FLOW OF FOAM MIXTURES ON INCLINED FLUMES AND SURFACES

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Abstract: Experimental tests were conducted to study the rheology and flowability of foam mixtures. Foaming agent with two different foam-water ratios of 0.1 and 0.2 were used in this study. The Herschel-Bulkley model was used to predict the shear stresses of foam mixtures with an index of n=1/6. A strong linear correlation was found between foam viscosity and shear rate with a slope of −1 in log-log scales. This correlation indicated the shear thinning behavior and the existence of a yield stress in foam mixtures. A series of flume tests were employed to model the two-dimensional flow of foam mixtures. Flume tests were conducted for two slopes of 10 and 15 degrees. Correlations were developed to predict the foam length and its frontal velocity with time using dimensional analysis. It was found that the normalized frontal velocity of foam mixtures decreased with normalized time with a slope of −0.6 in logarithmic scale. To study the effect of bed slope on the flowability of foam mixtures, spreading tests were carried out for four slopes of α =10, 12, 15 and 18 degrees. Variations of the foam front location in spreading test showed that the foam front location advanced almost linearly with time. For foams with lower foam-water ratio, variation of the foam length with time was independent of the surface slope for α>10 whereas for foam mixtures with higher foam-water ratio, the foam front advanced linearly with time and the frontal velocity increased with increasing the bed slope.

1. INTRODUCTION

Foam mixtures can be made by adding of either powders or liquid foaming agents to water to create a uniform mixture with a macroscopic continuous structure. Physical and rheological properties of foams have been of great importance due to their distinctive characteristics and potential engineering applications. Foam mixtures can be employed in underground mines to control underground coal mine fires (Chasko et al., 2003) and fire-fighting purposes (Bobert et al., 1997). Field study of Chasko et al. (2003) showed that around 50% of foam loses its volume during the foam generation and transport which was due to bubble breakage and foam compression. In addition, foam mixtures can be used as a drilling fluid with good cutting and transport characteristics. Gumati and Takahshi (2011) conducted experimental and numerical studies to evaluate the effect of foam-water ratio on the structure of foam-cuttings mixtures by measuring the pressure loss in horizontal pipes. The foam-cutting mixture consists of a commercial surfactant (KA-Foam) as a foaming agent and spherical glass beads as a drilled cutting material. They found that higher foam-water ratio enhances the efficiency of the transport of the cutting spheres. Recently, Azimi (2015) studied the rheological properties of sand-foam mixtures in detail. It was found that the peak shear stresses occur less than five seconds from the onset of measurements and they decrease afterwards. The peak time is relatively short compared with the high-density tailings (i.e., 30 seconds) reported by Gawu and Fourie (2004). Those peak values were used to plot the correlations of shear stress with shear rate and to calculate the apparent viscosity.

Experimental investigations of the steady and time-dependent shear flow properties of foam were carried out by Khan et al. (1988). They examined the effect of gas volume fraction ϕ on the rheological properties of the foam. It was found that foams made from a mixture of gas and liquid foaming agent (i.e., A polymer-surfactant-based aqueous solution) behaved like a shear thinning liquid and had a yield stress. Three different foams with gas volume fraction of ϕ = 0.92, 0.95 and 0.97 were studied in the experiments of (Khan et al., 1988) with an average bubble diameter of 65±3 μm. They found that both yield stress and viscosity were higher for larger gas volume fractions. Rheological properties of alcohol resistant foam were measured to estimate the pressure losses through pipelines for fire-fighting purposes (Bobert et al., 1997). Bobert et al. employed three different foam concentrations to test the rheological properties of the foam and compared their data with a horizontal pipe tests. Rheological characteristics of foam mixtures to design pipeline network and pump operation were also studied using horizontal pipe and horizontal flume tests (Briceno and Joseph, 2003).

Inclined flume and surface tests have been used to perform the flowability of non-Newtonian fluids and mixtures [Clayton et al., 2003; Chanson et al., 2006; Cochard and Ancey, 2009]. Those tests were used to identify the yield stress and expansion rates of the mixtures in transient and steady state conditions. Coussot and Boyer (1995) examined the accuracy of the inclined surface test to determine the yield stress of the clay-water mixture whose yield stress ranged from 35 to 90 Pa. They used a 1m long flume with a slope ranging from 10^o to 30^o. They have shown a relatively good agreement between yield stress measurements from inclined surface and rheometrical tests if the edge effects being considered. Coussot and Proust (1996) employed the Herschel-Bulkley model to predict the longitudinal and lateral mean velocities and fluid depths of mudflows. The Herschel-Bulkley model can be defined as:

[1] $$\dot{\gamma} = 0 \Leftrightarrow \tau < \tau_c; \qquad \dot{\gamma} \neq 0 \Leftrightarrow \tau = \tau_c + K\dot{\gamma}^n$$

where $\dot{\gamma}$ is the shear rate, τ and τ_c are the shear stress and the critical shear stress. K is the consistency and n is an index of the model and both of them are positive numbers. Coussot and Proust (1996) have employed the mixture of fine mud suspensions at different solid concentrations to model the expansion of mudflows in an inclined plane. Cochard and Ancey (2009) studied the spreading of viscoplastic fluids (I.e., Carbopol Ultrez 10) on a plane surface, whose inclination ranged from 0^o to 18^o. It was found that the front position of the flow varied as a power function of time and an empirical formulation was developed to predict the front position of the flow. The proposed formulation was a function of time and plane inclination.

[2] $$X_f = t^{0.275(\sin\alpha)^{1/3}} (\sin\alpha)^{5/4}$$

where X_f is the front position, t is the time and α is the inclination. A series of laboratory experiments were conducted using a tilting flume with a slope of 15 degrees to study the flowability of Bentonite suspension (Chanson et al., 2006). The frontal position of the Bentonite clay flowing in the flume X_f and its velocity V_f at each time were normalized with the initial reservoir depth H_o and acceleration due to gravity g. The following formulations were proposed describe the flowability of Bentonite clay in a flume with a slope of 15^o. Chanson et al. (2006) indicated that those formulation provide reasonable accuracy for $t\sqrt{g/H_o}$ <6.

[3] $$\frac{X_f}{H_o} = \frac{1}{2}\left(t\sqrt{\frac{g\sin\alpha}{H_o}}\right)^2$$

[4] $$\frac{V_f}{\sqrt{gH_o}} = t\sqrt{\frac{g\sin\alpha}{H_o}}$$

This paper investigates the physical and rheological properties of foam mixtures for different foam-water ratios of G_f = 0.1 and 0.2. The foremost objective of this work is to evaluate the effects of bed slope and foam-water ratio on the flowability of foam mixtures. Accurate determination of the rheological characteristics and flow properties of the foam mixtures is important for numerical simulation and transport of the foam in inclined surfaces and pipes.

2. EXPERIMENTAL SETUP

Two sets of laboratory experiments were carried out to study the flowability of foam mixtures. Details of laboratory experiments and mixture characteristics were shown in Table 1. Twenty grams of foaming agent (CLSM admixture, Rheocell Rheofill, BASF Co., US) were mixed with 100 ml and 200 ml of demineralized water to form a well-mixed foam with a foam-water ratios of G_f = 0.2 and 0.1, respectively. It was found that a mixing duration of 5 minutes can provide a uniform mixture. Foaming agents were mixed with water for 5 minutes at 1200 rpm using a high shear stirrer with a wire and tooth profile geometries. Density of unpacked foam powder ρ_f and density of water ρ_w were around 300 and 1000 kg/m^3, respectively. Densities of foam-water mixtures before expansion ρ_{mo} for G_f = 0.1 and 0.2 were 1011 and 1023 kg/m^3, respectively.

The rheological properties of foam mixtures were measured using a Brookfield DV-II+ Programmable Viscometer. Tests were carried out by controlling the shear stress rates. Vane spindles with designation of V-73 and V-74 (RV) were used for these tests. The ranges of shear stress for these spindles are 10-1000 Pa with an error of ±1% of full scale (Brookfield, 2005). A vane-to-container diameter of less than 0.75 was desired to ensure ample clearance when measuring large-particle suspensions. In all rheological tests, a beaker of 500 ml capacity was used in the measurement with the inner diameter of 81.3 mm. The temperature was controlled by Thermosel and all the measurements were made at room temperature of 20 ^oC. Great care was brought to ensure accuracy and reproducibility of experiments.

Table 1: Details of laboratory experiments and mixture characteristics.

Test Type	Test number	G_f	ρ_{mo} (kg/m^3)	ρ_m (kg/m^3)	*Slope*
Surface test	1	0.1	1011	78.8	10, 12, 15, 18
	2	0.2	1023	81.7	10, 12, 15, 18
Flume test	1	0.1	1011	78.8	10, 15
	2	0.2	1023	81.7	10, 15

Flume tests were conducted using a 2.4m long, 0.115m wide and 0.3m high Plexiglas flume which the bed was covered with fine sand paper to minimize slippage. A removable gate was designed to block the flow of foam before the onset of experiment. Experiments were conducted with two slopes of 10^o and 15^o for two different foam-water ratios of G_f = 0.1 and 0.2. The total duration of each flume study was around 800 seconds. Plane surface tests were conducted to study the three-dimensional spreading of foam mixtures. A thick laminated timber sheet (2.8m x 1.6m) was used to examine the spread of foam mixtures at different angles of 10^o, 12^o, 15^o, and 18^o. A sets of white grid lines forming squares of 0.1x0.1 m^2 were printed to correct any lens distortions. The total duration of each plane test ranged from 300s to 1200s.

A 0.24m long, 0.215m wide and 0.4 high Plexiglas box was used as a foam reservoir with an opening of 0.215m x 0.1m. A gate inside the Plexiglas box was removed quickly at the onset of experiments and the foam spread and its height were recorded by two cameras simultaneously. The flow spread of foam mixtures were recorded by a CCD camera [TM 1040, Pulnix America Inc.] with a resolution of 1400 x 1000 pixels and a speed of 15 frames per second. The camera was controlled by a computer frame grabber system (Stream 5, IO Industries Inc.) and located 1.5m from the flume and 4m above the plane. The recorded images were used to study the development of foam mixtures with time and calculate the frontal velocity of foam mixtures.

3. RESULTS AND DISCUSSION

3.1 Viscosity and Yield Stress

In order to find the correlation between shear stress and shear rate, variations of the shear stress with time for different shear rates were measured and the peak shear stresses at each shear rate were recorded. By subjecting the mixture to a constant shear rate, stress within the mixture increased in an approximately linear relation and then decreased with increasing time. Typical shear stress and shear rate diagram for foam mixtures is plotted in Figure 1. Experimental investigations on the rheology of low expansion foam being used for fire-fighting purposes indicated a lower shear stress by approximately one order of magnitude (Gardiner, 1998). The lower shear stress in low expansion foam can be due to the higher water content in the foam.

Herschel-Bulkley model (i.e., $\tau = \tau_c + K\dot{\gamma}^n$) can be used to predict the relationship between shear stress and shear rate of foam mixtures. The value of τ for Test #2 at the lowest shear rate of 0.01 s^{-1} was measured and it was 22.3 Pa. Coussot (1994) indicated that the consistency value of K is normally one-third of the τ_c. The Herschel-Bulkley parameters of K and n were 6, 1/6, respectively. This model predicts a yield stress value of 19.8 Pa. Figure 1a shows the sensitivity of the index n in Herschel-Bulkley model which the index value of n=1/6 fits better with measurements.

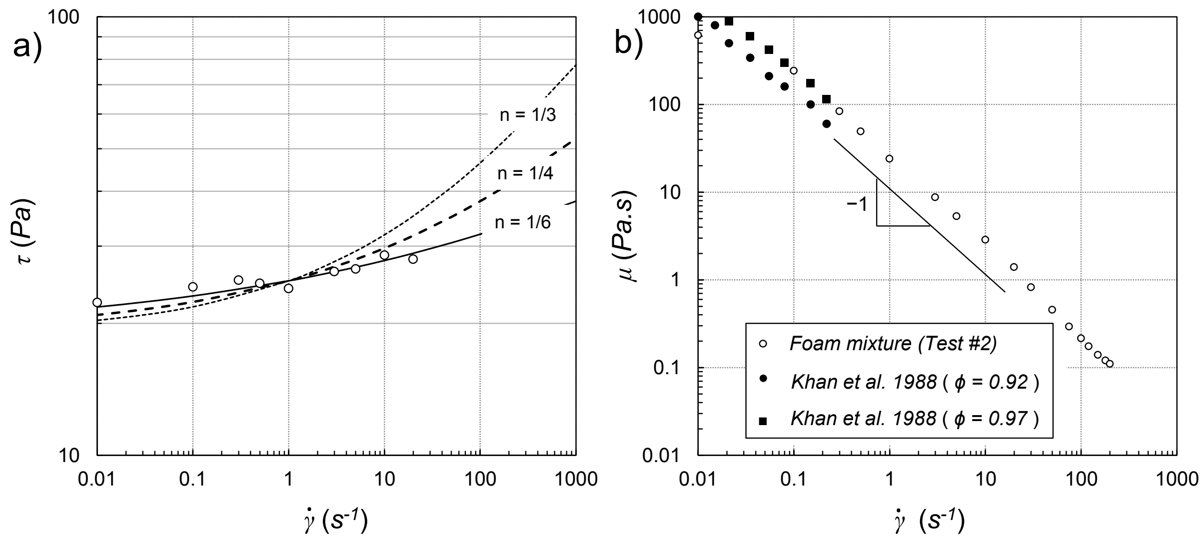

Figure 1: Relationship between shear stress and shear rate of foam mixture (Test #2). a) Performance of index n in Herschel-Bulkley model to predict the shear stress of foam mixtures. b) Variations of the foam viscosity with shear rate indicate a shear thinning behavior.

Figure 1b shows the variations of foam viscosity with shear rate in log-log scale. Experimental data of Khan et al. (1988) on foam rheology of a mixture of aqueous foaming agent and nitrogen gas for two gas volume fractions of ϕ=0.92 and 0.97 are shown for comparison (Solid symbols). Variations of foam viscosity with shear rate indicated a shear thinning behavior (Barnes, 1997). A strong linear correlation between viscosity and shear rate with a slope of approximately −1 in log-log scales indicated the existence of a yield stress.

3.2 Flume Tests

The flow of foam mixtures with time in an inclined flume with a slope of $\alpha = 15^o$ are shown in Figure 2. As can be seen the addition of foaming agent reduced the flowability of foam mixtures. The frontal position of the flow of foam mixture can be detected by basic digital image processing techniques (Gonzalez, 2010). The distance between the frontal position of the foam and the gate was considered as the length of the foam at each time, X_f. Figure 3a shows the variations of the foam length with time for all four flume tests. As can be seen from Figure 3a, the addition of foaming agent decreased the frontal velocity of the foam mixture. Both time and length scales can be normalized to develop a model for prediction of frontal location of foam mixture.

The time scale can be normalized with gravitational acceleration g and the initial height of the foam H_o. Effect of bed slop can be added by including the sinα. The foam length can be also normalized with the initial height of the foam H_o. Dashed curves on Figure 3b show the correlations between the normalized time and frontal position. Power law functions are selected for predictions of Tests #1 and #2 with the coefficients of 0.536, 0.159 and indexes of 0.38 and 0.48, respectively.

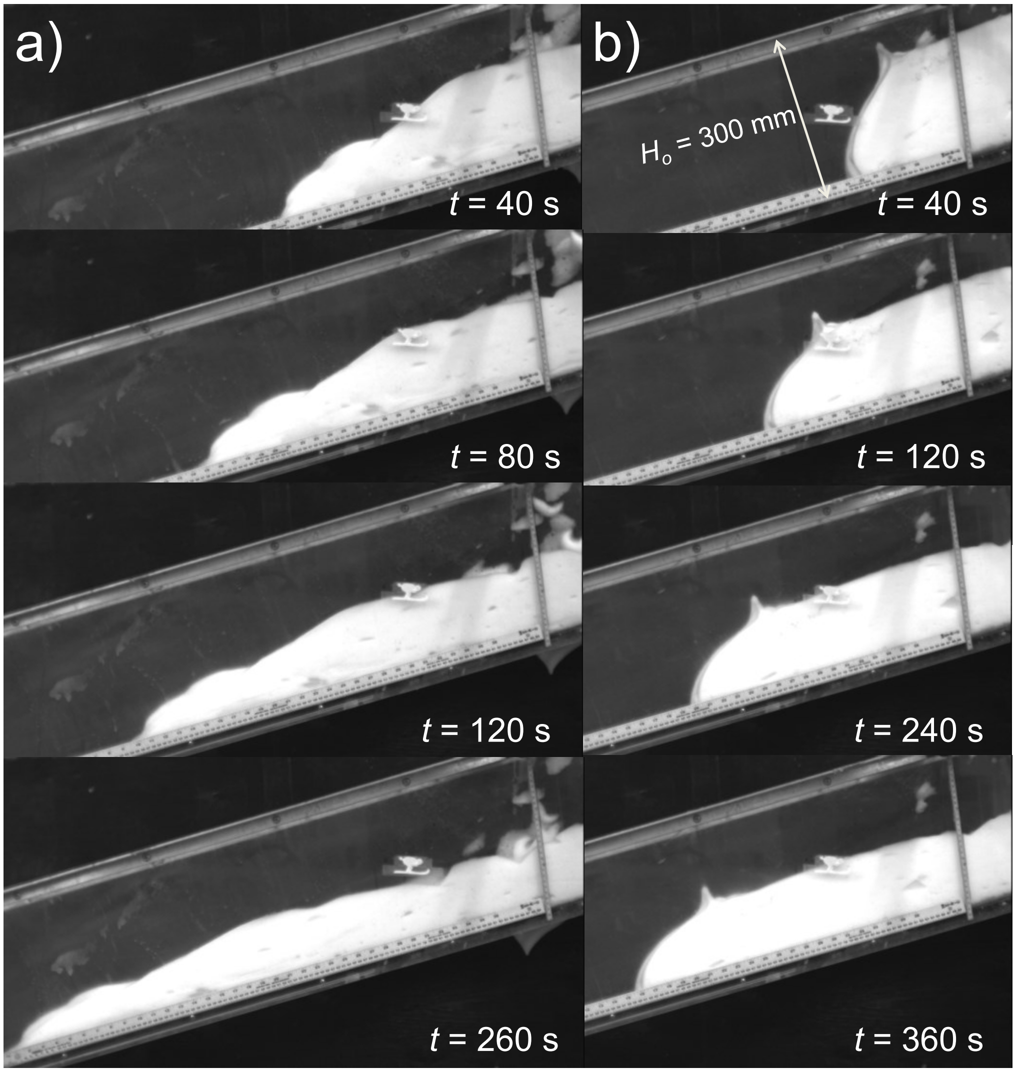

Figure 2: Flow of foam mixtures in an inclined flume with a slope of 15^o at different times after the beginning of experimental tests, a) Test #1 with a foam-water ratio of 0.1, b) Test #2 with a foam-water ratio of 0.2.

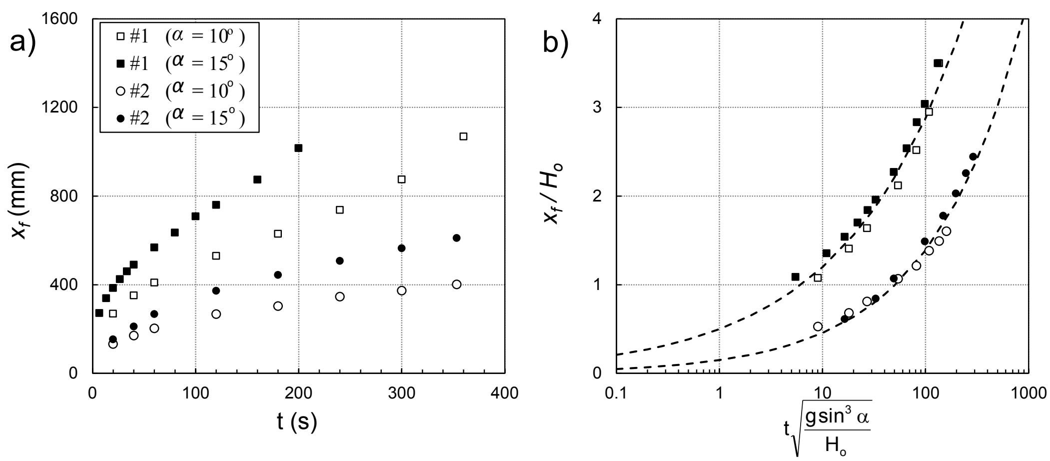

Figure 3: Effects of slope and foam-water ratio on the flow extent of the foam mixtures. a) Variations of the frontal location of foam with time. b) Variations of the normalized foam location with normalized time.

Frontal velocity of foam mixtures V_f can be measured from raw images. Figure 4a shows the variations of the frontal velocity with time for all four flume tests. The frontal velocities of foam and time were normalized to group similar tests and to provide a mathematical formulation. A power law formulation was selected to model the variations of the frontal velocity of foam mixtures with time. It was found that, regardless the foam-water ratio, the frontal velocity decreased with an index of −0.6. The coefficients of the power law formulation for both Tests #1 and #2 are 0.22 and 0.11, respectively.

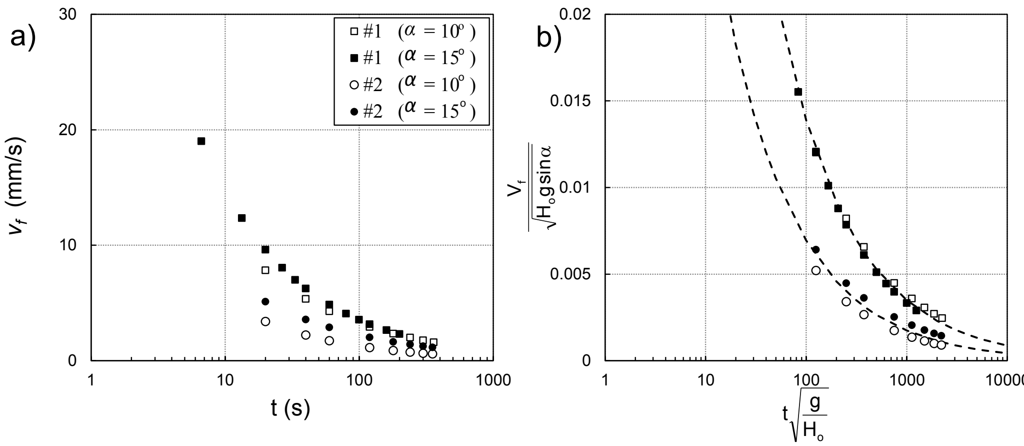

Figure 4: Effects of slope and foam-water ratio on the frontal velocity of foam mixtures. a) Variations of the frontal velocity of foam with time. b) Variations of the normalized frontal velocity with normalized time.

3.3 Plane Tests

Flow development and spreading of foam mixtures on an inclined plane with inclination ranging from 10° to 18° were studied. Figure 5 shows a series images of the flow development on an inclined plane with a slope of 18° at different times. The foam mixture held its integrity up to 50 seconds after the beginning of experiment.

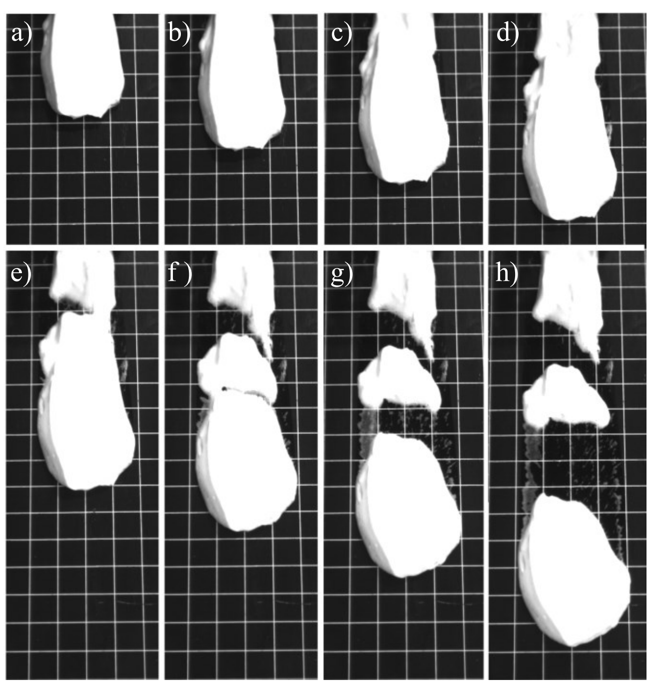

Figure 5: Flow extent and spreading of foam mixture on an inclined plane with a slope of 18° at different times after the beginning of the test (Test #2). a) 20s, b) 30s, c) 40s, d) 50s, e) 60s, f) 70s, g) 80s, h) 100s. The edge length of the squares drawn on the plane is 10 cm.

A discontinuity on foam mixture occurred (Figure 5e) around 60 seconds from the onset of the test. At this time, the imbalance between the horizontal component of the foam weight and the tensile strength of the foam mixture can be the reason of foam discontinuity. The second discontinuity occurred at t = 70 s. As can be seen from Figures 5g and 5h, only the frontal part of the foam moved and the movement of the middle and upper parts of the foam were negligible. Effect of bed slope on the development of foam spreading is shown in Figure 6. Images 6a-6c were taken 180 seconds after the onset of the tests and image 6d was taken 100 seconds from the beginning of the test. As can be seen from Figure 6, by increasing the bed slope the frontal velocity of the foam mixtures increased. By increasing the bed slope, larger amount of foam released from reservoir to plane surface. The excess weight of the foam at the front and larger magnitude of the horizontal component of the weight (sinα) for test with α=15 and 18 degrees, result in the foam discontinuity (see Figures 6c and 6d). Figure 6d shows the flow of foam mixture with $\alpha=18^o$. The frontal velocity in this case is almost 1.8 times of the foam with $\alpha=15^o$.

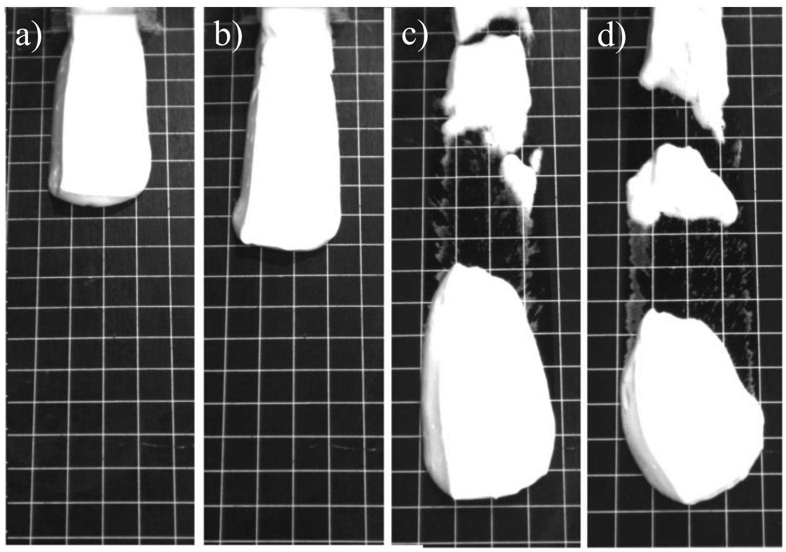

Figure 6: Effect of bed slope on the flow and spreading of the foam mixture (Test #2). Images 6a-6c show 180 seconds after the onset of the test and Image 6d shows 100 seconds after the onset of the test, a) 10^o, b) 12^o, c) 15^o, d) 18^o.

Figure 7 shows the advancement of the foam front with time in plane tests. As can be seen for both foam types, the frontal position in plane tests advanced almost linearly with time. For foams with lower foam-water ratio, variation of foam length with time was independent of the plane slope for $\alpha>10^o$ (see Figure 7a). For higher foam-water ratios, the frontal position of the foam advanced linearly with time and the frontal velocity increased with increasing the bed slope.

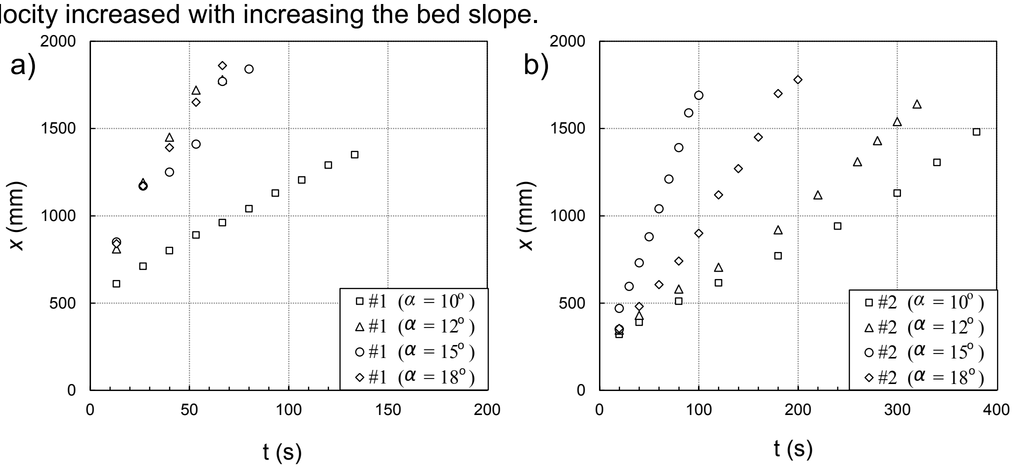

Figure 7: Effects of bed slope and foam-water ratio on variations of the foam length with time. a) $G_f=0.1$. b) $G_f=0.2$.

4. CONCLUDING REMARKS

A series of experimental tests were conducted to examine the effects of bed slope and foam-water ratio on the rheological properties and flowability of foam mixtures. Rheological measurements showed that the foam mixtures were shear thinning with a yield stress. The Herschel-Bulkley model was employed to model the foam mixtures and it was found that this model can predict the shear stress properly with an index value of n=1/6. Flume test studies showed the effect of foam-water ratio on the flowability of the foam mixtures. It was found that foaming agents can significantly reduce the flowability of the foam. The extent of foam length with time was modeled using dimensional analysis. Power-law formulations were used to predict the frontal position of the foam in flume test studies. Similar functions were used to model the frontal velocity of foams. It was found that for both foam-water ratios, the frontal velocity decreased with time with a slope of −0.6 in log-log scales. The coefficients of the power law formulation for both Tests #1 and #2 were 0.22 and 0.11, respectively.

Spreading tests of foam mixtures on inclined plane showed a foam discontinuity which can be a function of time and bed slope. Spreading test studies at t = 180s showed that the foam discontinuity can occur for α=15 and 18 degrees. Variations of the foam front with time in plane tests showed that the foam length increased almost linearly with time. For foams with G_f=0.1, the variation of the foam length with time was independent of the plane slope for $\alpha>10^o$ whereas for foam mixtures with G_f=0.1, the foam advanced linearly with time and the frontal velocity increased with increasing the bed slope.

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