SIZE REDUCTION OF SOLIDS

2.1 CONCEPT OF SIZE REDUCTION

- **Size reduction** refers to *an operation wherein particles of solids are cut or broken into smaller pieces.*
- *Size reduction is a mechanical process of breakdown of solids into smaller size particles without altering the state of aggregation of solids. It is also called comminution.*
- Solids are reduced in size by compression, impact, attrition and cutting.

2.2 IMPORTANCE OF SIZE REDUCTION

In the process industries, this operation is usually carried out in order –

(i) to increase the surface in order to increase the rate of a physical or chemical process. In most reactions and unit operations (e.g., leaching) involving solid particles, the rate increases by increasing the area of contact between solid and second phase since the rate is proportional to the area of contact between the phases involved.

In combustion process, the rate of combustion is proportional to the area presented to the gas. Thus, the rate of combustion of solid particles is high if the particles are of small size.

In leaching, the rate of extraction increases because of the increased area of contact between the solid and the solvent.

(ii) to effect the separation of two constituents in cases where one is dispersed in small isolated pockets.

(iii) to meet stringent specifications regarding the size of commercial products.

(iv) to accomplish intimate mixing of solids in a solid-solid operation since the mixing is more complete if the particle size is small.

(v) to improve dissolution rate, solubility, binding strength and dispersion properties.

(vi) Many solid materials exist/present in sizes that are too large to be used directly. Thus, such materials must be reduced in size before use.

Size reduction machines more commonly reduce the size of solids by (a) compression, (b) impact, (c) attrition, or rubbing, and (d) cutting. In general, compression is used for the coarse reduction of hard solids (to yield relatively few fines), impact gives coarse, medium, or fine products, attrition gives very fine products from soft, non-abrasive materials and cutting produces a product of a definite particle size and sometimes a definite shape, with few or no fines.

Applications of Size Reduction (Examples) :

- Size reduction operation is carried out in coal washeries, ore processing industries, chemical industry, paint industry, cement industry and food processing industry.

2.3 ENERGY AND POWER REQUIREMENT FOR SIZE REDUCTION EQUIPMENTS

- The cost of power is a major expense in the crushing and grinding operations. Thus, an accurate estimation of the energy required is important in the design and selection of a size reduction equipment.
- During size reduction, the solid particles are first distorted and strained, work required to strain them is stored temporarily in the solid particles as mechanical energy of stress. By applying additional force, the stressed particles are distorted beyond their ultimate strength and suddenly break into smaller particles. Thus, new surface is generated.

- As a unit area of solid has a definite amount of surface energy, the generation of new surface requires work, which is provided by the release of energy of stress when the particles break. The energy of stress in excess of the new surface energy created appears as heat.
- It is not possible to estimate accurately the power requirement of crushing and grinding equipments to achieve the size reduction of a given material. Thus, for the same a number of empirical laws have been put forward, such as Rittinger's law, Kick's law and Bond's law.

2.3.1 Rittinger's Law

- It states that *the work required for the crushing operation is directly proportional to the new surface created.* Mathematically, the law can be written as

$$\frac{P}{\dot{m}} = K_r\left[\frac{1}{\bar{D}_{sb}} - \frac{1}{\bar{D}_{sa}}\right] \quad ...(2.1)$$

where P = power required by machine

$\dot{m}$ = feed rate to machine

K_r is constant (known as Rittinger's constant)

$\bar{D}_{sa}$, $\bar{D}_{sb}$ = volume-surface mean diameter of the feed and product respectively.

2.3.2 Kick's Law

- It states that *the work required for crushing a given material is proportional to the logarithm of the ratio between the initial and final diameters.*

$$\frac{P}{\dot{m}} = K_K \ln(D/d) \quad ...(2.2)$$

where K_K is a constant (known as Kick's constant) and D and d are the initial and final sizes respectively.

- Since the energy required is directly related to the reduction ratio (D/d), the energy required to crush a given quantity of material from a 100 mm size to a 50 mm size is the same as that required to reduce the particle size from 12 mm to 6 mm.
- Kick's law is more accurate than Rittinger's law for coarse crushing where the amount of surface produced is considerably less.

2.3.3 Bond's Law and Work Index

- Bond has proposed a law intermediate between Rittinger's and Kick's law for estimating the power required for crushing and grinding operations.
- It states that *the work required to form particles of size D_p from very large feed is proportional to the square root of the surface-to-volume ratio of the product (S_p/v_p), $S_p/v_p = 6/\phi_s D_p$.*

Thus,

$$\frac{P}{\dot{m}} = \frac{K_b}{\sqrt{D_p}} \quad ...(2.3)$$

where D_p is the particle size and K_b is a constant that depends on the type of machine and the material being crushed.

- The Bond's law is somewhat more realistic in estimating the power requirements of commercial size reduction machines.
- For using Equation (2.3), a work index W_i is defined as the *amount of energy in kilowatt-hours per ton of feed material, required to reduce a very large feed to such a size that 80 percent of the product passes through a 100 μm screen.*
- If D_p is in mm, P in kW, and $\dot{m}$ in tons per hour, then the relationship between K_b and W_i based on the definition of work index is

$$K_b = \sqrt{100 \times 10^{-3}}\ W_i = 0.3162\ W_i \quad ...(2.4)$$

Scanned with CamScanner

- If 80 percent of the feed passes through a mesh of size D_{pa} mm and 80 percent of the product passes through a mesh of size D_{pb}, then from Equations (2.3) and (2.4) we get

$$\frac{P}{\dot{m}} = 0.3162\, W_i \left(\frac{1}{\sqrt{D_{pb}}} - \frac{1}{\sqrt{D_{pa}}}\right) \quad \text{... (2.5)}$$

where D_{pa} and D_{pb} are the particle size of the feed and product in mm respectively.

- Since the work index include the friction in the crusher, the power given by Equation (2.5) is the gross power. Typical work indices for some common materials are given in Table 2.1.

Table 2.1 : Work indices for dry crushing* or wet grinding

Sr. No.	Material	Working Index (W_i)
1.	Clay	6.30
2.	Gypsum rock	6.37
3.	Bauxite	8.78
4.	Phosphate rock	9.92
5.	Cement raw material	10.51
6.	Limestone	12.74
7.	Coal	13
8.	Quartz	13.57
9.	Coke	15.13
10.	Gravel	16.06

* For dry grinding, multiply by 4/3.

2.3.4 Crushing Efficiency

- It is defined as the *ratio of the surface energy created by crushing to the energy absorbed by the solid.*

$$\eta_c = \frac{e_s (A_b - A_a)}{W_n} \quad \text{... (2.6)}$$

where
η_c = crushing efficiency
W_n = energy absorbed by material, J/kg
e_s = surface energy per unit area, J/m^2
A_b = area of product, m^2
A_a = area of feed, m^2.

- The surface energy created by fracture is very small as compared to the mechanical energy stored in the material at the time of its rupture. Most of the mechanical energy stored in the material is converted into heat and thus crushing efficiencies are low.
- The energy absorbed by the solid (W_n) is less than the energy supplied to the machine (W). Part of the total energy input to the machine is utilised to overcome the friction in the bearings and other moving parts, and the remaining part is available for crushing. The mechanical efficiency is the *ratio of the energy absorbed to the energy input.*

$$\eta_m = \frac{W_n}{W} \quad \text{... (2.7)}$$

where
η_m = mechanical efficiency
W = energy input to the machine
W_n = energy absorbed by the solid

From Equations (2.6) and (2.7), we get

$$W = \frac{W_n}{\eta_m} = \frac{e_s (A_b - A_a)}{\eta_m \cdot \eta_c} \quad \text{... (2}$$

If $\dot{m}$ is the feed rate of solids to a machine, then the power required by the machine is given by

$$P = W.\dot{m} = \frac{\dot{m}\, e_s (A_b - A_a)}{\eta_m \cdot \eta_c} \quad \text{... (2}$$

where A_a, A_b are the specific surface area per unit mass of feed and product respectively.

The specific surface is given by

$$A = 6/\phi\, \bar{D}_s\, \rho_p$$

where ϕ = sphericity, ρ_p = density, $\bar{D}_s$ = volume-surface mean diameter. Volume-surface mean diameter used to specify particle size for a mixture of particles.

- A number of empirical laws that are mentioned earlier have been put forward to estimate the ener required for size reduction.

2.4 TYPES OF SIZE-REDUCTION EQUIPMENTS

- Size-reduction equipments are divided into four principal types as given in Table 2.2.
- Crushers are employed for breaking large pieces of solid materials into small lumps.
- A primary crusher is the one which crushes very large lumps to yield a product 150 to 250 mm in si A secondary crusher is the one which takes the product from a primary crusher and reduces it to particles about 6 mm size.
- Grinders are the machines which reduce crushed feed to powder. An intermediate grinder yield a produ that might pass a 40 mesh screen. A fine grinder gives a product most of which would pass a 200 me screen. Ultrafine grinders are the machines which accept feed particles having a size less than 6 mm a yield a product of size 1 to 50 µm.
- Cutters are size-reduction machines which give particles of definite size and shape, usually 2 to 10 mm length.

Table 2.2 : Principal types of size-reduction machines

1. Crushers (coarse and fine)
   (a) Jaw crusher, (b) Gyratory crusher, (c) Crushing rolls
2. Grinders (Intermediate and fine)
   (a) Hammer mills
   (b) Rolling-compression mills
      (i) Bowl mills, (ii) Rolling mills
   (c) Attrition mills
   (d) Revolving mills
      (i) Rod mills, (ii)Ball mills; pebble mills, (iii) Tube mills
3. Ultrafine grinders
   (a) Hammer mills with internal classification
   (b) Fluid-energy mills
   (c) Agitated mills
4. Cutting machines
   (a) Knife cutters, dicers, slitters.

- The size reduction machines perform their work in distinctly different ways. Crushers employ compression while grinders employ impact and attrition. Ultrafine grinders employ attrition. A cutting action is the characteristic of knife cutters, dicers and slitters.
- The factors to be considered while selecting the equipment for size reduction are :
  - (i) Properties of the feed to be handled such as hardness, crushing strength, etc.
  - (ii) Nature of the product required.
  - (iii) Quantity of the material to be handled.
  - (iv) Size of the material to be handled.
  - (v) Speed of the size reduction equipment.

2.4.1 Crushers

- Crushers are slow-speed machines employed for the coarse reduction of large quantities of solids. Jaw crushers, gyratory crushers and smooth-roll crushers are different types of crushers. They operate by compression and can break large lumps of hard materials. They find application in rockary and mining industries.

2.4.1.1 Jaw Crushers

- Jaw crushers compress the feed between a stationary jaw and a movable jaw.

Types of jaw crushers :

1. Blake jaw crusher. 2. Dodge jaw crusher.

- In the Blake jaw crusher, the movable jaw is pivoted at the top, thus giving greatest movement at the bottom.
- In the Dodge jaw crusher, the movable jaw is pivoted at the bottom, thus giving greatest/maximum movement at the top.
- The Dodge crusher is less widely used because of its tendency to choke due to the minimum movement of the jaw at the bottom.

Difference between Blake Jaw Crusher and Dodge Jaw Crusher :

(i) Blake Jaw Crusher : (i) movable jaw is pivoted at the top, (ii) maximum movement is at the bottom, (iii) no tendency to choke/clog (freedom from choking), (iv) suitable for high production rates, (v) large reduction ratio is not possible, (vi) low maintenance, (vii) comparatively made in large sizes, (viii) does not give uniform product, (ix) commonly/widely used.

(ii) Dodge Jaw Crusher : (i) movable jaw is pivoted at the bottom, (ii) maximum movement is at the top, (iii) tendency to choke (no freedom from choking), (iv) suitable for low production rates, (v) large reduction ratio is possible, (vi) high maintenance, (vii) comparatively made in smaller sizes, (viii) gives uniform product, (ix) seldom/less widely used.

1. The Blake Jaw Crusher

Principle :

- It works on the principle of compression. It reduces size by compressive force. That is, it utilises compressive force for size reduction.

Construction :

- A schematic diagram of the Blake jaw crusher is shown in Fig. 2.1. It has a fixed jaw and a movable jaw. The movable jaw is pivoted at the top. The jaws are set to form a V open at the top. The swinging jaw (movable jaw) which reciprocates in a horizontal plane usually makes an angle of 20 to 30° with the fixed jaw (which is nearly vertical).

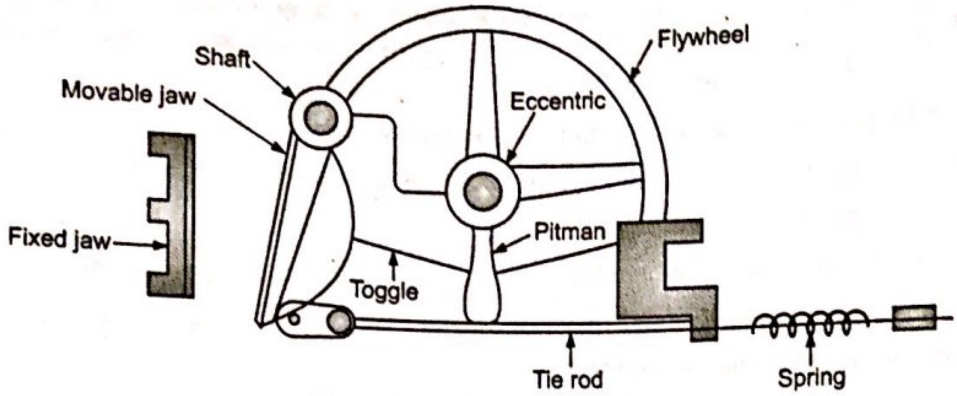

Fig. 2.1 : Blake Jaw Crusher

- The jaws are usually made of manganese steel or some other material that will withstand abrasion. The faces of the crushing jaws are usually corrugated for concentrating the pressure on relatively small areas.
- In addition to the jaws, crusher consists of a pitman, toggles, flywheel, eccentric shaft, drawback rod and springs and frame. In this machine, an eccentric causes the pitman to oscillate in a vertical direction, and this vertical movement is communicated horizontally (reciprocating motion) to the movable jaw by the toggles.
- The speed of operation should not be high or otherwise a large quantity of fines is produced as the material cannot escape quickly and gets repeatedly crushed. Since the crushing action is intermittent, the loading on the machine is uneven and due to this the crusher incorporates a heavy flywheel.
- Since the maximum movement of the jaw is at the bottom (discharge), there will be little tendency for the crusher to choke.

Protection of Machine :

- The machine is usually protected so that it is not damaged if accidental pieces of iron such as hammer heads, stray bolts, etc. enter into the crusher, by making one of the toggles in the driving mechanism relatively weak. That is, one particular toggle is made into two pieces which are held together with bolts that are purposely made the weakest part in the crusher so that, if stresses are set up, these bolts shear first.
- Thus, the failure is made at a point that can be easily and quickly repaired, instead of breaking some vital part of the machine.

Working :

- The material to be crushed is admitted between two jaws from the top. The material caught between the upper part of the jaws is crushed to a smaller size during forward motion by compression. The crushed material then drops/falls into the narrower space below during the backward motion and is recrushed as the jaws close next time. After sufficient reduction, the crushed material drops out the bottom of the machine.
- The jaws usually open and close 250 to 400 times per minute.

2.4.1.2 Gyratory Crusher

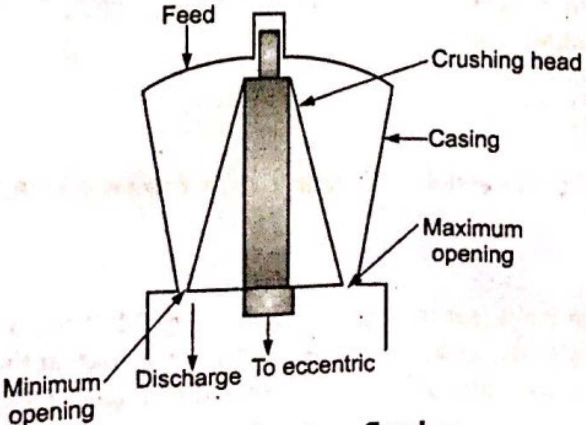

Fig. 2.2 : Gyratory Crusher

Principle :

- It works on the principle of compression.

Construction :

- It consists of a funnel shaped casing, open at the top. A conical crushing head, in the form of a truncated cone, gyrates inside a casing. The crushing head is mounted on a heavy shaft pivoted at the top of the machine.
- The upper end of the shaft is held in a flexible bearing and the lower end of the shaft is driven by an eccentric so as to trace a circle.
- Thus, at any point on the periphery of the casing the bottom of the crushing head moves towards, and then away from the stationary wall. The crushing action takes place around the whole of the cone.

Working :

- The material to be crushed is charged from the top. The conical head gyrates inside the casing. At any point on the periphery of the casing, the bottom of the crushing head moves towards and then away from the stationary wall.
- The solids caught in the V-shaped space between the head and the casing are broken and rebroken until they drop out from the bottom of the machine. The speed of the crushing head usually lies between 125 to 425 gyrations per minute.
- Since some part of the crushing head is working at all times, the discharge from this crusher is continuous instead of intermittent as in a Blake crusher.

Features :

- 1. continuous in action 2. fluctuations in stresses are smaller 3. load on the motor is nearly uniform 4. power consumption per ton of material crushed is smaller and 5. requires less maintenance than a jaw crusher.
- Since the capital cost of this crusher is high, it is suitable only where large quantities of materials are to be handled.

Jaw Crusher	Gyratory Crusher
(i) It is a reciprocating machine.	(i) It is a gyratory machine.
(ii) Intermittent in action, i.e., discharge is discontinuous.	(ii) Continuous in action, i.e., discharge is continuous.
(iii) It is a primary crusher. It takes a feed of larger size.	(iii) It is a secondary crusher. It takes a feed of smaller size.
(iv) The load on the motor is not uniform.	(iv) The load on the motor is nearly uniform.
(v) More maintenance is required.	(v) Less maintenance is required.
(vi) Power consumption per ton of material crushed is more.	(vi) Power consumption per ton of material crushed is lower.
(vii) Capital cost is relatively low.	(vii) Capital cost is high.
(viii) It has smaller capacity when used to produce/effect a small size reduction.	(viii) It has large capacity when used to produce/effect a small size reduction.

2.4.1.3 Crushing Rolls / Roll Crushers

Smooth Roll Crusher :

Principle :

Size reduction is achieved by compression (i.e., it employs compressive force for size reduction).

Construction :

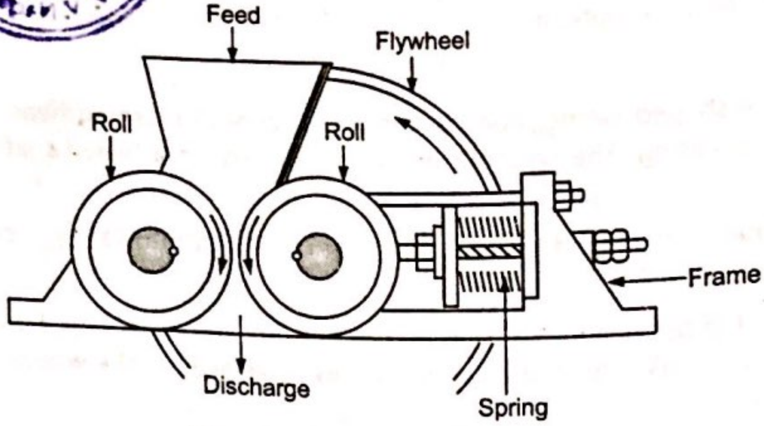

Fig. 2.3 : Smooth roll crusher

- Smooth-roll crusher consists of two heavy metal rolls (Fig. 2.3) of the same diameter placed side by side each other in the horizontal position. The rolls, mounted on shafts, are rotated towards each other at the same speed. One of the shafts moves in the fixed bearings while other moves in the movable bearings.
- The clearance between the rolls can be adjusted according to the size of feed and the size of product required. One of the rolls is driven directly and the other by friction with the solids being crushed. The rolls have relatively narrow faces and are large in diameter, therefore they can nip moderately large lumps. The material fed to the machine is reduced in size by compression and discharged from the bottom.
- The machine is protected by spring loading (i.e., by mounting the bearings of one of the roll shafts against coiled springs) against damage due to tramp and very hard material.
- The speed of rolls varies from 50 to 300 rev/min. Crushing rolls are secondary crushers accepting feed 12 to 75 mm in size and yielding products-12 mm to about 20 mesh.

Working :

- The material to be crushed is fed from the top. As the rolls rotate, the material gets caught between them and gets reduced in size by compression and discharged from the bottom.

Selection of Crushing rolls (Derivation of the angle of nip)

- In selecting the rolls for a certain duty, it is necessary to know the size of the feed and the size of the product.
- Consider a system as shown in Fig. 2.4 wherein the spherical particle B of a material is just being caught between the rolls. A and A' are the centres of two crushing rolls of radius r.

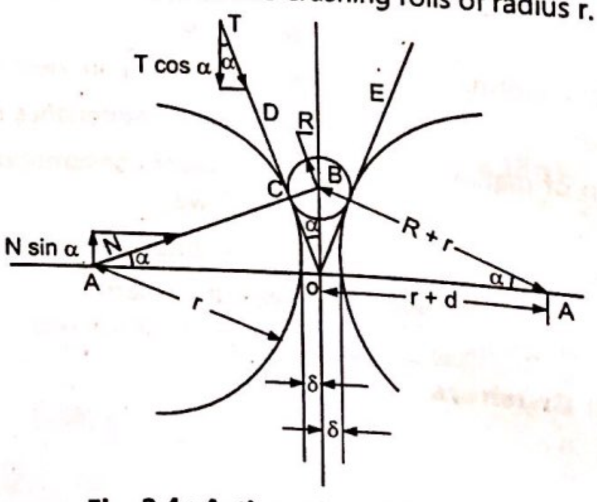

Fig. 2.4 : Action of crushing rolls

- The line AB passes through the centre of the left-hand roll, through the centre of particle, and through point C where the particle is in contact with the roll. Let the angle between line AB and the horizontal i.e. line joining two centres of rolls be 'α'. The line OD is tangent to the roll at point 'C'. As the line OD is perpendicular to line AB, it makes the same angle α with the vertical. Neglecting the gravity force, the two forces acting at point C are : the tangential frictional force T having a vertical component T cos α, and the radial force 'N', having a vertical component N sin α. The force T is related to the force N through the coefficient of friction μ, so T = μN.
- The vertical components of the forces T and N are opposed. Force N sin α (a resolved component of the force N) tends to expel the particle from the rolls, while force T cos α tends to draw the particle between the rolls. If the particle is to be drawn between the rolls and crushed,

$$T \cos \alpha \geq N \sin \alpha \qquad \text{... (2.10)}$$

T and N are related through

$$T = \mu N \qquad \text{... (2.11)}$$

$$\therefore \quad \mu N \cos \alpha \geq N \sin \alpha \qquad \text{... (2.12)}$$

$$\mu \geq \tan \alpha \qquad \text{... (2.13)}$$

- That is, the tangent of angle 'α' must be less than the coefficient of friction. The value of μ varies from material to material, but for all practical purposes, the value of the angle α is usually taken about 16°. The angle DOE, which is twice the angle α, is called the *angle of nip*.
- **Angle of nip** is the *angle formed by the tangents to the roll faces at a point of contact with a particle to be crushed.*
- Let R be the radius of the feed particle, r be the radius of the roll and 2d be the distance/gap between the rolls (the diameter of the largest particle in the product).
Then, in the triangle ABG (Fig. 2.5), the angle BAG is 'α' (half the angle of nip), AG is r + d, and AB is r + R. Then, from the simple geometry of the figure, the angle of nip is given by

$$\cos \alpha = \frac{AG}{AB} = \frac{r + d}{r + R} \qquad \text{... (2.14)}$$

- Equation (2.14) gives the relationship between the size of the feed, radius of rolls, gap between the rolls, and the angle of nip. With this equation, the roll diameter can be determined by knowing values of the size of feed, size of product and angle of nip.

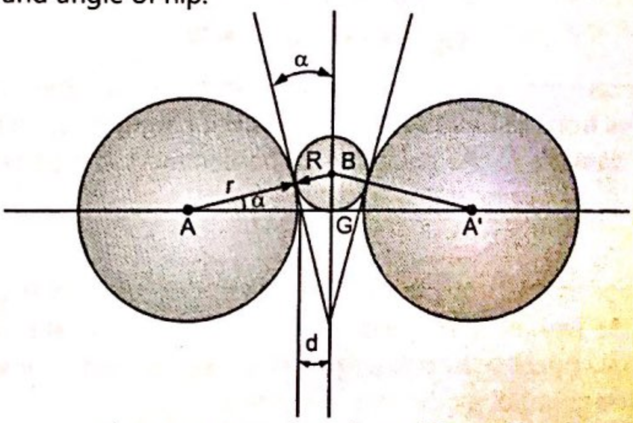

Fig. 2.5 : Capacity of crushing rolls

- If α = 16°, then cos α = 0.961 and we have

$$0.961 = (r + d)/(r + R) \qquad \text{... (2.15)}$$

- Crushing rolls are widely used for crushing of oil seeds and in the gun powder industry.

2.5 GRINDERS

- Grinding *means sub-dividing the solids to a finer product than crushing*. The size reduction machines employed for an intermediate duty are referred to as grinders. A grinder is often charged with the product from a crusher which it reduces to powder. The commercial grinders described in this section are hammer mills and revolving mills.

2.5.1 Hammer Mill

Principle :

Size reduction is achieved by impact and attrition.

Construction :

- The hammer mill consists of a high speed rotor turning inside a cylindrical casing. The rotor is mounted on a shaft which is usually horizontal. The swing hammers are pinned to a rotor disk. The hammers are rectangular bars of metal with plain or enlarged ends. In this mill, the particles are broken by the sets of swing hammers. The product falls through a grate or screen which forms the lower portion of the casing.

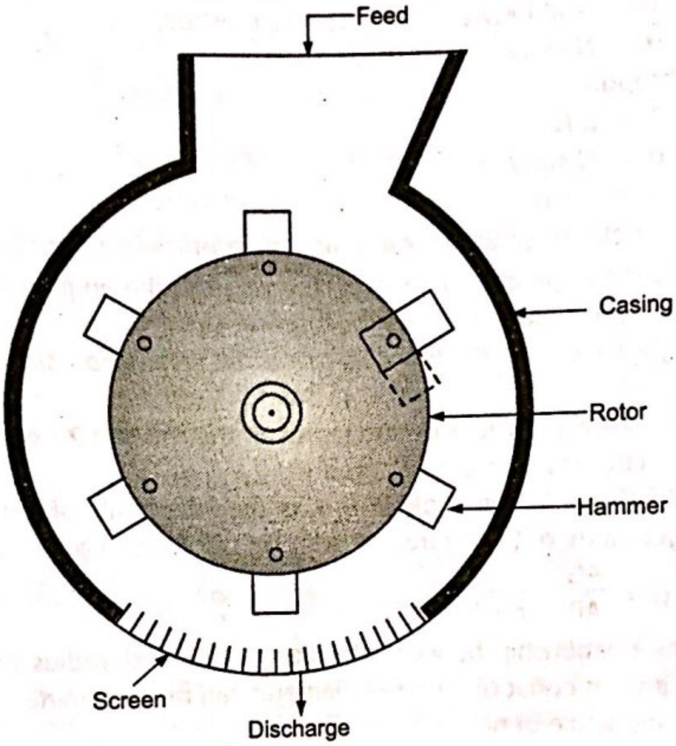

Fig. 2.6 : Hammer Mill

- Several rotor disks each carrying four to eight swing hammers are often mounted on a single shaft. The rotor disk diameter ranges from 150 mm to 250 mm. As the hammers are hinged, the presence of any hard material does not cause damage to the equipment. The hammers can be readily replaced when they wear out.

Working :

- The material to be crushed is fed from the top of the casing. The shaft is rotated at a high speed and centrifugal force causes the hammers to swing out radially. The material is beaten by the hammers around inside of the casing and by impact against the breaker plates (located on inside of the casing) or the screen. It is crushed until it is small enough to fall through the screen.
- Hammer mills are employed to grind tough fibrous solids like bark or leather, steel turnings, hard rock, sticky clay, etc.

2.5.2 Revolving Mills / Tumbling Mills

- *A revolving/tumbling mill is a cylindrical shell slowly rotating on a horizontal axis and charged with a grinding medium to about half of its volume.* The shell is usually made of steel and lined with abrasion resistant materials such as manganese steel, ceramic or rubber. The grinding medium is usually made of flint, ceramic or metal. Ball, pebble, tube and rod mills are the various types of revolving mills. The ball mill differs from the tube mill in that it is short in length; the length is approximately equal to its diameter.

- The grinding medium more commonly used in the ball mill is steel balls.
- The tube mill is usually long in comparison with its diameter; the length being twice the diameter or more. It employs smaller balls, and produces a finer product. The pebble mill is a tube mill employing flint or ceramic pebble as a grinding medium.
- The rod mill employs metal rods (steel rods) as a grinding medium and delivers more uniform product than any other revolving mills. In a ball mill, or pebble mill, much of the reduction is effected by impact, while in a rod mill, much of the reduction is effected by rolling, compression and attrition. The ball mill and pebble mill are very easy to operate and versatile in use.
- Revolving mills may be operated batchwise or continuously. In a batch machine, a known quantity of the material to be ground is charged into the mill through an opening in the shell. The opening is then closed and the mill is rotated for a certain time, and finally the product is discharged. In continuous mill, the material flows steadily through the revolving shell, entering and leaving through hollow trunions at opposite ends of the mill.

2.5.2.1 Ball Mill

- It is a mechanical device used to grind (crushed) materials (to powder form). The grinding medium is the balls (which are made of stainless steel, steel, ceramic or rubber).

Principle :

- It works on the principle of impact, i.e., size reduction is done by impact as the balls drop from near the top of the shell.

Construction :

- A ball mill consists of a hollow cylindrical shell rotating about its axis. The axis of the shell may be either horizontal or at a small angle to the horizontal. It is partially filled with balls. The grinding medium is the balls which may be made of steel, stainless steel or rubber.
- The inner surface of the cylindrical shell is usually lined with an abrasion-resistant material such as manganese steel or rubber. The length of the mill is approximately equal to its diameter.
- The balls occupy about 30 to 50 percent of the volume of the mill. The diameter of ball used is/lies in between 12 mm and 125 mm. The optimum diameter is approximately proportional to the square root of the size of the feed. The shell is rotated at low speed through a drive gear (60-100 rpm) and in a large ball mill, the shell might be 3 m in diameter and 4.25 m in length.

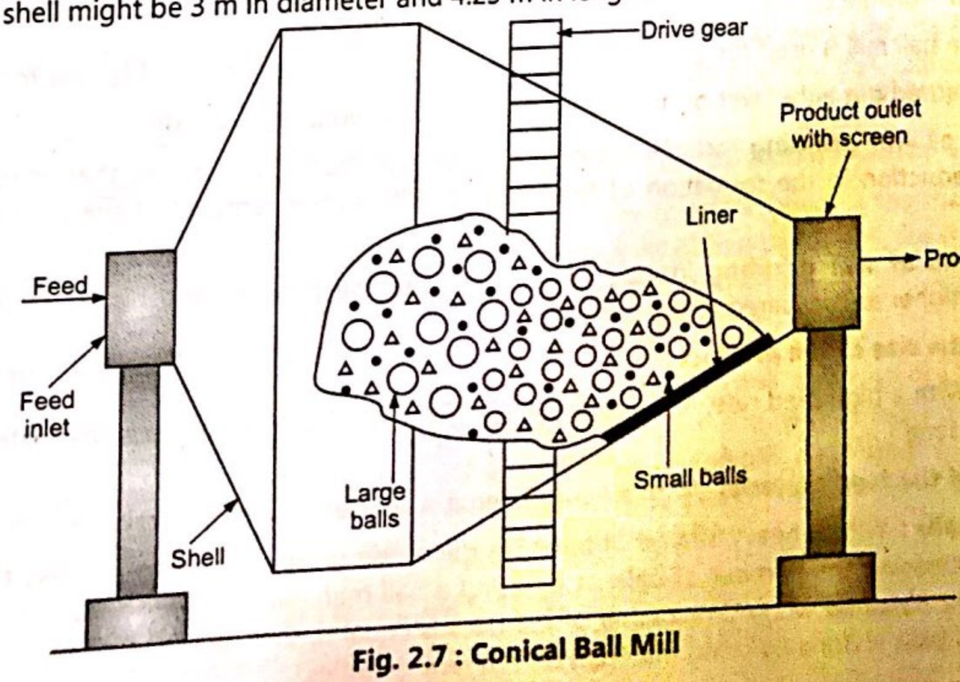

Fig. 2.7 : Conical Ball Mill

- The ball mill may be operated in a batch or continuous fashion, wet or dry. In a continuously operated mill as shown in Fig. 2.7, the outlet is normally covered with a coarse screen to prevent the escape of the balls.

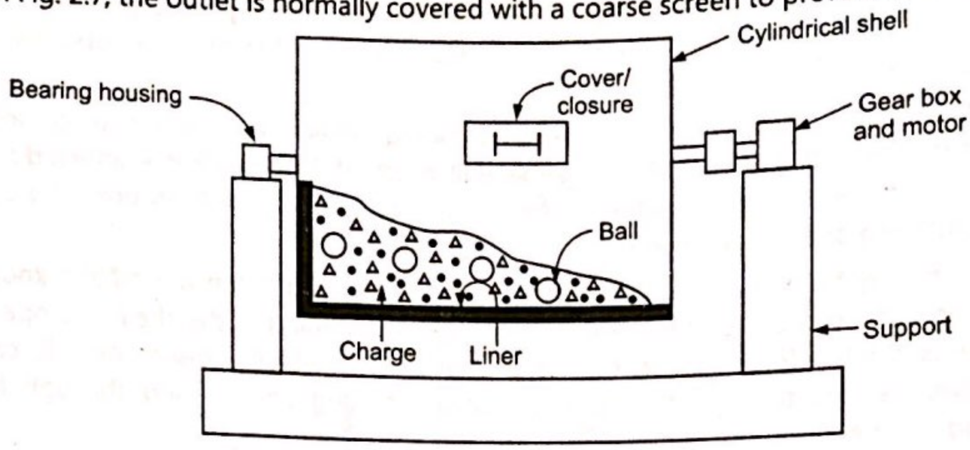

Fig. 2.8 : Batch operated Ball mill (Lab. scale)

Working :

- In case of continuously operated ball mill, the material to be ground is fed from the left through a 60° cone and the product is discharged through a 30° cone to the right. As the shell rotates, the balls are lifted up on the rising side of the shell and then they cascade down (or drop down on to the feed), from near the top of the shell. In doing so, the solid particles in between the balls are ground and reduced in size by impact.
- The mill contains balls of various ages and sizes since the balls continually wear by attrition and are replaced by new ones. As the shell rotates, the large balls segregate near the feed end and small balls segregate near the product end/discharge. The initial breaking of the feed particles is done by the largest balls dropping from the largest distance and small particles are ground by small balls dropping from a much smaller distance. If the rate of feed is increased, a coarser product will be obtained and if the speed of rotation is increased (less than critical speed), the fineness for a given capacity increases.
- During grinding, balls themselves wear and are constantly replaced by new ones so that mill contains balls of various ages and thus of various sizes.
- In case of batch operated mill, a known quantity of material to be ground is charged into the mill through the opening in the shell. The opening is then closed and the mill is rotated for a predecided time. It is then stopped and the product is discharged.

Applications : The ball mill is used for grinding materials such as coal, pigments, and felspar for pottery.

Grinding can be carried out either wet or dry but the former is carried at low speeds.

The advantages of wet grinding include lower power consumption (20-30% less than it for dry grinding), increased capacity, reduction in the formation of fines/dust, facilitates the removal of the product and no dust formation.

The disadvantages of wet grinding include necessity to dry the product and high wear on the grinding medium (about 20% higher as compared to dry grinding).

Factors influencing the size of the product :

(a) Feed rate : With a high feed rate, less size reduction is resulted since in this case the material is in the mill for a shorter time.

(b) Properties of the feed material : With a hard material, a smaller size reduction is achieved.

(c) Weight of balls : With a heavy charge of balls, we get a fine product. We can increase the weight of the charge by increasing the number of balls or by using a ball material of higher density. Optimum grinding conditions are obtained when the volume of the balls is equal to 50% that of the mill. So the variation in the weight of balls is done by using materials of different densities.

(d) **Speed of rotation of the mill :** At low speeds, the balls simply roll over one-another and little grinding is obtained, while at very high speeds, the balls are simply carried along the walls of the shell and little or no grinding takes place. So for an effective grinding, the ball mill should be operated at a speed (optimum speed) equal to 50 to 75 percent of the critical speed.

(e) **Level of the material in the mill :** A low level of material in the mill results into a reduction in the power consumption. If the level of material is increased, the cushioning action increases and power is wasted by the production of undersize material in an excessive quantity.

Advantages of the Ball Mill :

(i) The cost of installation is low.

(ii) The cost of power required is low.

(iii) It is suitable for materials of all degrees of hardness.

(iv) It is suitable for batch as well as continuous operation.

(v) It can be used for grinding of certain explosive materials since it can be used with an inert atmosphere.

(vi) It is suitable for open as well as closed circuit grinding.

(vii) The grinding medium is cheap.

Action in Revolving / Tumbling mills

- When the revolving mill is in operation, the balls are picked up by the mill wall and are carried near the top of the mill. The balls then break contact with the wall and drop down to the bottom. During the upward movement of the balls, centrifugal force keeps the balls in contact with the wall and with each other. The balls when in contact with the wall surface, perform some grinding by slipping and rolling over each other, but most of the grinding takes place when free falling balls strike the bottom of the mill (by impact).
- The balls are projected across the mill depending upon the speed of rotation. At low speeds of operation, the balls simply roll over each other resulting into little crushing action. If the mill is operated at slightly higher speeds, the balls will be carried up further inside the mill and greater will be the power consumption. But at the same time, as the balls fall down from higher distances, greater will be the impact at the bottom, and larger will be the capacity of the mill.
- If the mill is operated at very high speeds, the balls are carried right round in contact with the sides of the mill and the mill is said to be **centrifuging**.
- *The minimum speed at which centrifuging occurs* is called the **critical speed** of the mill, and under these conditions, centrifugal force will be exactly balanced by the weight of the ball. Little or no grinding takes place when the mill is centrifuging.
- If the mill is to operate practically, the **operating speed** must be less than the **critical speed.**
- The critical speed of a grinding mill (e.g., a ball mill) is the rotation speed of the mill where a centrifugal force is exactly balanced by a gravitational force at the inside shell surface of the mill. It is the speed at which balls will not fall away from the inside surface of the shell of the mill.

Derivation of critical speed of a ball mill

- The speed at which the outermost balls break contact with the wall depends on the balance between centrifugal force and gravitational force. This can be shown with the help of Fig. 2.9. Consider the ball at point B on the periphery of the ball mill. Let R be the radius of the mill and r be the radius of the ball. R–r represents the distance between the centre of the ball and the axis of the mill. Let 'α' be the angle between OB and vertical through the point O. The forces acting on the ball are :

  1. The force of gravity, mg where 'm' is the mass of the ball and
  2. The centrifugal force, $mv^2/(R - r)$, where 'v' is the peripheral speed.

- The component of gravity opposing the centrifugal force (centripetal component) is (mg) cos α. As long as the centrifugal force exceeds the centripetal component of the force of gravity, the particle will not lose contact with the wall. As the angle α decreases, the centripetal force increases. Unless the speed crosses the critical value, a stage is reached where the above opposing forces are equal and the ball is ready to fall away from the wall. The angle at which the said phenomenon occurs is found out by equating the two opposing forces. Thus,

$$mg \cos \alpha = \frac{mv^2}{(R-r)} \quad \text{... (2.16)}$$

$$\cos \alpha = \frac{v^2}{(R-r)\,g} \quad \text{... (2.17)}$$

The relationship between the peripheral speed and the speed of rotation is given by

$$v = 2\pi N (R-r) \quad \text{... (2.18)}$$

Substituting the value of v from equation (2.18) into equation (2.16), we get

$$\cos \alpha = \frac{4\pi^2 N^2 (R-r)}{g} \quad \text{... (2.19)}$$

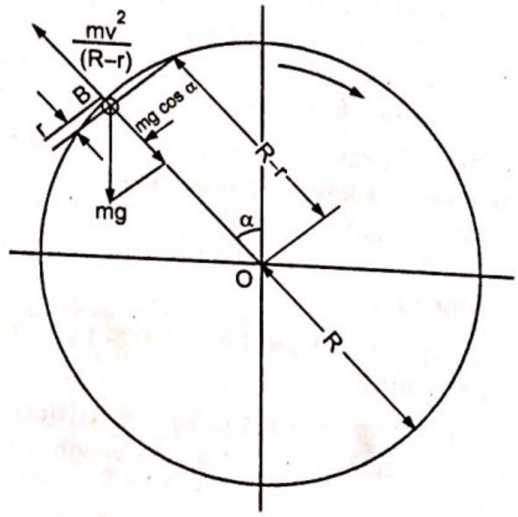

Fig. 2.9 : Forces on ball in Ball mill

At the critical speed : α = 0, and thus cos α = 1 and N becomes the critical speed N_c.

$$\therefore \quad \cos \alpha = 1 = \frac{4\pi^2 N_c^2 (R-r)}{g} \quad \text{... (2.20)}$$

$$N_c^2 = \frac{g}{4\pi^2 (R-r)} \quad \text{... (2.21)}$$

$$N_c = \frac{1}{2\pi}\sqrt{\frac{g}{R-r}} \quad \text{... (2.22)}$$

The operating speed/optimum speed of the ball mill is between 50 and 75 percent of the critical speed.

Scanned with CamScanner

2.6 COMPARISON OF CRUSHING AND GRINDING OPERATION

Crushing as well as grinding are aimed at size reduction. But there are certain differences in these operations which are cited below.

Crushing	Grinding
1. The solid particles are reduced in size by compression.	1. The solid particles are reduced in size by impact and attrition.
2. It is aimed at breaking large pieces of solid material into small lumps.	2. It is aimed at reducing crushed feed to powders.
3. Mostly crushing equipments are operated in open-circuit.	3. Grinding equipments are always operated in closed-circuit.
4. When crushers are operated in closed-circuit, dry screens are used as a size separation unit.	4. In grinders operated in closed-circuit, some sort of classifier is used as a size separation unit.
5. This operation is performed on dry feed material.	5. This operation can be performed on dry as well as wet feed.
6. In crushing operation, the reduction ratio seldom exceeds 6 to 8.	6. In grinding operation, the reduction ratio as high as 100 is possible.
7. Crushing is usually one shift operation as residence time in the crusher is less and throughput is large.	7. Grinding is carried out in all shifts as in the grinding machines the residence time is larger and throughput is smaller.
8. Crushers are of two types, e.g., primary crushers and secondary crushers.	8. Grinders are of two types, e.g., fine grinders and ultrafine grinders.
9. Crushers are heavy duty, low speed machines.	9. Grinders are relatively light duty, high speed machines.
10. In coarse crushing, the feed size is 1500 to 40 mm and product size is 50 to 5 mm.	10. In fine grinding, the size of feed is 5 to 2 mm and product size is 0.1 mm (about 200 mesh).
11. Energy consumption per unit mass of product is low due to coarse particle production.	11. Energy consumption per unit mass of product is high due to fine particle production.

Ultrafine Grinders

- Many commercial powders must contain particles averaging 1 to 20 μm in size. Mills which reduce solids to such fine particles are called as **ultrafine grinders**.

2.7 FLUID ENERGY MILL

- Grinding takes place by attrition.
- A fluid energy mill is a size reduction unit in which size reduction results from attrition between rapidly moving particles of the material being ground. A source of compressed air or gas or high pressure superheated steam that enters the grinding chamber through nozzles in the periphery at high speed provides energy to the particles to achieve high velocities.
- In fluid energy mill there is no moving parts and no grinding media.
- It consists of a flat horizontal cylindrical chamber provided with tangentially arranged jet nozzles in the inner wall. The energy for milling (grinding) is supplied by a compressed air or nitrogen gas. The compressed air/gas issuing through the nozzles forms a very high velocity tangential circle within the grinding chamber. The material to be ground is fed into the same tangential circle through a venturi feeder. The material in the circle gets rapidly accelerated, causing it to impact against itself, hence breaking the particles to the low micron range. The particles that are larger in size are held towards the outer periphery of the chamber by centrifugal force, while the particle smaller in size travel in a spiral movement towards the central outlet from where they exit into a cyclone below for bottom discharge.

- The fluid energy mill can handle powders having an initial size ranging from 150 microns and can g materials upto one micron. Usually powders from pulverizers are handled in it. The materials that can processed include food products, antibiotics, pigments, dyes, cosmetics, etc.

2.8 OPEN-CIRCUIT AND CLOSED-CIRCUIT GRINDING

- In many machines, the feed material is reduced to satisfactory size by passing it once through the machi
- If the material is passed only once through the machine (crushing or grinding), and no attempt is made return the oversize material to it for further reduction, the process is known as *open-circuit grinding.*
- If the partially ground material from the machine is sent to a size separation unit, from where the unders is withdrawn as the product and the oversize material is returned to the machine for reground, the proc is known as *closed-circuit grinding.*
- In case of coarse particles, the size separation unit is a screen or grizzly while it is some form of classifie case of fine powders. Closed-circuit grinding though useful for any crusher, it is commonly employed machines yielding a fine product.

2.8.1 Open Circuit Grinding

- Open circuit grinding consists of one or more grinding mills arranged in series or parallel witho classification equipment. This method discharges a final ground as it comes from a mill and there is n return of coarse discharge back to the mill.
- Some examples of open circuit grinding are : (i) Ball mill, (ii) Rod mill and (iii) Combination of ball mill ar rod mill.

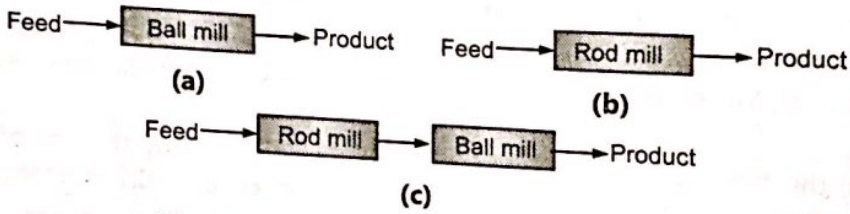

Fig. 2.10 : Open circuit grinding systems

- Some conditions that favour open circuit grinding are : (i) Small reduction ratios and (ii) Coarse reductio of particles.
- Advantages of open circuit grinding are : (i) Simplicity of operation, (ii) Minimum equipment requirements

2.8.2 Closed Circuit Grinding

- Closed circuit grinding consists of one or more grinding mills with classification equipment. The mill discharge ground product to classifier which returns the coarse product from it to the mill for furthe grinding.
- Some examples of closed circuit grinding are : (i) Ball mill and classifier, (ii) Rod mill and classifier and (iii) Rod mill, ball mill and classifier.

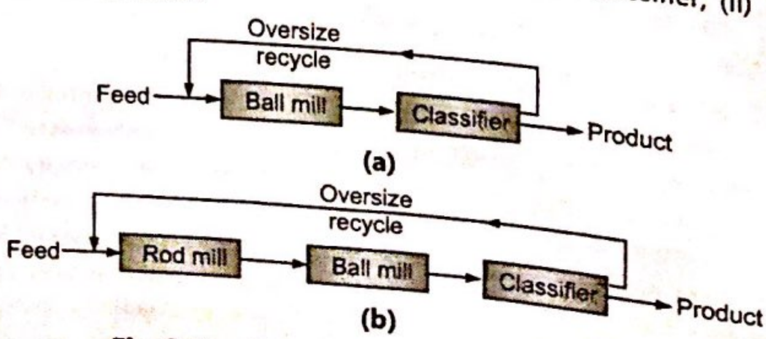

Fig. 2.11 : Closed circuit grinding systems

- Some advantages of closed circuit grinding are : (i) higher capacity, (ii) lower power consumption per ton of product, (iii) suitable for reduction to fine and ultrafine sizes, (iv) avoids coarse material in the final ground product by returning it to the mill, (v) eliminate overgrinding by removing fines early.
- Some conditions that favour closed circuit grinding are : (i) larger reduction ratios and (ii) fine reduction of particles.

The equipments which are used in industry are :

1. Jaw crusher in Cement Industry.
2. Ball mill in Paint Industry.
3. Ultrafine grinders in Cosmetic and Pharmaceutical Industries.
4. Cutters in Leather Tanning Industry.
5. Hammer mill in Food Industry.

Size reduction operation is carried out in coal washeries, ore processing, cement industry, paint industry, chemical industry and food processing industry.

SOLVED EXAMPLES

Example 2.1 : *A certain crusher accepts a feed material having a volume-surface mean diameter of 19 mm and gives a product of volume-surface mean diameter of 5 mm. The power required to crush 15 tonnes per hour is 7.5 kW. What will be the power consumption if the capacity is reduced to 12 tonnes per hour ?*

Solution : We have,

$$\frac{P}{\dot{m}} = K_r\left[\frac{1}{\bar{D}_{sb}} - \frac{1}{\bar{D}_{sa}}\right]$$

where P is the power consumption in kW, $\dot{m}$ is the feed rate in t/h and $\bar{D}_{sb}$, $\bar{D}_{sa}$ is the surface-volume mean diameters of product and feed respectively.

Case I : $P = 7.5$ kW, $\dot{m} = 15$ t/h, $\bar{D}_{sb} = 5$ mm $= 0.005$ m , $\bar{D}_{sa} = 19$ mm $= 0.019$ m

$$\frac{7.5}{15} = K_r\left[\frac{1}{0.005} - \frac{1}{0.019}\right]$$

$$K_r = \mathbf{3.4 \times 10^{-3}}$$ ... **Ans.**

Case II : $\dot{m} = 12$ t/h, $P = ?$, $K_r = 3.4 \times 10^{-3}$

$$\frac{P}{12} = 3.4 \times 10^{-3}\left[\frac{1}{0.005} - \frac{1}{0.019}\right]$$

$$P = \mathbf{6\ kW}$$ ... **Ans.**

Example 2.2 : *What will be the power required to crush 150 tonnes per hour of limestone if 80 percent of the feed passes 50 mm screen and 80 percent of the product a 3.125 mm screen ?*

Work index of limestone = 12.74.

Solution : We have,

$$\frac{P}{\dot{m}} = 0.3162\ W_i\left[\frac{1}{\sqrt{D_{pb}}} - \frac{1}{\sqrt{D_{pd}}}\right]$$

In this equation, P is in kW and D_p is in mm.

$\dot{m} = 150$ t/h, $W_i = 12.74$

D_{pb} = product size = 3.125 mm

D_{pa} = feed size = 50 mm

$$\frac{P}{150} = 0.3162 \times 12.74\left[\frac{1}{\sqrt{3.125}} - \frac{1}{\sqrt{50}}\right]$$

$$P = \mathbf{256.4\ kW}$$ ... **Ans.**