TECHNICAL UNIVERSITY OF CRETE

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CRUSHING OF CLAY BEARING LIMESTONE AND SERPENTINE USING A NOVEL CENTRIFUGAL CRUSHER

SUBMITTED IN THE PARTIAL FULFILMENT OF REQUIREMENT FOR INTERNATIONAL MATERS IN ADVANCED CLAY SCIENCE

BY

E M E J U L U C H U K W U D U B E M A N T H O N Y

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iv. **Scope**

The reason for this project is to fulfill the requirement of International Masters in Advanced Clay Science (IMACS).

The aim for this project is to define specific energy needs for a different a material with different samples using a prototype mill (a novel centrifugal crusher) various rotational speeds (rpm).

v. **Acknowledgement**

I thank the European Union for giving me this opportunity to study International Masters in Advanced Clay Science and explore life and cultures of different European countries.

My deepest gratitude goes to my supervisor Professor Elias Th.Stamboliadis for his valuable advice and guidance, critics and friendship throughout the whole duration of my work as well as for providing the necessary materials for the research work. Thank you for your advice, guidance, and encouragements. I have learned a lot from you including the essence of scientific research works.

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In preparing this thesis, I was also in contact with many people, researchers, Academicians and practitioners. They have contributed towards my understanding and thoughts; I own them my sincere gratitude.

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I am as many thanks to the supervising committee Prof. Kostas Komnitsas and Lecturer E.Steiakakis for they candid advice.

vi. **Abstract**

Crushing machines which are normally used for particle size reduction consume energy and the demand to select a crusher with less energy consumption is growing rapidly. The aim of this study is to find the specific energy needs to crush materials with different properties. For this study, a prototype mill (a novel centrifugal crusher) designed in Technical University of Crete; Greece was used to crush the samples. Two samples, namely Limestone from Kounoupidiana, northern part of Chania and Serpentine from Mantoudi, northern part of Euboea Island Greece were used. The samples were first crushed using a jaw crusher and classified into different size fractions. These size fractions were crushed with a novel centrifugal crusher by varying the rotational speed (rpm). The cumulative percentage passed and quantity of the produced mass finer than size x per Joule of the energy consumed (K) were determined. The result of this research work indicates that with the same energy, the bigger size fractions crush more and faster than the smaller ones.

vii. **Summary**

Two samples were used namely Marly Limestone which was collected from Kounoupidiana in the northern part of Chania Greece, and Serpentine from Mantoudi in the northern part of Euboea Island Greece.

They were crushed in the jaw crusher to reduce the size, and screened for grading of the materials to produce different size fractions (16-22.4mm, 8-11.2mm, 4-5.6mm, 2-2.8mm and 1-1.4mm).Each size fractions was crushed in a novel centrifugal crusher at different rotational speed (rpm). Second screen was carried out to find out the products of the crushing for each different sample, and weight measurement of each product to see the cumulatively passing%.

This equation was used $\varepsilon = (2.\pi.R.N)^2$ (where ε –Specific Energy.R - radius and N-Frequency) to find the specific energy, that depends on velocity $V=\sqrt{2}.\pi.2.R.N$.

Constant '*K*' was calculated by using this formular $P=Ro.\ (1-\exp(-K.\varepsilon)$ where P-is the produced %, in this case is the same with cumulatively passing, Ro-100(because all the particles in the size fraction are bigger than the particles of the products). The unit of the K=kg/J meaning the number of crushing in the kilos per Joule.

Mineralogical analysis (X-ray diffraction, Optical mineralogy)

X-ray diffraction (XRD) having wavelengths similar to the inter-atomic distances in crystals, they interact with a crystal lattice in the same way that light interacts with a conventional diffraction grating or with the tracks of a compact distances. X-rays are dispersed in different directions according to the wavelength. W.H. and W.L. Bragg showed that the diffraction of X-rays by crystals is described by $n\lambda = 2d\sin\theta$. Measurement of the various θ angles can be used to determine the inter-planar spacing d characteristic of the diffracting crystal. By diffracting crystal allows identification of element represent in the sample. For the study, we used BRUCKER - D8 Advance XRD spectrometer to identify crystals in the sample.

Optical mineralogy is the study of minerals and rocks by measuring their optical properties. Most commonly, rock and mineral samples are prepared as thin sections or polished sections for study in the laboratory with a petrographic microscope. For the present study, we used the polished sections, the dimension of grains bigger than 2mm; identified the mineralogical composition of materials in order to reveal their origin and evolution.

1. **Experimental Part**

1.1.0. Description of Materials

Marly Limestone and Serpentine were used

1.1.1. *Marly Limestone*

Limestone is a sedimentary rock composed largely of the minerals calcite and aragonite, which are different crystal forms of calcium carbonate($CaCO_3$). Many limestones are composed from skeletal fragments of marine organisms such as coral or foraminifera.

Fig1. *Marly Limestone*

Google

Fig2. *Thin Section of Marly Limestone with some impurities into it.*

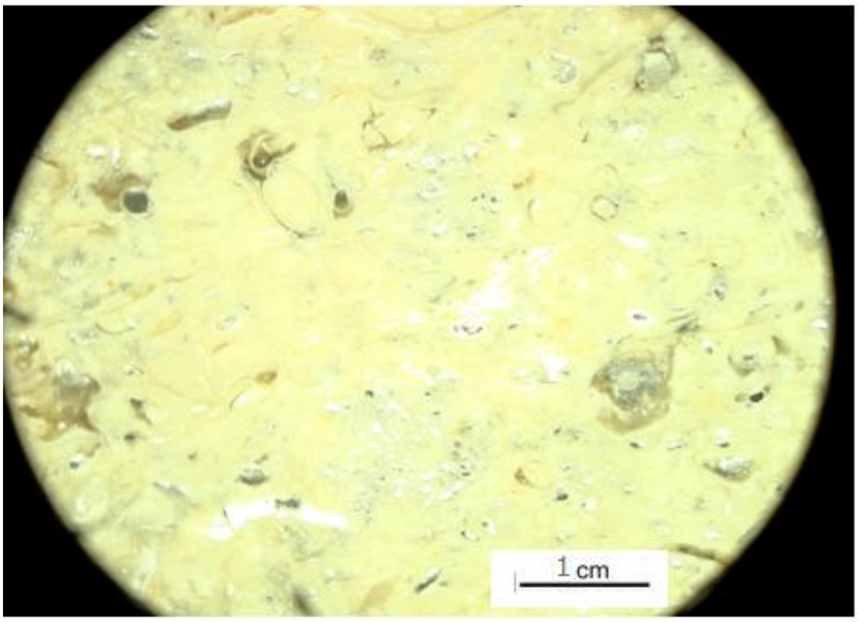
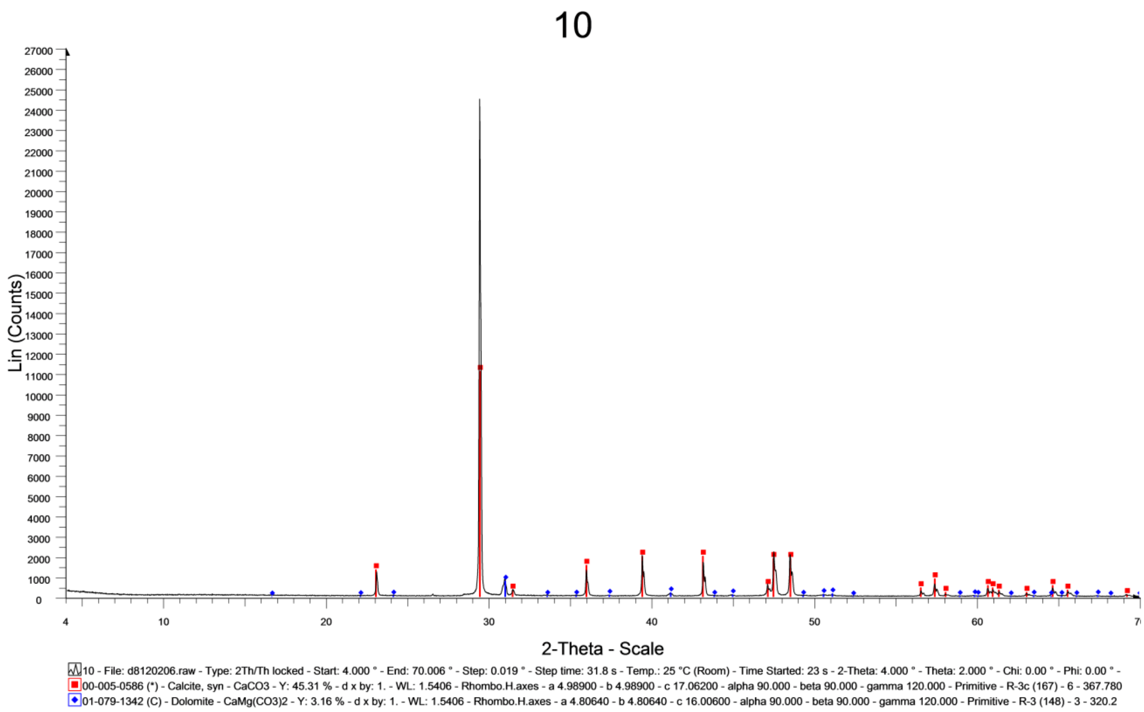


Fig3.shows XRD Pattern of Marly Limestone



XRD Pattern shows Dolomite and Calcite

This mineralogical analysis shows that marly limestone contains Dolomite and Calcite

1.1.2. Serpentine

Serpentine is a soft, green, grey, yellow or white, Mg-rich phyllosilicate with the general formula Mg3 [Si2O5](OH)4 tri-octahedral with a characteristic basal spacing of 0.7 nanometre (Deer et al. 1992). The main types of serpentine are: chrysotile (fibrous); lizardite (platy); and antigorite (elongate, and known as picrolite when fibrous). Chrysotile in fibrous form is the most common form of asbestos.

Fig 4. *Serpentine*

Fig5. *Thin Section of Serpentine* with *water in side and it oxidized at a bigger magnification. And the two crystals are not combining together because of the water space in between.*

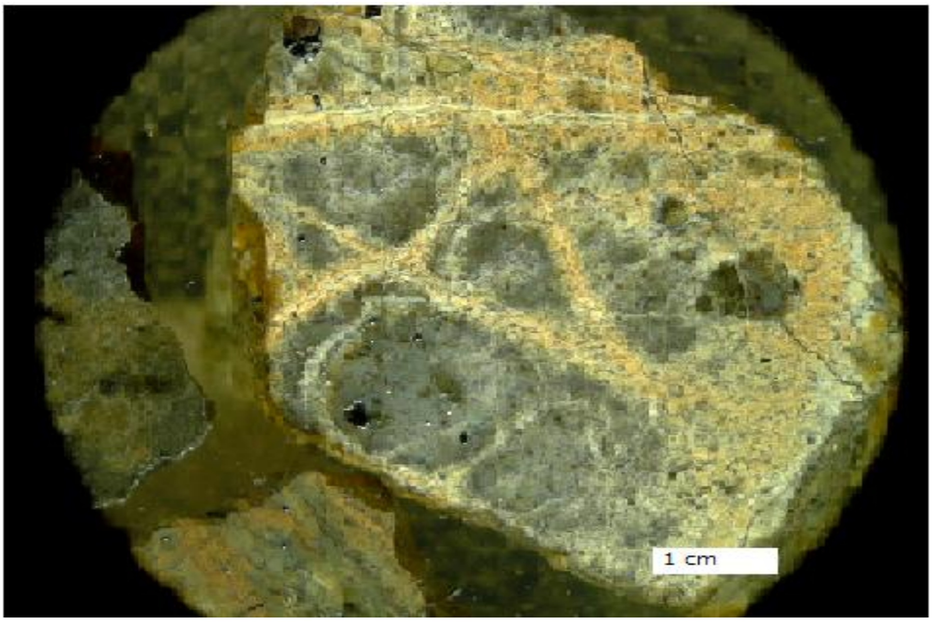
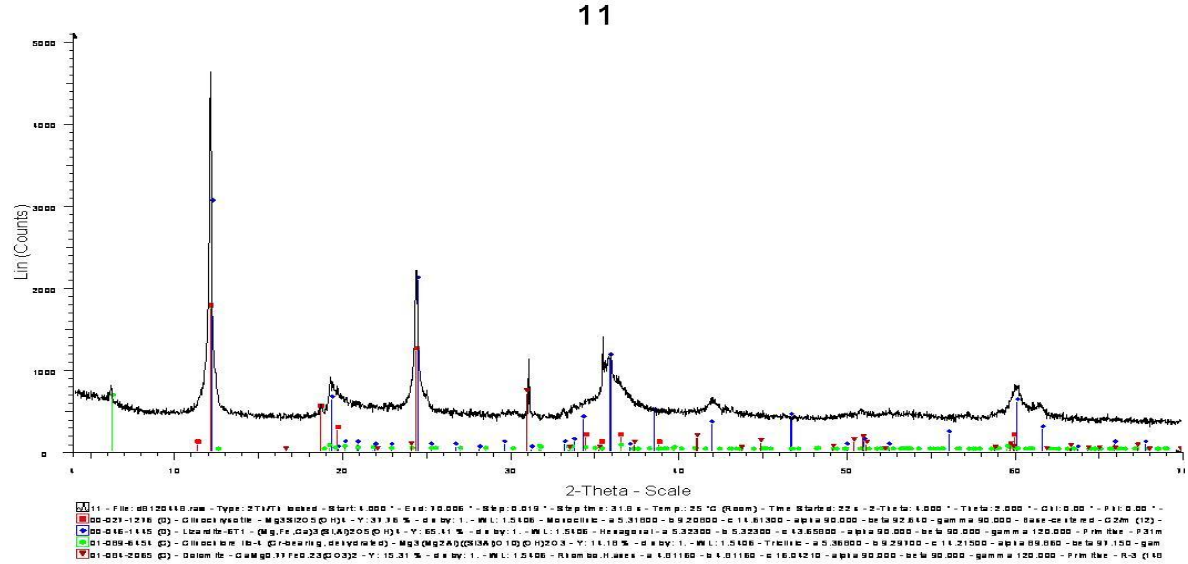


Fig6.*shows XRD Pattern of Serpentine*



XRD Pattern of Serpentine indicates Clinochrysotile, Dolomite, Lizardite and Clinochlore

In this mineralogical analysis some minerals were identified like Clinochrysotile, Dolomite, Lizardite and Clinochlore.

2. Technical Description of the Centrifugal Crusher

Centrifugal crusher was designed for inert materials based on the design structures

Centrifugal Crusher

This novel centrifugal crusher was designed by Prof.Stambolidis Elias, and is described by Dimitris Stambolidis. It is suitable for all types of material, including extremely hard input materials. Every single particle of the input material undergoes extreme acceleration in a patented chamber and is subsequently thrown against the fixed impact wall. The impact wall consists of hard steel blade.

Fig7. *Centrifugal crusher showing hard steel blade*

The crushing result can be decisively influenced by selecting the appropriate rotation speed. The rotation speed per minute can go from lower 750rpm to higher 2500rpm. The diameter of spinning plate is 0.5m and the angle of the blade is at 45°.

- Theory used to find the Specific Energy

The theoretical analysis presented below was provided by Prof.Elias Stambolidis

Assume a disk of radius *R* with a diametrical bar on its surface passing through its center. The disc rotates horizontally with a frequency *N* and any particle on it, is forced to rotate by the bar. Let a particle of mass *m* be at a distance *r* from the center of rotation. At this point it has a peripheral velocity given by eq.1

$$v_p = 2 \cdot \pi \cdot r \cdot N \tag{1}$$

On the particle acts a centrifugal force F_c that is related to its peripheral velocity according to eq.2 $F_c = \frac{m \cdot v_p^{\,2}}{r}$ (2)

The centrifugal force moves the particle to the perimeter with an acceleration calculated by Newton's law given in eq.3. $F_c = m \cdot \gamma_c$ (3)

Substituting (1) and (2) into (3) we have eq.4

$$\gamma_c = (2 \cdot \pi \cdot N)^2 \cdot r \tag{4}$$

From the laws of motion one has the relation between velocity, time t and acceleration given in eq.5 as well as that of velocity, time and radius given by eq.6

$$\frac{dv_c}{dt} = \gamma_c \quad (5) \qquad\qquad \frac{dr}{dt} = v_c \quad (6)$$

Equating and deleting dt from (5) and (6) one has eq.7

$$\frac{dv_c}{\gamma_c} = \frac{dr}{v_c} \qquad \text{OR} \qquad v_c \cdot dv_c = \gamma_c \cdot dr \tag{7}$$

Substituting (4) into (7) one has the differential eq.8 that relates the centrifugal velocity to the radius, that is the distance from the center of rotation.

$$v_c \cdot dv_c = (2 \cdot \pi \cdot N)^2 \cdot r \cdot dr \tag{8}$$

The integration of (8) as explained in appendix A is given by eq.9

$$v_c = 2 \cdot \pi \cdot N \cdot r + C \tag{9}$$

For r=0 then V_C=0 and consequently C=0

At the moment when the particle escapes from the disc r =R and the centrifugal axial velocity is given by (10). $V_c = 2 \cdot \pi \cdot R \cdot N$ (10)

At the same moment the peripheral velocity is given by eq.11 as is equal but vertical to the centrifugal velocity

$$V_p = 2 \cdot \pi \cdot R \cdot N \tag{11}$$

The vector sum of these two velocities is the actual escaping velocity V that is calculated from eq.12 $V^2 = V_c^{\,2} + V_p^{\,2}$ (12)

Taking into consideration (10) and (11) the final velocity is given by eq.13 and has a direction of 45° relative to the radius of the disc at the moment of escape.

$$V = 2 \cdot \sqrt{2} \cdot \pi \cdot R \cdot N \quad \text{OR} \quad V = \sqrt{2} \cdot \pi \cdot D \cdot N \tag{13}$$

Where D is the disc diameter *D=2R*

The kinetic energy E of a particle with velocity V is given by eq.14

$$E = \frac{1}{2} \cdot m \cdot V^2$$

(14)

Substituting (13) into (14) the kinetic energy of the particle at the escape point from the disc is given by eq.15

$$E = m \cdot (2 \cdot \pi \cdot R \cdot N)^2 \quad \text{OR} \quad E = m \cdot (\pi \cdot D \cdot N)^2 \tag{15}$$

The specific energy $e=E/m$ is then given by eq.16 and independent of the particle mass.

$$e = (2 \cdot \pi \cdot R \cdot N)^2 \quad \text{OR} \quad e = (\pi \cdot D \cdot N)^2 \tag{16}$$

In this case the radius is R= 0.25m, the frequency is given in RPM and N is calculated from the equation N=RPM/60.

In conclusion the specific energy depends only on the frequency, and radius of the centrifugal crusher, calculation was made for five different specific energy, because five different rotational speeds per minute were chosen for 750rpm-specific energy 385 J/kg, 1000 rpm - e=685,1500rpm e=1541,2000rpm e= 2739 and 2500rpm - e=4279 The initial specific energy e_0 =0.

2.2. Procedure

Scheme and Preparations

Samples used are Marly Limestone and Serpentine.

- ***Marly Limestone*** was collected and dried overnight and crushed in jaw crusher to reduce the size; the crushed material came in various shapes and sizes, and then uniformly separated into size fractions by selected sieves with decreasing apertures. Five different size fractions (16-22.4mm, 8-11.2mm, 4-5.6mm, 2-2.8mm and 1-1.4mm) were obtained and separated into 5 bags after making 5kg of each fractions

Fig8. Different Size Fractions of Limestone

- ***Serpentine*** was collected dried and the same procedure for crushing, sieving and separating into different size fraction was followed.

Fig9.Different Size Fraction of Serpentine

From each bag(5kg), 1000g of sample (feed) were taken and crushed in centrifugal crusher, at different rounds per minute (750rpm, 1000rpm, 1500rpm, 2000rpm and 2500rpm). After crushing, 25 samples were made from the five different feeds at five different rotational speeds, and screen for each sample, from different size fraction. Nine products of 16-22.4mm were made on 16, 8, 4, 2, 1, 0.5, 0.25, 0.125, 0.063 mm sieves. Eight products of feed for 8-11.2mm, seven products of feed for 4-5.6mm, six products of 2-2.8mm and five products of 1-1.4mm were made. The weight of each product was measured and used for calculation of cumulatively passing% for each feed.

3. Results

Table1. Shows the Alteration of RPM to Specific Energy

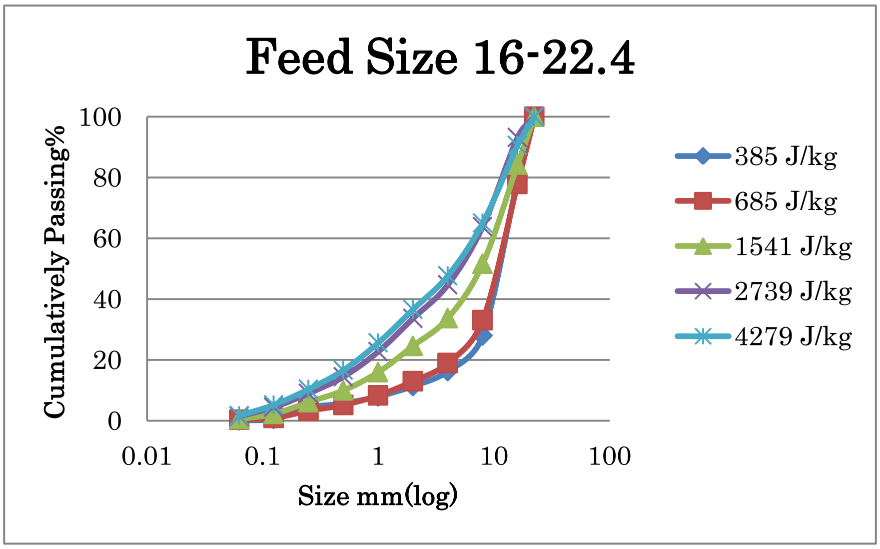
RPM	$N = \frac{RPM}{60}$	$V = (\pi \cdot D \cdot N)$	$Vo = (\sqrt{2} \cdot V)$	$E = [(\frac{1}{2}) \cdot m \cdot (Vo)^2]$	Specific Energy $\varepsilon = \frac{E}{m}$
750	12.5	19.6	27.75	385.14	385.14
1000	16.7	26.2	37.01	684.69	684.69
1500	25.0	39.3	55.51	1540.56	1540.56
2000	33.3	52.3	74.01	2738.78	2738.78
2500	41.7	65.4	92.51	4279.34	4279.34
Units	**Hertz**	**m/s**	**m/s**	**Joule**	**J/kg**
D=0.5m					
m=1 kg					
π=3.14					

3.1. Marly Limestone

Table 2. Indicates the cumulatively Passing % of feed (**16-22.4mm**).

RPM	0	750	1000	1500	2000	2500
J/kg	0	385	685	1541	2739	4279
Screen Size mm	**Cumulatively Passing %**					
22,4	100	100	100	100	100	100
16	0	79,20	77,89	84,25	93,18	90,59
8	0	28,00	33,06	51,63	63,84	65,06
4	0	16,30	18,97	33,74	44,73	47,70
2	0	11,40	12,98	24,59	33,68	36,61
1	0	8,00	8,32	15,96	22,73	25,63
0.5	0	5,70	5,17	9,96	14,46	16,63
0.250	0	4,30	3,25	6,10	8,99	10,36
0.125	0	0,60	0,91	2,24	4,44	5,23
0.063	0	0,10	0,30	0,51	1,45	1,67

Fig10. Cumulatively Passing % vs. Size mm (log)



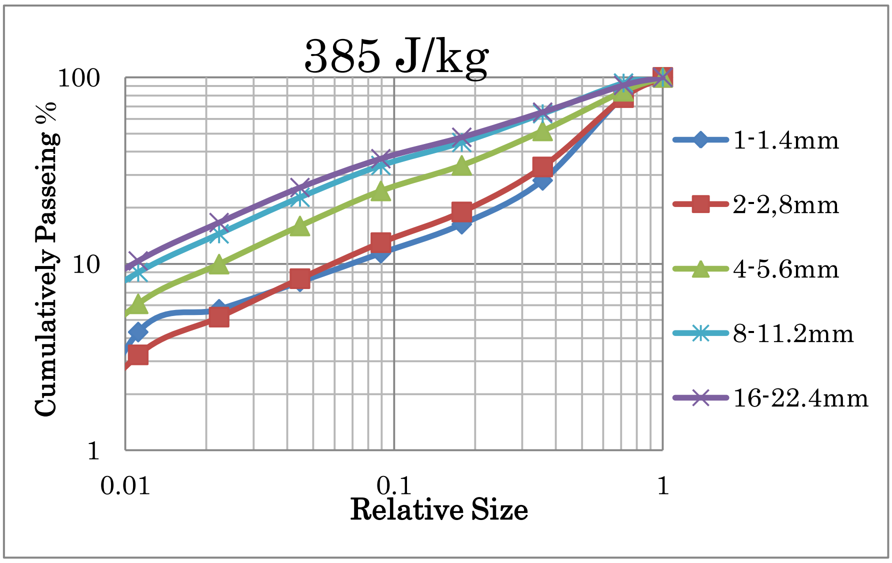
The figure above indicates that as the energy increases the curve moves to finer size

And the fine sizes become uniform.

Table 3. Alteration of Size to Relative Size

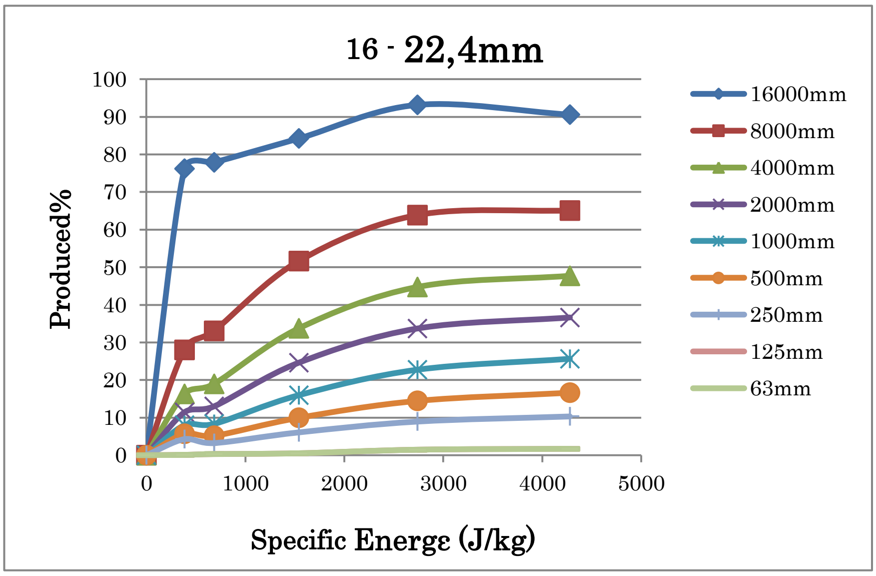
	RPM	750	1000	1500	2000	2500
	J/kg	385	685	1541	2739	4279
Size (mm)	Relative Size	Cumulatively Passing %				
22.4	1	100	100	100	100	100
16	0.7143	79,20	77,89	84,25	93,18	90,59
8	0.3571	28,00	33,06	51,63	63,84	65,06
4	0.1786	16,30	18,97	33,74	44,73	47,70
2	0.0893	11,40	12,98	24,59	33,68	36,61
1	0.0446	8,00	8,32	15,96	22,73	25,63
0.5	0.0223	5,70	5,17	9,96	14,46	16,63
0.250	0.0112	4,30	3,25	6,10	8,99	10,36
0.125	0.0056	0,60	0,91	2,24	4,44	5,23
0.063	0.0028	0,10	0,30	0,51	1,45	1,67

Fig11. Cummulatively Passing % vs. Relative Size



As shown in Figure 11 as the energy increases and size goes finer, the bigger size fraction for the same energy crushes faster than the small size fraction.

Fig12.Produced% vs. Specific Energy ε (J/kg)

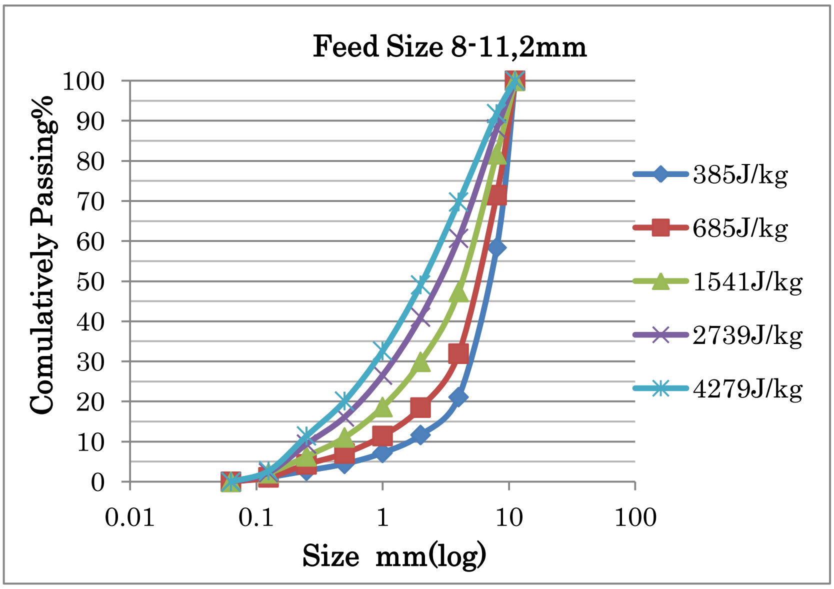


According Figure 12 bigger size fractions crushes in a faster rate than the small size fractions.

Table 4. Indicates the cumulatively Passing % of feed (**8-11.2mm**).

	RPM	750	1000	1500	2000	2500
	ε0	ε1	ε2	ε3	ε4	ε5
J/kg	0	385	685	1541	2739	4279
Screen Size mm	**Cumulatively Passing %**					
11.2	100	100	100	100	100	100
8	0	58,38	71,49	81,66	88,00	91,82
4	0	21,12	31,95	47,34	60,70	69,78
2	0	11,68	18,50	29,92	41,05	49,11
1	0	7,21	11,43	18,65	26,58	32,63
0.5	0	4,47	7,08	11,07	16,13	20,15
0.250	0	2,74	4,35	6,35	9,41	11,44
0.125	0	1,12	1,11	2,15	2,28	2,73
0.063	0	0	8,9E-15	0	7,5E-15	0

Fig13. Cumulatively Passing % vs. Size mm (log)

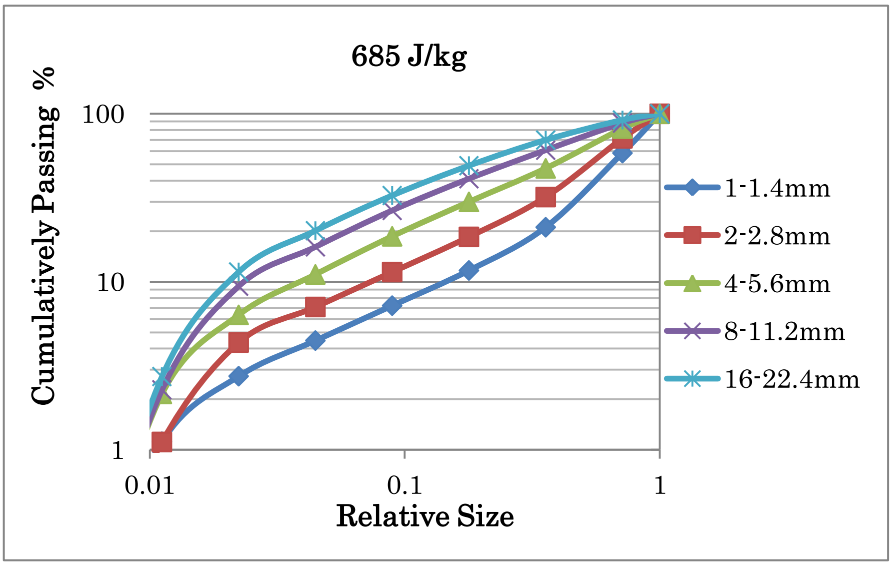


The Figure 13 indicates that as the energy increases the curve moves to finer size And the sizes become uniform.

Table 5. Alteration of Size to Relative Size

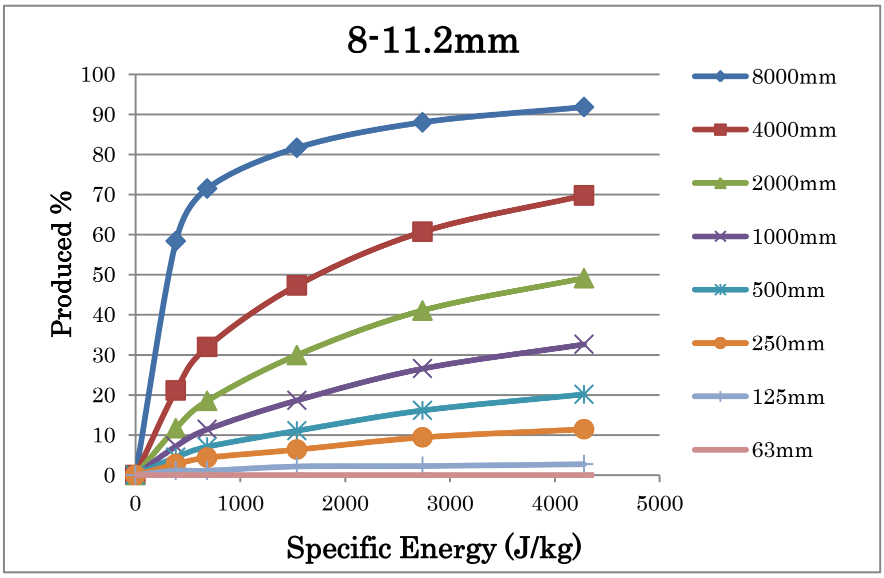
	RPM	750	1000	1500	2000	2500
Size (mm)	J/kg	385	685	1541	2739	4279
	Relative Size	Cumulatively Passing %				
11.2	1	100	100	100	100	100
8	0.7143	58,4	71,5	81,7	88,0	91,82
4	0.3571	21,1	32,0	47,3	60,7	69,78
2	0.1786	11,7	18,5	29,9	41,1	49,11
1	0.0893	7,2	11,4	18,6	26,6	32,63
0.5	0.0446	4,5	7,1	11,1	16,1	20,15
0.250	0.0223	2,7	4,3	6,4	9,4	11,44
0.125	0.0112	1,1	1,1	2,2	2,3	2,73
0.063	0.0056	0,0	0,0	0,0	0,0	0,0

Fig14. Cummulatively Passed% vs. Relative Size



As indicated in Figure 14 as the energy increase and sizes goes finer, the bigger size fraction for the same energy crushes faster than the small size fraction.

Fig15.Produced% vs. Specific Energy ε (J/kg)

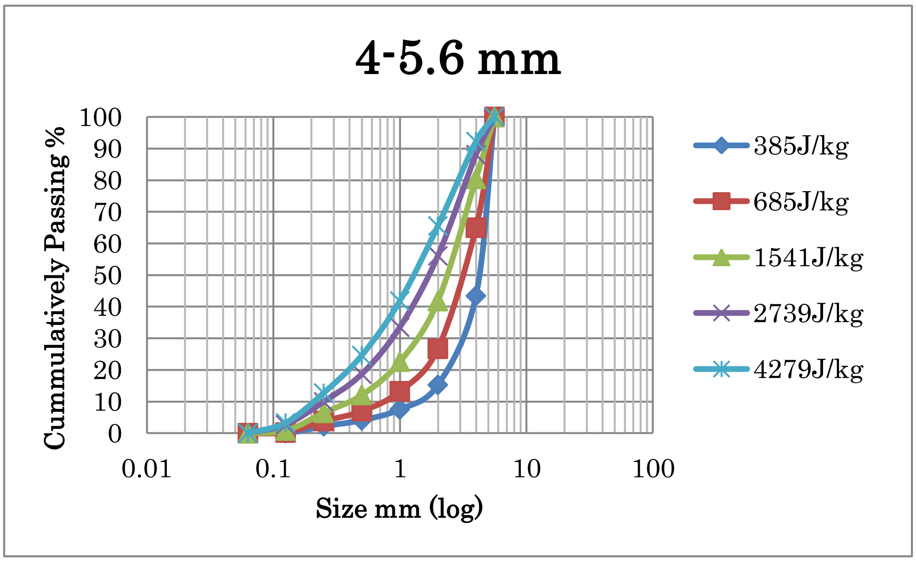


In Figure 15 bigger size fractions crushes in a faster rate than the small size fractions.

Table 6. Indicates the cumulatively Passing % of feed (**4-5.6mm**).

	RPM	750	1000	1500	2000	2500
	ε0	ε1	ε2	ε3	ε4	ε5
J/kg	0	385	685	1541	2739	4279
Screen Size mm	Cumulatively Passing %					
5.6	100	100	100	100	100	100
4	0	43.41	64.96	80.42	88.07	92.23
2	0	15.27	26.69	41.77	56.07	65.55
1	0	7.53	13.24	22.60	33.47	41.81
0.5	0	4.08	6.99	12.08	18.69	24.58
0.250	0	2.20	3.86	6.46	9.93	12.71
0.125	0	0.00	0.21	0.83	2.64	3.26
0.063	0	4.4E-15	9.5E-15	0	0	0

Fig16. Cumulatively Passing% vs. Size mm (log)

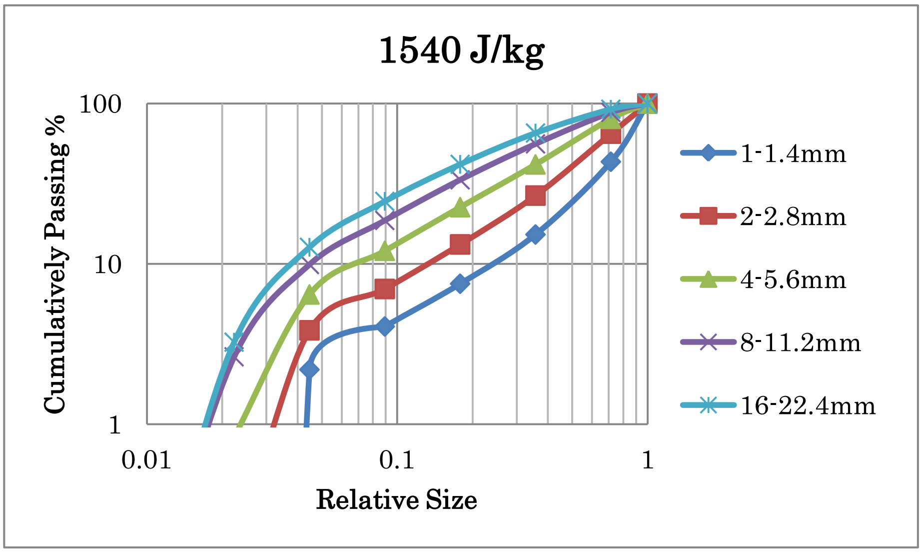


The figure 16 indicates that as the energy increases the curve moves to finer size And the sizes become uniform.

Table 7. Alteration of Size to Relative Size

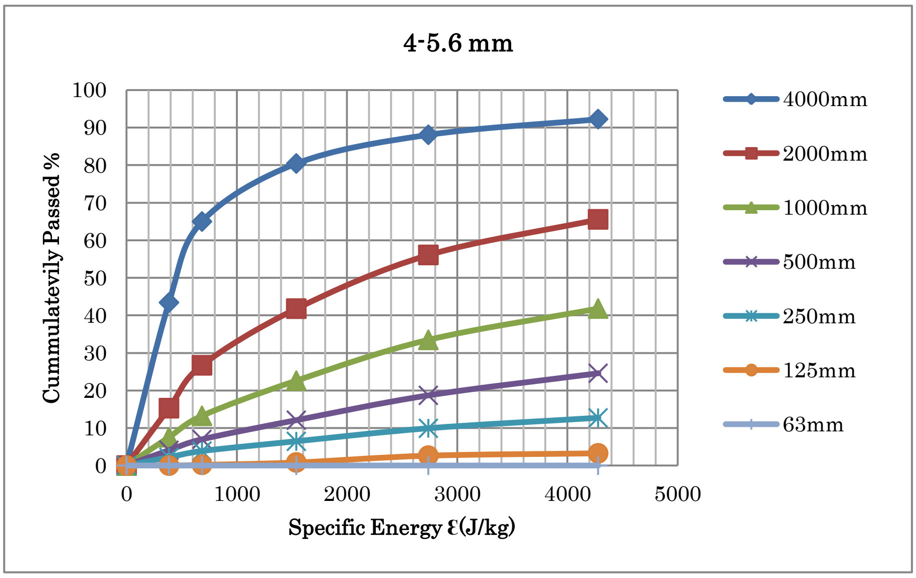
	RPM	750	1000	1500	2000	2500
	J/kg	385	685	1541	2739	4279
Size (mm)	Relative Size	Cumulatively Passing %				
5.6	1	100	100	100	100	100
4	0.7143	43.41	64.96	80.42	88.07	92.23
2	0.3571	15.27	26.69	41.77	56.07	65.55
1	0.1786	7.53	13.24	22.60	33.47	41.81
0.5	0.0893	4.08	6.99	12.08	18.69	24.58
0.250	0.0446	2.20	3.86	6.46	9.93	12.71
0.125	0.0223	0.00	0.21	0.83	2.64	3.26
0.063	0.0112	0.00	0.00	0	0	0

Fig17. Cumulatively Passing% vs. Relative Size



As indicated in Figure 17 as the energy increase and sizes goes finer, the bigger size fraction for the same energy crushes faster than the small size fraction.

Fig18.Produced% vs. Specific Energy ε (J/kg)

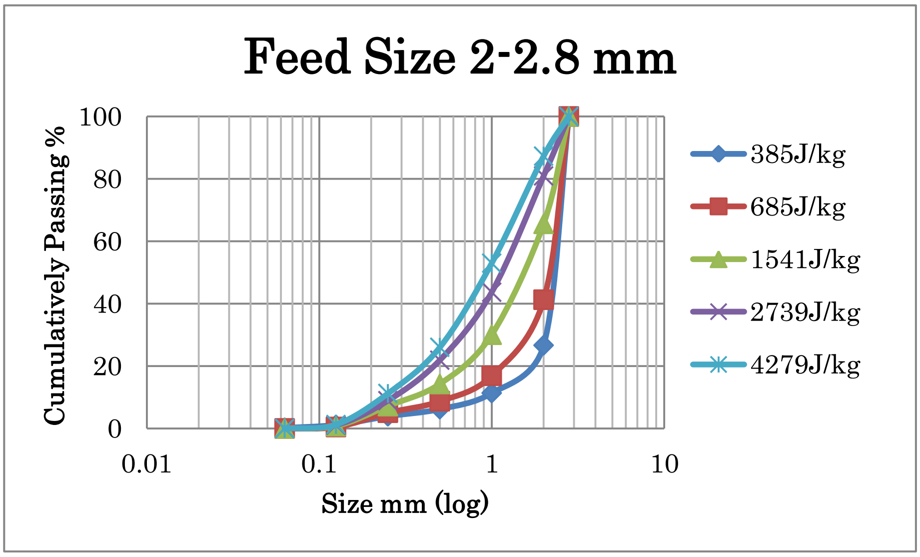


In Figure 16 bigger size fractions crushes in a faster rate than the small size fractions.

Table 8. Indicates the cumulatively Passing % of feed (**2-2.8mm**).

	RPM	750	1000	1500	2000	2500
	ε0	ε1	ε2	ε3	ε4	ε5
J/kg	0	385	685	1541	2739	4279
Screen Size mm	Cumulatively Passing %					
2.8	100	100	100	100	100	100
2	0	26.50	41.26	65.59	80.94	87.30
1	0	11.18	16.90	30.04	43.66	52.99
0.5	0	6.00	8.74	14.24	21.88	26.02
0.250	0	3.73	5.06	7.17	8.90	11.23
0.125	0	0.93	0.46	0.73	1.05	1.26
0.063	0	-3E-15	1E-15	-8E-15	0E+00	3E-15

Fig19. Cumulatively Passing % vs. Size mm (log)

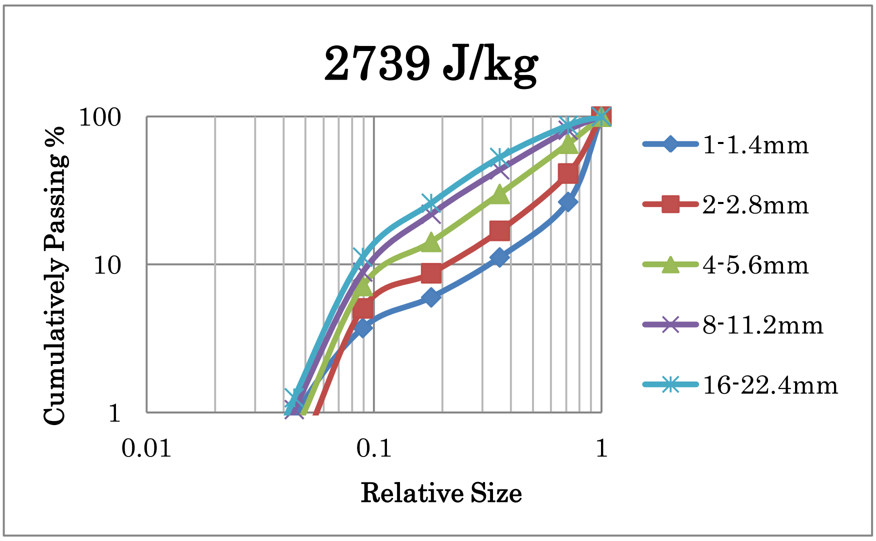


The figure 19 indicates that as the energy increases the curve moves to finer size And the sizes become uniform.

Table 9. Alteration of Size to Relative Size

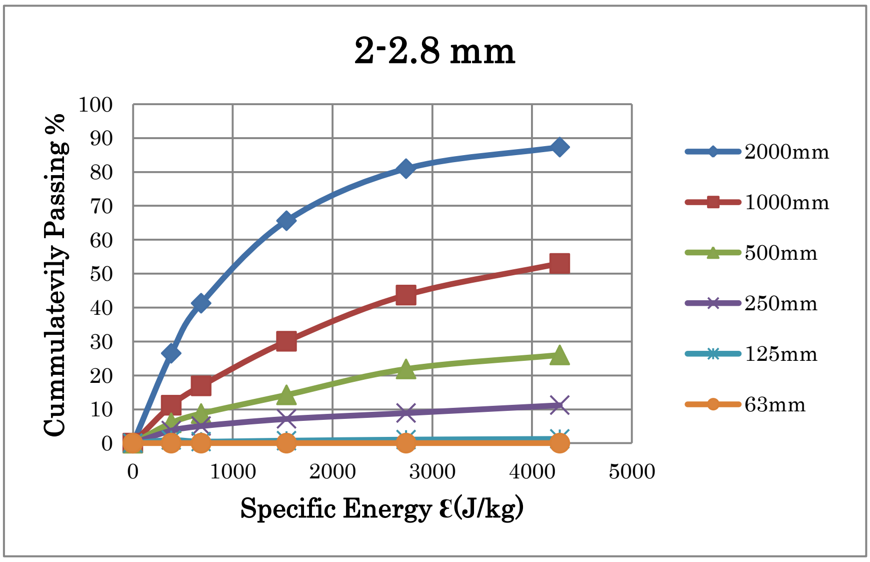
	RPM	750	1000	1500	2000	2500
	J/kg	385	685	1541	2739	4279
Size (mm)	Relative Size	Cumulatively Passing %				
2.8	1	100	100	100	100	100
2	0.7143	26.50	41.26	65.59	80.94	87.30
1	0.3571	11.18	16.90	30.04	43.66	52.99
0.5	0.1786	6.00	8.74	14.24	21.88	26.02
0.250	0.0893	3.73	5.06	7.17	8.90	11.23
0.125	0.0446	0.93	0.46	0.73	1.05	1.26
0.063	0.0223	-3E-15	1E-15	-8E-15	0E+00	3E-15

Fig20. Cumulatively Passing % vs. Relative Size



As indicated in Figure 20 as the energy increase and sizes goes finer, the bigger size fraction for the same energy crushes faster than the small size fraction.

Fig21.Produced% vs. Specific Energy ε (J/kg)

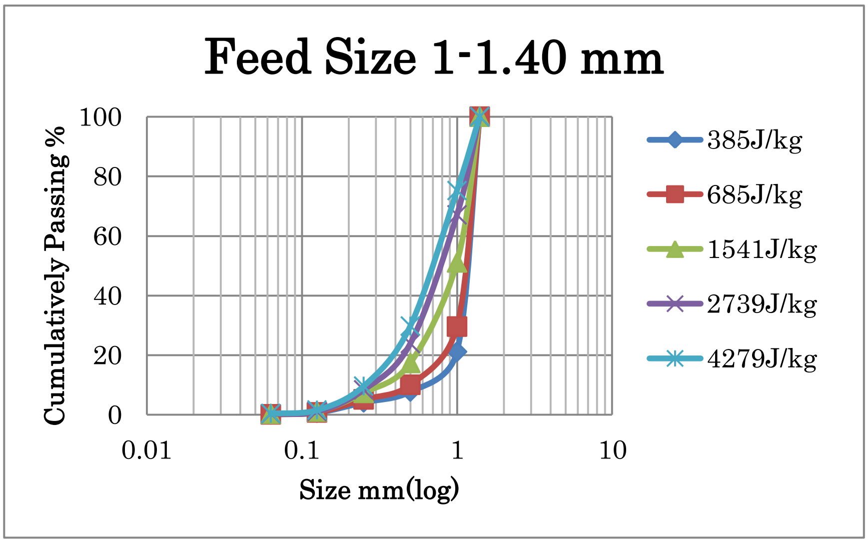


In Figure 21 bigger size fractions crushes in a faster rate than the small size fractions.

Table10. Indicates the cumulatively Passing % of feed (1-1.4mm).

	RPM	750	1000	1500	2000	2500
	ε0	ε1	ε2	ε3	ε4	ε5
J/kg	0	385	685	1541	2739	4279
Screen Size mm	Cumulatively Passing %					
1.4	100	100	100	100	100	100
1	0	21.05	29.49	50.94	66.95	75.11
0.05	0	7.69	9.94	17.09	23.62	29.45
0.250	0	4.05	5.02	7.02	8.05	9.22
0.125	0	0.61	0.64	0.73	0.74	1.17
0.063	0	1E-15	1E-15	4E-15	-1E-14	-2E-15

Fig22. Cumulatively Passed% vs. Size mm (log)

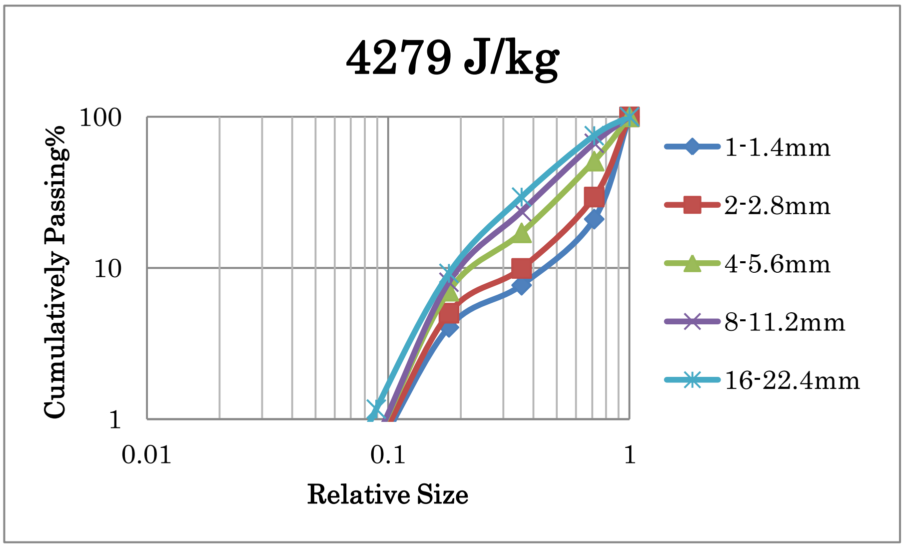


As indicated in Figure 22 while the energy increases the curve moves to finer size and the sizes become uniform.

Table 11. Alteration of Size to Relative Size

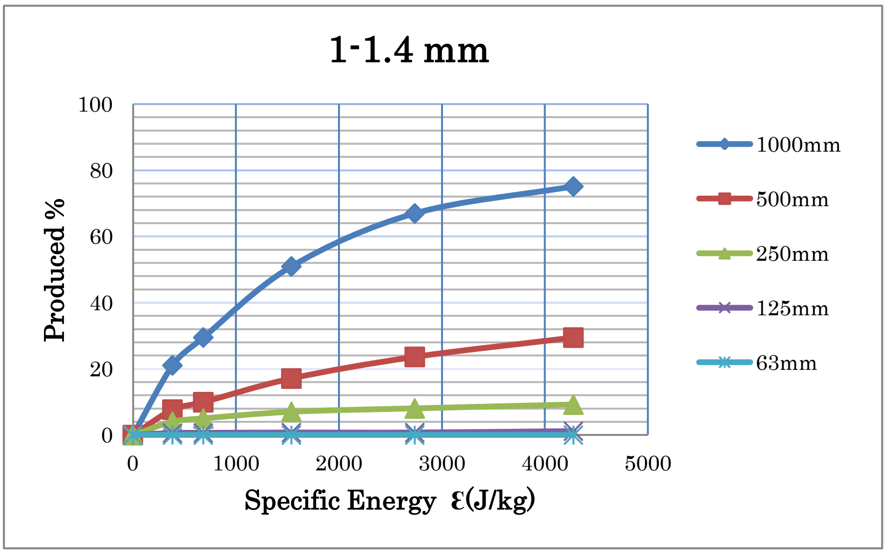
	RPM	750	1000	1500	2000	2500
	J/kg	385	685	1541	2739	4279
Size (mm)	Relative Size	Cumulatively Passing %				
1.4	1	100	100	100	100	100
1	0.7143	21.1	29.5	50.9	66.9	75.1
0.5	0.3571	7.7	9.9	17.1	23.6	29.4
0.250	0.1786	4.0	5.0	7.0	8.1	9.2
0.125	0.0893	0.6	0.6	0.7	0.7	1.2
0.63	0.0446	1.1E-15	1.22E-15	4.11E-15	-1E-14	-2.4E-15

Fig23. Cumulatively Passing % vs. Relative Size



As indicated in Figure 23 as the energy increase and sizes goes finer, the bigger size fraction for the same energy crushes faster than the small size fraction.

Fig24.Produced% vs. Specific Energy ε (J/kg)



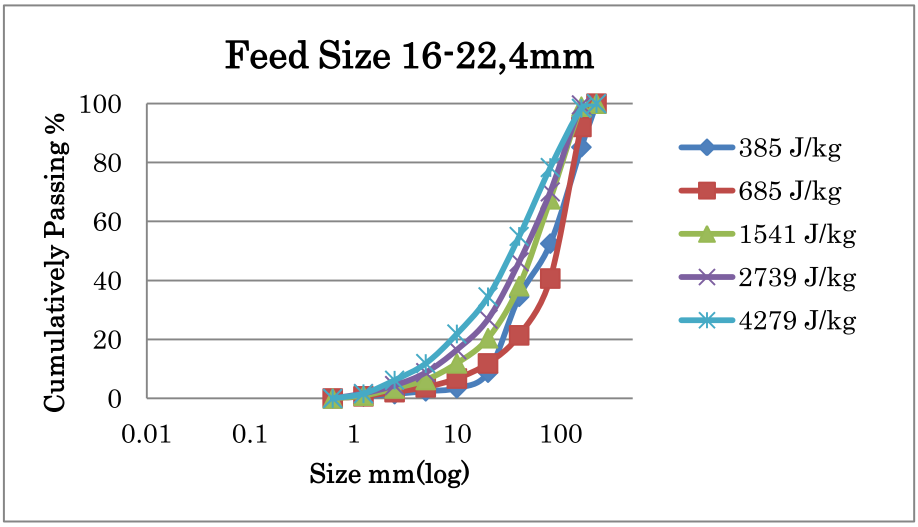
According to Figure 24 bigger size fractions crushes in a faster rate than the small size fractions.

3.2. Serpentine

Table 12. Indicates the cumulatively Passing % of feed (**16-22.4mm**).

	RPM	750	1000	1500	2000	2500
ε	ε 0	ε 1	ε 2	ε 3	ε 4	ε 5
J/kg	0	385	685	1541	2739	4279
Screen Size mm	Cumulatively Passing %					
22.4	100	100	100	100	100	100
16	0	85,23	92,11	98,97	99,58	98,40
8	0	52,53	40,68	67,56	70,07	78,34
4	0	34,49	21,41	38,09	46,30	54,96
2	0	8,76	11,89	20,43	26,90	34,47
1	0	3,48	6,76	11,91	16,48	21,88
0.5	0	2,43	3,79	6,26	8,76	11,85
0.250	0	1,48	2,15	3,39	4,38	6,19
0.125	0	0,63	0,72	0,92	1,67	1,60
0.063	0	0,00	0,00	0,00	0,00	0,00

Fig25. Cumulatively Passed% vs. Size mm (log)



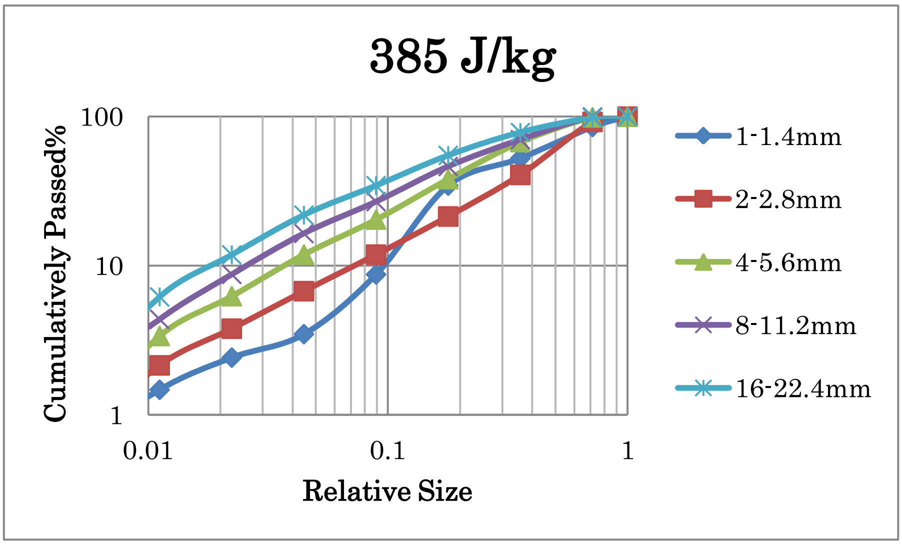
The Figure 25 above tells that as the energy increases the curve moves to finer size

And the fine sizes become uniform.

Table 13. Alteration of Size to Relative Size

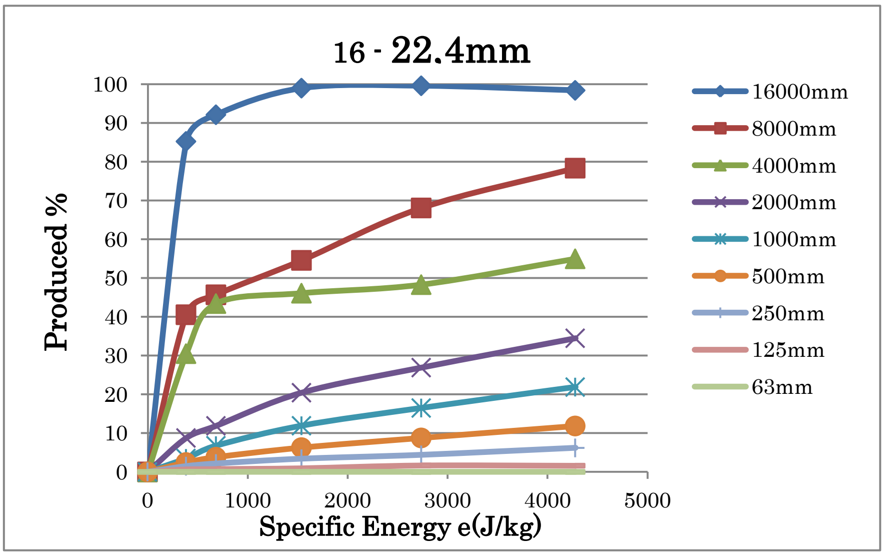
	RPM	750	1000	1500	2000	2500
	J/kg	385	685	1541	2739	4279
Size (mm)	Relative Size	Cumulatively Passing %				
22.4	1	100	100	100	100	100
16	0.714	85,23	92,11	98,97	99,58	98,40
8	0.357	52,53	40,68	67,56	70,07	78,34
4	0.179	34,49	21,41	38,09	46,30	54,96
2	0.089	8,76	11,89	20,43	26,90	34,47
1	0.045	3,48	6,76	11,91	16,48	21,88
0.5	0.022	2,43	3,79	6,26	8,76	11,85
0.250	0.011	1,48	2,15	3,39	4,38	6,19
0.125	0.006	0,63	0,72	0,92	1,67	1,60
0.063	0.003	0,00	0,00	0,00	0,00	0,00

Fig26. Cummulatively Passing% vs. Relative Size



As shown in Figure 26 as the energy increase, the bigger size fraction for the same energy crushes faster than the small size fraction.

Fig27.Produced% vs. Specific Energy ε (J/kg)



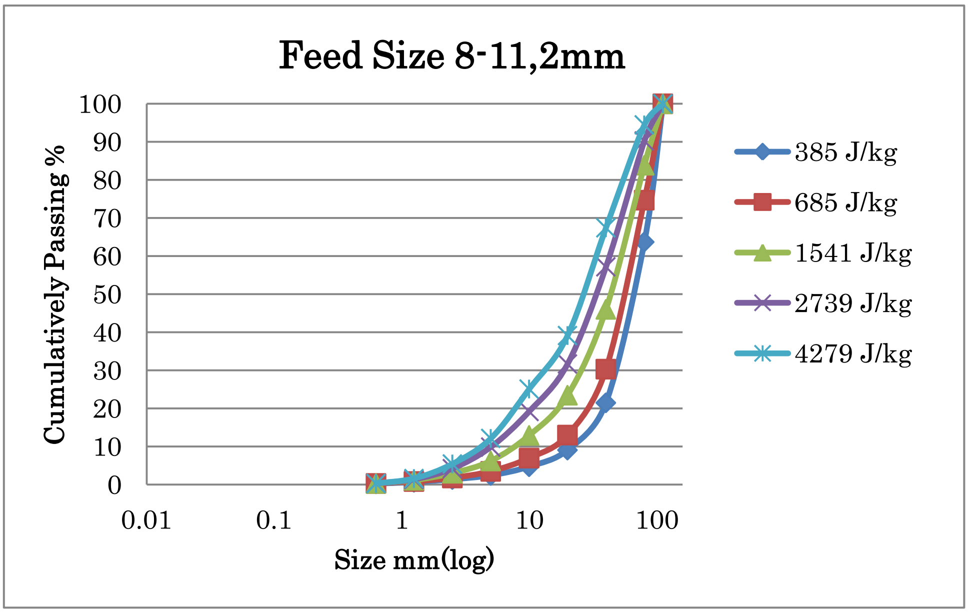
According Figure 27 bigger size fractions crushes in a faster rate than the small size fractions.

Table 14. Indicates the cumulatively Passing % of feed **(8-11.2mm)**

	RPM	750	1000	1500	2000	2500
ε	ε0	ε1	ε2	ε3	ε4	ε5
J/kg	0	385	685	1541	2739	4279
Screen Size mm	Cumulatively Passing %					
11.2	100	100	100	100	100	100
8	0	63,71	74,69	83,87	90,24	94,47
4	0	21,48	30,33	46,02	57,19	67,45
2	0	9,07	13,01	23,47	31,69	39,15
1	0	4,69	6,97	12,93	19,20	25,11
0.5	0	2,40	3,48	6,20	9,86	12,13
0.250	0	1,36	1,74	3,00	4,20	5,43
0.125	0	0,63	0,82	1,14	1,36	1,60
0.063	0	0,21	0,31	0,31	0,31	0,32

.

Fig28. Cumulatively Passing % vs. Size mm (log)

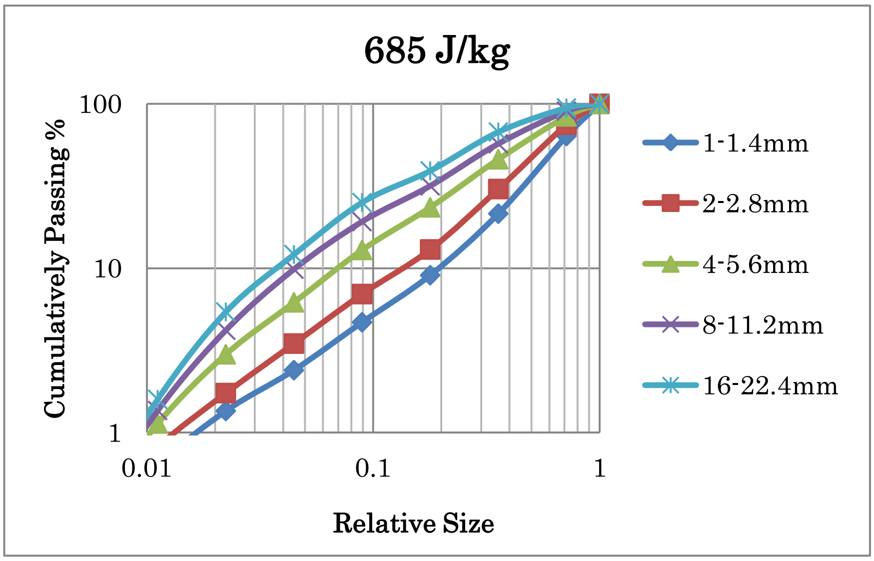


The figure 28 above tells that as the energy increases the curve moves to finer size And the fine sizes become uniform.

Table 15. Alteration of Size to Relative Size

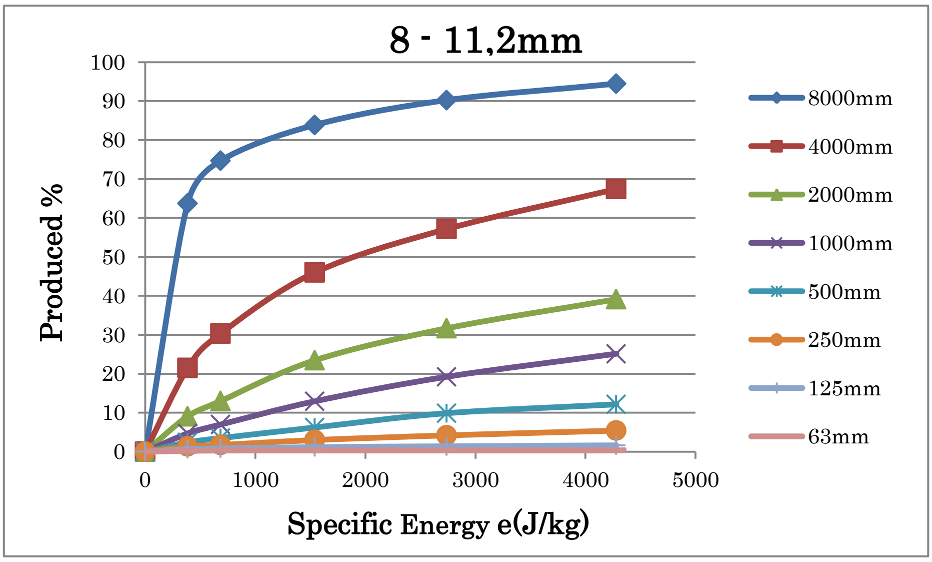
Size (mm)	RPM	750	1000	1500	2000	2500
	J/kg	385	685	1541	2739	4279
	Relative Size	Cumulatively Passing %				
11.2	1	100	100	100	100	100
8	0.714	63,71	74,69	83,87	90,24	94,47
4	0.357	21,48	30,33	46,02	57,19	67,45
2	0.179	9,07	13,01	23,47	31,69	39,15
1	0.089	4,69	6,97	12,93	19,20	25,11
0.5	0.045	2,40	3,48	6,20	9,86	12,13
0.250	0.022	1,36	1,74	3,00	4,20	5,43
0.125	0.011	0,63	0,82	1,14	1,36	1,60
0.063	0.006	0,21	0,31	0,31	0,31	0,32

Fig29. Cumulatively Passing % vs. Relative Size



As shown in Figure 29 as the energy increase and sizes goes finer, the bigger size fraction for the same energy crushes faster than the small size fraction.

Fig30.Produced% vs. Specific Energy ε (J/kg)



According Figure 30 bigger size fractions crushes in a faster rate than the small size fractions.

Table 16. Indicates the cumulatively Passing % of feed (**4-5.6mm**).

	RPM	750	1000	1500	2000	2500
ε	ε0	ε1	ε2	ε3	ε4	ε5
J/kg	0	385	685	1541	2739	4279
Screen Size mm	Cumulatively Passing %					
5.6	100	100	100	100	100	100
4	0	27,52	38,20	63,52	80,21	85,79
2	0	12,46	18,89	31,45	43,60	51,50
1	0	5,71	9,29	16,14	24,76	31,20
0.5	0	2,60	4,38	7,97	12,28	15,60
0.250	0	1,25	2,30	4,30	4,66	5,45
0.125	0	0,42	1,04	1,57	1,80	1,92
0.063	0	0,00	0,31	0,42	0,42	0,43

Fig31. Cumulatively Passing % vs. Size um (log)

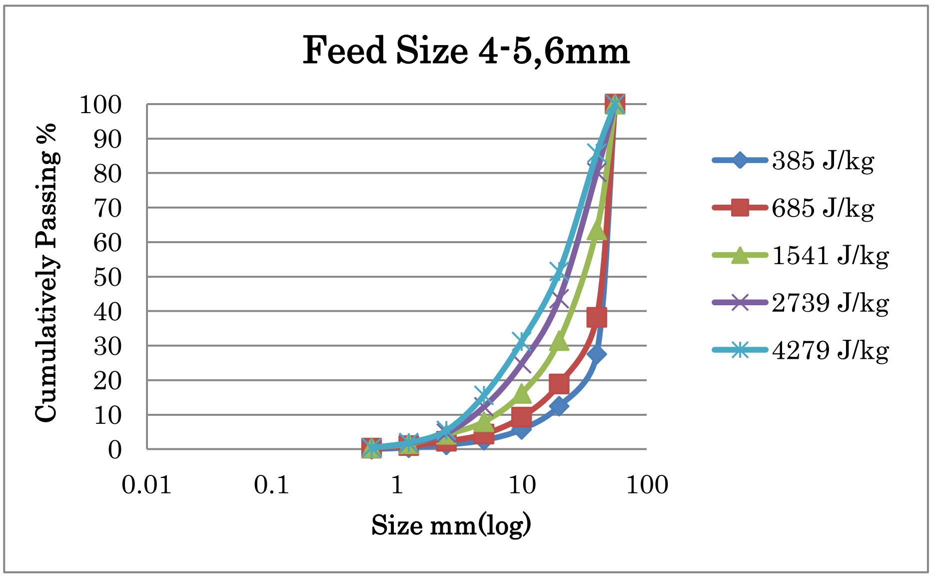
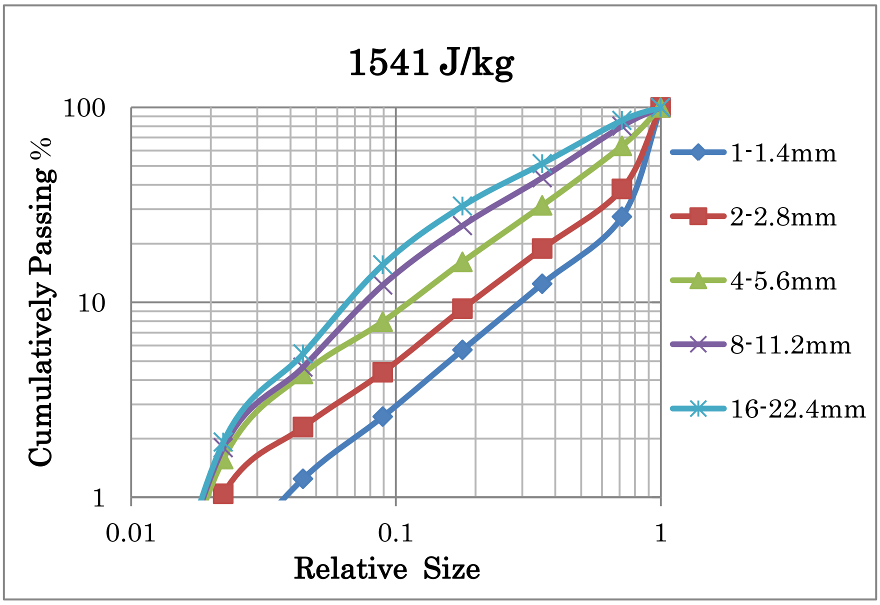


Figure 31 above tells that as the energy increases the curve moves to finer size And the fine sizes become uniform.

Table 17. Alteration of Size to Relative Size

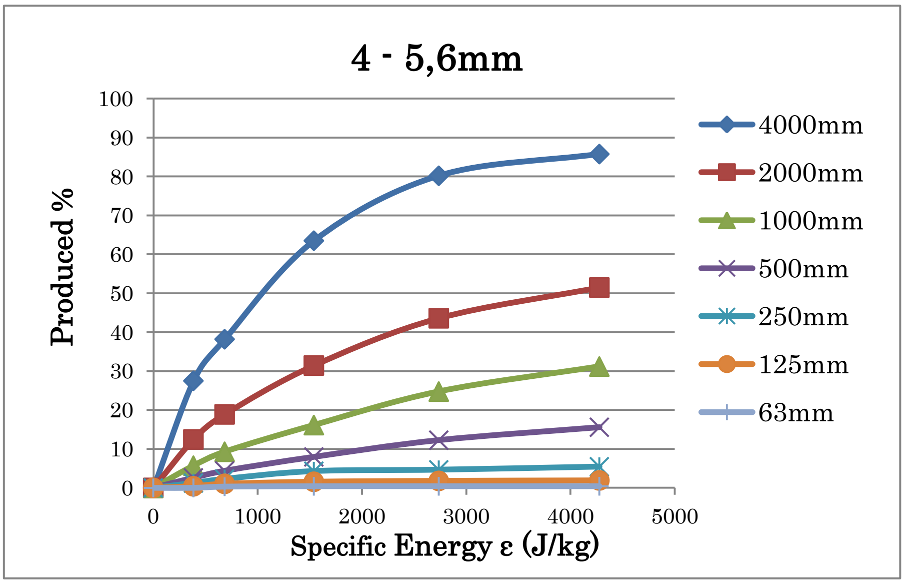
	RPM	750	1000	1500	2000	2500
	J/kg	385	685	1541	2739	4279
Size (mm)	Relative Size	Cumulatively Passed %				
5.6	1	100	100	100	100	100
4	0.714	41,37	59,54	81,05	88,04	89,90
2	0.357	13,95	23,57	42,59	57,45	64,54
1	0.179	6,93	11,99	23,80	36,07	42,57
0.5	0.089	4,06	7,14	14,36	22,97	27,90
0.250	0.045	2,82	4,87	9,75	15,89	19,10
0.125	0.022	1,87	3,20	5,98	9,42	11,81
0.063	0.011	0,92	1,39	1,95	3,01	3,84

Fig32. Cumulatively Passing % vs. Relative Size



As shown in figure 32 as the energy increase, the bigger size fraction for the same energy crushes faster than the small size fraction.

Fig33.Produced% vs. Specific Energy ε (J/kg)



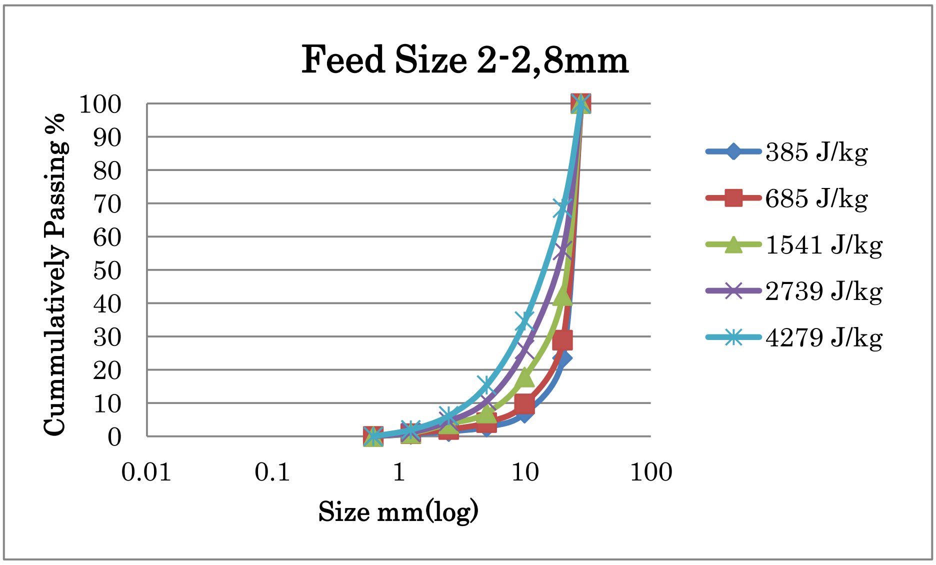
According Figure 33 bigger size fractions crushes in a faster rate than the small size fractions.

Generally as the energy increases the particle size that passes decreases.

Table 18. Indicates the cumulatively Passing % of feed (**2-2.8mm**).

	RPM	750	1000	1500	2000	2500
ε	ε0	ε1	ε2	ε3	ε4	ε5
J/kg	0	385	685	1541	2739	4279
Screen Size mm	Cumulatively Passing %					
2.8	100	100	100	100	100	100
2	0	23,54	28,93	42,33	55,87	68,59
1	0	6,98	9,78	17,86	26,14	34,66
0.5	0	2,81	4,16	7,04	10,69	15,44
0.250	0	1,46	2,08	3,78	4,55	6,20
0.125	0	0,63	0,83	0,95	1,16	2,00
0.063	0	0,00	0,00	0,00	0,00	0,00

Fig34. Cumulatively Passed% vs. Size um (log)

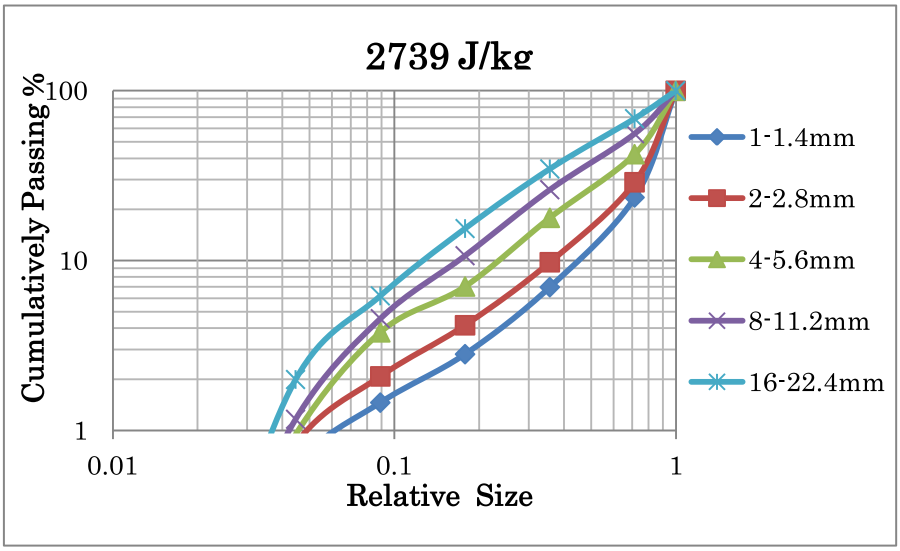


According figure 34 above shows that as the energy increases the curve moves to finer size And the fine sizes become uniform.

Table 19. Alteration of Size to Relative Size

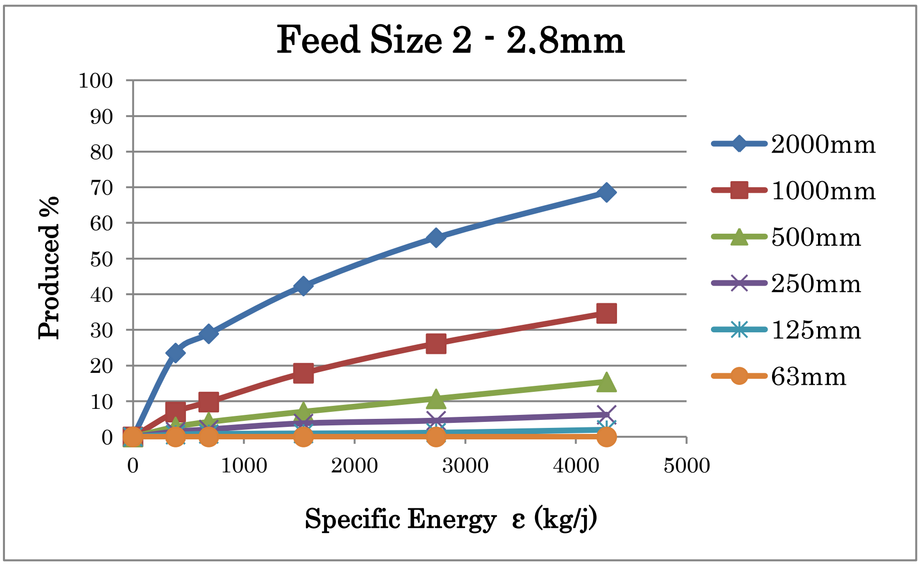
	RPM	750	1000	1500	2000	2500
	J/kg	385	685	1541	2739	4279
Size (mm)	Relative Size		Cumulatively Passing %			
2.8	1	100	100	100	100	100
2	0.714	23,54	28,93	42,33	55,87	68,59
1	0.357	6,98	9,78	17,86	26,14	34,66
0.5	0.179	2,81	4,16	7,04	10,69	15,44
0.250	0.089	1,46	2,08	3,78	4,55	6,20
0.125	0.045	0,63	0,83	0,95	1,16	2,00
0.063	0.022	0,00	0,00	0,00	0,00	0,00

Fig35. Cummulatively Passing % vs. Relative Size



According Figure 35 as the energy increase, the bigger size fraction for the same energy crushes faster than the small size fraction.

Fig36.Produced% vs. Specific Energy ε (J/kg)

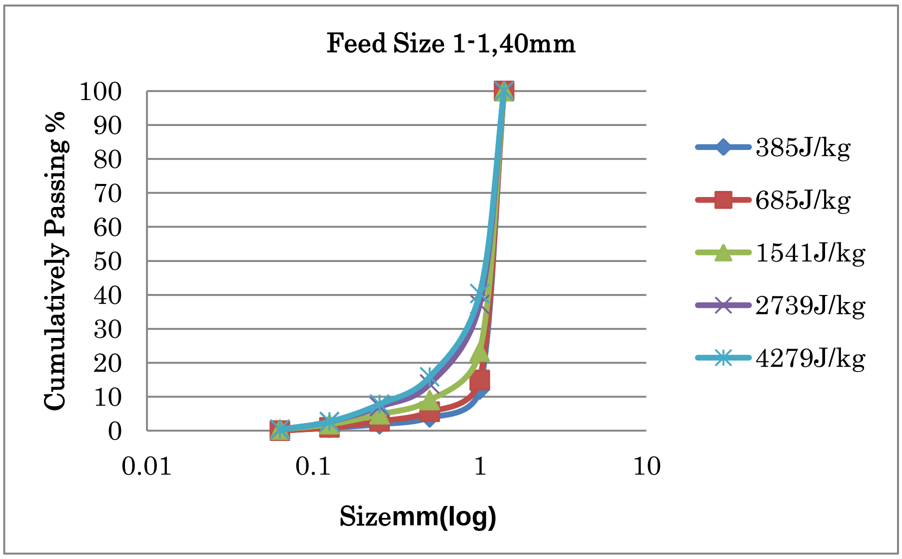


Indication of Figure 36 shows that a bigger size fraction crushes in a faster rate than the small size fractions.

Table 20. Indicates the cumulatively Passing % of feed (**1-1.4mm**).

	RPM	750	1000	1500	2000	2500
ε	ε0	ε1	ε2	ε3	ε4	ε5
J/kg	0	385	685	1541	2739	4279
Screen Size mm	Cumulatively Passing %					
1.4	100	100	100	100	100	100
1	0	12,09	14,90	23,27	37,17	40,36
0.5	0	3,89	5,56	9,01	13,73	15,85
0.250	0	1,89	2,73	4,82	7,07	7,82
0.125	0	0,84	0,94	1,89	2,64	2,68
0.063	0	0,00	0,00	0,31	0,32	0,43

Fig37. Cumulatively Passing % vs. Size mm (log)



According to Figure 37 above shows that as the energy increases the curve moves to finer size, and the fine sizes become uniform.

Table 21. Alteration of Size to Relative Size

	RPM	750	1000	1500	2000	2500
Size (mm)	J/kg	385	685	1541	2739	4279
	Relative Size	Cumulatively Passing %				
1.4	1	100	100	100	100	100
1	0.714	12,09	14,90	23,27	37,17	40,36
0.5	0.357	3,89	5,56	9,01	13,73	15,85
0.250	0.179	1,89	2,73	4,82	7,07	7,82
0.125	0.089	0,84	0,94	1,89	2,64	2,68
0.063	0.045	0,00	0,00	0,31	0,32	0,43

Fig38. Cumulatively Passing % vs. Relative Size

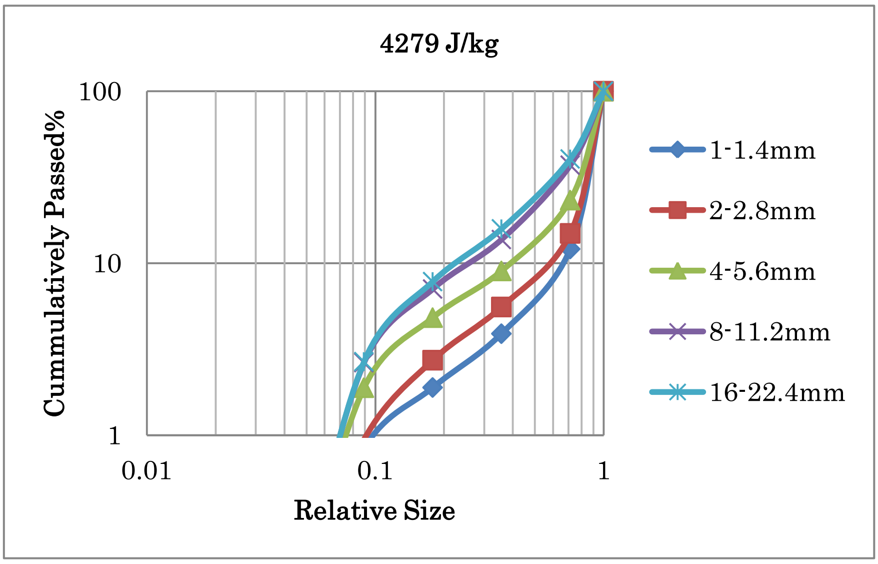
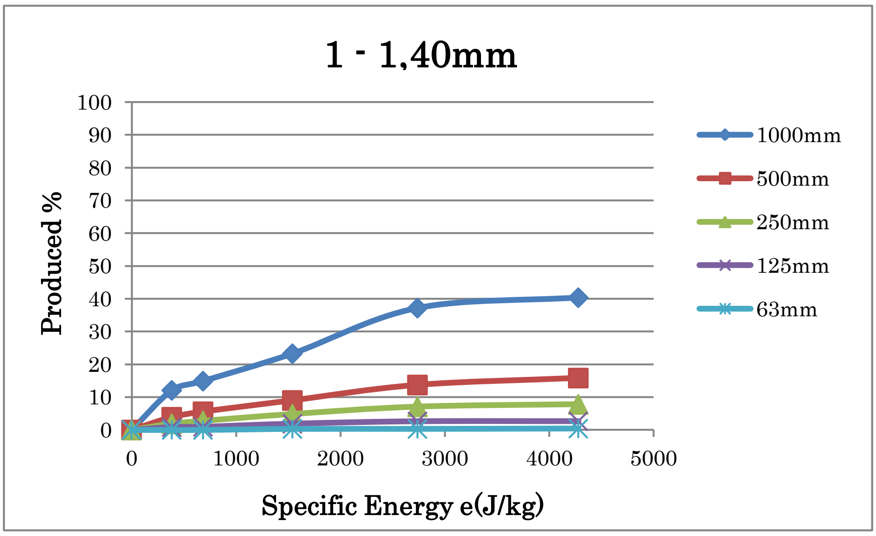


Figure 38 the bigger size fraction for the same energy crushes faster than the small size fraction.

Fig39.Produced% vs. Specific Energy ε (J/kg)



According to Figure 39 which shows that bigger size fractions crushes in a faster rate than the small size fractions.

3.3. Constant *k*

Calculation of constant k

Screen was carried out on material, produced a quantity R which is the remaining material in the sieve and one quantity P which is the passing material.

Consequently:

$$R + P = 100 \;\; or \;\; R + P = 1 \tag{1}$$

The pace to break the coarse material is given by the following relation, where ε is the specific energy:

$$\frac{dR}{d\varepsilon} = -k \cdot d\varepsilon \quad \Leftrightarrow \quad \frac{dR}{R} = -k \cdot d\varepsilon \quad \Rightarrow \tag{2}$$

$$\overset{(2)}{\Rightarrow} \int \frac{dR}{R} = -k \cdot \int d\varepsilon \quad \Rightarrow \ln R = -k \cdot \varepsilon + c \tag{3}$$

So c = Ro (4), where Ro is the remaining material for specific energy $\varepsilon_0 = 0$. Therefore, add equation (3) and equation (4), it gives equation (5):

$$R = Ro \cdot e^{-k \cdot \varepsilon} \tag{5}$$

The quantity of material produced P_r that appears after the fracture is given by the equation: P_r = Ro-R (6). So, if we add equation (5) and (6) it will gives equation (7):

$$\mathrm{Pr} = Ro - Ro \cdot e^{-k \cdot \varepsilon} \;\; \Rightarrow \;\; Pr = Ro \cdot (1 - e^{-k \cdot \varepsilon}) \tag{7}$$

In this case Ro = 100 is the percentage, because the size of the feed was bigger than the size of the products. Therefore, the entire quantity (100%) remains in the sieve for $\varepsilon_0 = 0$ (before the crushing).

Having done the experiment we found the percentages of the produced products $Pr_{(exp)}$ %. A calculation was carried out using the equation (7), to find the $Pr_{(cal)}$ % for each of the product of the five different Feeds with the following procedure. Firstly, used an indicator k for the calculation of the equation (7) and then calculate the difference in the square, $(Pr_{(exp)} - Pr_{(cal)})^2$ on each of the five specific energies ε_1, ε2, ε3, ε4 and ε_5. And changing every time the constant

k by trying to calculate the smallest sum of the differences.
This procedure can be done either by hand or with Microsoft Excel using the Goal Seek command.

So for each product of five different feeds a constant k was calculated, with the smallest error .i.e. (the smallest sum of the differences SUM $(Pr_{(exp)} - Pr_{(cal)})^2$).

The results k against size makes a quadratic equation that shows the A and B ($Y=Ax^2+Bx$) which is the description of materials.

Constant k is the best solution for k that can give the smallest sum of the differences
This procedure can be done with trend line command.

3.3.1. Marly Limestone

Table 22. Constant k and Size for the feed (**16-22.4 mm**)

Size (mm)	k (kg/J)
16	0.003155369
8	0.000398537
4	0.00019669
2	0.000136506
1	0.00007666
0.5	0.00004740
0.25	0.00003074
0.125	0.00001384

Fig40. Constant k vs. Size (mm)

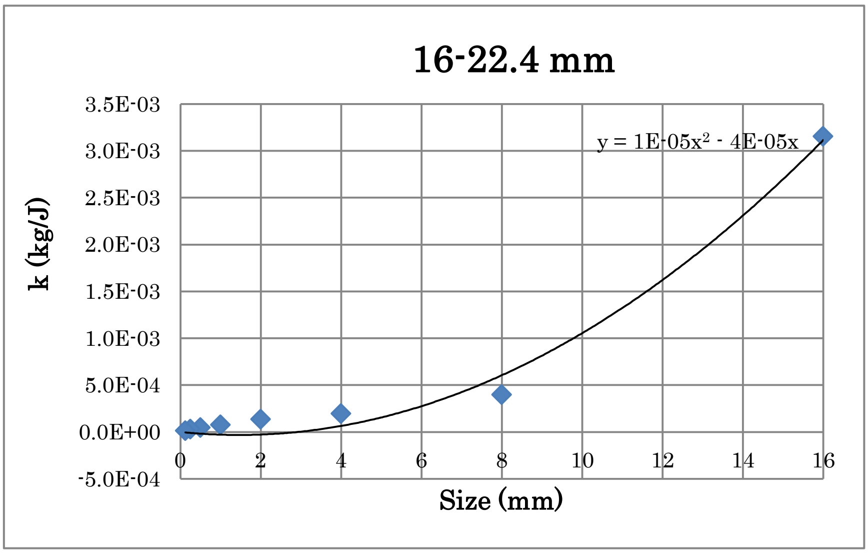


Table 23. Constant k and Size for the feed (**8-11.2 mm**)

Size (mm)	k(kg/j)
8	0.0020067
4	0.0003560
2	0.0001880
1	0.0001000
0.5	0.0000598
0.25	0.0000330
0.125	0.0000079

Fig41. Constant k vs. Size (mm)

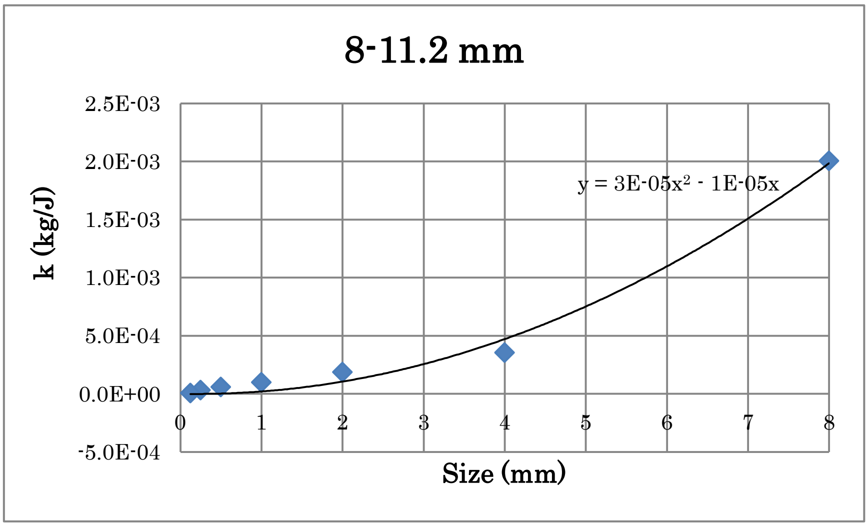


Table 24. Constant k and Size for the feed (**4-5.6 mm**)

Size (mm)	k(kg/J)
4	0.0014117
2	0.0003069
1	0.0001422
0.5	0.0000712
0.25	0.0000353
0.125	0.0000077

Fig42. Constant k vs. Size (mm)

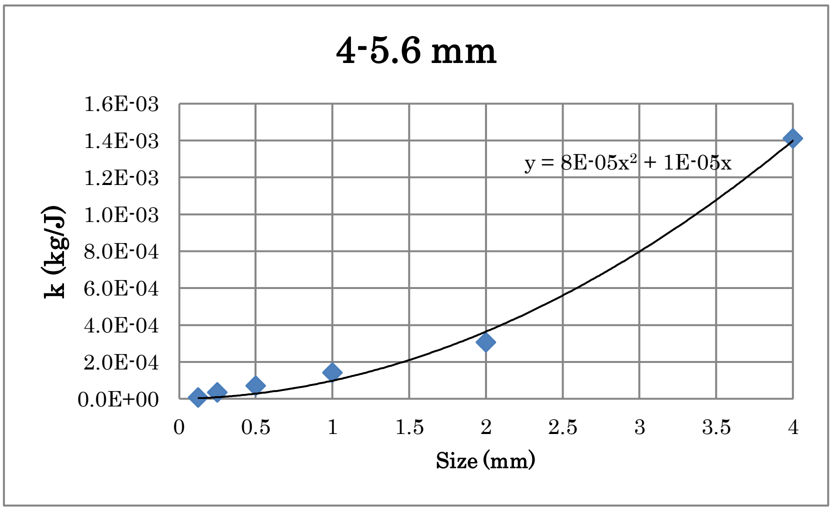


Table 25. Constant k and Size for the feed (**2-2.8 mm**).

Size (mm)	k (kg/J)
2	0.0006799
1	0.0002034
0.5	0.0000807
0.25	0.0000327
0.125	0.0000035

Fig43. Constant k vs. Size (mm)

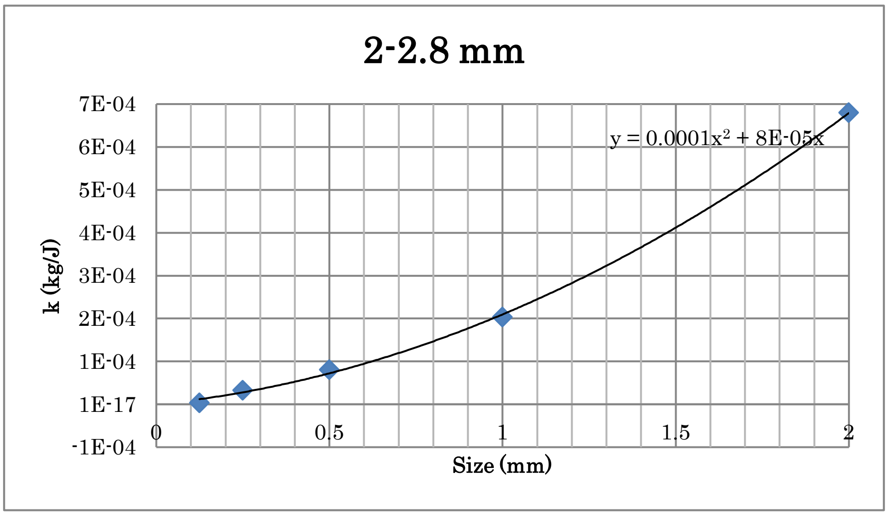
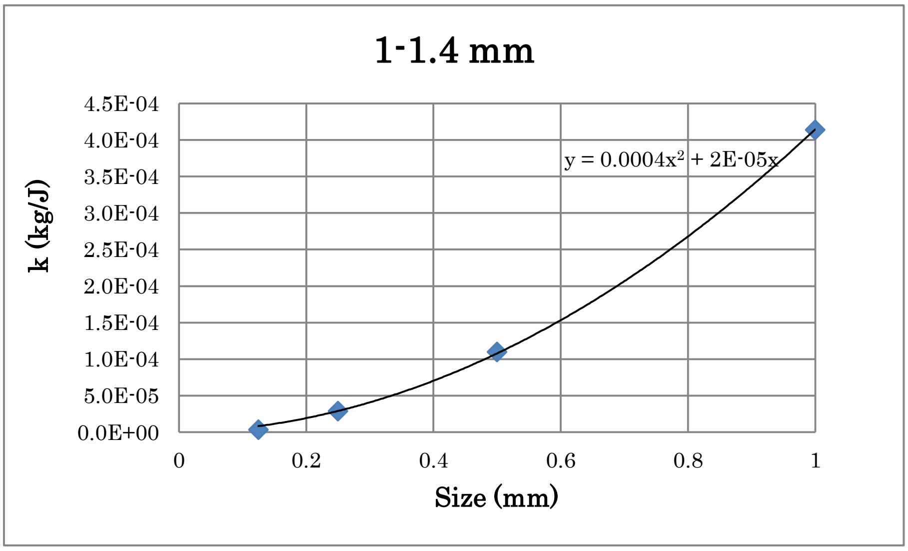


Table 26. Constant k and Size for the feed (**1-1.4 mm**).

Size (mm)	k (kg/J)
1	0.0004140
0.5	0.0001100
0.25	0.0000290
0.125	0.0000036

Fig44. Constant k vs. Size (mm)



Constant *K* of all feeds

Fig 45. K marly limestone vs. Size (mm)

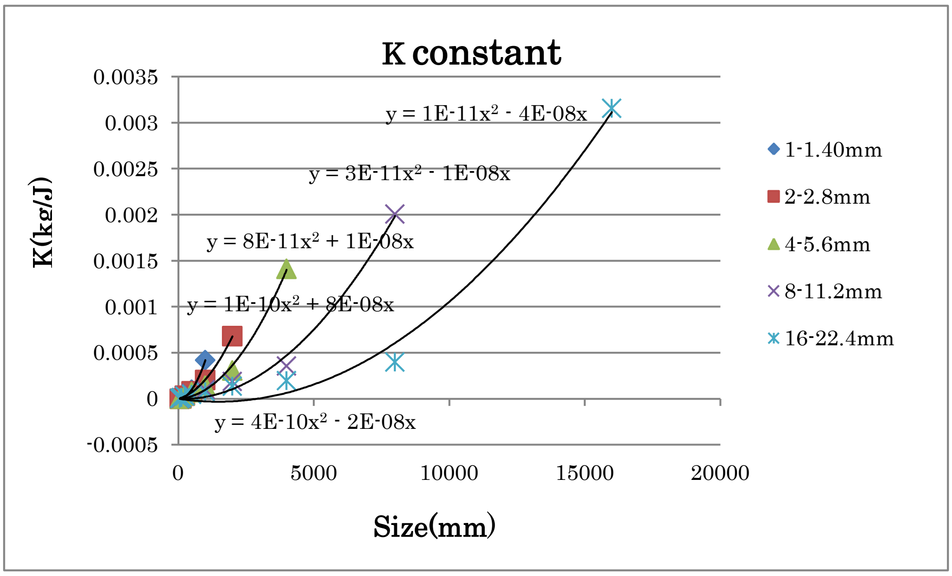


Figure 45 indicates that as a material is crushed, the rate of the breakage is higher in the bigger size fractions than in the smaller size fractions.

3.3.2. Serpentine

Table 27. Constant k and Size for the feed (**16-22.4 mm**)

Size (mm)	k (kg/J)
16	0.0047134
8	0.0007110
4	0.0002576
2	0.0001133
1	0.0000636
0.5	0.0000324
0.25	0.0000164
0.125	0.0000047

Fig46 Constant k vs. Size (mm)

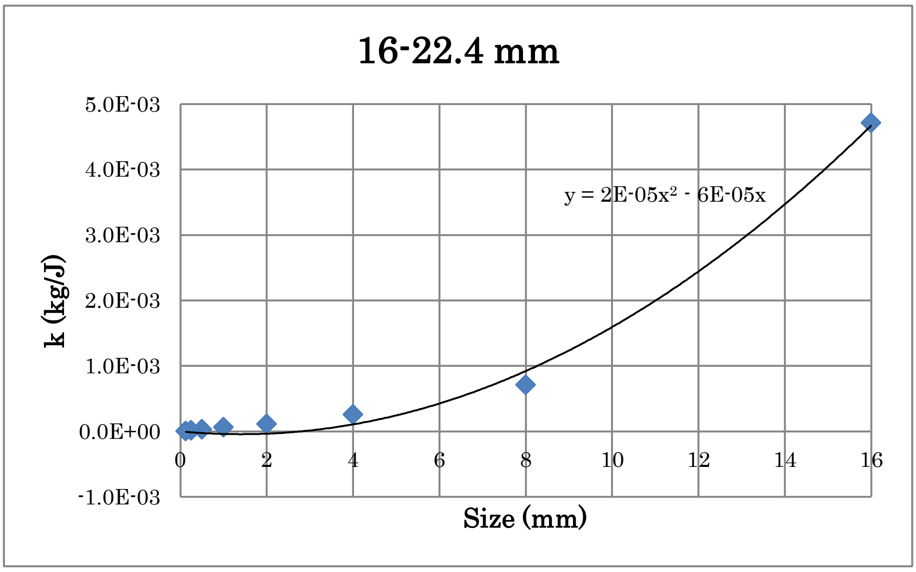


Table 28. Constant k and Size for the feed (**8-11.2 mm**)

Size (mm)	k(kg/J)
8	0.0021781
4	0.0003360
2	0.0001367
1	0.0000752
0.5	0.0000319
0.25	0.0000143
0.125	0.0000045

Fig47 Constant k vs. Size (mm)

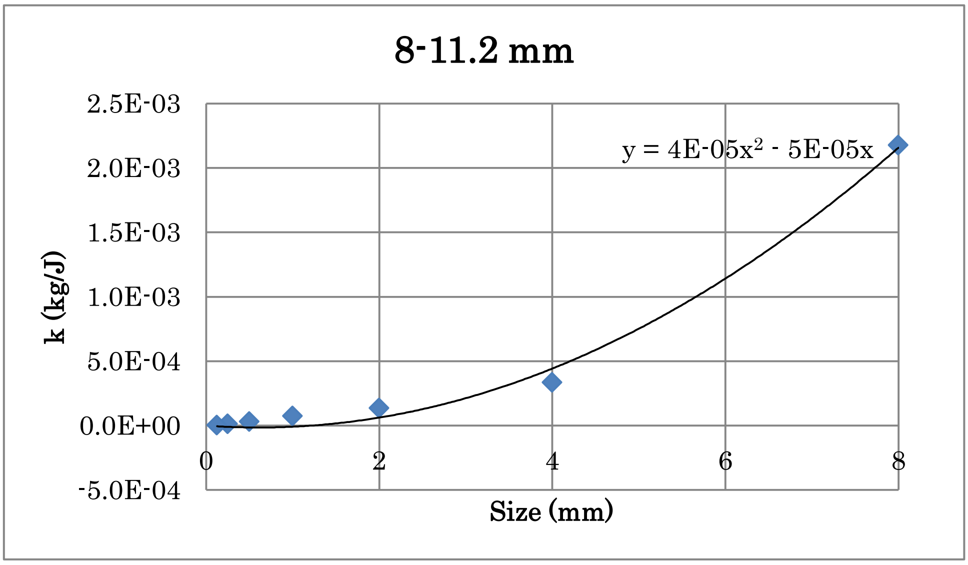


Table 29. Constant k and Size for the feed (**4-5.6 mm**)

Size (mm)	k(kg/J)
4	0.000649
2	0.000205
1	0.000097
0.5	0.000044
0.25	0.000016
0.125	0.000006

Fig48 Constant k vs. Size (mm)

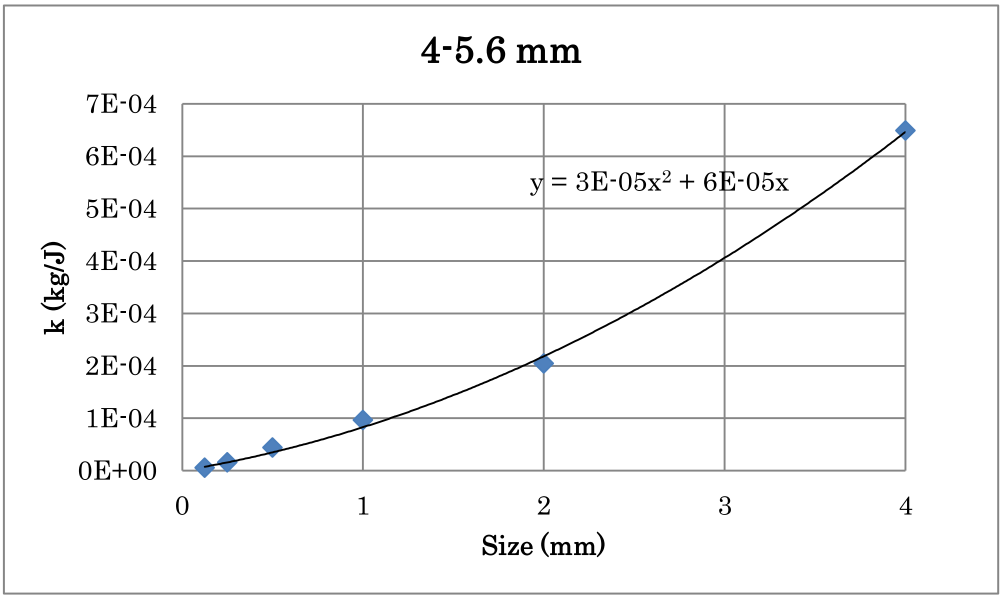


Table 30. Constant k and Size for the feed (**2-2.8 mm**).

Size (mm)	k (kg/J)
2	0.0003330
1	0.0001067
0.5	0.0000408
0.25	0.0000154
0.125	0.0000049

Fig49 Constant k vs. Size (mm)

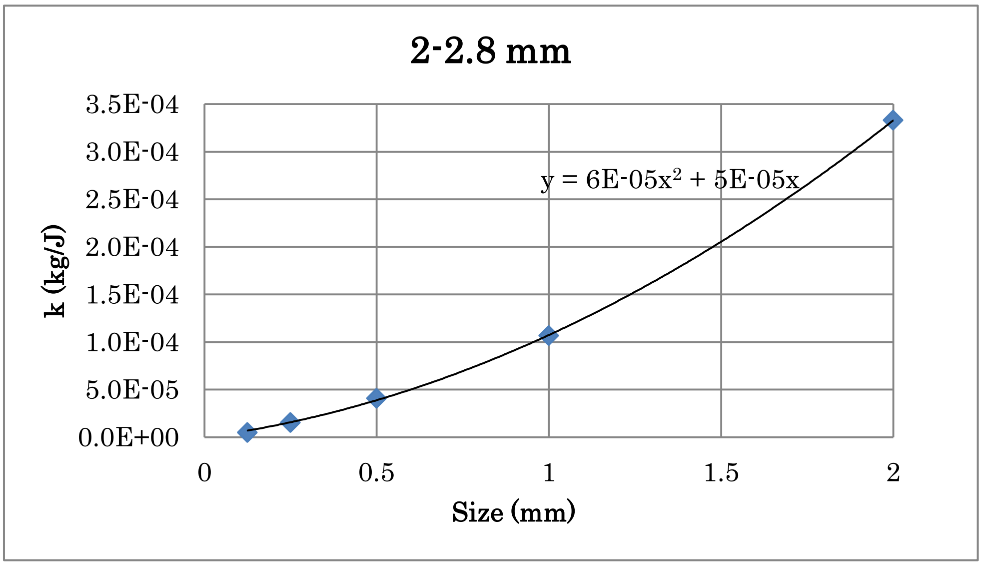
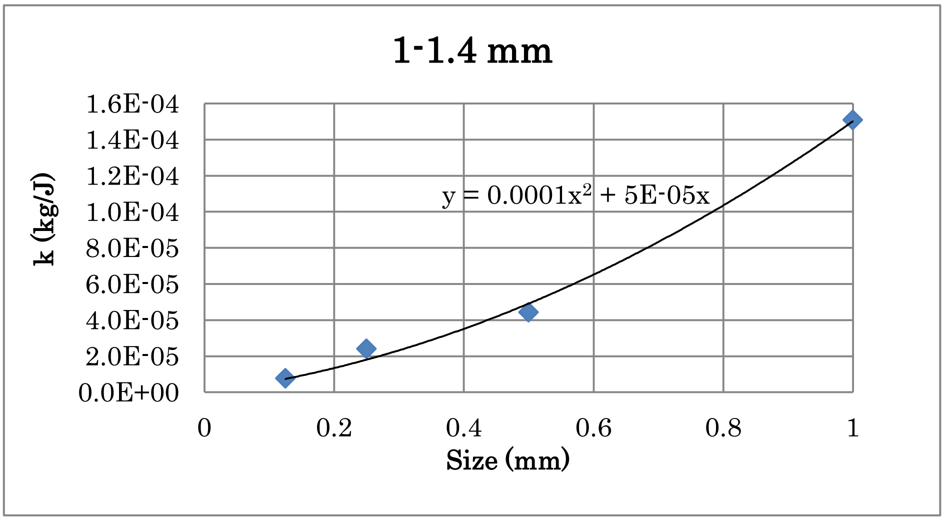


Table 31. Constant k and Size for the feed (**1-1.4 mm**)

Size (mm)	k (kg/J)
1	0.0001510
0.5	0.0000444
0.25	0.0000242
0.125	0.0000078

Fig50 Constant k vs. Size (mm)



Constant *K* of all feeds

Figure 51. Constant k of serpentine vs. Size (mm)

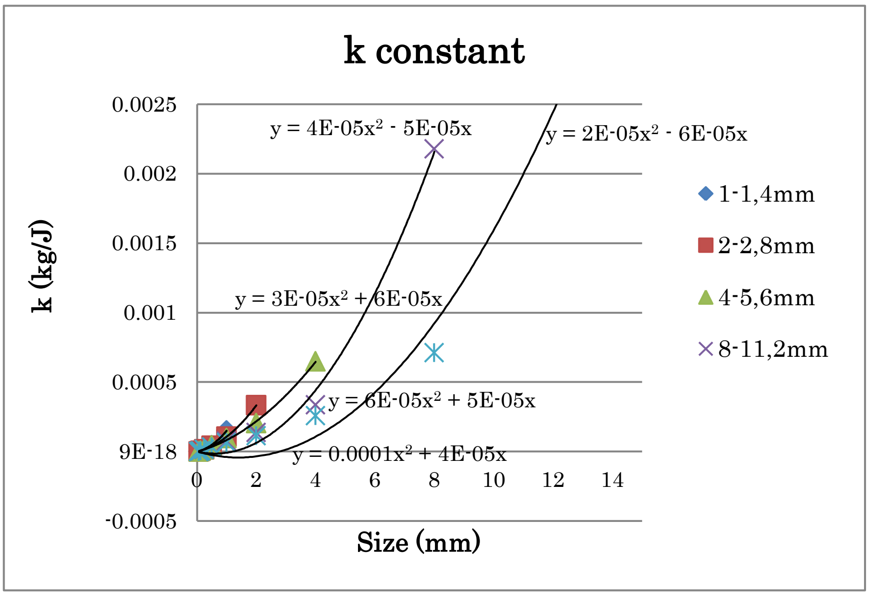


Figure 51 shows that it is easy to produce with finer material than producing with coarser material. According to the figure above, it shows that as a material is crushed the rate of the breakage is higher in the bigger size fractions than in the smaller size fractions.

4. Discussion and Conclusion

This study has shown that some materials crushed faster and with lesser energy than others. Before running the experiments to determine the change of the specific energy of a novel centrifugal crusher and how it changes the particle size of the crushed materials some preliminary experiments were carried out in order to estimate how the specific energy changes by varying the rotational speed.

Size fractions were crushed in a centrifugal crusher at different speed (rpm). Second screen was carried out in other to observe the products of each different sample, and the weight measurement of each product was done to see the cumulatively passing% by using the equation $\varepsilon = (2.\pi.R.N)^2$ (where ε –Specific Energy.R - radius and N-Frequency) to find the specific energy, that depends on velocity $V=\sqrt{2}.\pi.2.R.N$.

to find the '*K*' which is the rate of the reaction by using this formular $P=Ro.\ (1\text{-}\exp\ (\text{-}K.\varepsilon)$ where P-is the produced %, in this case, is the same with cumulatively passing, Ro-100 (because all the particles in the size fraction are bigger than the particles of the products) and from the values of '*K*' *one* can find the average of every product. Unit of the K=kg/J is the number of crushing in the kilos per Joule. The two samples were compared to see the differences as indicated below

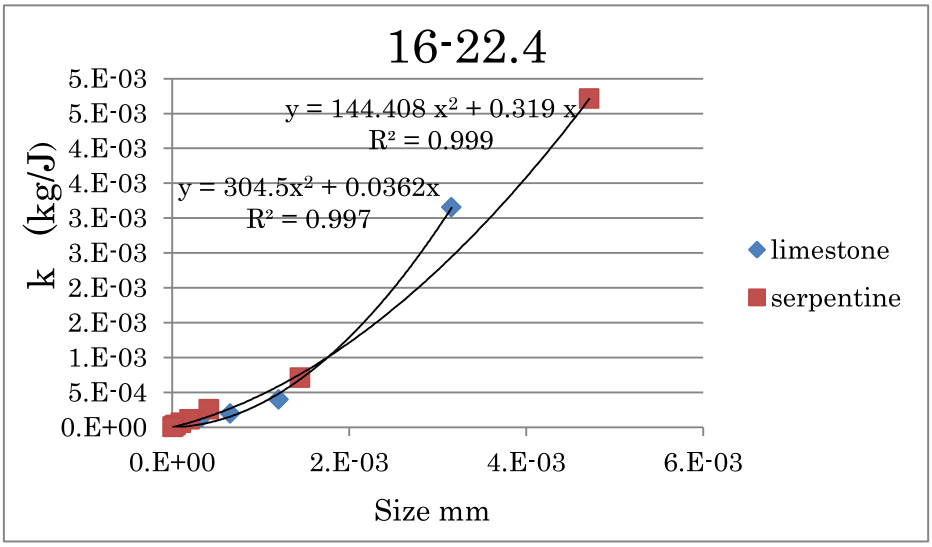


Figure 52 .16-22.4 of the two samples vs. size (mm).

According to the figure above increases with size in the two samples but the rate at which it increases in serpentine is higher, but lower in marly limestone.

The energy required for crushing serpentine increases sharper and the increment is very high. While in the marly limestone the rate of crushing is low and with limited increment.

According to figure 6 the Polish Section of the serpentine shows some cracks which may be the reason why serpentine crushes easier than the marly limestone.

Lastly ,the results indicates that every size crushes in a rate of different speed, and the bigger particle size fractions crushes faster than the small size fraction and when the specific energy increases the particle sizes crushes in a higher rate.

5. References

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