An ASABE Meeting Presentation

Paper Number: 076047

Modeling and Characterization of Biomass Size Reduction

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Written for presentation at the
2007 ASABE Annual International Meeting
Sponsored by ASABE
Minneapolis Convention Center
Minneapolis, Minnesota
17 - 20 June 2007

Abstract. *Forestry and agricultural biomass are modern energy feedstock to produce process heat, power and liquid fuels. Preparation and pre-processing of biomass involve a number of operations including drying, size reduction, and fractionation. Among them, size reduction is one of the important operations, which consumes relatively high amount of energy. Depending on the type of biomass conversion technologies (such as combustion, gasification, fermentation and densification), special particle size ranges of materials is needed. In this paper, the mathematical modeling of particle size distribution of biomass (a fibrous material) during grinding is conducted based on the population balance method. The changes in the size distribution during the primary breakage of a narrow size are studied. The model developed to predict particle size distribution during grinding is validated with experimental data.*

Keywords. Size Reduction, Swichgrass, Cutting Mill, Population Balance

Introduction

Preparation of biomass for biofuel production consists of harvesting or gathering the material from the field, pretreatment and transportation. Pretreatment can be done in the field or in an intermediate place near the harvesting area. Some steps of pretreatments may take place in the final destination where the biomass is utilized (end process). Among all the preparation processes, size reduction has a major role. Relative to the other processes, it consumes most of the energy. There have been many efforts for optimizing the process to make it as efficient as possible. Size reduction is also sensitive to the process, as each end process needs its own special size of material.

Size reduction is a unit operation that is used in many industries like food and mining. During the process of size reduction, one is unable to see the breakup event in detail, instead the distribution of smaller sizes that results from the breakup process can be observed. (Render S. 1990) The distribution depends on the breaking mechanisms that are controlling the process. The breaking mechanism is based on material property, the geometry of the material that is going through the process, and the basis of the size reduction machinery. There are a wide range of size reduction machinery such as cutting mills, hammer mills, attrition mills, and knife mills.

Figure 1 depicts overall ranges of particle sizes and equipment used to generate the sizes. It has been reported that for different burners in combustion and gasification the particle size has to be from 6mm to 50mm (Badger, 2002). For pellet production the particles should be less than 3.2mm (Mani 2003) and for the briquette production particle's size should be in the range of 6-8mm (Samson, 2005). According to US Patent No. 5677154 ethanol production needs a size between 1-6mm of ground biomass. Bio-oil production needs 2mm size of particles. For pyrolysis, the size depends upon the speed of the process. For fast pyrolysis where bio-oil is produced, the smaller the particle is the more efficient the process because of the required high rate of heat transfer. For slow pyrolysis like charcoal making, the size of particle can be as big as 50 mm where the heat treatment is very slow. There are also problems in handling and storage of material depending on the size. The bigger the size the lower the bulk density and it will be more expensive to transport.

There have been many studies on modeling the process of size reduction. In all of the models, it has been attempted to optimize the process by predicting the energy consumption and size distribution of the product. One of the early attempts was proposed by Rittinger and Kick on late 1800 s (see Perry, 1997). It was later modified by Bond in 1952 and 1961. The objective of these models is to help to compare power requirements for various degrees of reduction. Bond developed his idea by introducing the work index that can be determined by Bond Grindability Tests. In all of the tests the characteristic that defines the feed and product is 80% of the passing size. Although the model is very successful for designing and improving the performance of ball mills in mining industries, but the importance of size distribution of the particles is ignored. Modeling of the process of size reduction based on population balance was proposed by Epstein in 1948 (Ramasamy, 2006). It describes the grinding of material in a mill as a rate process in a way similar to a chemical reaction in a reactor. (Austin, 1971) The model includes the size distribution and its change during the grinding and the power drawn by the mill. The objective of this study is to apply the population balance model for the preliminary step of size reduction of switch grass.

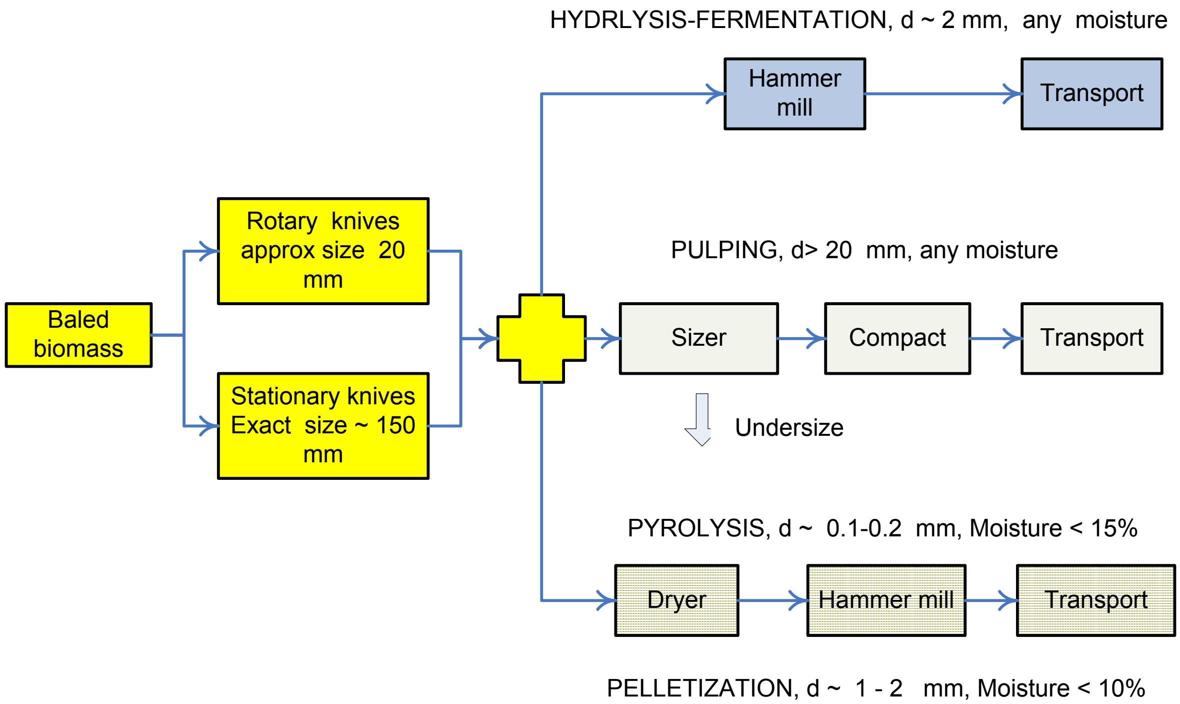

Figure 1. The overall ranges of particle sizes and equipment used to generate the sizes.

The Model

The general form of the model (Mishra, 2000) is:

$$\frac{dx(n,t)}{dt} = [Inflow] - [Outflow] + [Birth] - [Death] \quad (1)$$

Where *x(n,t*) refers to mass or number of particles that belong to each size interval *n* at time *t*. Size interval means sizes between *d* and *d+δd* . Usually these intervals are dictated by the sieve openings. The right hand side refers to the change of *x(n,t*), in time interval dt. For each size interval *inflows* means mass of particles *entering* the control volume and *outflows* refers to the particles *leaving* the control volume. Increase or decrease of the material due to agglomeration and breakage cause the *birth* and *death* of particles in each size interval, respectively.

In batch grinding there is no *inflow* and *outflow*. The death and birth of material is introduced by two characteristics, rate of grinding, *S*(*i*), and breakage distribution parameter, *b*(*i,j*). Based on the general model and definitions the mass-rate balance is: (Austin, 1971)

$$\frac{dx(i,t)}{dt} = -S(i)x(i,t) + \sum_{j=1}^{i-1} x(j,t)S(j)b(i,j) \quad (2)$$

Equation (2) implies that the change of the material in each size interval occurs due to two processes: 1. It decreases because of the size reduction process defined by rate of grinding *S*(*i*). For each size interval *i*, it represents the rate of disappearance of the material due to size reduction. It increases because of the breakage of the bigger particles and adding up to the material on the smaller size intervals. Breakage distribution parameter, *b(i,j)* refers to the material that leaves the size interval *j* and goes to size interval *i*. The two parameters change with time and mill composition because the coarse particles may break differently in the presence of different size distribution of materials in the mill. Figure 2 displays a simplified three size intervals and the mass-rate balance written for them. As it goes from the upper size intervals to lower size intervals the more terms of the summation are considered.

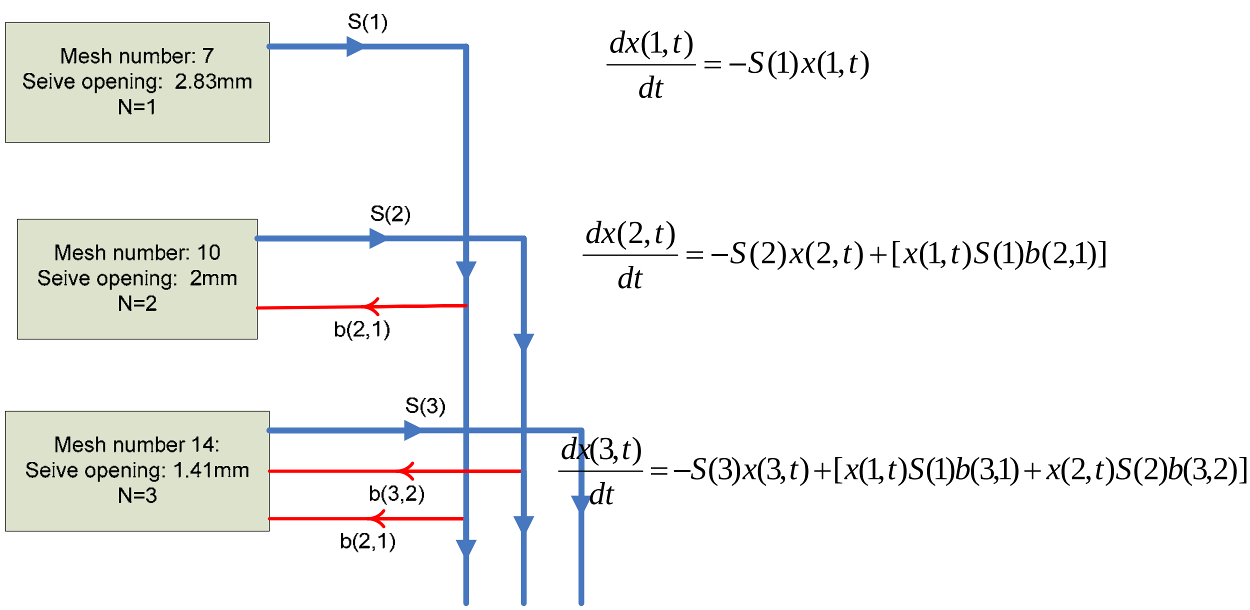

Figure 2. The simplified 3 steps of size intervals and the correspondent mass-rate balance.

Another way of displaying the results is the cumulative breakage distribution, *B(i,j)*. In this case, the size range is split into a number of size intervals and numbered 1 for the top size interval, 2 for the second, and so on down to *n*. *B(i,j)* is then the weight fraction of material broken from size *j* which falls less than upper size of size interval *i*. Cumulative breakage distribution relates to the non-cumulative form by Equation (3).

$$b(i,j) = B(i,j) - B(i+1,j) \quad (3)$$

Klimple (1970) proposed that *S(i)* varies with *S(1)* according to Equation (4):

$$S(i) = S(1)\, f(d_i) \quad (4)$$

In Equation (4), d_i is the mean size of the upper and lower sieve size openings. Each *S(i)* is related to the power drawn by the mill and the mill holdup(Narayanan et al, 1987):

$$S(i) = S^e \frac{P}{y_m} \quad (5)$$

S^e is a characteristic of the material. *P* is the power drawn by the mill and y_m is the percent solids in the mill. It was shown that this model can be applied to a wide variety of types of mill (Austin, 1976). One of the mills that were tested was shredder cutter mill. The results from tests on the grinding of a fibrous material (like corn) were gathered and it was shown that grinding is a first-order process (Jindal, 1975).

$$S(i) = a\, d_i^2 \quad (6)$$

a is a constant. And to a fair approximation:

$$B(i,j)=[d_i/d_j]^6 \quad (7)$$

di and *dj* are the mean size of the upper and lower sieve size openings.

Among all the mills tested, this is the only case in which the relationships that are established for the forms of *S* and *B* satisfy the experimental data.

Data for the grinding rate *S(i)* of different sizes are gathered by batch grinding of narrow size feed.

Materials and method

Switch grass (*Panicum Virgatum, L*) were collected as round bale from a farm in Manitoba. The stalks were precut manually to exactly 7.5cm length. The moisture content was measured according to the ASAE standard (ASAE S358.2 DEC99). Three samples of 25gr each were dried at 103°C for 24h. The average moisture content is 6.5% wb.

The bulk density of the material was measured. A cylindrical container with 24.7cm diameter and 25cm of height was weighted. It was filled with precut 7.5cm length of particles. The filling process was in a manner that the material was pour down in the container from a height of 30cm of the edge of the container until it was filled with the material. The container was tapped a few times. The slight change of the height of the material which was due to the slipping of the particles on each other and filling the empty spaces between themselves inside the container was compensated by adding material and filling the container again. The material and container were weighted. The procedure was repeated three times and the bulk density was calculated to be 46.7 kg/m^3. Two series of tests was conducted. The goal of the first series of the tests was to analyze the size distribution of the particles after one preliminary stage of grinding. The goal of the second tests was to understand the change of grinding rates based on particle size.

First series of tests. The sample of 65gr of materials was weighted and fed to the cutter mill, which is a Retsch model SM 100 with the standard funnel. The sample was gradually hand fed into the grinder. No screen was used in the mill so the outlet of the device was open without screen installed and all the material immediately leaves the grinder. It is assumed that the preliminary stage of grinding is completed in the process. The ground material was collected and sieved by a RoTap shaker. The sieves sizes were ¼, 3½, 5, 7, 10, 14, 18, 25, 35 and 45 mesh respectively. The sieving time was set for 10 minutes (ASAE S319.3). The material on each sieve was recovered in a separate pan and weighed. The sieved materials were well mixed and re-fed to the cutter mill. The product was collected and subjected to the sieve analysis. The material was sieved and the its weight on each sieve was measured. The second grind material also was fed to the cutter mill and the sieving and weighting of the material were repeated. All the procedure was repeated for 5 samples of 65gr of material in each sample. The first two tests were rejected due to errors. The process of mixing, grinding and sieve analysis was repeated for a third time. The data collected from three tests are summarized in Tables 1, 2 and 3.

Second series of tests. All the material from all three grind tests is mixed together for further tests. Four sieves of mesh numbers 7, 10, 14 and18 were selected. The material with smaller size is collected in the pan and was tested as the fifth fraction. Figure 6 shows the picture of the materials for the second series of tests. The outlet of the cutter mill was blocked by a 5mm thick aluminum sheet. In each test 45gr of the material was fed to the cutter mill and let it grind for 25s. The sheet was removed and the material inside the grinder collected. It has been sieve analyzed by shaker and the material on each sieve was weighed. The collected data are included in Tables 4 to 8.

Results

For the first series of tests the distributions of the fractions based on the total weight are shown in Figure 3. It is shown that when more steps of grinding proceeds the particles size of the product gets smaller and fits narrower size interval. The cumulative weights are depicted in Figure 4. The trend is close to log-normal distribution. The correlations for the data based on log-normal distribution are also shown in Figure 5. The correlations constants are shown in Table 9. It is shown that as the more steps of grinding completed the log-normal distribution fails to match with the data.

Figure 6 shows the picture of the materials for the second series of tests. For all the 5 fractions, the bulk density (ρ_b) of the material was measured according to ASAE S269.4 . The third column of table 10 shows that bulk density is increases with the particle size. The particle density(ρ_s) is measured with multi-pyconmeter with Nitrogen. Column 4 of Table 10 shows that particle density is increasing as the particle size increases. This shows that although the material is switch grass and it is expected to have the same particle density for all the particle sizes, but an increase is observed for the particle density as the particle size increases. The porosity of the particles is calculated according to Equation 8.

$$\varepsilon_p = 1 - \frac{\rho_b}{\rho_s} \qquad (8)$$

Porosity is calculated and shown for each size interval in column 5 of Table 10. Porosity tends to decrease with the size increase except in one case.

Tables 4 to 8 show the results with the goal of grinding rate measuring. *b(i,j)* has also been measured for each fraction. Based on the results in the first row of Tables 4 to 8, the grinding rate can be calculated. The data of the remaining rows shows how the ground material is distributed to the lower size intervals, *b(i,j)*'s. The calculated grinding rates are summarized in the last column of Table 10. The data for the three fractions on mesh 10, 14 and 18 are showing a trend but the first and last fractions are far from the other ones. That is because for these two fractions the material is a mixed of wide range of sizes so it is rejected. For predicting a trend for grinding rate additional tests for narrow size intervals are required.

Conclusion and Future work

Biomass utilization consists of several steps such as collection, size reduction and fractionation. Size reduction is an important step as it is the main consumer of energy. Also it is sensitive because each end process needs its special size or narrow size range of biomass particles. The aim for this paper is to understand the relation between grinding rate *S(i)* and size of the particles. Five grinding rates are measured. As the first and the last one was for a mixture of sizes, only three of them can be considered. It has been realized that additional tests has to be performed to complete the data.

For the size distribution of the particles the log normal distribution can predict the first steps of grinding. As the grinding proceeds the other distributions has to be examined and the best distribution defined.

Nomenclature

a constant;

b(i,j) weight fraction of material broken out of size interval j which falls into interval I;

B(i,j) weight fraction fo material broken from size interval j which falls less than upper size interval I;

di mean size of the upper and lower sieve size opening;(mm)

i size interval;

j size interval;

N sieve fraction counter;

P power drawn by the mill;(w)

S(i) grinding rate of material in size interval i;(s^{-1})

S^e grinding characteristic of the material;

t time;(s)

x weight fraction;

y_m percent of the solid in mill;

ε_p porosity;

ρ_b bulk density;(kg/m^3)

ρ_s particle denstiy; (kg/m^3)

Table 1. The weight on each sieve for the first grind.

First Grind, Sieving time: 10min			
Feed (gr)→	65	65	65
Sieve Opening(mm)	1st Run	2nd Run	3rd Run
0.000	0.59	0.66	0.67
0.345	0.20	0.19	0.23
0.5	0.55	0.51	0.57
0.707	1.83	1.41	1.78
1.000	7.55	6.52	7.23
1.410	13.00	13.14	12.73
2.000	13.70	14.01	13.54
2.830	13.05	13.56	12.93
4.000	6.40	6.36	7.1
5.650	4.04	4.26	4.38
6.35	3.81	4.33	3.65
Total	64.72	64.95	64.81

Table 2. The weight on each sieve for the second grind.

Second Grind, Sieving time: 10min			
Feed (gr)→	64.72	64.95	64.81
Sieve Opening(mm)	1st Run	2nd Run	3rd Run
0.000	1.11	0.90	1.21
0.345	0.41	0.38	1.37
0.5	1.28	1.20	1.37
0.707	5.44	4.77	5.4
1.000	13.94	13.66	14.23
1.410	16.21	16.56	16.39
2.000	11.50	12.03	12.10
2.830	8.63	13.56	12.93
4.000	3.43	3.36	2.58
5.650	1.07	0.96	1.17
6.35	1.00	1.13	1.01
Total	64.02	64.37	64.61

Table 3. The weight on each sieve for the third grind.

Third Grind, Sieving time: 10min			
Feed (gr)→	64.02	64.37	64.61
Sieve Opening(mm)	1st Run	2nd Run	3rd Run
0.000	1.43	0.69	1.65
0.345	0.53	0.66	1.67
0.5	2.52	2.16	2.37
0.707	7.85	8.13	8.88
1.000	17.37	17.37	17.59
1.410	17.43	17.43	16.10
2.000	8.83	8.83	9.44
2.830	5.73	5.37	5.44
4.000	1.06	1.06	1.25
5.650	0.37	0.37	0.35
6.35	0.40	0.40	0.44
Total	63.25	63.47	64.54

Table 4.Grinding rate of the material on sieve with Mesh 7

Feed: Material on Mesh 7		
Weight of sample before grinding(gr)		45
Weight of sample after grinding(gr)		44.45
Grinding time(s)		30
Sieving time(min)		10
mesh no.	Sieve Opening,mm	weight(gr)
7	2.83	5.24
10	2	3.22
14	1.41	3.27
18	1	6.24
25	0.707	8.29
Pan		17.85
Total		44.11
Grinding rate,s-1= 0.029403825		

Table 5.Grinding rate of the material on sieve with Mesh 10

Feed: Material on Mesh 10		
Weight of sample before grinding(gr)		43
Weight of sample after grinding(gr)		42.77
Grinding time(s)		25
Sieving time(min)		10
mesh no.	Sieve Opening,mm	weight(gr)
10	2	5.59
14	1.41	5.15
18	1	7.18
25	0.707	8.46
35	0.5	5.93
Pan		10.06
Total		42.37
Grinding rate,s-1= 0.34772		

Table 6.Grinding rate of the material on sieve with Mesh 14

Feed: Material on Mesh 14		
Weight of sample before grinding(gr)		45
Weight of sample after grinding(gr)		44.77
Grinding time(s)		25
Sieving time(min)		10
mesh no.	Sieve Opening,mm	weight(gr)
14	1.41	8.39
18	1	8.40
25	0.707	9.78
35	0.5	6.63
45	0.354	3.41
Pan		8.05
Total		44.66
Grinding rate,s-1= 0.32504		

Table 7.Grinding rate of the material on sieve with Mesh 18

Feed: Material on Mesh 18		
Weight of sample before grinding(gr)		45
Weight of sample after grinding(gr)		44.04
Grinding time(s)		25
Sieving time(min)		10
mesh no.	Sieve Opening,mm	weight(gr)
18	1.	11.92
25	0.707	12.25
35	0.5	7.45
45	0.354	3.62
60	0.25	3.14
Pan		5.64
Total		44.02
Grinding rate,s-1= 0.29173		

Table 8. Grinding rate of the material on Mesh 25

Feed: Material on Mesh 25		
Weight of sample before grinding(gr)		45
Weight of sample after grinding(gr)		44.5
Grinding time(s)		25
Sieving time(min)		10
mesh no.	Sieve Opening,mm	weight(gr)
25	0.707	15.42
35	0.5	10.3
45	0.354	5.75
60	0.25	4.85
80	0.177	3.28
Pan		4.77
Total		44.37
Grinding rate,s-1= 0.021783		

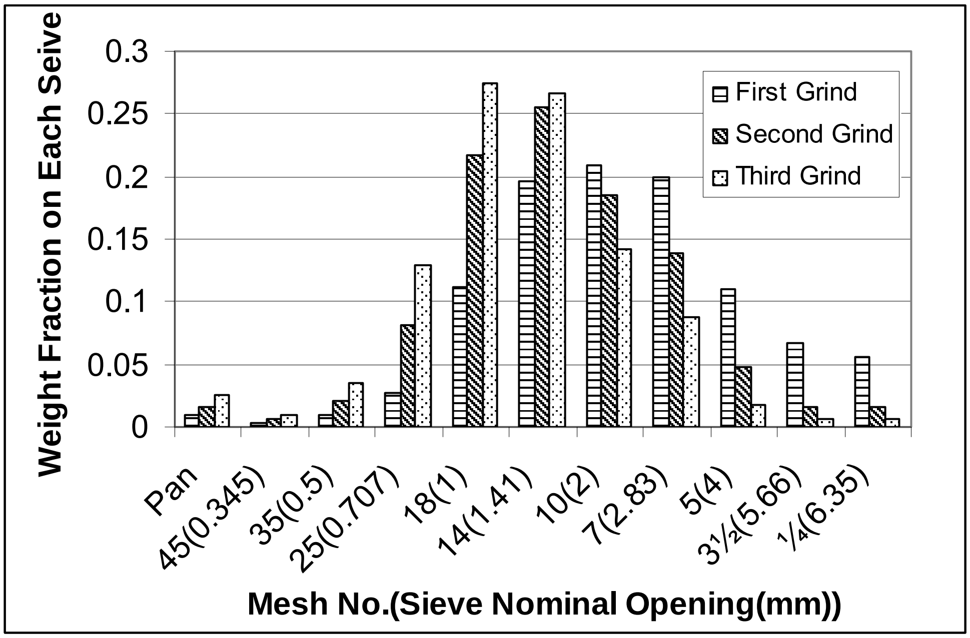

Figure 3. Size distribution of switch grass grind: Fraction vs. Mesh Number.

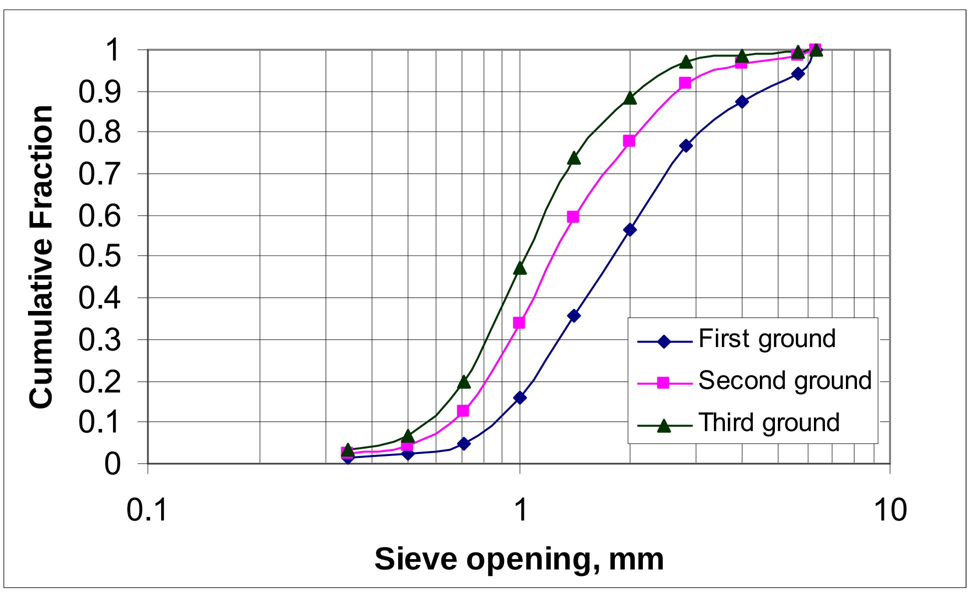

Figure 4 .Cumulative size distributions of the three grinds vs. sieve opening.

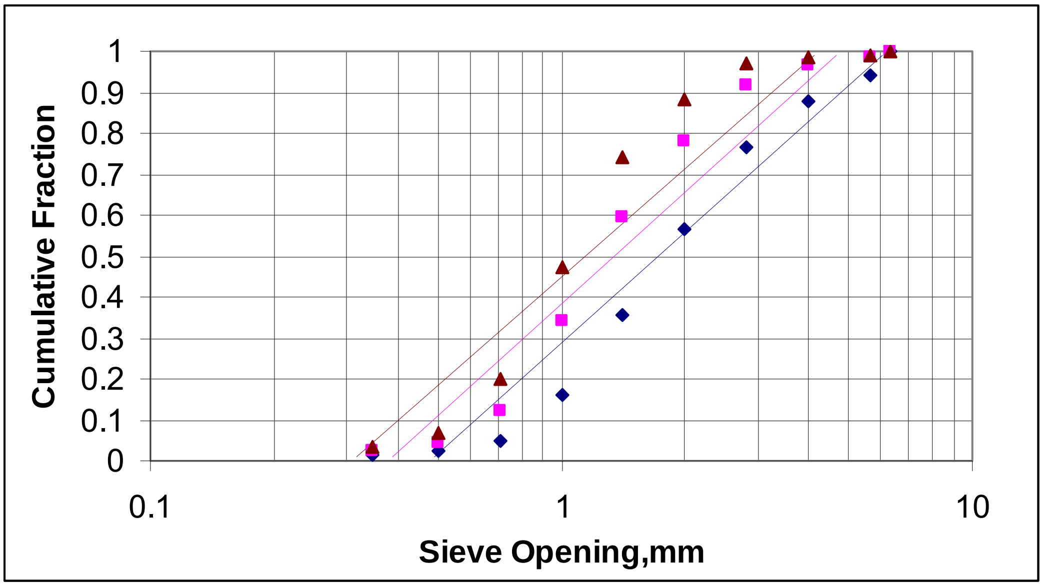

Figure 5. The cumulative fractions with their corresponding correlations.

Table 9. The Log-Normal Distribution for the Three Grinds

Y=a log(x)+ b			
Grind	a	b	R^2
1	0.89	0.29	0.955
2	0.90	0.38	0.945
3	0.87	0.45	0.91

Figure 6. Pictures of the material stays on different sieves

Table 10. Bulk density, particle density and porosity of the material on each sieve.

Mesh No.	SieveOpening, mm	Bulk Density, kg/m3	Particle Density, kg/m3	Porosity	Grinding rate, S(i), s^{-1}
∞/7	2.8	79	691(±9)	0.88	0.0299
7/10	2.0	92	715 (±12)	0.87	0.3477
10/14	1.41	107	745(±18)	0.85	0.3250
14/18	1.00	143	782(±9)	0.82	0.2917
18/∞	0.707	148	927(±5)	0.84	0.0218

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