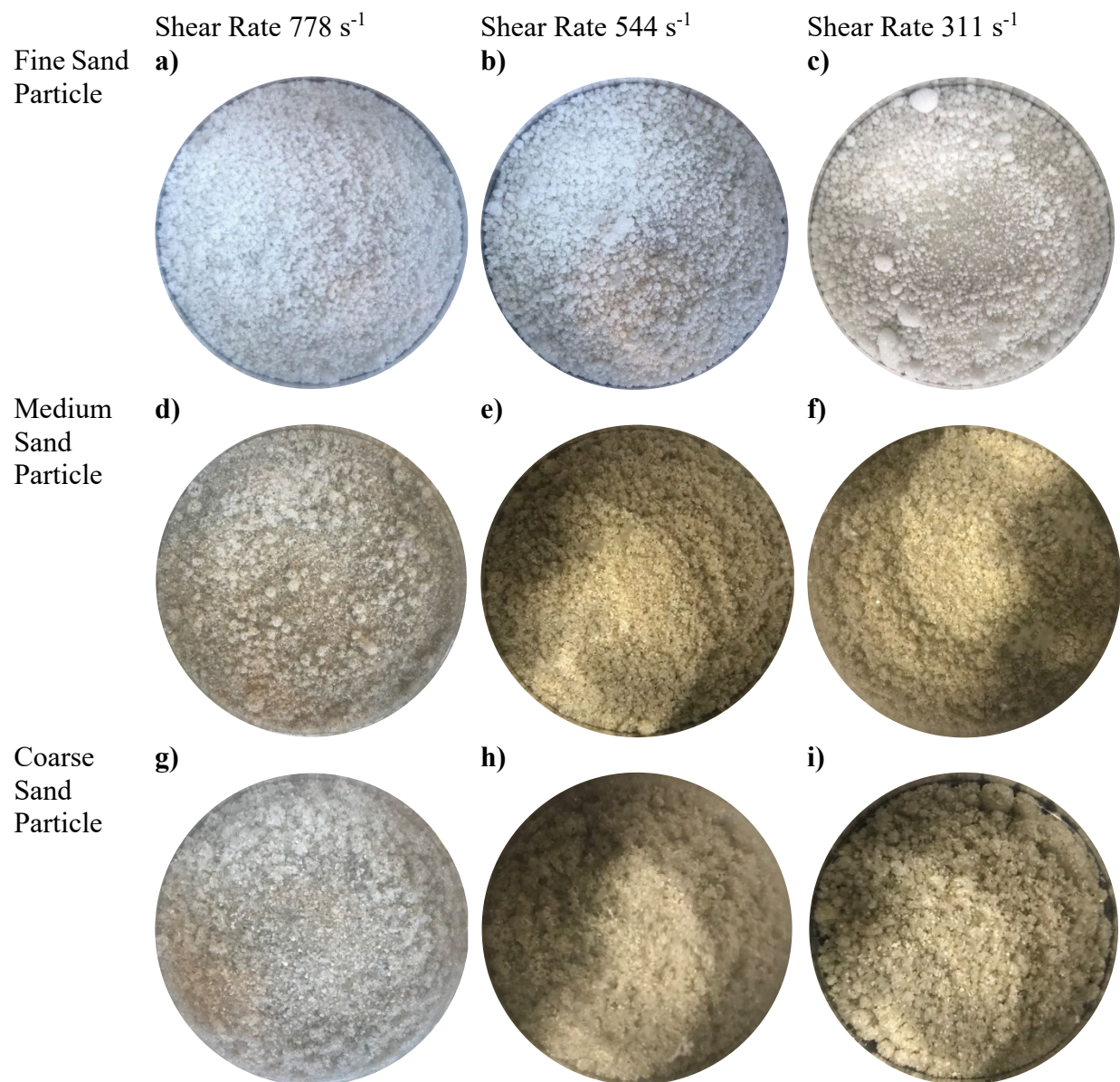


Figure 4.7. Top Views of Cups A to I in Figure 4.6.

4.2 Evaluation of the Mixture Air Entrapment and Density

The total volume of air trapped in hydrophobic liquid marbles within mixtures is quantified with the specific air content (**Eqn. 3.4**), and thus, the bulk density of hydrophobic sand slurries decreases compared to hydrophilic sand slurries. The entrapped air in the three-phase mixture is

measured by subtracting the initial water and solid volumes from the total final mixture. The measurement error of volume falls within ± 1 mL. **Table 4.2** shows a comparison of air entrapments produced with hydrophobic and hydrophilic fine, medium, and coarse sands for a mixing time of 10 – 120 seconds, a shear rate of $311 - 778 \text{ s}^{-1}$, and an initial solid volumetric concentration of 5 – 25%. As introduced at the beginning of the article, debris flows with regular hydrophilic soil can entrap air bubbles if the debris flow impacts an obstacle (Lugni et al., 2006; Song et al., 2021) or wave surges (Arguden & Rodolfo, 1990); however, it can be seen that hydrophilic sand does not have as strong capability to trap air during the mixing process as hydrophobic sand.

Table 4.2. A comparison of air entrapment with hydrophobic and hydrophilic sand under selected conditions. V_s is the volume of sand particles, V_w is the volume of water, and e^* is the specific air content.

Sand Particle Type	V_s/V_w	Shear Rates	Mixing Time	e^* for Hydrophilic sand	e^* for Hydrophobic Sand
	(%)	(s^{-1})	(s)	(%)	(%)
Fine	5	778	60	0.0	17
Fine	11	778	60	4.3	22
Fine	18	778	60	2.9	23
Fine	25	778	60	4.3	27
Fine	25	778	10	6.5	70
Fine	25	778	120	4.3	15
Fine	25	544	60	4.3	39
Fine	25	311	60	6.5	49
Medium	5	778	60	0.0	13
Medium	11	778	60	0.0	19
Medium	18	778	60	2.9	20
Medium	25	778	60	4.3	22
Medium	25	778	10	4.3	43
Medium	25	778	80	2.2	18
Medium	25	544	60	4.3	26
Medium	25	311	60	4.3	33
Coarse	5	778	60	0.0	9
Coarse	11	778	60	0.0	12
Coarse	18	778	60	2.9	13
Coarse	25	778	60	2.2	16
Coarse	25	778	10	4.3	48
Coarse	25	544	60	2.2	26
Coarse	25	311	60	4.3	35

Fig. 4.8 shows the correlation between the specific air content and shear rate. When the shear rate increases, the specific air content decreases. The decreasing behavior of air entrapment changes at around $300\ s^{-1}$. Before this separating shear rate, air entrapment decreases faster as the shear rate increases. Low mixing power at a low shear rate causes more uneven mixing results, leading to extremely diverse physical appearances of liquid marbles. When mixing at high shear rates, the mixing powers are strong enough to cause a more uniform physical appearance of marbles. Hydrodynamic forces from mixing speed must be coupled with other forces, such as

resisting forces due to gravity, at low shear rates when investigating their effect on air entrapment. Group "Hydrophobic Fine, $V_s/V_w = 11\%$ " provides the range of shear rates to form stable liquid marbles.

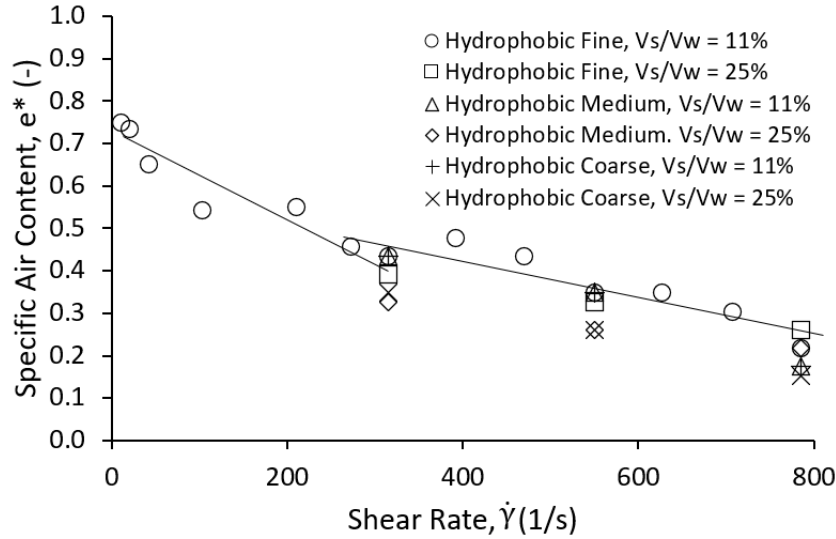


Figure 4.8. Specific air content vs. shear rate, where all the experiments mixing exceeds 60 seconds.

Fig. 4.9 further quantifies how the mixing time decreases trapped air aiming towards the equilibrium state by partial degassing. The equilibrium state is defined as the internal structure of the mixture that is stable against longer and more vigorous mixing, characterized by stable liquid marbles. **Figs. 4.9a-c** show that with smaller diameters and less observable in some cases, liquid marbles form when the mixture undergoes prolonged mixing. It can be seen that coarser sand needs less time to reach the equilibrium, and higher initial solid concentration mixes need a longer time to reach the equilibrium state. **Fig. 4.9d** synthesizes coupled effects and serves as a base for the proposed empirical relationship:

$$\frac{e^*}{V_s/V_w} = 4.44(tD_p)^{-0.31} \quad (4.1)$$

Fig. 4.9e describes an empirical correlation between air entrapment normalized by initial solid volumetric concentration and Bo^* , which depends on the mean particle diameter and mean velocity (see **Eqn. 2.12**). Therefore, besides describing the time effect on the specific air content, this paper proposes another empirical correlation focusing on the velocity effect on the specific air content:

$$\frac{e^*}{V_s/V_w} = -0.56 \ln Bo^* + 1.92 \quad (4.2)$$

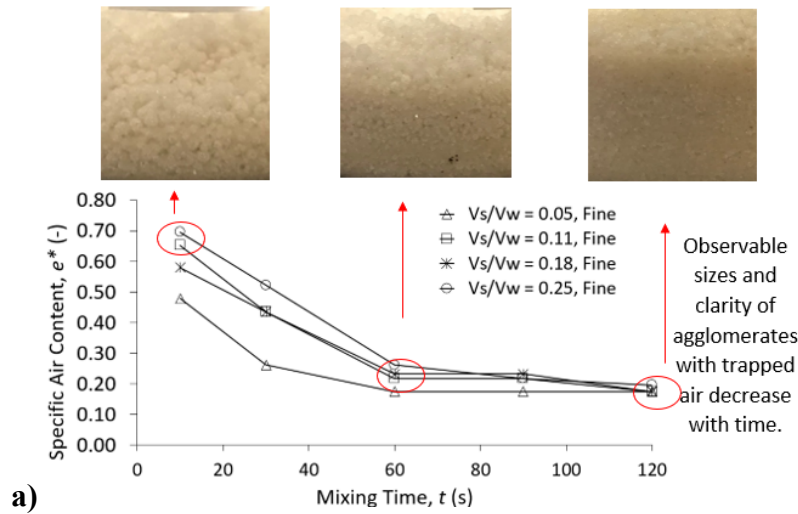
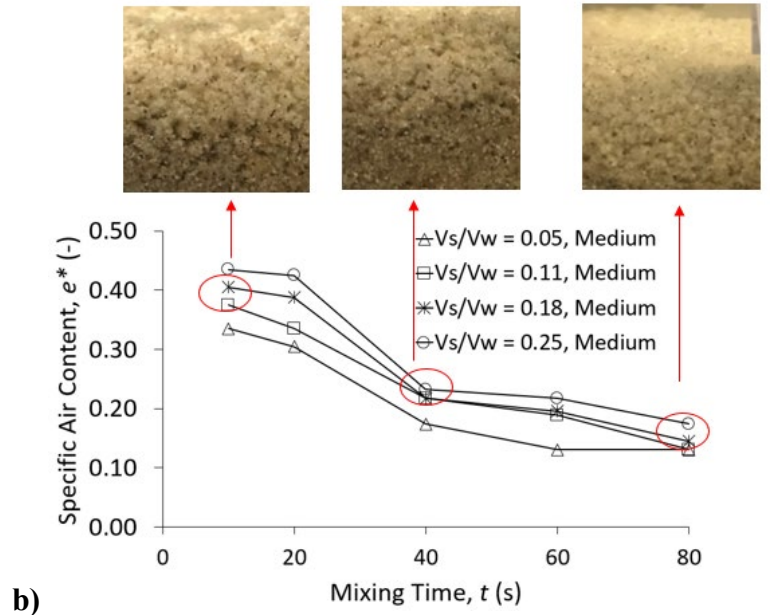
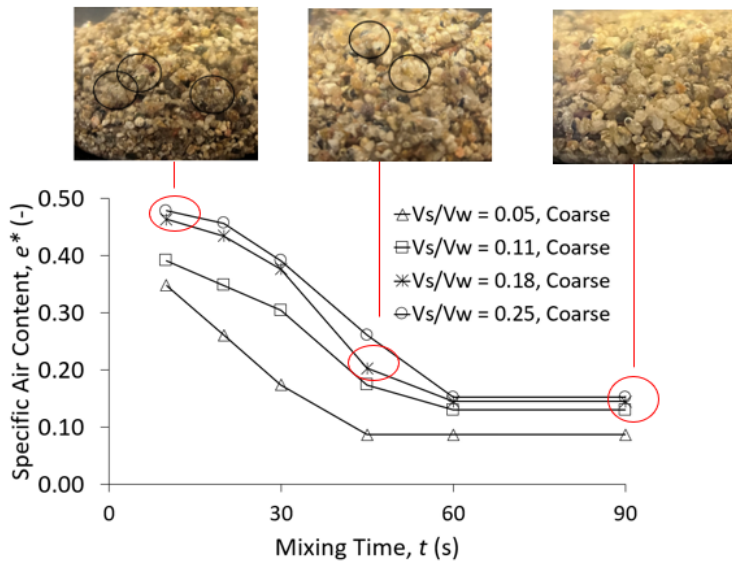


Figure 4.9. Coupled effect mixing time and types of sand particles on the ability to trap air phase for **a)** fine sand particles, **b)** medium sand particles, **c)** coarse sand particles, and **d)** combined results. **e)** Empirical correlation between specific air content normalized by initial solid volumetric concentration and modified Bond Number.



b)



c)

Figure 4.9 (Continued). Coupled effect mixing time and types of sand particles on the ability to trap air phase for **a)** fine sand particles, **b)** medium sand particles, **c)** coarse sand particles, and **d)** combined results. **e)** Empirical correlation between specific air content normalized by initial solid volumetric concentration and modified Bond Number.

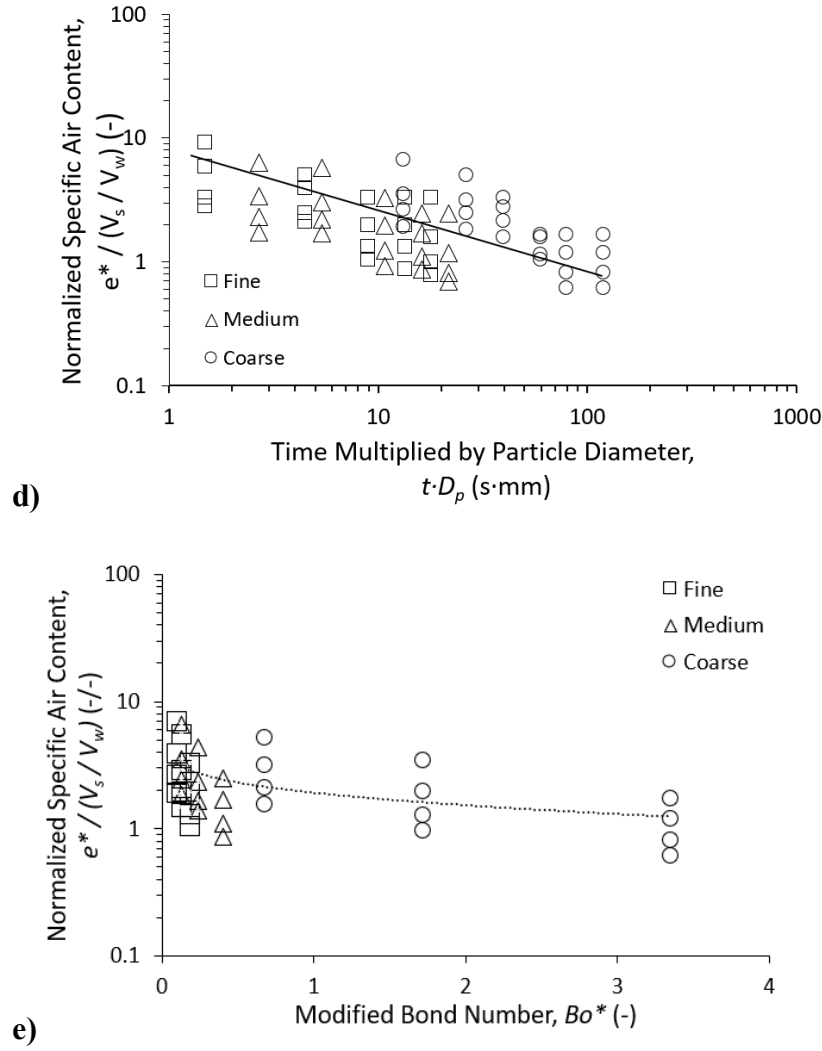


Figure 4.9 (Continued). Coupled effect mixing time and types of sand particles on the ability to trap air phase for **a)** fine sand particles, **b)** medium sand particles, **c)** coarse sand particles, and **d)** combined results. **e)** Empirical correlation between specific air content normalized by initial solid volumetric concentration and modified Bond Number.

Besides air entrapment as an essential indicator of the mixing behavior of hydrophobic particles, water, and air, density change before and after mixing is necessary for mudflow models. The density reduction indicates how much water-sand slurry will reduce due to the additional entrapment of air phases when the same amount of sand becomes hydrophobic. **Fig. 4.10a** shows the effect of mixing time on the density changes of the final mixture. The density reduction will reach a stable condition for the extended mixing time, which is shorter for coarser particles. The

average final density reduction is 17%, 13%, and 11% for fine, medium, and coarse sand particles, respectively, when the shear rate is 778 s^{-1} (i.e., the equivalent downhill mixing speed is 7.8 m/s). After ruling out the time effect (i.e., air entrapment is relatively stable after mixing over 60 seconds), the shear rate consistently impacts all types of sand (**Fig. 4.10b**). **Fig. 4.10b** defines two bounding equations as a speed function to provide a range of estimation of density change normalized by initial solid concentration. For numerical simulations that treat (postfire) debris flow as a uniform homogeneous material with effective parameters, the density reduction finding can possibly be applied to the momentum equations in Navier-Stoke Equations with a smaller density. For example, if the solid density is 2600 kg/m^3 and water density is 1000 kg/m^3 for a debris flow with a solid concentration of 20%, then the effective density of such an assumed homogenous material will be 1320 kg/m^3 . Taking the minimum density reduction of 10% in this paper, then the reduced effective density will be 1188 kg/m^3 .

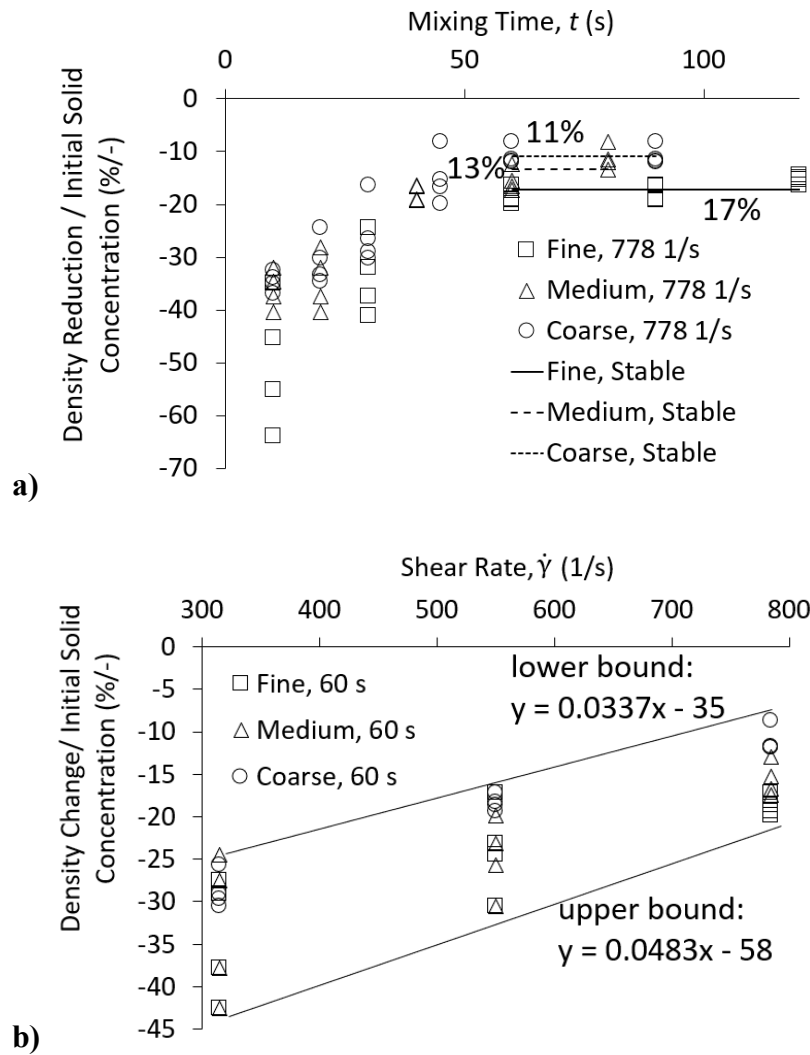


Figure 4.10. Density reduction due to **a)** mixing time and **b)** shear rate.

Acknowledgment

Chapter 4 is currently being prepared for submission for publication of the material entitled “Air Phase Entrapment Role in Hydrophobic Particle-Water-Air Mixtures Internal Structure and Density”. Ma, Wenpei; Tomac, Ingrid. The dissertation author was the primary researcher and first author of this manuscript. Melissa Lepe did some preliminary analysis, and her work was greatly appreciated.

Chapter 5 Rheological Behavior of Experimental Post-Wildfire Debris Flow

5.1 Bagnold Number Analysis

The Bagnold number relates the grain collision stresses to the viscous fluid stresses in granular flow by quantifying shear rates and the corresponding liquid marble diameter. Iverson (1997) provides the definition equation of the Bagnold number for granular debris flow material, as shown in **Eqn. 5.1**:

$$Ba = \frac{C_v}{1 - C_v} \frac{\rho \delta^2 \dot{\gamma}}{\eta} \quad (5.1)$$

where, C_v is the volumetric concentration of solid (i.e., the volumetric concentration of liquid marbles in this paper, dimensionless), ρ is the density of solid (i.e., the averaged density of liquid marbles in this paper, kg/m^3), δ is the characteristic diameter of liquid marbles (m), $\dot{\gamma}$ is the shear rate (s^{-1}), and η is the dynamic viscosity of the pore fluid (kg/m-s). The Bagnold number increases as granular collisions dominate over viscous force in debris flows. At low shear rates, the measured shear stress is predominantly the viscous forces of the carrying fluid in the pores (Iverson, 1997). A Bagnold number less than 40 corresponds to this first regime, the viscous force-dominated regime. As the shear rate increases, the granular collisions begin to increase, and viscous forces become less apparent in the measured shear stress. The transition regime is defined as a second regime when the Bagnold number is between 40 and 450. The measured shear stress is predominantly the granular collisions at high shear rates. A third, collision force-dominated regime corresponds to a Bagnold number larger than 450.

Figs. 5.1a-d plots the liquid marble diameters vs. shear rates from 1 to 100 s^{-1} . The figure also shows two dividing lines for each test condition based on Bagnold numbers 40 and 450. The first viscous force-dominated regime is the region to the left of the $\text{Ba} = 40$ line. The third collision force-dominated regime is the region to the right of the $\text{Ba} = 450$ line. The second regime, the transition regime, is the region between the two lines. Therefore, there are three different regimes for each type of final mixture with liquid marbles made of different sand particles. This paper shall consider 9 different scenarios in total.

For hydrophobic fine sand particle tests (**Figs. 5.1a-b**), the first regime exists when the shear rate is less than 10 s^{-1} , and the third regime corresponds to the shear rate higher than 100 s^{-1} . The second regime is located at the shear rate between 10 and 100 s^{-1} . For hydrophobic medium sand particle tests (**Fig. 5.1c**), the first regime exists at a very low shear rate of less than 5 s^{-1} . The third regime occurs roughly around 30 s^{-1} (varies from 20 to 40 s^{-1}). The second regime corresponds to a shear rate from 5 to about 30 s^{-1} . For hydrophobic coarse sand particle tests (**Fig. 5.1d**), the first regime does not exist. The second regime has a narrow shear rate range with a shear rate of less than 5 s^{-1} . The third regime is the widest among all conditions. The third regime dominates the flow behavior as long as the shear rate is higher than 5 s^{-1} .

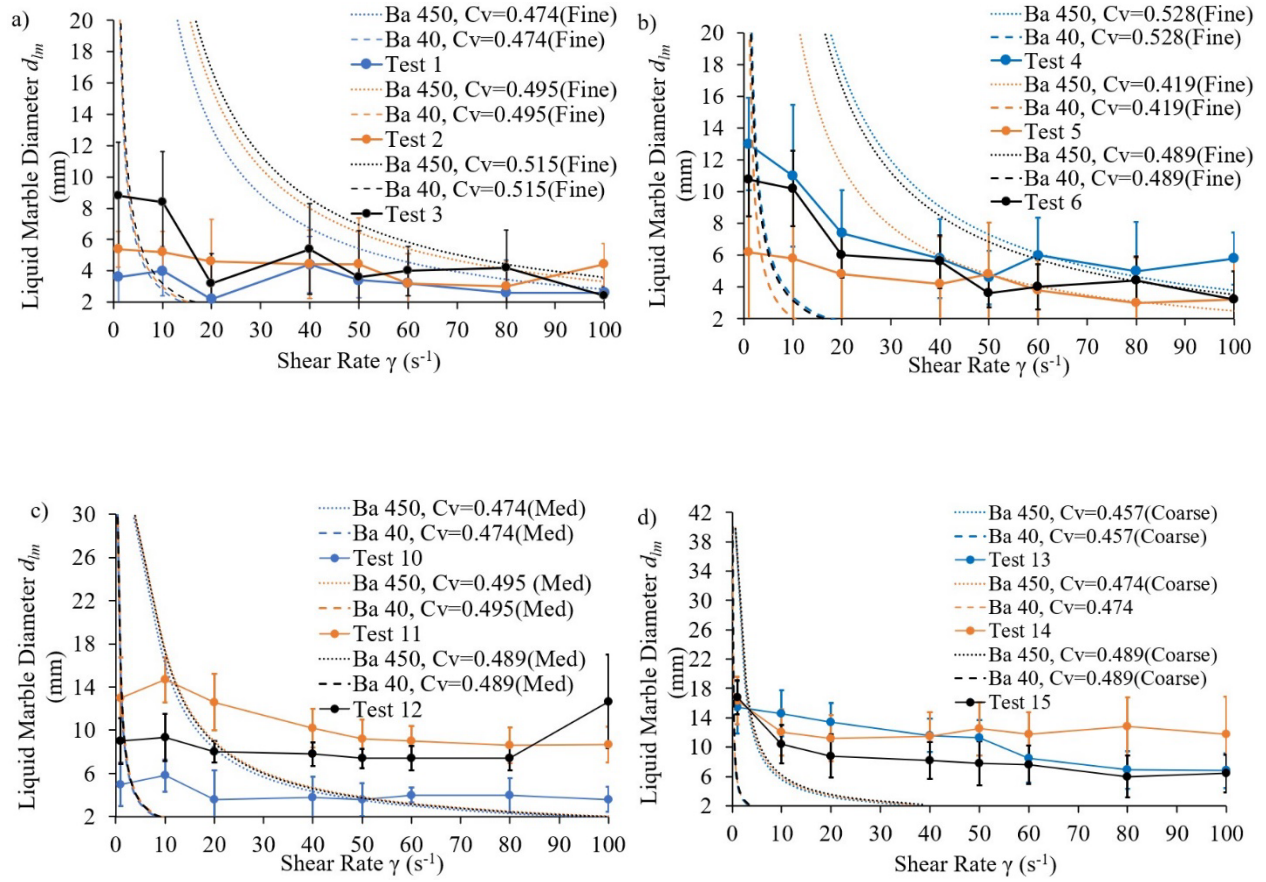


Figure 5.1. Liquid Marble Diameter vs. Shear Rate and Bagnold Criteria (Ba=40, and Ba=450) for Mixtures with Liquid Marbles from a) Hydrophobic Fine Sand (Tests 1-3), b) Hydrophobic Fine Sand (Tests 4-6), c) Hydrophobic Medium Sand (Tests 10-12), and d) Hydrophobic Mediums Sand (Tests 13-15). C_v is the volumetric concentration of liquid marbles.

5.2 Effect of Air Entrapment in Shear Stress

The mixture made of liquid marbles has higher shear stress if the sand particles are coarser (Fig. 5.2). The average observed shear stresses for mixtures made of hydrophobic fine sand particles under different air entrapment ratios and selected shear rates are generally less than 200 Pa. The average observed shear stresses are between 200 and 400 Pa for mixtures made of hydrophobic medium sand particles. As for mixtures made of hydrophobic coarse sand particles, the average observed shear stresses are around and above 600 Pa.

Air entrapment can reduce the shear stress of the mixture (**Fig. 5.2**). At air entrapment ratios of 0, the mixture is made of hydrophilic sand particles only. Therefore, the shear stresses corresponding to this case have no liquid marbles. Based on the figure, The shear stresses at zero air entrapment are all higher than the shear stresses at different air entrapment levels when looking at the dashed line portion. Lower shear stress means that the mixture has smaller shearing resistance during the flow. Thus, air entrapment helps to reduce the shear resistance during the mixture flow process, causing potential high flow speeds.

Higher air entrapment causes smaller shear stresses (**Fig. 5.2**) when looking at the solid line portion in the figure. Since mixture shear stress during flow has already reduced due to the initial air entrapment, the reduction trend continues when there are more air entrappings. However, the reduction trend is insignificant when the air entrapment ratio exceeds 40%.

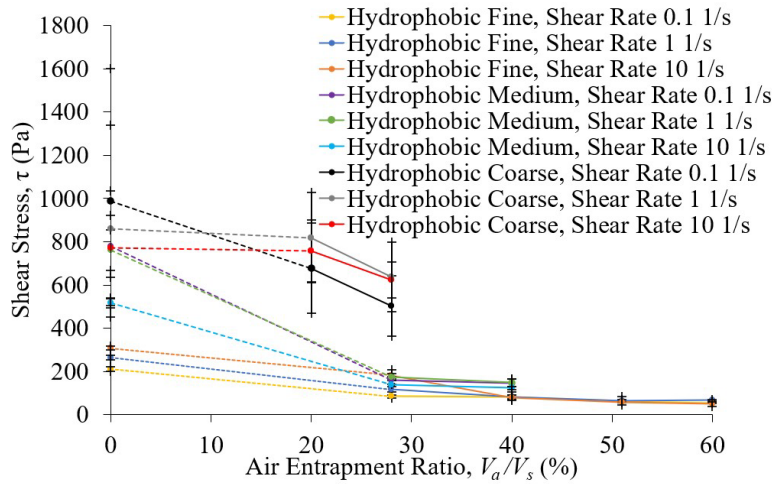


Figure 5.2. Effect of Air Entrapment in Shear Stress for Mixtures with Liquid Marbles Made from Hydrophobic Fine, Medium, and Coarse Sand Particles.

5.3 Effect of Liquid Marble Diameter in Shear Stress

The shear stress behavior of a hydrophobic-sand-air-water mixture depends on the diameter of the liquid marble. A liquid marble is a type of structure with core air bubbles covered with hydrophobic sand particles. This is very different from slurries with hydrophilic sand particles, where only individual sand particles are present in the water body. **Fig. 5.3** shows that a larger liquid marble diameter leads to larger shear stresses. Tests 1, 10, and 14 correspond to fine, medium, and coarse hydrophobic sand particles, respectively. All three tests have the same air bubble entrapment ratio of 28% and sand particle volumetric concentration of 70%. Previous experiments show that the diameter of liquid marble is proportional to the diameter of sand particles. Therefore, the horizontal axis in **Fig. 5.3** is the liquid marble diameter instead of the sand particle diameter. Since the mixture has local heterogeneity, the measurement results are not uniform. Therefore, all data include error bars. For coarse hydrophobic sand conditions, the error bars are larger. At lower shear rates of 0.1 and 1 s^{-1} , the shear stress vs. liquid marble diameter relationship is monotonically increasing. For a higher shear rate of 10 s^{-1} , shear stress decreases slightly and then increases significantly as the liquid marble diameter increases. Some explanations for regular slurries composed of hydrophilic particles may also apply to the complex mixture where hydrophobicity is involved. At high particle concentrations, the shear stress of a multiphase slurry flow depends on particle diameter, while intermittent locking or jamming of particles is more likely to occur (Savage & McKeown, 1983). Larger particles have an increased capability to form structures that expand the entire measuring space; therefore, strong resistance to shearing motion can more likely occur during the shearing test (Orlando & Shen, 2012). At the same time, the particle diameter effect on shear stress in a granular flow is also coupled with particle concentration and boundary conditions (Orlando & Shen, 2012).

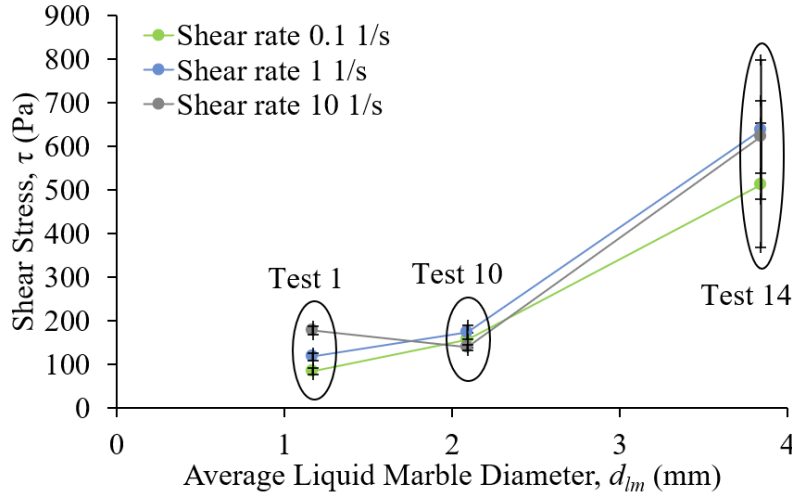


Figure 5.3. Effect of Liquid Marble Diameter on Shear Stress

5.4 Rheological Behaviors of Experimental Post-Wildfire Debris Flows

The shear rate affects the internal structure of the final mixture. However, the effect also highly depends on the initial physical state of liquid marbles. **Figs. 5.4a-d** select several representative cases.

When the final mixture has a small amount of air entrapment by hydrophobic fine sand particles (**Fig. 5.4a**, Test 1, $V_a/V_s = 28\%$), the shear rate effect is relatively small on the internal structural change of the final mixture. When the air entrapment ratio is small, the final mixture is mixed rigorously after a relatively long time and at high speed. Therefore, the initial physical states of the liquid marbles are small, and the size distribution is relatively uniform. After shearing at 0.1, 1, and 10 s^{-1} rates, the physical state of liquid marbles has no major change. Only after shearing at 100 s^{-1} , smaller liquid marbles form during the shearing process.

When the final mixture has a high amount of air entrapment by hydrophobic fine sand particles (**Fig. 5.4b**, Test 4, $V_a/V_s = 60\%$), the shear rate effect is significant on the internal structural change of the final mixture. When the air entrapment ratio is small, the final mixture

overcomes short mixing time and low mixing speed. Thus, the initial physical states of liquid marbles are highly heterogeneous. Liquid marbles can be really large, and the size distribution is wide. Although the physical states in **Fig. 5.4b** look similar to **Fig. 5.4a** after 0.1, 1, 10, and 100 s^{-1} , it is still clear that the shear rate after 100 s^{-1} has a much stronger impact on internal structure in **Fig. 5.5b**.

When the final mixture has a small amount of air entrapment by hydrophobic medium sand particles (**Fig. 5.4c**, Test 10, $V_a/V_s = 28\%$), the shear rate effect is again relatively small on the internal structural change, similar to **Fig. 5.4a**. Due to the relatively small liquid marble size and relatively uniform size distribution, the shear rate has a limited ability to break internal structures.

Liquid marbles made from hydrophobic coarse sand particles are relatively weak (**Fig. 5.4d**, Test 14, $V_a/V_s = 28\%$). Liquid marbles in this condition are hard to observe from side views; thus, **Fig. 5.4d** shows only the top views. Liquid marbles are diminishing since the shear rate is 10 s^{-1} .

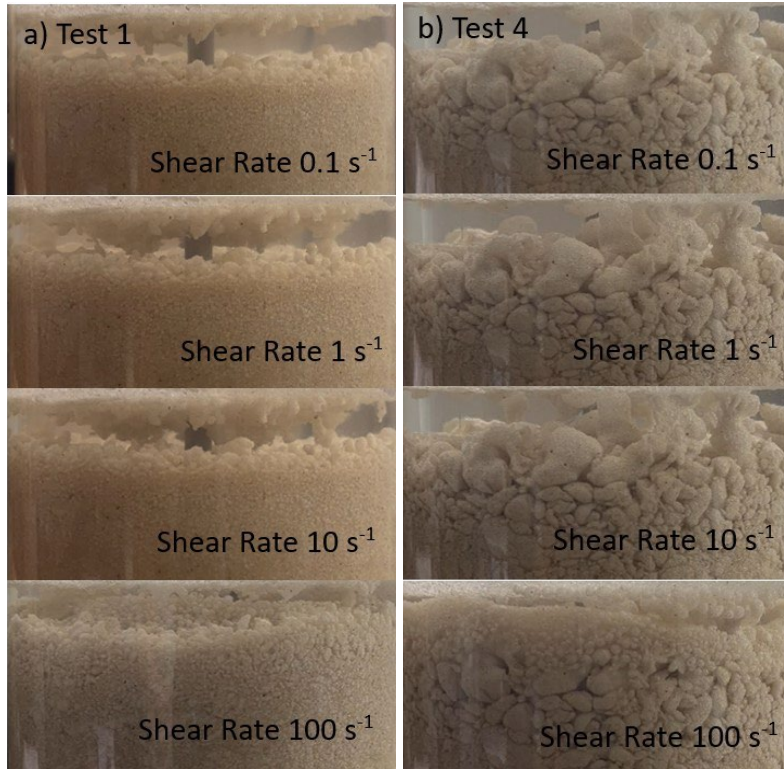


Figure 5.4. Images for the internal structural change of the final mixtures when liquid marbles are made of a) hydrophobic fine sand particles at low air entrapment ratio, b) hydrophobic fine sand particles at high air entrapment ratio, c) hydrophobic medium sand particles at low air entrapment ratio, and d) hydrophobic coarse sand particles at low air entrapment ratio.

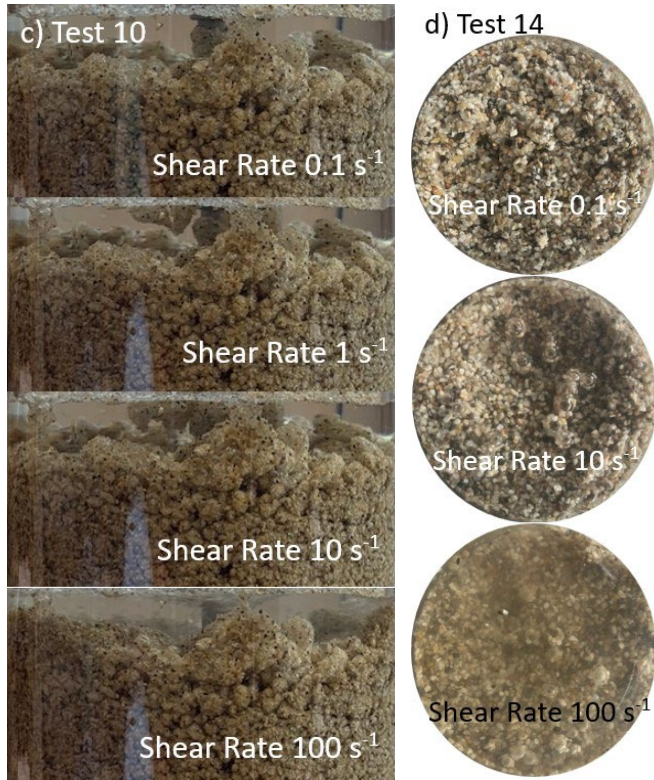


Figure 5.4 (Continued). Images for the internal structural change of the final mixtures when liquid marbles are made of a) hydrophobic fine sand particles at low air entrapment ratio, b) hydrophobic fine sand particles at high air entrapment ratio, c) hydrophobic medium sand particles at low air entrapment ratio, and d) hydrophobic coarse sand particles at low air entrapment ratio.

The shear stress vs shear rate investigation of the final mixture with liquid marbles made of hydrophobic fine sand particles includes three groups (**Figs. 5.5a-c**). **Fig. 5.5a** has the condition that all final mixtures have the same sand particle volumetric concentration but different air bubble entrapment ratios. The final mixture does not have a monotonically increasing trend for shear stress as the shear rate increases. Applying the Ba number helps identify possible shear rate ranges where regime transitions exist from a viscous fluid flow regime to a collision-dominated flow regime. For example, Test 1 has a clear boundary where the shear stress vs shear rate relation changes the pattern. This boundary occurs at a shear rate of 10 s^{-1} . Higher air entrapment (i.e., from Test 1 to Test 3) leads to a smaller shear stress response when the final mixture is under shear flow. When

the final mixture contains a very high air bubble entrapment ratio (i.e., Test 4), the shear stress increases slightly but keeps decreasing for a long range of shear rate. This phenomenon is mainly due to the constant and significant internal structure change, as shown in **Fig. 5.4b**.

A second group compares the conditions when there are different sand particle volumetric concentrations (**Fig. 5.5b**). Tests 1, 5, and 6 have 70%, 56%, and 75% of sand particle volumetric concentrations while keeping the same air bubble entrapment ratio of 28%. As sand particle volumetric concentration increases, the shear stress response of the final mixture under shear flow also increases. Tests 6 and 7 have the same sand particle volumetric concentration but different air bubble entrapment ratios. The observation that a higher air bubble entrapment ratio decreases the shear stress response of the final mixture also holds in this comparison.

A third group considers when the final mixture does not have a rigorous pre-mixing procedure (**Fig. 5.5c**). A huge decrease in shear stress response occurs when the shear rate is between 10 and 100 s^{-1} for Tests 8 and 9. This phenomenon is also due to the violent internal structure change during the shearing procedure.

The shear stress responses for the final mixtures with liquid marbles made of hydrophobic medium and coarse sand particles (**Figs. 5.5d-e**) have similar trends to those with hydrophobic fine sand particles (**Figs. 5.5a-b**). Tests 10 to 15 do not have a monotonically increasing trend in the shear stress vs. shear rate relationship. Again, higher sand particle volumetric concentrations lead to a higher shear stress response of the final mixture under shear flow. The shear stress measurements vary greatly under low shear rates until about 10 or 20 s^{-1} .

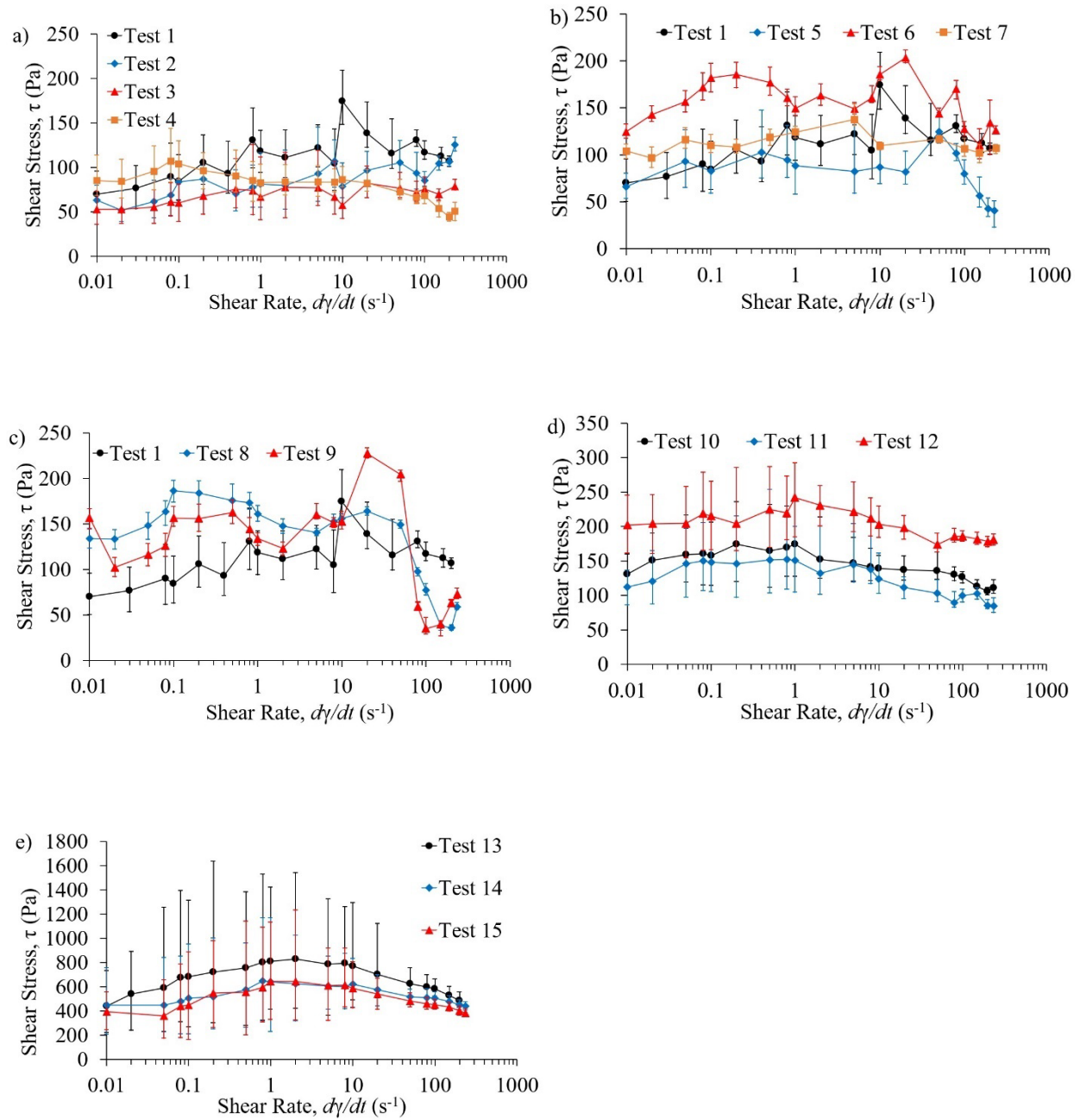


Figure 5.5. Shear stress vs. shear rate measurements for the final mixture with liquid marbles made of different types of sand: a) hydrophobic fine sand particles for Tests 1-4; b) hydrophobic fine sand particles for Tests 1, 5, 6, 7; c) hydrophobic fine sand particles for Tests 1, 8, 9; d) hydrophobic medium sand particles for Tests 10-12; and e) hydrophobic coarse sand particles for Tests 13-15.

Based on viscosity measurement results (**Figs. 5.6a-e**), all tests show shear-thinning behavior with no exceptions. That is, viscosity decreases as the shear rate increases for all the final mixtures with liquid marbles made with hydrophobic fine, medium, or coarse sand particles under shear flow conditions. In addition, larger sand particles lead to a higher viscosity of the final mixture. Higher air entrapment and lower sand particle volumetric concentration lead to smaller viscosity measurements. When the pre-mixing procedure is short and slow, the significant internal structural change of the final mixture is shown under a higher shear rate (**Fig. 5.6c**, Tests 8 and 9). The viscosity vs. shear rate curves for those two tests have clear irregular behavior after the shear rate of 50 s^{-1} .

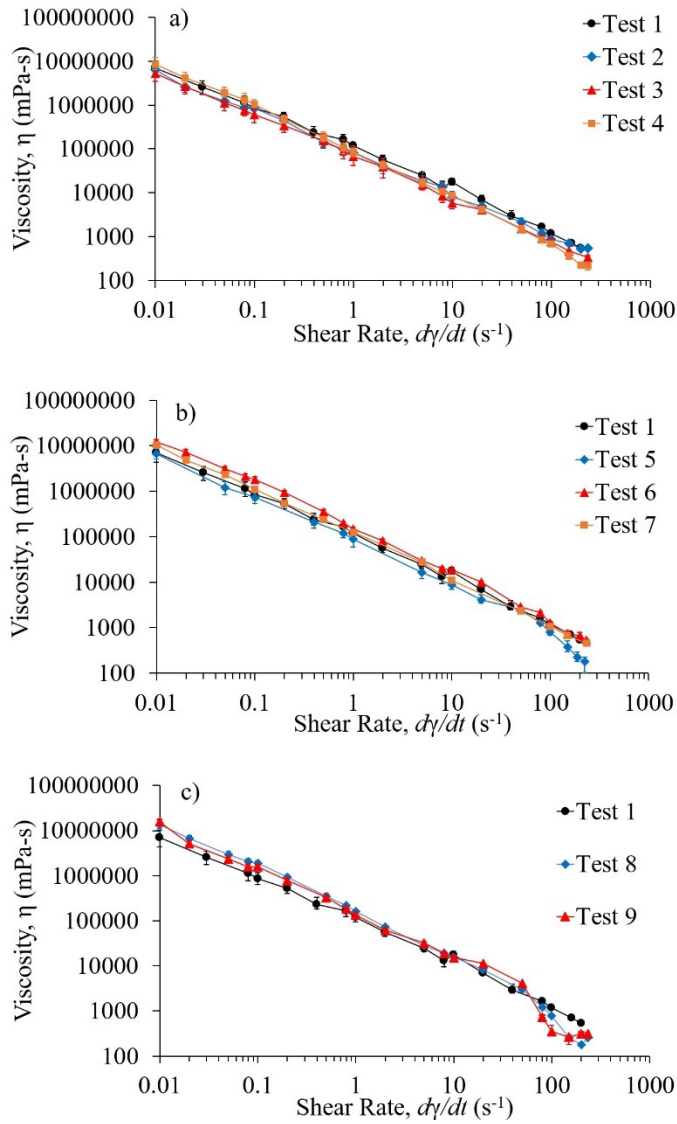


Figure 5.6. Viscosity vs. shear rate measurements for the final mixture with liquid marbles made of different types of sand: a) hydrophobic fine sand particles for Tests 1-4; b) hydrophobic fine sand particles for Tests 1, 5, 6, 7; c) hydrophobic fine sand particles for Tests 1, 8, 9; d) hydrophobic medium sand particles for Tests 10-12; and e) hydrophobic coarse sand particles for Tests 13-15.

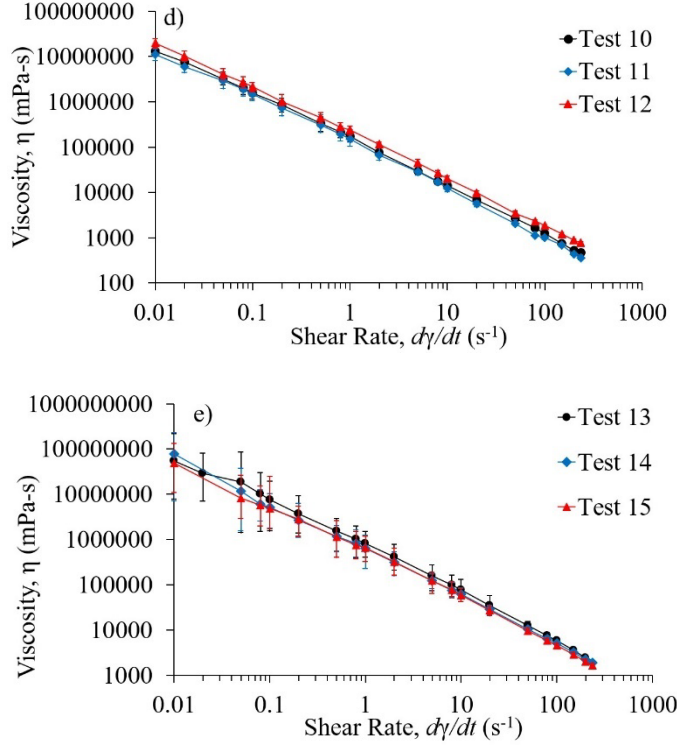


Figure 5.6 (Continued). Viscosity vs. shear rate measurements for the final mixture with liquid marbles made of different types of sand: a) hydrophobic fine sand particles for Tests 1-4; b) hydrophobic fine sand particles for Tests 1, 5, 6, 7; c) hydrophobic fine sand particles for Tests 1, 8, 9; d) hydrophobic medium sand particles for Tests 10-12; and e) hydrophobic coarse sand particles for Tests 13-15.

As discussed in **Figs. 5.1a-d**, the Bagnold number is a powerful indicator for cutting multiphase flow into different regimes. In this paper, Regime I refers to the viscous fluid flow regime, Regime II refers to the transition flow regime, and Regime III refers to the collision-dominated flow regime. **Figs. 5.7a-f** tries to predict the shear behavior of the final mixture for different types of sand particles and for different regimes, considering the role of air bubble entrapment ratio and liquid marble volumetric concentration.

Fig. 5.7a compares the prediction model and experimental data for the final mixture with hydrophobic fine sand particles in Regime I. The shear stress vs. shear rate prediction model for this scenario is shown in **Eqn. 5.2**, where a is a constant, b is a function of the volumetric

concentration of liquid marble ($b = f(C_v)$), and c is a function of air bubble entrapment ratio ($c = f(V_a/V_s)$). Due to the high variation in measurement, this prediction model can only predict the average estimate of shear stress given a known shear rate.

Fig. 5.7b compares the prediction model and experimental data for the final mixture with hydrophobic fine sand particles in Regime II. The shear stress vs. shear rate prediction model for this scenario is shown in **Eqn. 5.3**, where a , b , and c are the same as in **Eqn. 5.2**, and d is viscosity (η). The prediction is closer to the experiment data when the air bubble entrapment ratio is higher.

Unfortunately, insufficient experiment data are available to compare the prediction model and experimental data for the final mixture with hydrophobic fine sand particles in Regime III.

Fig. 5.7c compares the prediction model and experimental data for the final mixture with hydrophobic medium sand particles in Regime I. **Eqn. 5.2** can be applied for this scenario again to predict shear stress response vs. shear rate. Similar to **Fig. 5.7a**, the prediction only shows an average trend of shear stress responses due to the high variation in measurement.

Fig. 5.7d compares the prediction model and experimental data for the final mixture with hydrophobic medium sand particles in Regime II. The prediction model is shown in **Eqn. 5.4**, where a is the same as in **Eqns. 5.2 - 5.3**, and e is a function of both air bubble entrapment ratio and volumetric concentration of liquid marble ($e = f(C_v, V_a/V_s)$). **Eqn. 5.4** also applies to the scenario with hydrophobic medium sand particles in Regime III (**Fig. 5.7e**).

The final mixture with hydrophobic coarse sand particles in Regime I does not exist. **Eqn. 5.2** is applicable for the scenario with hydrophobic coarse sand particles in Regime II (**Fig. 5.7f**). **Eqn. 5.4** is applicable for the scenario with hydrophobic coarse sand particles in Regime III (**Fig. 5.7g**).

$$\tau = a * \left(\frac{\dot{\gamma}}{b}\right)^c \quad (5.2)$$

$$\tau = c * (d\dot{\gamma})^b + a \quad (5.3)$$

$$\tau = \frac{e}{\dot{\gamma}} + a \quad (5.4)$$

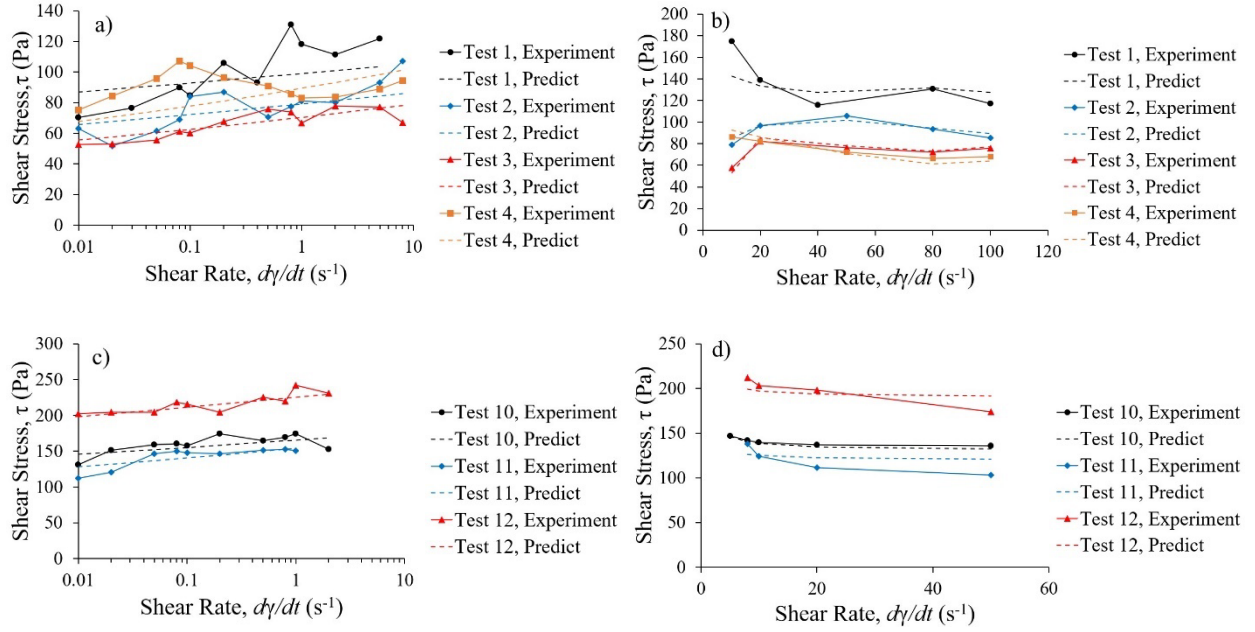


Figure 5.7. Comparison of prediction model and experimental data for shear stress vs. shear rate relationship under the scenarios of a) hydrophobic fine sand particles, Regime I; b) hydrophobic fine sand particles, Regime II; c) hydrophobic medium sand particles, Regime I; d) hydrophobic medium sand particles, Regime II; e) hydrophobic medium sand particles, Regime III; f) hydrophobic coarse sand particles, Regime II; and g) hydrophobic coarse sand particles, Regime III.

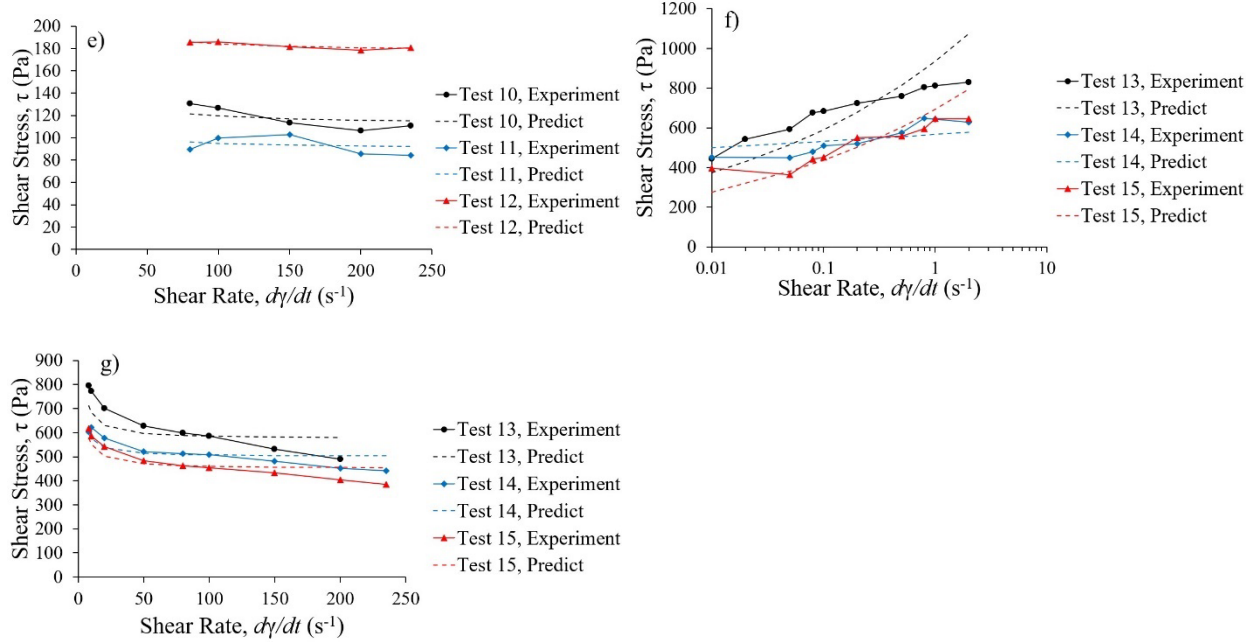


Figure 5.7 (Continued). Comparison of prediction model and experimental data for shear stress vs. shear rate relationship under the scenarios of a) hydrophobic fine sand particles, Regime I; b) hydrophobic fine sand particles, Regime II; c) hydrophobic medium sand particles, Regime I; d) hydrophobic medium sand particles, Regime II; e) hydrophobic medium sand particles, Regime III; f) hydrophobic coarse sand particles, Regime II; and g) hydrophobic coarse sand particles, Regime III.

5.5 Shear Rate and Shear Stress Fluctuation

Shear stress fluctuation across all physical conditions and all shear rates is common in this research during rheometer measurement. It is the main reason that all figures with shear stress have error bars in this paper. At the same time, viscosity measurements also have fluctuation. An increase in shear rate increases particle collision frequency (Balakin et al., 2012; Meyer & Deglon, 2011). Particle collision frequency also depends on preferential concentration (Meyer & Deglon, 2011). During the particle collision process, particles undergo spatial re-arrangement and local displacement (Jain et al., 2021; Rathee et al., 2017), interparticle interactions and self-assembly of particles change the internal structure of the multiphase slurry (Jain et al., 2021). As the shear rate increases, local high-stress regions also increase (Rathee et al., 2017). For multiphase slurries with

high solid concentrations, fluctuation of local particle concentration leads to local increase of viscosity and local jamming, forming force chains that sustain the flow and leading to stress fluctuation (Lootens et al., 2004). **Figs. 5.8a-c** shows that shear stress fluctuation frequency depends on the shear rate of the mixture. There are only 15 local shear stress peaks within the 60s measurement interval for the mixture with a shear rate of 0.1 s^{-1} . However, when the shear rate increases to 1 and 100 s^{-1} , there are 17 and 19 local shear stress peaks for the same mixture, respectively. Hence, the higher the shear rate is, the higher the shear stress fluctuation frequency will be.

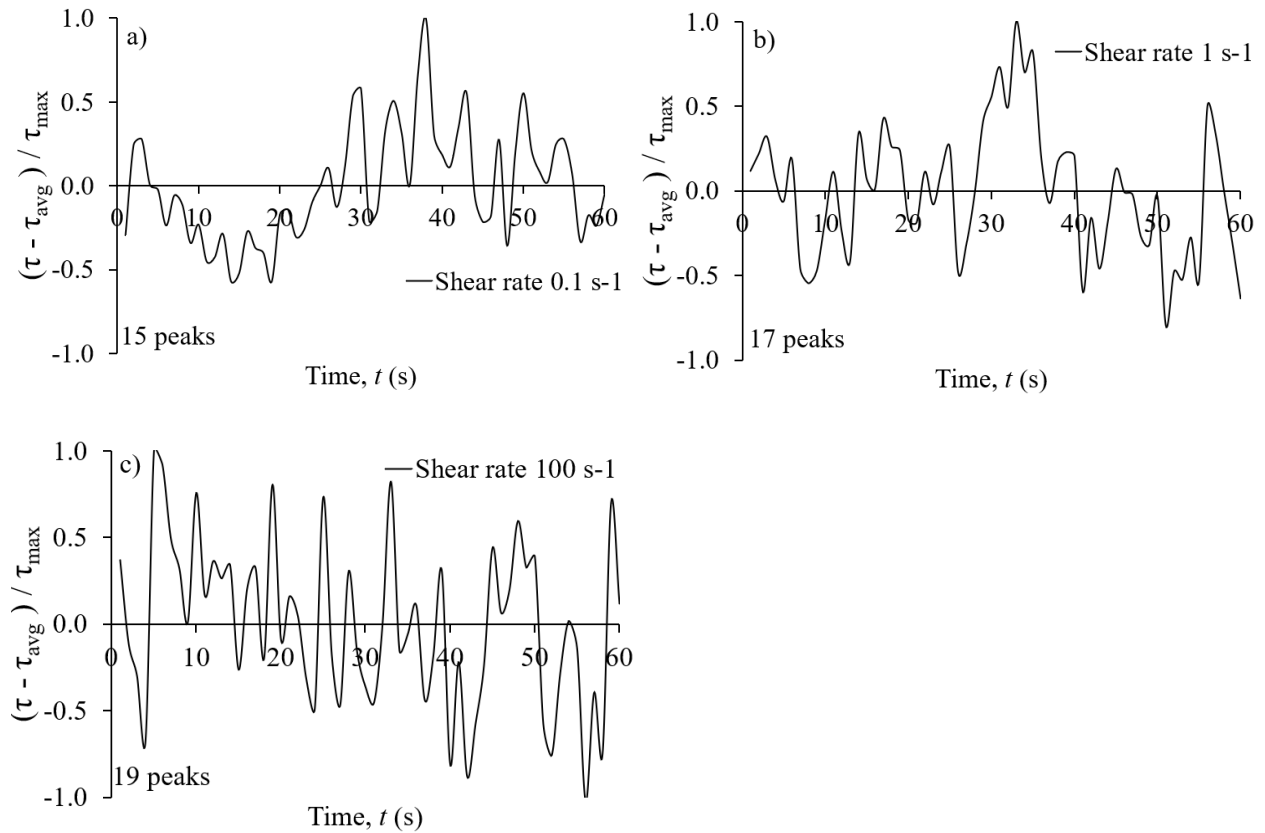


Figure 5.8. Shear Stress Fluctuation within 60s Intervals for Mixtures Composed of Hydrophobic Fine Sand Particles at Shear Rates of a) 0.1 s^{-1} , b) 1 s^{-1} , and c) 100 s^{-1} .

Acknowledgment

Chapter 5 is currently being prepared for submission for publication of the material entitled “Rheology of experimental post-wildfire debris flow with entrapped air”. Ma, Wenpei; Kim, Caitlin; Depoint-Spang, Teagan; Tomac, Ingrid. The dissertation author was the primary researcher and first author of this manuscript. The work done by undergraduate students Caitlin Kim and Teagan Depoint-Spang from the REU program was greatly appreciated.

Chapter 6 Role of Mixed Hydrophobicity

6.1 Physical Appearances of Air Entrapment across Hydrophobicity

Air entrapment noticeably decreases as the level of hydrophobicity decreases. Liquid marbles made of fine sand particles are easily observable until 0.5 hydrophobicity (**Fig. 6.1a**). Liquid marbles will only be partially observable at the top of sediment for less hydrophobicity. Clear liquid marbles made of medium sand particles (**Fig. 6.1b**) can only be clearly observable until 0.75 hydrophobicity. As for liquid marbles made of coarse sand particles (**Fig. 6.1c**), liquid marbles are only clearly observable at full hydrophobicity. For scenarios when liquid marbles are not clearly observable at the surface, even measurements indicate the existence of liquid marbles; the only explanation is that those hidden liquid marbles are covered inside the sediment.

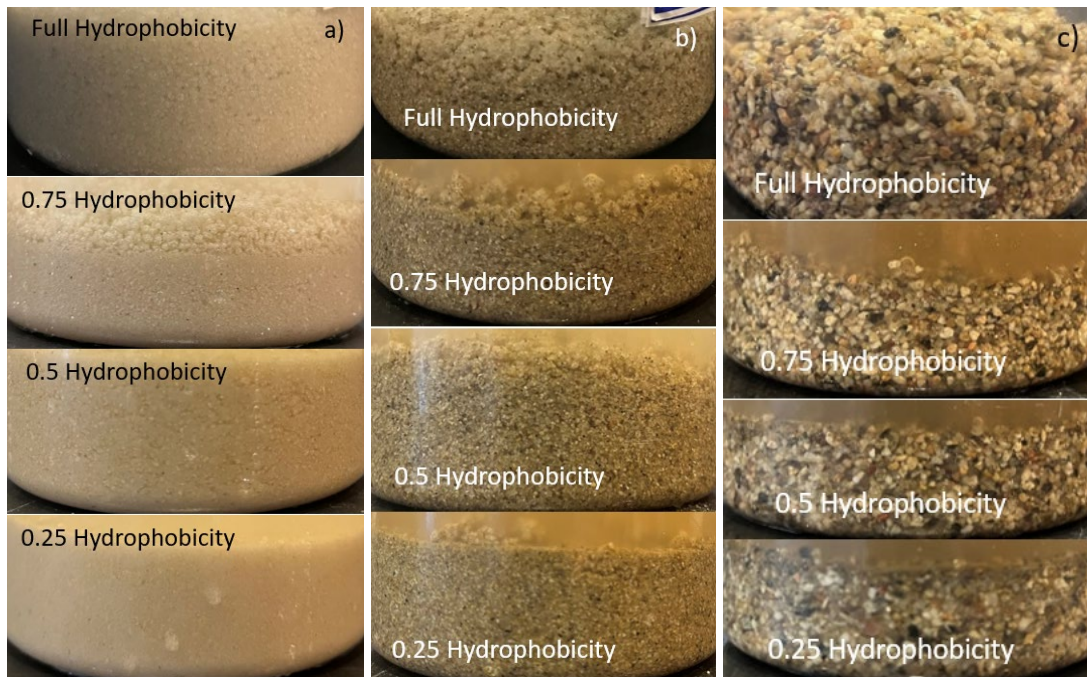


Figure 6.1. Physical appearances of liquid marbles made of a) fine sand particles, b) medium sand particles, and c) coarse sand particles across different levels of hydrophobicity.

6.2 Air Entrapment Results

Air entrapment depends on the initial amount of solid sand particles available (Ma & Tomac, 2024). More available sand particles (i.e., higher V_s/V_w ratio) lead to a higher air entrapment. This observation still holds across different levels of hydrophobicity (**Figs. 6.2a-d**). Similar to Ma & Tomac (2024), this paper also confirms that fine sand particles have the outstanding ability to entrap more air bubbles in the final mixture. Comparing air entrapment results from **Fig. 6.2a** to **Fig. 6.2c**, fine sand particles can always entrap more air bubbles in all tested initially available solids and in all levels of hydrophobicity.

When looking at fine sand particles only (**Fig. 6.2a**), the highest level of entrapped air bubbles occurs at 0.75 hydrophobicity. The measurement holds for all initial available solid levels. The observation that the highest level of air entrapment does not occur at full hydrophobicity is counter-intuitive. In a series of experiments conducted by Akbarzadeh et al. (2023), elongated air bubble tails occur after two hydrophobic particles fall into the water domain. In addition, air bubble tails can also occur after a pair of hydrophobic and hydrophilic particles fall into the water domain as long as the particle separation distance is very small. Those air bubble tails are a major source of entrapped air bubbles in the final mixture. Considering the separation distance among hydrophilic and hydrophobic particles in this experiment, it is reasonable to assume that the hydrophilic particles also induce entrapped air bubble tails when they are injected into the water body during the mixing process.

For medium sand particles (**Fig. 6.2b**), the highest level of entrapped air bubbles occurs at 0.75 hydrophobicity only if there are high levels of initially available solids. Under a low level of initial available solid, the highest level of entrapped air bubbles occurs at full hydrophobicity. As for coarse sand particles (**Fig. 6.2c**), the highest level of entrapped air bubbles occurs at 100%

hydrophobicity. **Fig. 6.2d** selects and compares the air entrapment volume across different levels of hydrophobicity for only two levels of initially available solids. The combined effect of hydrophobicity and available solid particles is especially clear for fine sand particles.

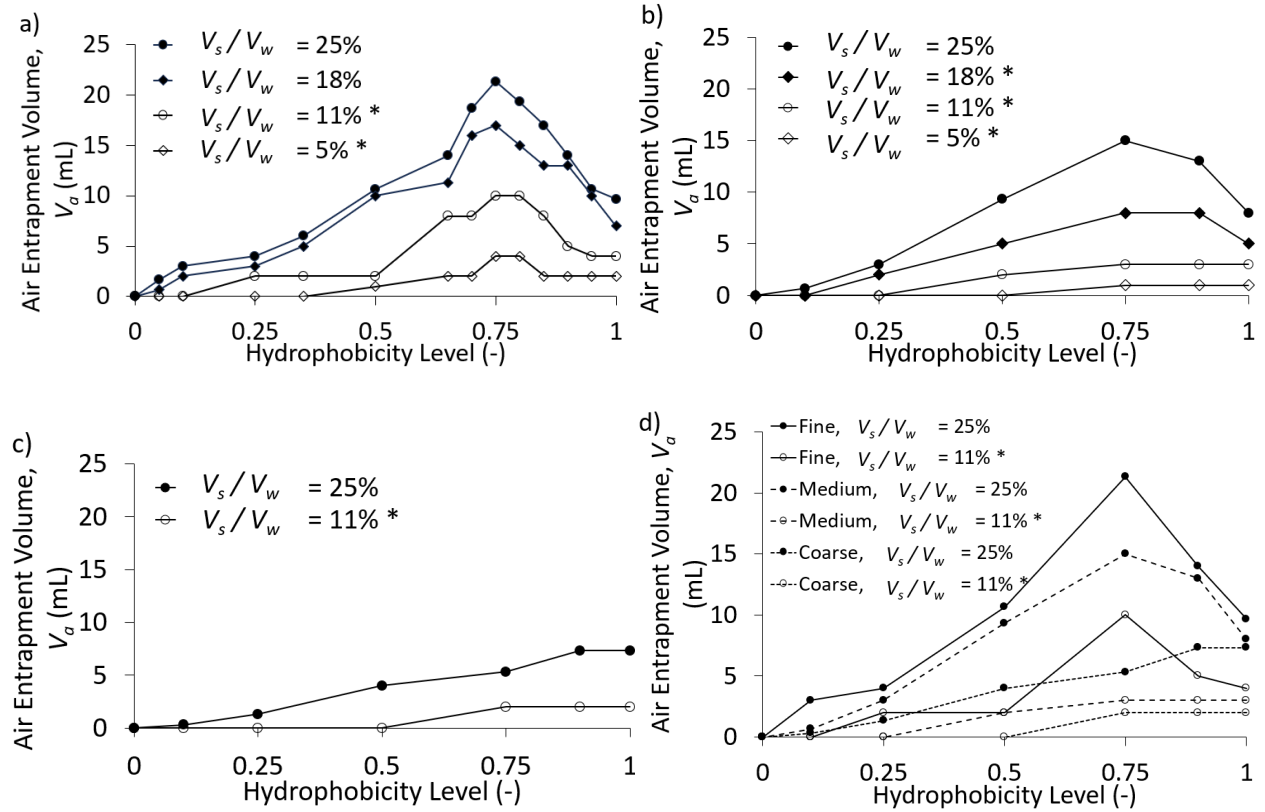


Figure 6.2. Air Entrapment Volume (V_a) across Different Levels of Hydrophobicity with different Initial Available Solid Concentrations (V_s/V_w) for a) Fine Sand Particles, b) Medium Sand Particles, c) Coarse Sand Particles, and d) Different Sand Particle Types. Starred tests are only composed of one single test result, while other tests are the averaged results of three repeated tests.

6.3 Rheological Behavior Measurement Results

Classical fluid rheological models do not fit such a complex mixture. Mixtures composed of hydrophobic and hydrophilic fine sand particles (**Fig. 6.3a**) at least follow a classical fluid model trend: shear stress increases as the shear rate increases. Herschel-Bulkley fluid model can provide rough estimates. Although shear stress could decrease regionally at a low level of hydrophobicity

(for example, no hydrophobicity at 10-100 s⁻¹ range; 0.25 hydrophobicity at 0.2-0.5 s⁻¹ range), the overall trend still obeys the classical fluid model. The local shear stress variation can be due to inter-particle interaction (He et al., 2006). It is possible that the shearing process is more rapid than the particle motion so that local accumulation of solid particles forms and behaves like a solid locally. For medium and coarse particles (**Figs. 6.3b-c**), the classical fluid model is no longer applicable. In such cases, the rheological model has to be divided into several fluid domains using the Bagnold number.

Due to the air entrapment in mixtures with hydrophobic fine and medium sand particles (**Figs. 6.3a-b**), shear stress is significantly reduced across all levels of the shear rates. Comparing full hydrophobicity and no hydrophobicity levels for fine sand particles, shear stress when air gets entrapped is generally reduced to about 30% to 35% of the original level when there is no air in the mixture. As for medium sand particles, the stress reduces to about 15% to 25% of the original level. Besides, a no hydrophobicity level provides the upper bound of shear stress behavior, and a full hydrophobicity level provides the lower bound of shear stress behavior for both fine and medium sand particles. With intermediate levels of hydrophobicity, the shear stress behavior can be estimated according to linear interpolation. However, for coarse sand particles (**Fig. 6.3c**), the above trends observed for fine and medium sand only apply when the shear rate is low. When the shear rate is high, air entrapment does not show a strong effect on shear stress behavior.

The viscosity vs. shear rate curves (**Figs. 6.4a-c**) are similar to shear stress curves (**Figs. 6.3a-c**) for fine, medium, and coarse sand particles. First of all, viscosity measurements show that mixtures with complete regular, complete hydrophobic, or mixed hydrophobic fine, medium, or coarse sand particles all have shear-thinning behavior. Viscosity decreases significantly as the shear rate increases. At low shear rates, inter-particle motion contributes to the shearing

resistance of such a mixture. At a high shear rate, the fluid phase dominates the shear behavior over sand particles or entrapped air bubbles. Besides, for mixtures with fine and medium sand particles, no hydrophobicity level and full hydrophobicity level are the upper and lower bounds for viscosity. Due to the air entrapment (i.e., higher level of hydrophobicity), viscosity is clearly reduced across all shear rates. Finally, for mixtures with coarse sand particles, the upper and lower bounds are only clear for low shear rates.

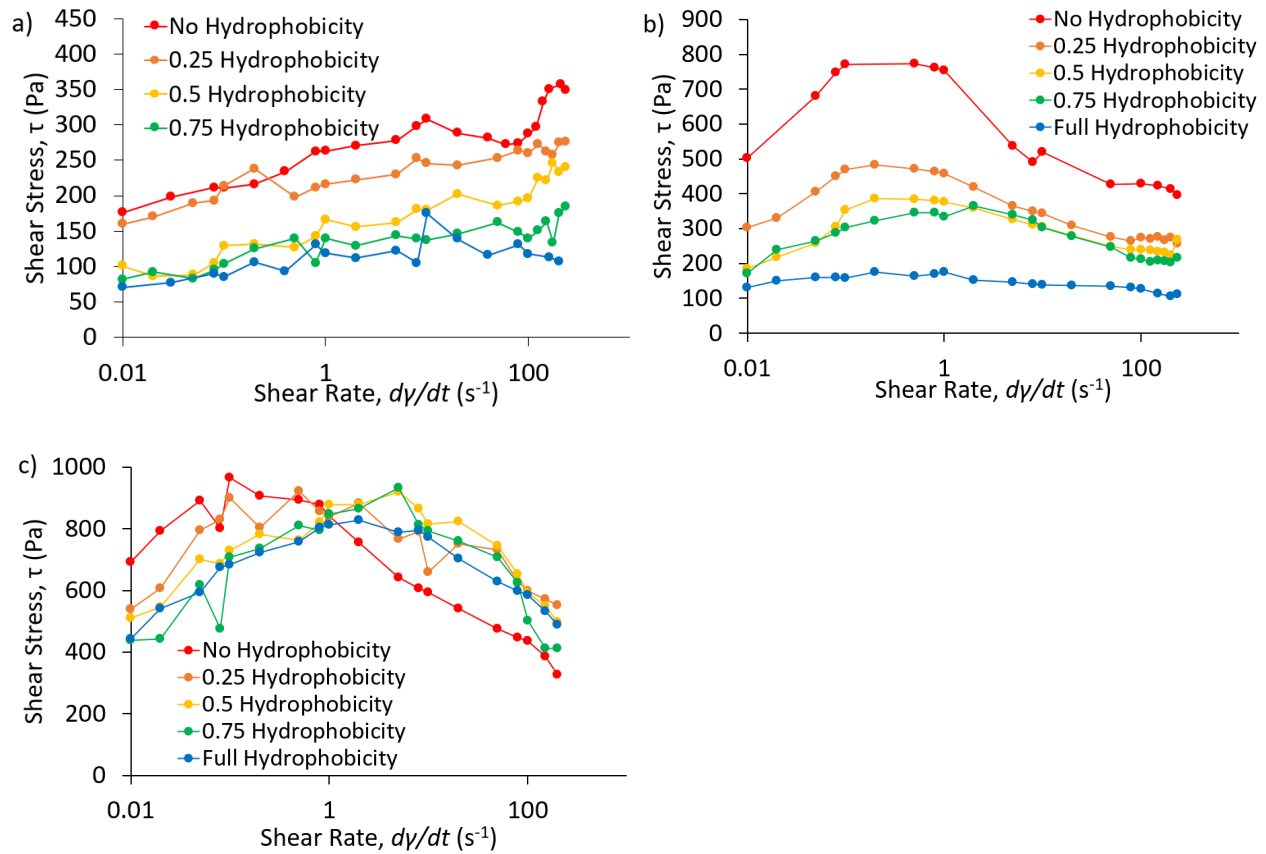


Figure 6.3. Shear stress vs. shear rate curve for a) fine sand particles, b) medium sand particles, and c) coarse sand particles across different levels of hydrophobicity.

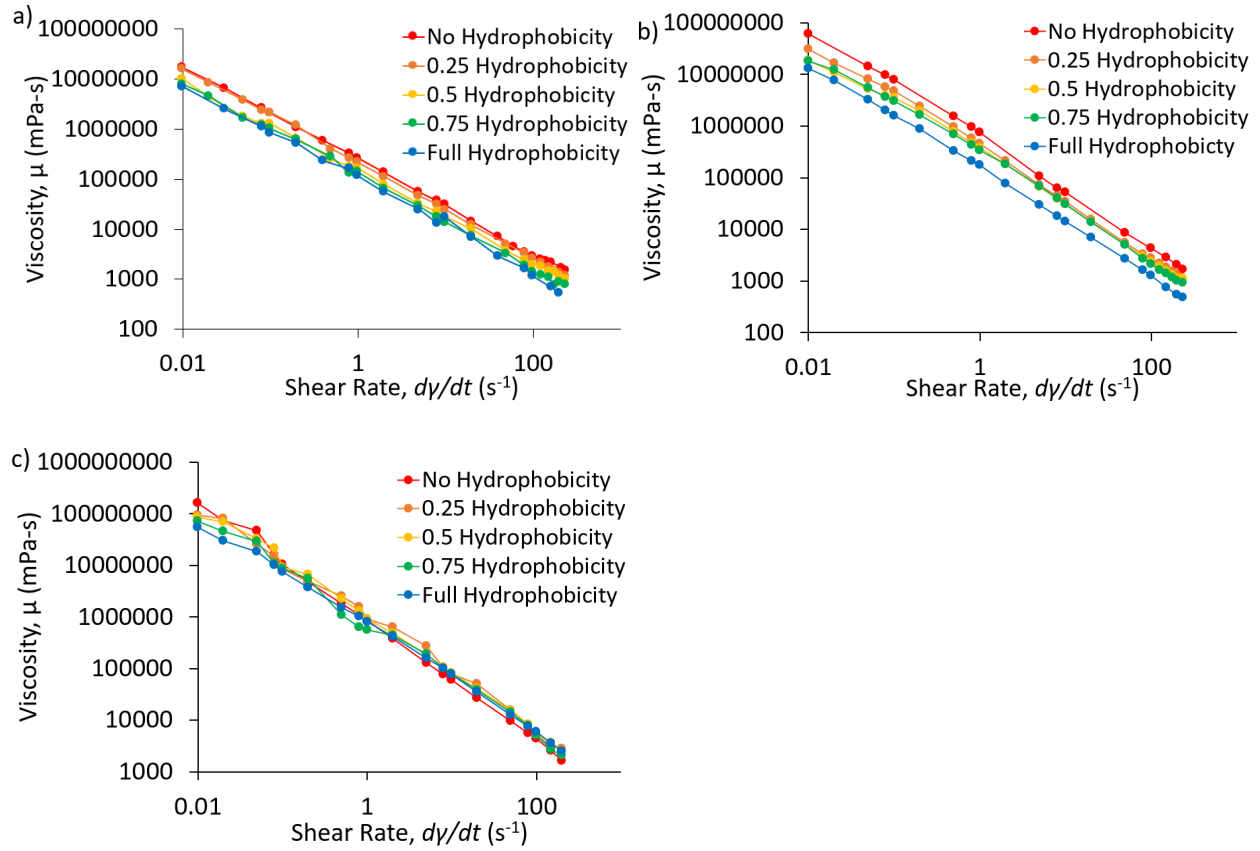


Figure 6.4. Viscosity vs shear rate curve for a) fine sand particles, b) medium sand particles, and c) coarse sand particles across different levels of hydrophobicity.

6.4 Results for Mixed Hydrophobic and Hydrophilic Fine Sand with Kaolinite Clay

Due to the presence of Kaolinite clay, the physical boundary and distribution of liquid marbles are clearer (**Fig. 6.5a**) in most cases. At full and 0.75 hydrophobicity, the liquid marbles are easily observed, and the texture is enhanced compared with the no-clay condition (**Fig. 6.1a**). Similar to the no-clay condition, the liquid marbles are not so easily observed at lower hydrophobicity levels. At 0.5 hydrophobicity level, only blocks of liquid marbles and surrounding hydrophilic sand particles are observable. However, the texture still outlines the distribution. At

0.25 hydrophobicity, due to a very low amount of air entrapment, no clear liquid marble rests outside that are observable.

The air entrapment trend for fine sand with clay (**Fig. 6.5b**) is similar to the coarse sand case (**Fig. 6.2c**). The highest air entrapment occurs in clay with full hydrophobic fine sand particles. As the hydrophobicity level decreases, air entrapment decreases. If there are fewer available hydrophobic sand particles given at a fixed hydrophobicity level, the air entrapment will also decrease. Comparing the clay condition (**Fig. 6.5b**) and the no-clay condition (**Fig. 6.4a**), clay in the environment brings the peak hydrophobicity level back to the full level where most air entrapment occurs.

The rheological measurement for the clay condition (**Figs. 6.5c-d**) is similar to the no-clay condition (**Figs. 6.3a, 6.4a**). Classical fluid rheological behavior, such as the Herschel-Bulkley fluid model, still holds for fine sand with clay. For most tests, the trend that a higher shear rate leads to higher shear stress is still clearly observable. At the same time, local stress variation from sand inter-particle motion also exists. In general, due to the appearance of clay, the shear stress of the mixture is generally smaller in clay conditions (**Fig. 6.5c**) than in no-clay conditions (**Fig. 6.3a**). Under clay conditions, the shear stress reduces from 10% to 15%, from the no hydrophobicity level to the full hydrophobicity level. Shear stress behavior can be linearly interpolated for any intermediate levels of hydrophobicity.

Viscosity measurement results are similar for the clay condition (**Fig. 6.5d**) and the no-clay condition (**Fig. 6.4a**). The mixture with the clay portion still has a shear-thinning behavior. As the shear rate increases, viscosity decreases significantly. Besides, no hydrophobicity and full hydrophobicity are upper and lower bounds for viscosity. There is only one major difference: the viscosity reduces to a much lower level at high shear rates. When there is no clay in the

environment, mixture shearing motion is dominated by fluid shearing and a moderate level of inter-particle friction. While in the clay environment, the inter-particle friction is lubricated by smaller clay particles in the fluid domain.

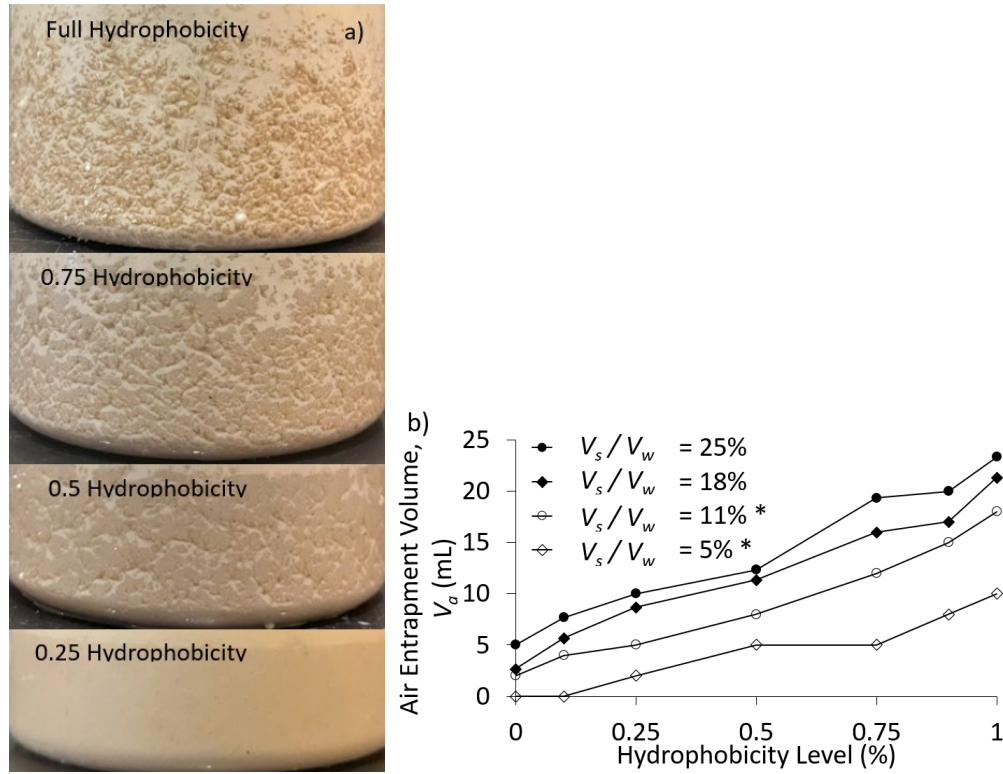


Figure 6.5. Results for hydrophobic fine sand plus Kaolinite clay. a) physical photos of the final mixture with different levels of hydrophobicity; b) air entrapment vs. levels of hydrophobicity at different initial solid concentrations; c) shear stress vs. shear rate for different levels of hydrophobicity; d) viscosity vs. shear rate for different levels of hydrophobicity.

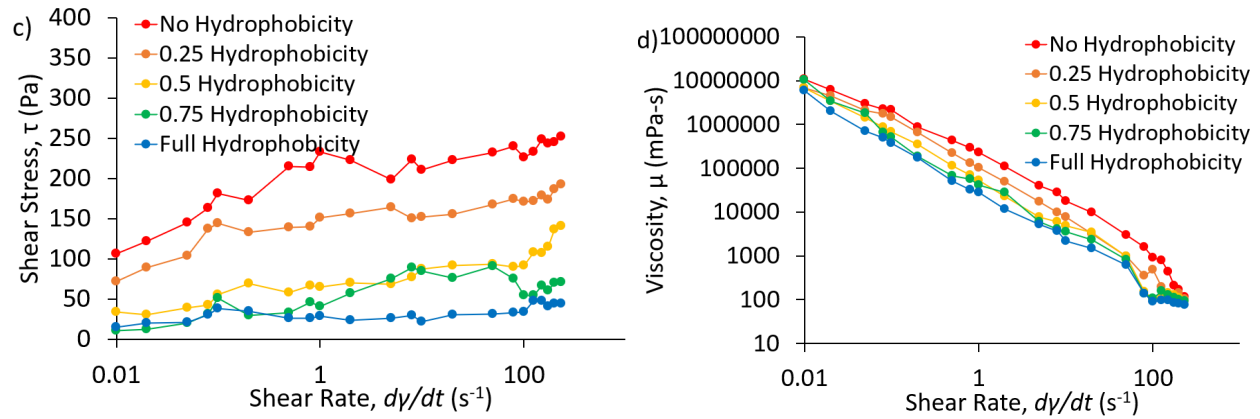


Figure 6.5 (Continued). Results for hydrophobic fine sand plus Kaolinite clay. a) physical photos of the final mixture with different levels of hydrophobicity; b) air entrapment vs. levels of hydrophobicity at different initial solid concentrations; c) shear stress vs. shear rate for different levels of hydrophobicity; d) viscosity vs. shear rate for different levels of hydrophobicity.

Acknowledgment

Chapter 6 is currently being prepared for submission for publication of the material entitled “Effect of Particle Hydrophobicity on Air Entrapment and Rheological Behavior of Experimental Postfire Debris Flows”. Ma, Wenpei; Tomac, Ingrid. The dissertation author was the primary researcher and first author of this manuscript.

Chapter 7 Open Channel Experiment

7.1 Effect of Hydrophobicity on Flow Profile

Figs. 7.1a-b show how entrapped air can change the velocity profiles. **Fig. 7.1a** focuses on the front window, while **Fig. 7.1b** focuses on the middle window. The left boundary of the front window of the photo is exactly aligned with the channel entrance. The left boundary of the middle window of the photo is exactly aligned 20 cm away from the channel entrance. The two profiles are taken at the same location in the photo, which is 0.1 cm away from the left boundary of the window. Each profile line is an average of 6 closely neighboring locations. Due to the air entrapment, the mixture flows naturally faster (Test 1 vs Test 13 in **Fig. 7.1a**). There is slip velocity at the channel bottom due to the air entrapment (i.e., Test 1 profile does not start with zero in **Fig. 7.1a**). As the mixture flows further down the channel, it becomes less turbulent (i.e., Test 2 vs. Test 1). Also, as the mixture develops along the channel, the completely hydrophilic case (Test 14 in **Fig. 7.1b**) has a more regular velocity profile, nearly a quadratic velocity profile.

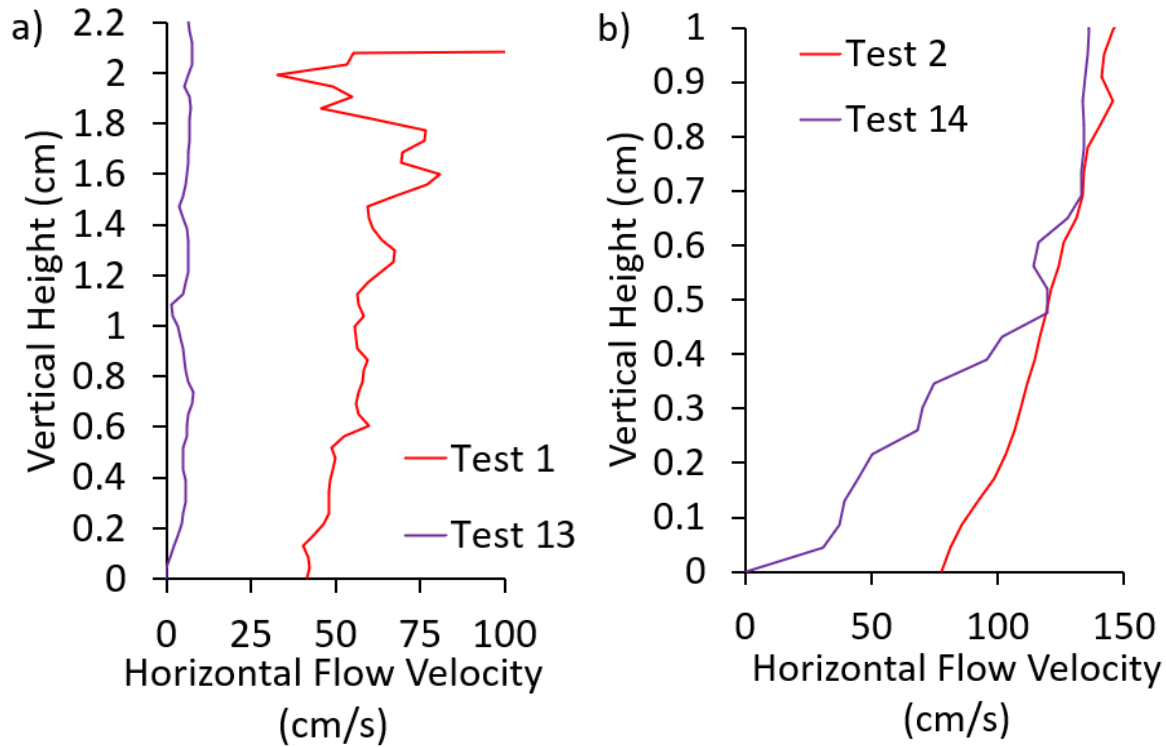


Figure 7.1. The effect of entrapped air on flow profile: a) Front Window (Test 1 for 100% Hydrophobicity and Test 13 for 0% Hydrophobicity), and b) Middle Window (Test 2 for 100% Hydrophobicity and Test 14 for 0% Hydrophobicity).

Figs. 7.2a-b show the effect of the level of hydrophobicity on the flow velocity profile. A higher level of hydrophobicity leads to a higher initial flow velocity (**Fig. 7.2a**). 50% hydrophobicity (Test 7 and Test 8) is the boundary. When the mixture is less than or equal to 50% hydrophobic, the flow does not have a slip velocity at the channel bottom. Slip velocity occurs when the level of hydrophobicity is larger than 50%. As the mixture flows further along the channel (**Fig. 7.2b**), the flow speed is larger due to the hydrophobicity level at the lower part of the mixture. However, the flow speeds are similar at the top part of the mixture across different levels of hydrophobicity.

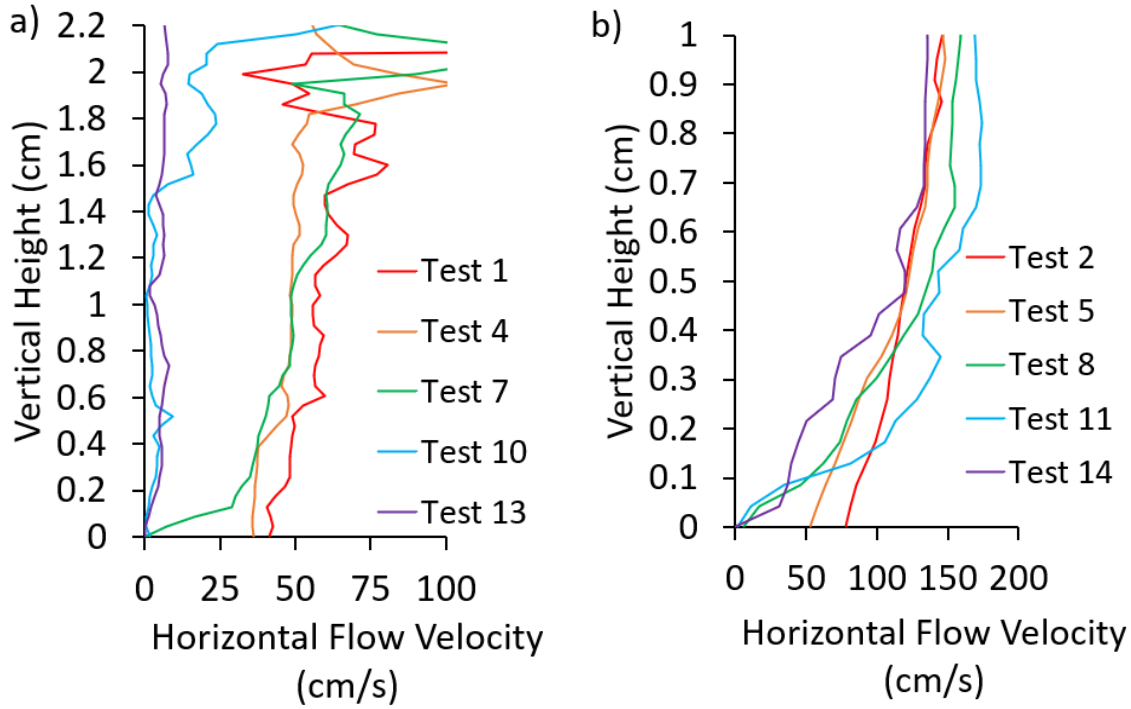


Figure 7.2. Flow velocity profile for different levels of hydrophobicity: a) Front Window and b) Middle Window

7.2 Effect of Slope Inclination

Test 16 and Test 17 are conducted at a slope inclination of 45° . Test 1 and Test 2 are conducted at a slope inclination of 15° . Near the entrance of the channel, the slope inclination has a clear effect on the flow velocity profile (**Fig. 7.3a**). A higher slope inclination leads to a higher flow velocity profile (i.e., Test 16 profile has a clearly larger number than Test 1 profile). As the mixture flows further to the channel, the flow velocity profiles are similar between different inclination slopes (**Fig. 7.3b**). Test 2 and Test 17 are close to each other. Note that the slip velocity is observed in all tests since the sand particles are all 100% hydrophobic in Tests 1, 2, 16, and 17.

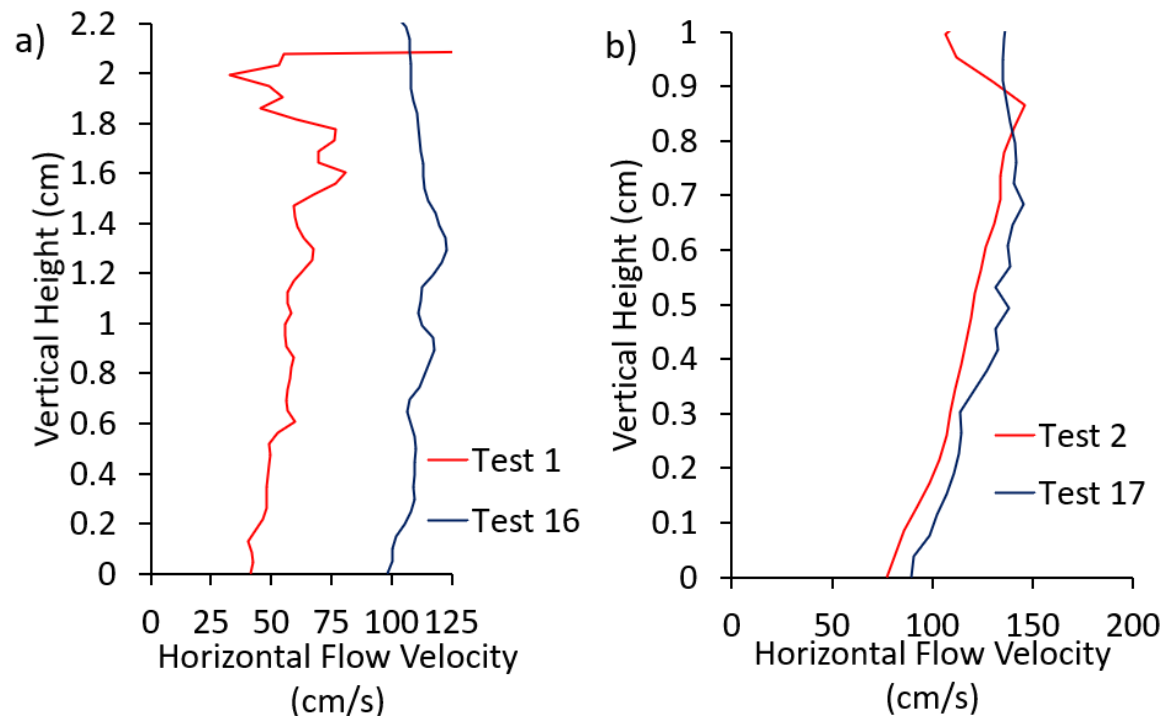


Figure 7.3. Effect of slope inclination on velocity profile: a) Front Window and b) Middle Window

Acknowledgment

Chapter 7 contains unpublished material. The experiment was conducted with the help of Omar Salem, and his work was greatly appreciated.

Chapter 8 Remediation for Hydrophobicity

8.1 Micro-structure of Hydrophobic Sand Modified with XG and SCI Powders

When treating hydrophobic well-graded sand with SCI powder, crystalline (Figs. 8.1b, d, f) and coating (Figs. 8.1a, c, e) cover the sand particle surfaces. Due to the amphiphilic property of SCI powder, water droplets easily flow down through the pores within the sand body. However, lines (Figs. 8.2a, b, f) and membranes (Figs. 8.2a, c, d, e) form in the pore spaces when treating hydrophobic well-graded sand with XG powder. Although XG powder also plays a critical role in a hydrophobic-hydrophilic environment, water droplets face resistance in the flow channel in the sand pore spaces due to those undesired extra byproducts.

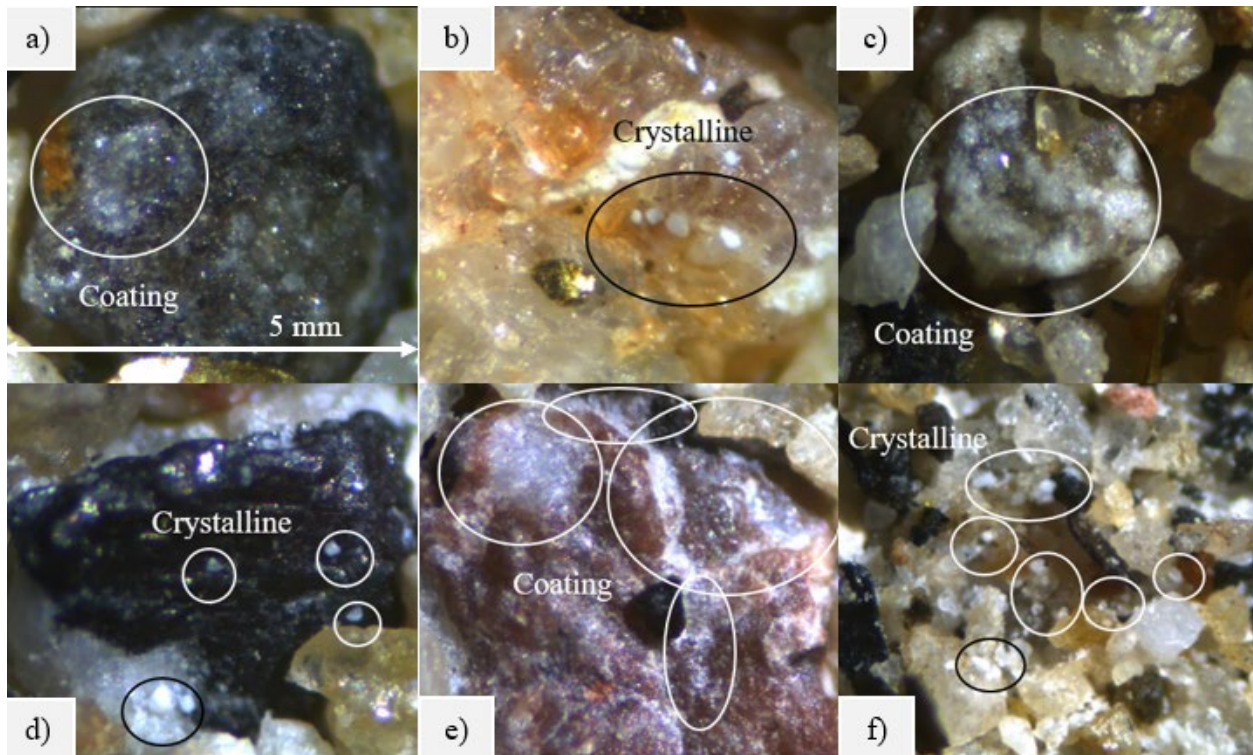


Figure 8.1. Microscopic image for hydrophobic sand particles treated with SCI powder.

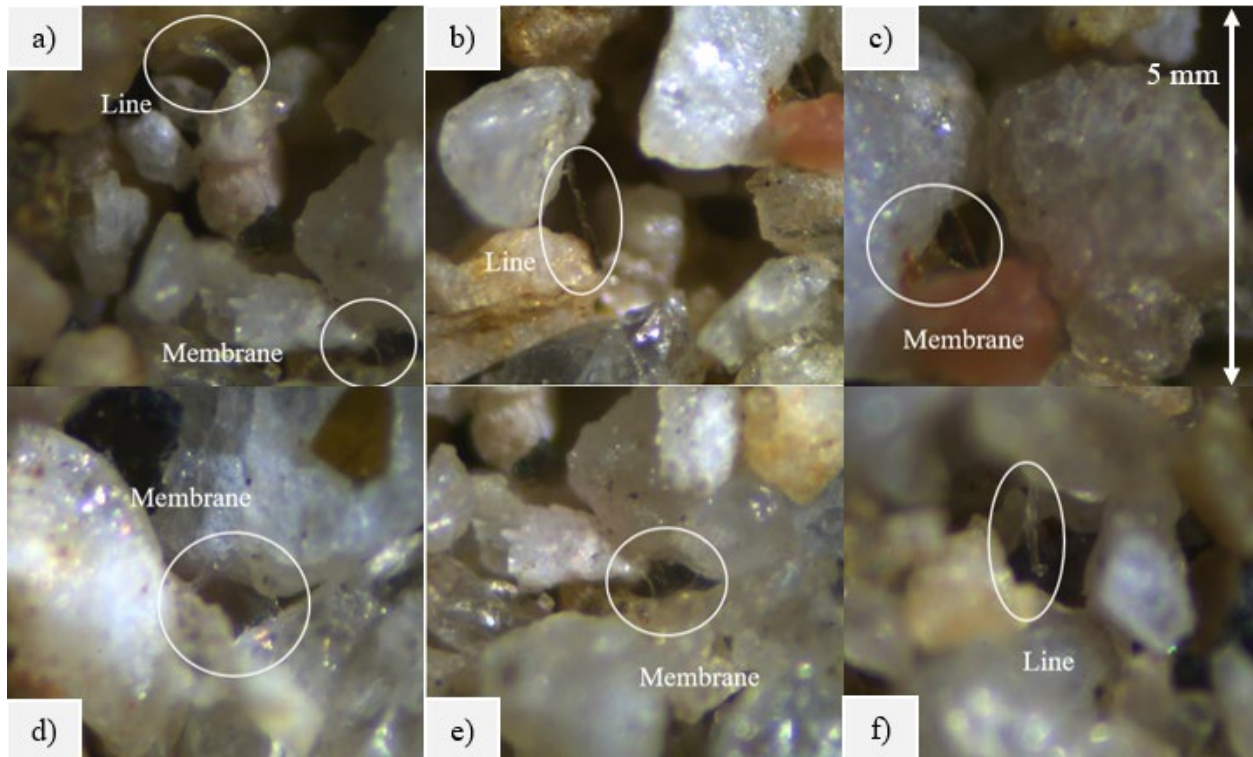


Figure 8.2. Microscopic image for hydrophobic sand particles treated with XG powder.

8.2 Contac Angle and WDPT Reduction due to XG and SCI Powders

Results show that XG powder and SCI powder coating contribute to reducing a hydrophobic sand sample contact angle (**Fig. 8.3a**). XG powder especially works significantly better in reducing the contact angle of hydrophobic sand samples. At 5% mass concentration of XG powder, the contact angle of the testing sample is reduced to around clean hydrophilic sand level (**Fig. 8.3a**). Although SCI powder also reduces the contact angle, the testing sample still has a higher contact angle measurement compared with XG-treated scenarios under all mass concentrations. A 5% mass concentration of powders applied to hydrophobic sand samples for both modifiers can reach the desired contact angle reduction performance.

Advancing and receding drop contact angles were measured on a 15° sloped surface. The advancing contact angle is on a slope's lower side of the water droplet. **Fig. 8.3b** illustrates that the

advancing angles are greater than the receding angles, on average by 15°, due to the sloped surface. As the modifier mass concentration increased, the formed advancing and receding contact angles decreased on the XG- and SCI-modified surfaces. The differences between advancing and receding angles are consistent for both modifiers across different mass concentrations.

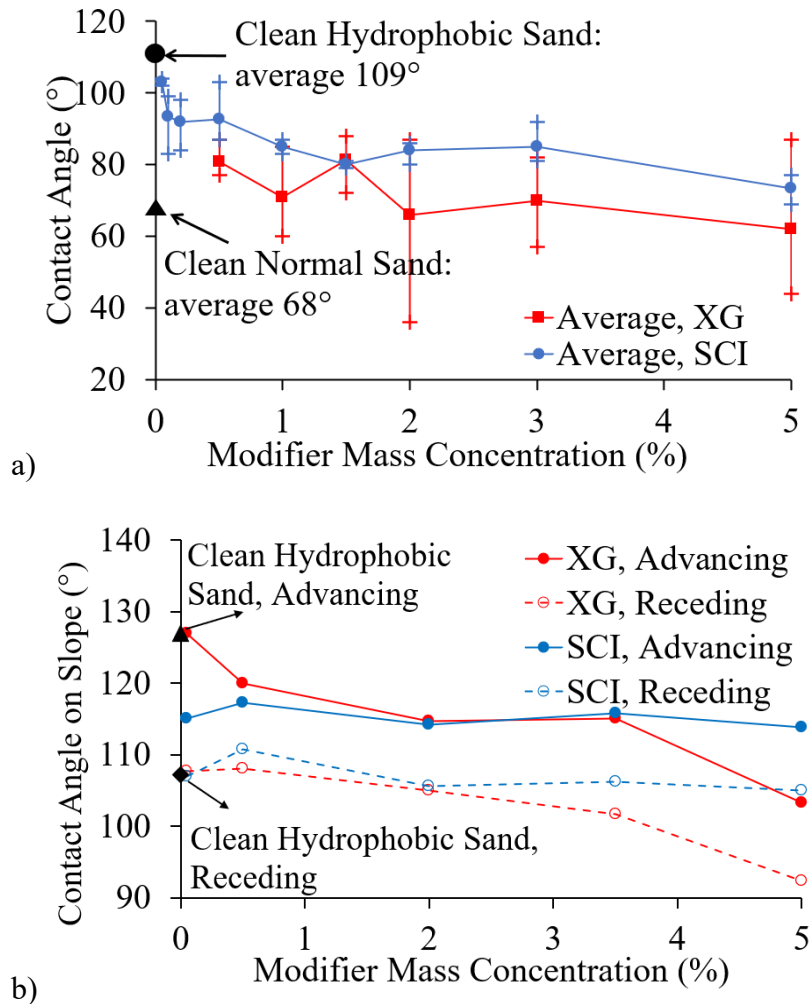


Figure 8.3. Contact angle reductions with XG and SCI modifiers with different modifier mass concentrations: a) on a horizontal surface and b) on a 15 ° sloped surface.

WDPT reduction effect is the opposite for XG and SCI powders. SCI powder is 1000 times more efficient in reducing WDPT measurements than XG powder (**Fig. 8.4**). A clean, purely

hydrophobic sand has an average WDPT value of 10800 s. XG powder can only reduce WDPT value to about half, around 4000 to 5000 s. In addition, a higher mass concentration of XG powder in well-graded sand does not further reduce the WDPT value. With less than 0.5% mass concentration of SCI powder, the WDPT value decreases from 5 s to 1.5 s as more SCI powder is added to the testing sample. After 0.5% mass concentration SCI powder, the WDPT value remains constantly low at around 1.2 s. Although both XG and SCI powder cannot reduce hydrophobic sand samples into hydrophilic conditions, SCI powder is still more favorable than XG powder.

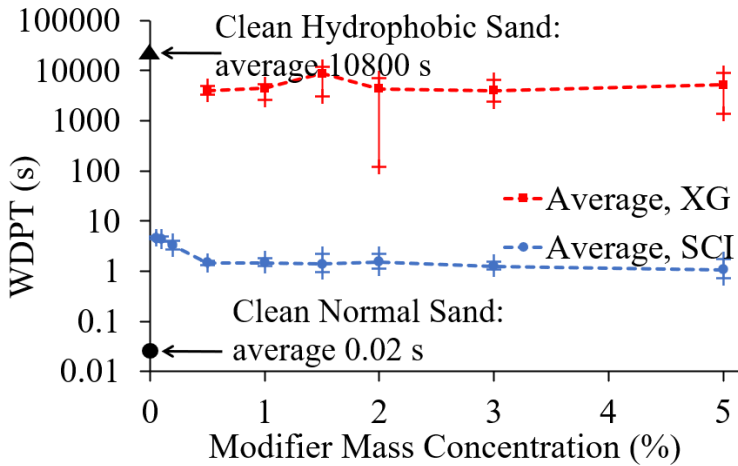


Figure 8.4. WDPT reduction of both XG and SCI powders on a horizontal surface.

8.3 Slope Erosion Control by Applying SCI Powder

Due to the high performance of SCI powder in reducing WDPT value, slope erosion tests only consider SCI powder rather than XG powder. Water drainage behavior is an important factor to consider when controlling slope erosion and stability. This research measures crater diameters of water droplets impacted on sand samples on three slope angles: 15°, 30°, and 45° with regular sandy soil, hydrophobic sandy soil, 5% mixed modifier sandy soil, and sprinkled modifier sandy soil. Crater diameter is the maximum diameter measured for a water droplet that impacts the

surface and forms a crater-like erosion pattern due to sandy soil particle displacement. **Figs. 8.5a-d** shows how crater diameter differs from varying sandy soil treatments and slope angles. Crater diameter is small when a water droplet falls onto a hydrophilic surface at a gentle slope of 15° . As the slope inclination angle increases, the crater diameter also increases. The crater diameter does not increase dramatically as more water droplets collect in the same spot. On a hydrophobic surface, the crater diameter increases since the water droplets do not infiltrate the sandy soil easily. Sand particle hydrophobicity does not allow high energy dissipation downward. As a result, water droplets flow sideways, increasing crater regions. However, the landslide phenomenon occurs at a high slope of 45° due to unstable inter-particle arrangement in a vibrating sandy soil environment. Displaced crater regions can be smaller since the upper sandy soil slides down and covers the crater.

On the 5% mixed modifier sandy soil, the droplets form a smaller crater diameter than the hydrophobic sandy soil except for a 45° slope angle. At low and moderate slope angles, water droplets can penetrate down to the sandy soil layer due to the existence of the SCI modifier. Therefore, less energy dissipates sideways, leaving a smaller crater diameter. Droplets on the sprinkled modifier surface spread out easily, increasing the crater diameter measurement for moderate and high inclination slopes.

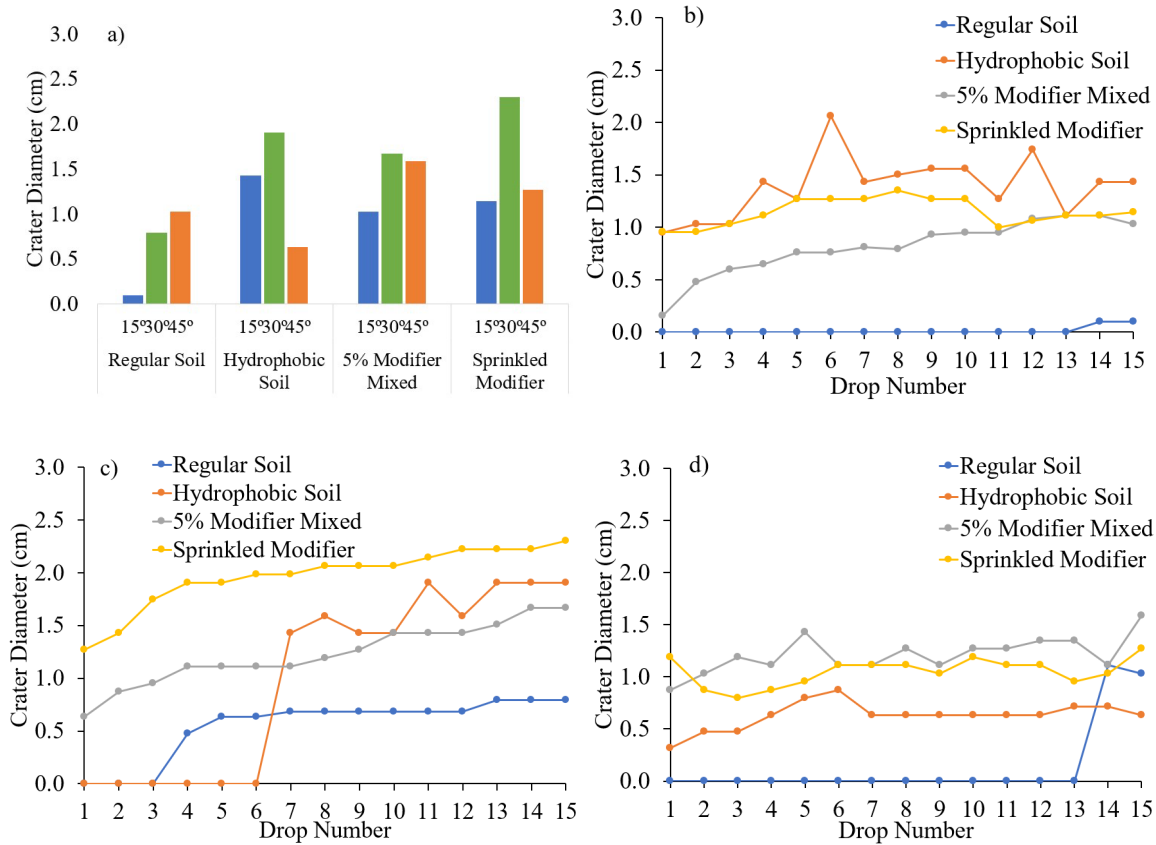


Figure 8.5. Erosion crater diameter development for regular sandy soil, hydrophobic sandy soil, hydrophobic sandy soil with well-mixed 5% SCI modifier, and hydrophobic sandy soil with sprinkled SCI modifier at the surface. a) erosion crater diameter after 15 drops of water. b) erosion crater diameter development over 15 drops at a 15° slope. c) erosion crater diameter development over 15 drops at a 30° slope. d) erosion crater diameter over 15 drops at a 45° slope.

While crater diameter measures the level of surface expansion of water droplets, tail length explores the effect of modifiers on the downward flow behavior of water drops. Erosion tail length is measured on varying slope angles (15°, 30°, 45°) on regular sandy soil, hydrophobic sandy soil, 5% mixed modifier sandy soil, and sprinkled modifier sandy soil. **Figs. 8.6a-d** shows erosion tail length under different scenarios. Erosion tail length is not observable on a hydrophilic slope, as the water droplets penetrate the sand layer easily. However, erosion tail length is observable at a high slope inclination angle due to the combined effect of surface sandy soil landslide and water droplet erosion. On a hydrophobic surface, the water droplet induces tail erosion immediately.

Sandy soil surface hydrophobicity makes water droplets flow easily along the slope. As the water accumulates, erosion tail length increases until it reaches the maximum in the erosion channel.

The addition of a modifier causes a reduction in erosion tail length. The 5% mixed modifier sandy soil has a higher tail length than the sprinkled modifier sandy soil for the low slope angle. The two modifier application methods have similar effects at moderate and high slope angles. Applying modifiers has a better erosion tail length reduction at lower slope angles. The erosion tail also increases in the horizontal direction, not measured but photo-taken. The next section shows this effect with image demonstrations.

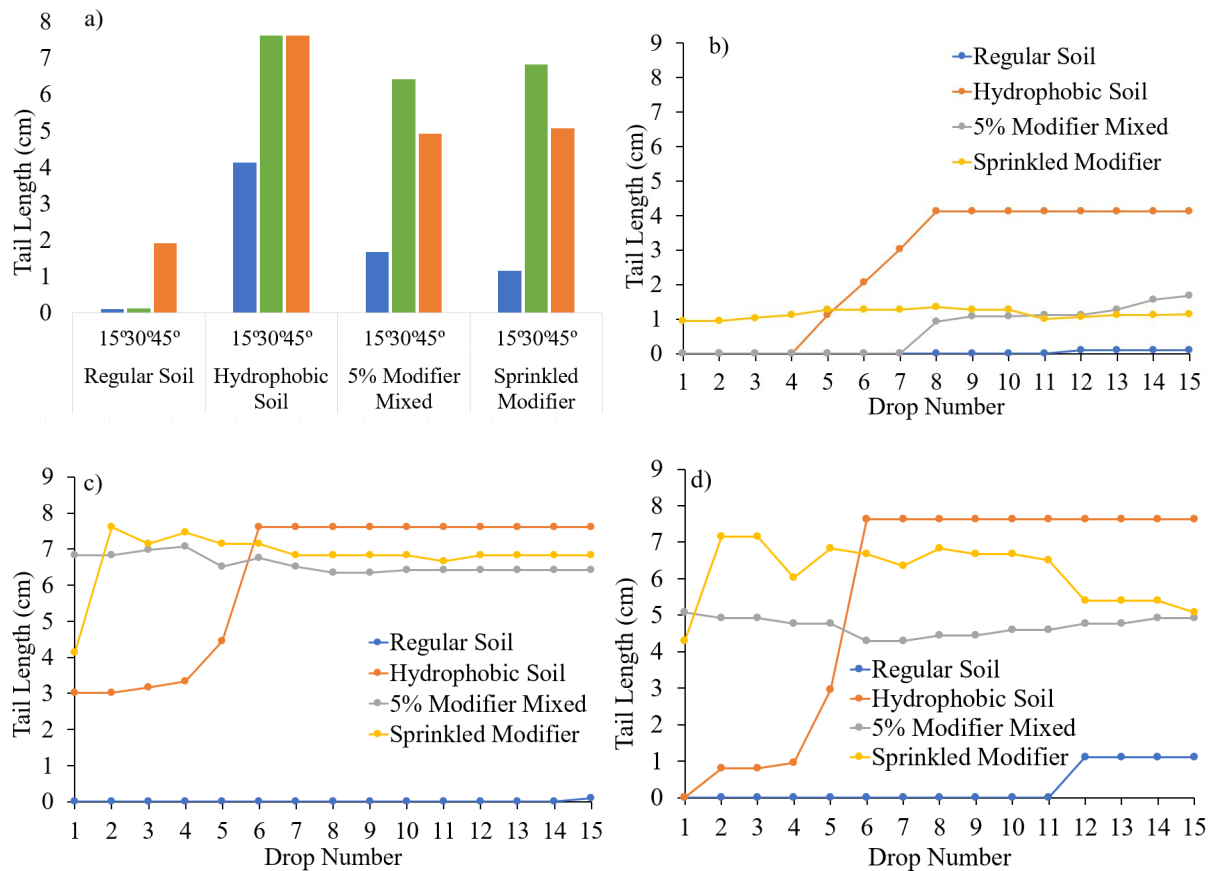


Figure 8.6. Erosion tail length development for regular sandy soil, hydrophobic sandy soil, hydrophobic sandy soil with well-mixed 5% SCI modifier, and hydrophobic sandy soil with sprinkled SCI modifier at the surface: a) erosion of tail length after 15 drops of water, b) erosion tail length development over 15 drops at a 15° slope, c) erosion tail length development over 15 drops at a 30° slope, d) erosion tail length over 15 drops at a 45° slope.

8.4 Erosion Patterns of Different Slope Conditions and Treatments

Erosion patterns that develop on micro-locations of drop impact are investigated in hydrophilic, hydrophobic, and treated hydrophobic sandy soils on slopes. First, on the regular hydrophilic sandy soil over a 30° slope, the water droplet accumulates and easily infiltrates but does not induce significant erosion tail, so only a vertical drainage path forms (**Fig. 8.7a**). **Fig. 8.7a** shows two noticeable patterns: crater due to waterdrop impaction and induced central void space due to sandy soil particle displacement (circled in green color) and affected wetted region from lateral water drop spill (circled in red color). However, the water droplet infiltration is delayed on the hydrophobic sandy soil over a 30° slope (**Fig. 8.7b**). As the water droplets accumulate on the surface, the crater size grows, and erosion tail length develops. Erosion patterns on hydrophobic surfaces may also become more complex than a straight path. For example, for drop number 10, the erosion tail length flows sideways, as shown in **Fig. 8.7b**. The erosion process forms two tails for drop number 20 in **Fig. 8.7b**. Before drop number 15, only a general crater from water drop impact was present at the origin of erosion. After drop number 15, the same void space due to sandy soil displacement inside the general crater appears as it is in the hydrophilic sand scenario. As a result, soil hydrophobicity significantly affects surface drop mobility and aids in the heterogeneity of flow paths, especially at steeper slopes, adversely affecting slope erosion processes.

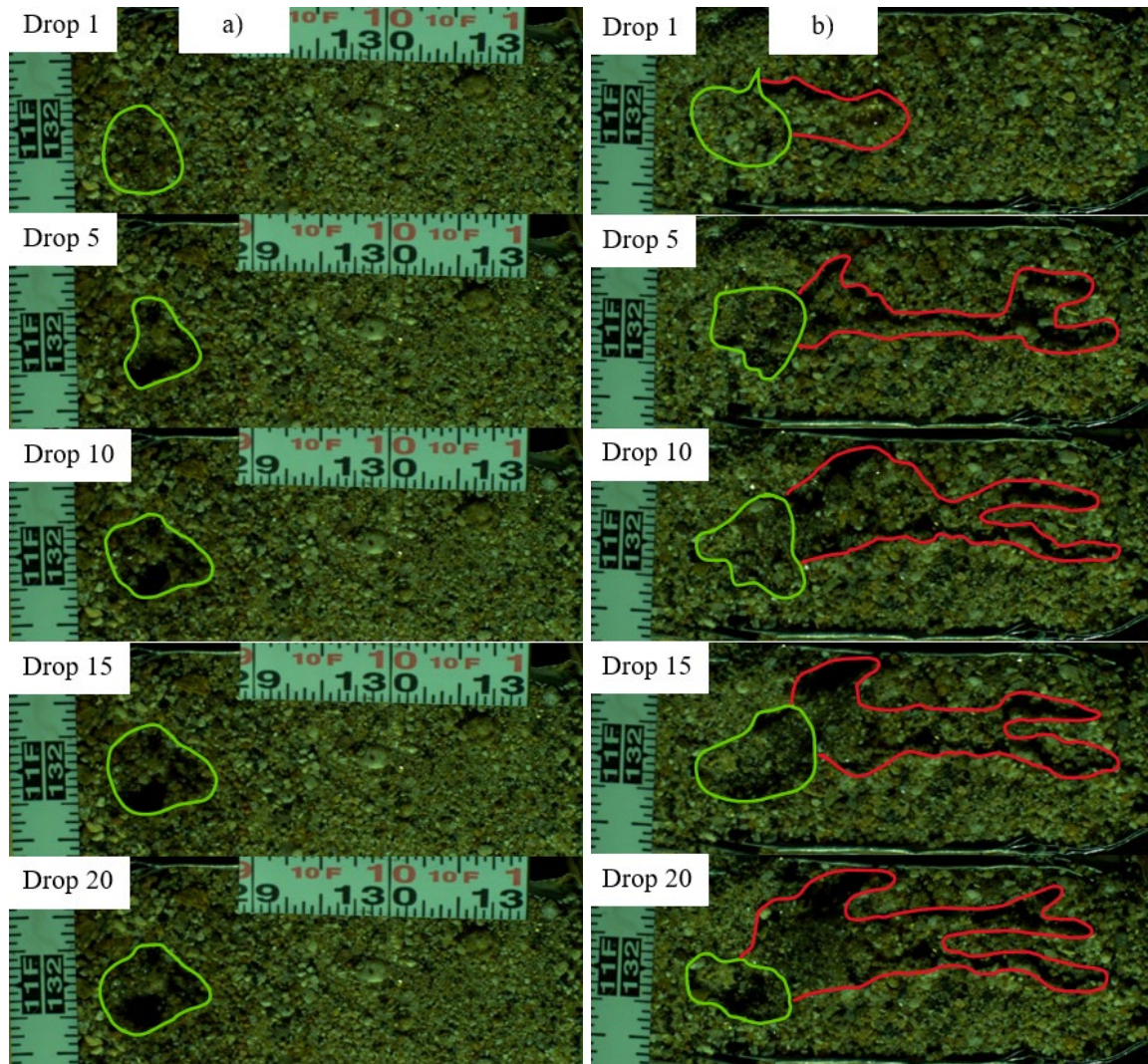


Figure 8.7. Water drop erosion processes on a 30° slope for a) regular hydrophilic sandy soil and b) hydrophobic sandy soil.

Drop water accumulation and tail path are examined for the SCI powder case because of the enhanced infiltration. On the contrary, as was shown in **Figs.8.2** and **8.4**, XG prevents water infiltration that is similar to hydrophobic sand and bonds loose sand particles; erosion of XG-treated slopes is not critical, and most of the water is expected to overflow across the slope. Both the hydrophobic sandy soil completely mixed with 5% SCI powder by mass (**Fig. 8.8a**) and the hydrophobic sandy soil with sprinkled modifiers at the surface (**Fig. 8.8b**) still have a greater erosion tail length and crater diameter than that of the hydrophilic sand. The droplets on the

modified sand experience similar crater diameter growth with water accumulation as a hydrophobic case but a wider and faster-growing erosion tail length. For the hydrophobic case (**Fig. 8.7b**), the wider erosion pattern occurs between drop number 10 and drop number 15. In the modifier case (**Figs. 8.8a-b**), the wider erosion pattern occurs between drop number 5 and drop number 10. Unlike pure hydrophobic sand, SCI-modified sand conditions make the erosion process more "sticky": the eroded materials need more energy to flow in the downslope direction. The sprinkled SCI powder method is more manageable on burn slopes than completely mixing the SCI into the sandy soil, making it a more achievable process in practice.

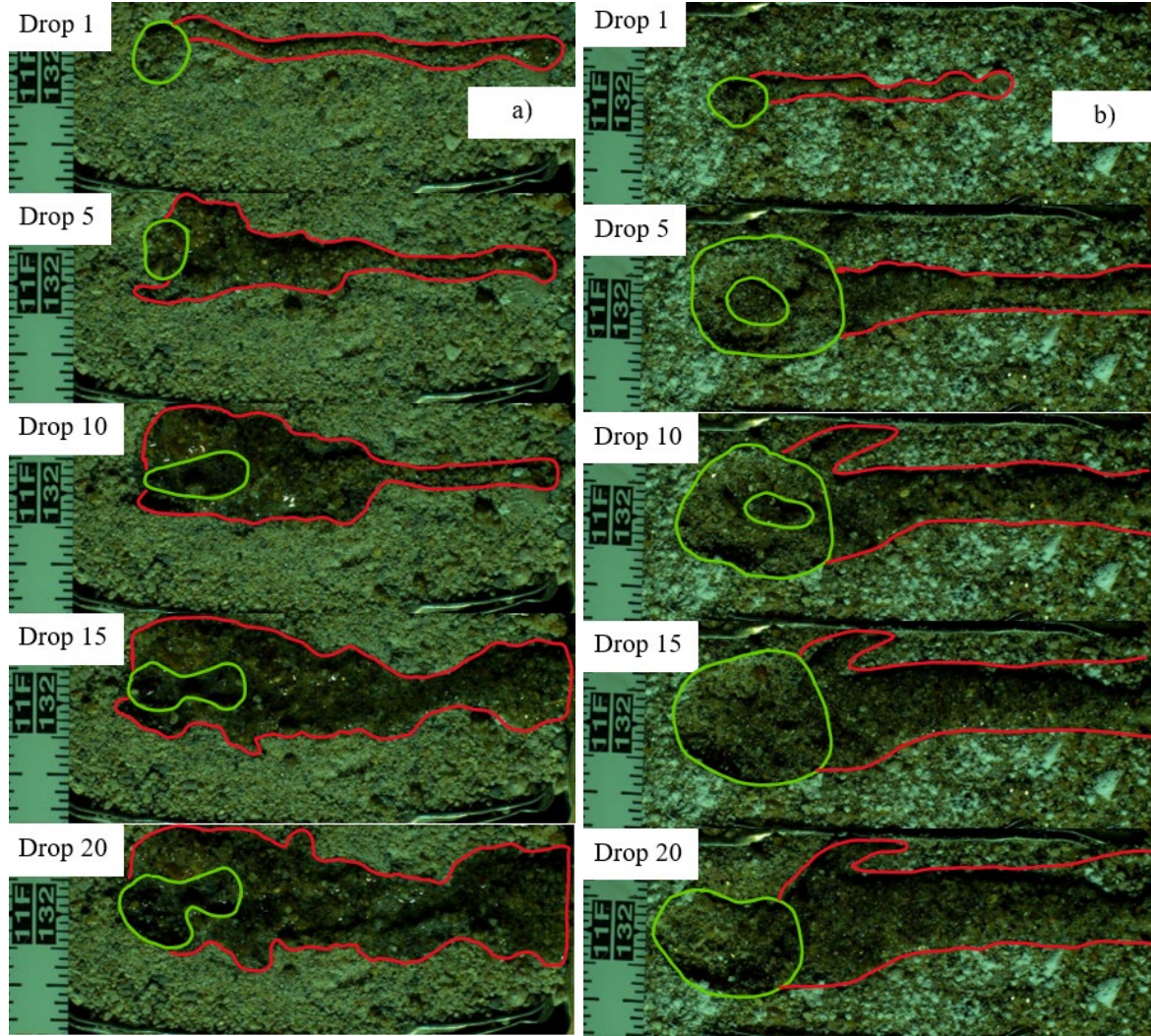


Figure 8.8. Treated hydrophobic sandy soil erosion using different modification methods on a 30° slope: a) completely mixed with 5% by mass SCI powder, b) sprinkled SCI powder at the surface.

The effect of the slope inclination degree is presented in **Figs. 8.9a-b**, modifiers sprinkled on the sand surface. The eroded region is very limited on a 15° slope (**Fig. 8.9a**), and the erosion pattern is close to a hydrophilic sand condition. While both surfaces have sprinkled SCI powders, the 15° slope has a shorter erosion tail length than the 45° slope, which can be expected. Furthermore, the crater is more observable on the 15° slope than on the 45° slope. Conversely, the

45° slope has a wider erosion tail (**Fig. 8.9b**). Besides, surface landslides exist for the 45° slope. Therefore, the effect of the modification method is highly susceptible at steep slopes.

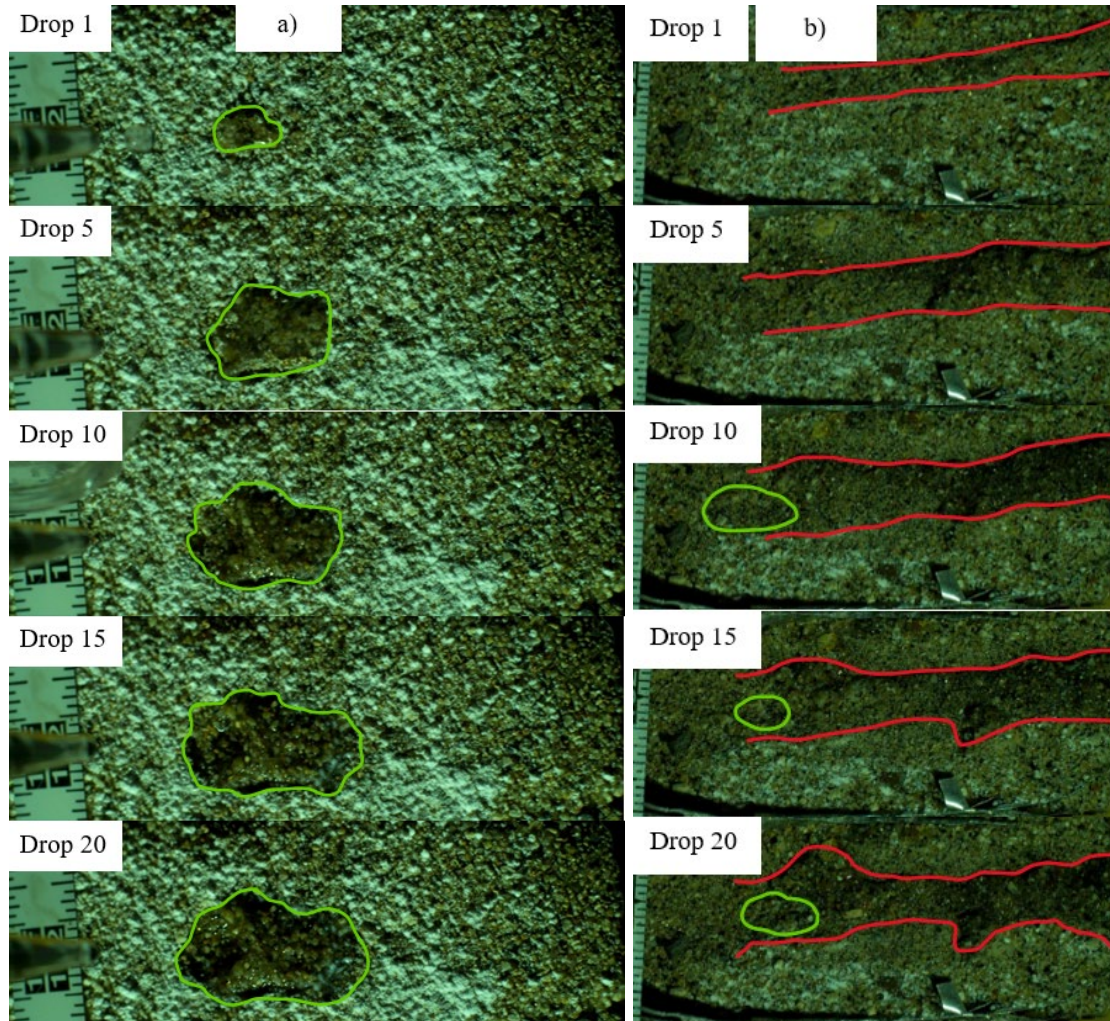


Figure 8.9. SCI powders are sprinkled on the hydrophobic sandy soil slope surface on a) 15° slope and b) 45° slope.

8.5 Theoretical Prediction of Modifier Infiltration and Overflow

Infiltration rate (IR) is the volume flux of water flowing into the profile per unit of soil surface area (Kirkham, 1961). A typical sandy soil has an infiltration rate of less than 30 mm/h or 0.008 mm/s (Gyamera, 2014). Infiltration rate also depends on water content: drier soil has a higher

infiltration rate, and IR can be up to about 1000 mm/h under a 95% confidence interval for dry soil samples (Diamond & Shanley, 2003). It can be seen from the WDPT's results that soil hydrophobicity significantly decreases IR, which can be calculated relative to the regular soil based on a single drop. When a single waterdrop with a diameter of 6 mm is dropped from 9 cm above the dry regular hydrophilic well-graded sand, the impact crater diameter is 15.6 mm. The WDPT is only 0.02 s. Therefore, the IR for hydrophilic is $2.37 \cdot 10^{-1}$ mm/s (**Fig. 8.10a**). The same waterdrop causes an impact crater diameter of 14 mm with a WDPT of 10800 s on dry, hydrophobic, well-graded sand. The IR for hydrophobic sand is then $5.44 \cdot 10^{-7}$ mm/s (**Fig. 8.10a**). Hence, hydrophobicity causes 6 orders of magnitude decrease in IR.

The IR increases when the sand samples are treated with XG and SCI modifiers. Under the XG treatment scenario, the same waterdrop causes an impact crater diameter of 13.3 mm and a WDPT of 4500 s. Thus, the IR for hydrophobic sand with XG treatment is $1.45 \cdot 10^{-6}$ mm/s (**Fig. 8.10a**). XG treatment is 1 order of magnitude more effective in increasing IR for a hydrophobic sand. Under the SCI treatment scenario, the same waterdrop causes an impact crater diameter of 14.7 mm and a WDPT of 1.2 s. Thus, the IR for hydrophobic sand with SCI treatment is $4.44 \cdot 10^{-3}$ mm/s (**Fig. 8.10a**). SCI treatment is 4 orders of magnitude more effective in increasing IR for hydrophobic sand.

The same IR analysis is conducted for hydrophilic and hydrophobic well-graded sand samples on different slopes with different modification methods (**Fig. 8.10b**). For hydrophilic well-graded sand samples on the 30° slope, the IR is $1.99 \cdot 10^{-1}$ mm/s, which has the same magnitude or order but is slightly lower than the horizontal surface case. A similar result applies to hydrophobic sand samples on the 30° slope whose IR is $2.08 \cdot 10^{-7}$ mm/s. The IRs for well-mixed SCI powders and sprinkled SCI powders on hydrophobic sand samples on the 30° slope fall

in the same magnitude of order for hydrophobic sand samples well mixed with SCI powder on horizontal surface, which are $6.67 \cdot 10^{-3}$ mm/s and $9.60 \cdot 10^{-3}$ mm/s respectively. Finally, steeper slopes reduce IR. The IRs for hydrophobic sand samples with sprinkled SCI powder on 15° and 45° slopes are $1.09 \cdot 10^{-2}$ mm/s and $7.93 \cdot 10^{-3}$ mm/s respectively.

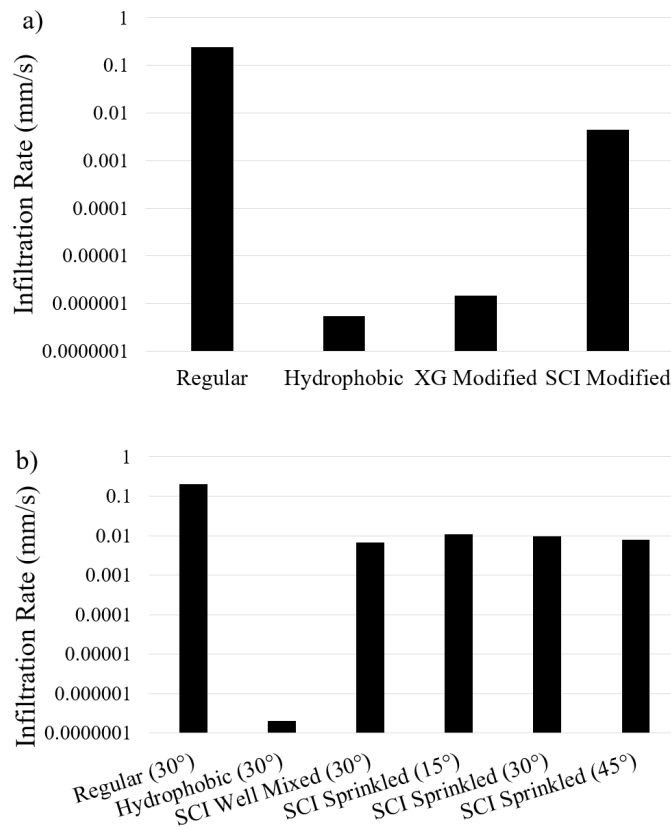


Figure 8.10. Infiltration Rate (IR) results under different conditions: a) horizontal surfaces, and b) sloped surfaces

Acknowledgment

Chapter 8 is currently being prepared for submission for publication of the material entitled “Sandy Soil Hydrophobicity and Slope Erosion Remediation by Applying Modifiers”. Ma, Wenpei; McKlin, Henry; Chan, Russell; Kim, Caitlin; DePoint-Spang, Teagan; Tomac, Ingrid.

The dissertation author was the primary researcher and first author of this manuscript. The work done by undergraduate students Henry McKlin, Russell Chan, Caitlin Kim, and Teagan Depoint-Spang from the REU program was greatly appreciated.

Chapter 9 Conclusion

Specific new findings show that a longer mixing time gradually decreases the amount of entrapped air. Mixing time affects the amount of air and relates to the time from the start of rain-induced erosion on the burned scar with hydrophobic particles to later times of mudflow dynamics. In addition, mixing time is coupled with the average particle size, and coarser sand needs consistently less mixing time than fine sands to reach a steady volume of trapped air in the mixture at all investigated equivalent downhill mixing speeds. Collision efficiency between a particle and a bubble is higher for coarser sands. Next, considering the mixing rate, air trapped in the mixture decreases as the mixing velocity and sand coarseness increase. Observing air bubbles and liquid marbles can explain the variation and decrease of entrapped air in the mixture under faster, longer mixing and with coarser hydrophobic sands. Coarser sand forms larger liquid marbles than finer sand, with a larger modified Bond number, which indicates higher initial bubble shape irregularities where larger marbles deform more and break more easily. Liquid marble breakage is more prominent at a higher speed with a longer mixing time in coarser sand than in other sand. This experiment provides evidence that local turbulence and flow instabilities make particle-bubble interaction more unpredictable and increase the vulnerability of formed liquid marbles toward breakage. As mixing velocity increases, experimental observation deviates more from theoretical calculation. Besides, as mixing velocity increases, larger liquid marbles are hard to survive.

The experiments shown in this paper specialize in narrow particle size to investigate the role of particle size in air entrapment. Although the small-scale mixing experiments in this research are limited compared to site and large-scale soil heterogeneity, they provide an excellent baseline.

Experiments show that coarser sand reduces the volume of entrapped air, and with gravel or boulders, air entrapment could be less because gravity forces from gravels or boulders and hydrodynamic forces from large particles can easier break the multiphase force balance among air bubbles, water, and solid particles. Larger particles, higher flow speed, and longer mixing time will have a smaller air entrapment effect. With less entrapped air, the upper and lower bounds will shift upward. Since the experiments only consider sand particles, the amount of trapped air could be different if the mixture contains hydrophilic particles and sand or clays. Those factors may also cause an upward shift in two bounds.

The density reduction would affect the numerical simulation results. This paper proves that postfire debris flows are lighter than regular debris flows. Therefore, predictions of behaviors of postfire debris flow would have the following updates: 1) the flow velocity of postfire debris flows would be slightly higher than regular debris flows; 2) soil surface erosion prediction would be larger due to the flow velocity increases, 3) impacted erosion area would be larger due to the higher flow velocities, 4) simulations will more likely to match potential extreme events with real-world record such as peak impact force of the flow on a barring wall and its damage.

Bagnold number is a powerful dimensionless number that separates different flow regimes of such a complex mixture. The shear flow behavior is identified as a viscous force-dominated regime at low shear rates, then the transition regime at intermediate shear rates, and finally, to a collision force-dominated regime at high shear rates. All three regimes exist for final mixtures with hydrophobic fine and medium sand particles. However, for final mixtures with hydrophobic coarse sand particles, the viscous force-dominated regime does not exist. As sand particles become coarser, the viscous force-dominated regime range becomes narrower.

As the air entrapment ratio increases, the shear stress response of the final mixture becomes smaller. Therefore, air entrapment helps to reduce the internal shear resistance when the final mixture is under shear flow. As the liquid marble diameter increases, the shear stress response of the final mixture becomes larger. The liquid marble diameter is also proportional to the sand particle diameter. Therefore, coarser sand particles enhance the internal shear resistance when the final mixture is under shear flow. As the air entrapment ratio increases, the internal structure overcomes larger damage during the shearing procedure, especially over the high shear rate region.

The rheological relationships are different for different flow regimes. The air entrapment ratio contributes to the rheological relationship.

The number of observable liquid marbles at the outermost edges and sides of the sediment is significantly decreasing as the level of hydrophobicity decreases. Fine sand particles have the peak air entrapment at 75% hydrophobicity. Coarse sand particles have the peak air entrapment at 100% hydrophobicity. Medium sand particles are in between peak air entrapment at 75% hydrophobicity when there are many initial solids and at 100% hydrophobicity when there are fewer initial solids. Similar to the 100% hydrophobicity case, no matter what partial hydrophobicity level it is, the total entrapped air increases with initial solids.

Pure hydrophilic conditions and pure hydrophobic conditions provide the upper and lower bounds for the rheological behaviors of the mixture composed of fine and medium sand particles. The lower bound is roughly 30% to 35% of the upper bound for fine sand particles. The lower bound is roughly 15% to 25% of the upper bound for medium sand particles. However, coarse sand particles do not have clear bounds. Coarser sand particles lead to a more deviating rheological behavior from classical fluid models. Coarse and medium sand, under all levels of hydrophobicity, cannot fit any classical fluid model. Rheological behavior has to be subdivided into different flow

regimes. Fine sand particles with no hydrophobicity or partial hydrophobicity can fit the Herschel-Bulkley fluid model for general estimation purposes. Rheological behavior for completely hydrophobic fine sand particles shall also be subdivided into different flow regimes.

When fine sand particles are mixed with Kaolinite clay, peak air entrapment only occurs at 100% hydrophobicity. Less hydrophobicity leads to smaller air entrapment. Pure hydrophilic fine sand with Kaolinite and pure hydrophobic fine sand with Kaolinite are upper and lower bounds in rheological behavior. The lower bound is about 10% to 15% of the upper bound. Classical fluid models, such as the Herschel-Bulkley model, can be used to provide rough estimates.

Hydrophobicity has a clear effect on the debris flow. The mixture flows faster due to air entrapment. Slip velocity at the bottom of the channel is observed when the sand particles are hydrophobic. Hydrophobic sand particles form liquid marbles that are flowing at the bottom. If the sand particles are less than 50% hydrophobic, slip velocity does not occur at the bottom. Otherwise, the slip velocity occurs. Therefore, 50% of sand hydrophobicity is the turning point of debris flow modes. Flow becomes more laminar through the channel under all levels of sand particle hydrophobicity.

At the beginning of debris flow in the open channel, the slope inclination has a clear effect on the flow velocity profile. A higher slope inclination leads to a clear increase in the flow velocity profile. As debris flow continues in the open channel, the flow profiles are similar to each other under different slope inclination conditions. Slip velocity still holds for complete hydrophobic sand condition.

SCI powders form crystalline and thin coating covering hydrophobic particles at locally oversaturated regions. However, XG powders form lines and membranes within the pore spaces of hydrophobic particle samples at locally oversaturated regions. Therefore, XG powders lead to

water flow-path blockage problems and reduce drainage capacity. A 5% mass concentration of powders applied to hydrophobic sandy soil samples for both modifiers can reach the desired contact angle reduction performance. The difference between advancing and receding contact angles for a water droplet on a sloped surface depends on the slope inclination angle. Although neither modifier can reduce the WDPT time of hydrophobic sand samples back to clean hydrophilic conditions, SCI powder is a thousand times more effective than XG powder. A higher mass concentration of XG does not affect the WDPT reduction.

Both mixing SCI powder and sprinkling it on the slope surface can reduce slope erosion problems. In the downward slope direction, SCI powder leads to water droplets spread in two dimensions rather than one dimension flow. Therefore, downslope erosion alleviates due to multi-directional energy dissipation on modified slope surfaces. Water droplets can also penetrate through the sand layer more easily due to the chemical properties of SCI powder. Thus, less energy will erode surface particles in modified surfaces than in hydrophobic surfaces. Erosion tail length develops slower on modified surfaces than on hydrophobic surfaces.

Since SCI powder allows water droplets to spread out more easily, crater diameter can actually be larger than in hydrophobic conditions. SCI powder makes the wetted hydrophobic sand surface more sticky, which requires more downslope energy to flush sand particles. At higher slope angles, surface erosion is coupled with landslide problems. Therefore, the effect of both modification methods is highly susceptible. Both XG and SCI powders can increase the IR of purely hydrophobic sandy soil. However, SCI powders can increase IR by 4 orders of magnitude, while XG only increases IR by 1 order of magnitude. Therefore, SCI provides better erosion control due to its ability to increase infiltration to the soil layer.

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