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SINGLE PARTICLE IMPACT BREAKAGE CHARACTERIZATION OF MATERIALS BY DROP WEIGHT TESTING

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A drop weight tester was designed for the purpose of analyzing single particle impact breakage characteristics of different materials. Test results were evaluated through the breakage distributions of different size fractions at various impact energy levels. Breakage parameter t10 (Narayanan, 1986) is used to represent the degree of size reduction which is assumed to be represantative of the breakage product size distribution obtained from drop-weight tests. Relation between specific comminution energy level and breakage index number (t10) was established on the size fractional base so that the variation in impact breakage characteristics of different materials can be evaluated. It can be concluded that, drop-weight test method is a useful and practical way of evaluating the impact strengths of various materials on the size fractional base and results of which can be used in the mathematical modelling of autogenous and ball milling.

Key words: grinding , modelling, breakage function, drop weight test.

INTRODUCTION

Breakage distribution of a material can be simply defined as the distribution of the fragments appearing after the breakage of single particles of different sizes. Although many methods are suggested in the literature for the measurement of breakage distributions experimentally, it is usually difficult to represent the breakage of materials by a standard method due to the mathematical formulation and non-normalizable breakage such as in the traditional approach of Austin (1984). Models of comminution equipments require the determination of breakage distributions known as breakage or appearance functions for the characterization of the material breakage. For example ball mills can be modelled by the perfect mixing model given in Equation 1.

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$$f_i - p_i\left(\frac{r_i}{d_i}\right) + \sum_{j=1}^{i} a_{ij}\, p_i\left(\frac{r_i}{d_i}\right) - p_i = 0 \quad (1)$$

In this comminution model, f_i and p_i are the feed rates (t/h) of size fraction i, a_{ij} is the mass fraction of particle of size j that appear at size i after breakage, and (r_i/d_i) is a combined model parameter where r_i is the breakage rate of particle size i (h^{-1}) and d_i is the discharge rate of particle size i (h^{-1}). Determination of breakage distribution functions experimentally will enable the calculation of model parameter (r_i/d_i) if the feed and product size distributions are measured at the steady state conditions of the ball mill.

For the determination of breakage distributions and understanding of complex nature of particle breakage took in industrial grinding mills, single particle breakage characterization test methods can be used which are grouped into three main classes depending on the breakage mechanism; single impact, double impact (dynamic loading) and slow compression. These tests were used by many researchers for the investigation of input energy-size reduction relationships on the basis of energy utilization.Test results provide practical informations on the impact strengths of individual particles of different ores types. Beside the traditional approach of Austin (1984), it was stated that, tumbling action in a ball mill can be simulated in the double impact tests such as drop weight and pendulum methods although the energy available for particle breakage can only be obtained from pendulum tests (Lynch et al, 1986).Thus these type of tests were widely used for the characterization of ore particles ground in wet or dry ball mills for many years. A general review of single particle test applications and their results were presented by Narayanan (1986). Applications of pendulum tests and corresponding results were explained in the literature (Narayanan, 1985; Narayanan 1987; Munn et al, 1996; Weedon 2001).

On the other hand, various kinds of drop-weight testers were developed by which the breakage distribution and energy utilisation during breakage of different materials were investigated (Gross, 1938; Piret, 1953; Fairs, 1954; Schönert, 1972; Rumpf, 1973; Narayanan and Whiten, 1983; Pauw and Marè, 1988). In a classical drop-weight breakage set up, a single particle is subjected to breakage between two solid surfaces where the drop weight can be a steel ball or a plate. Narayanan (1985) used a ball shaped drop-weight in his breakage set-up to characterize chalcopyrite and lead-zinc ores ranging in size 9.5mm and 2.36mm. Andersen (1988), Man (2000) studied the breakage of +8mm ore particles by using the drop-weight apparatus developed at the Julius Kruttschnitt Mineral Research Centre which was described in detail by Napier Munn et al (1996). Man (2000) carried out single particle breakage tests by using the JKMRC drop-weight tester to characterize basalt which was considered to be relatively homogenous material. Man used two types of drop-weight testers namely, larger drop weight for the breakage of basalt particles ranging in size 45mm and 8 mm and a smaller one for the breakage of particles ranging between 8mm and 2.8mm in which the dropping weights are steel plate and steel ball respectively. Test results showed that, breakage characteristics change with particle size and ore type on the otherhand at finer size fractions breakage product distributions do not vary. A different version of a drop weight tester was used by Asim (1984) for conducting bed breakage tests of clinker particles. In the drop-weight set up a bed of clinker, formed between four steel balls, was subjected to impact progressively by dropping a steel ball onto the centre of particle bed. Impact breakage of clinker was also studied by a twin pendulum device (Zhang, 1992).

Drop-weight tests have many recorded advantages compared to other single particle tests such as an extended input energy range, extended particle size range, shorter test duration, possibility to conduct particle bed breakage tests although they do not give any information about the actual energy consumed during the breakage of single particle. In order to understand the fracture and deformation characteristics of particles under impact loading, a different version of a drop weight tester known as the ultra-fast load cell was used by Tavares and King (1998) for the measurement of particle fracture energy, particle strength and particle stiffness. Many other studies concerning the investigation of breakage distributions of single particles in microscale with the aid of impact load cells were done by Weichert and Herbst (1986), Frandrich et.al (1998), Briggs (1997), Bourgeois and Banini (2002).

Evaluation of single particle breakage data through a single parameter is useful in the understanding of the main breakage characteristics namely size and input energy level dependency. Breakage characteristics of different size fractions can be examined at various impact energies expressed in kWh/ton or joules by determining the product size distribution of broken particle size at the selected energy level. A practical way of analysing single particle brekage data was given by Narayanan (1986). In that well-known approach, product size distributions are defined by a series of size distribution parameters such as t2, t4, t10, t25, t50 and t75 corresspondingly expressing the cumulative per cent passing size of x/2, x/4, x/10, x/25, x/50, and x/75 where x is the geometric mean of the size interval for the test particles.t10 is selected in a traditional way as a breakage fineness comparison parameter.

Narayanan and Whiten (1983;1988) investigated the breakage test results quantitatively by plotting out t10 values as a function of specific input energy level. By this means, material strength to impact breakage can be determined through a single distribution parameter and the power demand to achieve the desired product fineness can also be predicted.

Relationship between t10 and specific comminution energy is represented by the comminution model given in Equation 2 (Leung,1987) where A and b are the material specific impact breakage parameters and E_{cs} is the specific comminution energy level in kWh/t.

$$t_{10} = A\left[1 - \exp\left(-bE_{cs}\right)\right] \tag{2}$$

Value of A gives the maximum value of t10, whereas the slope of the t10 versus E_{cs} plot gives the value of b. This relation was verified for different ore types broken by a twin-pendulum device (Leung et.al.,1987) and drop weight tester (Napier Munn et al, 1996 ; Man 2000).

The aim of this research was to investigate single particle impact breakage characteristics of different materials by the drop-weight test method.

BREAKAGE SET-UP AND EXPERIMENTAL STUDIES

SINGLE PARTICLE BREAKAGE SET-UP

Drop weight tester manufactured for the purpose of breakage study at the Mineral Processing Laboratory of Hacettepe University. A photograph of the drop weight apparatus is shown in Figure 1. It mainly comprises a steel anvil made from steel alloy, plate shaped drop weight head, an electromagnet through which an electromagnetic field is formed so that weights can be hold or released from desired heights. Drop weight head mass has a series of lead weights which can be added or removed when required. Drop weight apparatus is fitted with a 5.870 kg fixed head mass which can be extended to 44.16 kg with a maximum drop height of 51.50cm. representing a wide energy range. In this experimental set up, plate shaped drop weight is raised to a known height through a mechanical arm and then subjected to free fall onto a particle that is placed on the center of the steel anvil so that the impact breakage of particles are achieved. Breakage area is enclosed by an aluminium casing in order to prevent the losing of the broken fragments during the test. Drop weights of the breakage set up is tabulated in Table 1.

Table 1. Drop weights

	Drop weights
Fixed head weight	5.870 kg
Lead weights	11.690kg-10.550kg-9.300kg-4.421kg
Steel weights	1.429-3x4kg-11 kg-4.5kg
Extra weights added during the test: 0.624kg-0.3956kg-Small bolt:0.0535 kg-Big bolt:0.1150kg	

Tests were conducted on various size fractions of colemanite, quartz, copper ore, trass, limestone, gypsum, clay and cement clinker samples. Samples were dry sieved to the desired narrow size intervals and representative samples were taken from each size interval for each breakage energy level. For the calculation of breakage energy level, number of particles in each set of sample was counted to determine the mean mass of the particles. To achieve the desired specific comminution energy levels for each size, appropriate height and drop weights were calculated. Impact energy supplied by the plate shaped weight is calculated from the equations given by Napier-Munn et al (1996).

Fig. 1. A photograph of the drop weight apparatus

$$E_i = m_d g(h_i - h_f) \tag{3}$$

where,

Ei : Impact breakage energy (m^2 kg/sec^2)

m_d : Mass of drop weight head (kg)

h_i : Initial height of the drop-weight above the anvil (m)

h_f : Final height of the drop-weight above the anvil (m)

$$Ecs = E_i / m_p \tag{4}$$

where,

E_{cs} : Specific comminution energy in kWh/t

m_p : Mean particle mass in g.

Single particle breakage tests were conducted on each set of sample at the required energy levels and the broken fragments were collected from each set of particles, and dry sieved on a root 2 sieve series on a ro-tap sieve shaker for 15 minutes. Finally, breakage product size distributions of each sample was determined. Size fractions, average number of particles broken in each size fraction and experimental breakage energy levels are summarized in Table 2.

Table 2. Experimental conditions

Size fractions (mm)	Nominal particle size (mm)	Number of particles broken in each energy level	E_{input} levels (Joule)	E_{cs} levels (kWh/t)
Material: Colemanite				
-28+25.4	26.67	8	36.98 - 23.4 - 4.99	0.33 - 0.20 - 0.09
-22.4+19	20.63	15	37.16 - 23.67 - 9.85	0.59 - 0.38 - 0.16
-16.0+13.2	14.53	30	23.96 - 10.21	1.42 - 0.60
Material: Quartz Type I				
-63+55	58.86	2	140.37-222.25	0.11-0.17
-45+38	41.35	4	45.49-226.58-106.14	0.10-0.48-0.22
-31.5+25	28.06	10	38.99-167.23-228.75	0.25-1.03-1.44
-22.4+19	20.63	17	51.78-119.25-13.30	1.08-2.52-0.26
-16+13.2	14.53	35	39.36-16.71-4.09	2.52-1.07-0.26
Material: Quartz Type II (Bergama)				
-13.2+11.2	12.16	33	2.07-3.08-3.73	0.24-0.35-0.43
-9.5+8.0	8.72	58	2.04-2.71-3.85	0.49-0.67-0.92
-8.0+6.7	7.32	150	1.96-2.99-4.09	0.86-1.32-1.77
-5.6+4.75	5.16	233	1.96-4.09	2.47-5.16
Material: Copper ore				
-16+13.2	14.53	30	27.88	1.10
-13.2+11.2	12.16	60	17.88	1.07
-9.5+8.0	8.72	100	5.91	1.05
-5.6+4.75	5.16	175	4.09	3.15
Material : Trass Type I (cement additive)				
-16+13.2	14.53	30	4.94-10.04-15.43-15.36	0.39-0.80-1.22-1.79
-13.2+11.2	12.16	50	4.94-10.32-15.58	0.60-1.28-1.89
-9.5+8.0	8.72	70	4.91-10.56-15.58	1.72-3.87-5.61
Material : Trass Type II (cement additive)				
-9.5+8.0	8.72	100	3.57	1.04
Material : Limestone Type I (cement additive)				
-16+13.2	14.53	25	4.10-9.89-15.15	0.22-0.52-0.80
-13.2+11.2	12.16	40	4.25-10.17-15.22	0.34-0.81-1.21
-9.5+8.0	8.72	60	4.78-10.44-15.63	1.19-2.67-3.90
Material : Limestone Type II (cement additive)				
-9.5+8.0	8.72	100	3.80	1.00
Material : Gypsum Type I (cement additive)				
-16+13.2	14.53	26	15.70-10.32-4.76	1.09-0.72-0.34
-13.2+11.2	12.16	36	15.70-4.91-10.44	1.92-0.59-1.26
-9.5+8.0	8.72	70	15.82-10.56-5.03	5.73-3.82-1.82
Material : Clay				
-9.5+8.0	8.72	100	3.80	0.95
Material: Cement clinker typeI				
-22.6+16	19.02	20	13.95-35.73-67.11-90.19	0.47-1.06-2.01-3.04
-9.5+8.0	8.72	80	4.15-7.16-9.66-10.67-11.56-14.92-16.17	1.07-1.97-2.86-3.00-3.32-4.14-4.4
Material: Cement clinker typeI				
-13.2+11.2		40	3.04-2.25-3.85	0.32-0.25-0.42
-9.5+8.0	8.72	100	2.87-2.11-3.74	0.90-0.61-1.20
-5.6+4.75	5.16	265	1.96-3.74	2.89-5.53

RESULTS AND DISCUSSION

Impact breakage test results were evaluated through the size distributions of the breakage products. Breakage distributions of some of the test materials are presented in Figures 2, 3, 4, 5, 6, 7 and 8. 80% passing particle sizes (P80) of breakage distributions are tabulated in Tables 3 and 4.

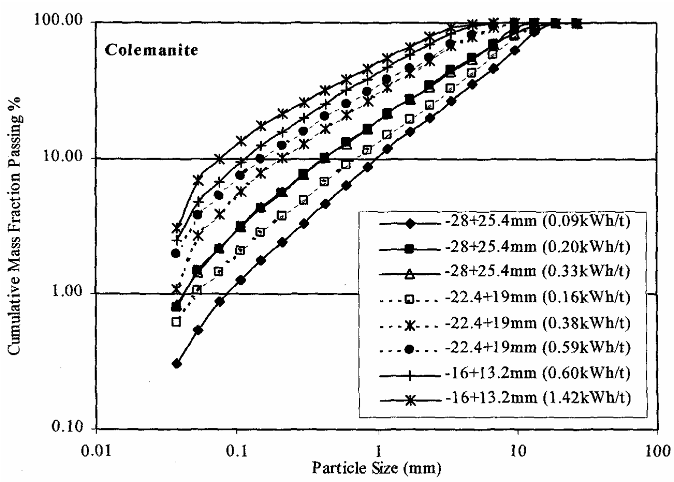

Fig. 2. Cumulative impact breakage distributions of colemanite ore at different energy levels

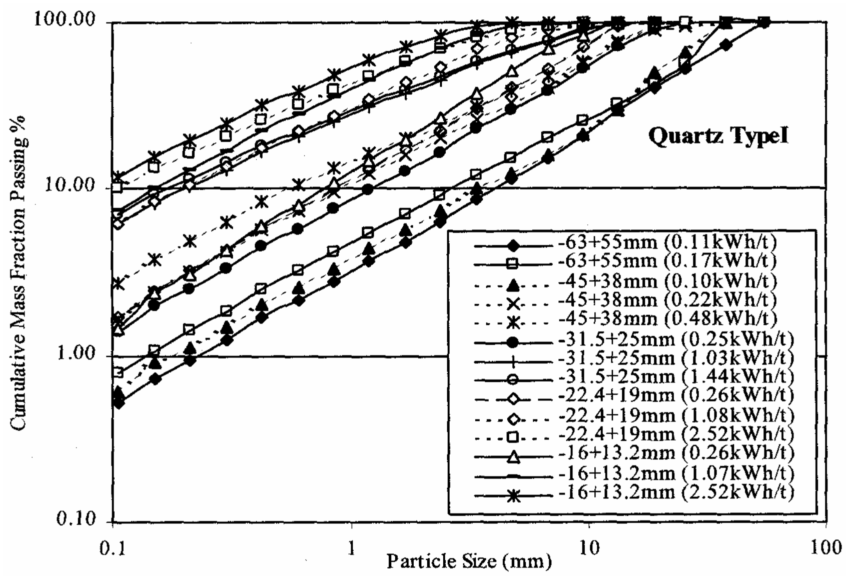

Fig. 3. Cumulative impact breakage distributions of quartz at different energy levels

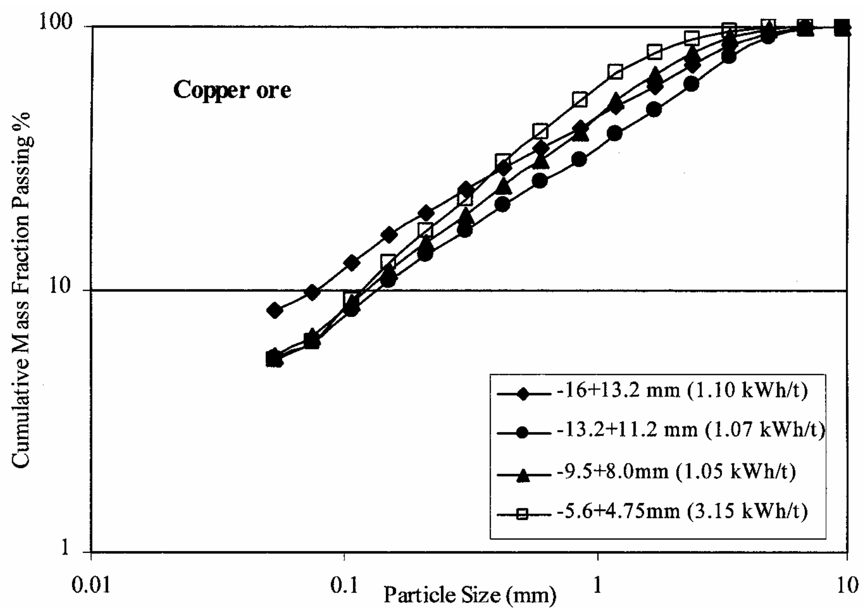

Fig. 4. Cumulative impact breakage distributions of copper ore at different energy levels

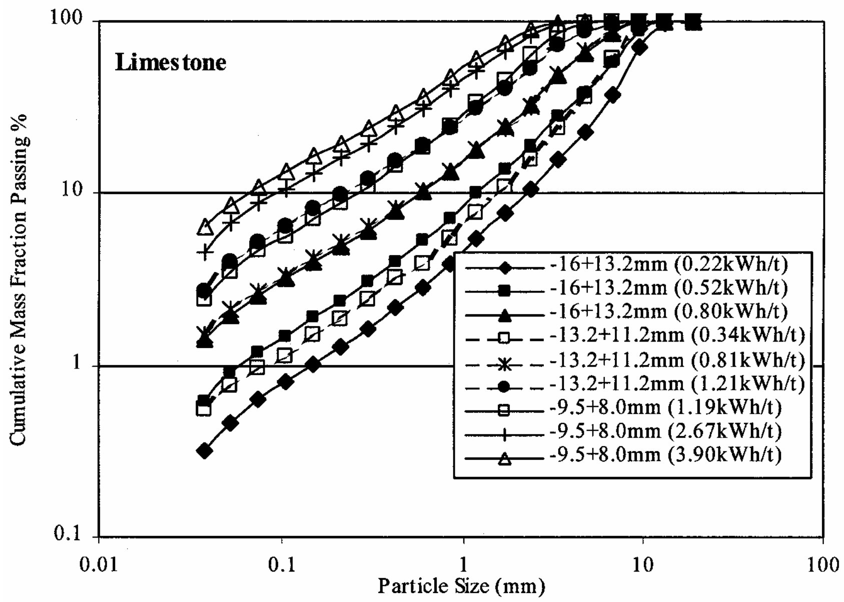

Fig. 5. Cumulative impact breakage distributions of limestone at different energy levels

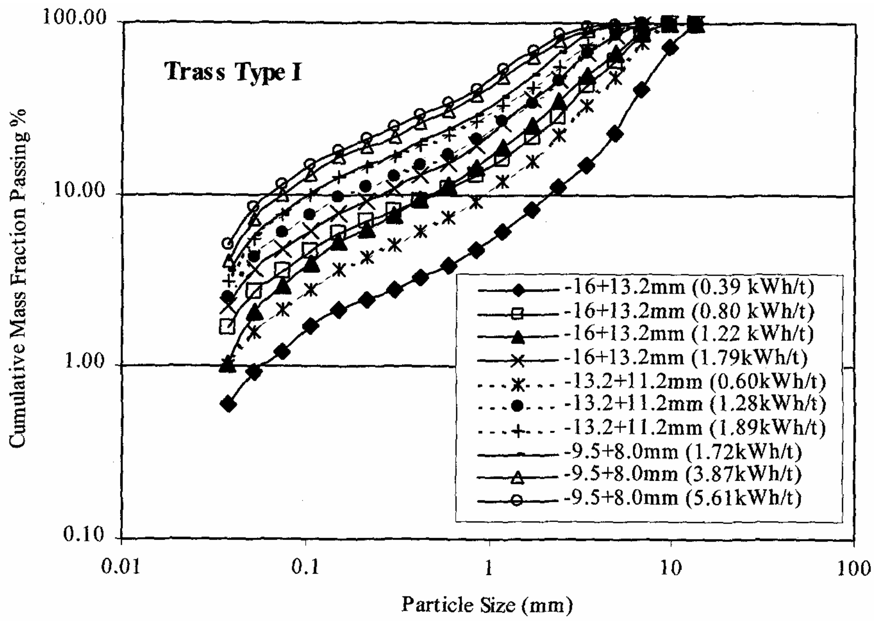

Fig. 6. Cumulative impact breakage distributions of trass at different energy levels

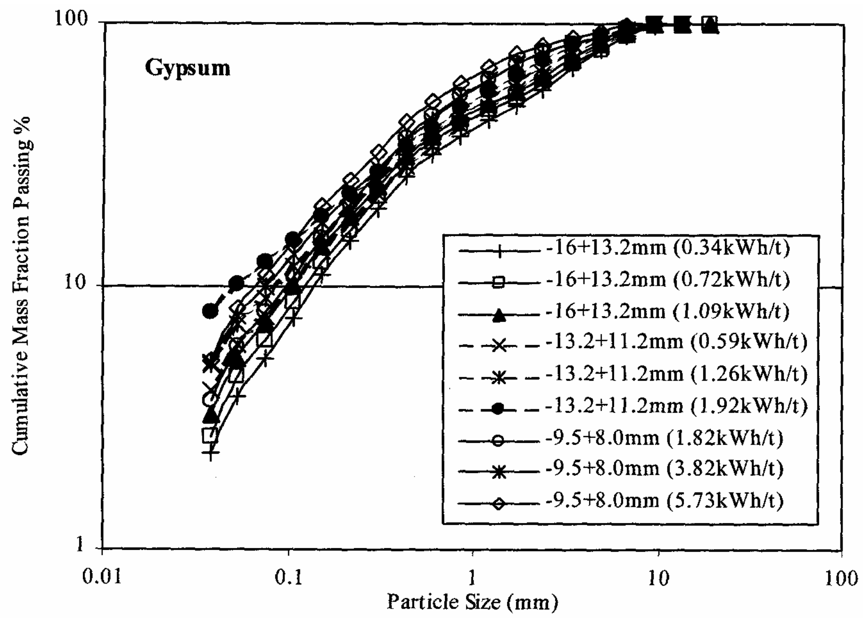

Fig. 7. Cumulative impact breakage distributions of gypsum at different energy levels

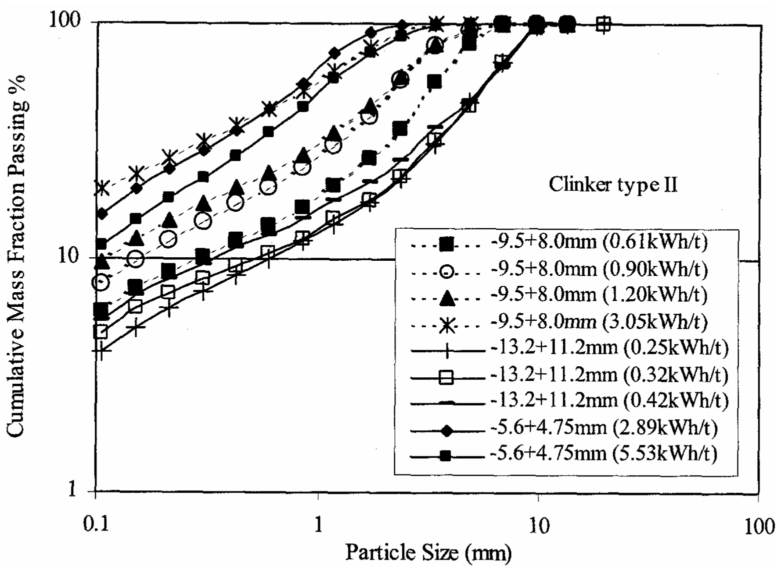

Fig. 8. Cumulative impact breakage distributions of clinker type II at different energy levels

Breakage product size distributions indicated that, increase in breakage energy level increases the fineness of the breakage distributions whereas, size distributions start to become closer at higher energy levels indicating no more size reduction would occur such as in case of –13.2+11.2mm and –9.5+8.0mm particles of limestone sample (Figure 5).

Table 3. Breakage product fineness variations with size and breakage energy level

Quartz Type I	*-22.4+19mm*			*-16+13.2mm*		
Ecs (kWh/t)	0.26	1.08	2.52	0.26	1.07	2.52
P80 (mm)	10.47	4.56	3.23	8.54	2.98	2.09

Quartz Type I	*-63+55mm*		*-45+38mm*			*-31.5+25mm*		
Ecs (kWh/t)	0.11	0.17	0.10	0.22	0.48	0.25	1.03	1.44
P80 (mm)	39.15	28.14	27.16	14.34	14.01	15.29	6.95	7.03

Colemanite	*-28+25.4mm*			*-22.4+19mm*			*-16+13.2mm*	
Ecs (kWh/t)	0.09	0.20	0.33	0.16	0.38	0.59	0.60	1.42
P80 (mm)	12.17	7.77	8.79	9.75	4.83	4.50	2.99	2.41

Copper ore	*-16+13.2mm*	*-13.2+11.2mm*	*-9.5+8.0mm*	*-5.6+4.75mm*
Ecs (kWh/t)	1.1	1.07	1.05	3.15
P80 (mm)	2.9	3.53	2.39	1.68

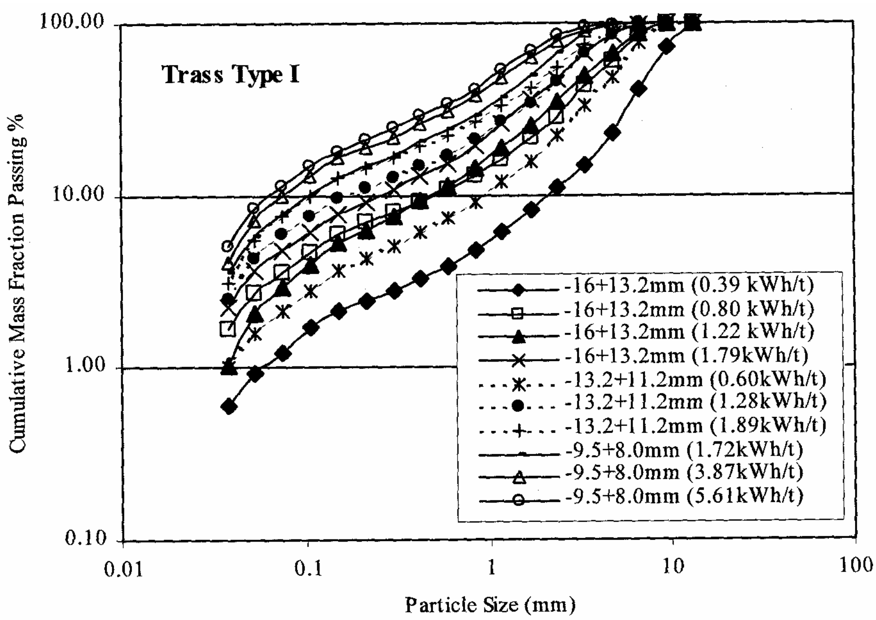

Table 4. Breakage product fineness variations with size and breakage energy level for clinker and cement additive materials

Limestone	*-16+13.2mm*			*-13.2+11.2mm*			*-9.5+8.0mm*		
Ecs (kWh/t)	0.22	0.52	0.80	0.34	0.81	1.21	1.19	2.67	3.90
P80 (mm)	10.30	8.57	5.99	7.87	5.65	3.91	3.02	2.16	1.86
Trass type I									
Ecs (kWh/t)	0.39	0.80	1.22	0.60	1.28	1.89	1.72	3.87	5.61
P80 (mm)	9.84	6.25	5.77	7.02	4.32	3.73	2.90	2.40	2.13
Gypsum									
Ecs (kWh/t)	0.34	0.72	1.09	0.59	1.26	1.92	1.82	3.82	5.73
P80 (mm)	0.34	4.89	4.14	4.38	3.60	3.01	2.59	2.77	2.05
Clinker typeII									
	-13.2+11.2mm			*-9.5+8.0mm*				*-5.6+4.75mm*	
Ecs (kWh/t)	0.25	0.32	0.42	0.61	0.90	1.20	3.05	2.89	5.53
P80 (mm)	7.40	7.48	7.54	4.63	3.34	3.23	1.73	1.30	1.91

Fineness of the breakage products was represented by the t10 values and the relation between specific comminution energy level and t10 was established for the test materials. Typical relations between Ecs and t10 parameter are given for some of the test materials in Figure 9. It was observed that, colemanite ore was broken easily compared to the other materials. Highest resistance to impact breakage was observed in the breakage event of quartz type II which belongs to a gold deposit. Impact breakage result of gypsum showed that, selected energy levels are so high that small deviations in t10 values are obtained at energy levels higher than 0.3kWh/t indicating the mineral softness. Maximum or limiting value of breakage index (t10) which is defined by the parameter A in the E_{cs}-t_{10} model (Leung, 1987) is obtained at lower energy levels for coarse size fractions of the test materials.

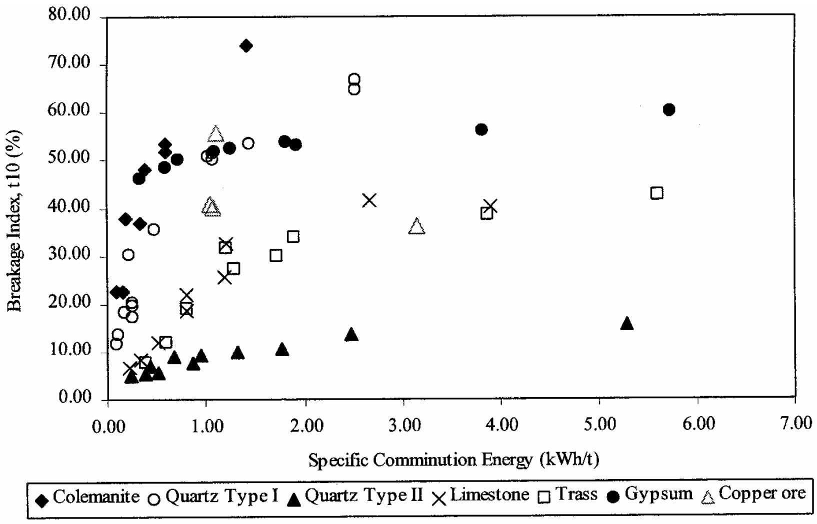

Fig. 9. Comparison of *Ecs-t10* relation for different materials

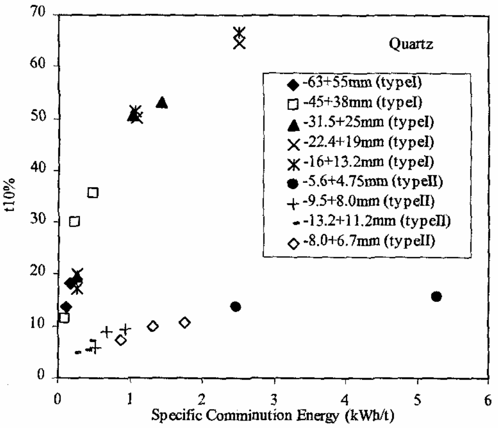

Fig. 10. Comparison of Ecs-t10 relation for two different quartz

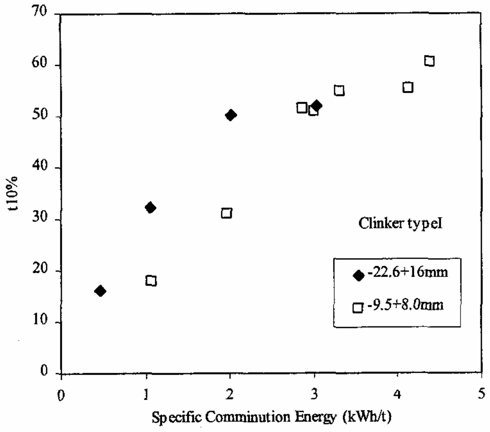

Fig. 11. Comparison of Ecs-t10 relation for test size fractions of clinker type I

Breakage index values of both quartz types and clinker type II were compared on the size fractional base in Figures 10 and 11 respectively. It was observed that, strength of particles vary with particle size at the same level of specific comminution energy such as in case of approximately 0.2kWh/t for particles of –63+55mm (t10%:18.33) and –45+38mm (t10%:30.15). On the other hand excluded of –45+38mm size fraction, impact breakage of other size fractions produced the same amount of fines at 0.25kWh/t. Overall breakage resistance of both quartz types are completely different leading to have different grindability values with variations in breakage distributions of some particle sizes. Clinker also showed a size dependent breakage behaviour.

In case of complex copper ore, which is not a homogeneous material, size independent breakage behaviour was observed for size fractions of –9.5+8.0mm (t10%:40.83) and –13.2+11.2mm (t10%:40.29) whereas –16+13.2mm (t10%:55.71) particles broke in a different manner. Result of such variations in breakage strengths of different size fractions of the same material can be due to the microstructure, mineralogical composition and the included probable microcracks.

At the same level of specific comminution energy, breakage result of –9.5+8.0mm size fraction was compared for different materials through breakage index value of t10 in Figure 12. Results showed that impact strength of copper ore is the lowest among the test materials on the considered size fraction. Clinker and limestone samples of different plants also showed variation in their breakage characteristics.

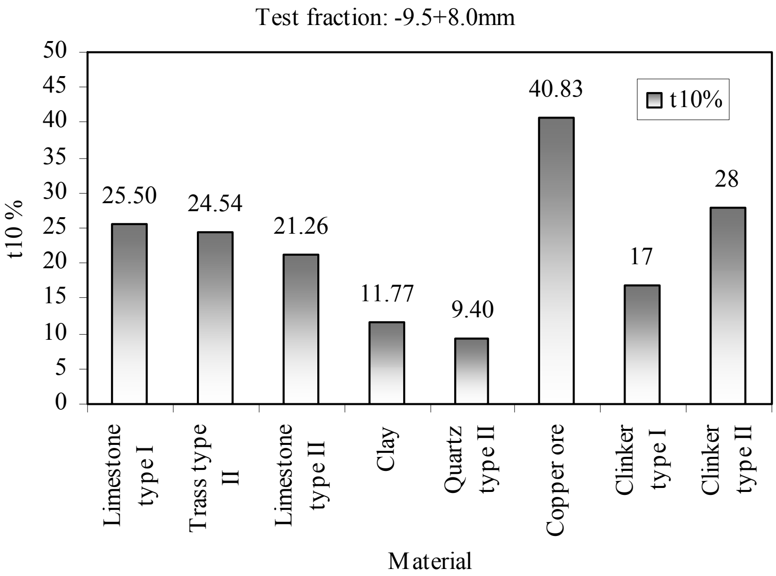

Fig. 12. Breakage index values of different materials at an impact energy level of around 1kWh/t

CONCLUSION

Drop weight test results can be used to evaluate the single particle breakage strengths of materials on the size fractional base. Results of such tests can then be used in the comminution models of autogeneous and ball mills. Size dependent breakage behaviour of materials is an important problem in terms of grinding modelling studies since the breakage distributions of the mill feed materials are commonly determined by using the breakage data of single particle size broken at an appropriate specific comminution energy level. In most of the modelling studies, breakage distribution function of materials are assummed to be independent of particle size just to ease the grinding modelling work which is not true for most of the materials. In order to achieve more reliable grinding simulation results, a detailed breakage study should be carried out in such a way that, different size fractions of the same material should be broken from the same level of specific energies.In fact breakage distribution of each size fraction should be defined in comminution models in some way.

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Analizowano skutki kruszenia udarowego pojedynczego ziarna różnych materiałów za pomocą metody zrzutu ciężaru. Wyniki badań oceniano drogą analizy rozkładów kontrolowanych klas ziarnowych przy różnych poziomach energii udaru. Stopień pomniejszania ziarn w teście zrzutowym odpowiadający rozkładowi rozmiarów ziarn produktu skruszonego reprezentował parametr rozkruszenia t10 zaproponowany w pracy Natarayanana (1986). Zależność pomiędzy właściwą energią rozdrabnia i indeksem skruszenia t10 oceniano na podstawie rozmiaru ułamkowego, co umożliwia szacowanie zmienności charakterystyki kruszenia udarowego różnych materiałów. Stwierdzono, że metoda testu zrzutu ciężaru jest użytecznym narzędziem oceny naprężeń udarowych różnych materiałów na podstawie rozmiaru ułamkowego i może być wykorzystana w modelowaniu matematycznym procesów mielenia w młynach autogenicznych i kulowych.