A SIMPLE METHOD FOR STUDYING CRUSHABILITY AND GRINDABILITY OF ROCKS AND MINERALS

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ABSTRACT

This paper deals with describing a plain and simple method to assess the crushability and grindability of rocks and minerals in order to use for different purposes. This behavior is related to the physical properties of rocks and minerals such as strength, hardness and friability. This can be made use of for different applications such as size reduction of rocks and minerals as well as drillability of rock material on basis of comparison with an index rock whose properties and crushability index values are previously determined in a later research based on this.

For this purpose a simple laboratory device has been machined consisting of a vertical cylinder (60 cm. in height and 11 cm. inner diameter)containing slots every 10 cm. along its length and standing on a bace representing the sample holder with different weights representing drop hammers and sieving analysis has been used as a tool to examine the degree to which the relevant rock particles have been crushed (or reduced in size) after being subjected to mechanical impact by the drop hammers (drop weights). The number of drops and the heights of fall could represent the energy level imposed on rock particles. The rock samples used consist of particles of red kaolinite (50)gm. each.

It has been concluded that the effectiveness of size reduction increases with the increase of drop weight , drop height and number of blows. It has been also concluded that the key sieve size most adequate for doing the comparative study was (2.8) mm. which can be used for future work.

It has been recommended to use the following optimum operating variables:Drop weight =993.5 gm, Drop height = 30 cm, Number of blows =2, Key sieve size for the analysis = 2.8 mm.

This method can serve as a plain and simple guide to assess the ease with which the rocks and minerals can be reduced in size (crushed or ground).

INTRODUCTION

The different rocks and minerals differ widely in their physical and mechanical properties. From these properties the most important include terms such as hardness, the different strength properties such as compressive, tensile and shear strength, Young's modulus, Shear modulus, Bulk modulus, Poisson's ratio in addition to other properties which may have an indirect influence on the behavior of rock particles under loading. Although the behavior of natural material such as rocks and minerals under loading may differ widely due to their heterogeneous composition and structure which is caused by the different environmental and confining conditions to which they are subjected, it is worthwhile finding some means of describing and quantifying some behavioral properties of these materials whereby the basis of comparison and analogy can help in this respect. Hard rocks react to any mechanical loading differently from medium hard or soft ones.[3]

The rock samples which have been used for this study consisted of red kaolinite. Many theories and laws have been suggested to relate the energy consumed in the process of size reduction (Rittinger, kick and Bond laws) but no single law could relate the energy consumption to the size reduction satisfactorily because a great deal of this energy does not go to the actual process of size reduction. This part of energy represent losses being consumed for heat, noise, change of shape, gearing, and other mechanical changes[1,5].

When a rock material is subjected to a certain stress it will be strained whereby the stress – strain relationship may show different ranges on the way of being collapsed after exceeding the ultimate strength. These ranges are:

1. Elastic Range: During this range the strain is directly proportional to the stress according to hook's law which takes the from:

$$E = \sigma/\varepsilon$$

Whereby E = Elastic modules
σ = stress
ε = strain

This range is characterized by the fact that the material returns to its original shape and size after removing the stress.

2. Plastic range: Whereby the shape of stress – strain relationship will deviate from being linear and some of the strain will remain in the material even after the stress has been removed.
3. Yield or Failure: This happens after reaching and exceeding the point of ultimate strength.

We can distinguish here between two types of rocks: Brittle and Ductile rocks, see Fig. (1)[3].

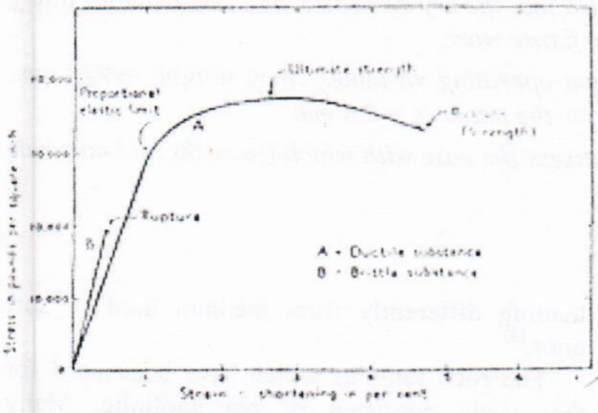

Fig. (1): The general shape of stress – strain relationship.[3]

The process of size reduction may be divided into the following ranges:

1. Primary crushing.
2. Secondary crushing.
3. Coarse grinding.
4. Fine grinding.
5. Ultra fine grinding.

The rock breakage may happen due to different mechanisms such as:

A. Breakage by mechanical impact or compression due to vertical or nearly vertical forces.
B. Breakage by chipping due to inclined forces.
C. Breakage by abrasion due to parallel forces to the particle surface (fig. 2).[1],[5]

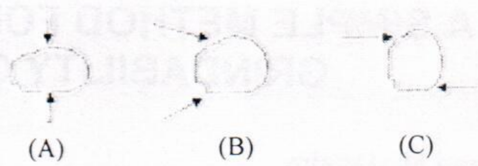

Fig. (2): The mechanisms of rock breakage.[1],[5]

EXPERIMENTAL WORK

Equipments

1. A simple laboratory device for studying the crushability and grindability of rocks has been designed and manufactured. This device consists of: (a) a steel pipe with dimensions of; length = 60 cm, outer diameter = 12 cm, and inner diameter =11 cm. (b) Slots have been made in the pipe perpendicular to its axis with a width of 5 cm. and height of 0.5 cm. The interval between the slots was 10 cm. A holding plate is used to be inserted in these slots to hold the weights. The pipe is placed standing on a base consisting of a short cylinder slightly greater in diameter than the pipe and closed from the bottom. This base serves to hold the rock samples being crushed. (c) Different weights in the form of solid cylinders slightly less in diameter than the pipe and each weight contains a hanging loop at the center of top surface. This serves to hold the weights by strings being tied to the weights (fig. 3a & 3b).

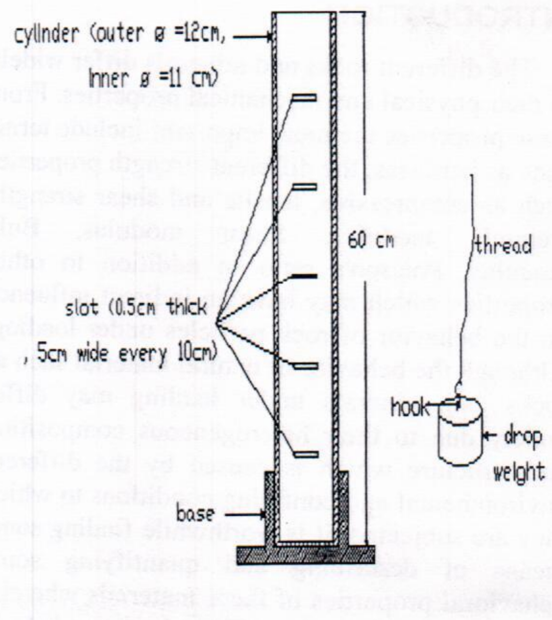

Fig. (3a) a sketch of the manufactured device

Fig. (3b) The manufactured device

2. A set of sieves and a sieve shaker to perform sieving analysis. (Fig. 4)
3. A simple laboratory balance.

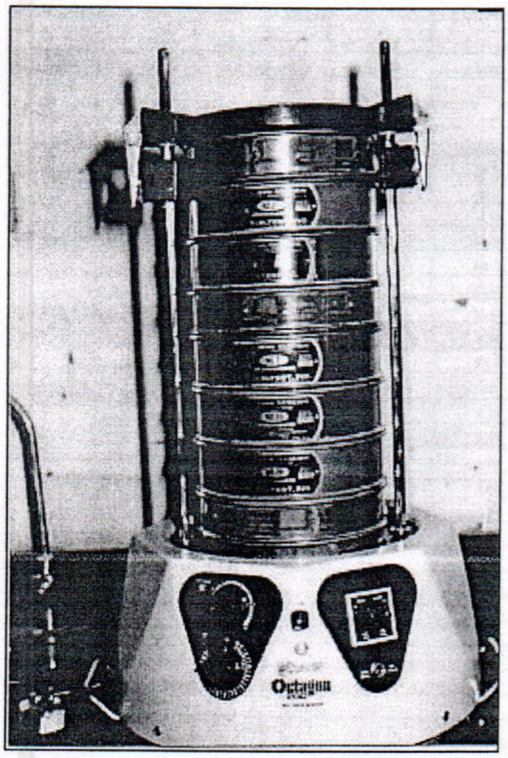

Fig. (4) A sieve shaker and nest of sieves

Experimental Procedure

1- Various granular rock samples of same weight (50 gm.) and size range are prepared.

2- The sample is placed at the bottom of the base of device evenly to form a bed of equal thickness.

3- The pipe is placed inside the base and the required weight is fixed standing on the holding plate at the required height.

4- The holding plate is pulled horizontally in a fast way out of the slot to let the weight drop on the bed of rock particles exerting a load or impact which crushes the rock particles.

5- The process is repeated by lifting the weight by the string to the same level and being let drop down in the same manner. This is repeated to the required number of times.

6- The sample is taken out of the base and a sieving analysis is performed where the results are tabulated.

7- The same process is repeated on another sample by changing the number of blows whereby the same above – mentioned procedure is repeated for each number of blows. The number of blows acts as one of the variables.

8- By using the same weight the above - mentioned procedure is repeated for different heights. The height is looked upon as another variable.

9- The same process can be repeated on similar rock samples by changing the drop weights. The drop weight is another variable.

10- The results are tabulated in a proper manner and then graphically represented.

RESULTS AND DISCUSSION

The results obtained from the experimental work have been tabulated in different tables (table 1 till table 8). Tables (1-3) show the results of experiments for drop weight 585 gm. with varying the drop height (10, 20 and 30 cm.) successively. In each table of these three tables four different values of blows (drops) were used, namely 5,10,15 and 20 blows. Tables (4-6) show the results of experiments for the alternative drop weight 993.5 gm. with varying the drop height also (10, 20 and 30 cm.) successively.

Four different values of number of blows were also used in each of these three tables (5,10,15 and 20 blows).

In all these tables the weight retained (gm), individual weight retained percentage and the cumulative weight percentage passing through the different sieves were tabulated against the opening size of each sieve (mm.). These represent the overall results of the sieving analysis of each experiment.

For the purpose of comparison a comparative summary of the results of the cumulative weight percentage passing through sieve openings (1.7 and 2.8 mm.) for the two-drop weights used were shown on tables (7 and 8) successively. The aim of this type of presentation was to show the results of the different variables in a comparative manner in order to draw some conclusions regarding the effectiveness of size reduction for the different variables used in the experiments.

Table (1) Results of sieving analysis of sample: red Kaolinite, drop weight=585 gm, drop height = 10 cm

cumulative wt. (%) passing	Individual weight % retained	weight retained (gm)	opening	No. of Blows
17.6	82.4	41.2	6.4	
5.6	12.0	6.0	5.7	
2.6	3.0	1.5	3.4	
2.2	0.4	0.2	2.8	5 Blows
1.3	0.9	0.45	1.7	
0.7	0.6	0.3	1.4	
0.0	0.7	0.35	1.4 >	
31.0	69.0	34.5	6.4	
15.6	15.4	7.7	5.7	
8.8	6.8	3.4	3.4	
7.6	1.2	0.6	2.8	10 Blows
6.1	1.5	0.75	1.7	
5.5	0.6	0.3	1.4	
0.0	5.5	2.75	1.4 >	
64.2	35.8	17.9	6.4	
41.6	22.6	11.3	5.7	
22.6	19.0	9.5	3.4	
18.8	3.8	1.9	2.8	15 Blows
13.1	5.7	2.85	1.7	
11.5	1.6	0.8	1.4	
0.0	11.5	5.75	1.4 >	
86.2	13.8	6.9	6.4	
63.2	23.0	11.5	5.7	
47.0	16.2	8.1	3.4	
36.6	10.4	5.2	2.8	20 Blows
21.4	15.2	7.6	1.7	
18.0	3.4	1.7	1.4	
0.0	18.0	9.0	1.4 >	

Table (2) Results of sieving analysis of sample: red Kaolinite, drop weight=585 gm, drop height = 20 cm

cumulative wt. (%) passing	Individual weight % retained	weight retained (gm)	opening	No. of Blows
16.2	83.8	41.9	6.4	
9.2	7.0	3.5	5.7	
4.5	4.7	2.35	3.4	
3.2	1.3	0.65	2.8	5 Blows
1.9	1.3	0.65	1.7	
1.3	0.6	0.3	1.4	
0.0	1.3	0.65	1.4 >	
31.0	69.0	34.5	6.4	
21.2	9.8	4.9	5.7	
13.0	8.2	4.1	3.4	
11.2	1.8	0.9	2.8	10 Blows
7.8	3.4	1.7	1.7	
6.6	1.2	0.6	1.4	
0.0	6.6	3.5	1.4 >	
57.4	42.6	21.3	6.4	
41.4	16.0	8.0	5.7	
22.6	18.8	9.4	3.4	
19.2	3.4	1.7	2.8	15 Blows
13.2	6.0	3.0	1.7	
11.4	1.8	0.9	1.4	
0.0	11.4	5.7	1.4 >	
91.0	9.0	4.5	6.4	
67.0	20.0	10.0	5.7	
40.7	26.3	13.15	3.4	
37.7	5.6	2.8	2.8	20 Blows
24.1	15.6	7.8	1.7	
19.5	4.6	2.3	1.4	
0.0	19.5	9.75	1.4 >	

Table (3) Results of sieving analysis of sample: red Kaolinite, drop weight=585 gm, drop height = 30 cm

cumulative wt. (%) passing	Individual weight % retained	weight retained (gm)	opening	No. of Blows
20.0	80.0	40.0	6.4	
12.8	7.2	3.6	5.7	
4.4	8.4	4.2	3.4	
3.5	0.9	0.45	2.8	5 Blows
2.5	1.0	0.5	1.7	
1.8	0.7	0.35	1.4	
0.0	1.8	0.9	1.4 >	
53.94	46.06	23.03	6.4	
41.78	12.16	6.08	5.7	
20.72	21.06	10.53	3.4	
18.66	2.06	1.03	2.8	10 Blows
10.0	8.66	4.33	1.7	
7.23	2.77	1.38	1.4	
0.0	7.23	3.615	1.4 >	
87.6	12.4	6.2	6.4	
70.6	17.0	8.5	5.7	
37.6	33.0	16.5	3.4	
31.8	5.8	2.9	2.8	15 Blows
18.8	13.0	6.5	1.7	
16.2	2.6	1.3	1.4	
0.0	16.2	8.1	1.4 >	
95.8	4.2	2.3	6.4	
89.6	6.2	3.1	5.7	
63.6	26.0	13.0	3.4	
54.6	9.0	4.5	2.8	20 Blows
36.6	18.0	9.0	1.7	
33.2	3.4	1.7	1.4	
0.0	33.2	16.6	1.4 >	

Table (4) Results of sieving analysis of sample: red Kaolinite, drop weight=993 gm, drop height = 10 cm

cumulative wt. (%) passing	Individual weight % retained	weight retained (gm)	opening	No. of Blows
60.0	40.0	20.0	6.4	
30.6	29.4	14.7	5.7	
8.8	21.8	10.9	3.4	
6.4	2.4	1.2	2.8	5 Blows
3.8	2.6	1.3	1.7	
2.8	1.0	0.5	1.4	
0.0	2.8	1.4	1.4 >	
63.7	36.3	18.15	6.4	
40.4	23.3	11.65	5.7	
14.7	25.7	12.85	3.4	
12.2	2.5	1.25	2.8	10 Blows
7.3	4.9	2.45	1.7	
6.0	1.3	0.65	1.4	
0.0	6.0	3.0	1.4 >	
84.2	15.8	7.9	6.4	
61.4	22.8	11.4	5.7	
31.4	30.0	15	3.4	
25.2	6.2	3.1	2.8	15 Blows
15.2	10.0	5.0	1.7	
13.2	2.0	1.0	1.4	
0.0	13.2	6.6	1.4 >	
89.0	11.0	5.5	6.4	
68.6	20.4	10.2	5.7	
38.4	30.2	15.1	3.4	
33.8	4.6	2.3	2.8	20 Blows
20.6	13.2	6.6	1.7	
19.0	1.6	0.8	1.4	
0.0	19.0	9.5	1.4 >	

Table (5) Results of sieving analysis of sample: red Kaolinite, drop weight=993 gm, drop height = 20 cm

cumulative wt. (%) passing	Individual weight % retained	weight retained (gm)	opening	No. of Blows
86.4	13.6	6.8	6.4	
59.6	26.8	13.4	5.7	
25.0	34.6	17.3	3.4	
17.0	8.0	4.0	2.8	5 Blows
4.6	12.4	6.2	1.7	
2.4	2.2	1.1	1.4	
0.0	2.4	1.2	1.4 >	
90.0	10.0	5.0	6.4	
70.0	20.0	10.0	5.7	
39.2	30.8	15.4	3.4	
29.2	10.0	5.0	2.8	10 Blows
14.2	15.0	7.5	1.7	
9.2	5.0	2.5	1.4	
0.0	9.2	4.6	1.4 >	
93.2	6.8	3.4	6.4	
74.6	18.6	9.3	5.7	
39.0	35.6	17.8	3.4	
31.8	7.2	3.6	2.8	15 Blows
16.6	15.2	7.6	1.7	
13.6	3.0	1.5	1.4	
0.0	13.6	6.8	1.4 >	
96.6	3.4	1.7	6.4	
88.8	7.8	3.9	5.7	
56.8	32	16	3.4	
47.2	9.6	4.8	2.8	20 Blows
27.2	20.0	10.0	1.7	
20.6	6.6	3.3	1.4	
0.0	20.6	10.3	1.4 >	

Table (6) Results of sieving analysis of sample: red Kaolinite, drop weight=993 gm, drop height = 30 cm

cumulative wt. (%) passing	Individual weight % retained	weight retained (gm)	opening	No. of Blows
63.6	36.4	18.2	6.4	
38.6	25.0	12.5	5.7	
20.0	18.6	9.3	3.4	
19.0	1.0	0.5	2.8	5 Blows
12.4	6.6	3.3	1.7	
6.3	6.1	3.05	1.4	
0.0	6.3	3.15	1.4 >	
76.6	23.4	11.6	6.4	
60.6	16.0	8.0	5.7	
34.8	25.8	12.9	3.4	
30.8	4.0	2.0	2.8	10 Blows
18.4	12.4	6.2	1.7	
12.8	5.6	2.8	1.4	
0.0	12.8	6.4	1.4 >	
93.8	6.2	3.1	6.4	
86.2	7.6	3.8	5.7	
50.2	36.0	18.0	3.4	
42.0	8.2	4.1	2.8	15 Blows
26.4	15.6	7.8	1.7	
22.2	4.2	2.1	1.4	
0.0	22.2	11.1	1.4 >	
100.0	0.0	0.0	6.4	
97.2	2.8	1.4	5.7	
86.4	10.8	5.4	3.4	
74.4	12.0	6.0	2.8	20 Blows
52.4	22.0	11.0	1.7	
41.8	10.6	5.3	1.4	
0.0	41.8	20.9	1.4 >	

Table (7): comparative summary of Results of the cumulative weight percentage passing through sieve opening (1.7) mm. for the two drop weights used

Drop Weight = 993.5 gm.					Drop Wieght = 585 gm.				
No. of Blows				Drop hieght (cm.)	No. of Blows				Drc heo: (cn
20 Blows	15 Blows	10 Blows	5 Blows		20 Blows	15 Blows	10 Blows	5 Blows	
20.6	15.1	7.3	3.8	10	21.4	13.1	6.1	1.3	1
27.2	16.6	14.2	4.6	20	24.1	13.2	7.8	1.9	2
52.4	26.4	18.4	12.4	30	36.6	18.8	10	2.5	3

Table (8): comparative summary of Results of the cumulative weight percentage passing through sieve opening (2.8) mm. for the two drop weights used

Drop Weight = 993.5 gm.					Drop Wieght = 585 gm.				
No. of Blows				Drop hieght (cm.)	No. of Blows				Dro heog (cm
20 Blows	15 Blows	10 Blows	5 Blows		20 Blows	15 Blows	10 Blows	5 Blows	
33.8	25.2	12.2	6.4	10.0	36.6	18.8	7.6	2.2	10.
47.2	31.8	29.2	17.0	20.0	37.7	19.2	11.2	3.2	20.
74.4	42.0	30.8	19.0	30.0	54.6	31.8	19.7	3.5	30.

RESULTS AND DISCUSSION

The results shown in the previous tables were represented graphically in figures (5,6,7,8 and 9). Again I have tried to make the plot a comparative plot as much as possible. Fig. (5,6 and 7) represent a sieving analysis plot of the results whereby the cumulative weight percentage passing was put on the y-axis against the opening size in millimeters on the xaxis. On fig. (5) the results of drop weight 585 gm. and drop heights 10 and 20 cm. were plotted whereby a graph for each of the four variables of number of blows (5,10,15 and 20) was represented. Fig. (6) shows the results of drop weight 585 gm. and drop height 30 cm., whereby four curves for 5,10,15 and 20 blows were shown. On fig. (7) all results concerning experiments for drop weight 993.5 gm. with all variables including different drop heights (10,20 and 30 cm.) and also different number of blows (5,10,15 and 20 blows) were represented.

In order to compare between the cumulative weight percentages passing through each of the sieves (1.7 and 2.8 mm. opening) two plots were prepared. Fig. (8) represents a plot of the relationship between cumulative weight percentage passing through sieve opening 1.7 mm. and number of blows for the different drop weights and drop heights, whereas fig. (9) shows the same plot for sieve opening 2.8 mm.

Figures (5,6 and 7) which show plots of the results given in tables (1,2,3,4,5 and 6) enable us to make some remarks and extract some trends of the effect of different variables a adopted in the experimental work. These trends were obvious from the graphs showing a general increase in the effectiveness of size reduction as the drop weight; drop height and number of blows increase. This is based on the increase of energy consumed in the crushing process.

Figures (8 and 9) which show plots of the results tabulated in tables (7 and 8) enable us to make more precise comparative remarks for the two sieve openings (1.7 and 2.8 mm.). Obvious trends are also extracted from these plots showing a general increase in the effectiveness of size reduction with the increase of drop weight; drop height and number of blows. These remarks and trends are more elaborated in the conclusions which follow.

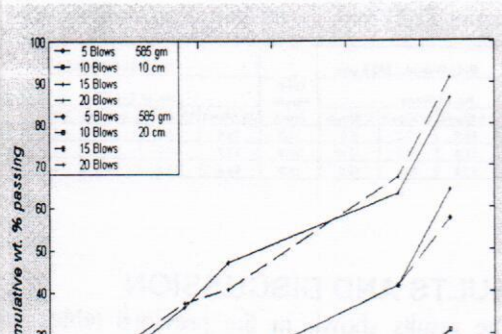

Fig. (5): Cumulative wt. % passing vs. opening size(mm.)for different number of blows& heights

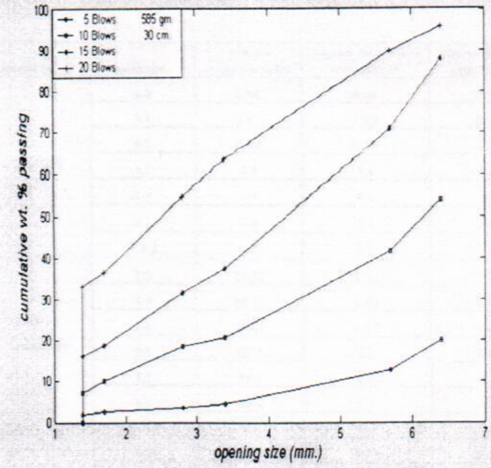

Fig. (6): Cumulative wt. % passing vs. opening size (mm.) for weight=585 gm

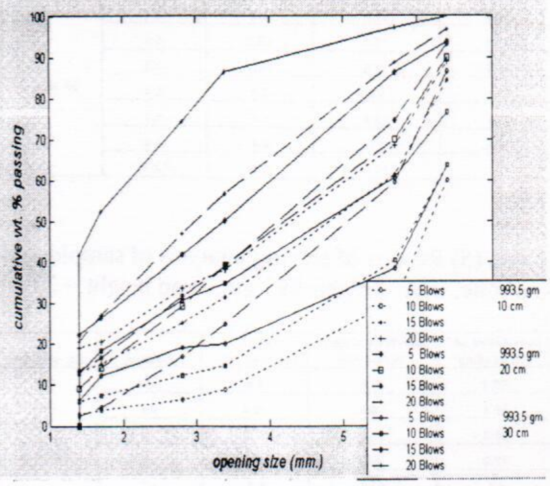

Fig. (7): Cumulative wt. % passing vs. opening size (mm.) for weight=993.5 gm. & different heights & number of blows

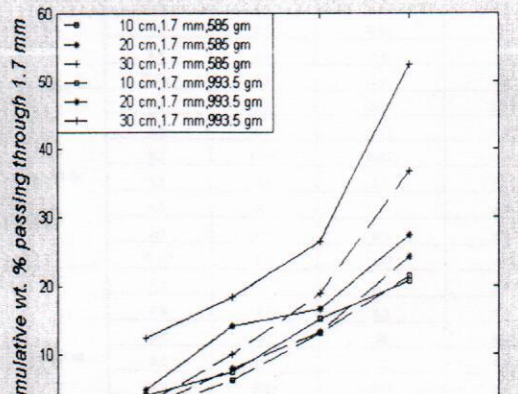

Fig. (8): Cumulative wt. % passing through sieve size 1.7 mm. vs. number of blows for different heights & weights

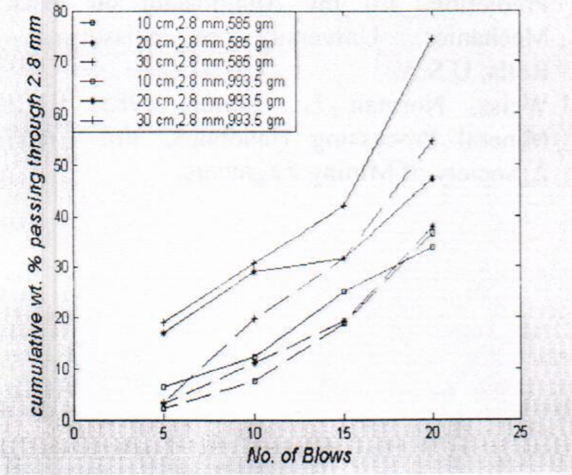

Fig. (9):Cum. wt. % passing sieve 2.8 mm. vs. no. of blows for different heights & weights

CONCLUSIONS

The following conclusions could be drawn from this study:

1. It is clear from the different plots that the effectiveness of size reduction (indicated by the cumulative weight percentage passing through some key sieves) increases with the increase of drop weight, drop height, number of blows (each of which being a function of the energy exerted on the particles being crushed). This common trend is obvious from all the plots made.
2. According to the results obtained (tabulated in the previous tables) and the plotted graphs we can deduct some key sieves being (1.7) and (2.8) mm. which give clearly comparative results and more precisely we can depend on sieve size (2.8) mm. as the key size for comparative study purposes. This is specifically useful for recommendations for future work.
3. The graphs shown in fig. (9) are steeper than those in fig. (8), which gives the reasoning for conclusion (2) mentioned above.
4. It is clear that the steepness of the curves rises as we go from 15 blows to 20 blows which enable us to conclude that the experiment with 20 blows give better and clearer results.
5. The results of experiments using the heavier drop weight (namely 993.5gm.) tend to give better and clearer results as shown in figures (8) and (9).
6. The larger drop height (namely 30cm.) tends to give better and clearer results generally. This is clear through the steepness of the relevant curves.

RECOMMENDATIONS

1. From the previous conclusions we can recommend making such a study more simplified and more economical in the time sence by reducing the variables to the largest extent. These optimum operating variables are: Drop weight = 993.5 gm, Drop height = 30 cm, Number of blows = 20, Key sieve size for the analysis = 2.8 mm.
2. Depending on the above – mentioned optimum parameters we can try to make comparative studies using such device between a reference rock having known properties and a rock under consideration in order to infer the properties required from the comparative results of such crushing experiments.
3. It is possible to make future studies by introducing new parametric studies which may include: (a) The number of layers of particles. (b) The thermal effect on the rock samples. (c) The effect of heating followed by sudden cooling on rock samples.

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