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**FRAGMENTATION ANALYSIS-FUNDAMENTAL
PROCESSES**

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Bureau of Mines

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13. ABSTRACT

To investigate the effect of energy on rock fragmentation, a drop test device was designed and constructed. Ninety specimens each of 3.0 to 3.5 inch size specimens of anorthosite and Wausau quartzite were fragmented in this device. Analysis of energy limitations of this device and test results led to the conclusion that a device supplying higher energy should be constructed. Consequently, an impact pendulum test device was also planned and constructed.

The analysis of the distribution results of the drop test experiments showed a strong tendency towards the level of energy applied being significant. However these results were not totally conclusive because of the limited energy available and the narrow band of drop heights available.

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FRAGMENTATION ANALYSIS - FUNDAMENTAL PROCESSES

Technical Report Summary

Objectives: To determine the relationship between the properties of a rock (including mechanical and possibly fabric properties) and energy input to determine the size distribution from a single fragmenting event. This relationship is of major importance to studies of fragmentation schemes for efficient utilization of breakage energy.

Research Plan: It was originally planned to test three monomineralic rocks of high, medium, and low compressive strengths, but both because a low strength rock was not immediately available and because it became evident that the drop test did not provide as much energy as desired, the final drop testing was limited to 90 specimens of Wausau quartzite and 90 specimens of anorthosite. .

A drop tester was built which could yield impact velocities up to almost 50 ft/sec to simulate the actual impact of rock such as in an autogeneous grinding process or an impact load type of fragmentation. It was later decided to use higher energy tests via an impact pendulum device. This device which consists of an impact pendulum, a rebound pendulum, and two pistons was planned and built. The specimen to be fractured is held by two circular plates between the two pistons. At the end of this reporting period, the test device was being modified and revised.

Major Accomplishments: Originally 64 specimens of Wausau quartzite were fragmented in a drop apparatus to estimate the number of samples that would be required in the final testing. It was concluded that 30 tests at each drop height were needed to obtain reproducible results.

Ninety specimens were fragmented by dropping 30 each from drop heights of 25, 30, and 35 ft. The percentage of the total weight in each sieve class was calculated. The cumulative percentage for each sieve class was then obtained and plotted for each specimen. A composite distribution was formed by adding the n individual weights together for each sieve class, and then finding the percentage and cumulative percentage for each sieve class for each of the three drop heights. The cumulative results were statistically analyzed to find which distribution fit best. Three distributions were calculated--power law distribution, exponential distribution, and the normal distribution. It was determined that the normal plots had the best correlation coefficients when the sieve data were separated into "fine" and "coarse" sieve classes.

The analysis of the distribution results of these experiments showed an apparent tendency for an increase in the applied level of energy to decrease the mean product size, but because of the low energy provided, this was not totally verifiable.

FRAGMENTATION ANALYSIS - FUNDAMENTAL PROCESSES

INTRODUCTION

The ultimate objective of this project is to determine the relationship between the properties of a rock (including mechanical and possibly fabric properties) and energy input and to determine the size distribution from a single elementary fragmenting event. It seems "intuitively obvious" that a relationship must exist between this distribution and the energy input. No such relationship has yet been defined. Consequently, test methods were to be devised in this project to measure energy per unit volume input.

In modern size reduction research, the concept of the breakage function matrix is utilized. In order to obtain the elements of such a matrix, it is necessary to fragment various rock types under the following conditions:

- . single event fragmentation
- . defined mode of energy application (e.g., impact, slow compression, shear or other types of loading)
- . measured energy per unit volume input
- . known rock fabric parameters (e.g., crack frequency, porosity, pore size distribution).

The scope of work in this report period was limited to testing of two rock types at low velocity drops. To effect this testing a drop test device was planned and constructed. In the process of testing it became obvious, as will be discussed in later sections, that energy supplied by this device was inadequate. Consequently, testing was limited to 90 specimens of each rock type (30 at each of 3 drop heights) and a higher energy--impact pendulum device was constructed.

EXPERIMENTAL PROCEDURES

EXPERIMENTAL MATERIAL USED

Samples of quarried rock pieces weighing from 100 to 1600 gm were used. The two materials selected were Wausau quartzite and anorthosite. Both of these were selected because they are monomineralic and therefore tend to behave more consistently when broken. It was originally planned to test three monomineralic rocks of high, medium, and low compressive strengths, but both because a low strength rock was not immediately available and because it became evident that the drop test did not provide as much energy as desired, the final drop testing was limited to 90 specimens of Wausau quartzite and 90 specimens of anorthosite.

Some of the physical properties of anorthosite and Wausau quartzite are listed in Table 1.

Table 1. - Physical Properties of Anorthosite and Wausau Quartzite

Property	Rock Type	
	Anorthosite	Wausau Quartzite
Compressive strength.....PSI	32,000	41,400
Compressive strength.....MN/M ²	221.0	285.7
Tensile strength.....PSI	1,300	740
Tensile strength.....MN/M ²	8.97	5.12
Shore hardness	91.72	111.64
Pulse velocity.....FT/MIN	22,500	16,800
Pulse velocity.....KM/SEC	6.866	5.130
Bar velocity.....FT/MIN	18,800	15,400
Bar velocity.....KM/SEC	5.742	4.679
Torsional velocity.....FT/MIN	11,100	12,000
Torsional velocity.....KM/SEC	3.396	3.383
Static Young's Modulus.....PSI	5.92x10 ⁶	10.51x10 ⁶
Static Young's Modulus.....MN/M ²	4.085	7.249
Dynamic Young's Modulus.....PSI	13.010x10 ⁶	8.321x10 ⁶
Dynamic Young's Modulus.....MN/M ²	8.971	5.741
Shear Modulus.....PSI	4.52x10 ⁶	4.35x10 ⁶
Shear Modulus.....MN/M ²	3.115	3.000

These properties were measured at Twin Cities Mining Research Center, U.S. Bureau of Mines.

No clear distinction in overall strength between these rocks can be made because, as can be seen from Table 1, some properties have higher values for anorthosite while others have higher values for Wausau quartzite.

EQUIPMENT

A drop tester was built which could yield impact velocities up to almost 50 ft/sec. This drop tester can be considered to crudely simulate the actual impact of rock such as in an autogeneous grinding process or

an impact load type of fragmentation. This tester consists of a container which can be hauled up to a maximum height of 35 ft by a motor/pulley arrangement. The container drops its cargo when a rope is pulled.

After it was decided (as described elsewhere) to go to higher energy tests via an impact pendulum device, a test set-up consisting of an impact pendulum, a rebound pendulum, and two pistons was planned and built. The specimen to be fractured is held by two circular plates between the two pistons. At the end of this reporting period, this test device was being modified and revised. A few trial tests had been made.

PROCEDURE FOR DROP TESTS

Three drop heights - 25, 30, and 35 ft were used. These yield impact velocities of 40.12, 43.95, and 47.47 ft/sec respectively.

A factorial experiment was designed to determine the number of replications at each drop height. A total of 64 specimens was used here - these weighed from 500 to 1000 gm. The results of these tests are described in the next section.

Another test series of specimens from 100 to 4500 gm weight in three shape categories was also carried out. The results of these tests are also described in the next section.

EXPERIMENTAL DATA

DATA ANALYSIS

Originally 64 specimens of Wausau quartzite weighing from 500 to 1000 gm were selected and fragmented in the drop apparatus. These initial specimens were used to attempt to estimate the number of samples that would be required in the final testing. From statistical analysis of this preliminary data it was concluded that 30 tests at each drop height were needed to obtain reproducible results.

Also, another preliminary study of specimens between 100 and 4500 gm was made to determine the effects of shape and size on probability of breakage. It appeared that: (1) "flat" specimens broke more often than "elongated" specimens, which in turn broke more often than "equidimensional" specimens and (2) large specimens broke more frequently than small specimens.

One purpose of this preliminary study was to find the effect of varying specimen parameters to obtain their effect on the parameter λ of the exponential distribution

$$Y = e^{-\lambda x}$$

where

Y = cumulative percent greater than x ,

x = size (linear dimension), and

λ = characteristic parameter of the distribution.

It was later found that the power law

$$Y = ax^b$$

where

Y = cumulative percent weight greater than x ,

x = size (linear dimension), and

a, b = parameters of the distribution,

yielded a slightly better fit of the data, but that the normal distribution yielded the best fit (in the least squares straight line sense).

Consequently, no further attempt was made to relate experimental data to the parameter λ .

Ninety specimens were fragmented by dropping 30 each from drop heights of 25, 30, and 35 ft. The first step in the data analysis was to calculate the percentage of the total weight in each sieve class and to obtain from this the cumulative percentage for each sieve class. This cumulative percentage ~~was~~ then plotted for each specimen that broke - all plots for one drop height being shown on the same graph. It was evident from these three graphs that the sample-to-sample variation was so great that an average over all $n \leq 30$ would yield a better description of all the samples and the general trend of the fragmentation process.

Consequently the next step was to form a composite distribution by adding the n individual weights together for each sieve class, and then finding the percentage and cumulative percentage for each sieve class. This was carried out for each of the three drop heights.

The next step was to statistically analyze and plot these cumulative results on three different types of graph paper to find which distribution fitted best. Three types of paper were used - log-log for the power law distribution, semi-log paper for the exponential distribution, and normal probability paper for the normal distribution. It turned out that the normal plots had the best correlation coefficient, but this was not evident until the following complication had been resolved.

The composite set of data points for a given drop height when plotted on normal paper yielded a set of data points which resembled a straight line segment and a slowly bending curve (connected at a middle point). These data points and curves for the two rock types are shown in Figures 1 and 2.

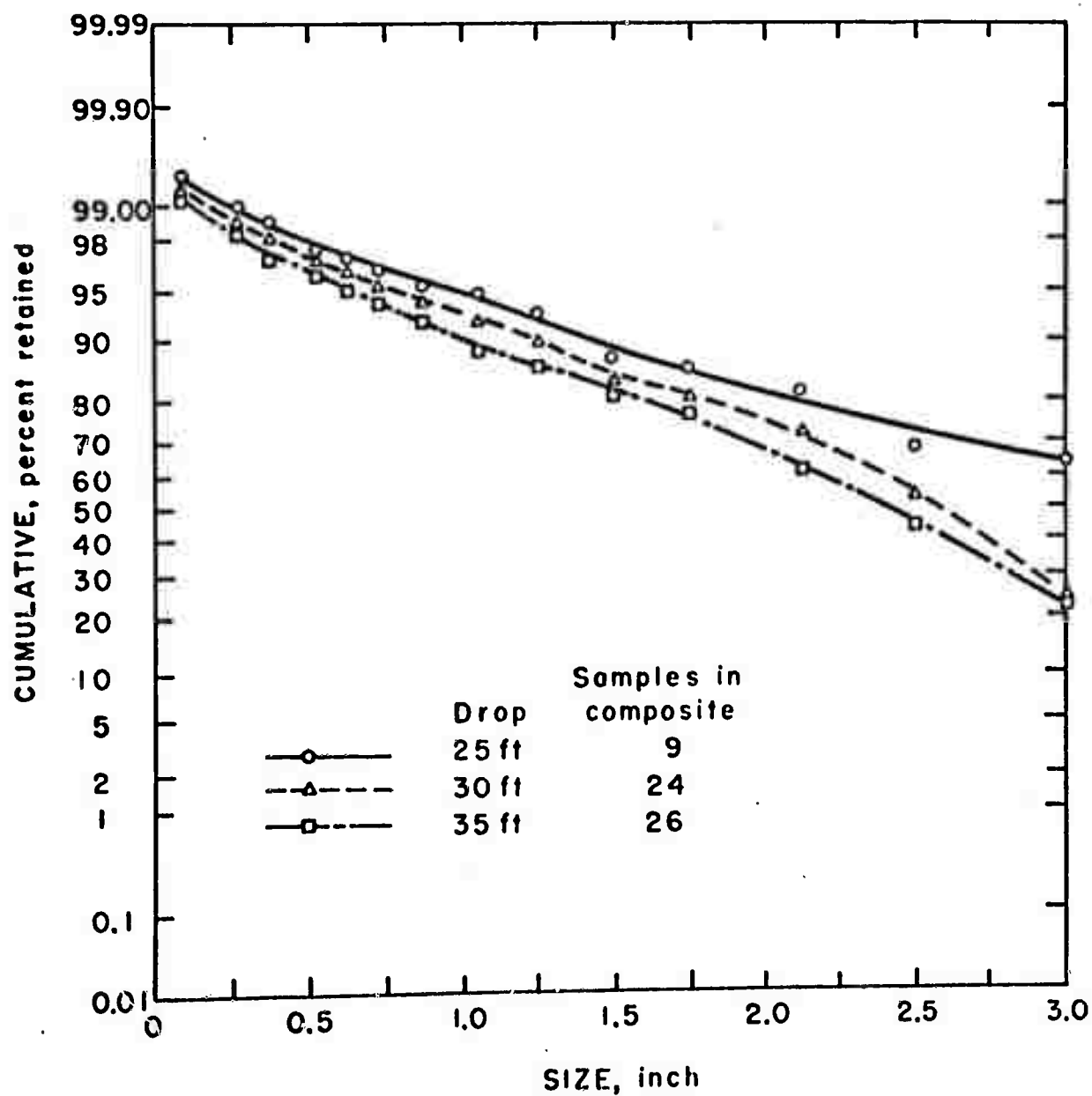


FIGURE 1. - Composite plots for broken Wausau quartzite.

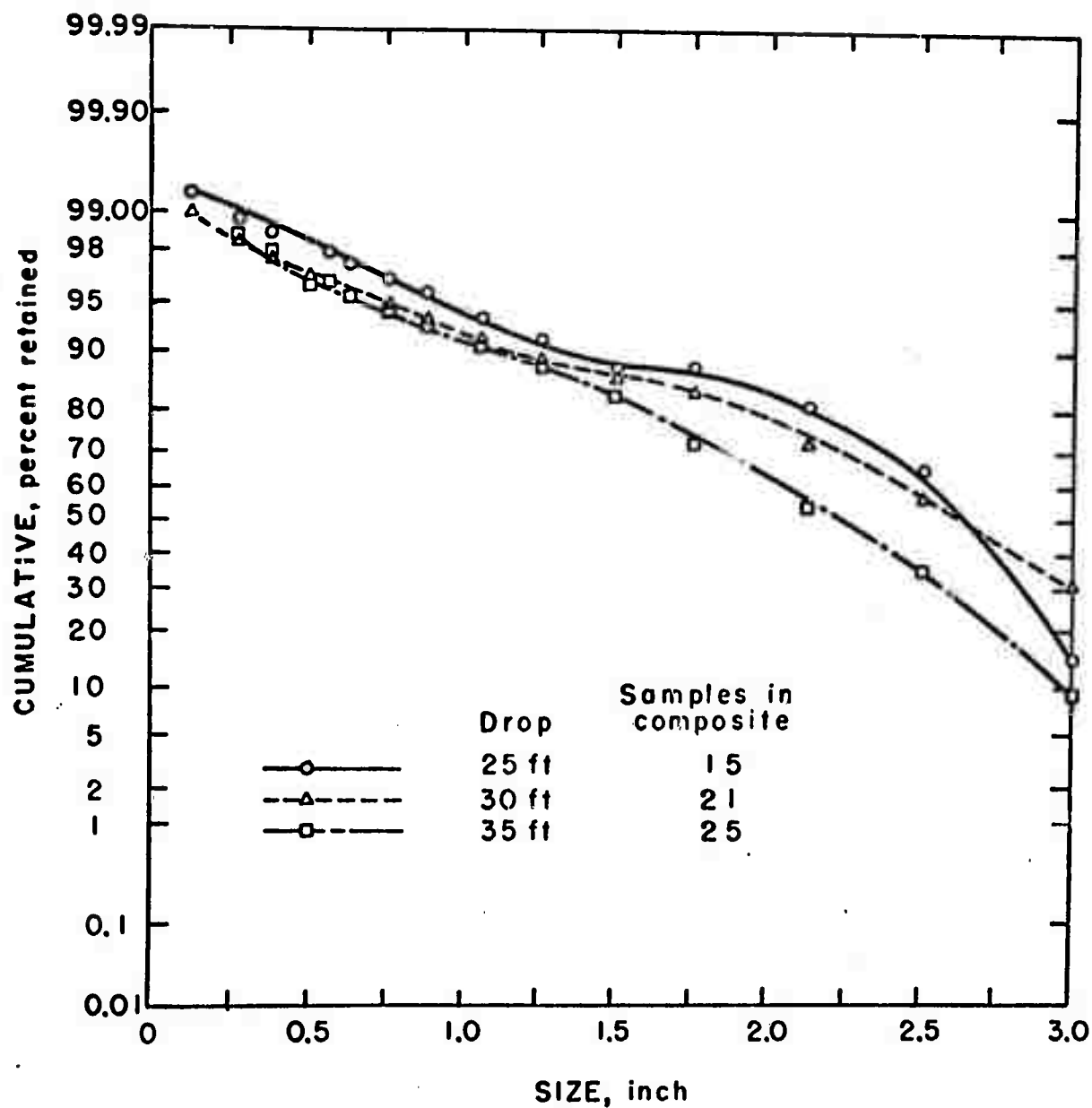


FIGURE 2. - Composite plots for broken anorthosite.

Consequently it was decided to separate the sieve data into two groups, "fines" sieve classes and "coarse" sieve classes. The cut-off point was selected as approximately 1.05 inches for the anorthosite and 1.25 inches for the Wausau quartzite. These two groups were then recompiled (renormalized) separately and each group was plotted separately. Thus where there were three "dual" segment plots before, there are now six separate sets of points and lines for each rock type. These are shown in Figures 3, 4, 5, and 6. These last six lines (on normal paper) were fitted by the least squares procedure. The correlation coefficient for each line showing goodness of fit is also shown on each figure.

DISCUSSION OF DATA ANALYSIS RESULTS

The drop test experiments were performed on random 3.0 to 3.5 inch specimens with the energy level being the only factor varied. The analysis of the distribution results of these experiments showed an apparent significant effect of the level of energy applied on the size distribution parameters.

While it was possible to make these observations based on fitting the data to a negative exponential distribution, it was apparent that this distribution is not sufficiently accurate for our purposes. One reason for this is that the experimental data were always bimodal rather than unimodal, as originally assumed. Subsequent analyses of the data have shown that the fine material can be fitted by a separate normal distribution from the normal distribution describing the major portion of the product.

Certain inconsistencies were observed in the experimental data. Neither the mean size nor the standard deviation of the product varied

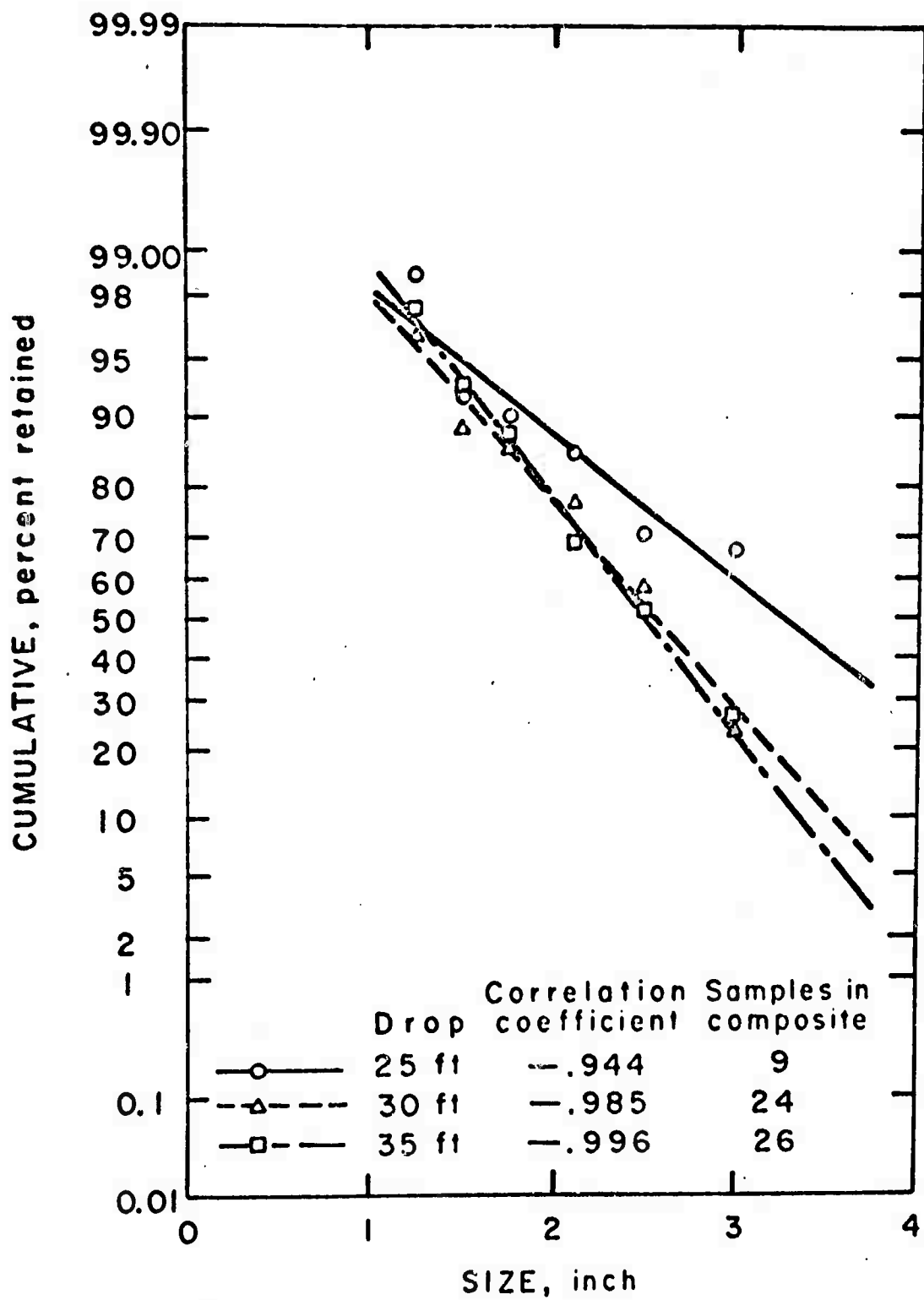


FIGURE 3. - Composite plots for broken Wausau quartzite (large fragments).

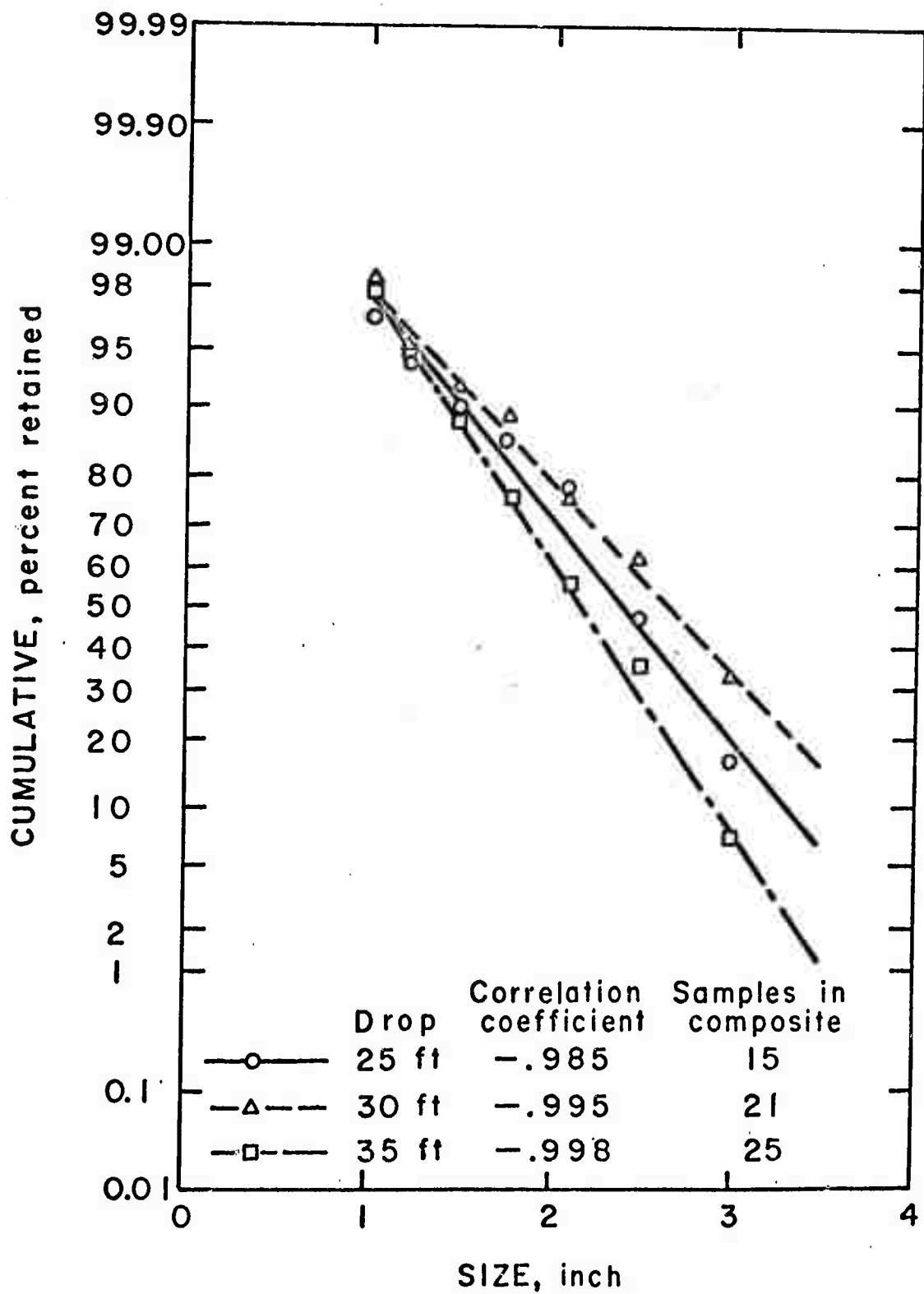


FIGURE 4. - Composite plots for broken anorthosite (large fragments).

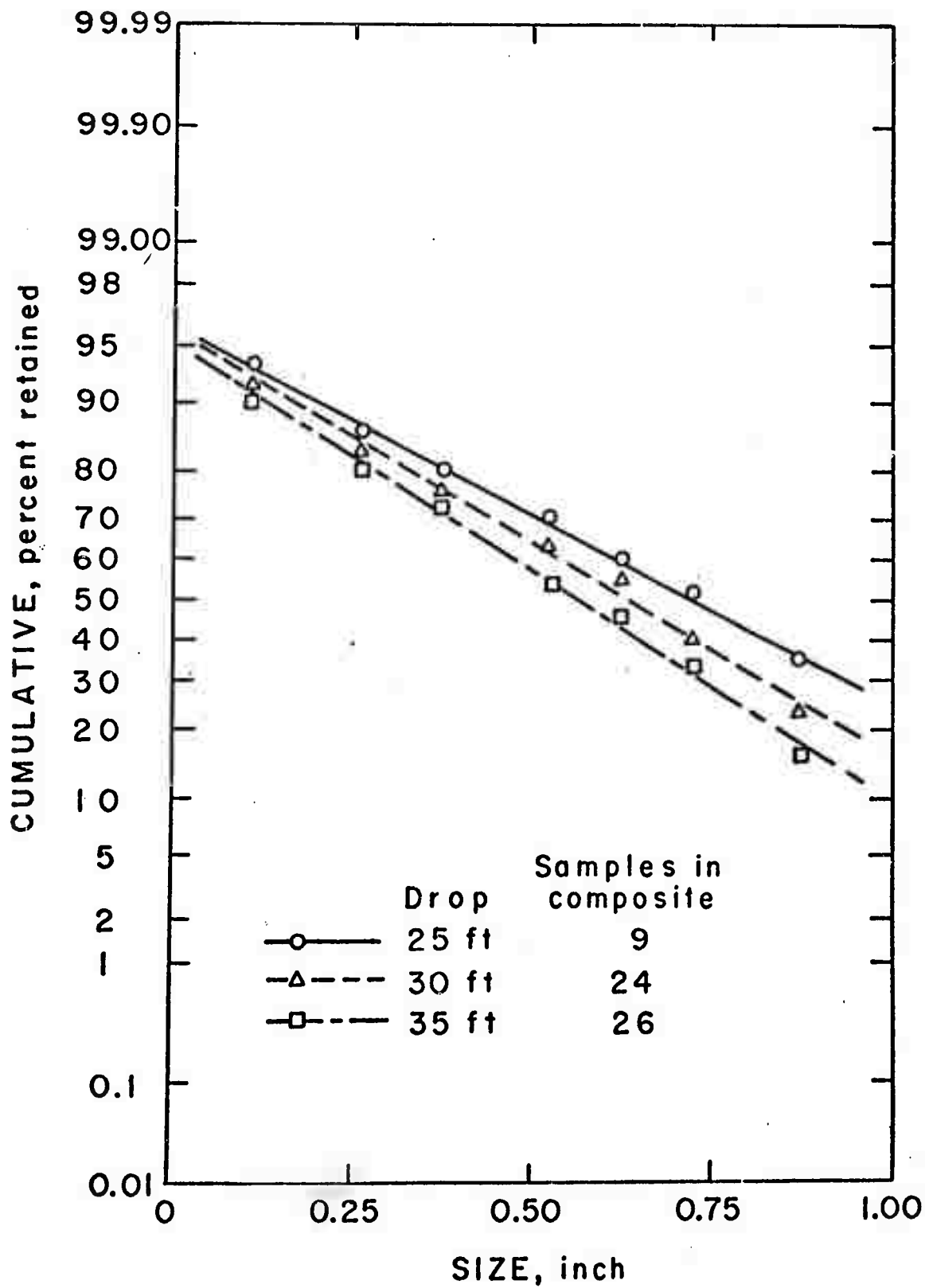


FIGURE 5. - Composite plots for broken Wausau quartzite (small fragments).

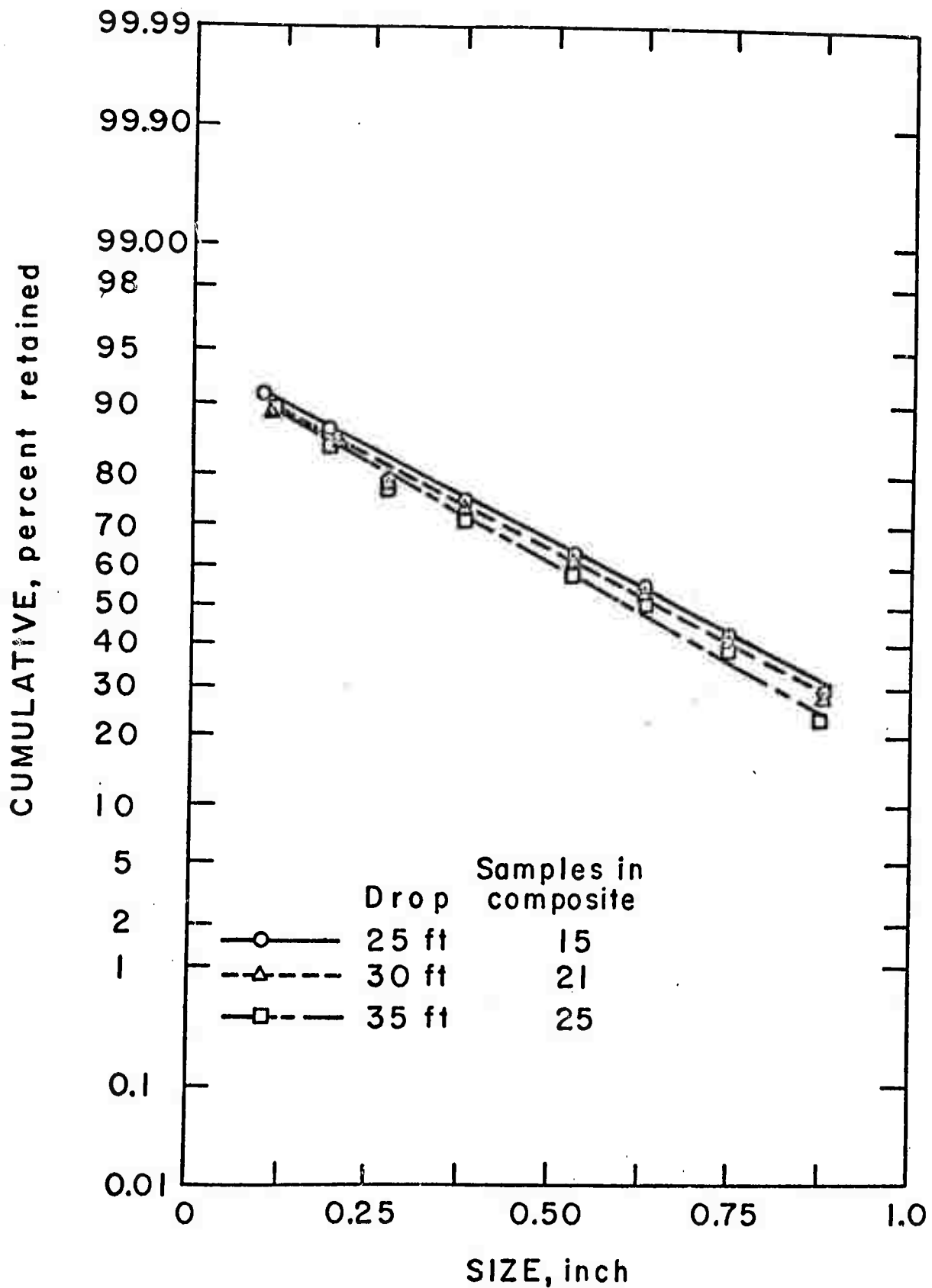


FIGURE 6. - Composite plots for broken anorthosite (small fragments).

in a regular manner with the applied energy. Also the slope of the probability plot fitted lines increased with drop height for the Wäusau quartzite, but did not increase for the anorthosite (see Figures 2 and 3). One cause of these inconsistencies, of course, is that not all the energy goes into breakage. Consequently, a new apparatus was constructed to test the specimens under impact load. Another cause is the small sample sizes that resulted from lack of breakage, particularly in the case of the 25 foot height. Additional specimens were not run to replace those specimens that failed to break, because the impact test procedure was shortly going to replace the drop test procedure.

CONCLUSIONS AND RECOMMENDATIONS

One conclusion to be drawn from the drop tests is that not enough energy was provided by this method of testing. Also in connection with this conclusion, because building size imposed a maximum height and an inadequate energy supply imposed a minimum height, the three drop heights used were not spaced sufficiently far apart to yield totally distinguishable results on fragment distributions. Another problem caused by insufficient energy was that too many variable-size large fragments were obtained. Thus, the recommendation was to go to a test that provided higher energy.