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**Flowability of Bulk Solids Used
in Shale Fracturing Grouts as Determined
by the Jenike and Johanson Method**

Earl W. McDaniel
H. O. Weeren

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GROUTS AS DETERMINED BY THE JENIKE AND JOHANSON METHOD

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FLOWABILITY OF BULK SOLIDS USED IN SHALE FRACTURING
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ABSTRACT

Smooth operation of the shale fracturing facility at Oak Ridge National Laboratory requires that an even, uninterrupted flow of dry solids be delivered to a mixer at a rate of approximately 1200 lb/min. Some operational difficulties have been experienced with the dry solids system at the existing facility. Occasionally the solids flow from a bin was difficult to initiate or was irregular, particularly when the storage bin was nearly empty. A new shale fracturing facility is now being designed with a solids handling system that will eliminate the current problems. This report describes the tests made to obtain the necessary information about bulk-flow properties of the dry solids that are required for the facility modifications.

The flow properties of fly ash, attapulgite, pottery clay, and a blended solids mix were determined in a Jenike and Johanson Flowfactor Tester. Tests with this unit involve the consolidation of a solid at a given pressure and the measurement of the force required to create a shear plane. The procedure is repeated several times at different consolidating pressures to determine a locus of points that can be displayed graphically.

The results indicate that a bottom-hopper opening of about 4 ft will be required on the new, bulk storage bins if mass flow is to be achieved. It was also found that the existing bins are quite unsuitable for either their present function (storage of dry mix) or their proposed function (storage of mix components). Since these bins have served moderately well for 14 years, the effect of aeration (not allowed for in these tests) is obviously major; these tests indicate only an upper limit to the size of the hopper opening that will be required.

Pottery clay and attapulgite were found to have flow characteristics considerably inferior to blended solids. It is known, however, that attapulgite clay will flow from the existing bins, and modification of the bin bottoms to enlarge the openings does not appear to be justified.

1. INTRODUCTION

The shale fracturing process for the permanent disposal of locally generated intermediate-level waste solutions is currently in use at Oak Ridge National Laboratory (ORNL). In this process, the waste solution is mixed with a solids blend of cement and other additives; the resulting grout is injected into an impermeable shale formation at a depth of 700 to 1000 ft.¹ The existing facility was built in 1963 and has since been used to inject over 2.5 million gal of waste grout.² One of the principal improvements that will be incorporated into the design of a new waste disposal facility will be modifications to the dry-solids handling equipment so that the flow of dry solids will be smooth and uninterrupted.

1.1 Existing Solids Handling System

The dry-solids handling system at the existing shale fracturing facility consists of a solids blending system and a dry-solids bulk storage system. A flow diagram of the two systems is shown in Fig. 1.

The ingredients of the dry solids blend (Portland cement, fly ash, attapulgitite drilling clay, pottery clay, and a small amount of retarder) are charged separately to a weigh tank. The amount of each ingredient charged is in the proper proportion to make up a batch of about 40,000 lb. The weigh tank is pressurized and the batch of solids is blown into the first of the blending tanks. This tank is then pressurized and the batch of solids is blown into the second blending tank. Finally, the batch of solids is blown from the second blending tank into one of the four bulk storage bins. Fifteen batches of dry solids are blended in this manner for each injection; this operation requires approximately five working days. The operating experience with this system has been quite good, and the system will be used in the same manner in the new facility.

The dry-solids bulk storage system consists of four storage bins, four air slides leading to a mixer hopper, and a small mixer hopper. Each of the storage bins is 12 ft in diameter. The height of the cylindrical part of the bin is 20 ft and the height of the conical bottom section is 8-1/2 ft (the included cone angle is 70°). An assembly of

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Fig. 1. Existing solids blending and dry-solids bulk storage system.

aeration nozzles is installed in the center of each bin near the bottom of the cone. From 100 to 150 cfm of air at a pressure of 30 psig is supplied to the aeration nozzles during each injection. At the bottom of each bin is an 8-in. butterfly discharge valve. During an injection, the dry solids are discharged through the bottom valve into an air slide from which they flow to the mixing hopper. An air slide is a covered trough with a porous bottom through which low-pressure air can diffuse to fluidize the solids. The mixing hopper is a small surge tank. Normally, a solids storage bin is aerated for about 30 min prior to the withdrawal of solids. Solids are generally withdrawn from only one bin at a time.

Some operational difficulties have been experienced at the existing facility with the dry solids system, such as:

1. problems in initiating the flow of solids from a bin;
2. irregular solids flow from a bin, particularly when a bin is almost empty. This irregular solids flow has caused severe problems with controlling the solids-to-liquid proportioning.

1.2 New Solids Handling System

In the new solids handling system, the bulk storage bins at the existing facility will be moved to the new site and used for the storage of individual mix components of attapulgit, pottery clay, and fly ash. The existing blending system will be used essentially as is. Two new bulk storage tanks will be built, each with a capacity of 500,000 lb of blended solids. Solids will be withdrawn from the bottom of these bins and pneumatically transferred to a head tank located above the mixer. The solids will flow by gravity out of the head tank to the mixer. A flow diagram of the new solids handling system is shown in Fig. 2.

A smooth flow of blended solids out of the head tank will be vital to the proper operation of the new solids system. Although smooth flow from the blended-solids bulk storage bins would be desirable, it is not quite as necessary. Adequate flow of individual mix components from the component storage bins will be desirable, but smooth flow is not essential in this case. The smooth flow of solids out of storage bins can be

Fig. 2. New solids handling system.

determined by design features such as the size of the bottom opening, cone wall angle, materials of bin construction, method of aeration, and number and location of vibrators. Before these features can be evaluated, the flow characteristics of the various dry solids must be determined.

1.3 Flow Characteristics of Solids

The theory of flow of bulk solids and the design of storage bins and channels for flow have been the subjects of extensive studies by Jenike.³ These studies have led to the concept of the different flow patterns that may occur within a solids storage bin: funnel flow (in which the solids drawn through an outlet form a channel within the stored solids) and mass flow (in which all the solids in the bin flow toward the outlet). Funnel flow can result in ratholing, doming or bridging of solids around the outlet, flooding, and difficulty in fully emptying a bin. Mass flow results in a smooth, even drawdown of solids from the bin. Jenike presents extensive data that can be used to determine the bin dimensions required to achieve mass flow with a particular bulk solid.³ These data are plotted in terms of measured flow characteristics of the individual solids, which are generally a function of particle size, moisture content, and time of standing. This theory assumes no aeration or vibration of the solids and therefore represents a worst-case approach.

2. THEORY

Jenike reasoned that any attempt to derive flow criteria for solids from liquid flow would be useless; he considered a bulk solid to be a plastic and viscoelastic continuum. Using such criteria, Jenike developed his theory of flow of bulk solids, which is used exclusively in this study.³ Jenike's work developed the following concept. The pressure strength curve of a solid is referred to as its flow function, and the dashed line (Fig. 3) is called the flow factor of the channel. When these two lines intersect, the point of intersection usually determines the minimum size of the outlet required to assure unobstructed gravity flow. The flow function is a property of the solid. The flow factor is a property of the bin. The various pressures may be described by following the flow of a solid in a channel. The particles of the solid are initially deposited at the top of the mass

Fig. 3. Determination of major consolidating force.

without impact. As the individual particles flow down the channel, they are covered by more particles and the pressure increases steadily. An abrupt change of pressure occurs at the junction between the vertical walls of the bin and the conical hopper. The pressure then decreases linearly toward zero at the vertex. These varying pressures in the bin cause a change in density of the solid during flow and are called consolidating pressures. A Jenike and Johanson Flowfactor Tester can be used to measure the effect of these various pressures on the flow properties of the solids.

Although many obstructions to flow may develop in a bin, Jenike analyzed only two, doming and piping. It is assumed that if a bin were designed so that these two obstructions cannot occur, satisfactory flow will result.

3. MATERIALS TESTED

3.1 Attapulgite-150

Attapulgite-150 is the trade name of a clay product from the palygorskite group of clay minerals and has the general formula $5\text{MgO} \cdot 8\text{SiO}_2 \cdot 9\text{H}_2\text{O}$. The attapulgite used in the shale fracturing operation has an unaerated bulk density of 35 lb/ft^3 and an average particle size of approximately 100 mesh.

Moisture absorbed from the atmosphere has an effect on the flowability of solids. In the case of attapulgite, the effect of moisture is even more pronounced due to swelling. The attapulgite used in testing was not dried so that field conditions could be more closely approximated.

3.2 Fly Ash

The fly ash used is a bituminous ash received from the TVA steam plant at Kingston, Tennessee or from the Southeast Fly Ash Company, Kingsport, Tennessee. The particle size is less than 300 mesh and the unaerated bulk density is 54 lb/ft^3 .

Of the properties that affect flow (i.e., moisture, bulk density, and particle size), only particle size presents a potential problem with fly ash. Ash that is approximately 300 mesh and 15μ diam remains very dry in storage and has a moisture content of $\leq 0.15\%$. Moisture acts as a particle binder, thus retarding flow.

3.3 Pottery Clay

Indian-red pottery clay is a dried and ground natural clay with an unaerated bulk density of 50 lb/ft^3 . Pottery clay does not swell on contact with water.

3.4 Cement

Cement was not tested because there are no plans to store it in the new shale fracturing facility. Cement was used, however, as a component of the dry solids blend. Type-I Portland cement (ASTM C150) was used for this application.

3.5 Dry Solids Blend

The dry solids blend is a mixture consisting of 38.5 wt % cement, 38.5 wt % fly ash, 7.7 wt % pottery clay, and 15.4 wt % Attapulgate-150 drilling clay. Both field-blended and laboratory-blended samples were tested. A Patterson Kelly Company twin-shell dry blender was used for the laboratory samples.

4. PROCEDURE

Many factors must be considered in any attempt to determine the ideal flow characteristics to be designed into a storage bin. All solids do not gain the same strength under equal pressure. For instance, dry sand is cohesionless, but clay that contains little moisture is very cohesive and gains strength rapidly as a function of pressure. Other factors are time of applied pressure and temperature. Because the geometry of the bin is a major factor in this current work, the bin was considered to be a right circular cylinder with a vertical wall and a conical discharge hopper.

4.1 Apparatus and Test Procedure

A model FT-3STEJ Jenike and Johanson Flowfactor Tester was used in all tests. Briefly, the instrument consists of a sample holder, a method of applying a consolidating force on the sample, and a strip-chart recorder to measure the shear force. A vertical force is applied to the cover of the sample holder; the horizontal shearing force is applied by means of a gear-driven motor that advances a stem toward the shear cell. The shear force is applied to a brace attached to the cover. The force acts in the plane of contact between the ring and the base. The shear stress is recorded on a strip-chart recorder.

The purpose of the tests is to measure the necessary flow functions, the bulk density, and the angle of friction between the solid and a material of the wall. Solids are consolidated at a given pressure and the force required to create a shear plane is measured. The procedure is repeated at several different consolidating pressures to determine a locus of points that can be displayed graphically. Prior to each shearing determination, a steady-state flow point is obtained. This point is always determined at the same consolidating pressure for a given set of data.

In the testing of a solid, vertical loads are assigned to provide a suitable distribution of results within the range of pressures expected in a storage bin. Bin pressures are proportional to the bulk density of a solid, and the load range varies appropriately. The weight ranges used were those recommended by Jenike and Johanson.⁴

4.2 Wall Adhesion Tests

The procedure for measuring the adhesion of a solid to a sample of bin wall material is to reduce the vertical load as soon as steady-state shearing force is achieved and continue until all weights are removed. The slope of the load vs the shearing force line determines the angle of friction between a solid and a wall. The density of a solid at the outlet of a channel, which must be considered in the solids flow calculations, was obtained for each material tested.

4.3 Plotting Test Results

A typical set of test data are shown in Table 1. From these data, a set of flow function properties at this one particular preconsolidation load can be calculated.

Table 1. Test on Attapulgate-150

	Test (lb)		
	1	2	3
Preconsolidation load, W	17.3	17.3	17.3
Shearing force, S	13.23	13.13	13.15
Vertical load, $\bar{W}$	15.3	10.3	5.3
Shearing force, $\bar{S}$	12.43	9.3	5.63

The vertical loads are plotted against the shearing forces (Fig. 4) and a line is drawn through those three points that had a vertical load less than the preconsolidation load. The curve defined by the plotted points is referred to by Jenike as the yield locus. The slope of this line, ϕ , is called the angle of internal friction. A Mohr-force semi-circle, passing through the origin and tangent to the yield locus curve, defines the unconsolidated yield strength, F_1 , at the intercept of the horizontal axis. A second Mohr circle is drawn tangent to the yield locus and passes through point W obtained at the preconsolidation load. The intercept of this circle and the horizontal axis (the intercept farthest from the origin) defines V_1 , the major consolidation force. A line drawn from the origin to the tangent point between the yield locus and the larger Mohr circle is called the effective yield locus; the slope of this line (δ) is the effective angle of friction. The results from one test series can thus be used to determine F_1 , V_1 , ϕ , and δ for a single consolidation force.

Fig. 4. Determination of consolidated yield strength and force.

The above procedure is repeated several times at different consolidating loads, the values of F_1 and V_1 that are obtained are plotted, and the points are connected by a continuous line. This line defines the flow function of a given solid. On a force diagram this line is similar to line FF that was shown in Fig. 3.

5. DATA UTILIZATION

The flow function, as described in Sect. 4, is used to calculate the minimum opening and the minimum cone angle required to permit uniform flow of bulk solids from a given bin. The flow function is a property of the material being tested and may vary with moisture, temperature, or particle size. Other necessary factors that must be determined experimentally are density and effective angle of friction. The final factor entering into the calculation of the minimum opening is called the flow factor. All flow factors used in this work have been determined by Jenike, which for a given bin are a function of the effective angle of friction (δ), the angle of friction between the solid and the wall material (ϕ'), and the angle of the hopper cone (measured from the vertical). The effective angle of friction is determined from consolidation tests (Sect. 4); the angle of friction between solids and wall is determined from wall adhesion tests (Sect. 4.2). The relationship between these various functions was plotted by Jenike; a typical curve is shown in Fig. 5. The angle of the hopper cone is given by the intersection of the experimentally determined value of ϕ' and the heavy diagonal line. This is the maximum limiting value of the hopper angle, and a safety margin of 3° is then applied. This new point gives the maximum hopper angle for unaerated mass flow from a bin (by reading vertically downward) and the flow factor number (ff) for that particular bin (the contour lines).

The flow factor number represents the slope of the ff line on the flow function curve, with one end of the line at the origin. The intercept between the ff line and the FF line (Fig. 3) is the major force in

Fig. 5. Conical-channel ff contours, $\delta = 50^\circ$. (Reproduced from "Storage and Flow of Solids," Utah Engineering Experiment Station Bulletin 123, p. 88; courtesy of A. Jenike.)

a dome and is used to calculate the minimum diameter of the opening required for unobstructed flow. The equation used is:

$$D = \frac{\bar{V}_1 13 H(\phi')}{\text{density}}$$

where

D = opening diameter, ft;

$\bar{V}_1$ = major force, lb;

$H(\phi')$ = geometric function of hopper slope angle, determined by Jenike for circular, square, and rectangular outlets;

density = bulk solids density, lb/ft³.

6. RESULTS

The maximum hopper angles and minimum hopper-opening diameters for unaerated mass flow were determined for the various dry solids of interest, shown in Table 2.

Table 2. Storage bin values for unpainted mild steel

Material stored	Moisture content (wt %)	Hopper angle (deg)	Internal angle of friction	Bin opening diam (ft)
Attapulgate	14.0	17.0	26.2	5.1
Pottery clay	1.9	12.0	29.6	6.9
Fly ash	0.12	23.5	19.0	1.6
Standard dry mix	3.3	21.0	24.2	4.0

Bin-wall adhesion tests were determined for four possible wall coatings. The major variations were observed with the standard dry mix. The adhesion angle ranged from 22.8° to 27.0° (Table 3).

Table 3. Adhesion angles for different wall coatings

Coating material	Adhesion (deg)			
	Standard mix	Fly ash	Attapulgate	Pottery clay
Unpainted mild steel	24.2	19.0	26.2	29.6
Exterior enamel	27.0	20.8	24.4	29.7
Auto paint lacquer	22.8	20.8	24.4	28.7
Grey-Silka protective coating	26.5	20.0	27.6	31.3

7. CONCLUSIONS

The results indicate that a bottom hopper opening of about 4 ft will be required on the new bulk storage bins if mass flow is to be achieved. These results also indicate that the existing bins are unsuitable for either the storage of dry mix or mix components; the existing hopper angle (35°) is much too large, and the existing hopper opening is much too small (8 in.). Because these bins have served moderately well for 14 years, it is obvious that aeration has a major effect. The tests described in this report do not consider this effect, and the results merely indicate an upper limit to the size of the opening that will be required. Thus, the opening in the new bulk storage tanks should be greater than 8 in. but less than the 48 in. indicated by this test.

Different coatings appear to make little difference in the flowability of the various solids.

Table 2 shows that pottery clay and attapulgite have flow characteristics considerably inferior to the standard dry mix, and they might be difficult to remove from the existing storage bins if they are used for component storage. It is known, however, that attapulgite will flow from the existing bins;¹ since the characteristics of pottery clay are only marginally worse than the characteristics of attapulgite, modifications of the bin bottoms to enlarge the openings does not appear to be justified.

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