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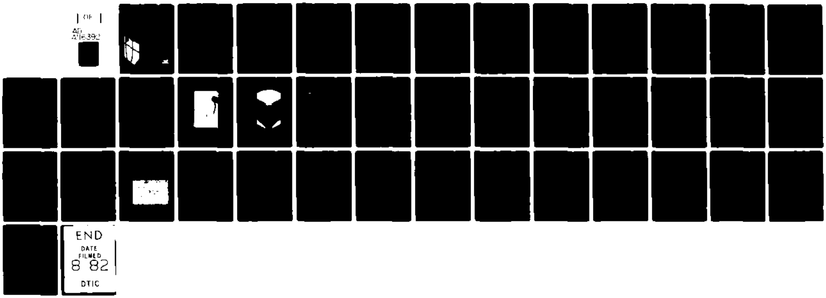

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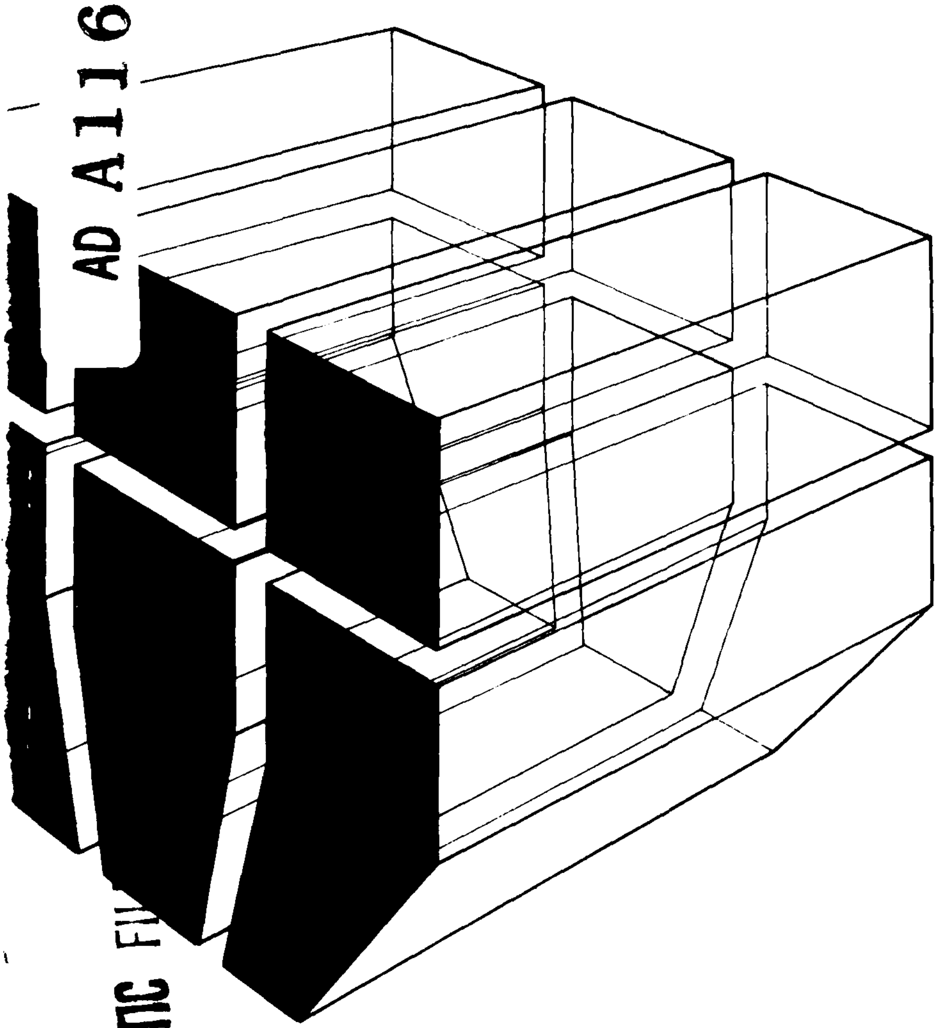
PHYSICAL CHARACTERISTICS OF DENSIFIED REFUSE DERIVED FUEL AND THEIR IMPACT ON FLOW PROPERTIES



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This project was performed to determine which properties of densified refuse derived fuel (dRDF) have a significant impact on its flow characteristics within bins, hoppers, and silos. The properties of moisture content, size distribution, and fines content were investigated. Flow characteristics were evaluated in terms of funnel angle and bulk shear strength.

This analysis showed that flow angle was the most sensitive characteristic for indicating how easily a material flows.

Block 20 continued.

Although the test plan did not include using bulk density as a flow characteristic, an analysis showed a correlation between bulk density and funnel angle. However, ease of flow is more sensitive to funnel angle than to bulk density.

No useful relationship between bulk shear strength and flow angle was observed. Therefore, bulk shear strength should not be used to evaluate the effects of dRDF flow properties.

Since funnel angle best indicates how much material will flow through a hopper, each dRDF property was evaluated in terms of its effect on funnel angle. Of the properties investigated, the amount of fines in the sample was found to have the greatest effect on funnel angle. As the amount of fines was increased from 0 to 30 percent, the funnel angle increased steadily. Moisture content showed less influence, with results indicating that increasing moisture increased flow angle. It was also observed that moisture content may permanently affect a sample's flow capabilities. Therefore, the moisture history of the dRDF may directly affect its flow capability. No significant effect on funnel angle could be associated with the size distribution of the pellets except for fines content. Whole, well-formed pellets of any combination of lengths flowed with funnel angles less than 45°.

FOREWORD

This basic research study was performed by Systems Technology Corporation, Xenia, OH, under Contract DACA 88-81-C-0002, for the Energy Systems (ES) Division, U.S. Army Construction Engineering Research Laboratory (CERL). The work was sponsored by the Directorate of Military Programs, Office of the Chief of Engineers (OCE) under Project 4A761102AT23, "Basic Military Research and Construction," Task B, "Energy Research and Alternate Fuels," Work Unit 018, "WDF/RDF Physical Properties and Material Flow Characteristics." Mr. A. N. Collishaw was the CERL Principal Investigator.

Mr. R. G. Donaghy is Chief of ES. COL L. J. Circeo is Commander and Director of CERL, and Dr. L. R. Shaffer is Technical Director.

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PHYSICAL CHARACTERISTICS OF DENSIFIED REFUSE DERIVED FUEL AND THEIR IMPACT ON FLOW PROPERTIES

1 INTRODUCTION

Background

Past research in the use of densified refuse derived fuel (dRDF) as an alternative for fossil fuel[1] has noted several problems with the storage and handling of dRDF: (1) it tends to stick to the sides of bins, hoppers, and silos; (2) it forms "ratholes," or funnel flow; (3) it bridges over in the storage vessel; and (4) it generally exhibits poor flow properties. To successfully use dRDF as a substitute fuel in its heating plants, the Army needs information about dRDF flow characteristics to support the design of fuel storage and conveying systems. The lack of such basic knowledge about dRDF physical characteristics motivated this study.

Objective

The objective of this research was to determine the effect of moisture content, size distribution, and percent fines on the flow characteristics of dRDF. The effects of these properties on flow characteristics were measured by their influence on the funnel angle produced by the material during flow and on bulk shear stress.

Approach

Samples of dRDF were obtained from Wright-Patterson Air Force Base (WPAFB), OH, which is firing commercially available dRDF mixed with coal in a heating plant.

The dRDF was treated to vary its moisture content, percent fines, and size. The material was then tested experimentally to evaluate its flow characteristics in terms of bulk shear strength and funnel angle.

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[1] S. A. Hathaway, J. S. Lin, D. L. Mahon, B. West, R. Marsh, and J. Woodyard, Production and Use of Densified Refuse-Derived Fuel (dRDF) in Military Central Heating and Power Plants, Technical Report E-159/ADA082773 (U.S. Army Construction Engineering Research Laboratory, 1980.

2 PROCEDURE*

Definitions

To facilitate a discussion of the procedures and results of this program a number of definitions will be presented in the following paragraphs. The primary objective of these paragraphs is to identify the variables and explain why each one was analyzed in the test program.

In this discussion, the variables that could be controlled are considered the properties of dRDF. Thus these properties form the set of independent variables. The effect of varying the properties was measured in the dRDF flow characteristics. Therefore, characteristics refer to dependent variables. Note that for some cases, the term "properties" can refer either to properties of individual pellets or to properties of an aggregate of pellets (bulk properties).

The following physical properties of dRDF were investigated:

1. Moisture content - This refers to free moisture of dRDF and is essentially the same for the aggregate of all dRDF particles in a sample or for individual pellets. Obviously, there can be some difference in moisture from one part of an aggregate pile to another, and the actual moisture content of the aggregate does vary with production and storage. Moisture content is measured by drying a suitably large sample at 220°F (105°C) for approximately 24 hours and comparing the dried mass of the sample to the undried mass of the sample. Moisture content of the aggregate has been varied artificially for testing purposes as described on page 12.

2. Density - The aggregate density is commonly referred to as bulk density and is determined by weighing a measured volume of material. The bulk density is affected by the individual particle density and also by the packing density (i.e., how closely together the individual particles can be when they are at rest). Bulk density is influenced by the moisture content since the moisture content affects the individual particle density. The bulk density is also affected by the fines content of the material (discussed below). The influences of moisture and fines on bulk density are secondary effects, but the only primary effect on bulk density is the shape and density of the individual pellets. This shape and density is a characteristic that is unique and different for each dRDF manufacturing process. Since all pellets tested herein were produced in the same manufacturing process, bulk density could not be controlled independently in this experiment.

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*Chapters 2 through 4 and Appendices A and B describe the dRDF testing and results. This information has been extracted from the Systems Technology Corporation report entitled Effects of Physical Properties of Densified Refuse Derived Fuel on Flow Characteristics, published in November 1981.

3. Size - This can refer to the size of the individual particles, or it could refer to the size distribution of particles in the aggregate. The most important aspect with regard to the flow properties of dRDF is the size distribution of the aggregate, especially the fines content (less than 3/8 inch). As the amount of fines increases in a sample of dRDF, the interstices or spaces between the large pellets can be filled more completely. As this filling occurs, the aggregate of dRDF becomes less and less mobile. For the purposes of this experiment, the size of dRDF refers to the size distribution of the aggregate sample, as determined through the use of American Society for Testing and Materials (ASTM) square hole sieves. The size distribution was varied by varying the fines content of the sample with the fines screened from larger samples. The effect of individual particle size was tested by segregating individual size ranges of dRDF for separate testing.

4. Mechanical Strength - Mechanical strength can refer to the tensile, shear, or compressive strength either of individual particles or of aggregates. This term could also deal with the modulus of elasticity (compressibility) of particles or aggregates. For purposes of this test, the mechanical strength of particles is referred to as a property of dRDF, and the mechanical strength of aggregate is dealt with as a flow characteristic.

   Individual pellet compressibility is a property that cannot be controlled because there is no variable in the manufacturing process that is known to control pellet compressibility. Thus this property could not be varied independently. Furthermore, there is no known theoretical or empirical relationship between bulk compressibility and rate of flow. Therefore, neither bulk nor particle compressibility could be meaningfully investigated.

   Since the tensile and compressive strengths of individual particles of dRDF are not expected to enter into the mechanics of flow, there was no need to measure these two properties. For a noncohesive material, there is no aggregate tensile or compressive strength; thus, these characteristics were not investigated.

   Bulk shear strength is a flow characteristic. This characteristic is a measure of the force required to overcome the friction between particles. Obviously, a low bulk shear strength would be characteristic of an easily flowing material, and a high bulk shear strength would be characteristic of a slow flowing or nonflowing aggregate material. A low bulk shear strength is a positive effect and high bulk shear strength is a negative effect of flow. But the efficacy of using bulk shear strength as a flow characteristic is unproven and will be evaluated during this test.

5. Funnel Angle - Funnel angle is one of the most important characteristics of flow through an orifice. If flow occurs, the funnel angle is the angle formed between the material that is freely flowing and the material which is nonflowing as measured at the interface between the orifice and the bottom of the container.

   This angle is measured with respect to the horizontal (a horizontal angle being 0° and vertical being 90°). A 90° funnel angle would be equivalent to what is called piping and is essentially a no-flow condition. Thus, a small funnel angle has a positive flow effect, and a large funnel angle has a negative flow effect. Based on the preceding discussion, it was decided to measure the flow characteristics of funnel angle and bulk shear while varying moisture, size, and fines content independently.

   Bulk density measurements were also taken during the tests to determine if bulk density could be correlated to funnel angle, thus forming a quick measurement of flow characteristics.

Test Plan

A test was performed on eight samples of dRDF having the characteristics described in Table 1.

Table 1

Test Samples

Sample No.	Moisture	Screen Size*	Fines Content (<3/8 in.)
1	As received (~10%)	As received	As received
2	Oven-dried (~2%)	As received	As received
3	Wetted (~30%)	As received	As received
4	As received	<3/8 in.	100%
5	As received	>3/8, <1 in.	0%
6	As received	>1 in.	0%
7	As received	As received	0%
8	As received	As received	30%

* 3/8 in. = 9.5 mm, 1 in. = 25.4 mm

These eight samples were tested to determine the positive and negative effects of their specific conditions on flow angle and bulk shear strength. This text matrix was carried out using the following plan.

One ton (.9 Mg) of pellets were removed from a fresh load of dRDF received at WPAFB. A 600-lb (275-kg) split was divided into three 200-lb (91-kg) samples. The first 200-lb (91-kg) sample of this pellet supply was subjected to triplicate funnel flow and bulk shear testing before any conditioning was performed on any pellets. This test provided the baseline for size and moisture testing. The entire second 200-lb (91-kg) sample was oven dried and funnel flow and bulk shear tested in triplicate (see Appendix B). The third 200-lb (91-kg) sample was wetted by spraying a measured amount of water onto the pellets in a closed container to raise the moisture content to approximately 30 percent. This sample was mixed, then funnel flow and bulk shear tested to complete the moisture variation test series.

Another 300-lb (136-kg) split was removed from the original 1-ton (.9-Mg) sample. This split was passed across a 3/8-in. (9.5-mm) screen to remove all fines and then subjected to funnel flow and bulk shear testing.

The remaining sample was screened into three size categories, i.e., <3/8 in. (9.5 mm), 3/8 to <1 in. (9.5 tp <25 mm), and >1 in. (25 mm). Each of these size categories was funnel flow and bulk shear tested.

Approximately 85 lb of the <3/8-in. (9.5-mm) size pellets (fines) were blended with the 200-lb (91-kg) split which earlier had only the <3/8-in. (9.5-mm) fraction removed. This blended sample was subjected to the final funnel flow and bulk shear test.

Property Determinations

Size Distribution

The size distribution of all pellets tested were determined by the analysis of a 25-lb (11.3-kg) representative sample of the pellets. This sample was analyzed according to a method derived from the ASTM Standard for Seive Analysis of Coal (ASTM-D410-38). The sample was passed through sieves of 3/8 in. (9.5 mm) and 1 in. (25 mm) nominal sizes. The three size fractions formed by the sieving were weighed with an accuracy of ±10 grams and the weight percentage of each size range was calculated.

Moisture Determination

At the time of shear and flow testing, three samples each weighing approximately 2 lb (1 kg) were taken from each of the eight test splits. Each dRDF sample was placed on a tared Teflon-coated tray 10 in. x 14 in. x 1 in. (25 x 36 x 2.5 cm), and the dRDF was spread out to a depth of no more than 1.5 in. (4 cm). The sample was then weighed to (±0.5 grams) to obtain the gross weight and placed in a convection oven set at 220°F (105°C) for 24 hr. The sample was then reweighed to obtain the dry weight. The percent moisture was then calculated as follows:

$$\frac{(\text{gross weight} - \text{tare}) - (\text{dry weight} - \text{tare})}{(\text{gross weight} - \text{tare})} \times 100 = \text{percent } H_2O \qquad \text{(Eq 1)}$$

Bulk Density

The bulk density of each of the eight test splits was determined. Each density determination was performed in triplicate, and the results were averaged. The procedure involved filling a 4-gal (15-liter) container with dRDF and leveling off the top without compacting the pellets. The container of pellets was weighed to the nearest 10 grams, and the tare weight of the container was subtracted. From this net weight and from the known volume of the container, the bulk density was calculated.

Flow Characterization

Funnel Angle

The funnel angle was determined through the use of a custom fabricated device illustrated in Figures 1 and 2. Figure 3 is a photograph of this same flow test fixture. Approximately 120 lb (55 kg) of dRDF was placed in the top of this device for each test run. A 5-in. × 5-in. (13-cm × 13-cm) orifice on the bottom was centered and adjacent to the plexiglas wall of the device. The selection of a 5-in. × 5-in. orifice size was arbitrary. However, earlier tests with this device indicated that smaller orifice sizes inhibit flow and larger sizes promote flow. To operate the device, a slide gate in the orifice was opened, and the dRDF was permitted to flow into a container placed below the orifice. When flow stopped, the angle of the top surface of the dRDF remaining in the fixture was measured and recorded (see Figure 4). The angle this surface formed with the horizontal was reported as the funnel angle. A triplicate of test runs was performed and the results averaged for each of the eight test conditions.

Bulk Shear Strength

The bulk shear strength was also determined through the use of a custom fabricated device. This device is illustrated in Figure 5. To operate the device, approximately 50 lb (25 kg) of dRDF was placed in the test fixture. The dRDF was leveled at the top of the sliding box, leaving a 6-in. (15-cm) depth of pellets above the shear surface. The shear surface is a plane formed by the interface of the sliding box and stationary fixture. This plane passes through 1 sq ft of dRDF when the fixture is loaded.

For each test run a bucket was suspended on the weight hook, and water was poured into this bucket. As the bucket filled, the slide box would begin to creep slightly and stop. Water would continue to be fed into the bucket at a steady rate until suddenly the slide box would be set into rapid motion, and

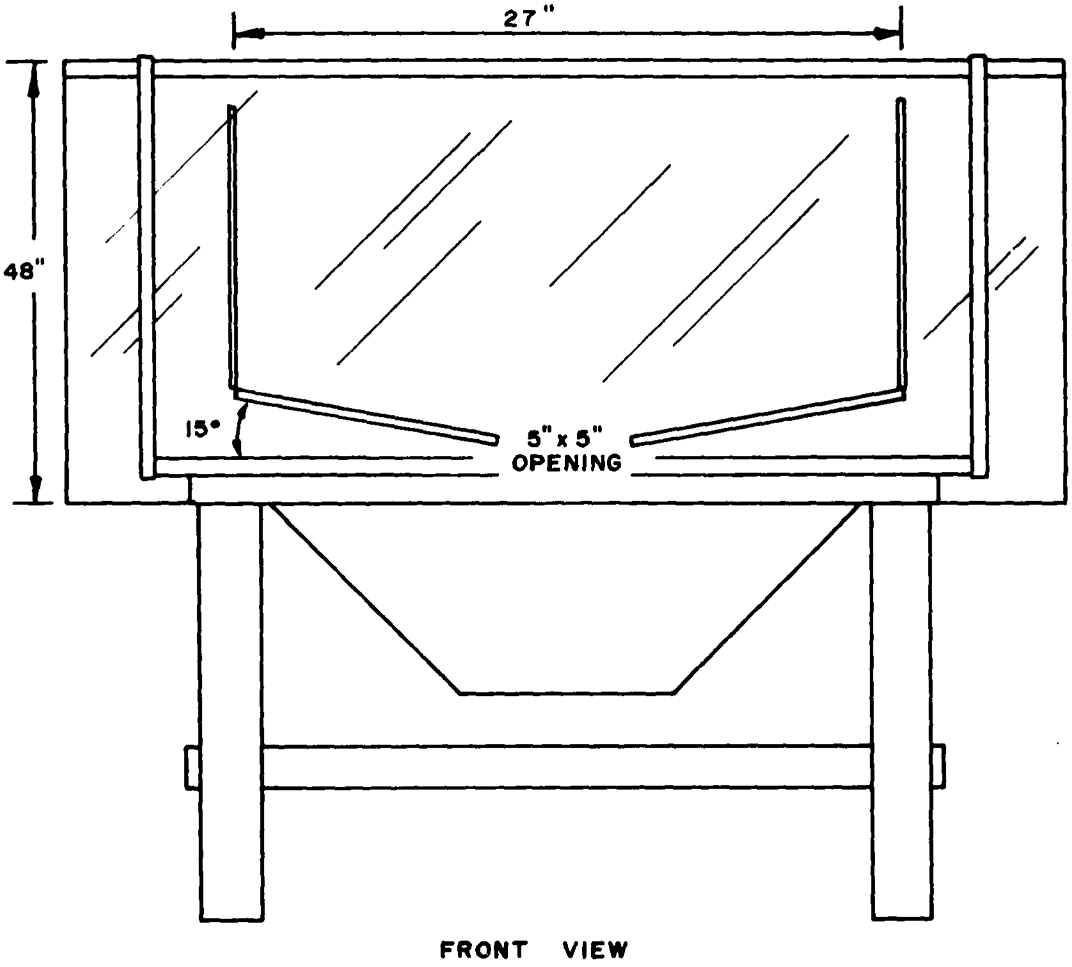


Figure 1. Flow test fixture front elevation.

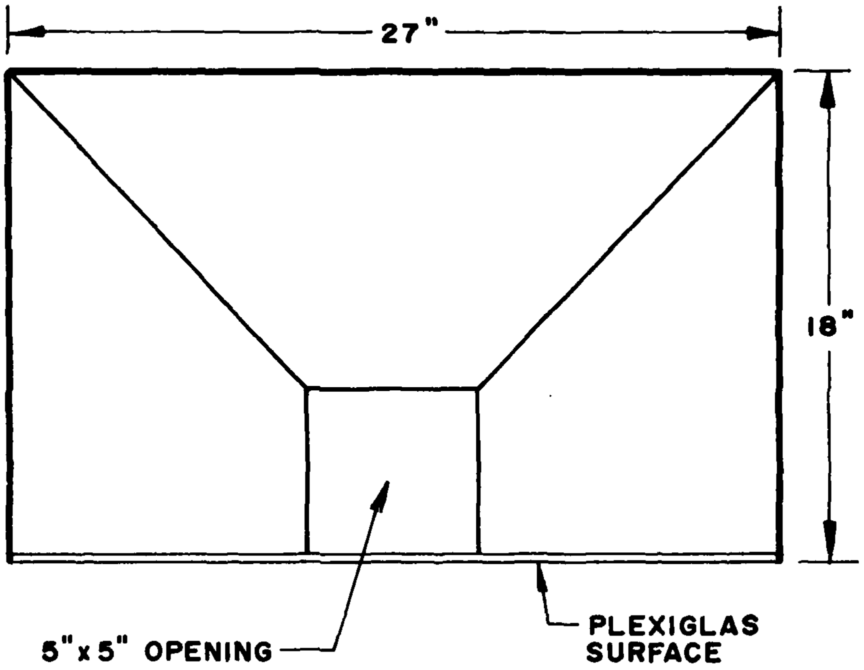
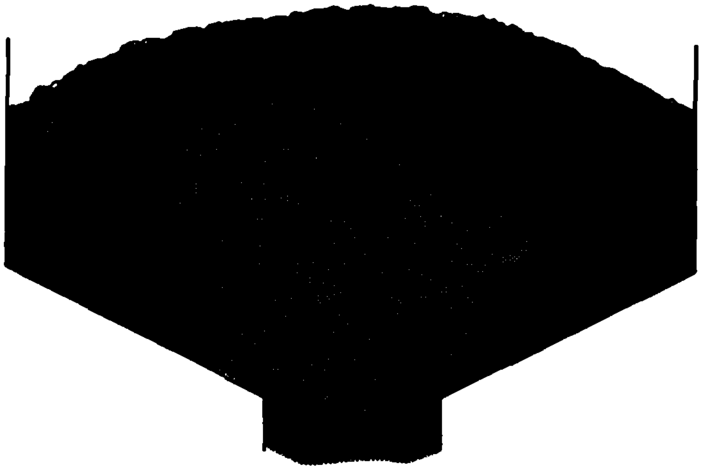
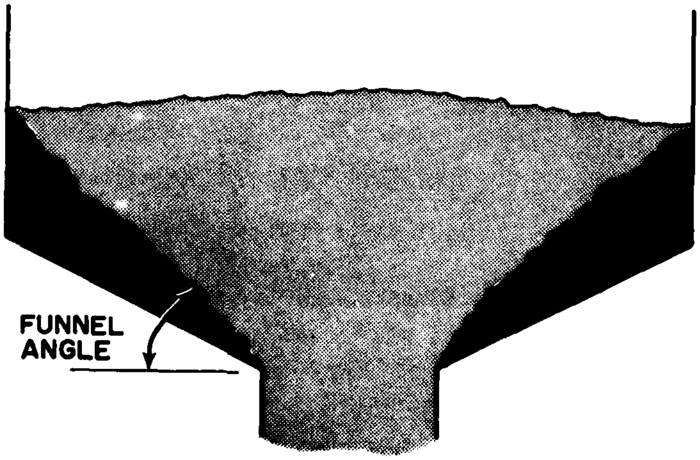


Figure 2. Test fixture plan view.

Figure 3. Flow test fixture.

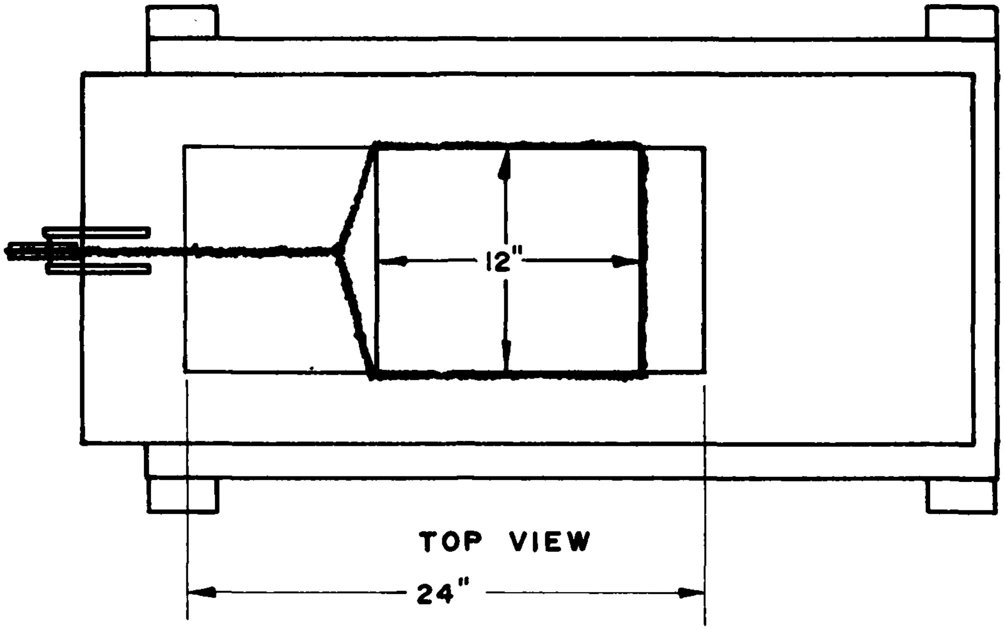


dRDF in fixture before flow test

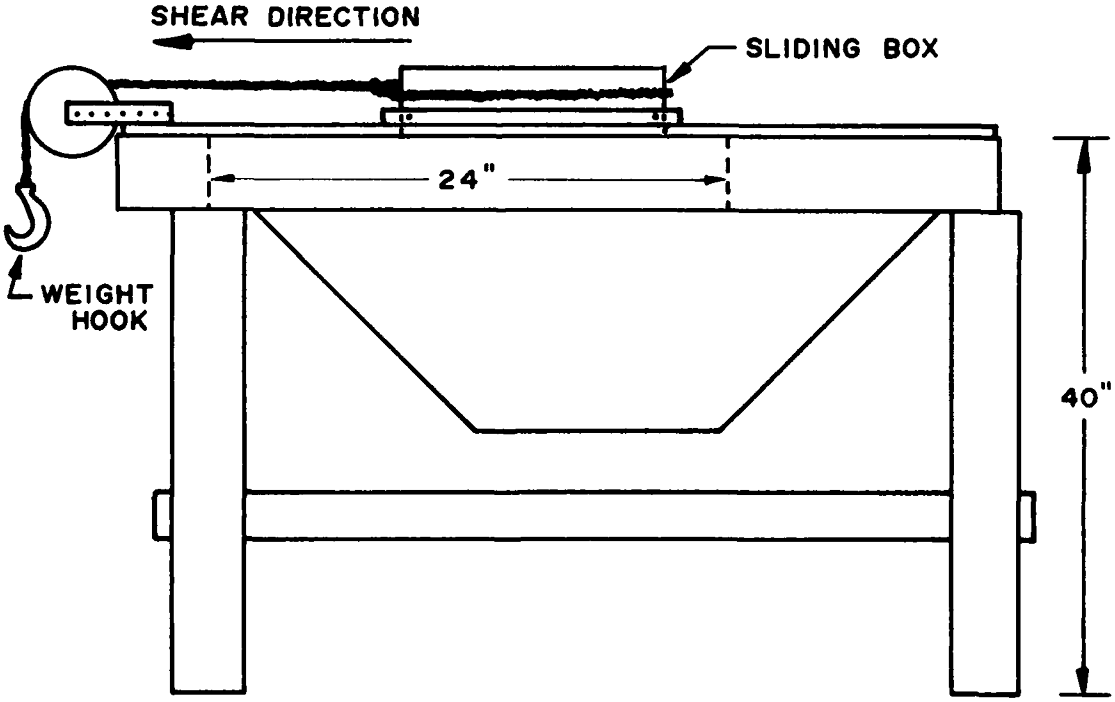


dRDF in fixture after flow test

Figure 4. Funnel angle in flow test fixture.



TOP VIEW



SIDE VIEW

Figure 5. Top and side views of bulk shear test fixture.

the bucket would be removed from the weight hook to stop the motion. The bucket of water was then weighed and the tare weight of the bucket subtracted. The weight of this water plus the weight of the hook were then recorded as the bulk shear strength of the test material in lb/sq ft.

Bulk shear tests were run in triplicate for each of the eight test conditions. The triplicate data was averaged, and a bulk shear strength value was reported for each independent variable (see Table 2, Chapter 3).

3 RESULTS

All results are reported in Table 2. The significance of each column of results is presented in the following sections. Complete test data are presented in Appendix A and Appendix B.

Moisture Effects

There was a noticeable increase in funnel angle as the moisture content of dRDF was increased from the as-received value of 11.5 percent to a much higher value of 33.7 percent. But, as can be observed in Figure 6, reduction in moisture content to the oven dried value of 2.4 percent did not improve the funnel angle. These results imply that this dRDF was at or very near its optimum moisture content in the as-received condition for flow characteristics. However, it must be pointed out that this implication is true for only this dRDF, and that dRDF produced by any other process may have a different optimum moisture content.

Variations in moisture content did not significantly affect bulk shear strength, just as variations in any of the properties had little effect on bulk shear strength (see Table 2). Surprisingly, the variations in moisture content did not measurably affect bulk density. Throughout this test program it appeared as though the pellets would swell and contract with moisture changes to maintain a constant bulk density.

Size Effects

Throughout the testing of various sized pellets, it was observed that a store of pellets of any size containing no fines will flow with similar ease. As Figure 7 illustrates, the medium-sized and larger-sized pellets flowed with equivalent ease and produced the lowest funnel angles observed in any of the tests. Furthermore, the funnel angle observed in Test 7, in which only the fines were removed and a combined sample of medium- and large-sized pellets remained, is not significantly different from that observed in other "fines-free" tests.

However, a sample of the fines (>3/8 in. [>9.5 mm]) alone would not flow at all. Therefore, the funnel angle for this condition is reported as 90°, the maximum possible. Of any of the tests, the only test for which bulk shear strength was significantly different was the one performed on the fines only sample.

The lower bulk shear strength of fines conflicts with the hypothesis that a low bulk shear strength implies easy flow. This result could be at least partially explained by the fact that the lower bulk density of the fines resulted in a reduced normal force on the shear surface in the Bulk Shear Test fixture.

Table 2

Summary of Results

Test No.	220°F moisture content Wt. %*	Bulk density lb/cu ft (kg/m³)	Pellet size (%) Fines <3/8 in. (<9.5 mm)	Medium 3/8 in.- 1 in. (9.5 mm-25 mm)	Large >1 in. (>25mm)	Bulk Shear Strength lb/sq ft (kg/m²)	Funnel Angle Θ above 5 in. × 5 in. orifice
1	11.5	34.7 (555)	9.7	62.9	27.4	16.6 (81.0)	53°
2	2.4	33.7 (540)	9.7	62.9	27.4	15.4 (75.3)	52°
3	33.7	31.7 (507)	9.7	62.9	27.4	14.9 (73.0)	77°*
4	10.1	18.5 (297)	100	-0-	-0-	11.4 (55.6)	90°**
5	11.0	34.5 (553)	-0-	100	-0-	16.3 (79.7)	43°
6	9.4	41.1 (658)	-0-	-0-	100	16.2 (79.1)	42°
7	10.5	36.8 (590)	-0-	69.7	30.3	17.1 (83.5)	45°
8	10.8	31.6 (505)	30	48	22	17.1 (83.4)	61°†

* No flow in 3 out of 5 replications

** No flow in all 3 replications

† No flow in 1 out of 3 replications

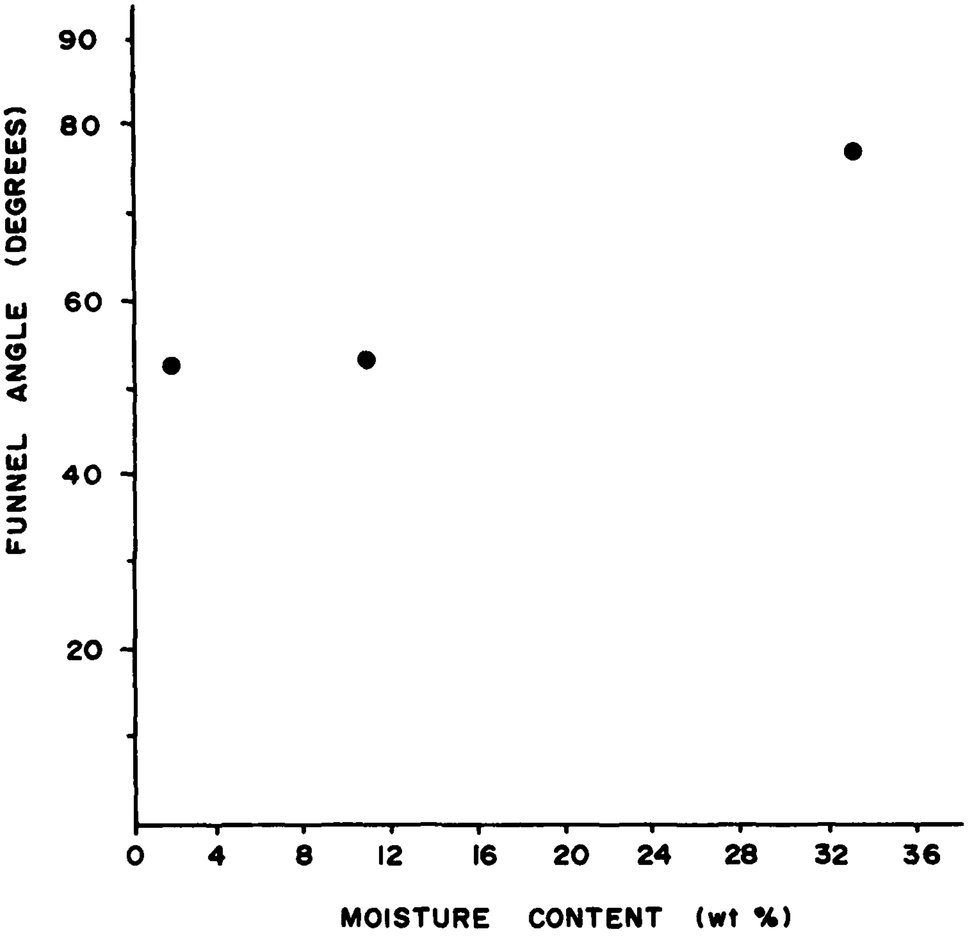


Figure 6. Moisture effect on flow.

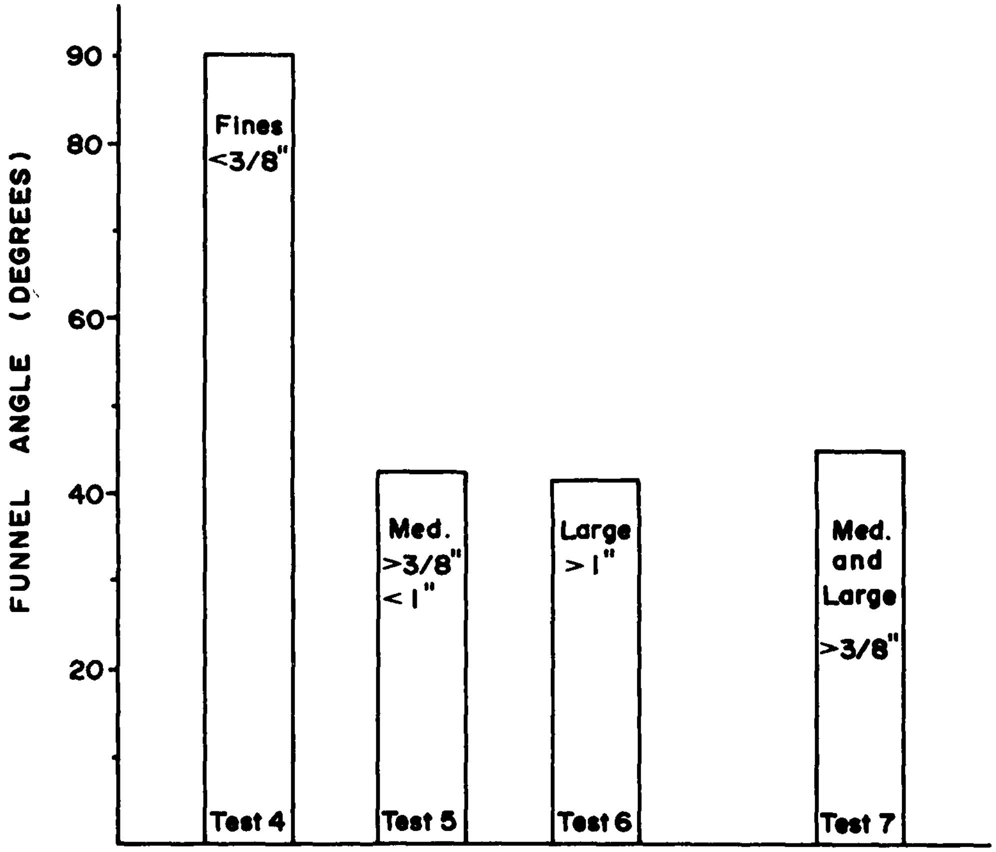


Figure 7. Effect of pellet size.

It was also observed that there is a relationship between bulk density and pellet size (see Figure 8). Bulk density increased along with pellet size. Since all the pellets were 1/2 in. (13 mm) in diameter, the different sizes were a function of length. The longer pellets were probably the stronger ones and the stronger pellets are the more tightly packed ones (because of the manufacturing process). Thus, these pellets have a higher individual pellet density and may have a better packing density for a higher overall bulk density.

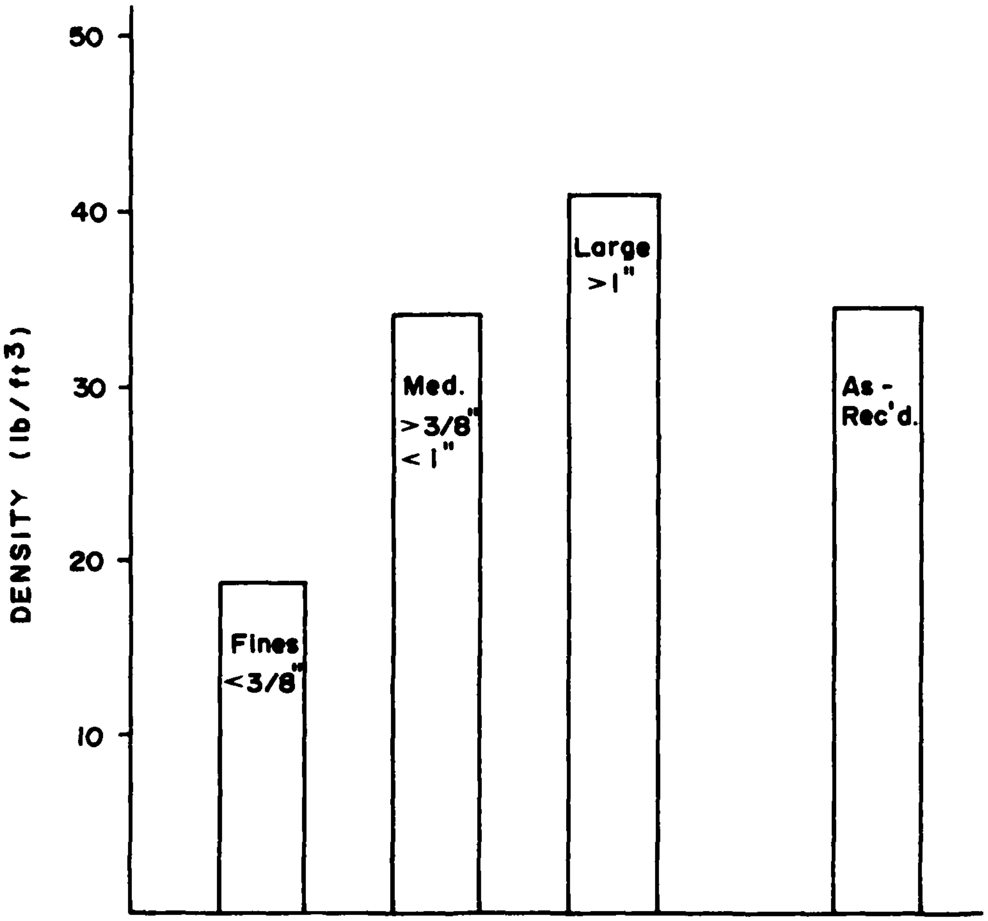


Figure 8. Effect of particle size on density.

Fines Content Effects

There was a pronounced increase in funnel angle and a decrease in flow as the fines content was increased. This effect is illustrated in Figure 9. With all other variables held constant, variations in the fines content consistently demonstrated the most significant effect on the flow characteristics.

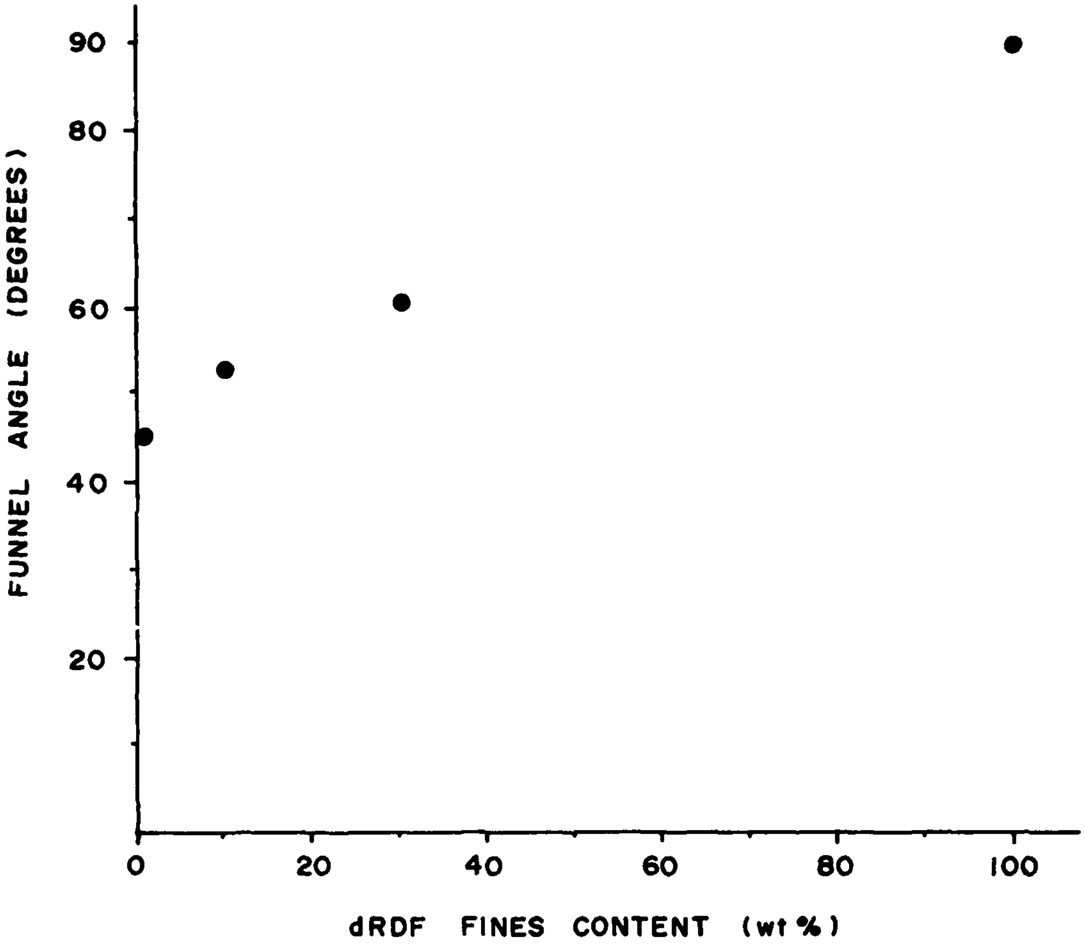


Figure 9. Effect of fines content.

There are two possible reasons why fines content has so great an effect on flow. First the fines fraction consists of material which is not pelletized and, therefore, does not have the high density and smooth surface properties of the pellets. Therefore, fines alone do not flow well (as was demonstrated in Test 4). Secondly, when blended with pelletized material, the fines can fill the interstices between the larger pellets and block the mobility of those pellets.

It was assumed that individual pellet strength has no effect on flow characteristics. But with respect to the effects of fines content, individual pellet strength may have a secondary effect because a low tensile strength may result in a large portion of fines in the aggregate.

Measurement of Flow Characteristics

The changes in bulk shear strength that resulted from variations in dRDF properties were small. In the test for fines, the only significant change (a decrease) of bulk shear strength occurred. This decrease was unexpected since a high (90°) flow angle was observed for the fines, and it was expected that flow angle and bulk shear would be directly related. Funnel angle was a direct measurement of the amount of material which flowed out of the test fixture and is probably close to the minimum acceptable slope at which a dRDF bunker or bin should be designed. As funnel angle decreased, less material was left in the hopper of the test fixture. As Figure 10 illustrates, there is a weak relationship, if any, between funnel angle and bulk shear strength. Therefore, it is concluded that the measurement of bulk shear strength cannot itself be used as a direct indication of the flow characteristics of dRDF. However, the bulk shear strength, when combined mathematically with other flow characteristics, may be useful in predicting dRDF flow behavior.

Although bulk density could not be controlled as the other independent variables could, the bulk density data were recorded. The possibility of using bulk density as a flow characteristic was investigated. The results did indicate that as bulk density increased there was a decrease in funnel angle and an improvement in flow. But the range of bulk density results was not as wide as the domain of funnel angle results (see Figure 11). Therefore, bulk density measurements are not as sensitive an indicator to changes in flow characteristics as are funnel measurements.

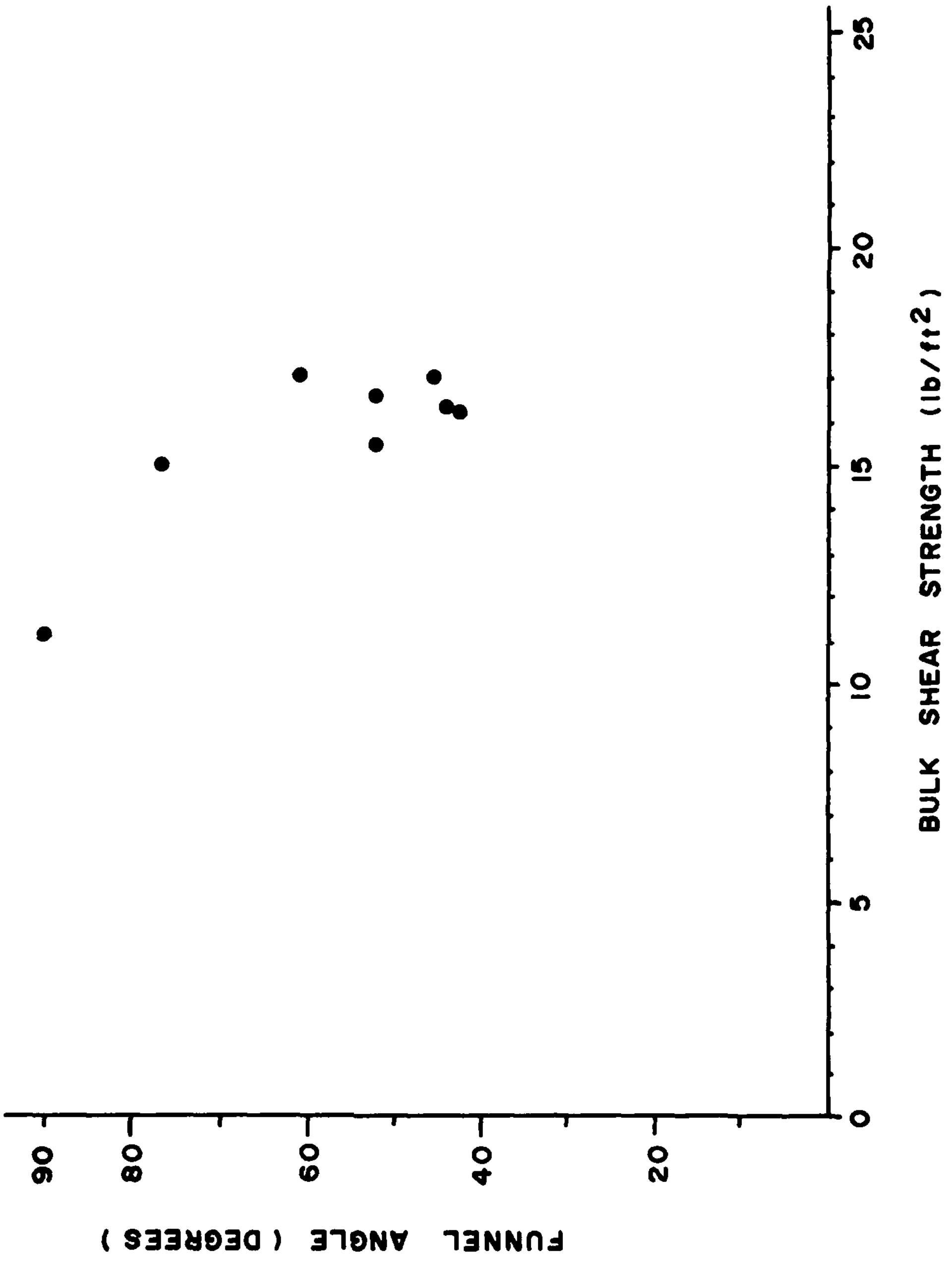


Figure 10. Relationship between bulk shear strength and funnel angle.

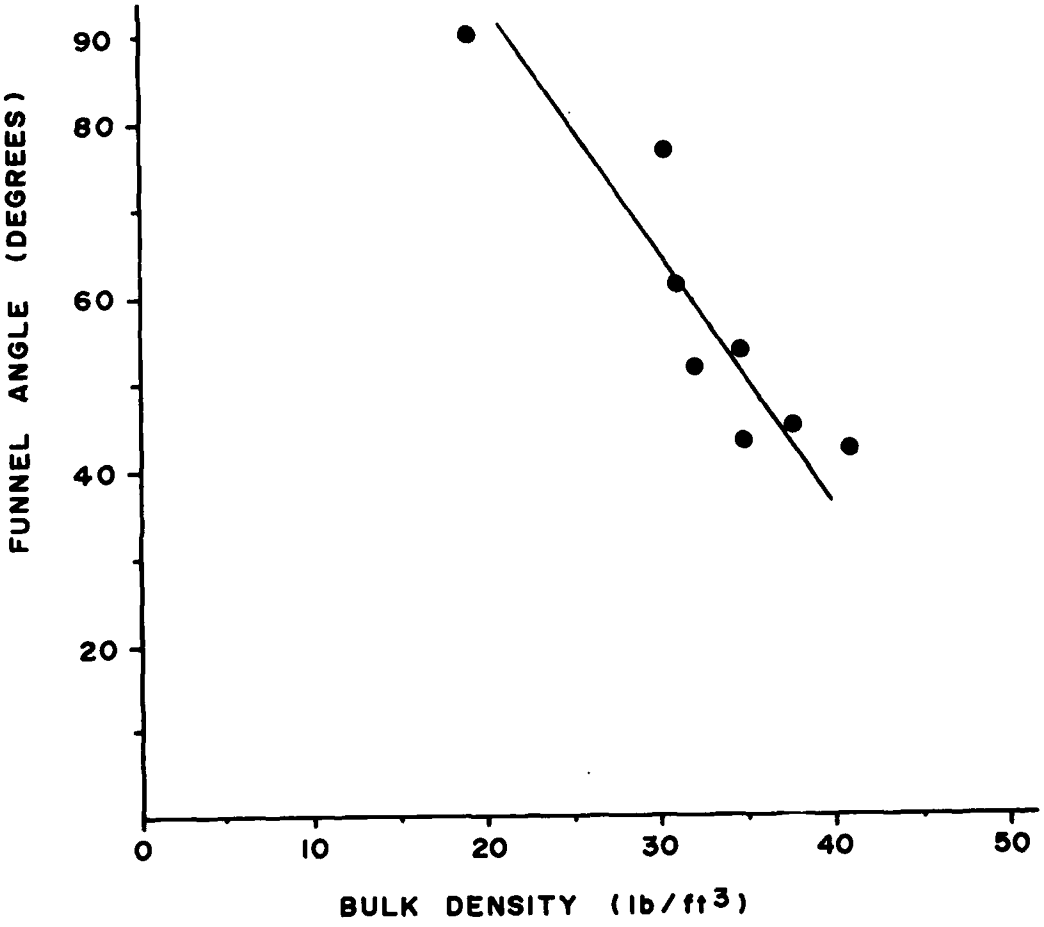


Figure 11. Relationship between bulk density and funnel angle.

When the moisture content of dRDF increases, it will swell, and the surfaces of the pellets will become serrated. These serrated surfaces cause considerable resistance to flow. When the same dRDF is dried, the pellets do not contract to their original shape, and the serrated surfaces are retained. If the sample tested at 34 percent moisture were then oven-dried and flow-tested again, it would probably form a funnel angle similar to that formed at 34 percent moisture. This theory is supported by the results of Test 2 where as-received pellets (10 percent moisture) were oven-dried and flow-tested. This oven-dried sample formed the same funnel angle as the original unprocessed sample.

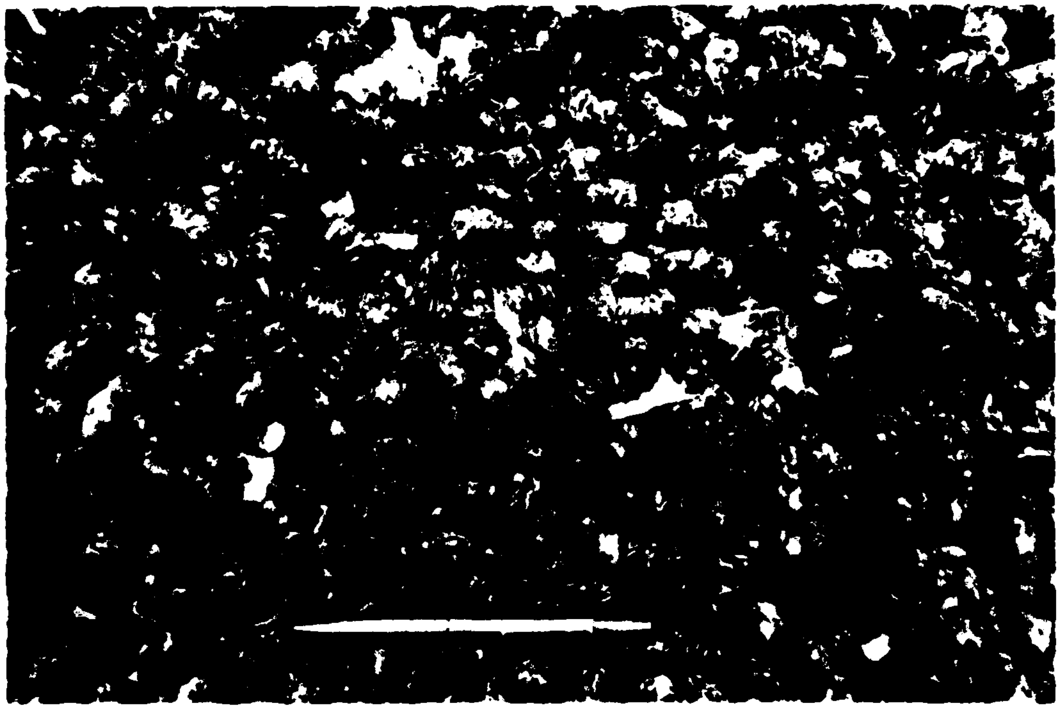


Figure 12. High moisture dRDF.

4 CONCLUSIONS AND RECOMMENDATIONS

Conclusions

Measurements of Characteristics

Based on this analysis of dRDF physical properties, the following measurements of flow characteristics are listed in order of decreasing sensitivity:

1. Funnel angle
2. Bulk density
3. Bulk shear strength.

The funnel angle is directly related to the volume of material remaining in the hopper of the flow test fixture after each test; therefore, only the funnel angle results were used to evaluate flow characteristics. Furthermore, the measured funnel angle is probably close to the minimum allowable slope at which the bottom of a fuel bunker or dRDF bin should be designed.

Although the test plan did not include using density as a flow characteristic, a correlation between density and funnel angle was discovered. However, ease of flow is more sensitive to funnel angle than to bulk density.

No useful relationship could be found between angle and bulk shear strength. The measurement of bulk shear strength may be useful when combined with other flow characteristics in a mathematical model that predicts flow behavior, but should not be used as a direct indicator of ease of flow.

The Effect of dRDF Properties

Based on the results of tests performed on 1/2-in.- (13-mm-) diameter dRDF pellets, the following properties of dRDF, in order of decreasing significance, were found to affect funnel angle:

1. Fines content
2. Moisture content
3. Pellet length.

There is a significant relationship between the fines content of each dRDF sample and the funnel angle of the test fixture. As fines were increased from 0 percent to 30 percent, the funnel angle also increased steadily. It is known that 100 percent fines will not flow, and that between 30 and 100 percent fines, there should be a point at which dRDF will cease to flow. A linear regression analysis on the "fines content" test results indicated that "no flow" conditions should be reached at about 80 percent fines content, much higher than would ever be seen.

Moisture content has the second greatest influence on flow characteristics. The direct effect of moisture is not as evident as is that of fines. It is possible that the moisture history of dRDF has more of an influence on flow than its actual moisture content.

No significant effect on flow could be associated with the sizes of the pellets (nominal length) except for fines. Whole, well-formed pellets of any combination of lengths flowed with funnel angles less than 45°, but fines alone would not flow at all.

Recommendations

To obtain more information about dRDF flow characteristics, the following recommendations are appropriate:

1. The funnel angle measurement should be used to determine flow characteristics, because it is easily performed, yet highly meaningful.
2. More tests should be performed to better determine the mathematical nature of the dependence of funnel angle on moisture and fines contents. Funnel angle should then be correlated to fines, moisture, and density through a multiple regression analysis.
3. The effects of the moisture history of dRDF should be further investigated.
4. Until more information is known, dRDF bins should be designed with bottoms sloped at more than 55° above horizontal. This would provide flow for dRDF of the sizes tested except those with high moisture or fines content.

APPENDIX A

PHYSICAL PROPERTY DATA

Table A-1

Moisture Determinations

Test number	Tray number	Tare	Tray and wet dRDF	Tray dry	Percent moisture
1	101	295.9	1,249.7	1,121.7	13.4
	006	286.3	1,049.8	964.4	11.2
	12	156.3	1,020.9	935.0	9.9
3	101	295.7	1,060.0	801.0	33.9
	006	285.8	1,008.0	761.5	34.1
	4	341.5	1,414.6	1,059.5	33.1
4	20	172.7	582.0	537.8	10.8
	105	275.8	727.5	684.1	9.6
	32	291.7	723.9	680.7	10.0
5	5	180.0	1,221.0	1,119.0	9.8
	1	333.4	1,216.5	1,113.3	11.7
	2	339.8	1,242.4	1,138.4	11.5
6	008	181.2	1,554.0	1,428.1	9.2
	69	285.8	1,353.8	1,267.9	8.0
	13	495.1	1,688.1	1,557.9	10.9
7	2	190.7	1,237.7	1,129.5	10.3
	5	182.6	1,070.0	972.3	11.0
	32	284.4	1,150.2	1,061.8	10.2
8	105	285.0	936.5	866.2	10.8
	13	182.0	857.5	784.0	10.9
	69	286.0	1,106.0	1,018.9	10.6

Temperature = 220°F on all three ovens.

Table A-2

Test Number 2
Oven Dried Pellets, Residual Moisture Analysis

Vessel number	Tare	Wet weight	Dry weight	Percent moisture
I2	27.9497	30.9340	30.8272	3.58
11	27.5294	29.2834	29.2211	3.56
Crack	26.5294	28.2007	28.1440	3.39
6	21.2780	22.6432	22.6040	2.87
GG	22.6290	24.7342	24.6565	3.69
E4	22.5465	24.8889	24.8052	3.57
			Average percent	3.44

Table A-3

Bulk Density Summary and Averages

Test number	Bulk Density		Average	Average
	(kg/m^3)	(lb/cu ft)	(lb/cu ft)	(kg/m^3)
1	575	35.90	34.7	555
	544	33.99		
	547	34.2		
2	538	33.6	33.7	540
	528	32.9		
	553	34.5		
3	518	32.4	31.7	507
	501	31.3		
	503	31.4		
4	285	17.8	18.5	297
	306	19.1		
	299	18.7		
5	555	34.6	34.5	553
	546	34.1		
	557	34.8		
6	651	40.6	41.1	658
	664	41.5		
	660	41.2		
7	581	36.3	36.8	590
	592	37.0		
	597	37.3		
8	512	32.0	31.6	505
	493	30.8		
	511	31.9		

Table A-4

Bulk Density Data, Field Measurements

Weight of container .88 kg
Volume of container 14,860 mℓ

Test number 1
- Bucket Number 1 = 9.42 kg
- Bucket Number 2 = 8.97 kg
- Bucket Number 3 = 9.01 kg

Test number 2
- Bucket Number 1 = 8.88 kg
- Bucket Number 2 = 8.72 kg
- Bucket Number 3 = 9.10 kg

Test number 3
- Bucket Number 1 = 8.58 kg
- Bucket Number 2 = 8.32 kg
- Bucket Number 3 = 8.36 kg

Test number 4
- Bucket Number 1 = 5.12 kg
- Bucket Number 2 = 5.42 kg
- Bucket Number 3 = 5.32 kg

Test number 5
- Bucket Number 1 = 9.12 kg
- Bucket Number 2 = 9.00 kg
- Bucket Number 3 = 9.16 kg

Test number 6
- Bucket Number 1 = 10.55 kg
- Bucket Number 2 = 10.75 kg
- Bucket Number 3 = 10.69 kg

Test number 7
- Bucket Number 1 = 9.52 kg
- Bucket Number 2 = 9.68 kg
- Bucket Number 3 = 9.75 kg

Test number 8
- Bucket Number 1 = 8.49 kg
- Bucket Number 2 = 8.20 kg
- Bucket Number 3 = 8.48 kg

Table A-5

Size Distribution Summary

Weight of pellets = 11.3 kg
Moisture, as-received
Size, as-received
Fines, as-received

Weight pellets (<3/8 in.) = 1.1 kg
Weight pellets (3/8 in. <x> 1 in.) = 7.11 kg
Weight pellets (>1 in.) = 3.09 kg

Percent (<3/8 in) = 9.73 weight percent
Percent (3/8 in. >1 in.) = 62.92 weight percent
Percent (>1 in.) = 27.35 weight percent

APPENDIX B

FLOW TEST DATA

Table B-1

Flow Test Fixture Results

Test number	Funnel angle (degrees)	Test number	Funnel angle (degrees)
1	55	5	42
1	50	5	42
1	55	5	42
2	48	6	40
2	49	6	41
2	55	6	44
3	77.5	7	48
3	76.5	7	43
3	NF	7	43
4	NF	8	55
4	NF	8	66
4	NF	8	NF

NF = no flow

Table B-2

Shear Tests

Weight of empty bucket = .86 kg
Weight of hook = .23 kg
Added weight required to move empty test fixture = 978.6 kg

Test Number 1
Moisture, as-received
Size, as-received
Fines, as-received

	Weight of bucket + water (kg)
Run Number 1	9.00
Run Number 2	7.70
Run Number 3	8.88
Run Number 4	7.68
Run Number 5	8.10
Average	8.27

Stress 16.6 lb/sq ft (81.0 kg/m^2)

Test Number 2
Moisture, oven dried
Size, as-received
Fines, as-received

	Weight of bucket + water (kg)
Run Number 1	7.49
Run Number 2	8.09
Run Number 3	7.65
Average	7.74

Stress 15.42 lb/sq ft (75.29 kg/m^2)

Test Number 3
Moisture, as-received
Size, as-received
Fines, as-received

	Weight of bucket + water (kg)
Run Number 1	7.26
Run Number 2	7.60
Run Number 3	7.72
Average	7.53

Stress 14.95 lb/sq ft (72.96 kg/m^2)

Test Number 4
Moisture, as-received
Size, <3/8 in.
Fines, 100 percent

	Weight of bucket + water (kg)
Run Number 1	5.97
Run Number 2	5.85
Run Number 3	5.92
Average	5.90

Stress 11.39 lb/sq ft (55.59 kg/m^2)

Table B-2

Continued

Test Number 5
Moisture, as-received
Size, 3/8 in <v< 1 in.
Fines, zero percent

	Weight of bucket + water (kg)
Run Number 1	8.86
Run Number 2	7.70
Run Number 3	7.90
Average	8.15

Stress 16.33 lb/sq ft (79.71 kg/m^2)

Test Number 6
Moisture, as-received
Size, >1 in.
Fines, zero percent

	Weight of bucket + water (kg)
Run Number 1	8.30
Run Number 2	7.93
Run Number 3	8.06
Average	8.10

Stress 16.20 lb/sq ft (79.10 kg/m^2)

Test Number 7
Moisture, as-received
Size, as-received
Fines, zero percent

	Weight of bucket + water (kg)
Run Number 1	8.32
Run Number 2	8.58
Run Number 3	8.61
Average	8.50

Stress 17.10 lb/sq ft (83.47 kg/m^2)

Test Number 8
Moisture, as-received
Size, as-received
Fines, 30 percent weight

	Weight of bucket + water (kg)
Run Number 1	8.39
Run Number 2	8.55
Run Number 3	8.55
Average	8.50

Stress 17.08 lb/sq ft (83.40 kg/m^2)

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