COMPRESSIVE COMMINUTION MECHANISM OF PARTICLE BEDS①

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ABSTRACT

Granular material mechanics, finite element analysis and crushing theory are applied to study the compressive comminution mechanism of particle beds in this paper. This is a new method by which we have established an equivalent model of granular material, determined the values and distributions of contact forces and discovered a crushing law. The model has been tested on the newly designed equipment and proved to be correct. Some new characteristics and laws of compressive comminution of particle beds have been found.

Key words: compressive comminution mechanism granular material equivalent model test machine of compressive comminution of particle beds

1 INTRODUCTION

The compressive comminution of particle beds means that materials are comminuted into multi-particle layers in a crusher cavity. While compressive comminution of particle beds was researched mainly as out process and a material box in a compression test machine, the main parameters such as crusher cavity size, displacement discharge opening size, etc can not be realized. The forces between particles and the crushing law can not be explained. Here, granular material mechanics, finite element analysis and crushing theory are applied to probe the comminution mechanism of particle beds, to build new way and equipment, which will provide a theoretical foundation for developing new types of particle bed crushers.

2 THE EQUIVALENT MODEL OF GRANULAR MATERIAL MECHANICS AND CALCULATION ANALYSES

2.1 *Equivalent Model of Granular Material*

In order to discover the stress-strain state between particles, we simplified the disorderly beds in a cavity into an equivalent model according to granular material mechanics methods. The principles are as follows.

(1) Suppose the key parameter for the compressive comminution of particle beds is the porosity of the granular material[1-8]. Equivalence means the porosity in the model is the same as that in the practical beds while particles are being crushed in large quantities.

(2) In the model, the number of contact points between a particle and another particle is 5. It has been determined, by stability analysis, that this is the most probable number of contact sites.

(3) To make theoretical analysis possible, we suppose the particles in the model are equal in grain diameter in a regular arrangement. The grain diameter is equivalent, and is chosen by the following methed:

$$\bar{d} = \sum d_i / n$$

$$D_i = (d_1 + d_2 + d_3) / 3$$

Where d_1, d_2, d_3 represent the particle lengths along three perpendicular directions respectively,

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and *n* refers to the sample particle number.

(4) The number of particles in the model is decided according to the condition that the model porosity is equivalent to that of practical material beds.

Fig. 1a is the model established in accordance with the grain diameters shown in Table 1.

Table 1 Rock particles distribution in the model

Grain size	120~60	60~30	30~15	15~10	10~0
Percentage	12.74	16.9	18.80	21.54	0

When establishing this model, we suppose that the ores in the cavity are very well graded, i.e., particles of different grain size are at different heights in the cavity.

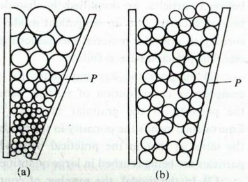

Fig. 1 Granular material model of compressive comminution of particle beds

(a) practical grain diameter distribution model;

(b) equivalent grain diameter distribution model

In order to find the underlying law, this paper first studies the equivalent grain diameter model. A straight line, regarded as a pole, is connected between the core of each neighboring particle in the model, and the internal force of the pole is the contact force between particles. Hence, the model becomes a pole system, as is shown in Fig. 2. By means of finite element analysis, calculations of what with full consideration of the characteristics of the contact between granular particles can be carried out by computer. The functions of the programme are as follows.

(1) Calculate the contact forces of *u*, *v*, and *w* along the three perpendicular directions.

(2) Make statistical analyses of the contact forces to get histograms.

(3) Use different colours to display contact force magnitudes between particles in the crusher cavity so as to observe the crushing law and behavior easily.

(4) By changing the values and distributions of forces on the moving jaw shown in Fig. 3, caculate and analyze the contact forces between particles in the crusher cavity.

Analysis of the results yields the following laws.

(1) The contact forces between particles with 5 contact points are greater than those of particles with 3 or 4.

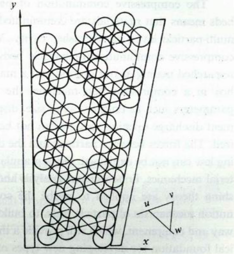

Fig. 2 Equivalent granular material mechanics model

(2) The compressive comminution of particle beds must meet some specific requirements. The principal demand is the realization of a specific porosity which should be similar to that arrangement with a contact point number of 5. A porosity either greater or less than this level would obviously reduce the number of particles between which the contact forces are greater than the unit force (p_j), i. e.

the crushing effect is not good.

(3) The arrangement of the particles in the cavity does not influence the crushing effect significantly. Therefore, the granular material particles have countless arrangements, so that even with a constant number of contact points, only one study is necessary.

(4) With a constant number of contact points and arrangements, the value and distribution of forces on the crushing jaw has an obvious influence on the number of particles between which the contact forces are greater than the unit force and the crushing regions. Shown in Table 2 are some statistical data.

Table 2 The statistical data of the contact (p_p) among particles and acting force (p_J) on the jaw

type of forcces		(a)	(b)	(c)	(d)	(e)	(f)
total unit force		10	15	21.5	15.5	12.2	14.4
$np_p>1.25p_J$		16	34	37	28	38	35
$np_p>2.4p_J$		2	7	16	9	15	13
$np_p>1.6p_J$		4	16	33	22	29	29
$n^2p_p>2.4p_J$		0	4	10	5	13	9
$n^2p_p>2.4p_J$		0	10	20	11	24	19
$(n^2p_p>2.4p_J)$ / $(nP_p>2.4p_J)$			0.57	0.63	0.56	0.86	0.69
$(n^2p_p>1.6p_J)$ / $(np_p>1.6p_J)$			0.63	0.60	0.50	0.83	0.66
n_c / P	$\sigma_p>2.4\sigma_J$	0.20	0.47	0.74	0.58	1.23	0.90
	$\sigma_p>1.6_J$	0.40	1.06	1.53	1.42	2.38	2.01
R	$\sigma_p>2.4\sigma_J$	0.04	0.15	0.34	0.19	0.32	0.28
	$\sigma_p>1.6\sigma_J$	0.085	0.34	0.70	0.47	0.62	0.62

* (a)~(f)—shown in Fig .3, n–the number of particles.

$np_p>1.25p_j$ stands for the number of that contact force of particles is more than 1.25 p_j, and so on.n^2–The particles number of two directions forcing.

R–The ratio of the number of crushing particles to the total number particles.

N_c / p–Unit force average number of crushed particles.

3 EXPERIMENTAL METHOD AND RESULTS

On the basis of the above mechanics model, we designed the test machine shown in Fig.4. for the compressive comminution of particle beds. The sample material was limestone graded by screening. The test grain diameters were graded as 10~15, 15~20, 20~25, 25~30, 30~45 mm.

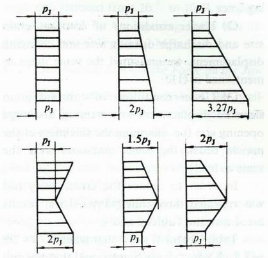

Fig. 3 Force and distribution model on the moving jaw

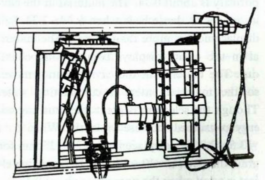

Fig. 4 The test machine for particle beds crushing

The experimental mesurements were as follows.

(1) Under conditions of constant displacement (l) of the swing jaw and discharge opening size (b) and varying feeding sizes (d), we measured and tested the initial porosity (ψ)and the final porosity (ψ'), the grain diameter distribution of the crushed particles, the selection function (S %) of one crushing event, the total crushing force (p) and the pressures $p_{t.r}$, $p_{t.l}$, $p_{b.r}$, $p_{b.l}$ borne by the upper and lower

transducers in the jaw (t, b, l, r stand for the locations of the transducers in the jaw, t—upper, b—lower, l—left, r—right) and the uprising force F.

(2) Under conditions of constant grain size and discharge opening size and changing displacement, we measured the same items as mentioned in (1);

(3) Under conditions of constant grain size and displacement and varying discharge opening size (i.e. changing the thickness of the paricle beds), the items measured were the same as in (1).

In order to reduce the error, every test was repeated three times. Typical test results are shown the Tables 3 and 4.

Tables 3 and 4, show that when $b/l = 2.8 \sim 2.5$, $\triangle S\% / \triangle p$ is biggest, and that the crushing effects are best for $d = 20 \sim 25$ mm. The porosity is about 0.34. The material in the cavity moves as dense beds when $b/l > 2.34$, i.e., displacement is more than 30 mm. The material in the cavity displays compaction behaviour. The material in the cavity cannot move, so the material enters a compacting state. Though the selection is great, the crushing energy consumed increase violently. When $b/l = 3.5 \sim 2.8$, i.e., displacement is $20 \sim 25$ mm for grain diameter $d = 10 \sim 15$ mm, the crushing effect is good when the porosity is about 0.4.

Analyses of the test results show the following.

(1) Indeed, the optimum porosity in practical crushing beds is the same as the optinom porosity obtained in the models above.

(2) Using statistical methods to work out the plane porosity corresponding to the three-dimensional one[6], we found that the plane different from the porosity in the plane model when the number of contact points is five as shown in Table 5.

(3) Before $b/l = 4.67$ (corresponding to a displacement of 15 mm), the result of compression mainly appears to be a deformation of the structure, i.e., particles get nearer to each other, and the arrangment tends to be tighter. Only a few particles are crushed, as is shown by a set of small slopes in the curve of crushing force and displacement shown in Fig. 5.

Table 3 Test results of particle crushing beds with grain diameter $d = 20 \sim 25$ mm

b^*/l	4.67	3.50	2.80	2.50	3.34**	2.17**	2**
η'	0.417	0.387	0.338	0.335	0.298	0.29	0.262
$S\%$	13.0	21.8	29.6	34.7	35.6	40.7	45.1
P / kN	117.0	175.4	238.1	259.7	>294		
$\triangle l$	8.8	7.8	5.1		0.9	5.1	4.4
$\triangle p_J$ / kN	57.8	62.7	21.6				
$\triangle l / \triangle PJ$	0.15	0.12	0.24				

* — $b = 70$ mm, ** — stands for compaction behaviour; $\triangle S\% / \triangle p$—shows that increase of the acting force will affect the crushing effect.

Table 4 Test results of partical crushing beds with grain size $d = 10 \sim 15$ mm

b/l	3.5	2.8	2.34	2.11
η'	0.407	0.389	0.346	0.295
$S\%$	14.0	19.9	26.1	32.2
p / kN	84.3	138.2	214.6	299.9
$\triangle l / \triangle P_J$	0.11	0.08	0.08	

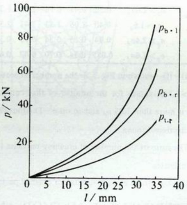

Fig. 5 Action force (p) in jaw and displacement (l)

When $b/l < 4.67$, particles are dense and the particles begin to be crushed. The number of crushed particles increases with displacemet. Some changes, which are not obvious, occur in $\triangle S\% / \triangle p$. This is shown by an almost straight line in the curve. When b / l reaches some specific value (e. g. d=20~25 mm, b / l=2.34, d=10~15 mm, b / l=2.12), compaction behaviour appears, and the slope of the curve increases quickly.

Table 5 The optimum space porosity (ψ) and plane porosity (ψ')

d / mm	10~15	20~25
ψ^{*}_{exp}	0.40~0.39	0.34
ψ_{cal}	0.397	0.400
ψ'_{cal}	0.269	0.225
ψ'	0.27~0.28	0.23~0.21

* "exp" refers to test results, cal refers to counting. ψ' shows the number contact points is 5.

4 ANALYSIS AND STUDY ON THE PERFORMANCE OF COMPRESSIVE COMMINUTION OF PARTICLE BEDS

4.1 *The Uprising Performance of Particle Beds and Its Force*

Unlike in ordinary crushers, the ores distribute in multi-layers in the crusher cavity when the force applied by the jaw, the extrusion among particles appears the particles uprising movement toward the top with little resistance. This reloosens the compressed beds and increases the porosity. This proves that we need to prevent the uprising movement of particles or control it to obtain the specific porosity and the best crushing effect.

Through measurement, we know the uprising force varies greatly. Its statistical average value improves with the displacement, as shown in Fig. 6. In the case of the best crushing, the pressure produced by the uprising force is about 0.71~0.81 MPa which is a unignorable. To reduce the infuence of the uprising may be useful to reduce mesh angles.

The principle for designing mesh angles in ordinary crushers is to prevent the single ore from sliding up when the mesh angles are stressed by the two jaw plates. In particle bed crushing, it is necessary to minimize the uprising force. In the experiments, when the mesh angle was reduced from 20° to 10°, the pressure produced by the uprising force was reduced from 0.8 MPa to 0.2 MPa.

4.2 *Distribution Laws of the Force on the Jaw*

Through statistical analysis of the oscillogram of force obtained from the experiments we have the followsing results.

(1) The counter force (p) on the jaw applied by the ores increases with displacement (l), as shown in Fig. 5.

(2) Fig. 7 shows the relation between the selection function ($S\%$), total crushing force (p) and displacement (l). The total force and the selection function both increase with the displacement, but the laws governing these behaviour are not always the same. This shows that $S\%$ and p are also influenced by many random factors. These statistical laws are found through many experiments. However, the material (ores) in some specific place always has a suitable displacement. with which the crushing effect is the best.

(3) The force is not balanced throughout the width of the whole jaw, but generally waves within 15 % of the average value.

4.3 *Influence of the Grain Diameter on Particle Beds Crushing*

Throughout the experiments, when the grain size varied, the chosen crushing amount (or the selection function) varied from 11.4 % to 31.6 %during one crushing event (see Fig. 8). The reason is that when the contact force is great, the grain diameter is larger.

This conclusion shows that with a large grain diameter, the volume deformation can be smaller than that with a small grain diameter, or the displacement can be smaller if the crushing force is same.

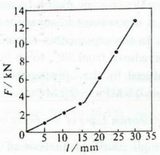

Fig. 6 Uprising force (*F*) and displacement (*l*)

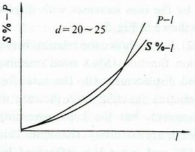

Fig.7 Selection function (*S*%),force (*p*) and displacement (*l*)

4.4 *The Relationship Between Discharging Opening Size and Displacement*

Choice of the displacement should assure the initial porosity corresponds to the best crushing state. It can be seen in Fig. 8 that *S*% increases with the displacement. The degree of increase depends on the grain diameter. The bigger the grain diameter is, the bigger the slope of the curve. Hence, crushing grain diameter should be taken into consideration in choosing the displacement.

The discharge opening size of the ordinary crusher is always determined by the grain diameter of the material to be discharged. The minimum discharge opening size should be 3 times as large as the discharging material.

Also, it should be taken into consideration that a large maximum discharge opening size would produce excessive particle layers and make *S*% decrease. This shows that it is not the case that the more the layers, the better the effect. Excess layers make *S*% decrease; fewer layers make *S*% too small. Hence, a reasonable number of layers is required.

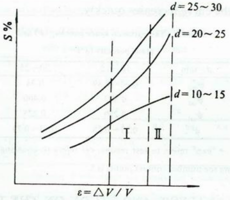

Fig. 8 Selection function (*S* %) and volume deformation (*ε*)

Therefore, the discharge opening size (*b*) and displacement (*l*) are the two main parameters. Their values influence the grain diameter, layers, selection function force and so on. The relative displacement (b/l), a non-dimensional parameter, is mentioned above, for practical use. Table 6 shows the relationships between b/l and other parameters.

When experimenting, we found that when $b/l<2.34$, the compaction phenomenon appears for $d=20\sim25$ mm. Table 6 shows that the sensible zone of b/l within $b/l=2.8\sim2.5$ which can create the best crushing effect when there is a small displacement (i.e $\triangle S\%/\triangle(b/l)$ is bigger). Different grain diameters would cause changes in the sensible xone. In some cases, the b/l value of small grains is greater. Because of the existence of this sensible zone, we should try to choose the discharge opening size and displacement in this zone when designing crushers.

As there exists a the boundary value of compaction, we should avoid compaction phenomenon when designing a crusher to choose the discharging opening size and displacement.

Table 6 The relation between b/l and other parameters when particle beds crushing for $d=20\sim25$ mm

b/l	4.67	3.5	2.8	2.5	2.34	2.17	2
$\triangle(b/l)$	1.17	0.7	0.3	0.16	0.17	0.17	
$\triangle S\%$	8.8	7.5	5.1	0.9	5.1	4.4	
$\triangle\varepsilon$	0.059	0.036	0.020	0.031	0.07	0.005	
$\triangle l/\triangle(b/l)$	7.52	10.70	17.00	5.62	30.0	25.88	
$\triangle l/\triangle\varepsilon$	149.2	216.6	255.0	290	728.0	176.0	

4 CONCLUSIONS

(1) This is the first time ore crushing mechanisms have been investigated by applying granular material mechanics, finite element analysis and crushing theory. The results show the model is practicable through calculational analysis and tests of the model.

(2) On the basis of theoretical analyses and test proof, we have found new laws of particle beds crushing, and attitudes on grain size, displacement, discharge opening size, uprising force, mesh angle, and forcing state which have practical value for improving and designing crushers.

(3) The tests of the compressive comminution of particle beds show that particle bed crushing has many advantages, such as being 4~6 times larger than the ordinary crusher (single particle crushing), energy efficiency, and uniformity of product grain size. The successful development of such crushers would benefit society.

(4) This paper studied the plane model of crushing beds. We will develop the space model and make computer simulations of the movement process of bed crushing. The results will be more practical.

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