DESIGN OF A LARGE VERTICAL PROP TRANSPORT MODEL

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ABSTRACT

A 4-ft by 12-ft transparent, vertical fracture model is used to study the prop-carrying abilities of both non-Newtonian and Newtonian fluids. The design parameters and difficulties encountered in building and operating the model are discussed. Solutions to problems such as uniform distribution of prop in the sample area, uniform flow across the sample area, and reduction of end effects are described. A novel technique is used to record and reduce the prop trajectories. Observations of suspended prop flow in vertical fractures are presented.

INTRODUCTION

Prediction of proppant distribution in a hydraulically created fracture has been the subject of many papers. Various approaches have been used in deriving empirical predictive equations. Among these approaches are "infinite" walled vessels to study falling rates of various propping agents, and scaled-down fracture prototypes to study equilibrium proppant bank buildup.

Proppant distribution in the fracture is very important; with improper distributions the production of the well can be greatly reduced or even completely shut off in some cases. Empirical methods have been developed to compute proppant distribution, [1,2,3,4,5] for prop packs formed under equilibrium conditions. However, prop distribution under non-equilibrium (suspended) conditions is not well understood. With the increased use of high-viscosity fluids, the non-equilibrium situation is more common. Methods for describing the actual settling velocities of particles under these conditions need to be developed. It is not our purpose to present a comprehensive review of the literature on prop bank buildup in vertical fractures. However, a short discussion of the methods that can be used to calculate vertical-settling velocities of particles falling in a liquid is necessary to provide the background for our study.

Most studies that have been conducted on particle transport by fluids have been carried out in pipes or cylindrical vessels. In most cases the diameter of the vessel is large relative to the diameter of the particles. This experimental technique minimizes wall effects but does not correspond to the boundary conditions that exist in a vertical fracture.

The falling velocity of a single spherical particle in an infinite walled vessel filled with a quiescent Newtonian fluid can be adequately described by a Stoke's law calculation. This calculation is also good for Newtonian fluids in laminar flow.

$$U_o = \frac{g(\rho_p - \rho_f)\, d^2}{18\mu}$$

The falling velocity is primarily dependent on the density of the fluid (ρ_f), the density of the particle (ρ_p), the diameter of the particle (d), and the viscosity of the fluid (μ). A problem arises in attempts to extend this calculation to non-Newtonian fluids. Govier and Aziz[6] suggest in their book on the flow of complex fluid in pipes that a Stoke's law calculation using an apparent viscosity (μ_{app}) in place of the Newtonian viscosity (μ) term is adequate.

Daneshy[7] has used a method that treats a spherical particle falling through a power law fluid by calculating the shear effects of the particle falling through the fluid while ignoring the shear of the fluid by the walls. This method should be adequate as long as the particle is traveling in the center of the vessel or parallel plates; but as the concentration of particles increases, more of the particles will be forced toward the walls, and the calculated settling velocities will be too low.

Another complication arises from particle-particle interaction and hydrodynamic interference within flowing slurries. These effects can result in an increase or a decrease in the particle settling rate depending on the nature of the particle-particle interaction. The effect of hindered settling, resulting in a decrease in falling rate, is well recognized and has been applied to prop transport in vertical fractures. The fact that particles can agglomerate (cluster) resulting in an increase in settling velocities has been ignored.

The particle interactions, wall effects, and non-Newtonian fluid effects also modify the horizontal transport efficiency. The horizontal transport efficiency is defined as the ratio of the prop velocity to the bulk fluid velocity.

DESCRIPTION OF MODEL

The vertical fracture model was designed to study prop transport as a function of fluid properties, prop size, prop concentration, fracture width, and pump rate (fluid velocity). The model dimensions are 4 ft high by 12 ft long. The size of the model (Figure No. 1) was dictated by the need to minimize edge and end effects. Because the effect of fracture width is considered important, the design included a means to vary the fracture width. Spacers can be inserted along the top and the bottom of the model, permitting the widths to be varied from 1/8 in. to 3/4 in.

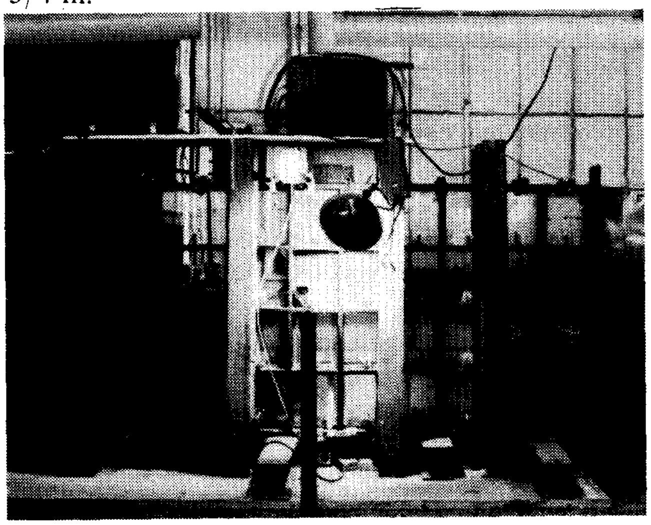

FIGURE 1—MODEL

The fluid handling system consists of two 500-gal paddle mixers and a variable speed pump capable of providing a flow rate of 4 ft per second within the 3/4-in. fracture width. An in-line magnetic flow meter monitors the volumetric flow rate.

A special inlet (Figure No. 2) was designed to ease the transition from pipe-flow geometry to slot-flow geometry. The inlet is designed so that the cross-sectional area at any point along its horizontal axis is equal to the cross-sectional area of the simulated fracture. This effectively minimizes acceleration of the fluid as it enters the model. Vanes were added to the inlet in an attempt to maintain a uniform distribution of particles from the top to the bottom of the model. Uniform mixing of the fluid and prop is assured by a series of static mixers on the discharge side of the centrifugal pump. Special care was needed in the design of the exit end of the model (Figure No. 3). Manifolded exit pipes were necessary to minimize the disturbance of the laminar flow pattern in the fracture. In addition, a stand pipe and a back pressure regulator were installed at the exit in order to maintain a head pressure over the entire model.

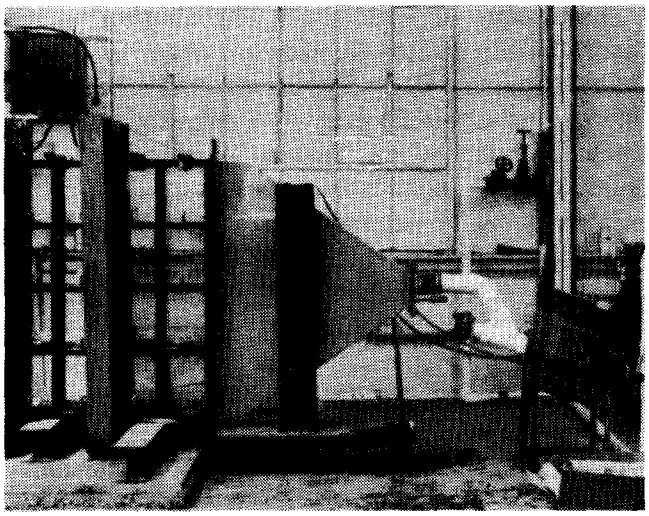

FIGURE 2—MODEL, INLET

Fracture width control was accomplished by erecting a rigid frame of 1-in. by 3-in. box iron on either side of the model. This resulted in a matrix of windows, one of which was selected as the viewing window. Final adjustments were accomplished with a pressure plate in each window, as shown in Figure No. 4. In order to minimize elastic deformation caused by internal pressures, the rigid box iron

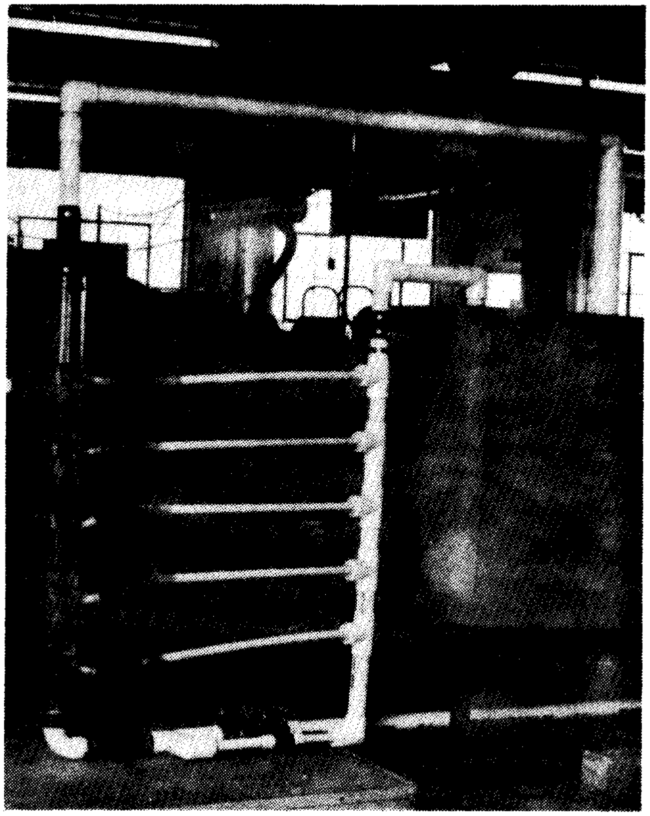

FIGURE 3—MODEL, EXIT END

frame is in turn supported by 10-in. I-beams. The beams were positioned to give maximum strength and optimum viewing area. Slot width around the viewing window was further controlled by adding hydrodynamically designed spacers above and below the viewing window. Tests established that these spacers did not create any flow disturbances in the viewing window. A light-reflecting technique (shown in Figure No. 5) was used to establish the actual slot width of each window. The fracture width variation at the viewing window is less than ± 0.005 in. In surrounding windows the limit is ± 0.01 in.

OPERATION OF MODEL

The design criteria required a large model. With size comes a certain amount of unwieldiness. Surprisingly, leaks were only a minor problem. The length and height of the model completely obscured edge and end effects once the exit was properly designed as described previously. The standpipe regulator design of the exit was required in order to eliminate the "breathing" effect that occurred with

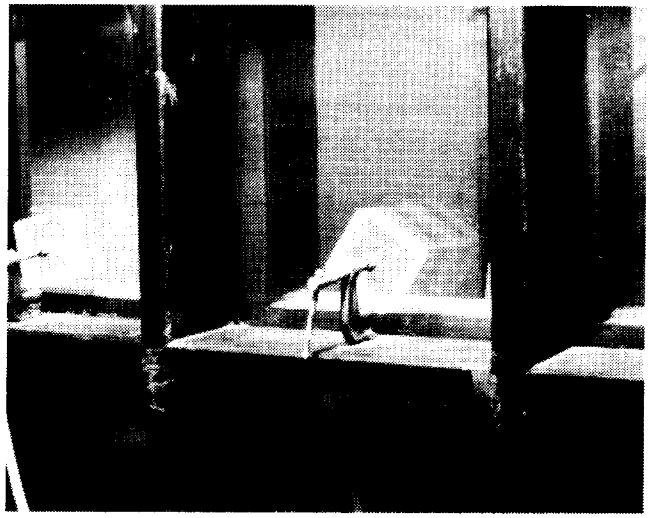

FIGURE 4—MODEL, WINDOW PRESSURE PLATE

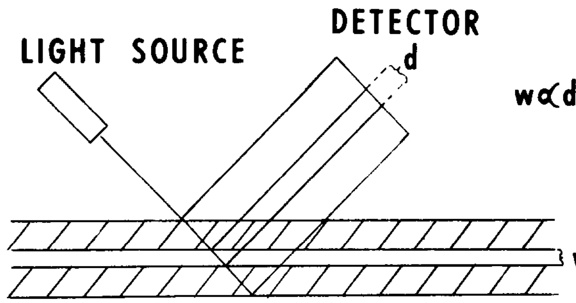

FIGURE 5—LIGHT-REFLECTING TECHNIQUE FOR MEASURING FRACTURE WIDTH

changes in pump rate. This breathing occurred because of the tendency of the plastic sheets to sag inward under their own weight. Maintenance of a head pressure eliminates the problem.

DATA COLLECTION

The sand movement is recorded with a 16-mm movie camera running at 64 frames per second. A 35-mm camera is used to record the flow meter reading, pressure, time, and settled pack height. The time is generated with a digital clock capable of timing in microseconds. The clock has two LED outputs so that the time can be recorded with each camera and the photographs correlated.

Tracking a single particle across the viewing window proved to be difficult because of particle interference, time lapse between frames, and dynamic changes in particle configuration. To improve our ability to follow a particle accurately, a grid (Figure No. 6) was carefully inscribed on the inner face of the viewing window. The grid allowed us to measure the particles relative to a fixed frame of reference. In addition, the grid minimizes the effect of inherent errors in the framing of the film.

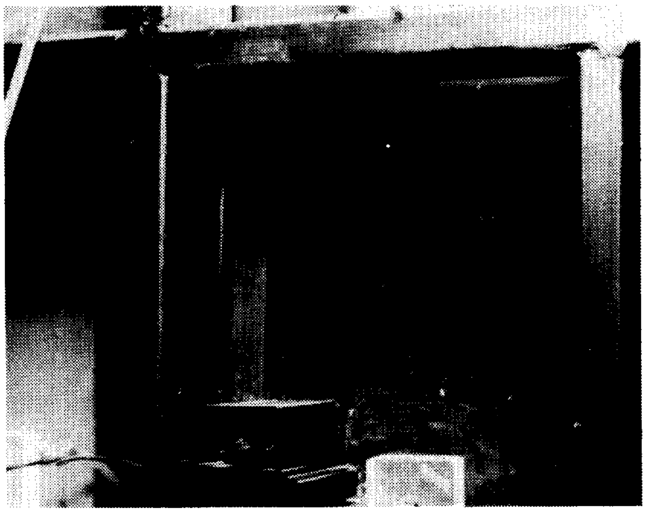

FIGURE 6—MODEL, VIEWING WINDOW

The particle movement is transformed from pictorial to numeric form by means of a Tektronix graphics tablet. The technique consists of projecting a single frame onto the Tektronics tablet, selecting a single particle, and placing a crosshaired cursor over the particle. When the switch on the cursor is depressed, the x-y coordinates of the grain image are sent to a computer where they are stored. The film is advanced one frame and the new position of the particle is transmitted. This process is repeated until the particle has traversed the width of the viewing window. At this time the film is reversed to the original frame, a new particle is selected, and the tracking process repeated.

Problems with this technique are twofold; namely, the alignment of the projector with the tablet screen, and the changes in framing from one frame to the next. The projector-screen alignment is checked before each run by recording the projected coordinates of the inscribed grid intersections and then tilting and rotating the projector until the horizontal lines of the grid have the same y-coordinate across their entire length and the vertical lines have the same x-coordinate along their length. The framing problem is handled by recording the location of a selected grid intersection for the initial frame. Its location for each succeeding frame is recorded and compared to the original location. Any deviations which occur are used to correct the x-y coordinate of the sand particle for that frame.

Scaling of the data from tablet units into feet is accomplished by using the ratio of the known inscribed grid window dimensions to the differences in the x-y coordinates of grid intersections. The time interval between frames is obtained from the LED displays recorded on the film. Hence the conversion is independent of changes in camera speed, etc.

The distance between grid intersections of the tablet is called a raster unit, which is 0.01 in. Tests of data reproducibility have a standard deviation of 1.4 raster units. Thus, 95% of the data should lie within ±2.8 raster units, or ±0.030 in., of the true location on the screen. This error represents ±0.015 in. in the actual physical model.

Data processing from this point on is all done in the computer, which prints out individual velocities for each particle from one frame to the next as well as a summary for all the sand grains within one time span.

RESULTS

The model was designed to study prop transport as a function of fluid properties, prop size, prop concentration, fracture width,and fluid velocity. Of these variables, fluid properties, prop concentrations, and pump rate have been most extensively studied. Prop concentrations are limited to approximately 2 lb/gal by our inability to find and track individual particles at higher concentrations. The standard prop concentrations are 0.5, 1.0, and 2.0 lb/gal for the tests. The prop sizes have been 20-40 mesh Ottawa sand and 30 mesh Texas Mining sand. At this time the data for the 30 mesh have not been completely analyzed. The fluids tested thus far are uncrosslinked hydroxypropyl guar gels of 20, 30, and 40 lb/1,000 gal for a non-Newtonian fluid. Glycerol was used as the Newtonian fluid. The viscosity range for the glycerol was 30 to 100 cps.

Data collection and analysis are still in progress. Therefore, we will limit this discussion of prop transport to qualitative observations. Initial indications are that the horizontal prop velocity lags behind the bulk fluid velocity. The horizontal transport efficiency appears to be between 70% and 90%. Further testing is needed to establish the significance of this data.

The vertical settling velocity was another quantity that was measured. A particle crossing the viewing window will follow a trajectory similar to that depicted in Figure No. 7. For a given set of conditions a number of particle trajectories must be measured and the vertical and horizontal components of the velocities averaged. At low concentrations of proppant this proved to be a straightforward task. At higher prop concentrations it was necesary to use small amounts of colored sand in order to follow a single particle with any degree of certainty. A tendency for particles to travel in clusters at prop concentrations greater than 1/2 lb/gal has been observed in both Newtonian and non-Newtonian fluids. It is difficult to determine the average size of these clusters or quantitatively characterize them. The appearance of clusters in the flowing fluids may be exaggerated by our experimental techniques. Further testing is needed before we can say that clustering commonly exists under normal frac treatment conditions. Particles traveling in clusters fall up to three times as fast as single particles. The implication is that hindered settling is not important under the test conditions that we have used.

The solid curve in Figure No. 8 represents a hindered settling correlation for suspended particles[6] The simplest form of particle-particle interaction is the two-particle (doublet) case represented by the dashed line in Figure No. 8. This shows that particle-particle interaction can increase the verticle settling velocity above that for a single particle. Multiple particle clusters greatly exaggerate the settling velocities over this doublet case.

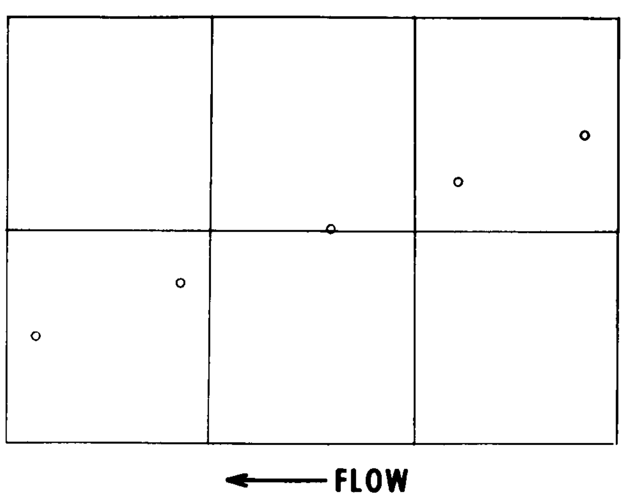

FIGURE 7--TRAJECTORY OF PARTICLE CROSSING VIEWING WINDOW

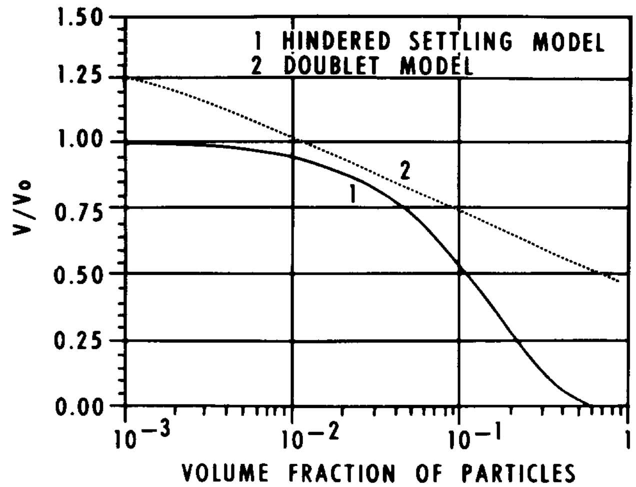

FIGURE 8 HINDERED SETTLING CORRELATION FOR SUSPENDED PARTICLES

The vertical settling of the propping agent immediately after shutdown but before fracture closure is important in the final distribution of prop within the fracture. The clustering effect can increase the prop settling velocities greatly. This is shown in Figure Nos. 9A, B, C, and D with a 40 lb/1,000 gal hydroxypropyl guar solution containing 1 lb/gal of sand. The elapsed time is 20 seconds. The clusters formed during the flow begin to settle and coalesce with other particles. As the clusters grow they fall even faster. The net result is that the real settling velocity is many times faster than that calculated for a single particle.

Future testing will determine the range of conditions under which cluster formation occurs. Also, quantitative correlations on horizontal prop transport efficiency as well as prop settling velocity will be determined for a wide range of fracture treatment conditions.

CONCLUSIONS

The following conclusions are based on the initial test runs with both Newtonian and non-Newtonian fluid systems.

1. This flow model will allow us to study suspended prop transport behavior over a wide range of conditions.

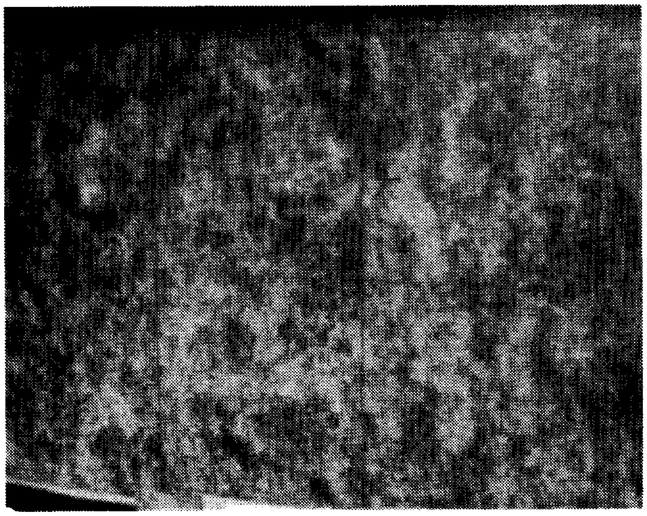

FIGURE 9A—CLUSTERING EFFECT INCREASES SETTLING VELOCITIES

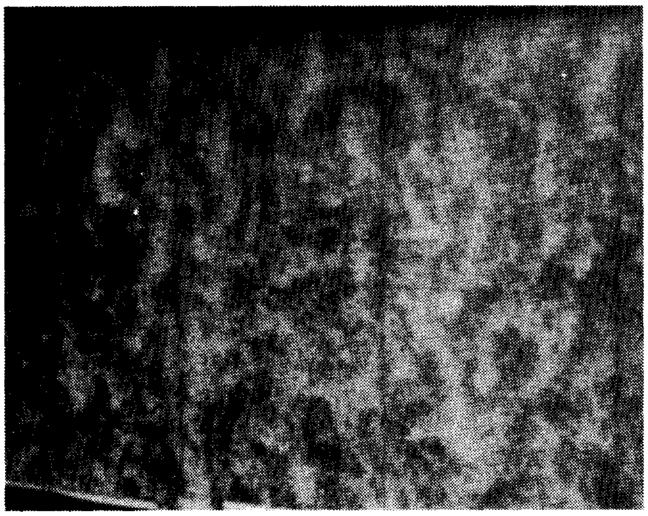

FIGURE 9B—CLUSTERING EFFECT INCREASES SETTLING VELOCITIES

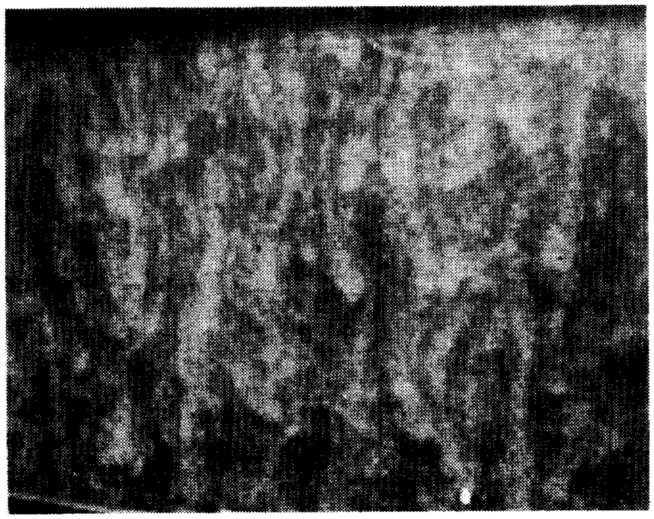

FIGURE 9C—CLUSTERING EFFECT INCREASES SETTLING VELOCITIES

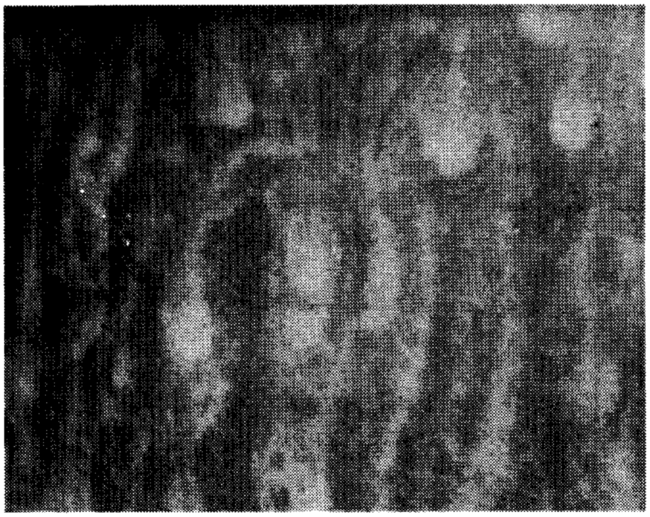

FIGURE 9D—CLUSTERING EFFECT INCREASES SETTLING VELOCITIES

2. Horizontal sand transport velocities ranged from 70% to 90% of the bulk fluid velocity.
3. Measured prop settling velocities during flow were up to three times the single particle fall rate.
4. An important factor in prop transport is the agglomeration or clustering effects observed during these tests.
5. When flow is stopped, the existing clusters begin to settle and coalesce with other particles. As the clusters grow, they fall faster, resulting in settling velocities many times greater than that for the single particle.

The test program in progress is designed to provide the data necessary to develop treatment design correlations.

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