Segregation of Granular Particles in Suspension Flow

by

Jessica Tsay

Submitted to the Department of Mechanical Engineering
in Partial Fulfillment of the Requirements
for the Degree of

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ABSTRACT

An experiment was conducted to investigate the development of longitudinal stripes of granular particles due to instabilities in particle suspension flow. Research was conducted to characterize environmental phenomena related to granular flows, namely avalanches, mudslides, and the movement of glaciers. Results show the stripes were found to appear with a particle concentration of 10% by volume at angles of 20 degrees, at a particle concentration of 20% and 30% by volume at 20, 30, and 40 degrees, and at a particle concentration for 40% by volume at 20 degrees. The application of a shear stress intensified the development of the instabilities, and in experimental trials where stripes were not initially seen, the application of a shear stress was able to induce the fluid to develop the instability.

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Undergraduate Thesis
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Introduction

Past research has shown the unique behavior of thin fluid films flowing down an inclined plane. Recently, the effects of viscosity and surface tension resulting in the fingering of thin film fluids has been studied in the Hatsopoulos Microfluidics Laboratory at MIT. The phenomenon has been observed in common situations such as excess paint dripping down a wall and exhibited by other viscous fluids fingering under the effects of gravity.

The experimental work described here was done primarily to validate the theories behind particle laden flows. The significance of this research is related to natural occurrences such as avalanches and mudslides, examining the behavior and movement of fluids containing a high concentration of particles. Specifically, peculiar behaviors that occur when small particles are mixed in the fluid were of interest, focusing on such phenomena as the movement of particles within the fluid during flow down an inclined plane, the tendency for segregation of the particles to occur in a striping pattern parallel to the direction of flow, and the effects of the segregation on fluid movement down the incline.

Background

The behavior of suspensions in the environment has been studied in detail. The primary interest lies in the magnitude of the downflows for such events as mudflows, avalanches, and glaciers. In the case of a mudflow, the mud incorporates rocks, topples trees, and destroys buildings in its path.[1] The primary factors that dictate its size and behavior are the incline of the slope and the mass and viscosity of the liquid mud. Instabilities have been studied in suspension flow-patterns, and indicate that debris flows at low gradients tend to be uniform and there have been few observed and experimentally recreated instabilities. [1]

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[1] Simpson, p. 119

Avalanches

Two general types of avalanches exist in nature: flow avalanches and airborne powder snow avalanches. Most are actually a mixture of the two types. While flow avalanches have a typical velocity of 60 m/s and heights of 5 to 10 m, powder avalanches move at speeds of up to 100 m/s and can be over 100m high. Flow avalanches are of made up of particular material; they tend to slide like a fluid but break up into smaller globules. The effect of the particles on the fluid flow is exactly the phenomenon of interest in this study.

Mudslides

Alluvial fans consist of deposits of debris of all sizes and shapes that flow down mountain ranges and spread out along the plain. While qualitative descriptions have been recorded about the appearance of the debris, the mechanism which brings about the depository patterns of the debris relates directly back to the study of particle suspensions.

Another issue is whether the movement is dominated by mass transfer or energy transport; this will be considered in the discussion of the behavior. The mechanics of an incompressible fluid flow down an inclined plane is one of the most fundamental concepts in the study of fluids. It can easily be described using simple geometry and laws of mass conservation.

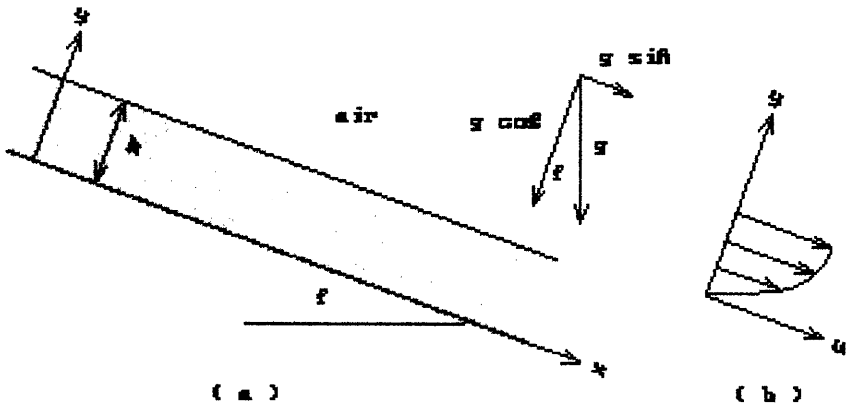

Figure 1: Geometry of a Flow Down an Incline

The release of a fixed quantity of fluid into a rectangular channel has been experimentally shown to produce a gravity current that passes through two distinct phases. After the initial collapse of the fluid after the gate is released, there is an adjustment phase during which the front advances at a constant speed. [1] The nature of the traveling disturbance differs depending on the density of the fluid suspension. The depth, h_0, of the dense fluid is equal to the depth of the rest of the fluid, H, in the channel.

The density gradient required for the development of segregation patterns is only a few percent; lower temperatures will result in a higher density difference between the elements of the mixture, depending on its nature (solid-liquid vs. liquid-liquid). Another issue is the state of the ambient environment. Because of the varying humidity, the water content of the air surrounding the experimental run should be noted.

The main force at work is gravity, which will translates into a horizontal motion on an inclined plane. For this reason, a larger angle should speed up the development of stripes.

The study of granular materials has remained almost completely unresearched for the better part of the last century. Only in the last twenty years, in the wake of Savage's [2] work did it become the subject of serious inquiry. [3]

Fluids have been shown to exhibit instabilities on both inclined planes [4] and in rotating cylinders [5]. The relevant parameters include fluid density, grain size, inclination angle in the former experiment, and rotational speed in the latter. The results of these studies focus primarily on instabilities due to fluid properties such as surface tension, contact lines, and viscous stress. Surface roughness, surface topography, have also been areas of experimentation in the research of fluid instabilities.

The experiment conducted for the purposes of this paper was an attempt to repeat the results obtained by Forterre and Poliquen [6] but in a vastly different parameter range. In the experiment that they conducted, an instability was observed in the flow of dry granular material down an inclined plane. Longitudinal stripes appeared on the surface of the sand in the direction of flow, as seen in figure 2 below.

Carpen and Brady [4] characterize the setting which drives an instability in suspension flow, and derive the governing equations in great detail. However, the derivation ignores inertial effects which is only an acceptable assumption for low Reynolds numbers(laminar flow). Additionally, the suspension is considered an incompressible fluid, which, for the purposes of the research, is appropriate. However, further research may dictate the need for consideration of additional experimental parameters.

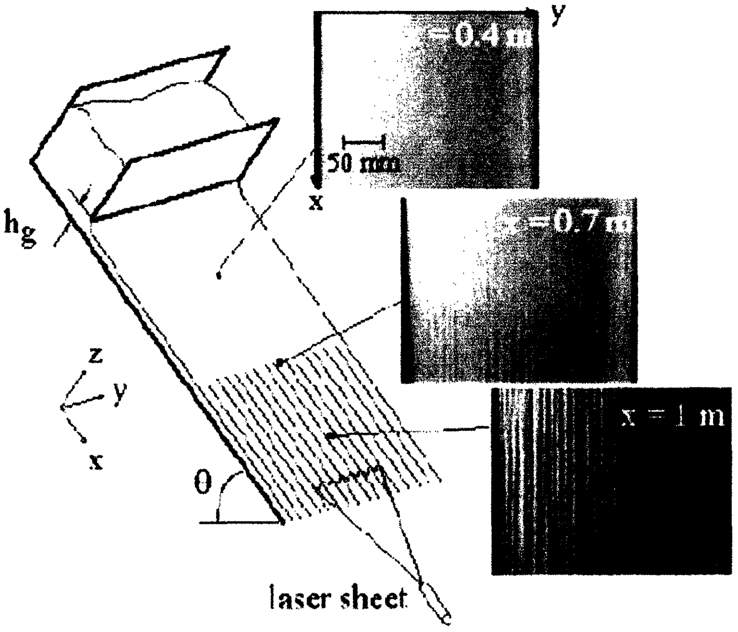

Figure 2: Experimental Setup from Poliquen and Forterre [6] ***Longitudinal vortices in granular flows***

Additional support for the development of instabilities in granular flows comes from Leighton and Acrivos [5]. In their research, they characterize the process of particle resuspension in viscous fluids. The aggravation of an initially settle bed of particles occurs in the presence of a shear force. The magnitude of the shear stress in laminar flows is much more prevalent in dictating the behavior of the fluid, and thus leads us to investigate the viscosity once again as an instigator of instabilities in granular flows.

Experimental Procedure

Experimental Design

Length and inclination angle were the two major factors that dictated the design of the experimental apparatus. While the angle was required to be adjustable, the length to width ratio had to be as large as possible. Initially, the incline was a sheet of 0.5" thick acrylic, 72" long and 12" wide. Using acrylic adhesive, two edges of the same material were mounted to create a 2" high sidewall on each side. However, after the experiment was conducted, it was discovered that the incline was too wide and very large volumes of fluid were required. After careful consideration, the acrylic sheet was cut in half using a bandsaw to a width of 6 inches.

Experimental Apparatus

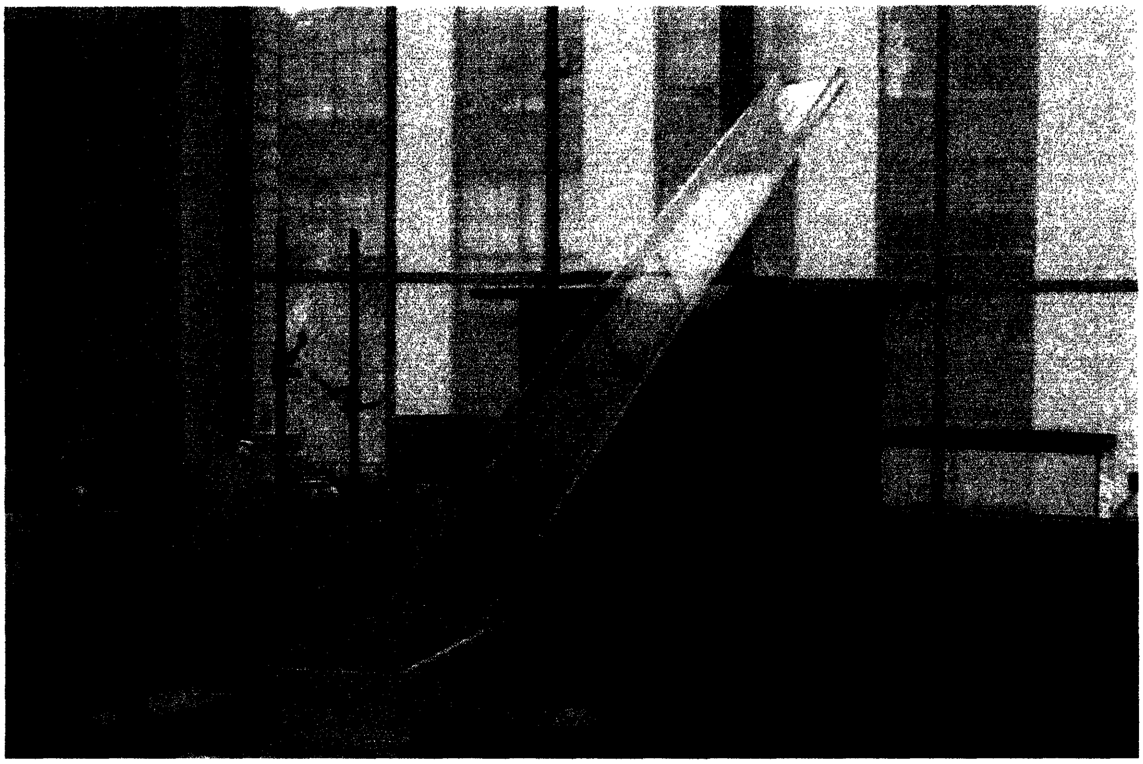

Figure 3: Photograph of Experimental Apparatus

Equipment

One 0.5"x6"x9" sheet of acrylic and two 0.5"x2"x96" pieces of acrylic were used to construct the incline. A Watson roller culture machine was used to mix the suspensions which were contained in 1L-capacity open neck Pyrex glass bottles. Glycerol was used as the experimental fluid, with suspended silica beads approximately 250-400 microns in diameter. Fluorescent desk lamps were used to illuminate the experimental setup while photos were taken using a Canon EOS 10D 6.3 megapixel camera.

Method

Construction of the Experimental Apparatus

The acrylic was bonded into a rectangular channel five inches wide using an acrylic adhesive on the joints and clamped overnight. The top end of the incline was propped up on a wooden stand approximately 1.5 ft high, and the bottom was placed in a low density polyethylene container to catch the liquid downflow after the experimental path.

Suspension Preparation

One liter samples were prepared with varying concentrations of silica beads in glycerol by filling first with 0.200L of glycerol, and adding the appropriate amount of silica beads by volume. The bottle was then filled with glycerol until the total volume was 1 liter.

Suspension Flow

Suspension fluids of varying concentrations were poured out of the 1 L bottle down the inclined plane forming a film layer approximately 1cm in depth.

Photographic Documentation of Results

The results of each trial were recorded by using a macroscopic lens on the Canon Digital camera. Four pictures of each experimental run were taken, and downloaded to be assessed and printed for the documentation of results.

Results

Images of the experimental results for each trial can be found in *Appendix A: Images of Experimental Results.*

Table 1: Appearance of instability for parameter sets

Incline (Degrees)	*10% by volume*	*20% by volume*	*30% by volume*	*40% by volume*
40	No	Yes	Yes	No
30	No	Yes	Yes	No
20	No	One	Yes	No

At lower concentrations, the fluid must be less viscous in order for the instability to develop and the striping pattern to appear. Lower viscosities allow for the fluid to flow slower, and a thicker film layer to develop. So a direct correlation can be seen in the density of the suspension, the viscosity, and the development of the stripes.

10% by volume

At a 10% by volume concentration, the stripes are not evident unless the fluid is accelerated and a thicker film develops. Higher mass flow contributes to the development of the stripes. The fluid was accelerated by applying a shear force on the fluid and forcing it to flow faster.

20% by volume

At a lower angle, very slight stripes develop. They are more pronounced at a higher incline, and are visible at 30 and 40 degrees.

30% by volume

At lower angles, the stripes develop, but at a 40 degree incline, the fluid is too viscous and the fluid starts to develop other instabilities that prevent the development of the stripes. Rather than rolling over itself, the fluid begins to move as a continuous body, and does not exhibit the behavior that the other experimental values show. It is characteristically different.

40% by volume

At this concentration, the stripes no longer develop. The high concentration disallows a large enough density gradient to develop. However, if the flow path were long enough, experimental results may differ from the obtained results.

Discussion

Preliminary Findings

The experimental design involved a bit of trial and error. Initially, the silica beads were suspended in silicon oil, which is hydrophobic. The silicon oil suspension was prepared with 10%, 20%, 25%, and 40% silica beads by volume, and tested at inclines of 45 and 30 degrees. However, the expected results were not attainable, and the working fluid was hard to manage. Another issue was that the high density of silicon oil reduced the density gradient, which, coupled with the thin-film requirement, created a non-conducive environment for the instability to occur.

The suspension fluid was then switched to glycerol, which, prepared at the same concentrations from above, produced the predicted striping behavior. The striping occurred on a 30 degree incline. However, one of the issues was the hydrophilic nature of glycerol. It is considerably less viscous than silicon oil, but after additional exposure to the ambient air, it becomes increasingly less viscous due to the aggregation and mixing with water vapor from the air.

The striping occurs on the bottom quarter of the incline, approximately 65-70 inches from the top. From observation, the striping seems to occur when the fluid depth is slightly greater than what can be considered a thin-film fluid; also observed is the occurrence of suspension particulate aggregation after a second wave of suspension fluid flows over an initial fluid layer. It seems that the shearing force between the two fluid layers creates a sort of rolling of the top fluid front, which aids the striping aggregation pattern of the silica beads. The silica beads quickly settle, and the liquid layer flows ahead of the sediment. Additional flow pushes the sediment down the incline, but the flow dynamics do not lend themselves to an environment that fosters the expected instability. However, if the fluid is accelerated using a squeegee, the fluid layer is thicker, and results in the clear striping behavior as well.

One of the greatest challenges was documenting this behavior. Initially, a fluorescent lamp was used to illuminate the experiment in the dark, but the images captured with the digital camera are blurry at best. Dying the silica beads (which are originally clear with a very slight greenish tint) was also considered, but the beads tend to stick together because of the paint. This problem was addressed by using sieves to filter out the clumps, but they just aggregated again when mixed with the glycerol. However, the biggest problem was the appearance of oil "slicks" in the glycerol during experimental runs. Clearly, the mixing of the paint affects the properties (viscosity, density) of the glycerol.

The salient conclusion of the Poliquen [6] study indicates the roughness of the plane as a major player in the development of instabilities. The dynamics behind the development of instabilities are fairly intuitive. However, in smooth surface flows, the results are most likely dominated by the effects of the viscosity and the effects of particle movement within the fluid.

The development of the stripes in only the middle range of experimental parameters seems to indicate an incompleteness in the experimental design. Strong conclusions cannot be drawn based solely on the results of this experiment. Rather, further research must be done, using alternative fluids, particle sizes, and flow parameters (width, distance, and film thickness) to further examine the development of instabilities in suspension fluids.

Appendix A: Images of Experimental Results

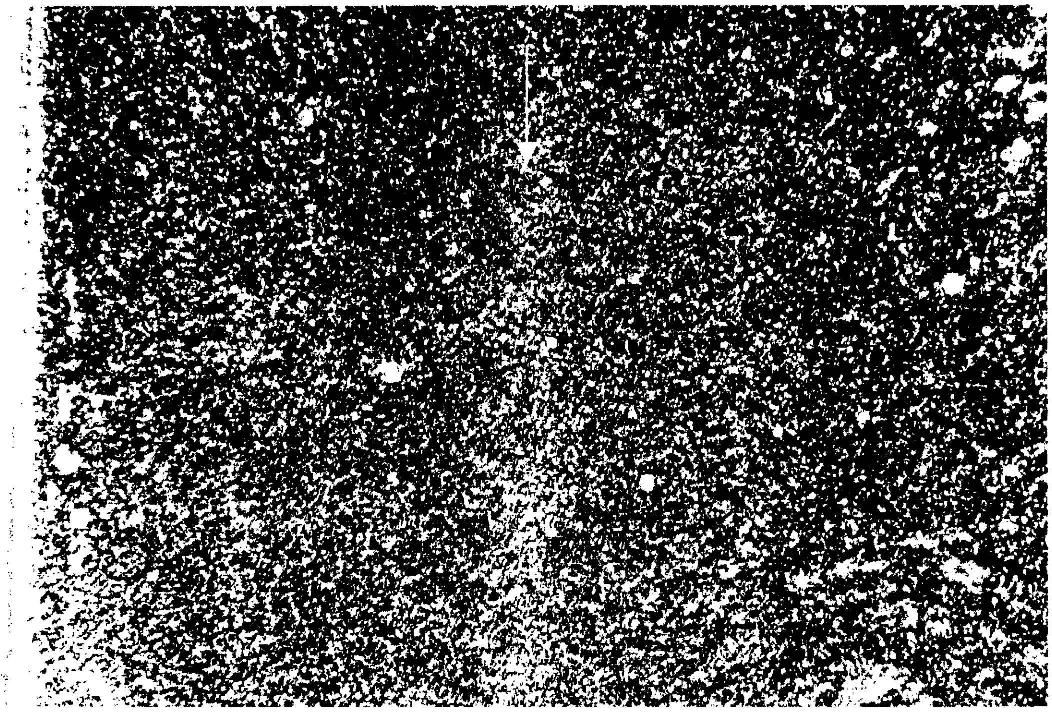

Image 1: 20% by vol, 20 degrees

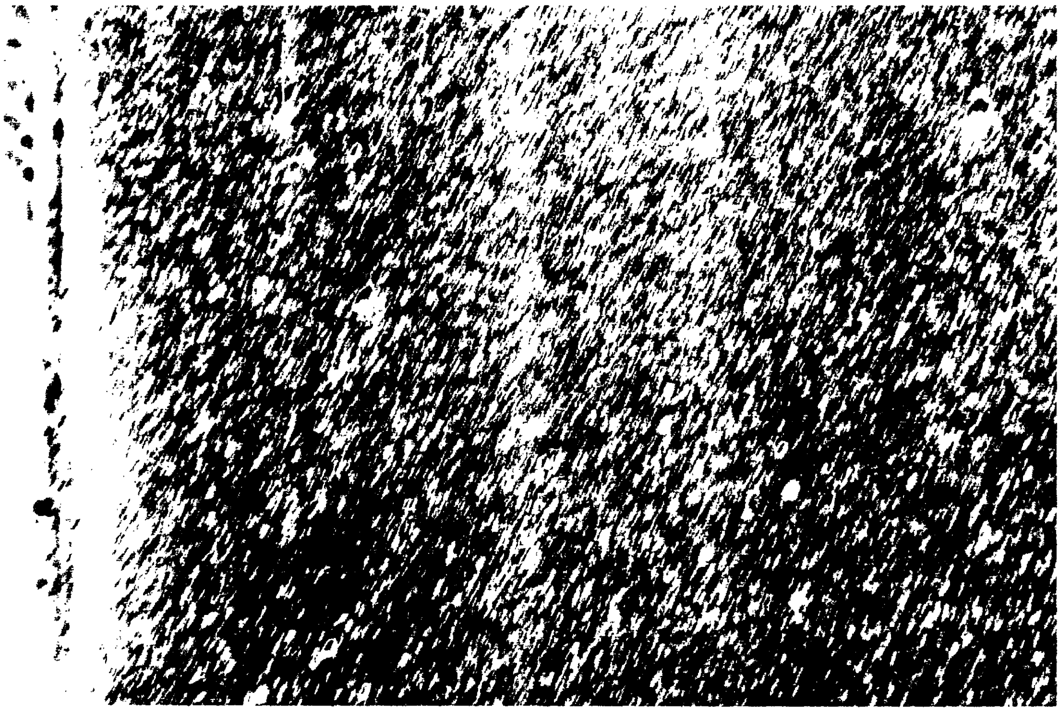

Image 2: 20% by volume, 30 degree incline

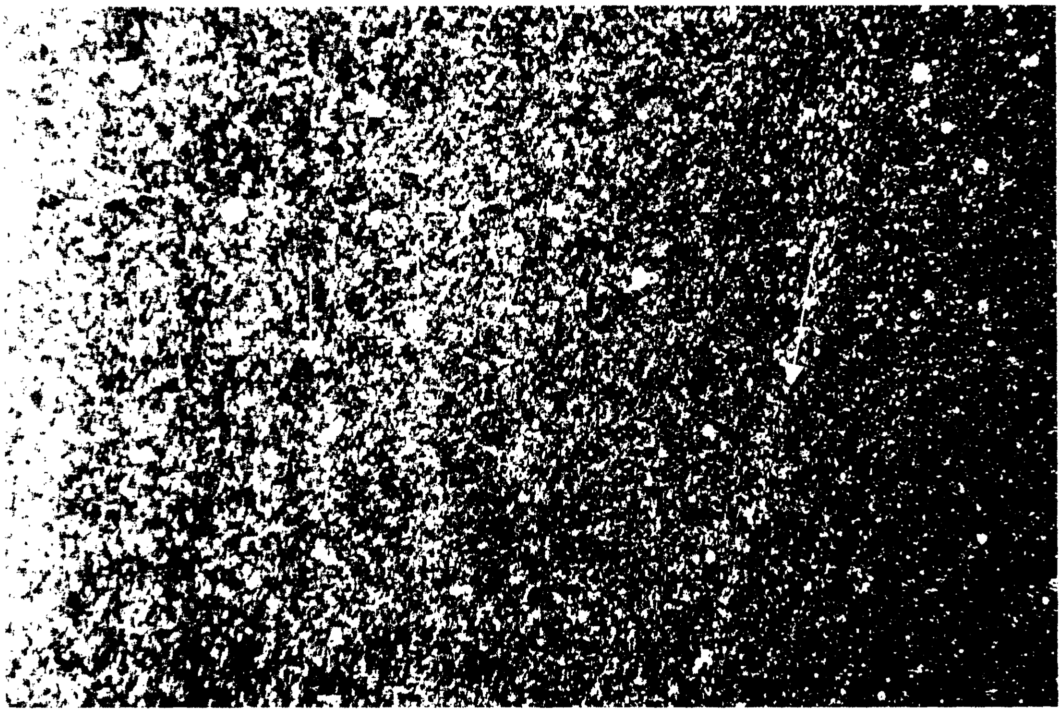

Image 3: 20% by volume, 40 degree incline

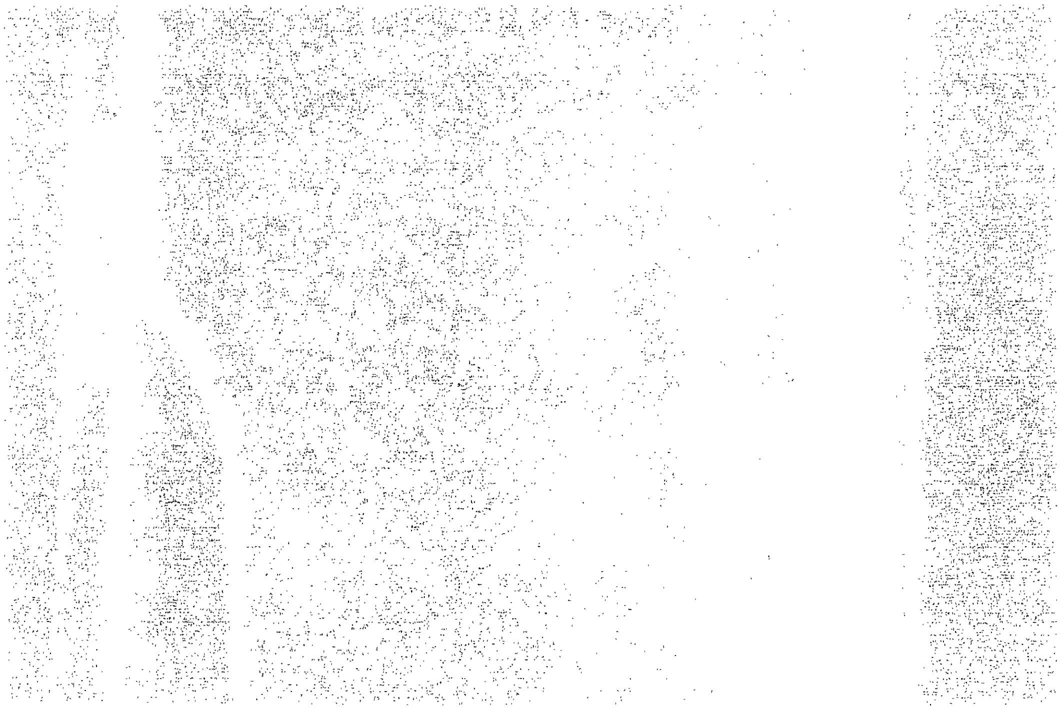

Image 4: 30% by volume, 20 degree incline

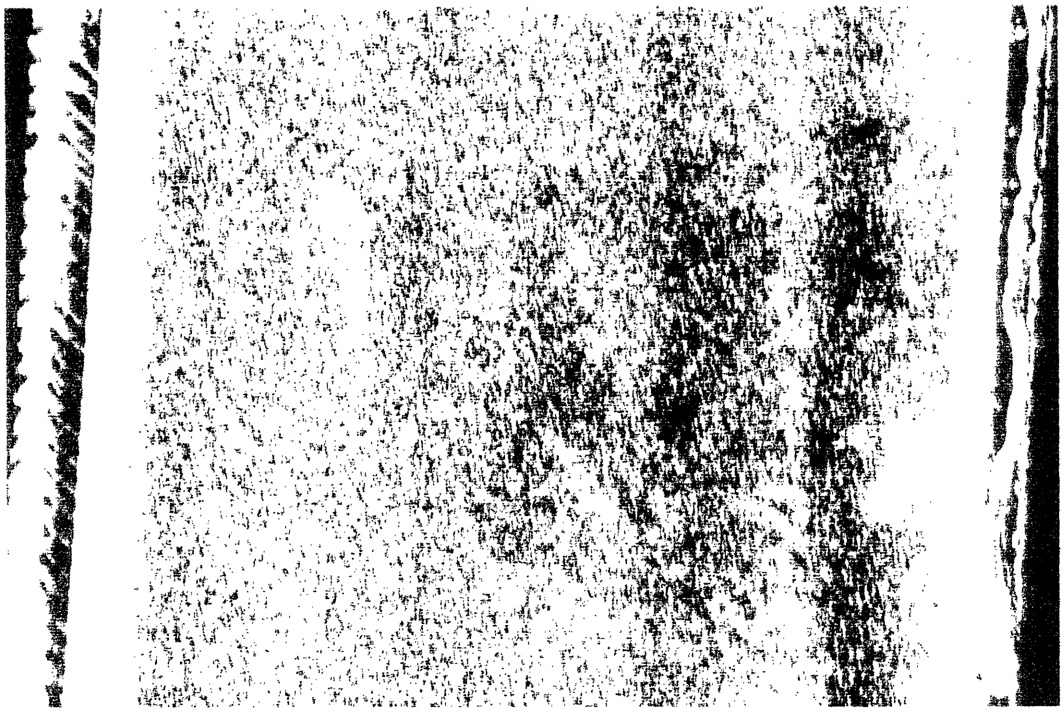

Image 5: 30% by volume, 30 degree incline

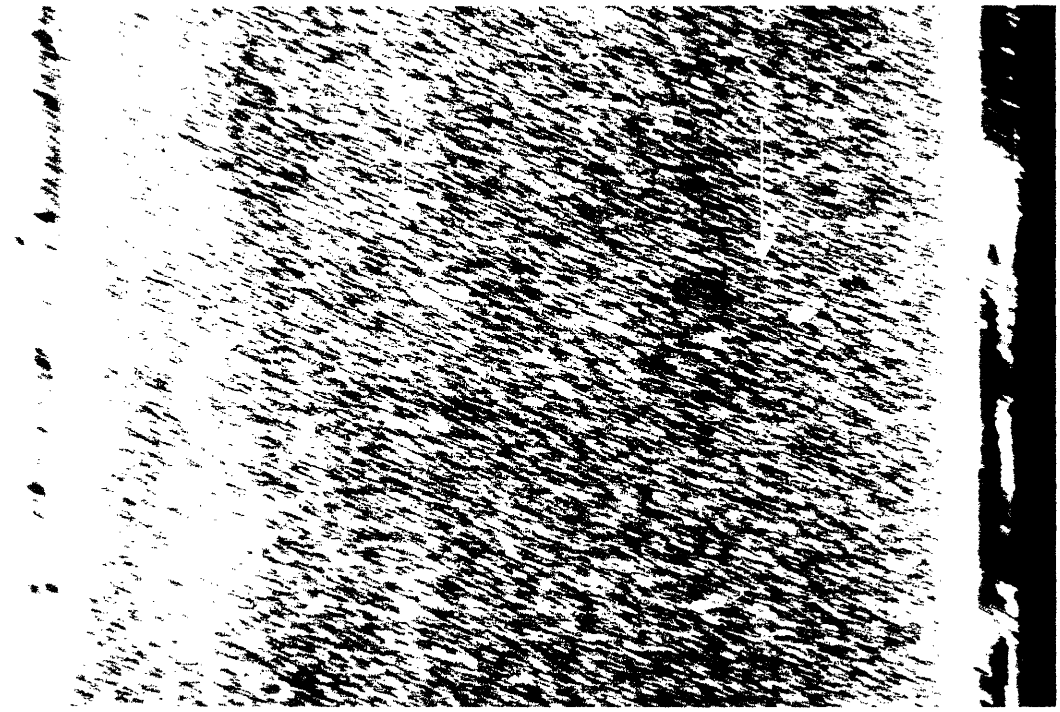

Image 6: 30% by volume, 40 degree incline

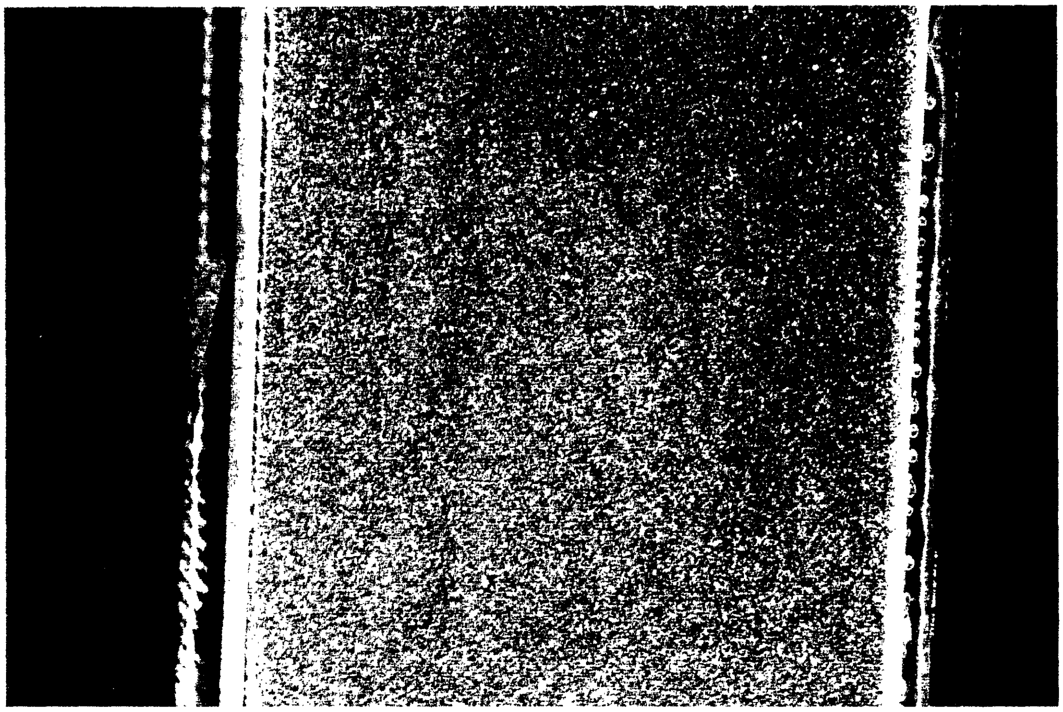

Image 7: 40% by volume, 20 degree incline

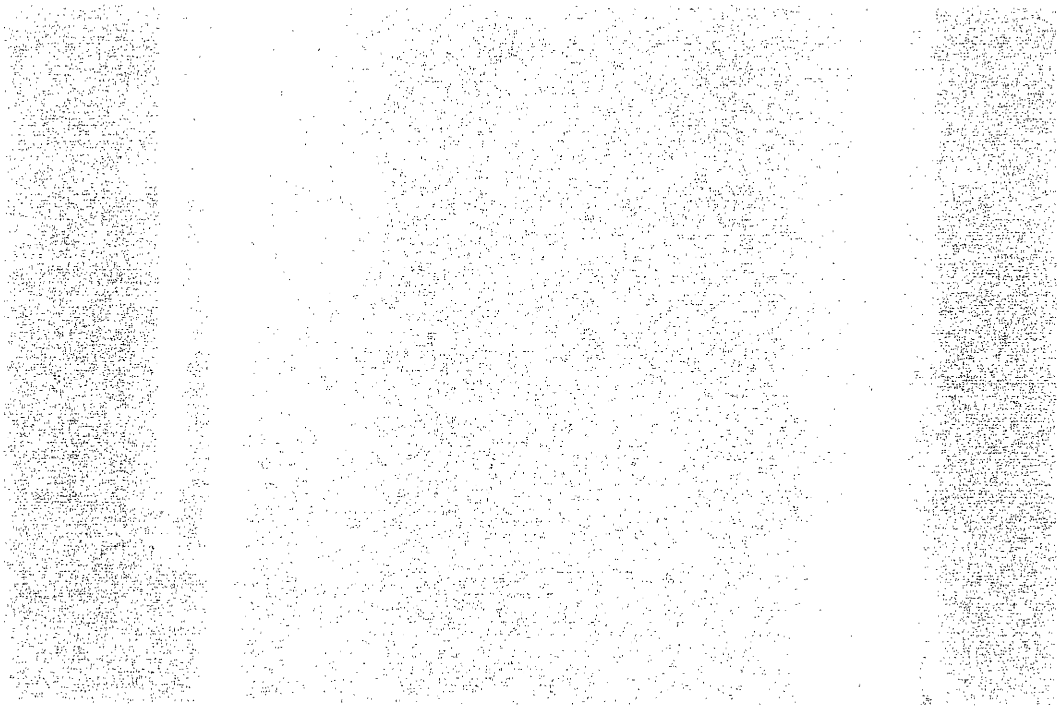

Image 8: 40% by vol 20 degrees

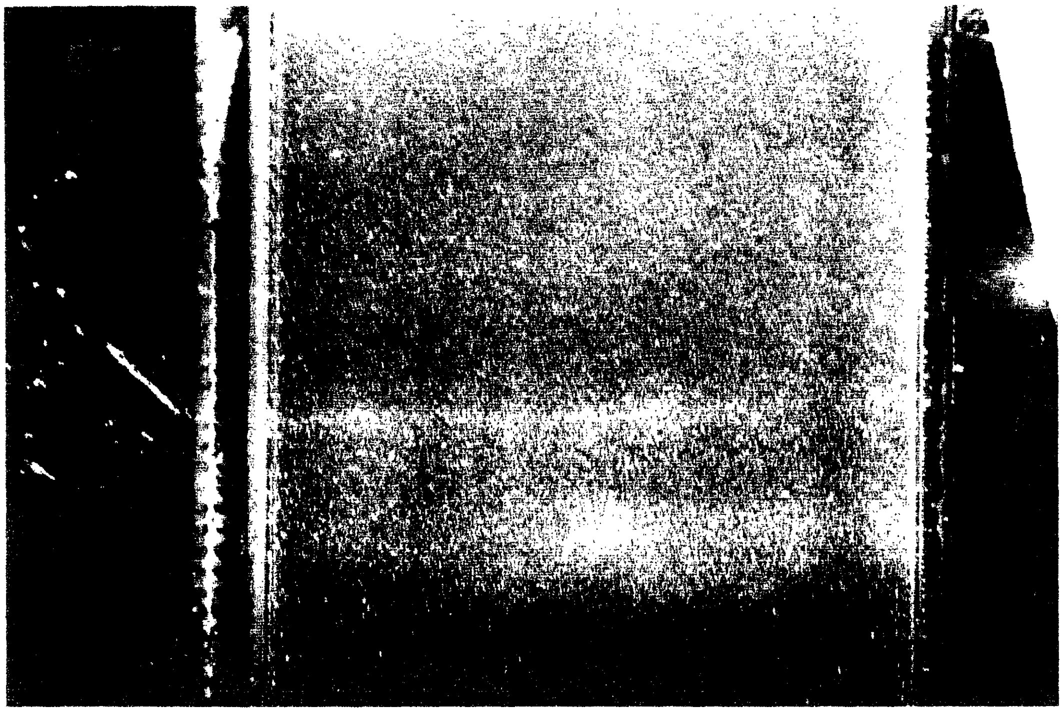

Image 9: 40% by volume, 30 degree incline

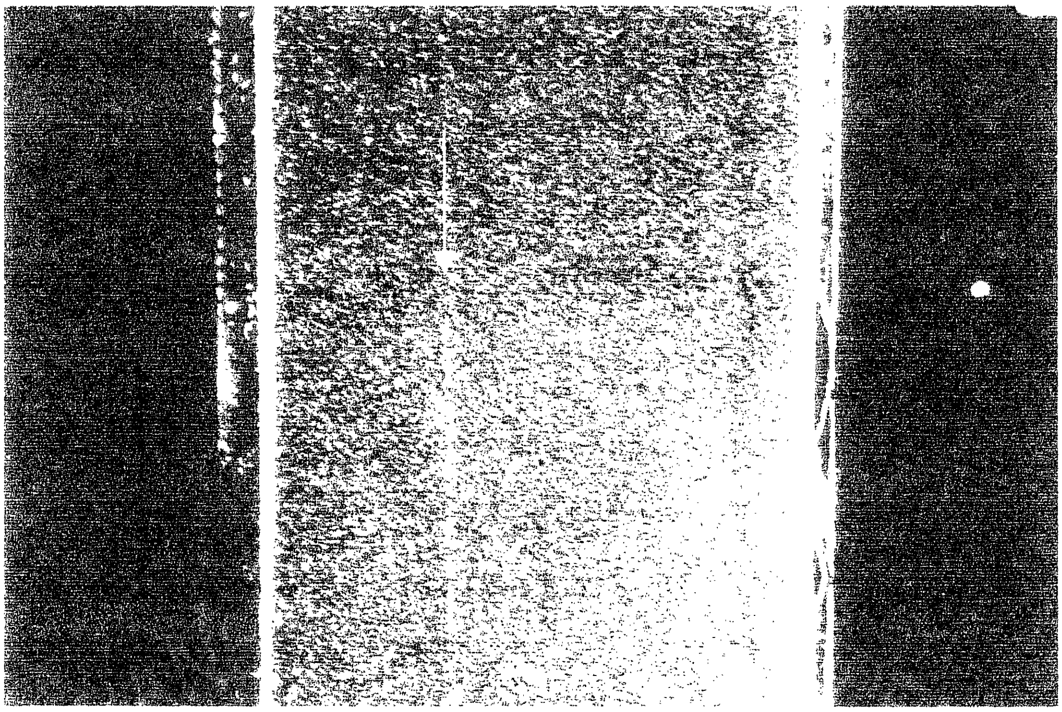

Image 10: 10% by volume after shearing

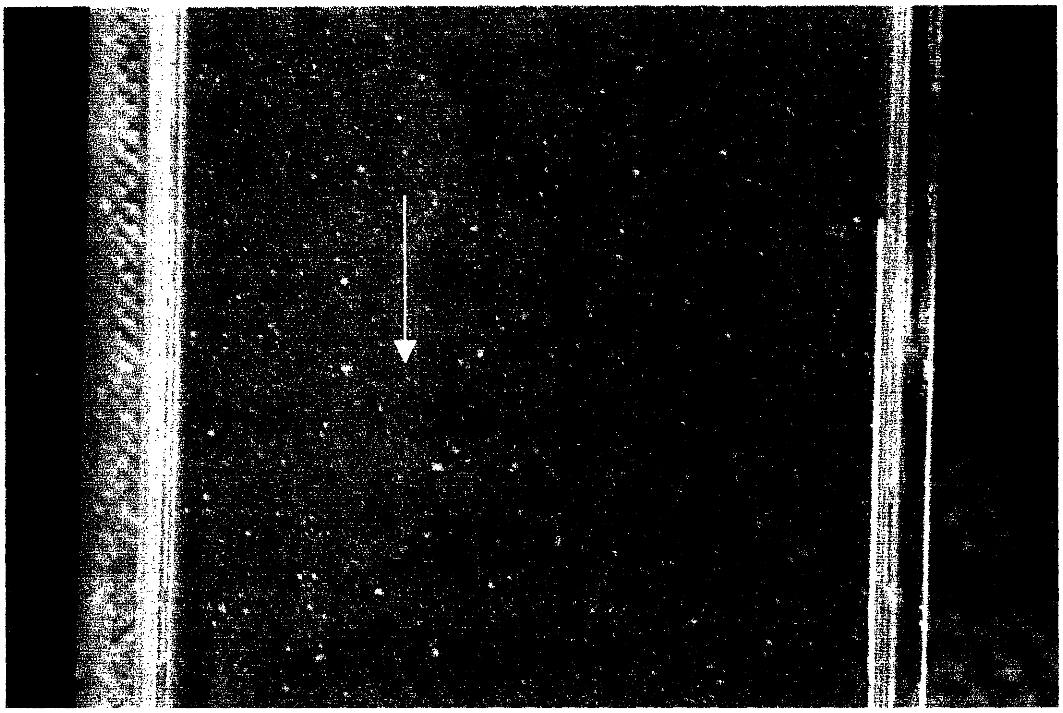

Image 11: 10% by volume, 30 degree incline after shearing

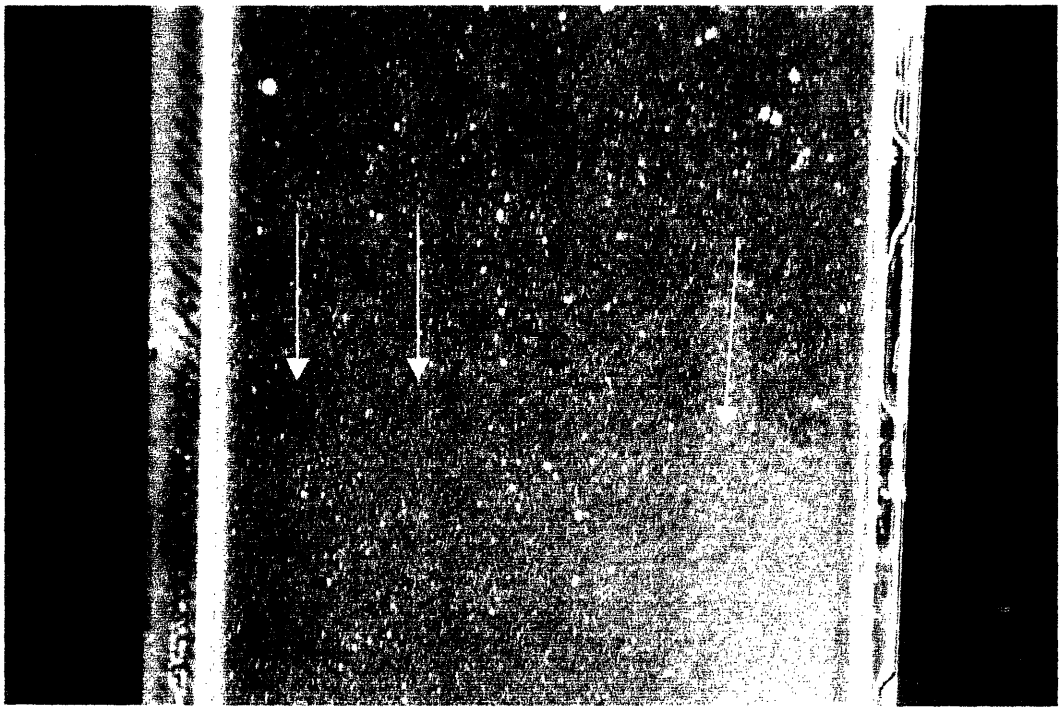

Image 12: 10% by volume, 40 degree incline after shearing

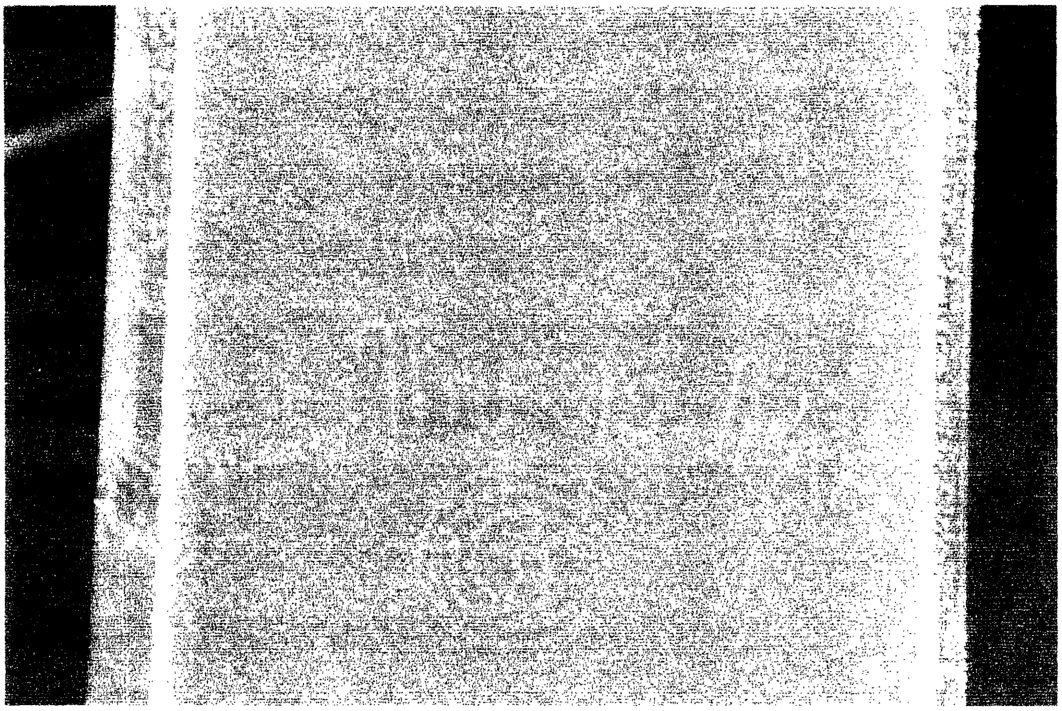

Image 13: Unedited Image of 30% by vol, 30 degrees

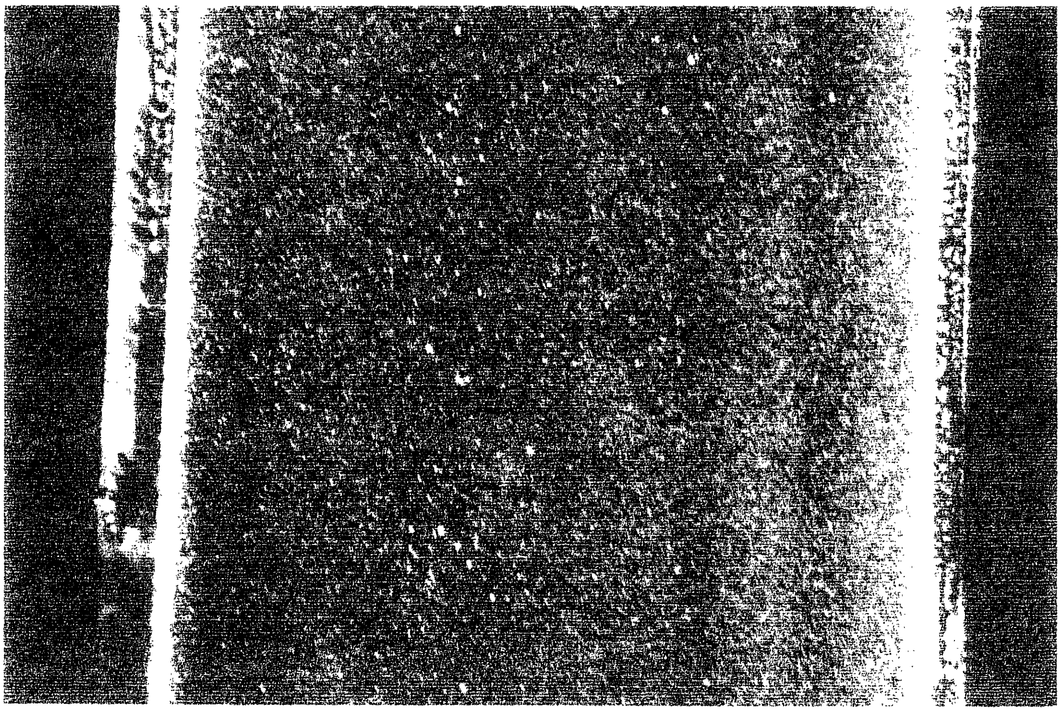

Image 14: Edited version to enhance striping

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[1] Simpson, J.E. *Gravity Currents in the Environment and the Laboratory.* London: Cambridge University Press, 1999.

[2] Savage, S.B. "The Mechanics of Rapid Granular Flows" *Advanced Applied Mechanics,* 24:289-366, 1984.

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